An enhanced gamma/hadron discrimination using next-generation water Cherenkov detectors powered by Machine Learning techniques

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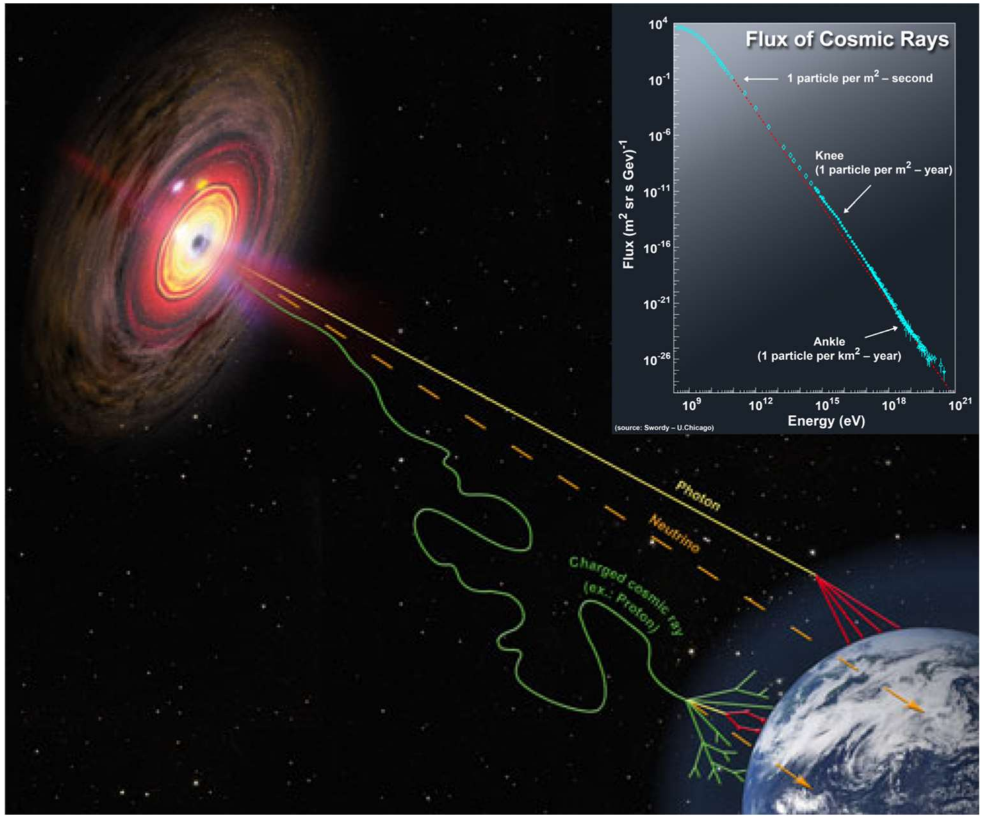
IDPASC PhD grant PRT/BD/151553/2021

Very high-energy gamma-rays

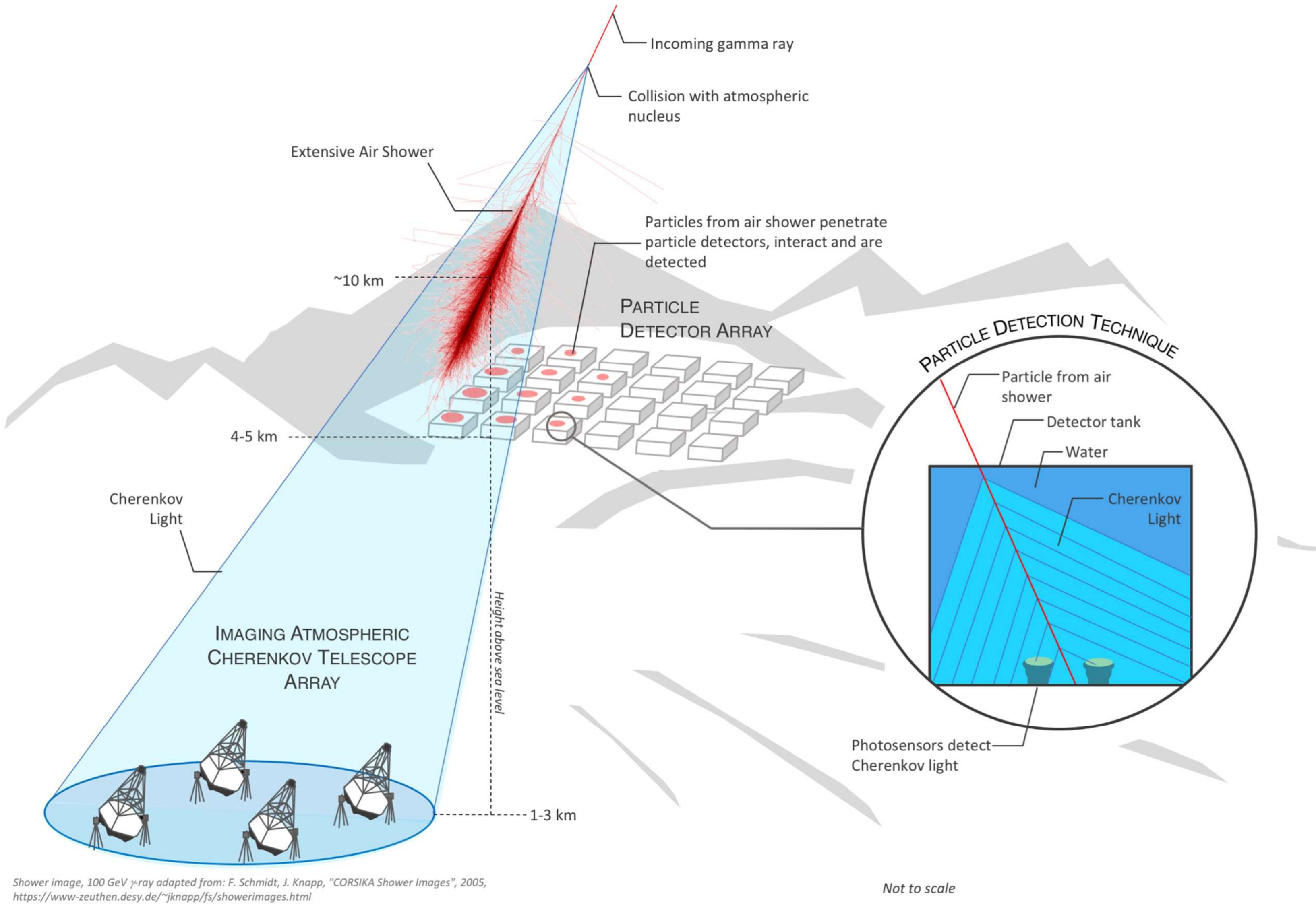
- Extremely energetic photons
  - From few hundreds of GeV up to the PeVs
  - They point to their production source

- Gamma-rays are related to some of the most extreme and energetic non-thermal events taking place in the Universe such as Gamma-ray Bursts (GRBs)

- Test the existence of new physics at fundamental scales beyond the standard model as for example Dark matter indirect searches

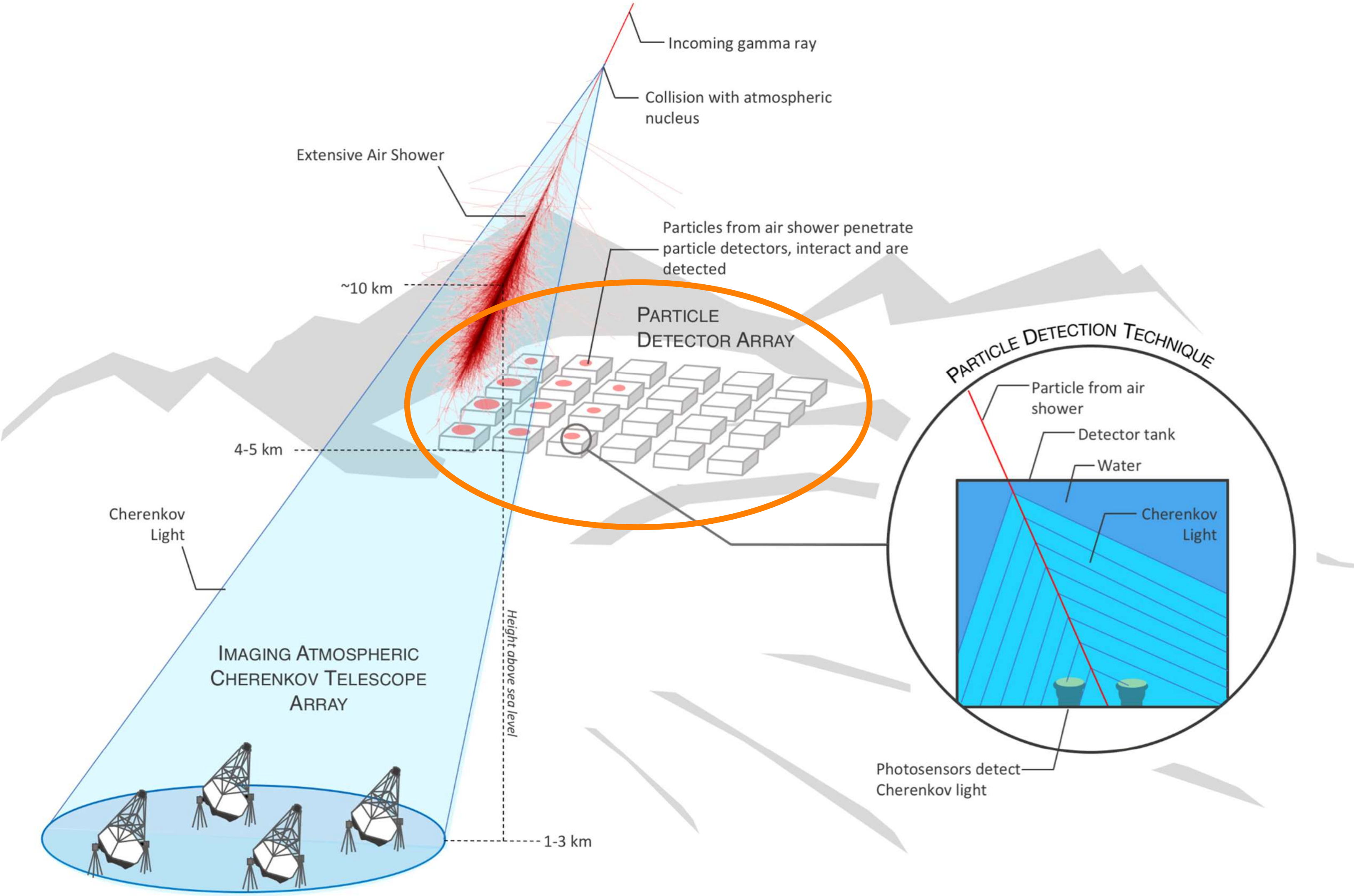


Indirect gamma-ray detection techniques



Source: https://www.swgo.org/

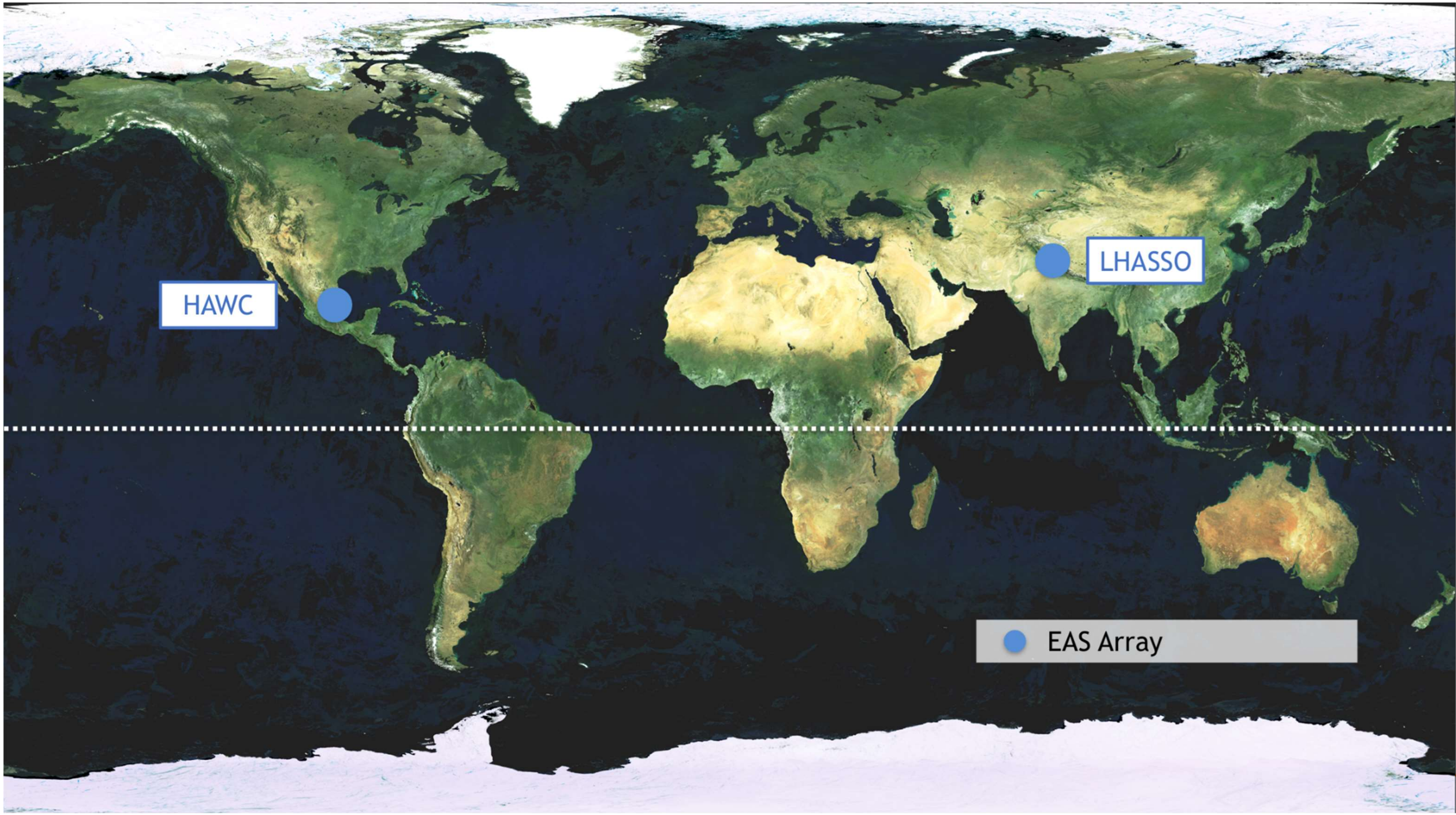
Indirect gamma-ray detection techniques



Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Source: https://www.swgo.org/

Current EAS arrays



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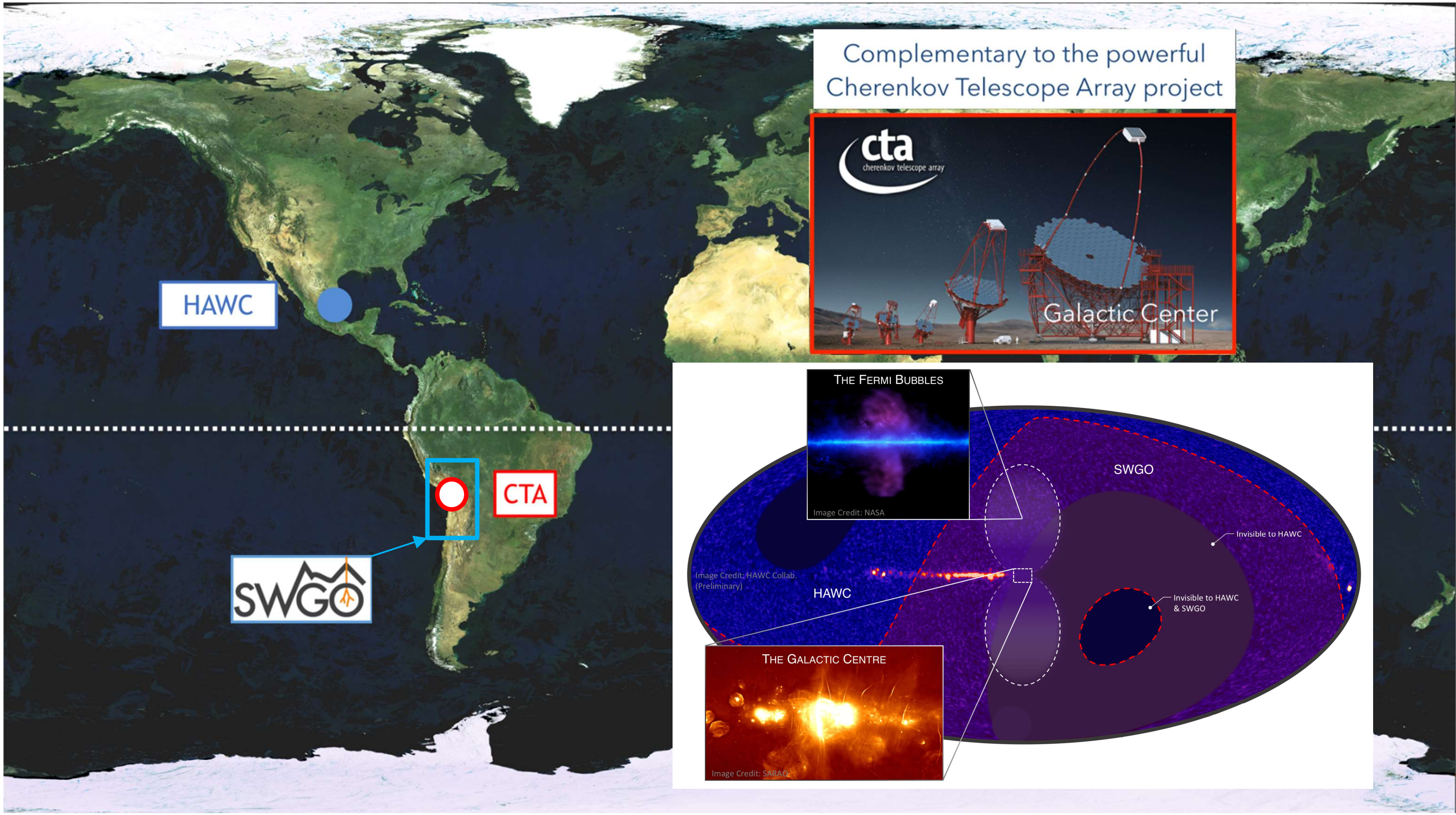
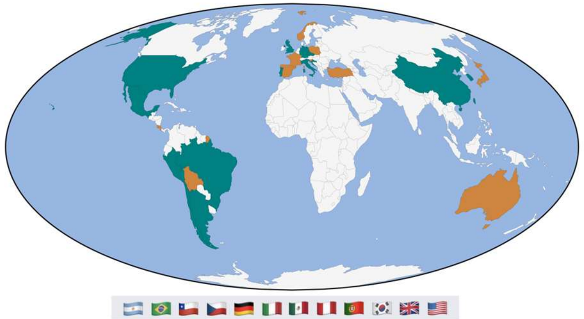


Southern **W**ide-field **G**amma-ray **O**bservatory: **SWGO**

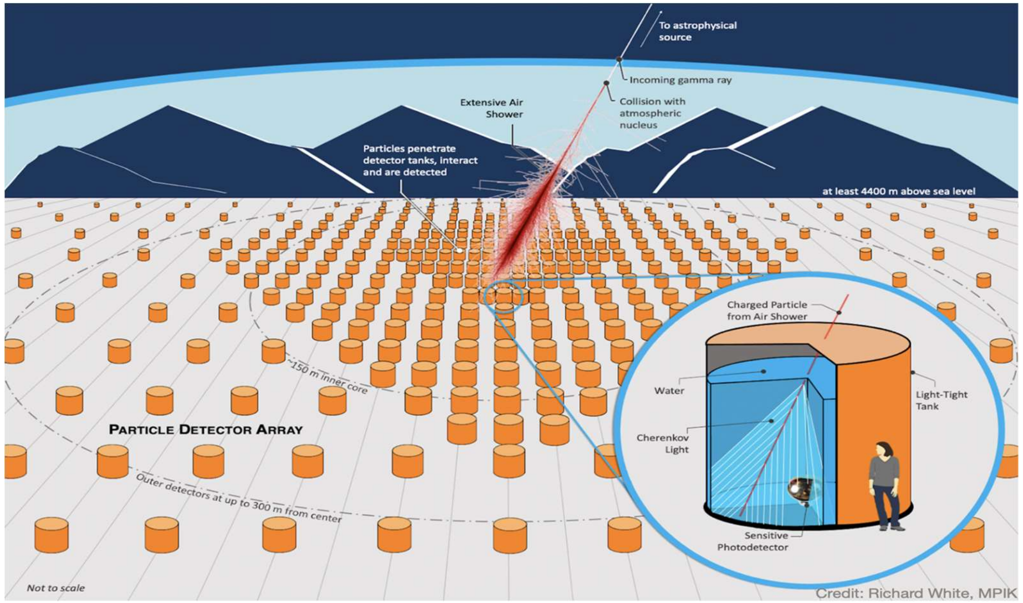
~3-year R&D project to design and plan the next generation wide field-of-view gamma-ray able to survey and monitor the Southern sky

- **S**outhern **W**ide-field **G**amma-ray **O**bservatory: **SWGO**
  - Formed at July 1st 2019
  - 14 Countries
  - ~ 50 institutes
  - More than 100 scientists
  - To be built in South America at a latitude between 10 and 30 degrees south.

The Southern Wide-field Gamma-ray Observatory

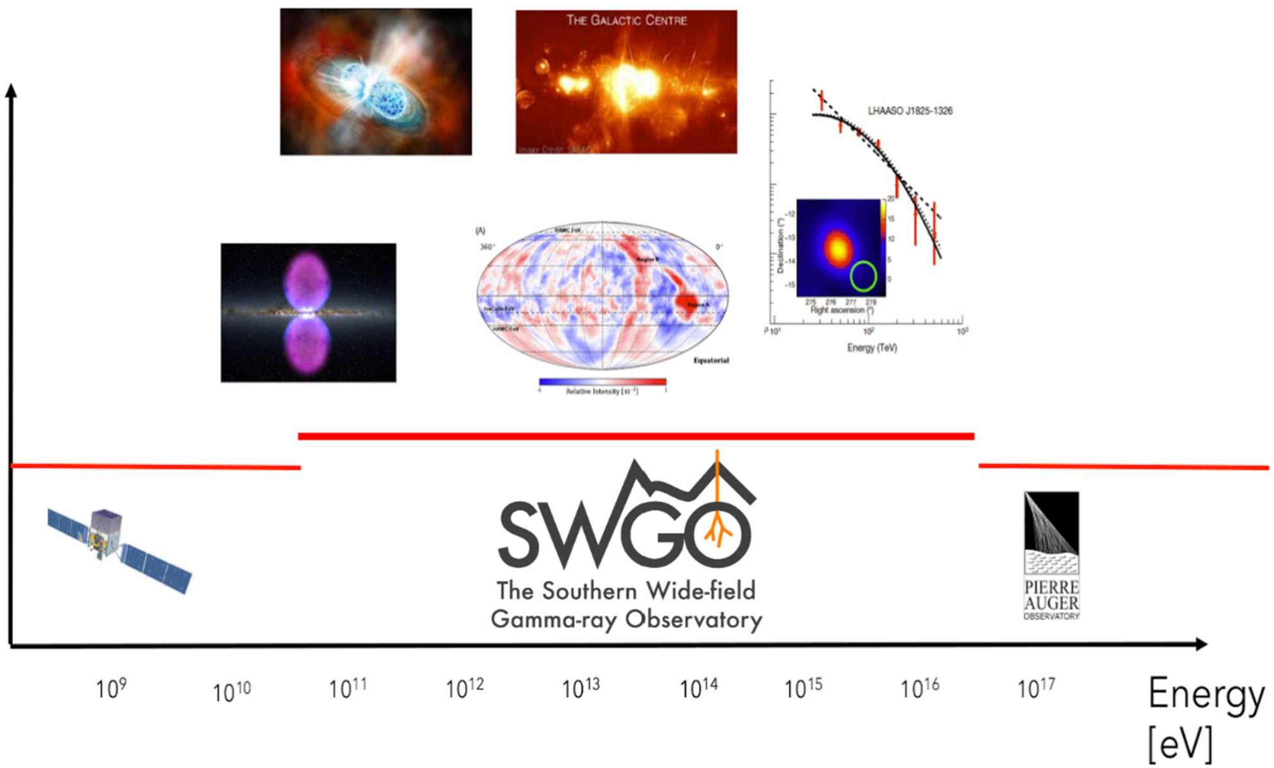


	SWGO R&D Phase Milestones	
✓	M1	R&D Phase Plan Established
✓	M2	Science Benchmarks Defined
✓	M3	Reference Configuration & Options Defined
✓	M4	Site Shortlist Complete
✓	M5	Candidate Configurations Defined
	M6	Performance of Candidate Configurations Evaluated
	M7	Preferred Site Identified
	M8	Design Finalised
	M9	Construction & Operation Proposal Complete



Source: https://www.swgo.org/

Energy range covered with SWGO

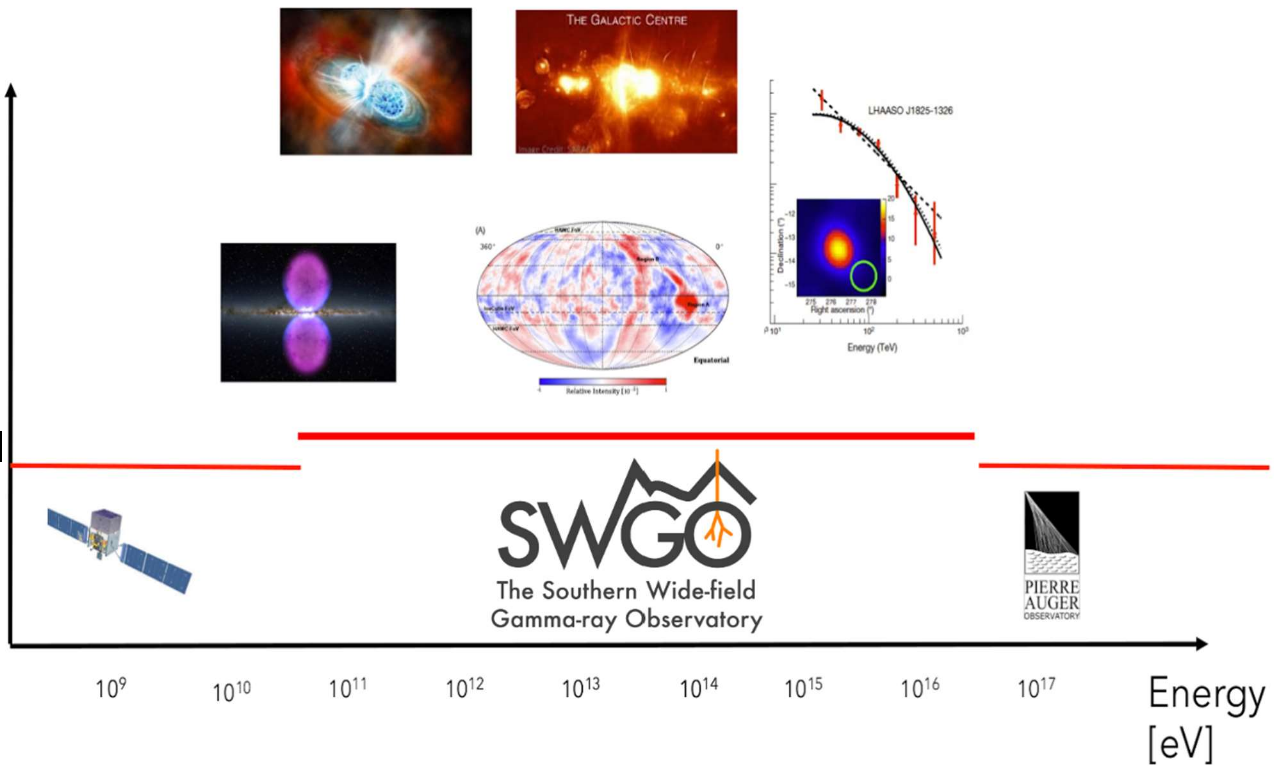


From a few hundreds of GeV to many tens of PeV.

Energy range covered with SWGO

Lowest energies:

- High altitude
- Compact array
- Dedicated ground detector design



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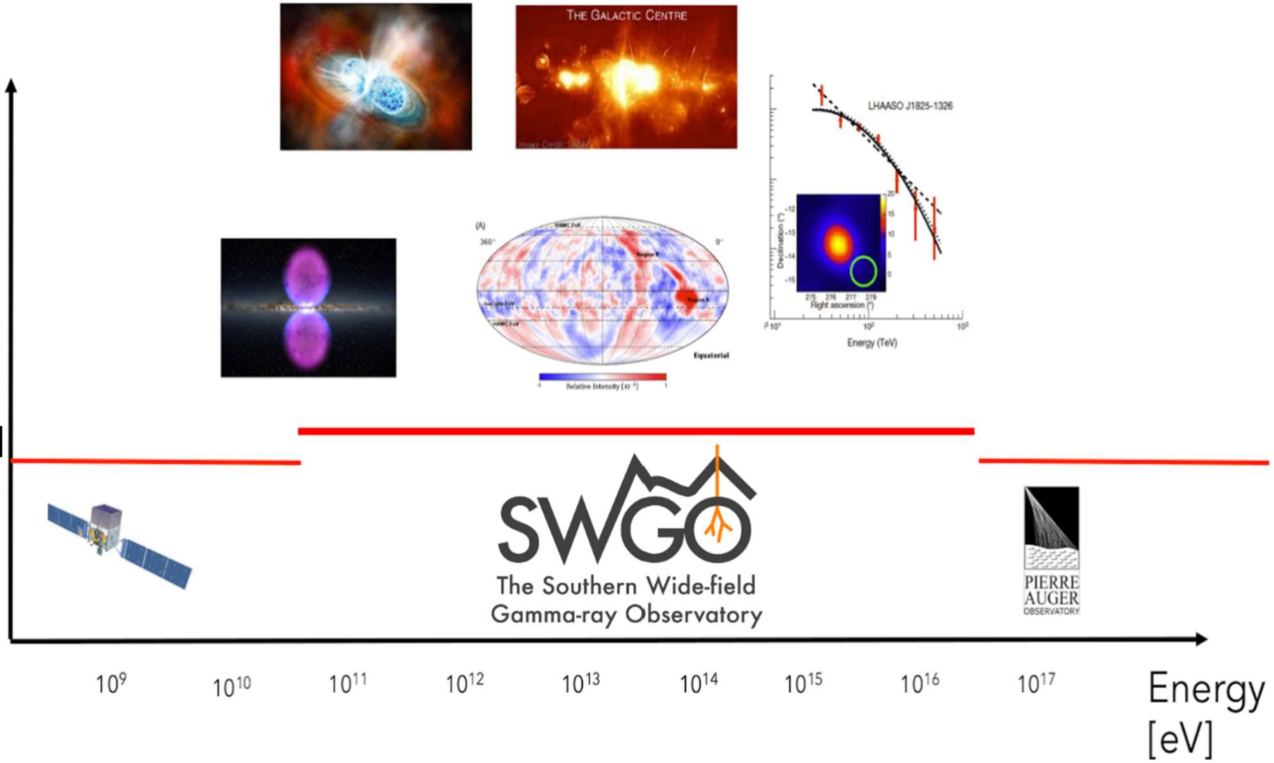
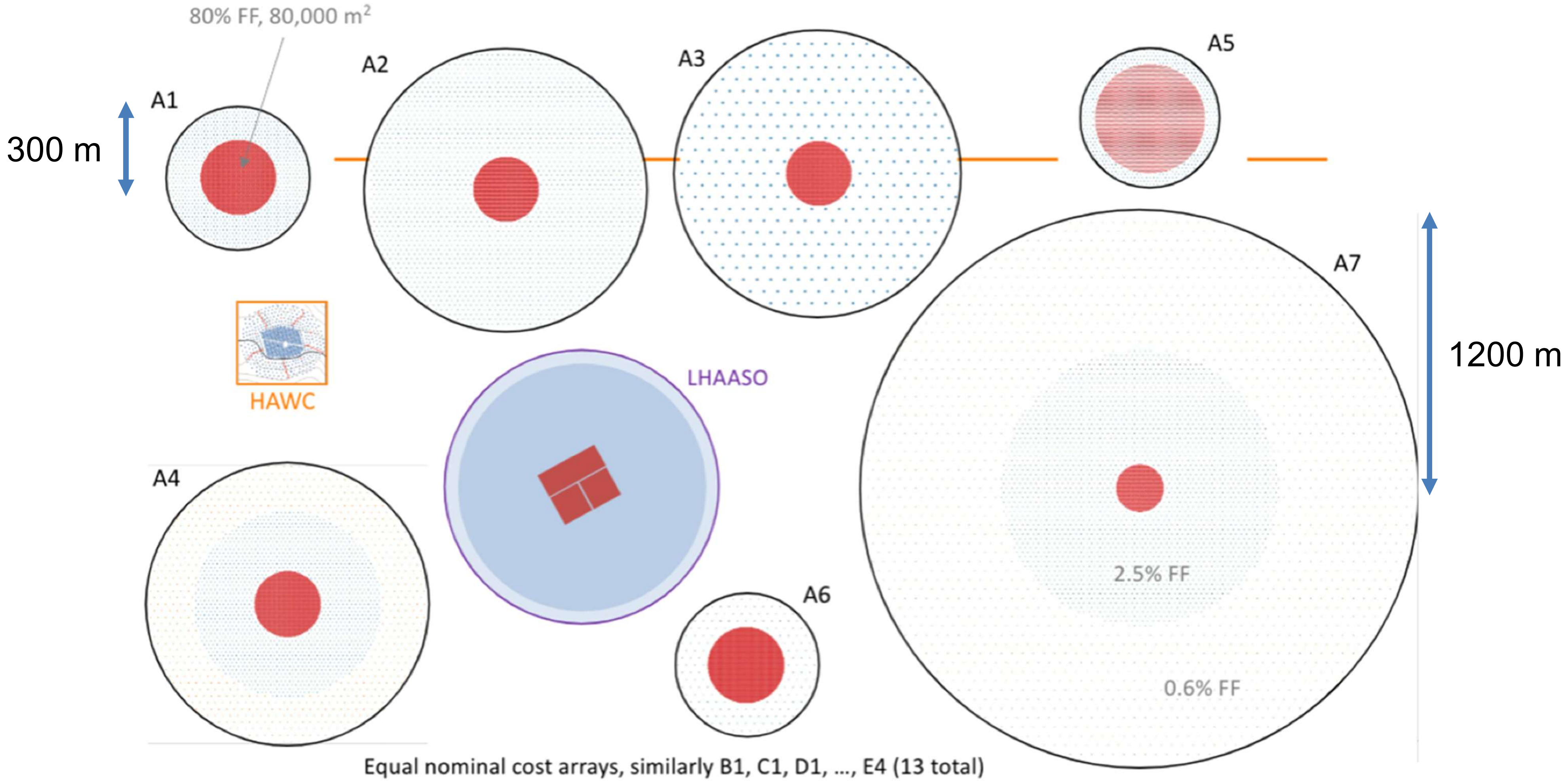


Highest energies:

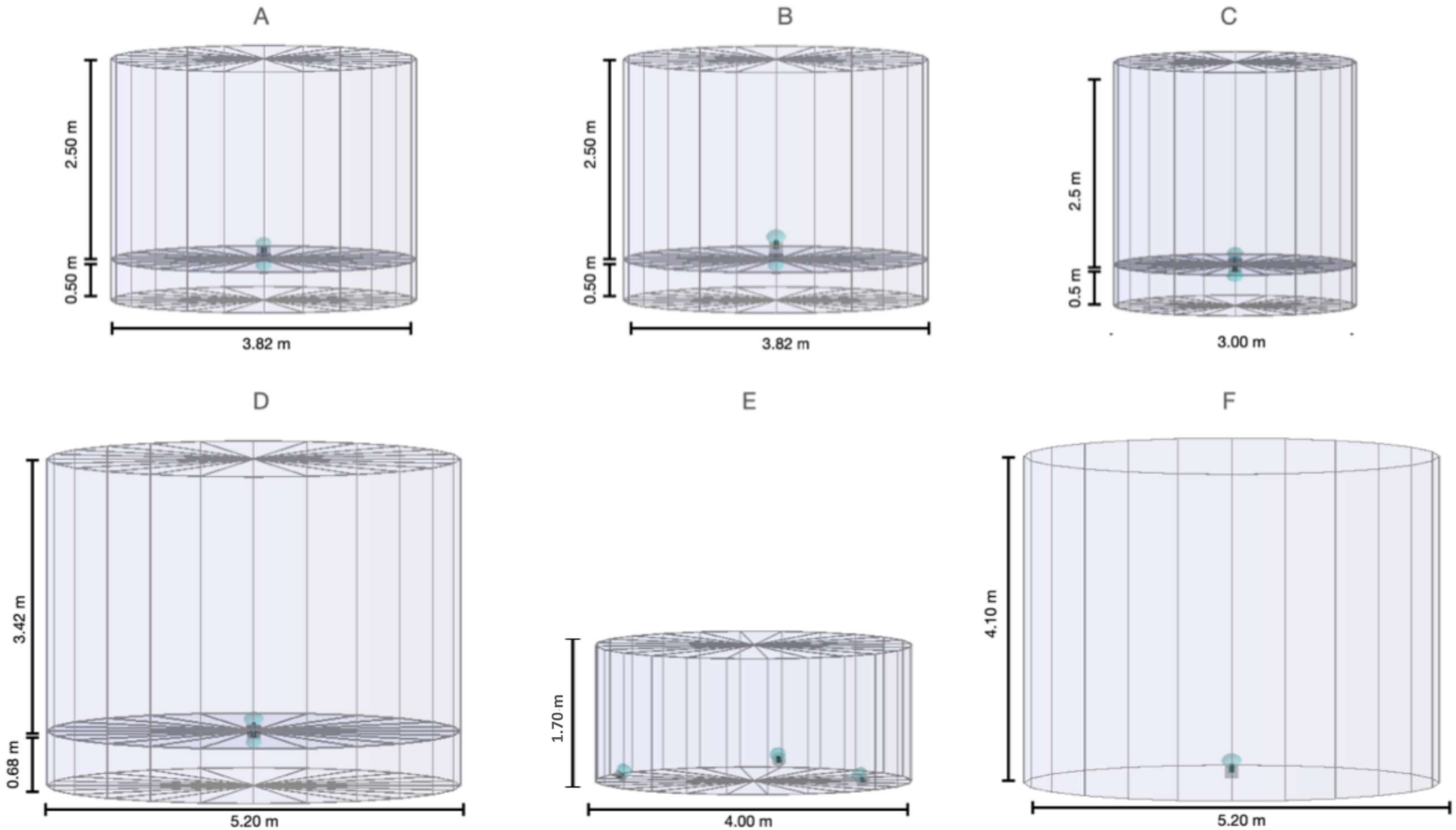
- Large array area (~1 km² or more)
- Modular
- Sparse array

From a few hundreds of GeV to many tens of PeV.

Explore different array layout configurations

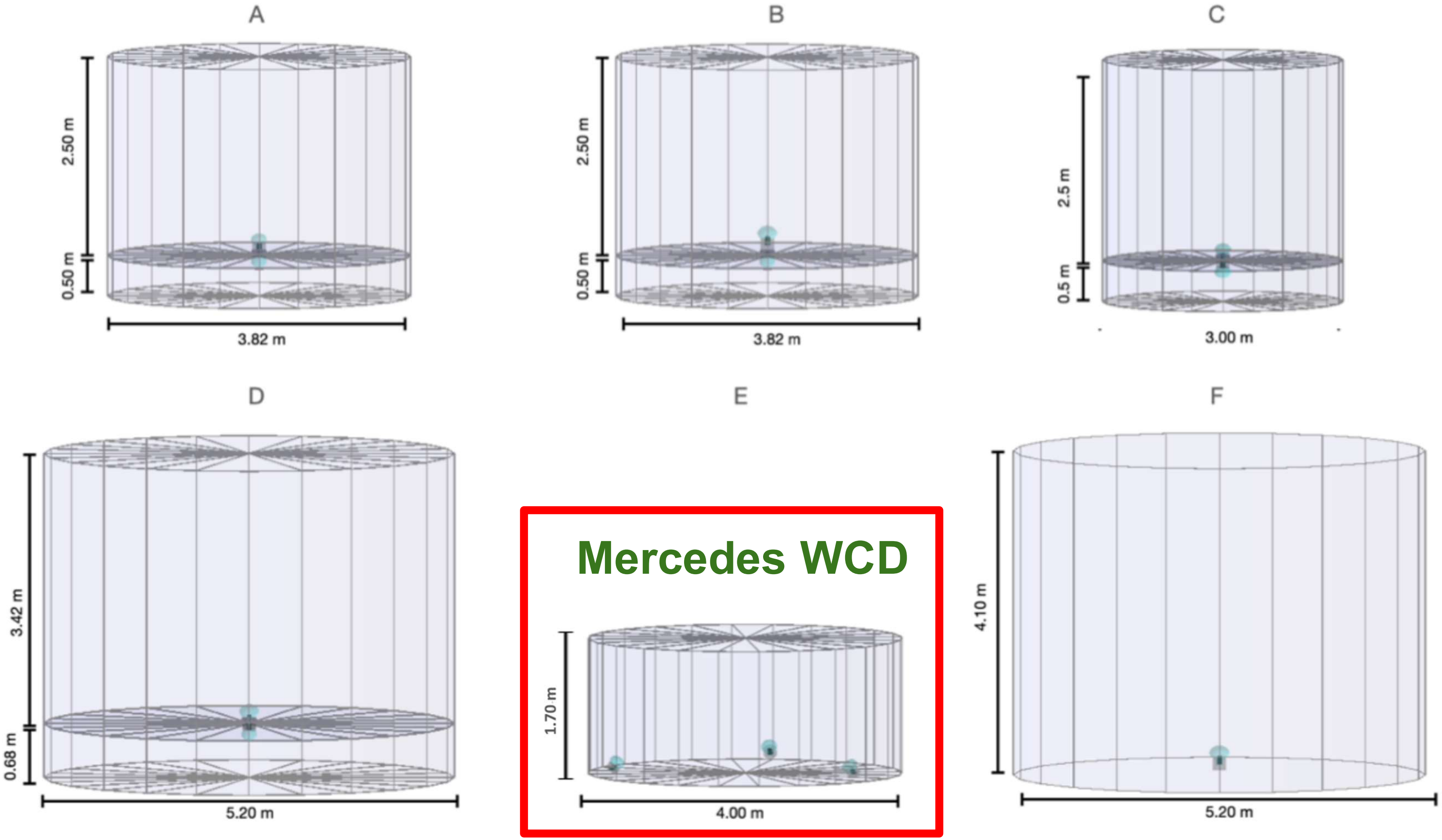


Possible WCD options



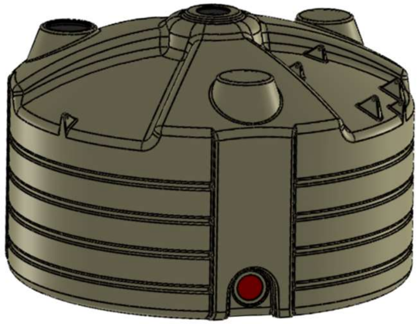
WCD design is essential for muon tagging and gamma/hadron discrimination

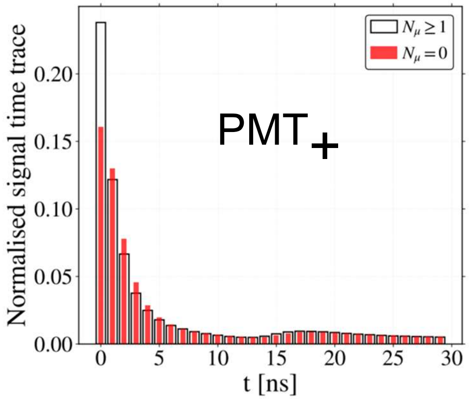
Possible WCD options

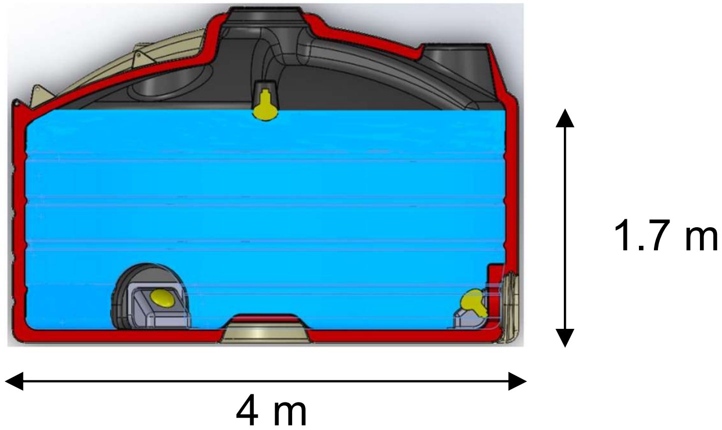


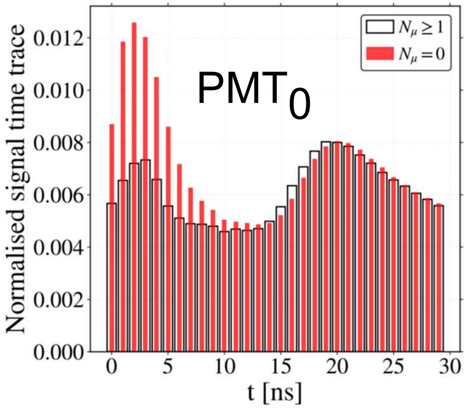
WCD design is essential for muon tagging and gamma/hadron discrimination

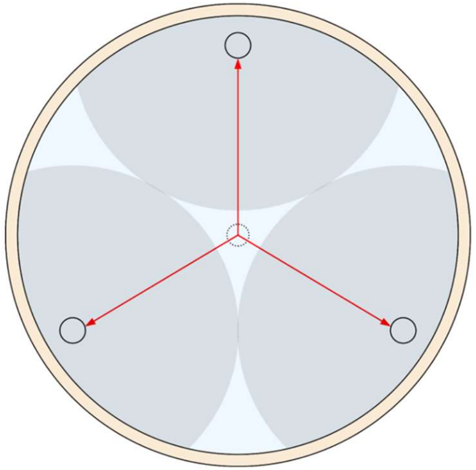
The Mercedes WCD

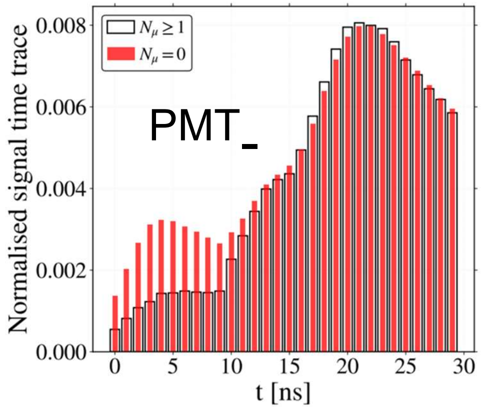








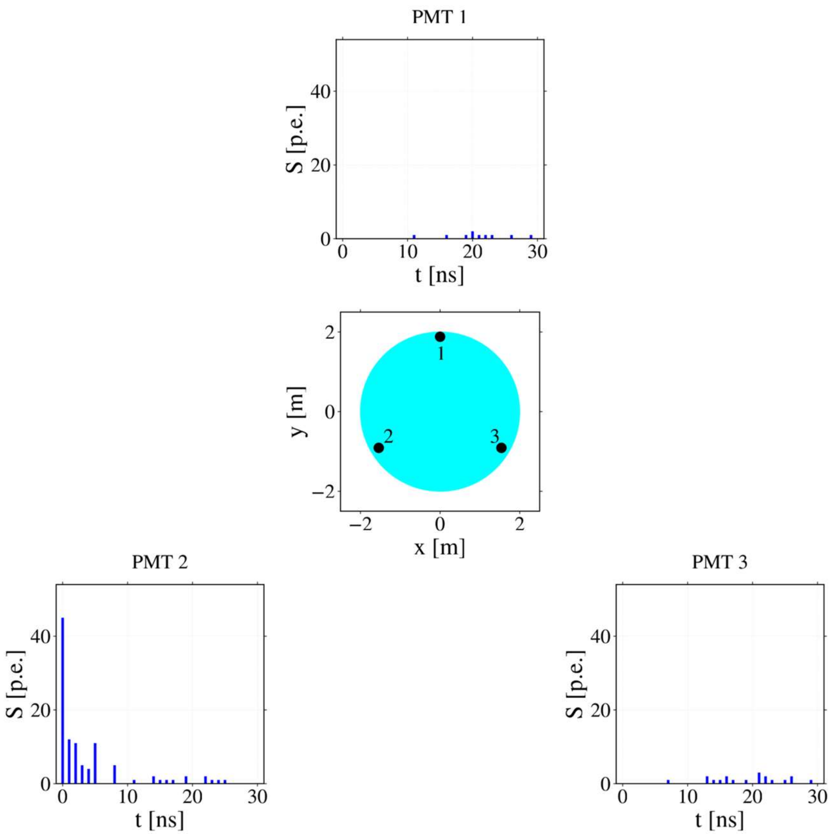


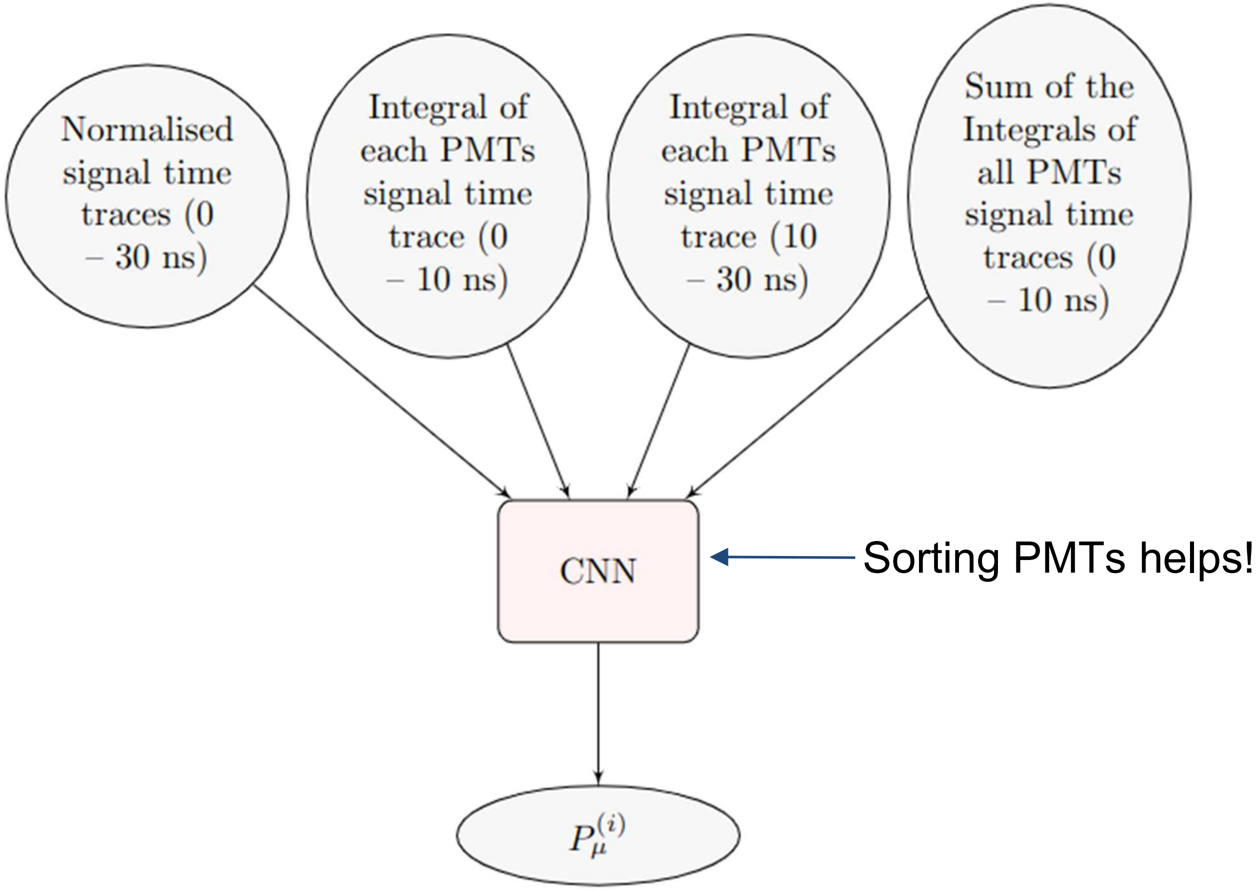


Dimensions optimised for Single Muon identification:

Maximisation of the signal asymmetry.

ML model



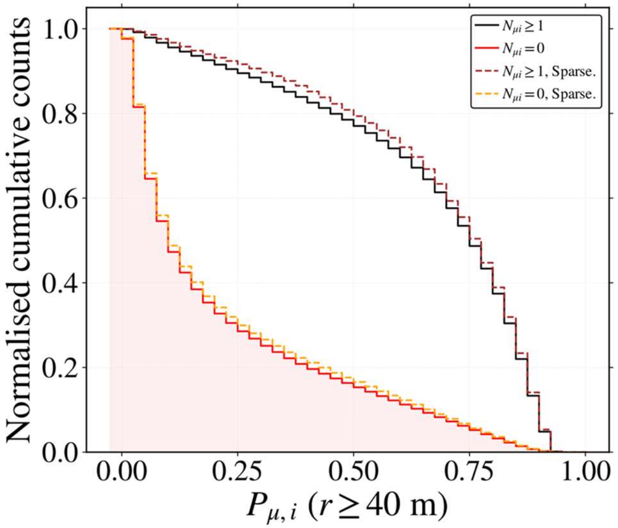


A **1-dimensional Convolution Neural Network**

provides the probability that a muon has passed through the WCD.

Muon tagging - G/H discrimination (E_0~1 TeV)

- Build a quantity to evaluate the gamma/hadron discrimination power and the muon quantity in the shower.



Single station perfomance

Muon tagging - G/H discrimination (E_0~1 TeV)

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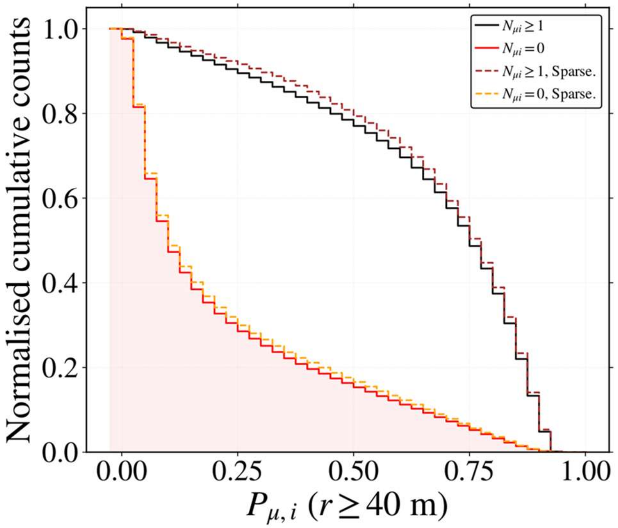
$$P_{\gamma h} = \sum_{k=i}^{n_{stations}} P_{\mu,i}$$



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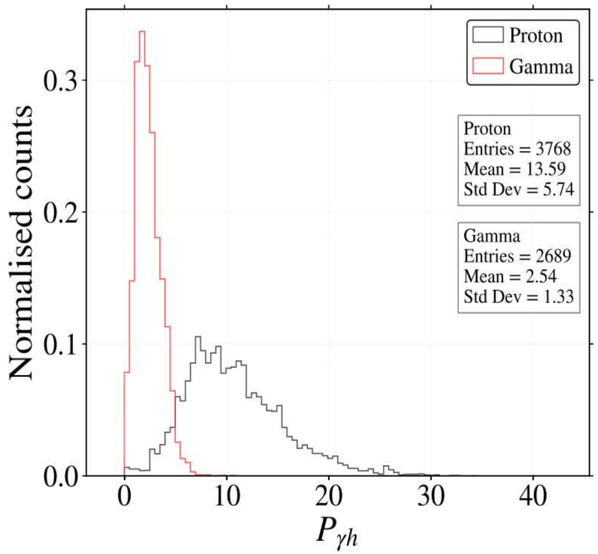

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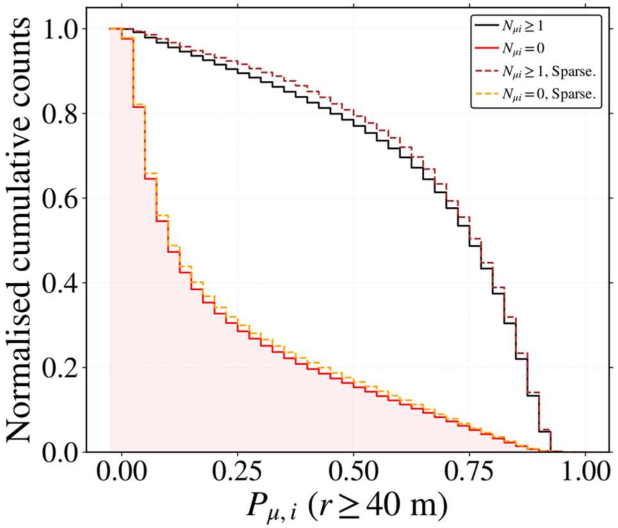

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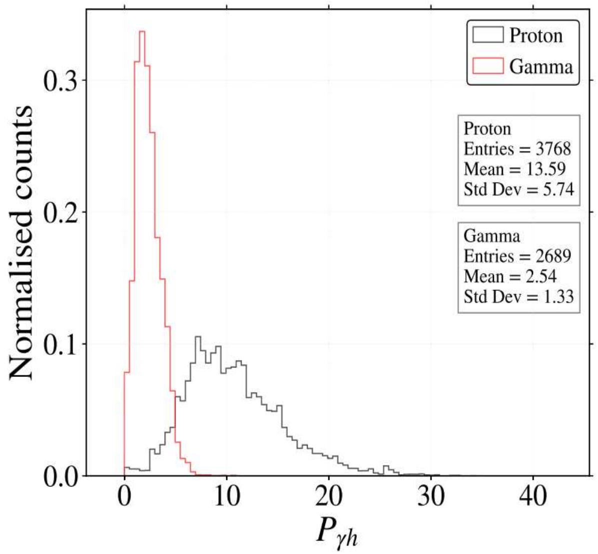
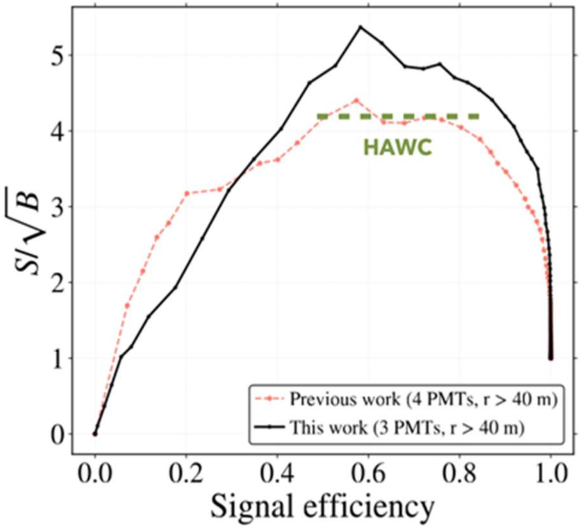


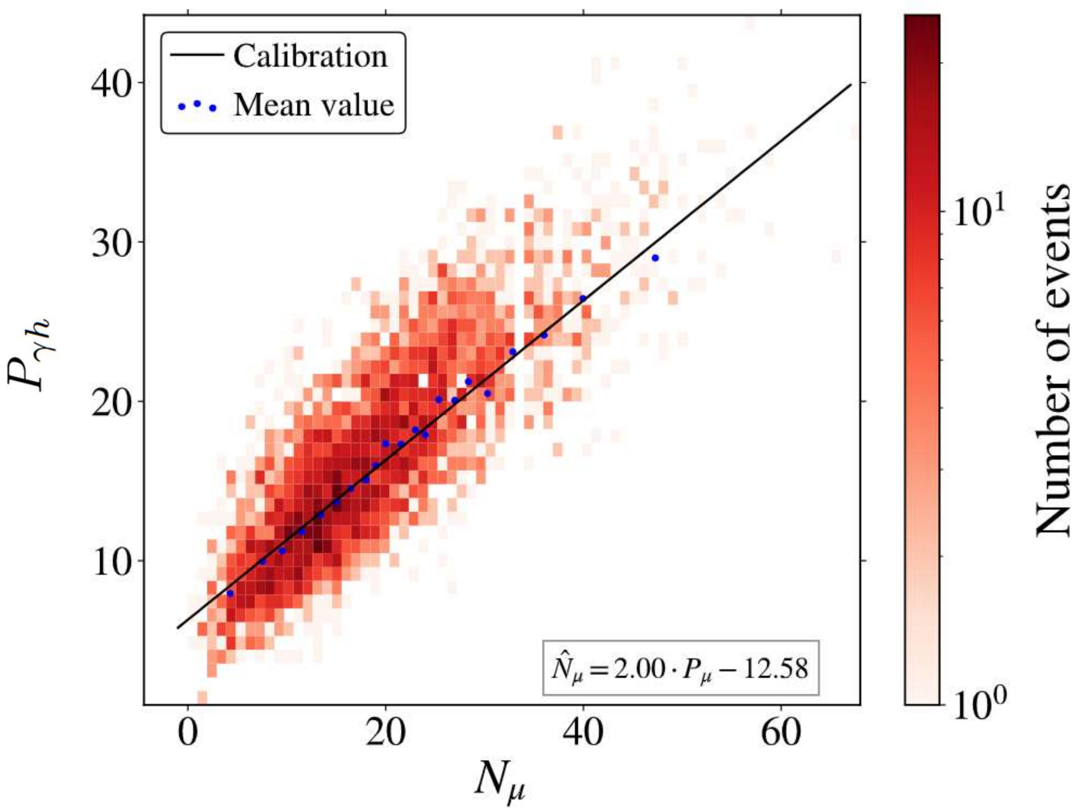


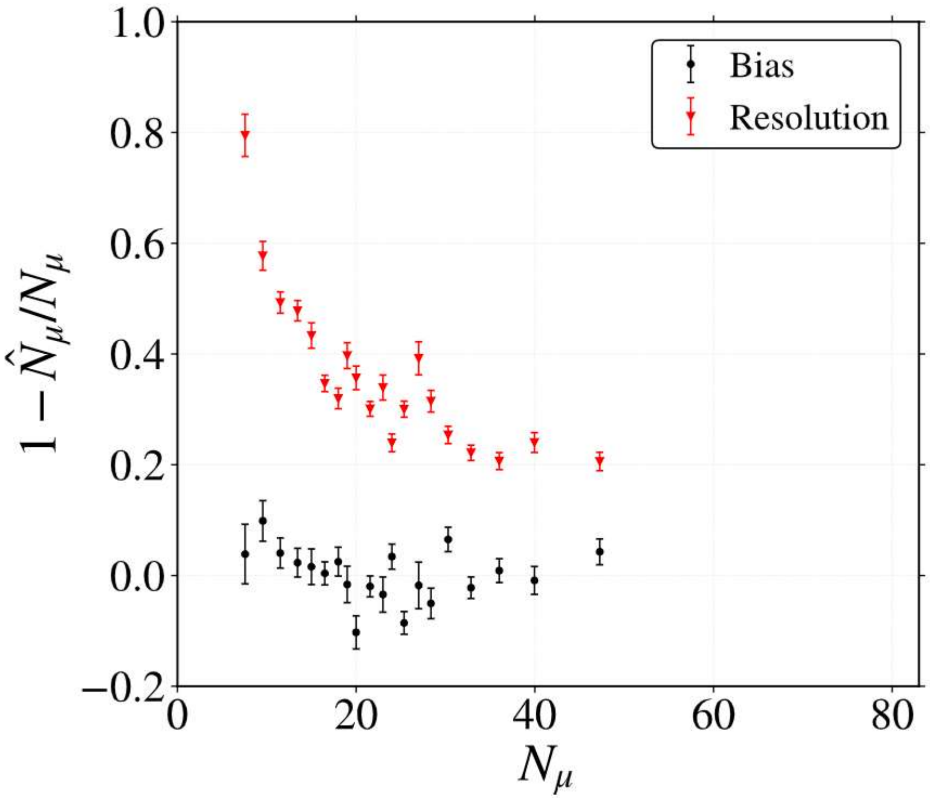
G/H separation perfomance

Excellent gamma/hadron discrimination at E ~ 1 TeV

$\frac{S}{\sqrt{B}}$ ~ 4 for S=0.8 (similar to HAWC)

Muon tagging - G/H discrimination (E_0~1 TeV)





Sensitive to the overall number of muons in the shower event

Small bias and the method has a resolution of ~20%

Conclusions

- Studies at few TeV show that it is possible to perform an excellent muon tagging/counting using a small WCD with multiple PMTs provided that the analysis is performed using ML techniques.
  - → Excellent gamma/hadron discrimination using stations with 3 PMTs.
  - → The method works in vertical/inclined showers and compact/sparse.
  - → One of the candidate designs for SWGO.
- On-going work and future steps:
  - → Test the performance of the method up to ~ 60 TeV.
  - → γ/h discrimination combining the WCD muon info with shower patterns.
  - → Optimisation studies to be conducted: WCD dimensions, array fill factor.

Thanks for your attention.

Acknowledgements:
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The Southern Wide-field Gamma-ray Observatory

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IDPASC PhD grant PRT/BD/151553/2021

Reference configuration for SWGO

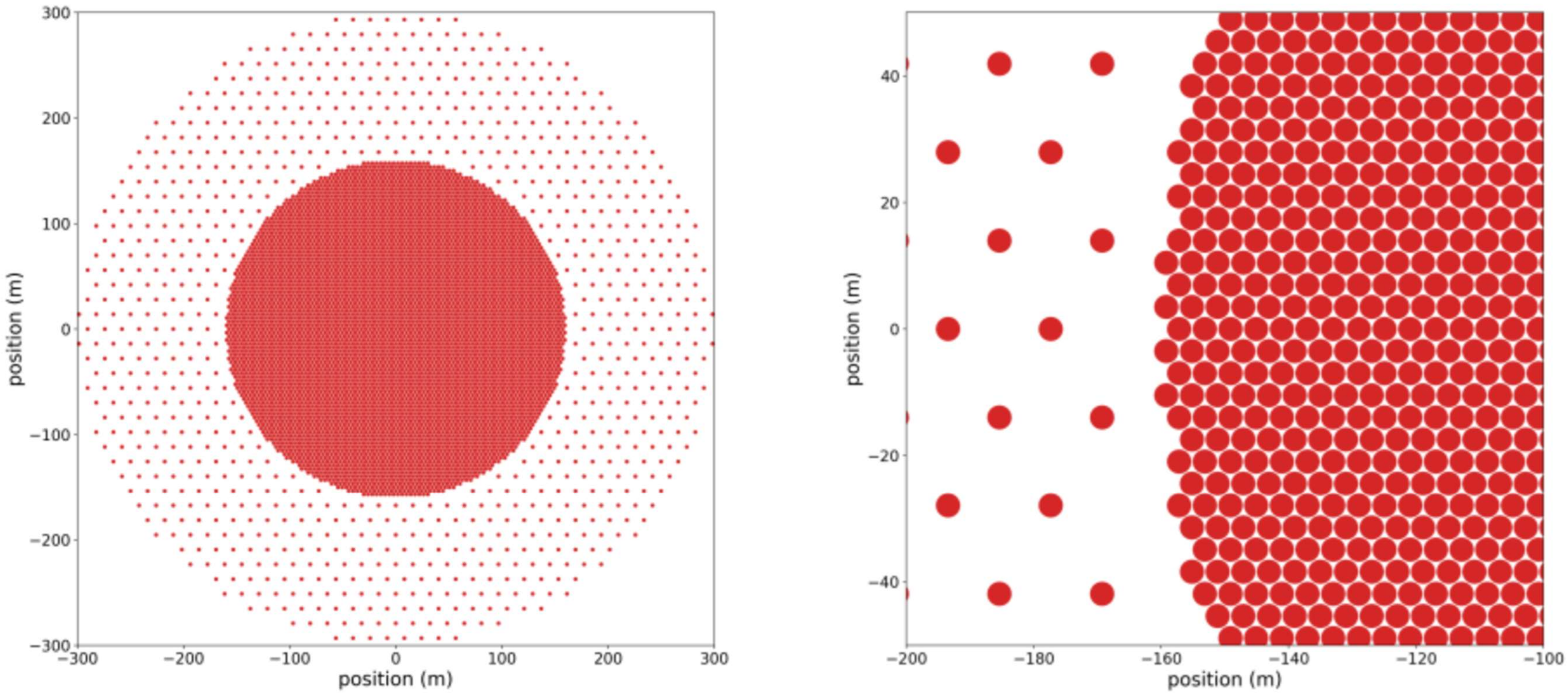


Fig. 1. Left: Reference Configuration layout. Right: zoom of the boundary between core array and outriggers.

Anticipated schedule for SWGO

Figure 5 illustrates the anticipated R&D project schedule in terms of expected dates for milestones to be met. In case of slippage, original dates are marked with a →.

Milestone	2019	2020				2021				2022				2023				2024			
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
R&D Phase Plan		M1																			
Science Benchmarks			M2																		
Reference Configuration				→	M3																
Site Shortlist Complete					→						M4										
Candidate Configurations							→			M5											
Perf. of Candidates Evaluated								→						M6							
Preferred Site Identified									→							M7					
Design Finalised											→							M8			
CDR Ready													→						M9		

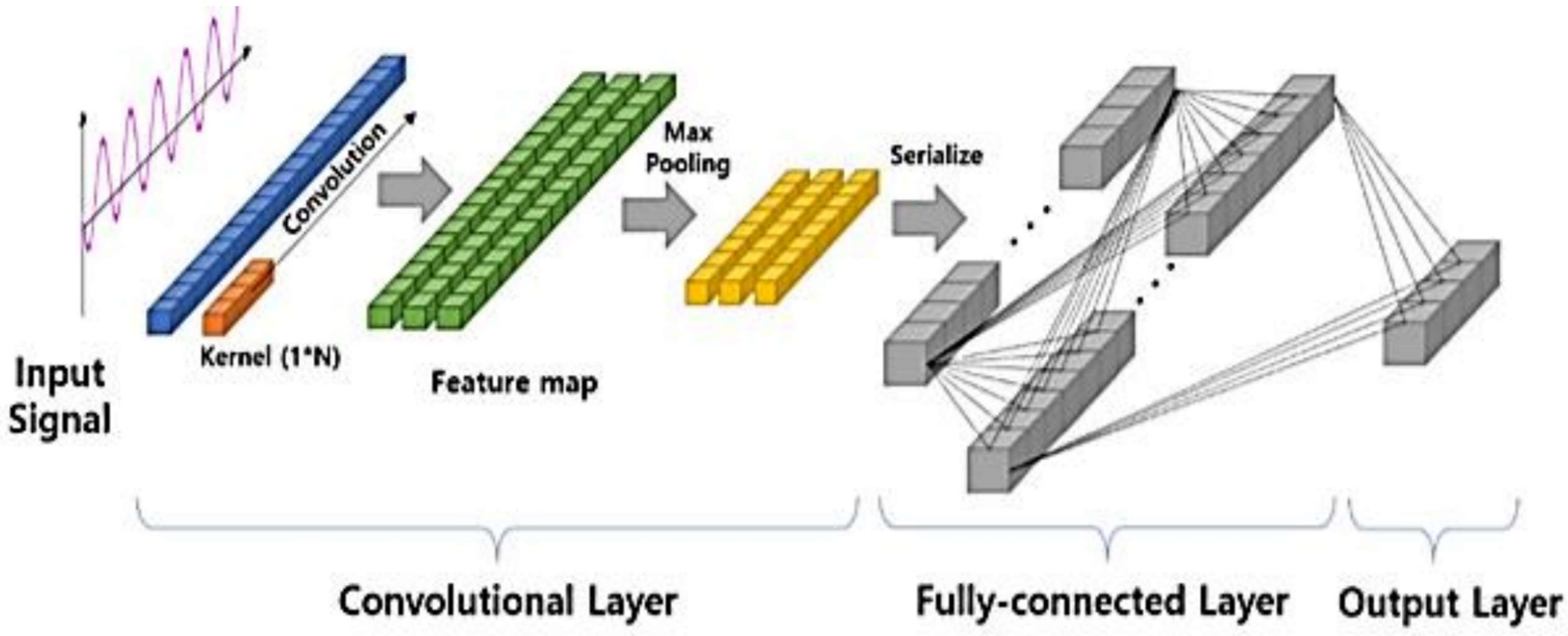
Figure 5: Indicative schedule for the milestones of the R&D phase. An arrow indicates a shift from the originally indicated date. Those milestones in orange are complete as of this revision of the R&D Plan.

EAS vs IACTs

	EAS-D	IACT
Duty-Cycle	High (≈100%)	Low (≈10-15%)
Field-of-View	Large (2 sr)	Small (4-5 deg)
Sensitivity	Good Sensitivity (5-10% Crab flux)	High Sensitivity (< mCrab flux)
Maximum Energy	~ PeV	<100 TeV
Energy Resolution	Modest (~30-40%)	Very Good (~15%)
Energy Threshold	High (~TeV)	Very Low (~10 GeV)
Angular resolution	Good (0.2-0.8 deg)	Excellent (≈0.05 deg)
Effective Area	decrease with zenith	increase with zenith
Background rejection	Good (~80%)	Excellent (>99%)
Zenith dependence	Very Strong ($[\cos\theta]^7$)	Weak ($[\cos\theta]^{2.7}$)

Source: *CTA & future astroparticle experiments.* D. della Volpe. LHC days 2018.

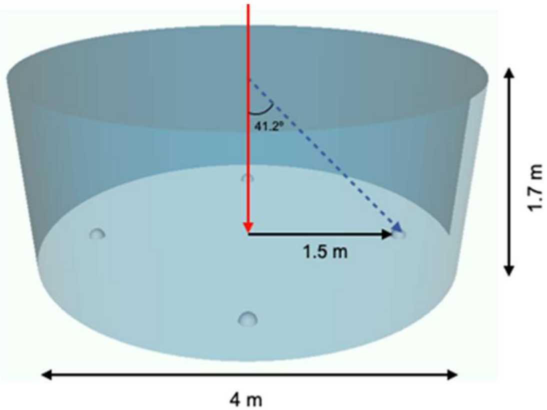
Typical structure of a CNN

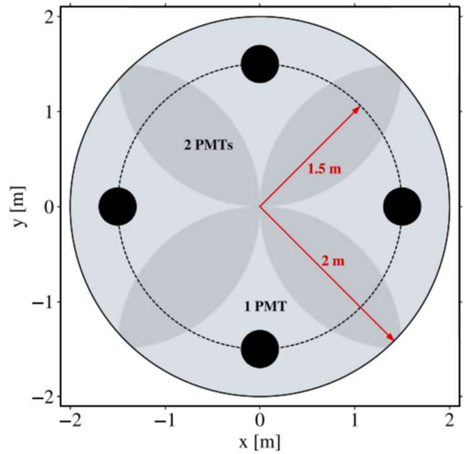


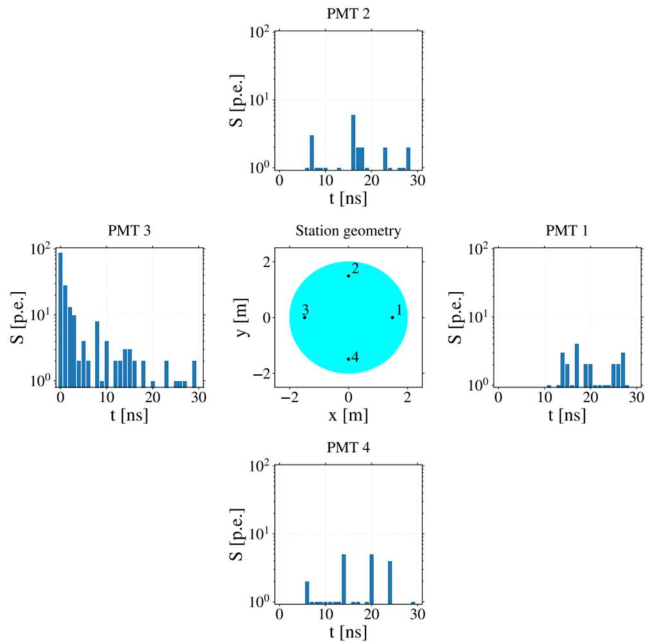
WCD with 4 photo-sensors

Approach using 4 PMTs

- Dimensions based on Single Muon identification.
  - No blind spots.
  - SM seen at most by 2 PMTs.
  - Maximisation of the signal asymmetry to find muons.
- Taking a base diameter: 4 m
  - Height: 1.7 m.
  - Distance of the PMTs to the center: 1.5 m.
  - Less water.
- White walls made of Tyvek.
  - Lower the energy threshold.
  - Shower geometry reconstruction taken from the direct Cherenkov light

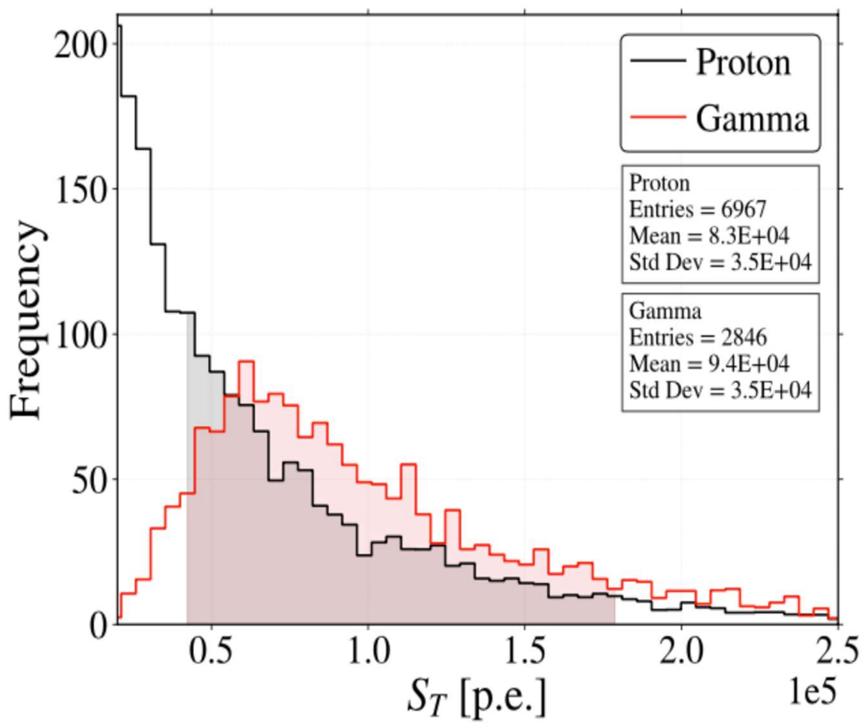






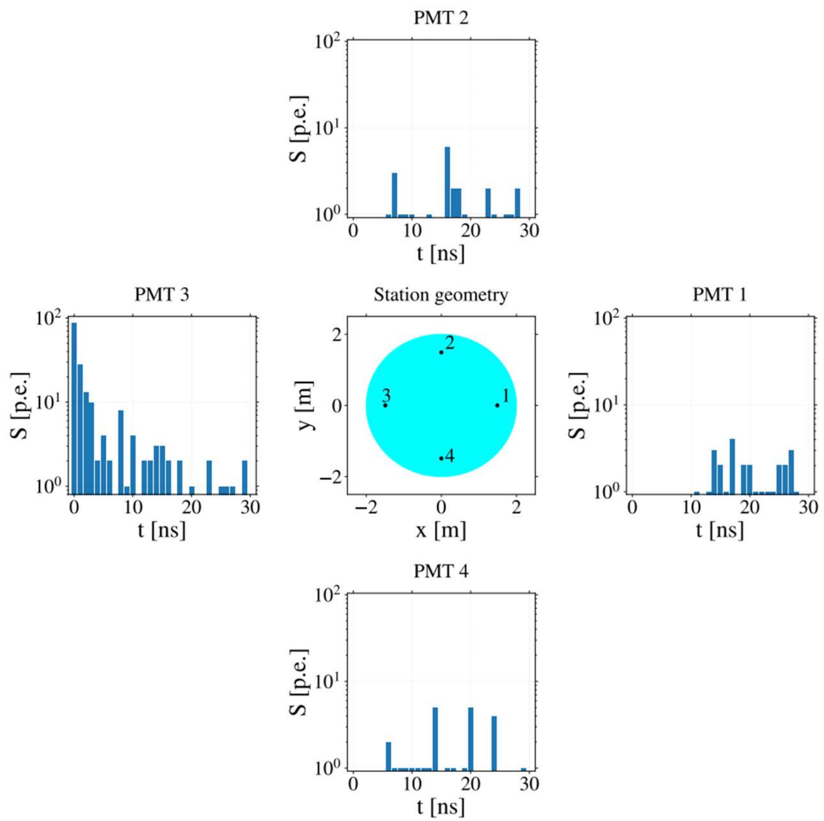
Simulation (4 PMTs)

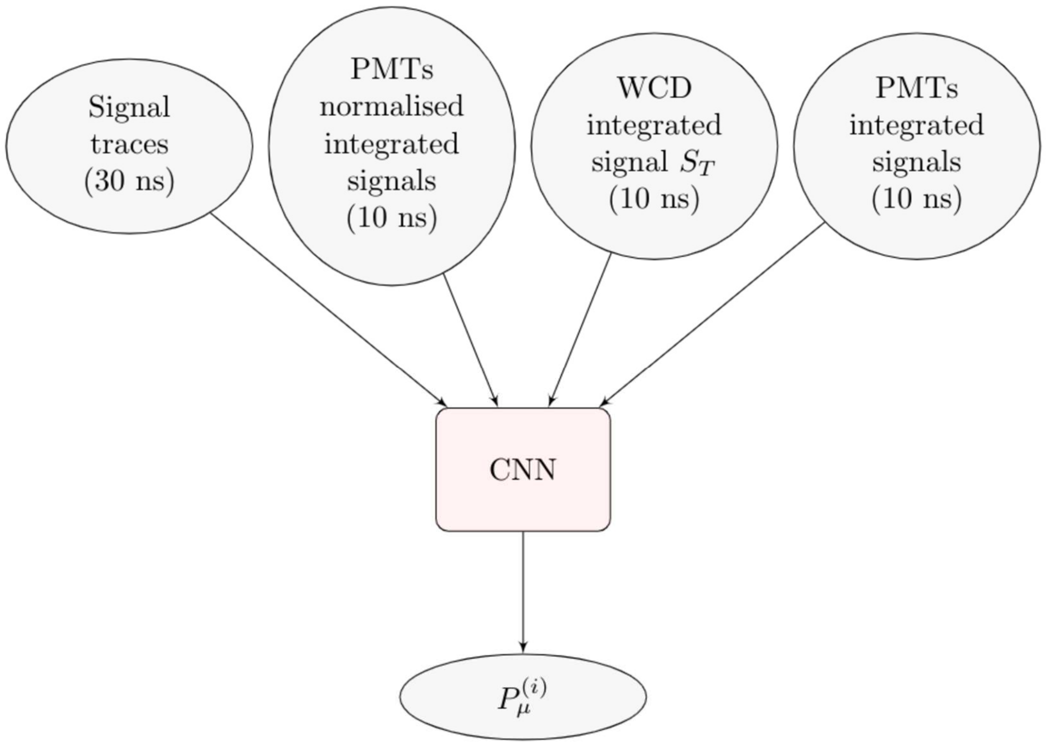
- Simulations:
  - Detector simulation using Geant4.
  - CORSIKA showers at 5200 m.
  - Proton: $E_0 \in [0.7,6]$ TeV.
  - Gammas: $E_0 \in [1,1.6]$ TeV.
  - Events with similar signal at the ground.
  - θ ∈ [5º, 15º] and [25º,35º].
  - Dense (FF=80%) and sparse (FF=30%) arrays covering an area of 80000 m^2.



Events with equivalent reconstructed energy ~ 1 TeV

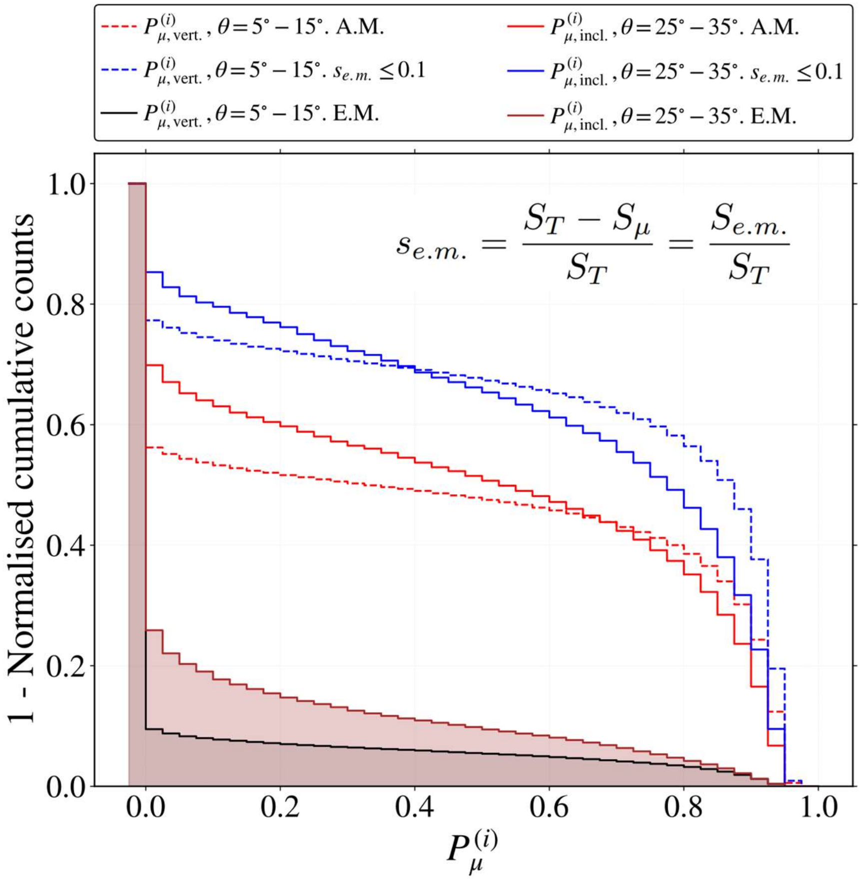
ML model (4 PMTs)



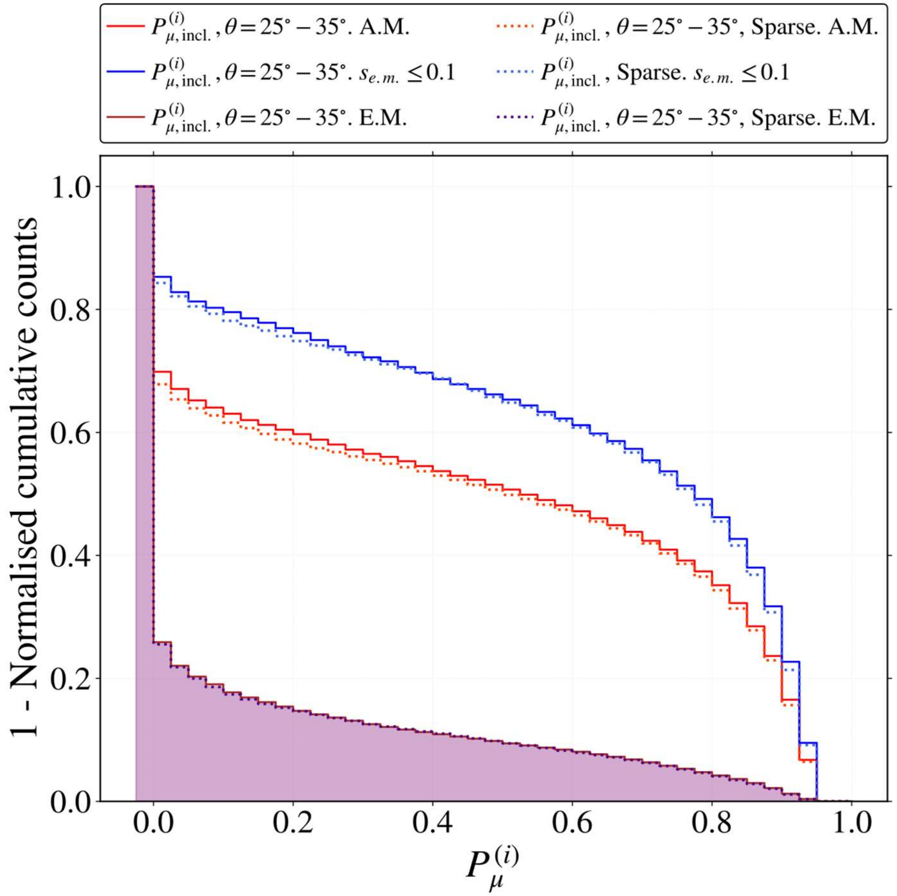


Analyse signal to get the probability that a muon has passed through the WCD.

Inclined showers and sparse array



Performances nearly independent of the shower inclination

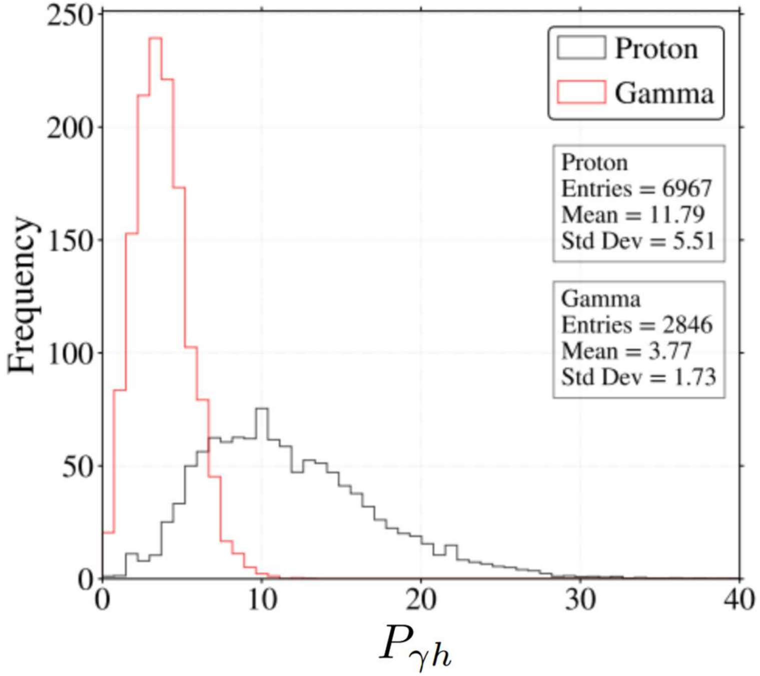


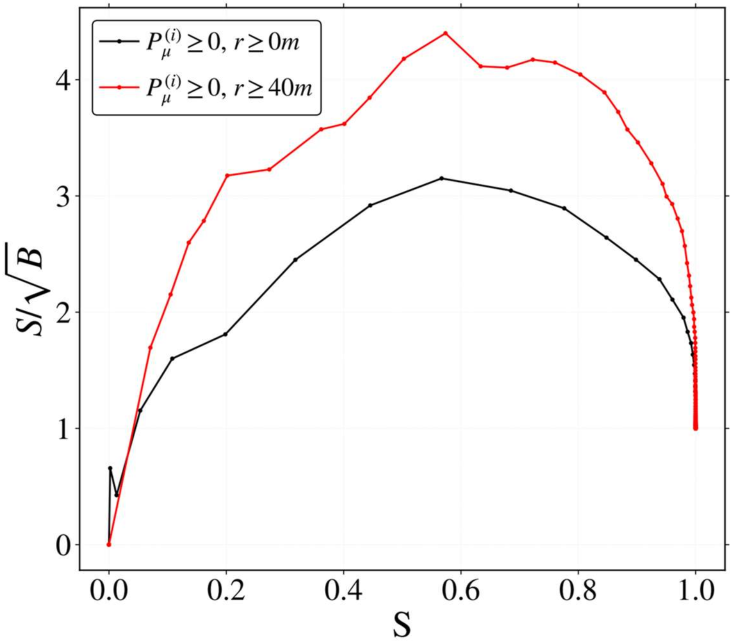
Stations in the sparse and dense array have the same performance.

Muon tagging - G/H discrimination (E_0~1 TeV)

- Build a quantity to evaluate the gamma/hadron discrimination power and the muon quantity in the shower.

$$P_{\gamma h} = \sum_{k=i}^{n_{stations}} P_{\mu,i}$$





Excellent gamma/hadron discrimination at E ~ 1 TeV

S/sqrt(B) ~ 4 (similar to HAWC)

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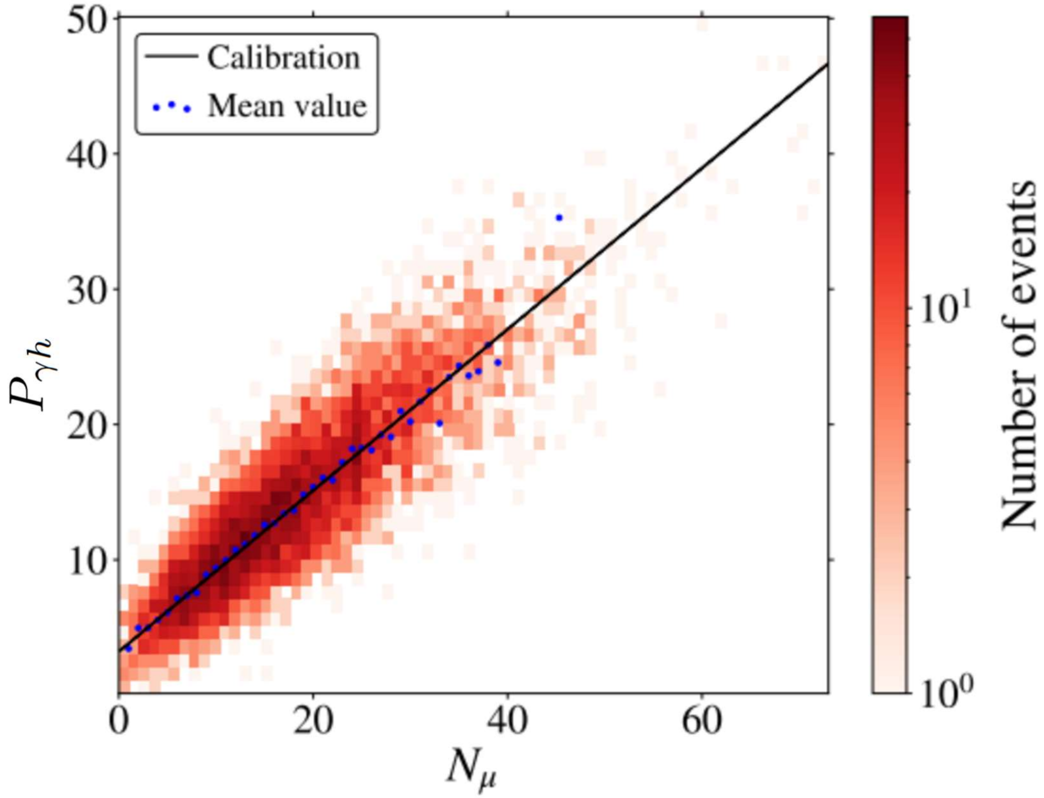

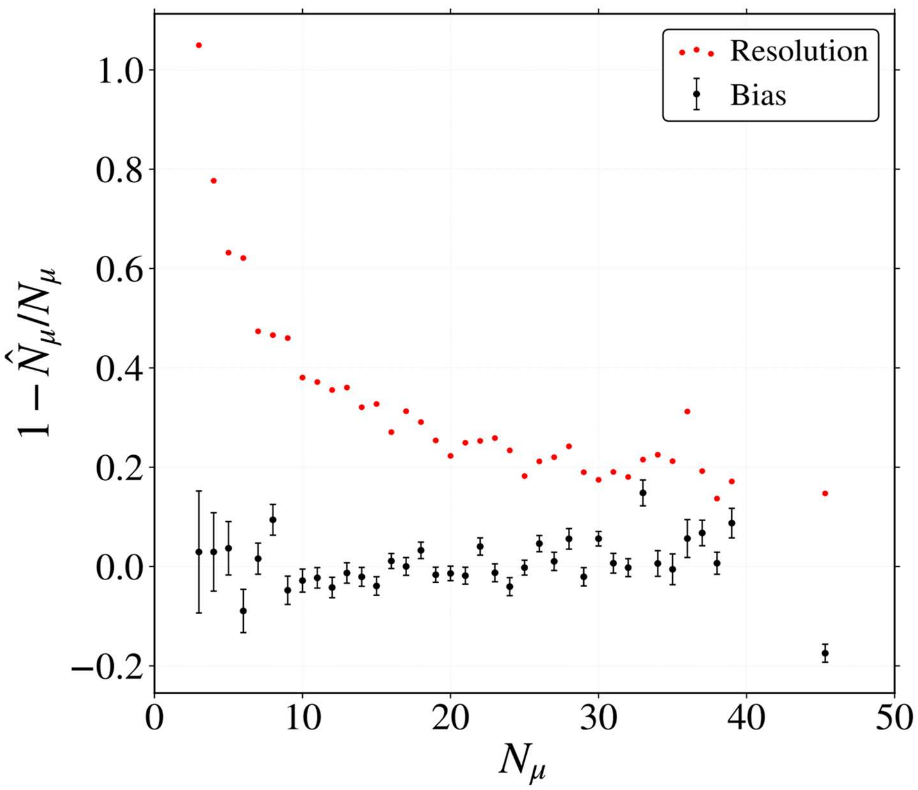

Sensitive to the overall number of muons in the shower event

Small bias and the method has an intrinsic resolution of 2%

$$\hat{N}_\mu = 1.67\ P_{\gamma h} - 3.22$$