Machine learning applications for SWGO

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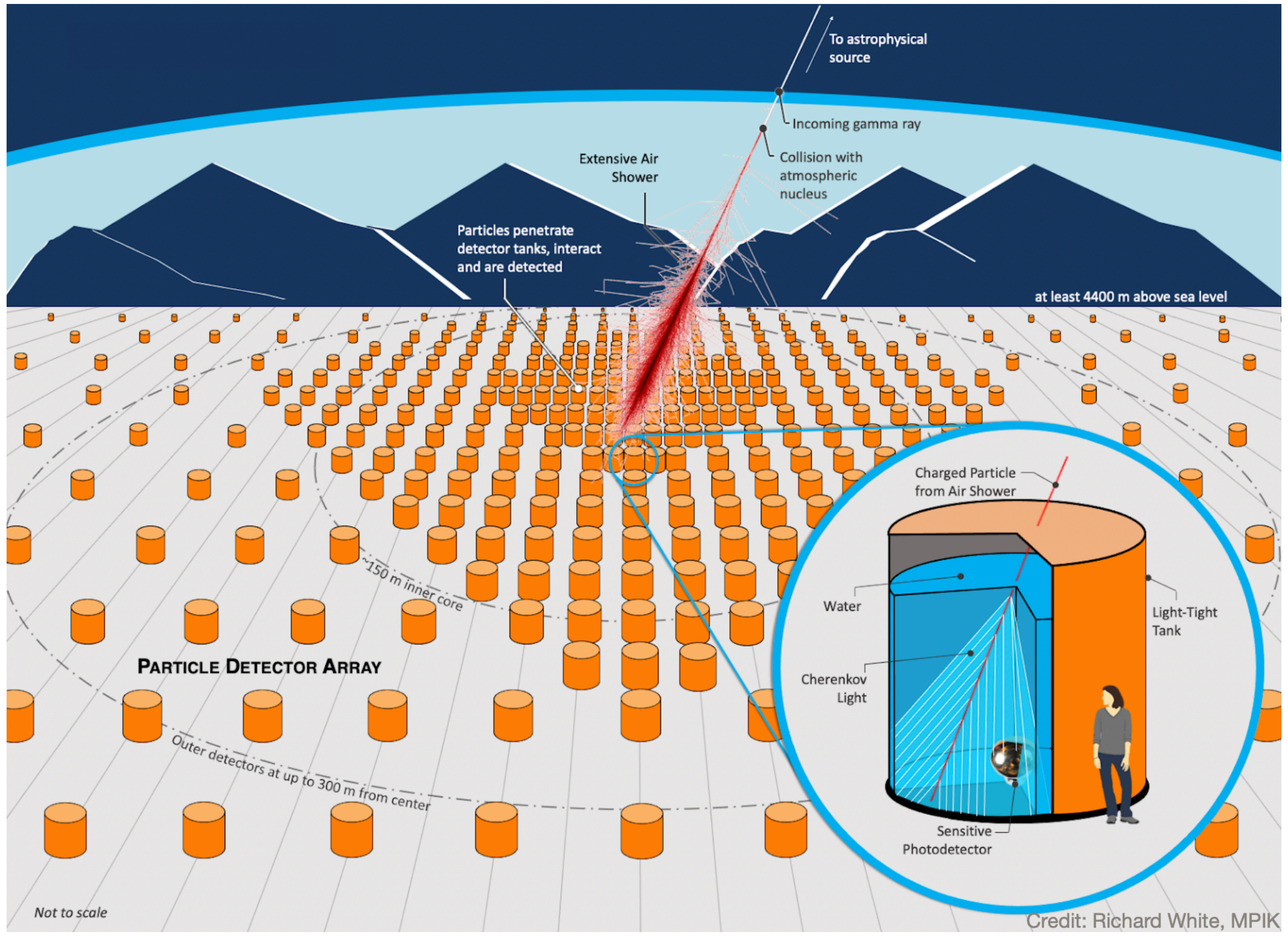
LIP
TÉCNICO LISBOA

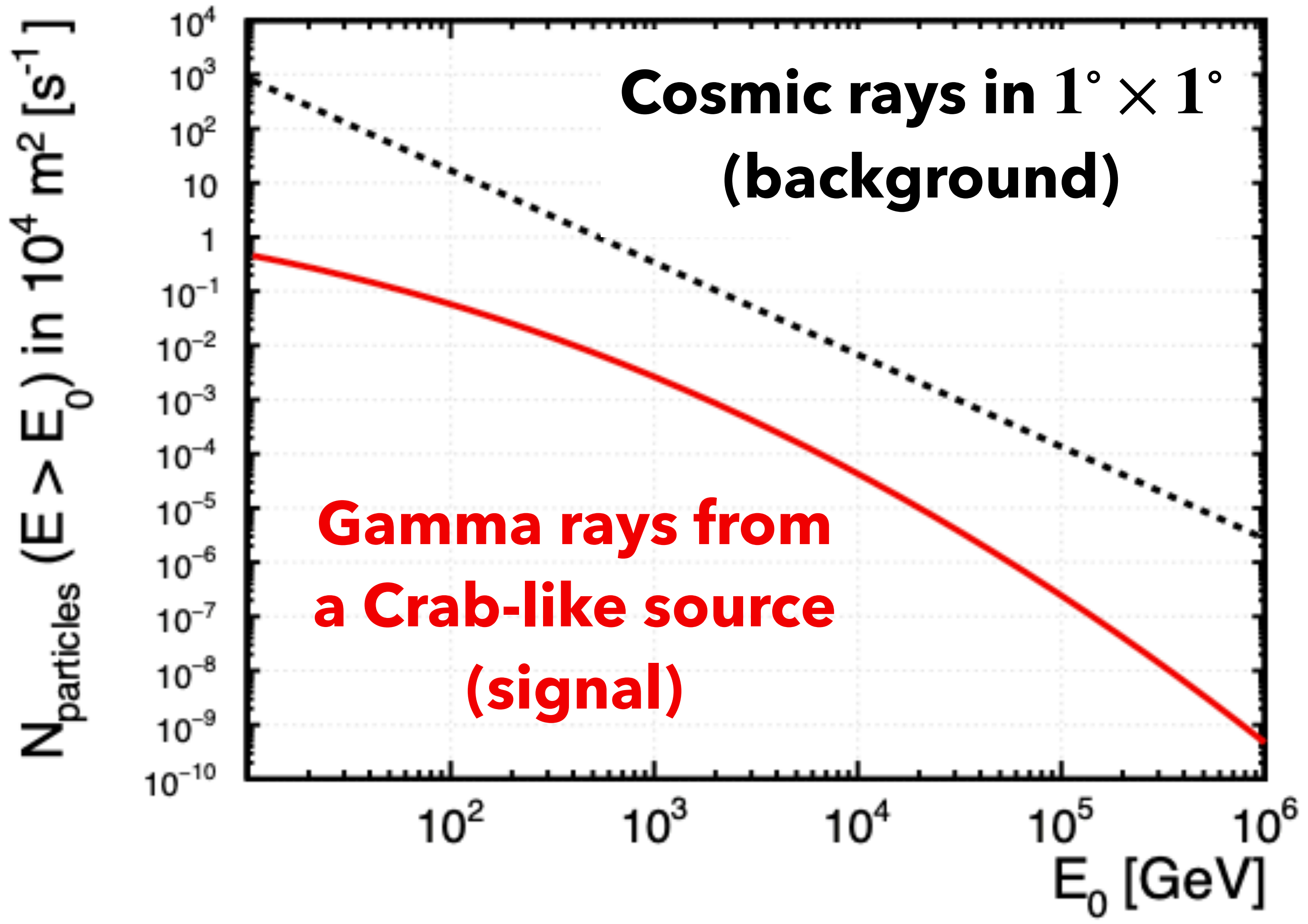
SWGO-LIP meeting, Lisboa, September 19th 2025

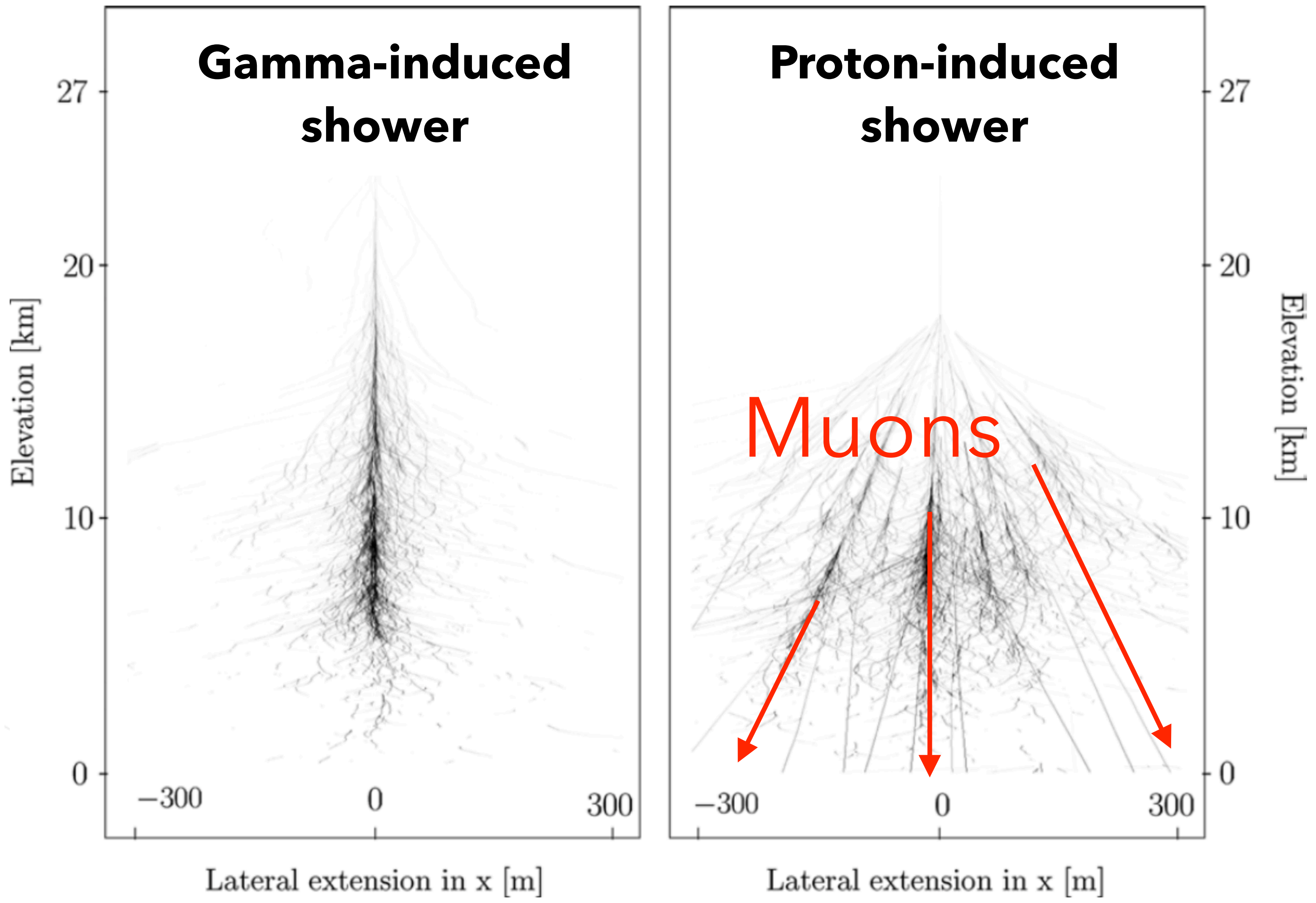
Find a needle in a haystack…

Gamma/hadron discrimination

SWGO
The Southern Wide-field Gamma-ray Observatory







Find a needle in a haystack…

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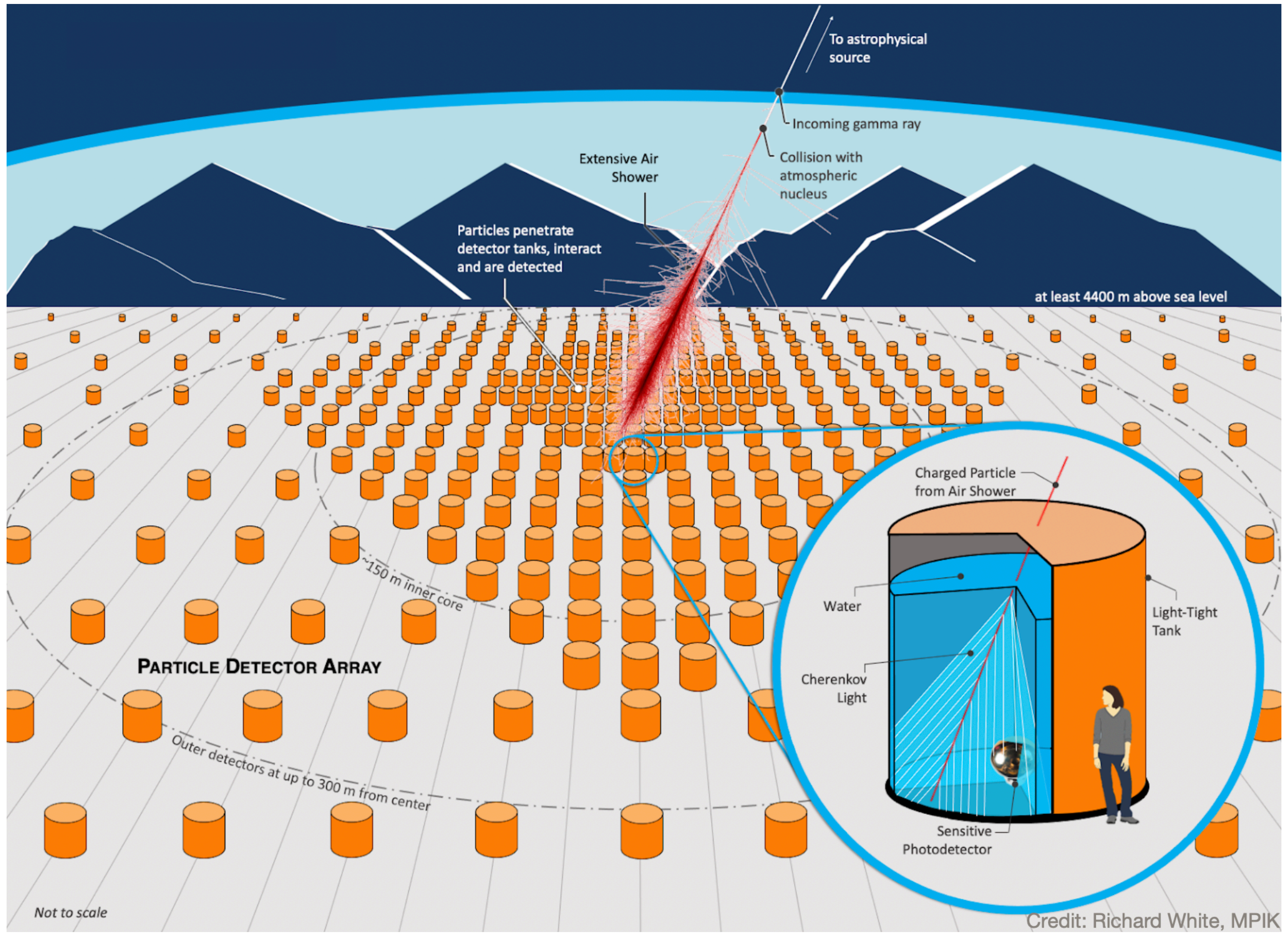
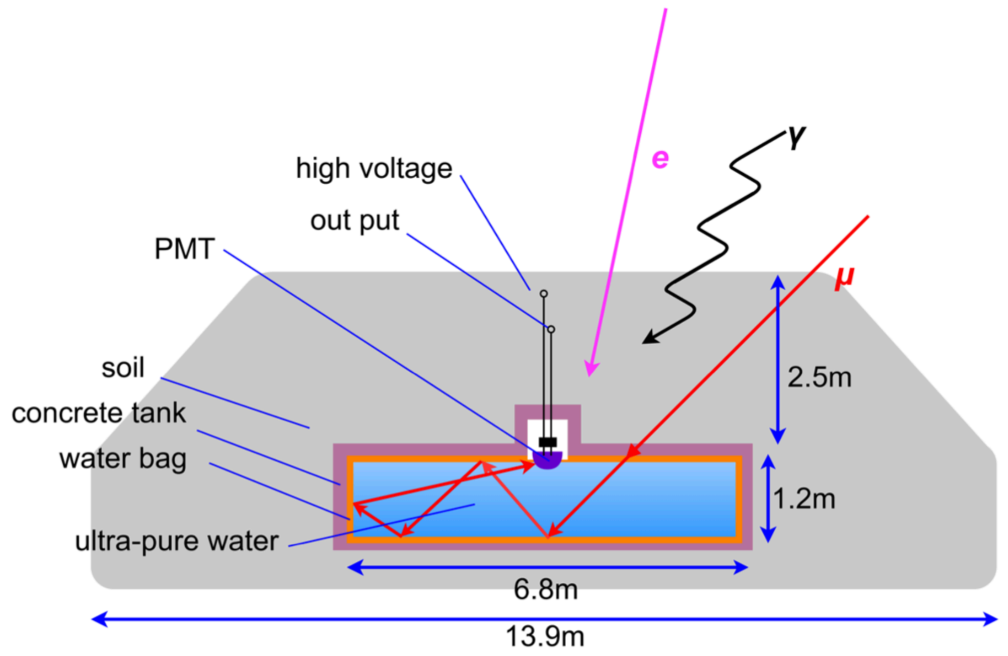
SWGO
The Southern Wide-field
Gamma-ray Observatory



Credit: Richard White, MPIK

LHAASO experiment - Tibet - 4400 m



Buried
Water Cherenkov Detectors

Absorb e.m. shower component to detect muons

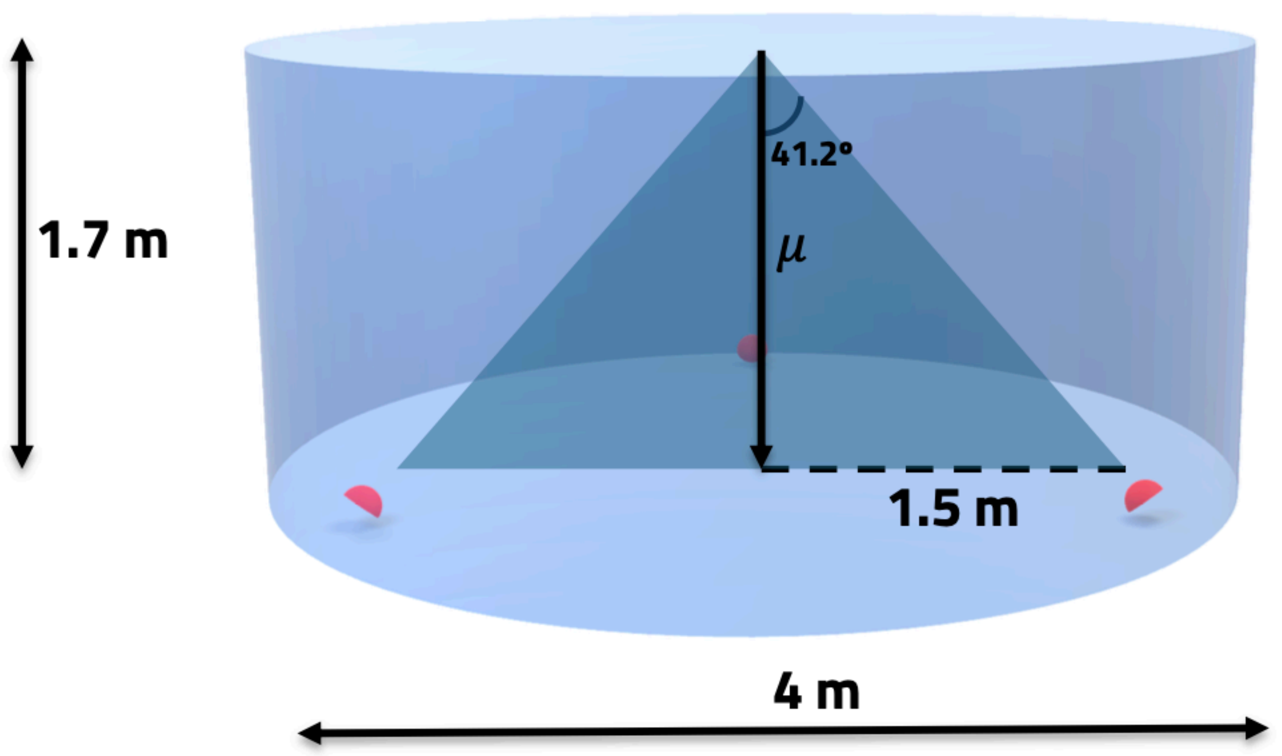
SWGO site

Atacama Natural Park - Chile - 4770 m a.s.l.

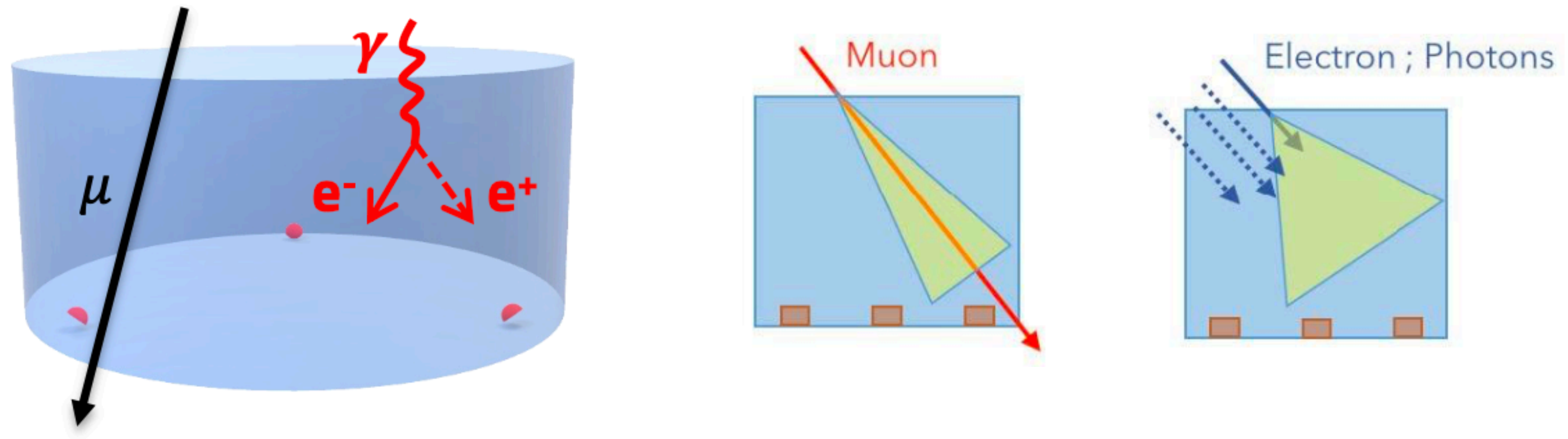
Burying detectors (LHAASO strategy) or building 5 m height water tanks (HAWC strategy) is **costly**, **impractical**, and **environmentally unfeasible**

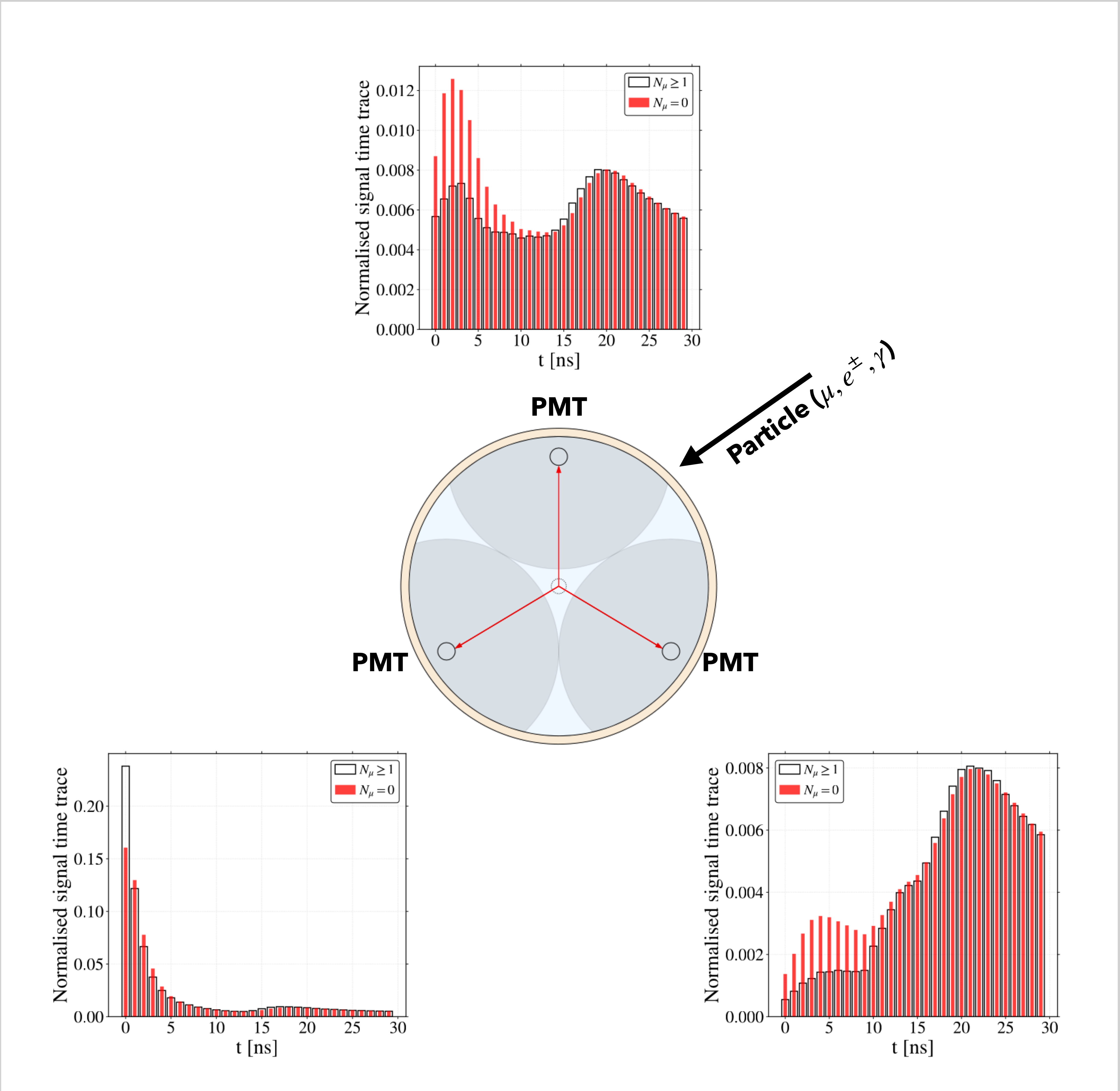
Looking for muons in shallow stations

The Mercedes WCD station



The concept





Conceição et al. Eur.Phys.J.C 81 (2021) 6, 542
González et al. Neural Comput & Applic 34, 5715–5728
Assis et al. Eur.Phys.J.C 82 (2022) 10, 899

Looking for muons in shallow stations

Conceição et al. Eur.Phys.J.C 81 (2021) 6, 542
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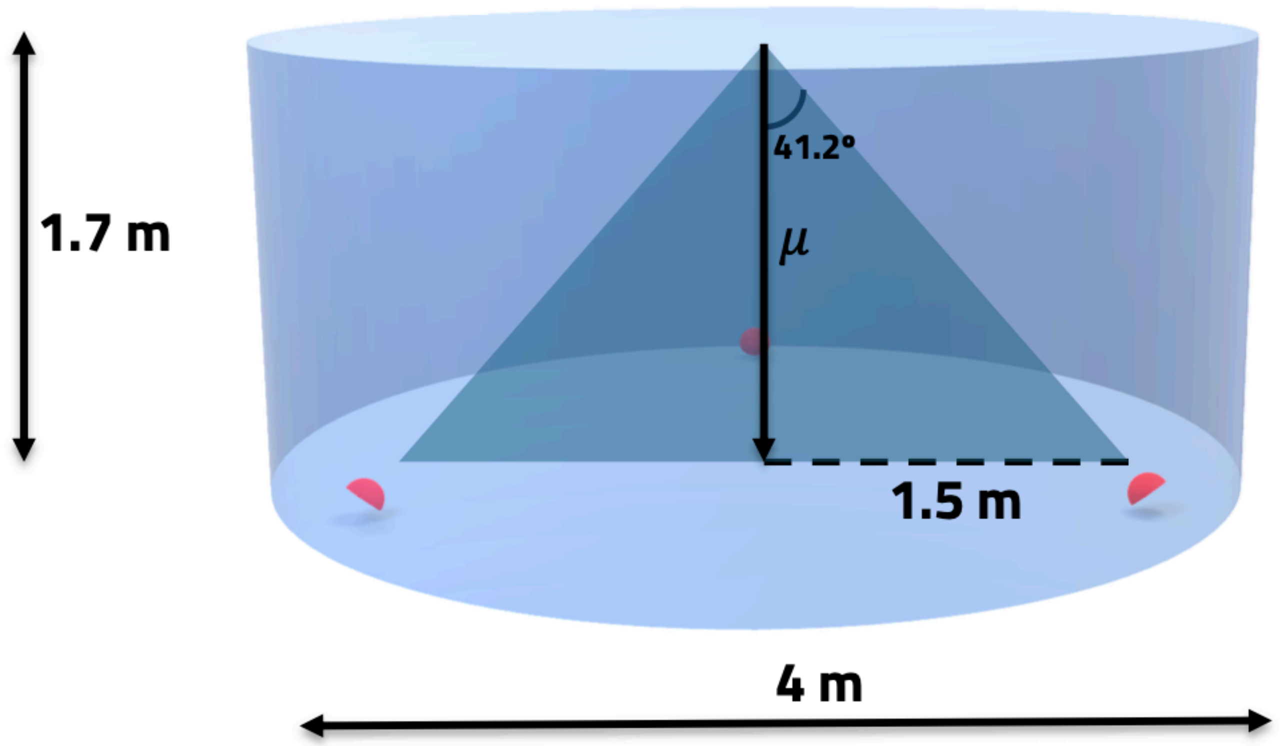
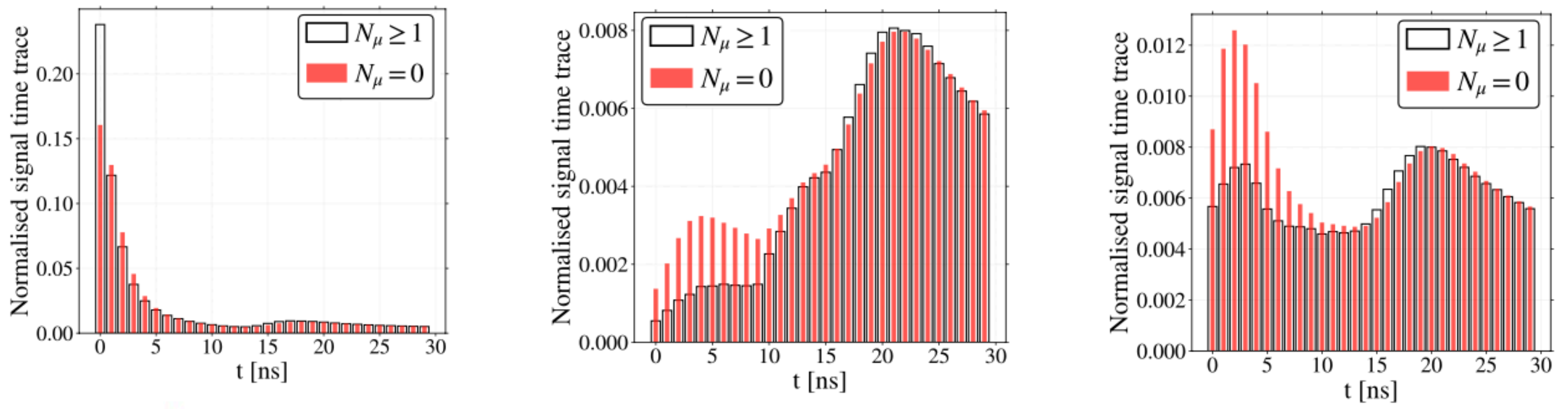
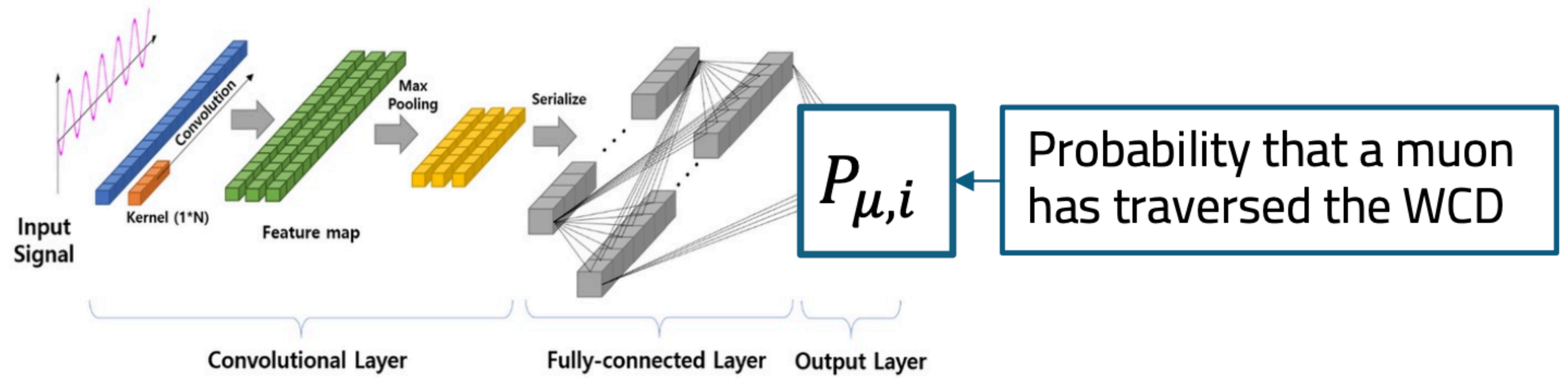
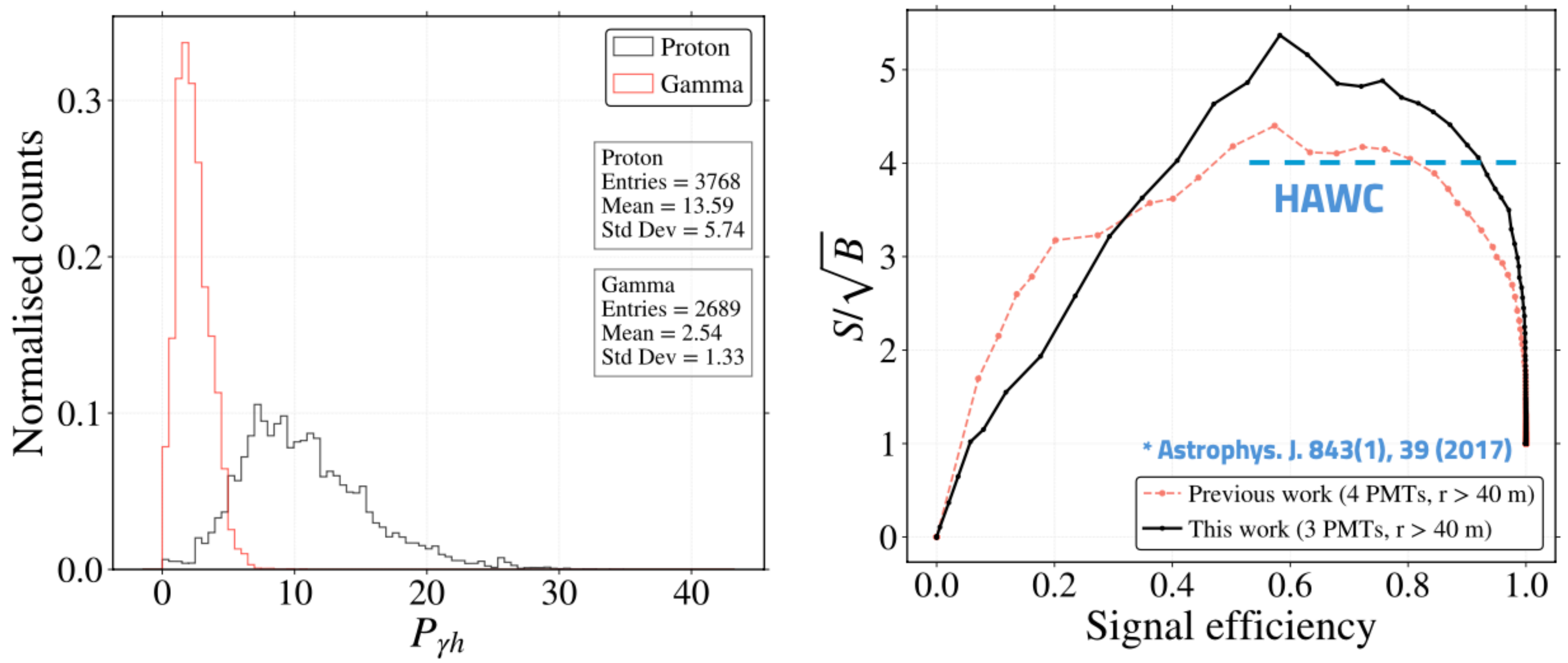


Analyse the PMT signal time trace recurring to ML algorithms





E~1 TeV, $\alpha = 1, r_{min} > 40$ m



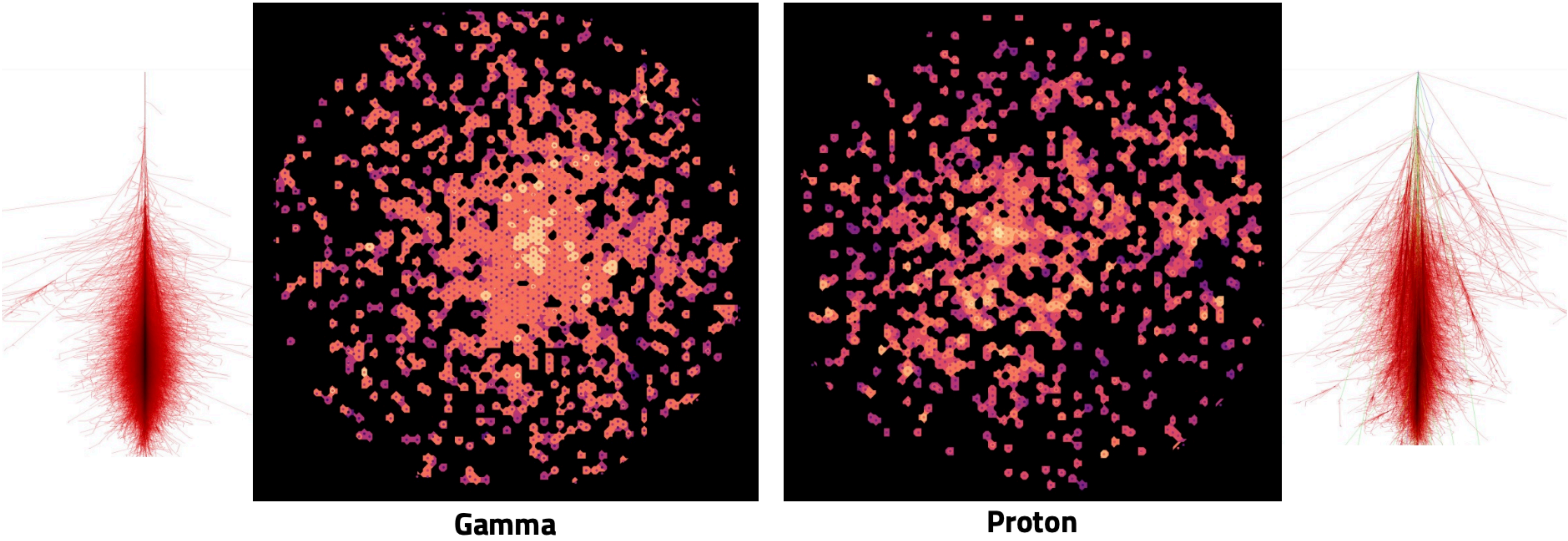
Gamma/hadron separation

$$P^{\alpha}_{\gamma h} = \sum_{i}^{n} P^{\alpha}_{\mu,i}\,(r > r_{min})$$

Conceição et al. Phys.Lett.B 827 (2022) 136969

Accessing sub-TeV shower energies…

What can be done when there aren't enough muons?

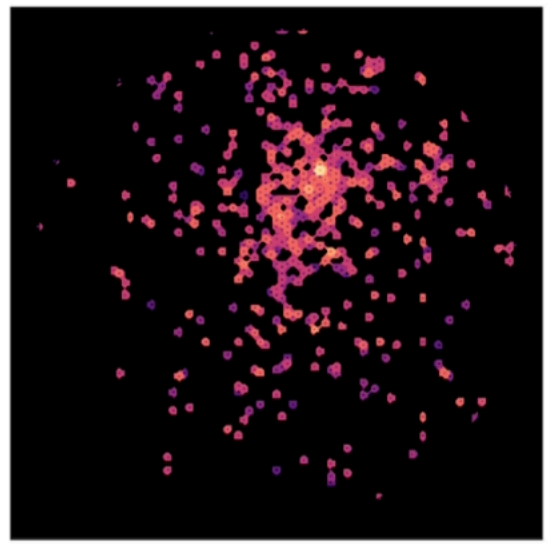


There's information in the shower footprint!

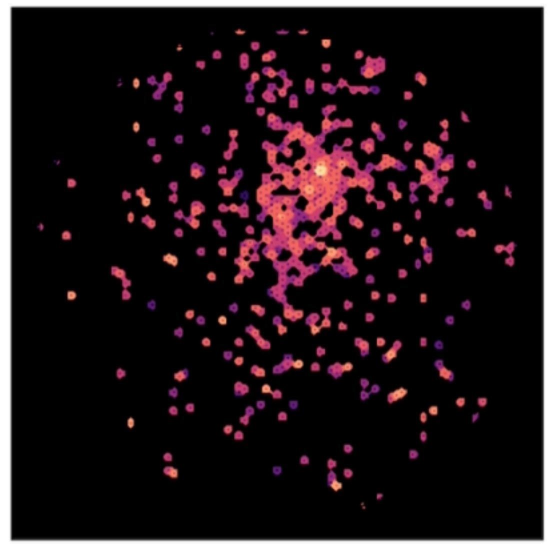
But the challenge lies in dealing with the overwhelming atmospheric muon background (~23 stations per event)

Exploring the shower footprint

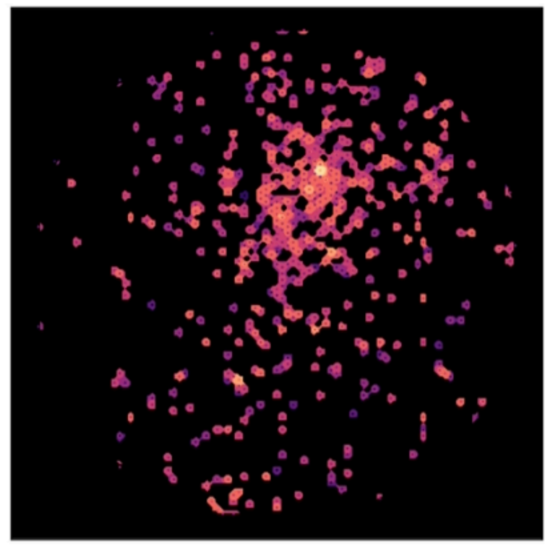
Conceição et al. Phys.Rev.D 111 (2025) 4, 043047



Shower
Noise-free



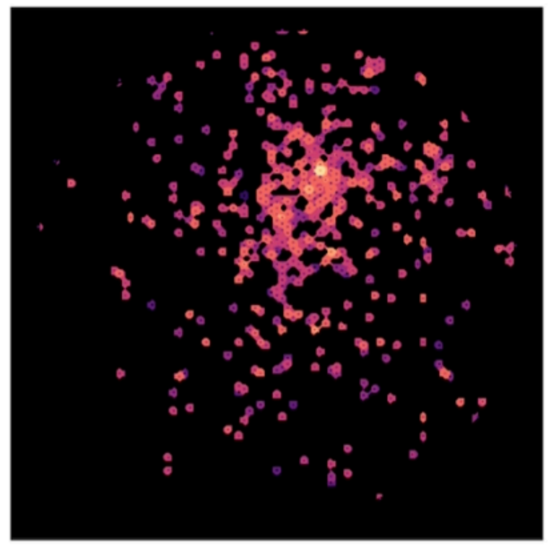
Shower
+
29 WCDs μ
(~6000 p.e.)



Shower
+
Proton shower
126 GeV
68 WCDs
(~2500 p.e.)

Exploring the shower footprint

Conceição et al. Phys.Rev.D 111 (2025) 4, 043047



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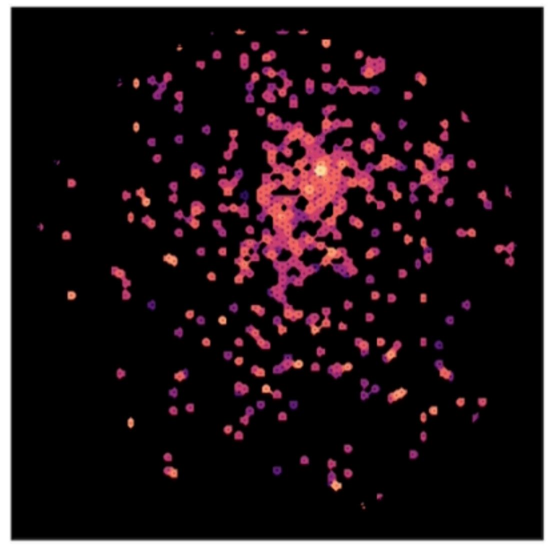

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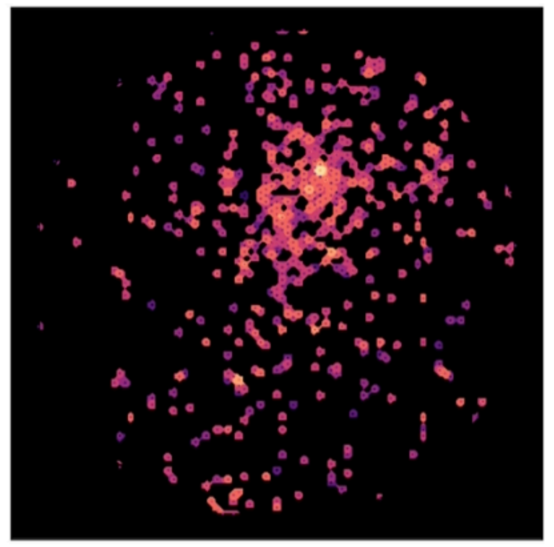

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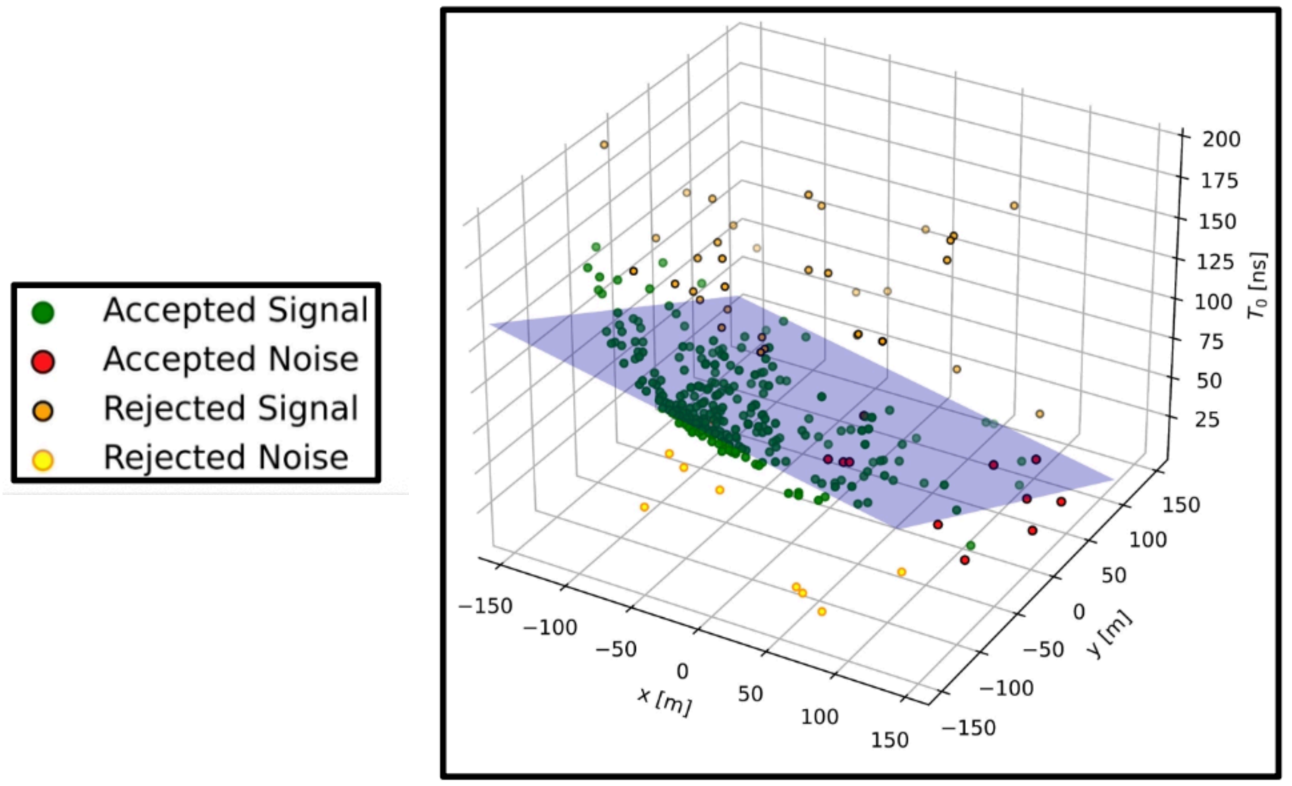
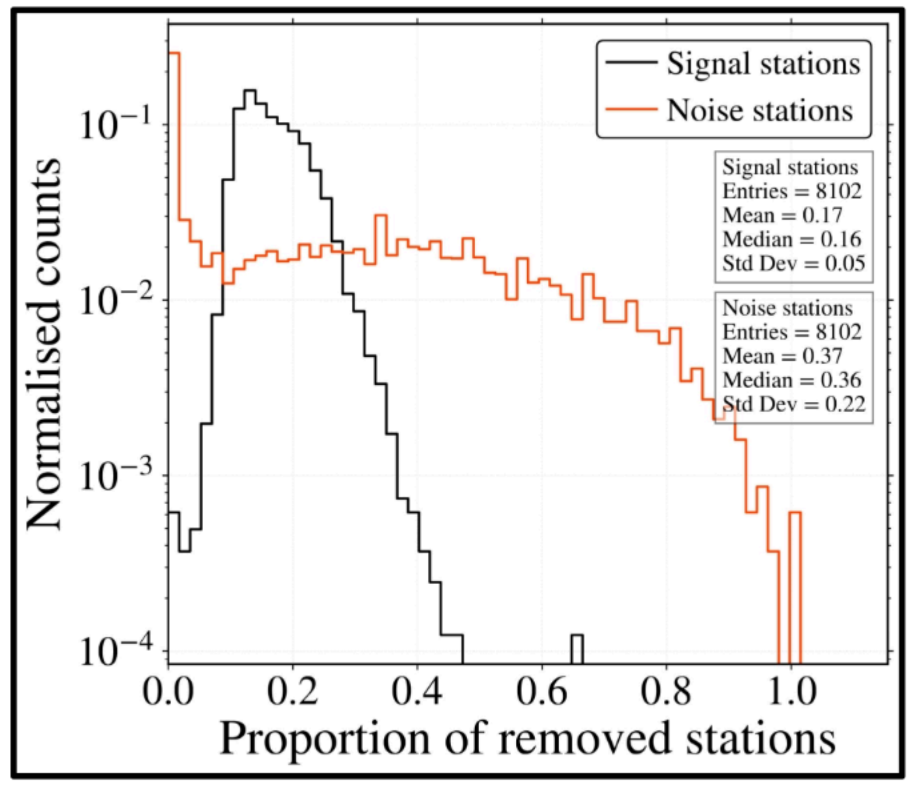
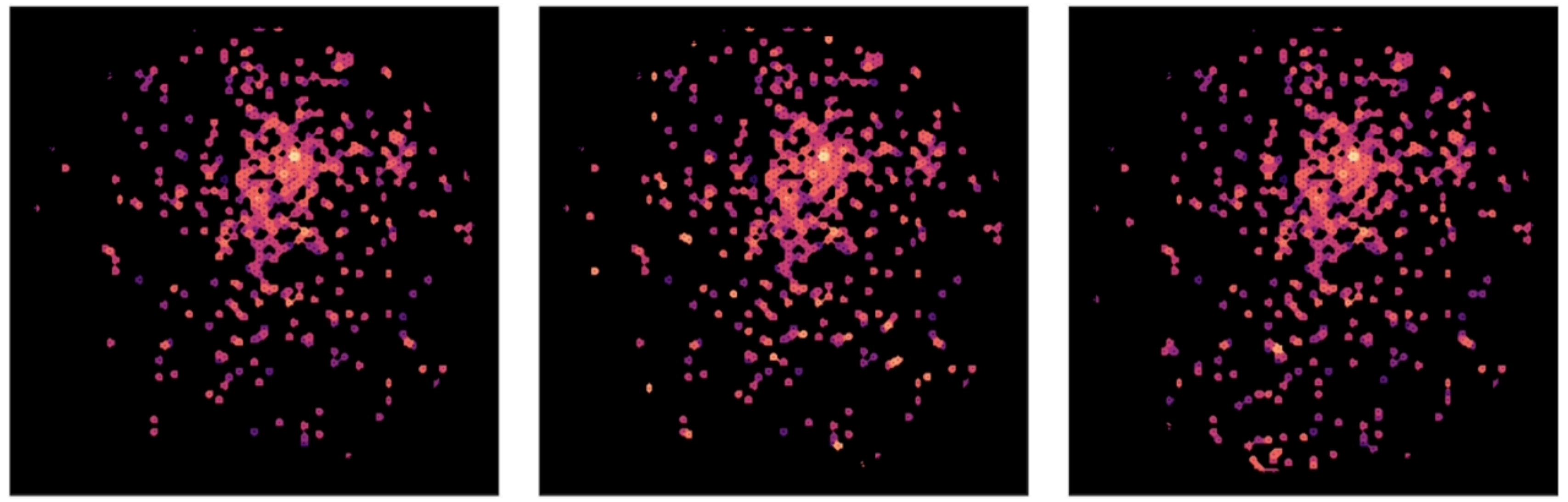




Exploring the shower footprint

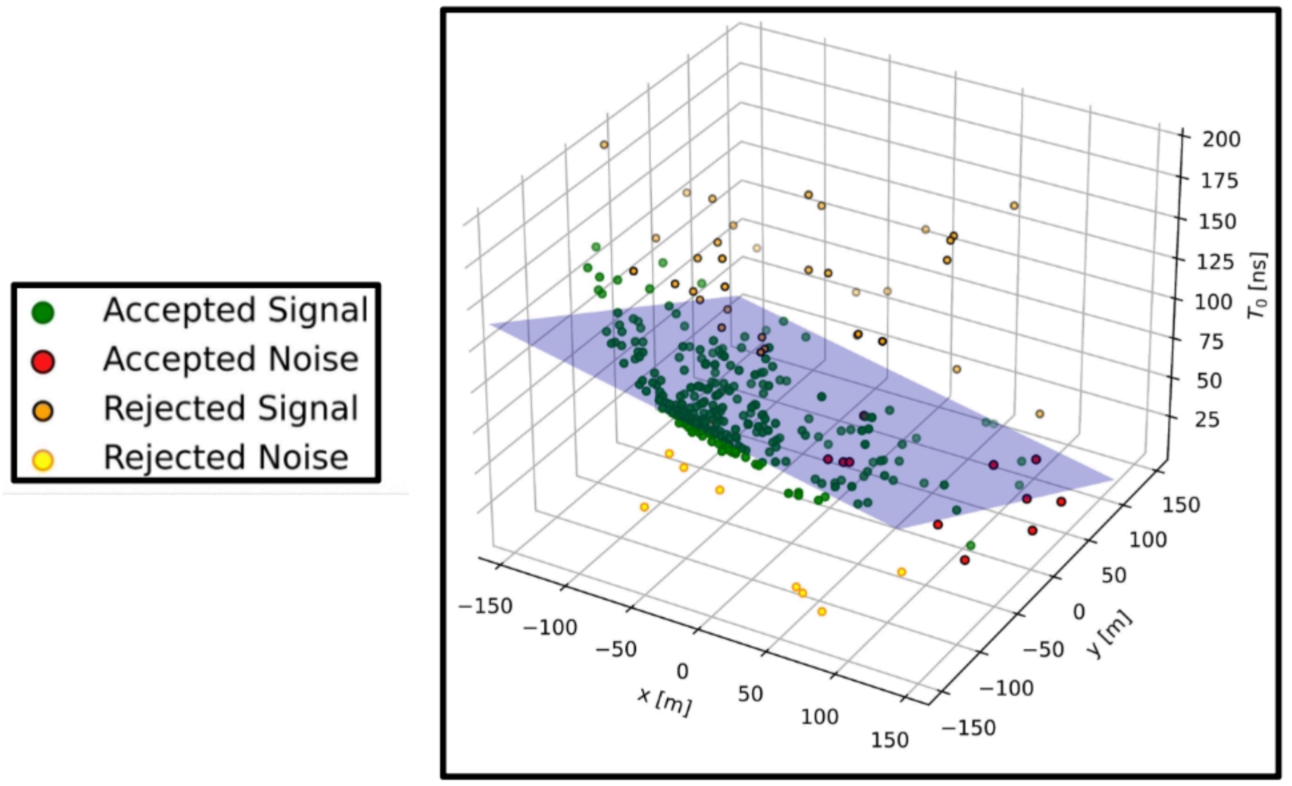
Conceição et al. Phys.Rev.D 111 (2025) 4, 043047

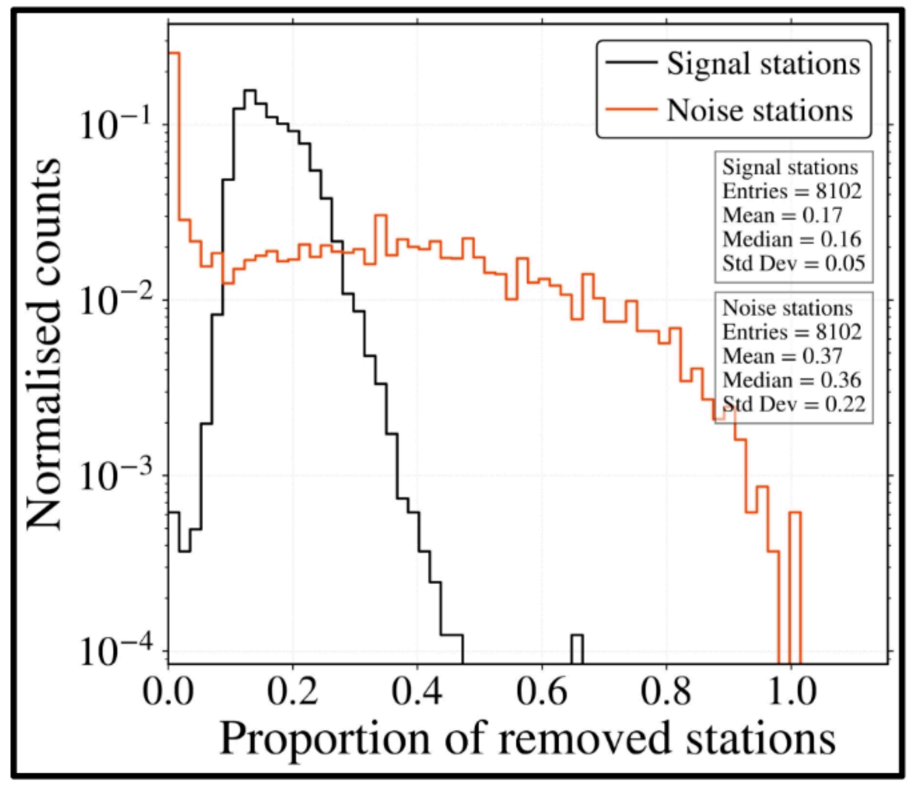


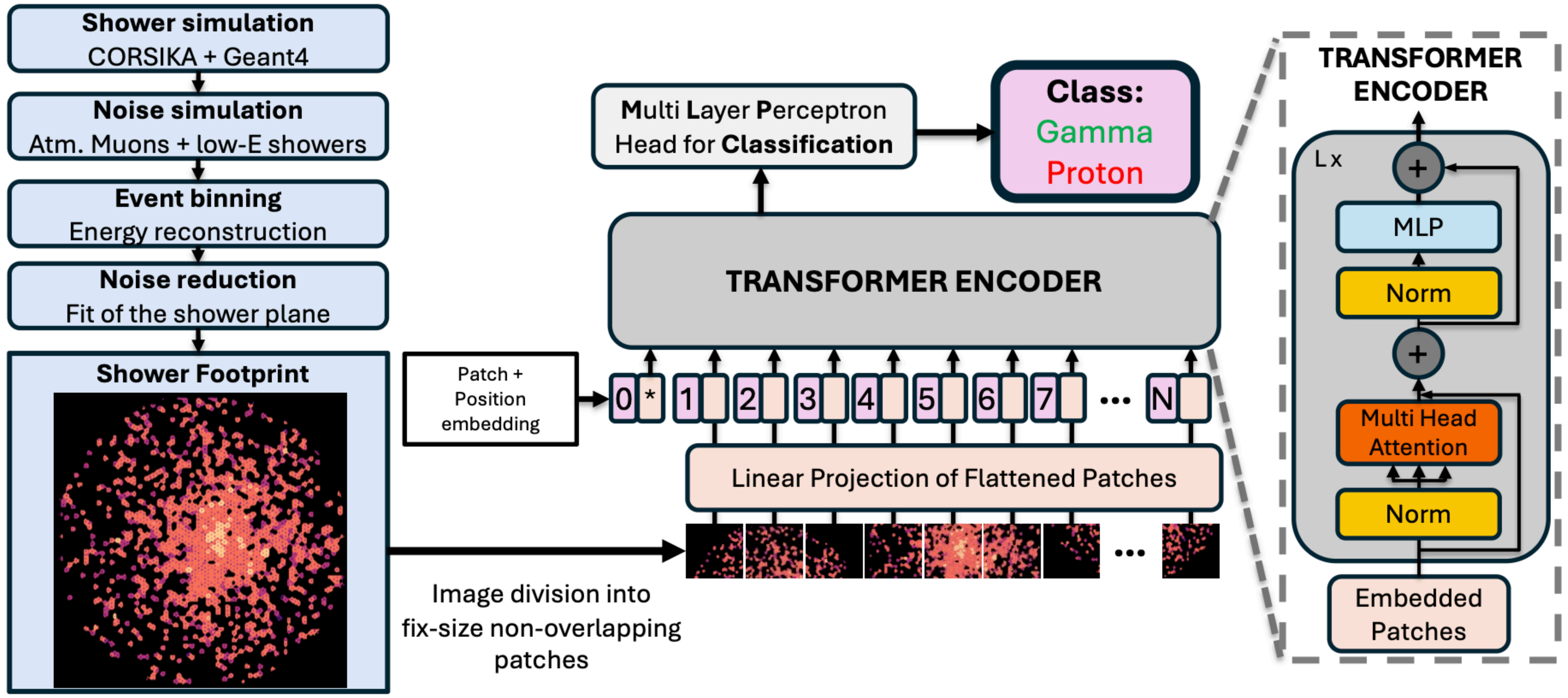
Shower **Noise-free**

Shower + **29 WCDs μ** (~6000 p.e.)

Shower + Proton shower 126 GeV **68 WCDs** (~2500 p.e.)







Exploring the shower footprint

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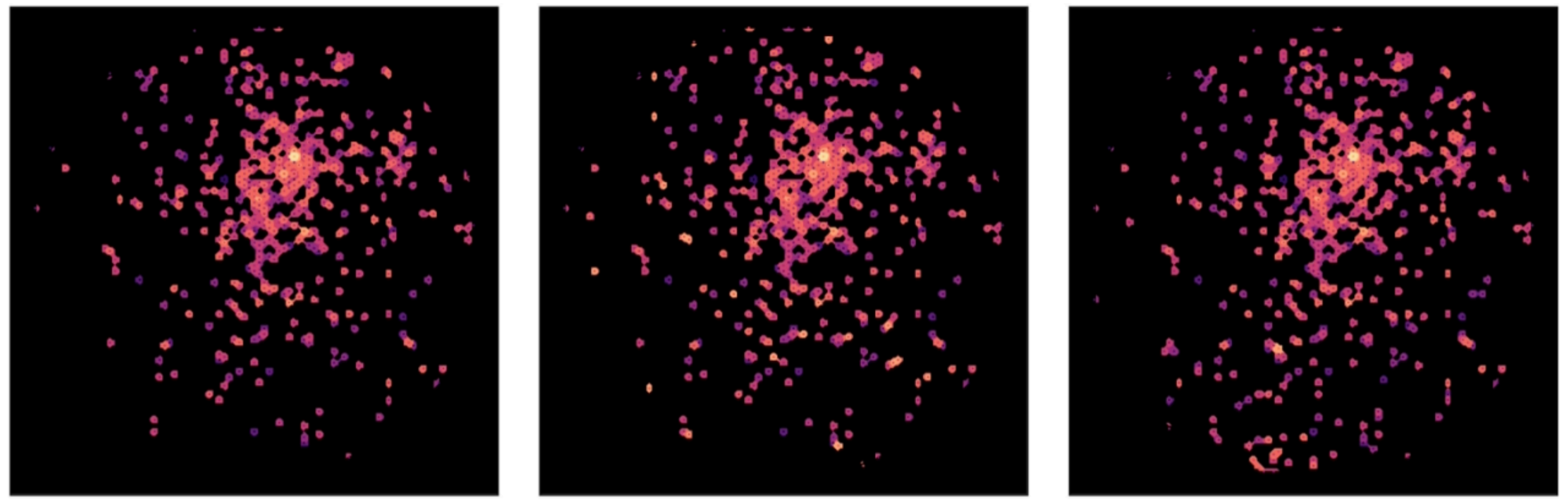

Shower
Noise-free

Shower
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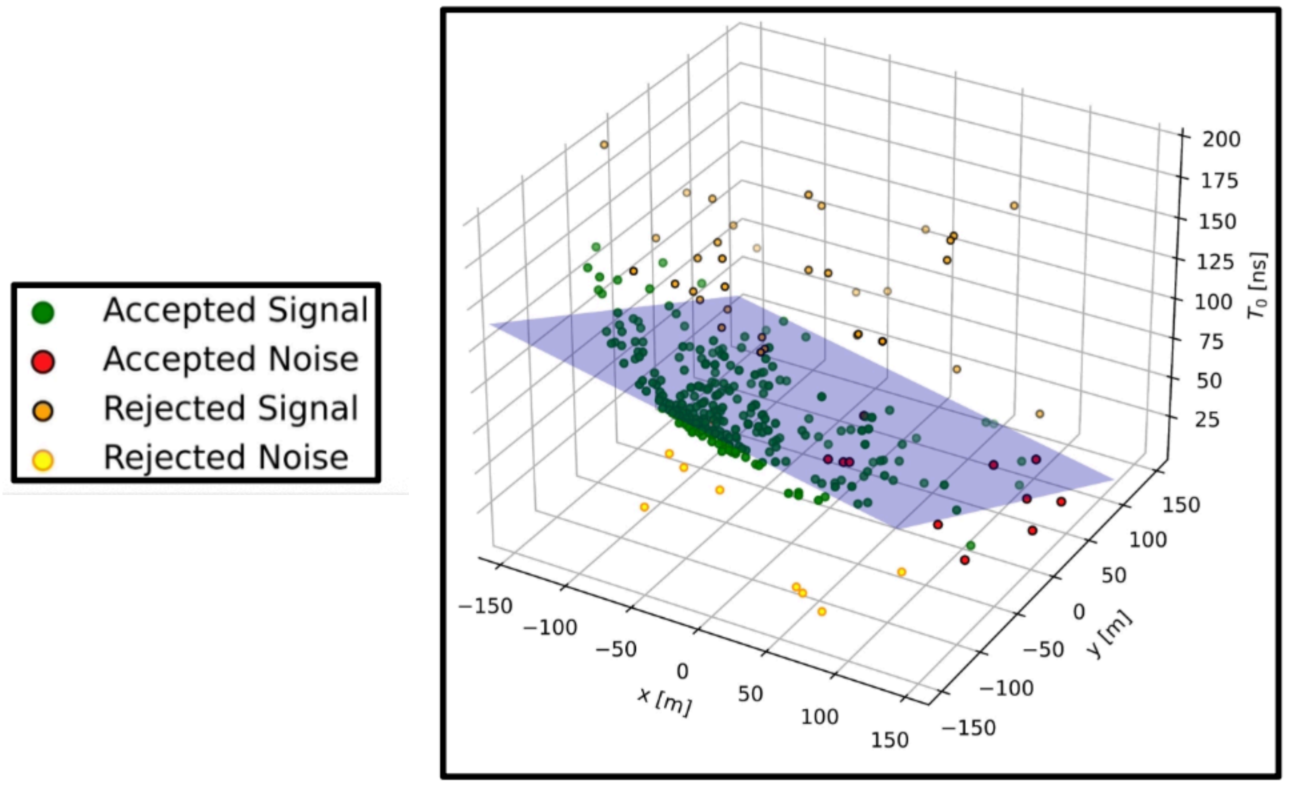
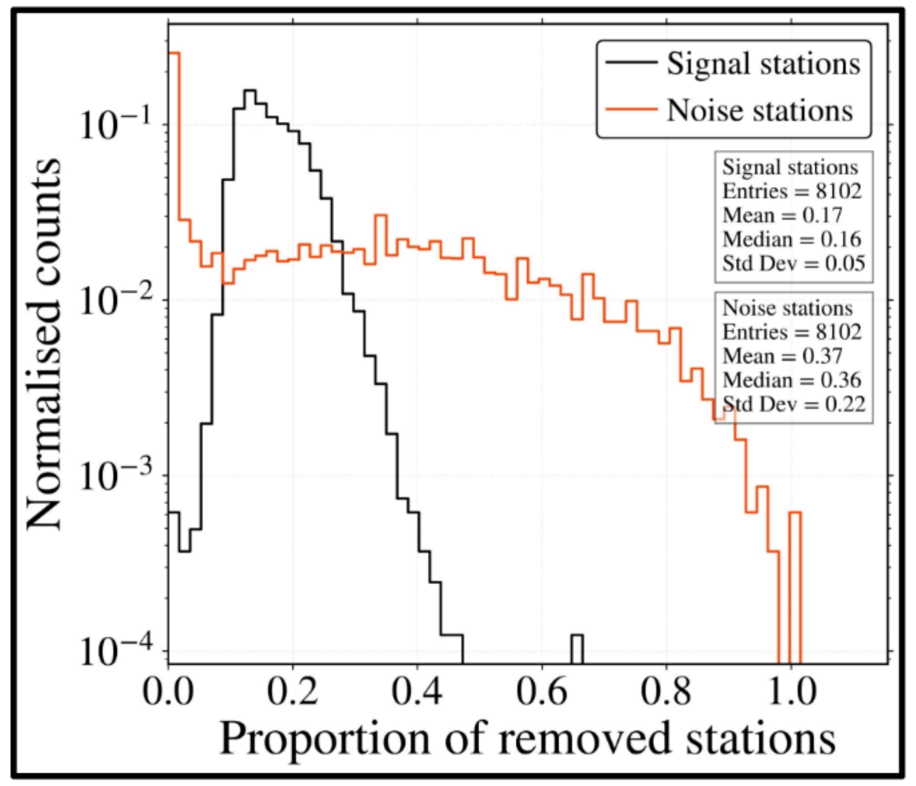
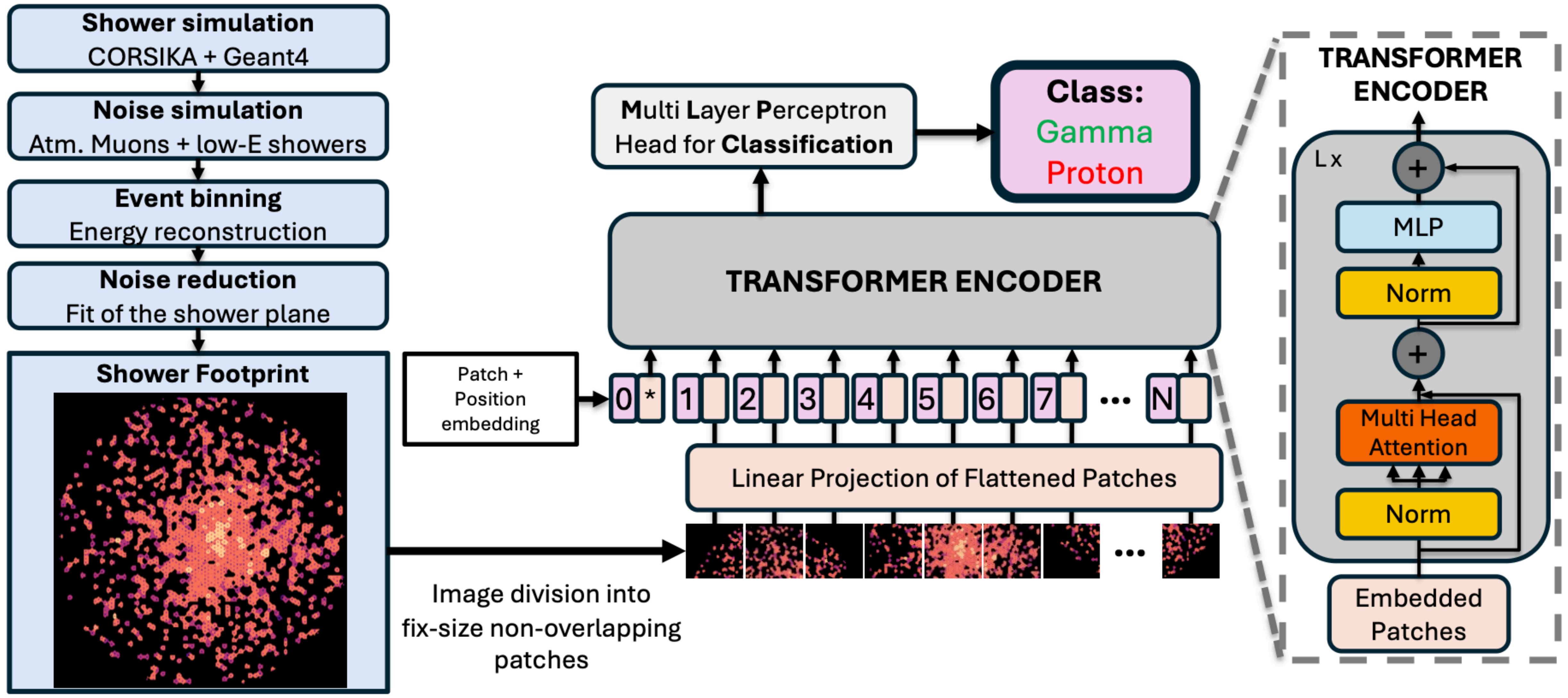
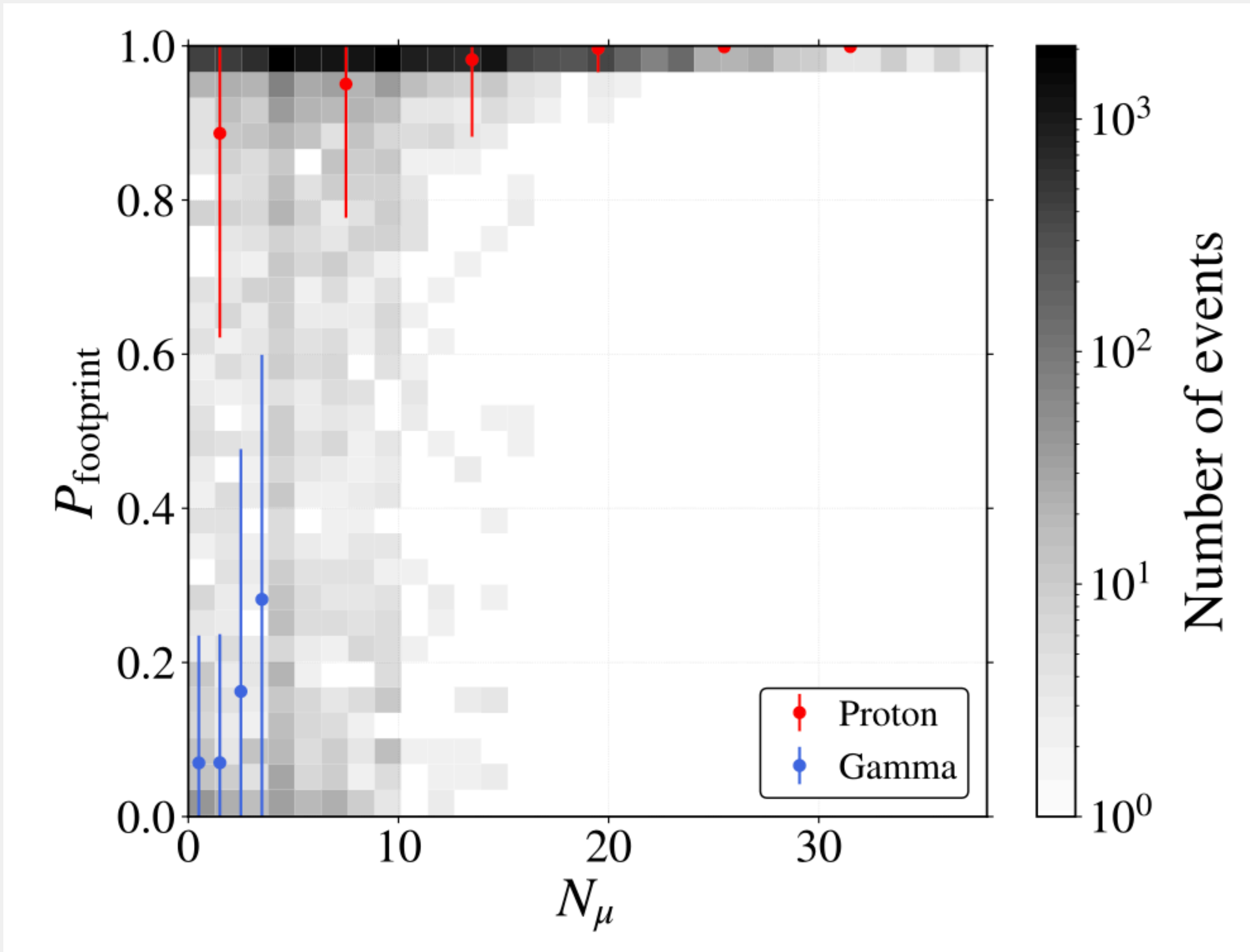








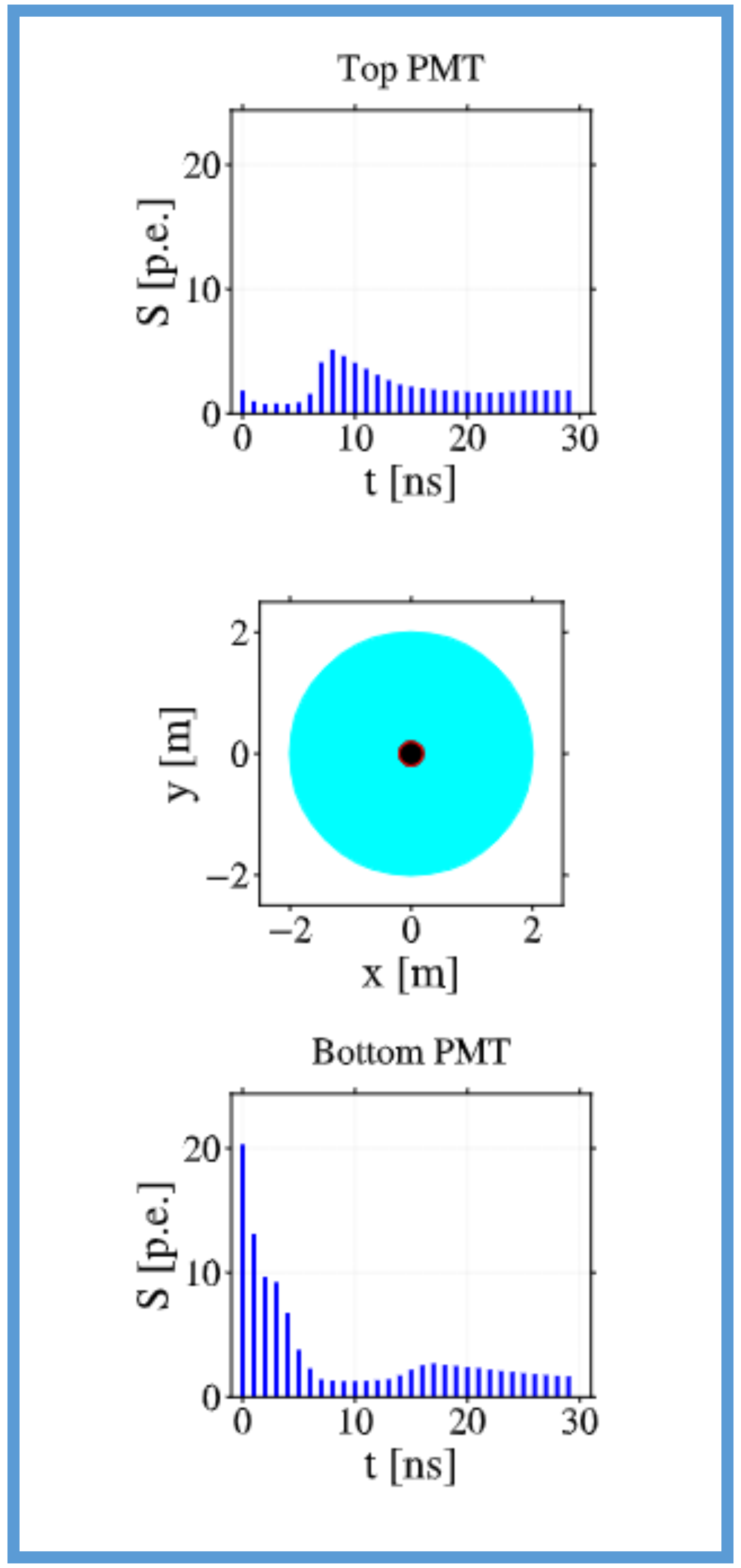
Excellent gamma/hadron separation even for proton showers with low muonic content

Further exploring a massive WCD array…

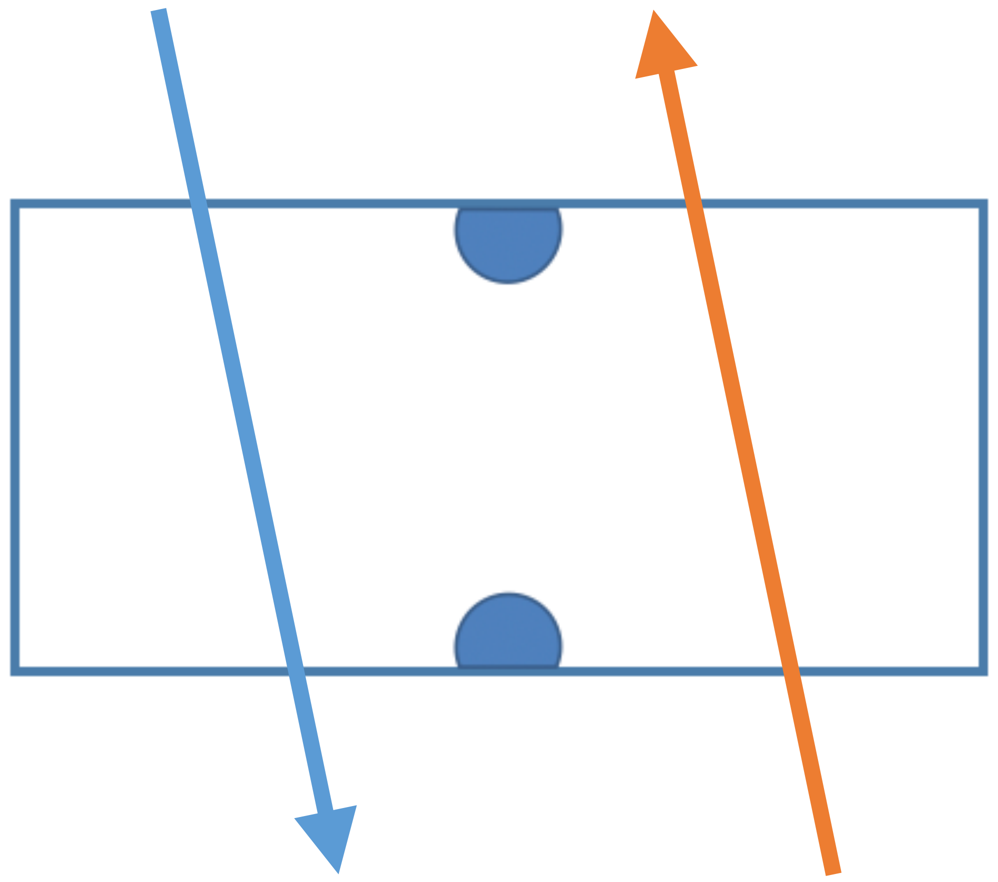
https://wminho.lip.pt/swgo/

Detection astrophysical HE neutrinos

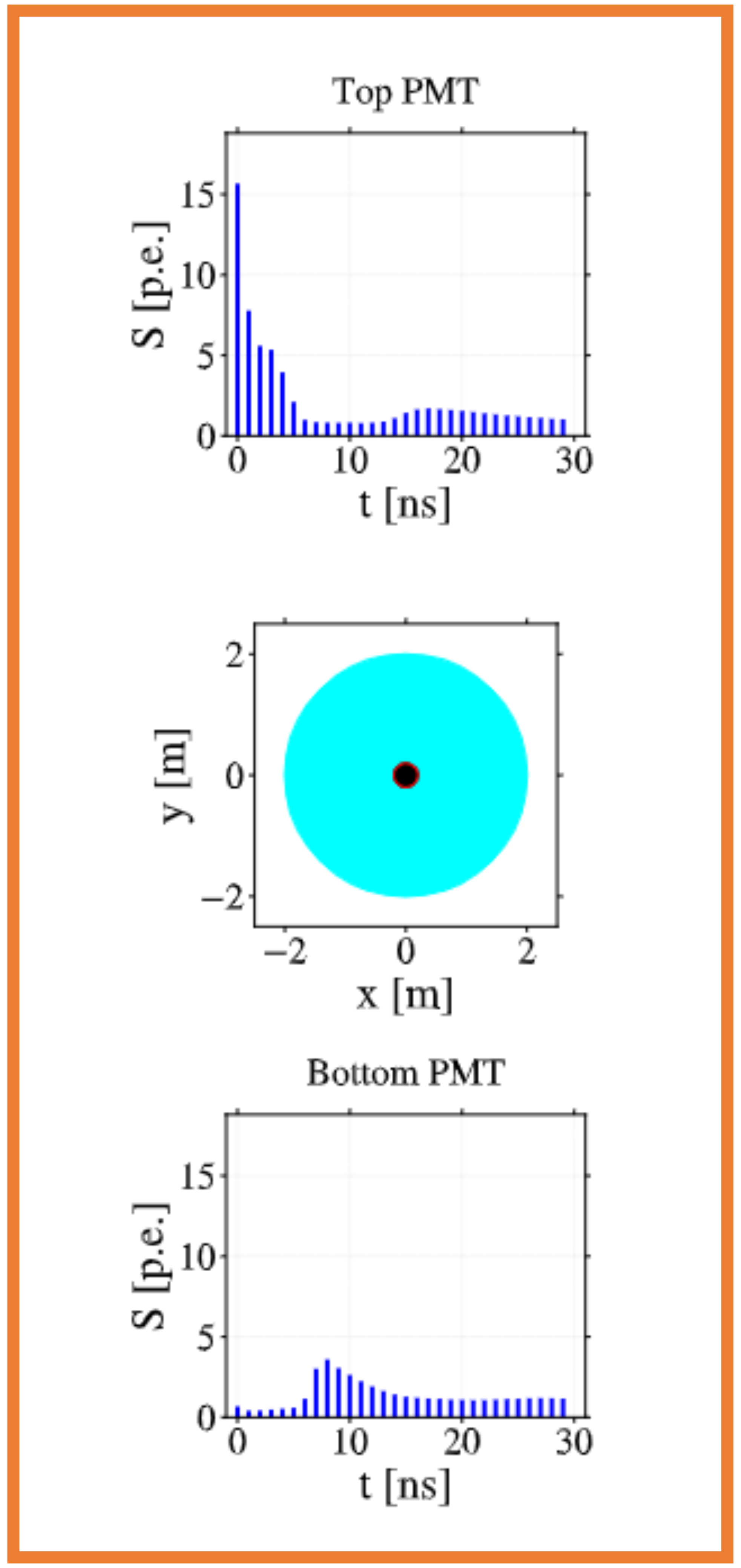
Background - cosmic ray events ($\theta < 40°$)



Down-going events



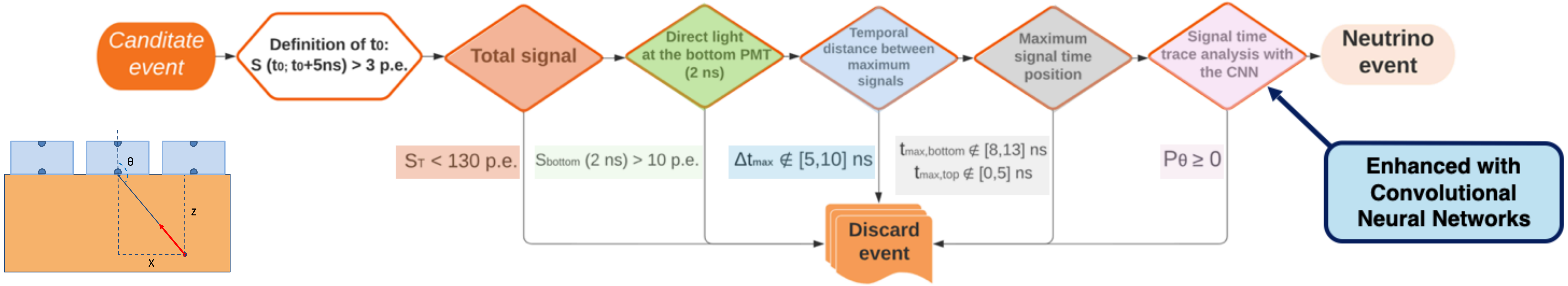
Signal - neutrino events ($\theta > 140°$)



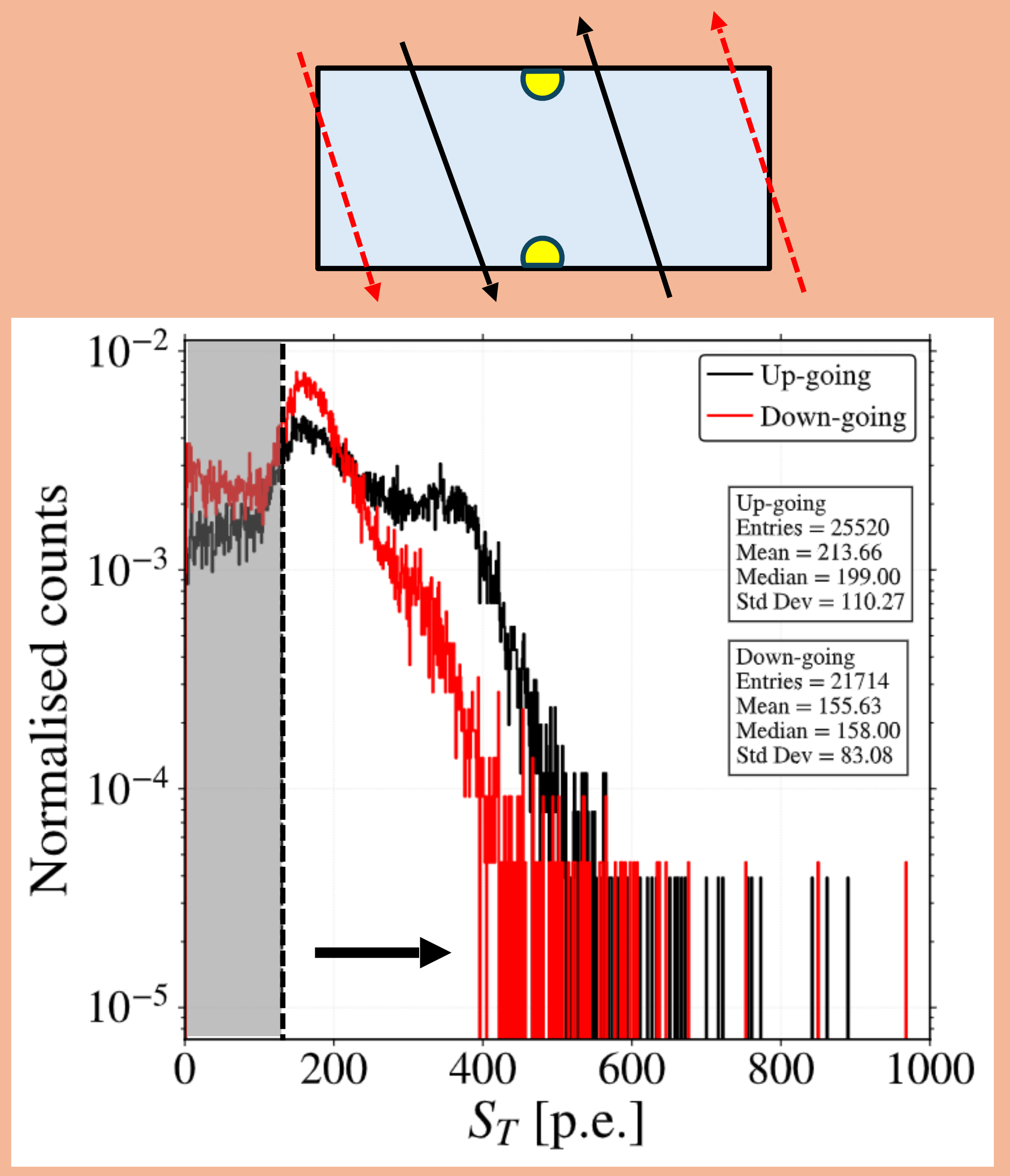
Up-going events

Upward-going neutrino identification chain

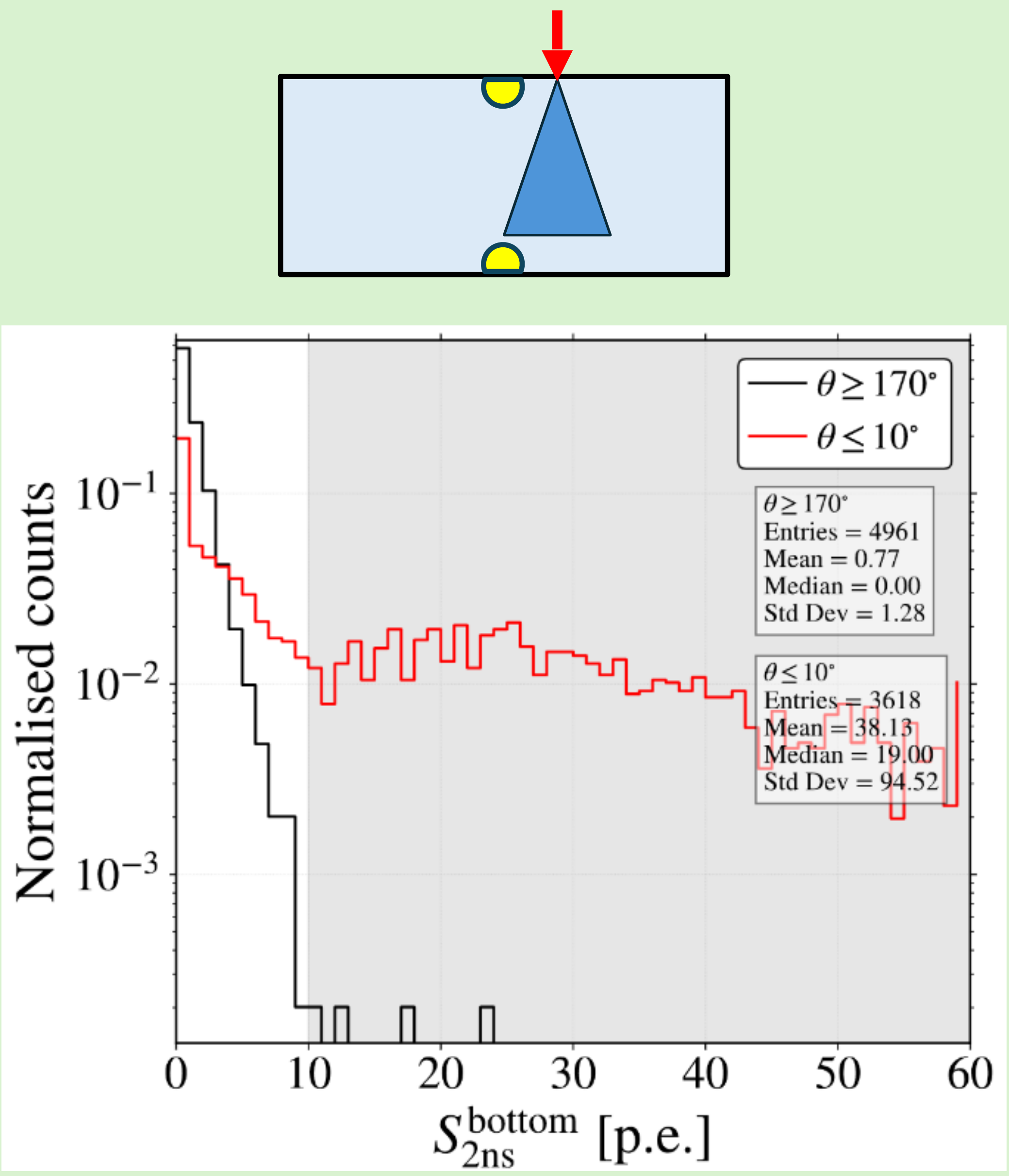
Alvarez-Muñiz et al. Phys.Rev.D 110 (2024) 2, 023032



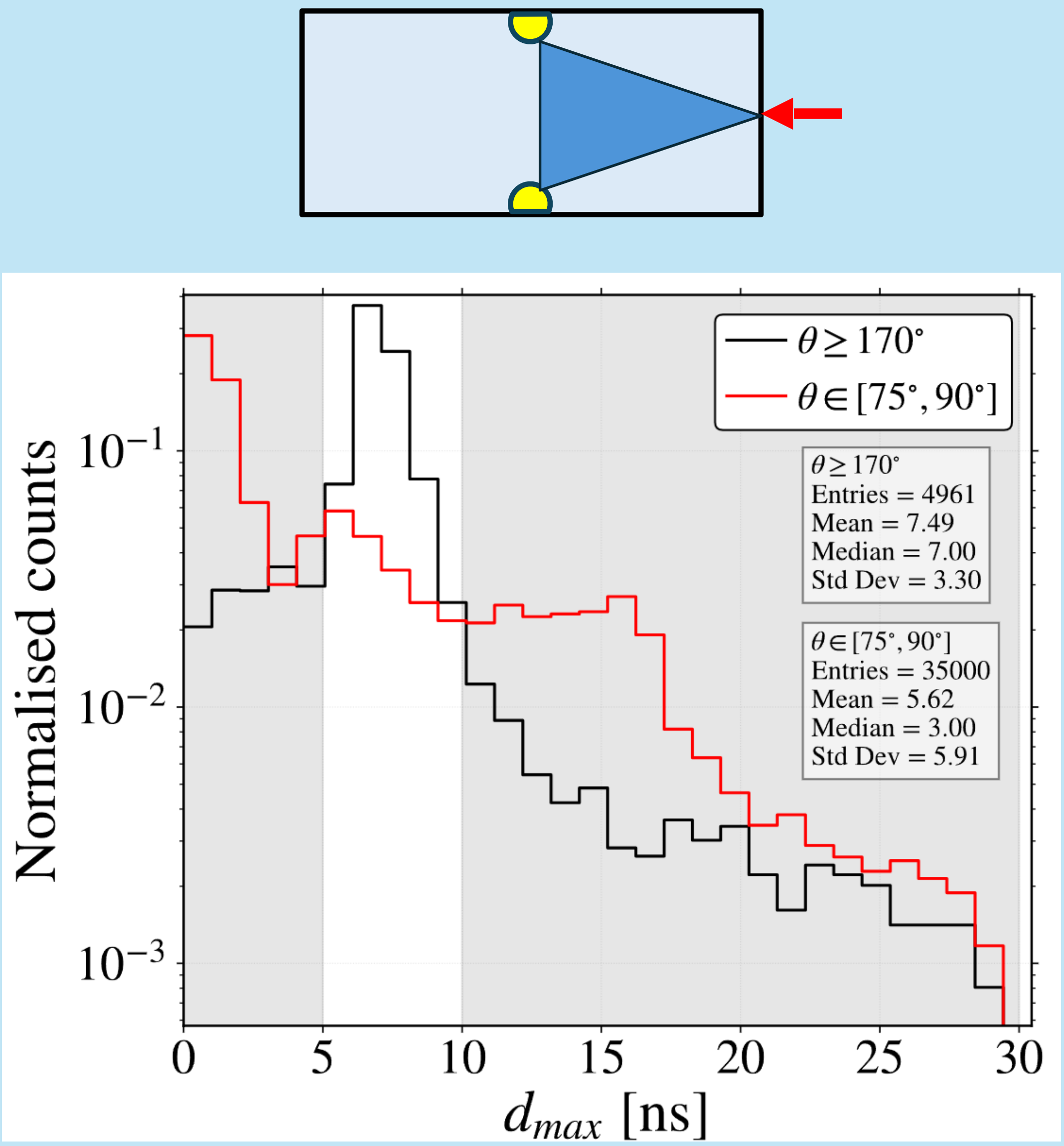
Large track lengths



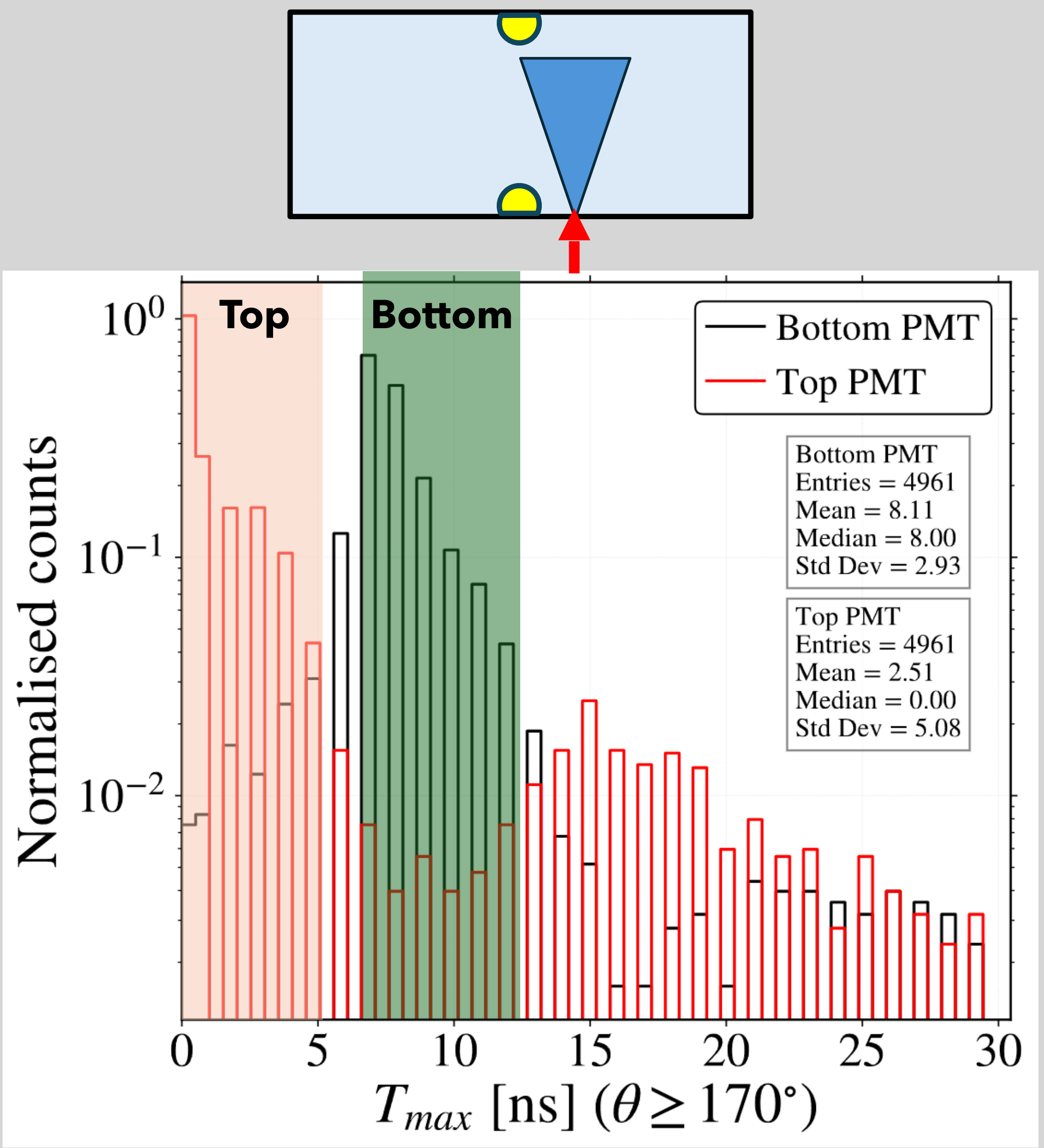
Down-going events



Horizontal events

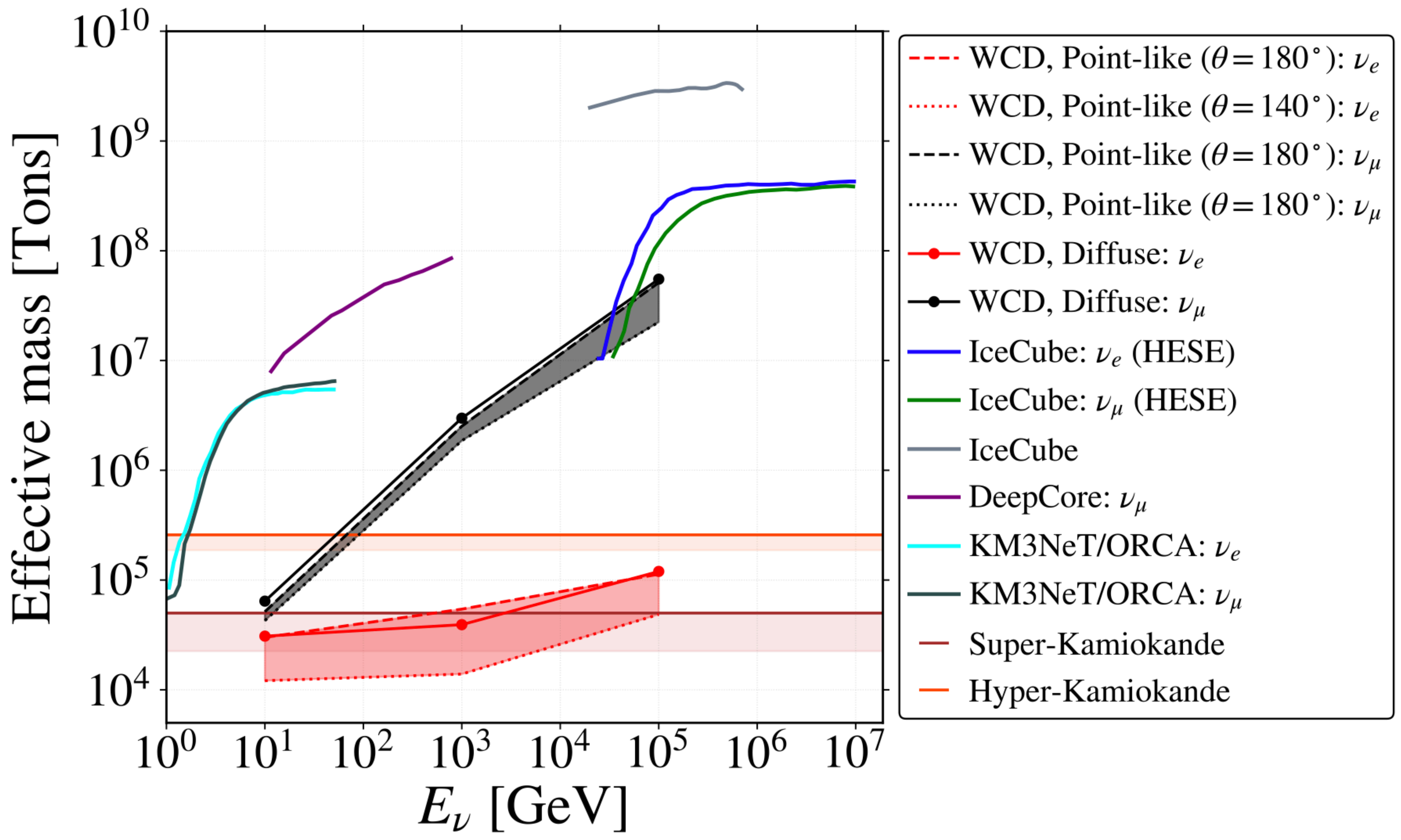


Geometry for up-going events

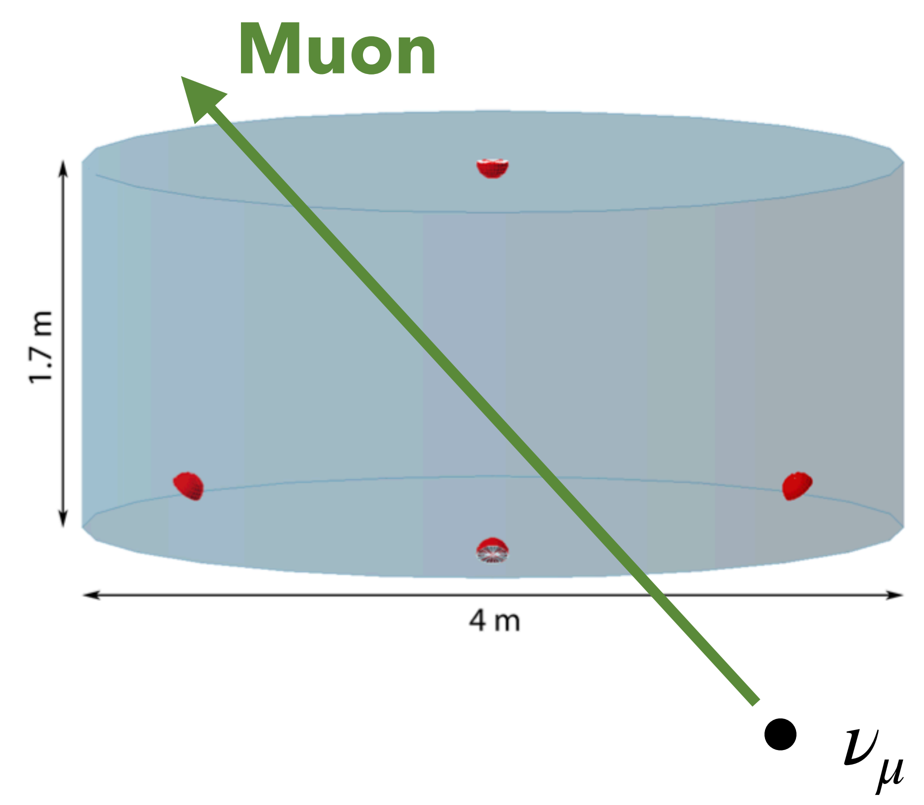


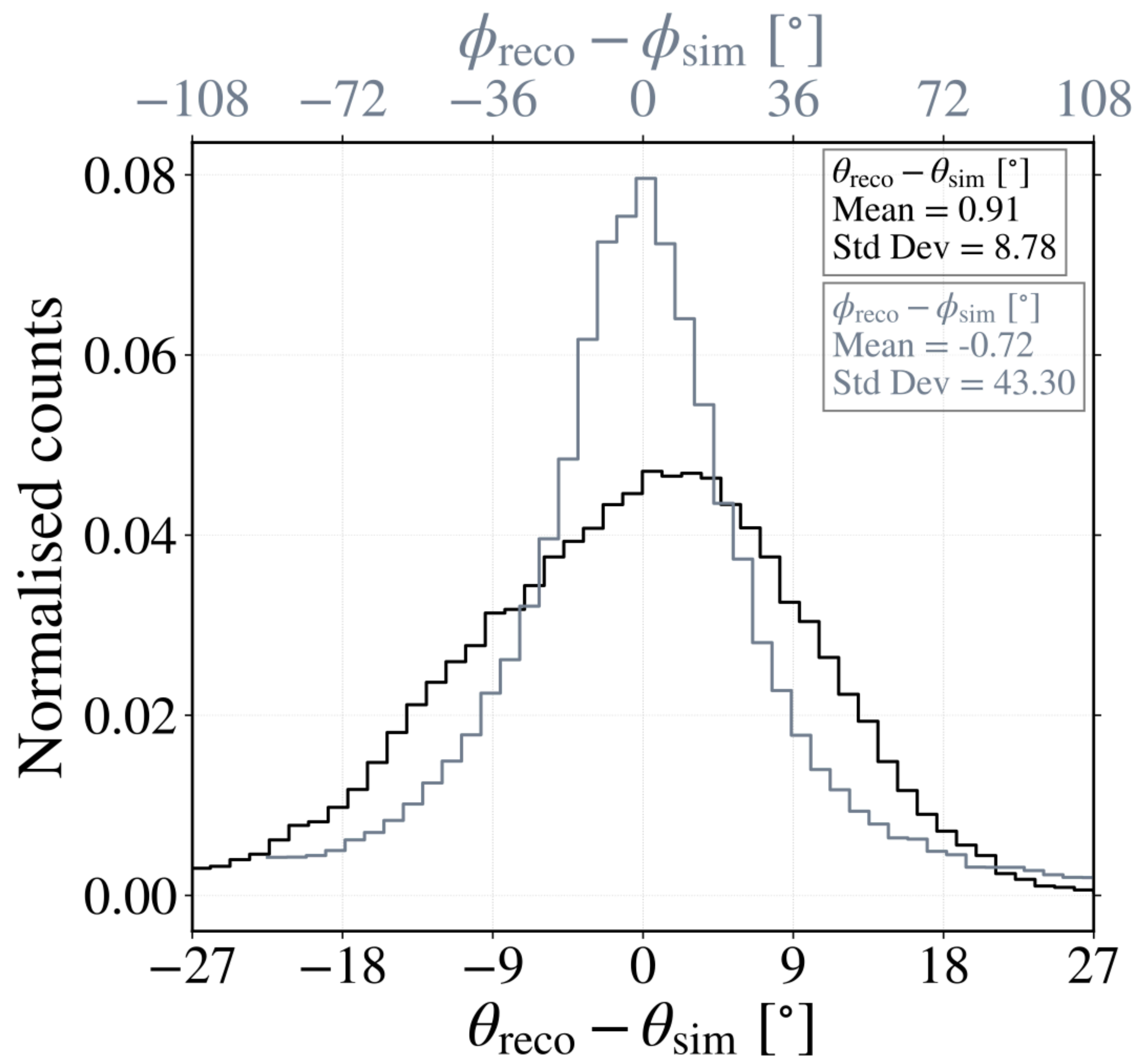
Background-free identification of **upward-going neutrinos** through the analysis of **PMT signal time traces.**

Catching neutrinos with a single WCD



Alvarez-Muñiz et al. Phys.Rev.D 110 (2024) 2, 023032



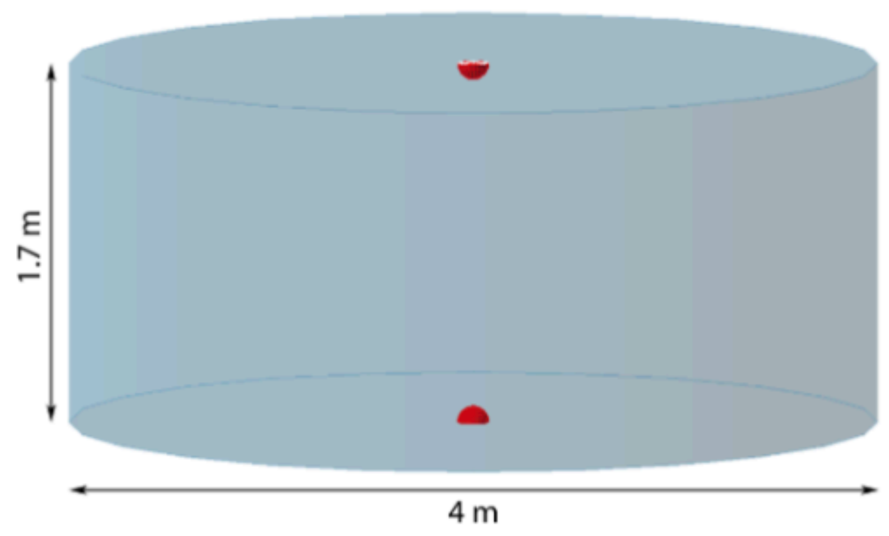


- Explore the PMT signal time trace structure recurring to ML algorithms (Transformer architectures based on self-attention mechanisms):
  - Identify up-going ν from cosmic ray background
  - Reconstruct the direction of the neutrino (i.e. the muon traversing the WCD)

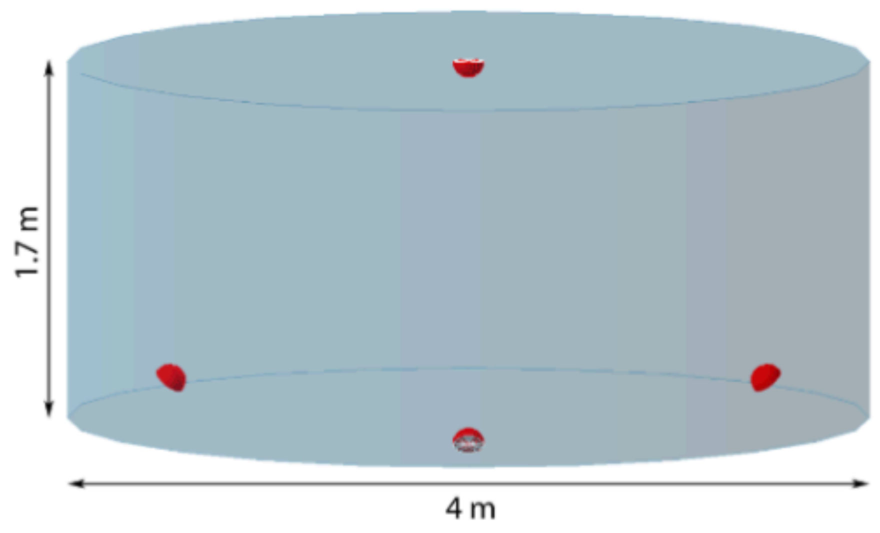
Improving the ν direction reconstruction

Alvarez-Muñiz et al. Eur.Phys.J.C 85 (2025) 8, 842

Multiple 8" PMTs

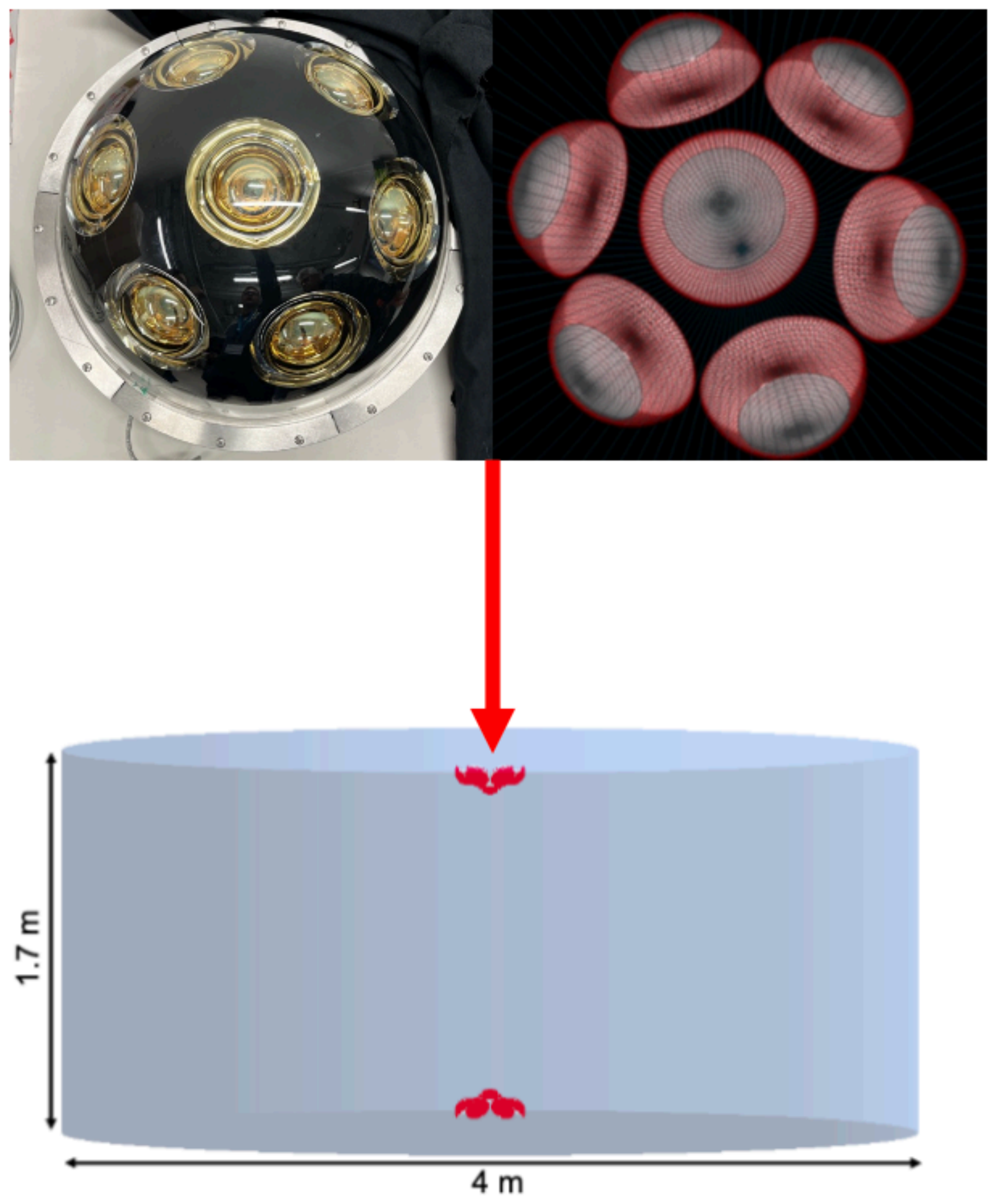


M1T1



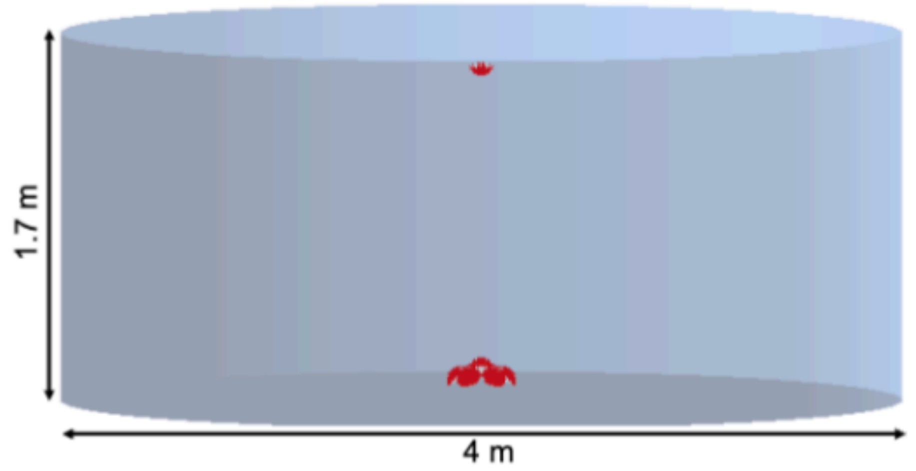
M3T1

Multiple 3" multi-PMTs

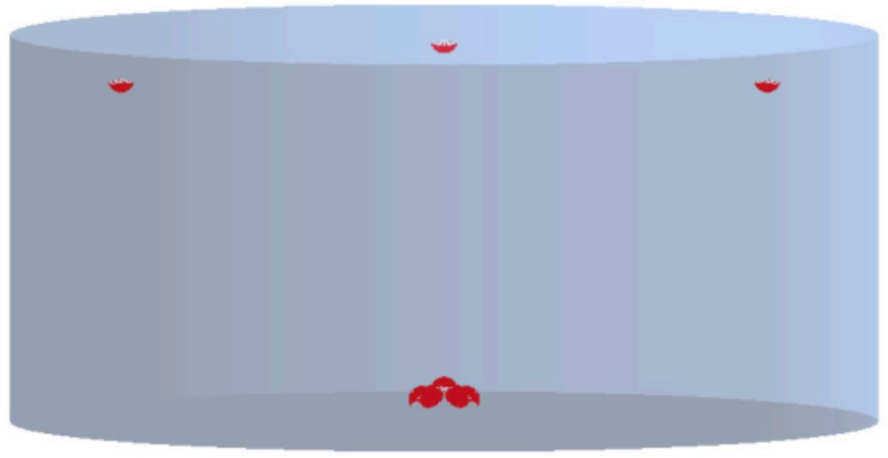


M1mT1m

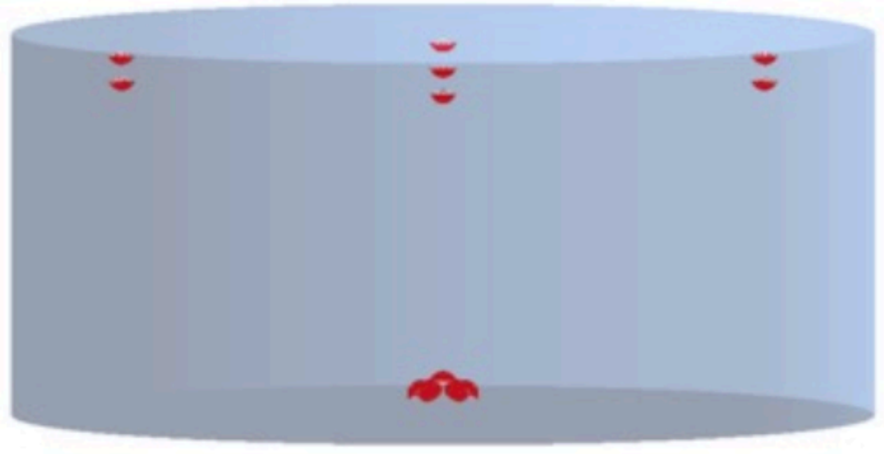
Bottom 3" multi-PMT + top 3" PMT(s)



M1mT1s



M1mT3s

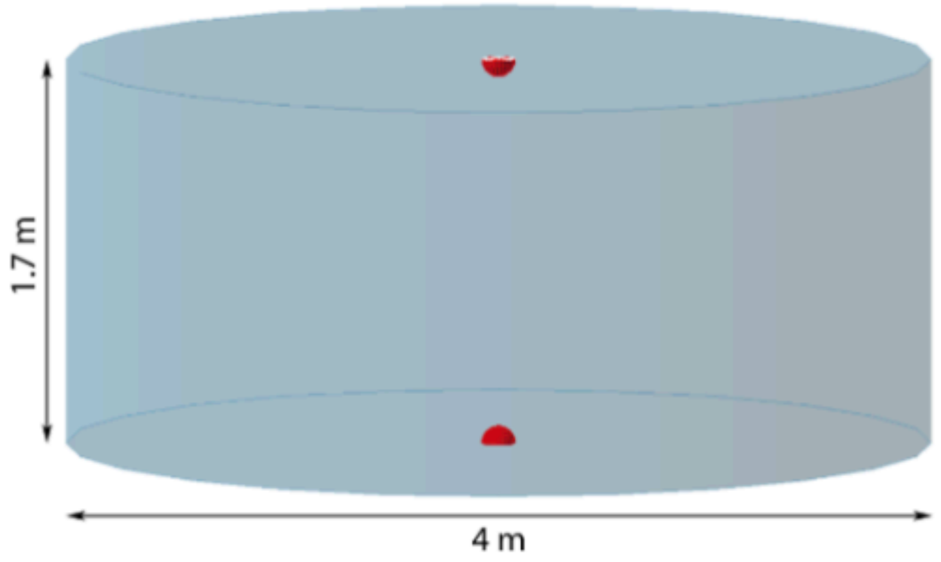


M1mT7s

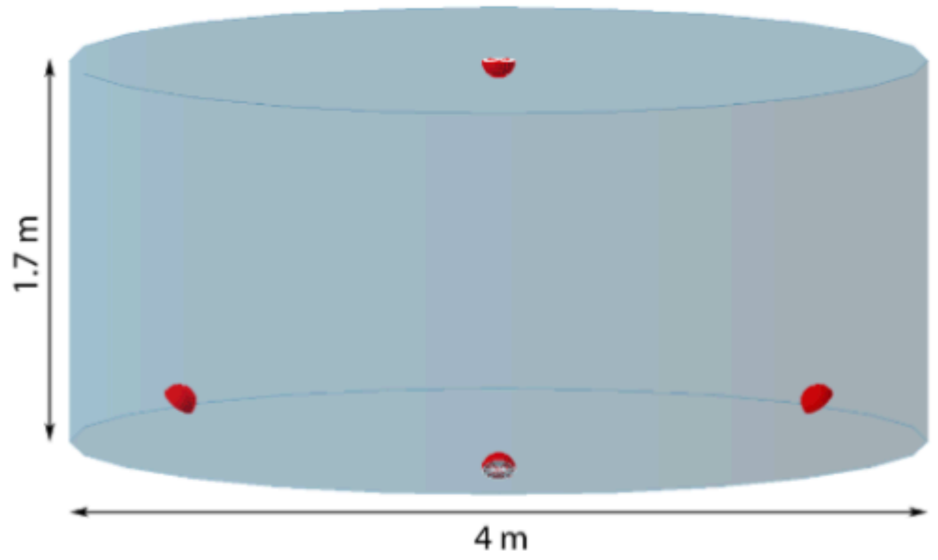
Improving the ν direction reconstruction

Alvarez-Muñiz et al. Eur.Phys.J.C 85 (2025) 8, 842

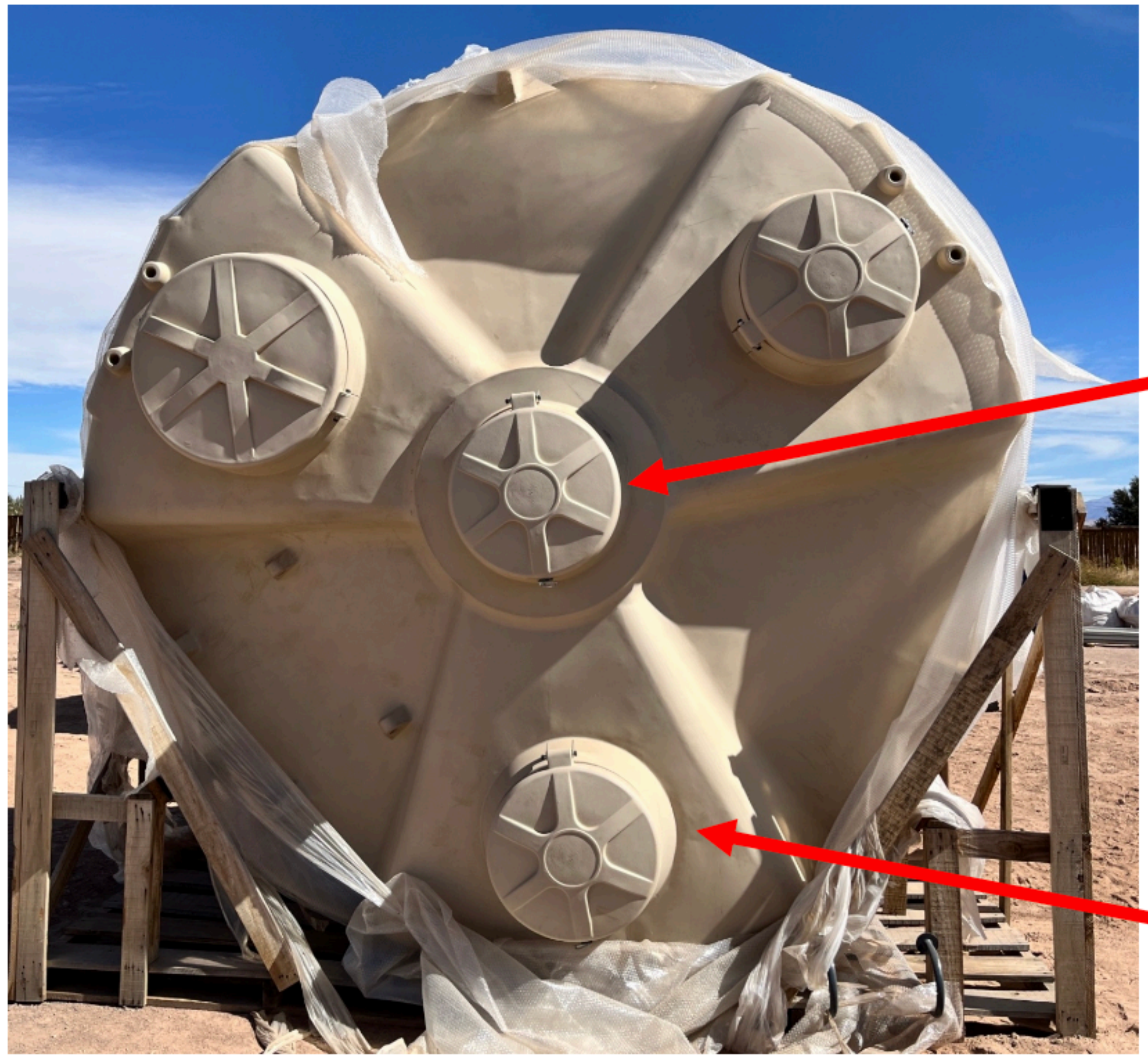
Multiple 8" PMTs



M1T1

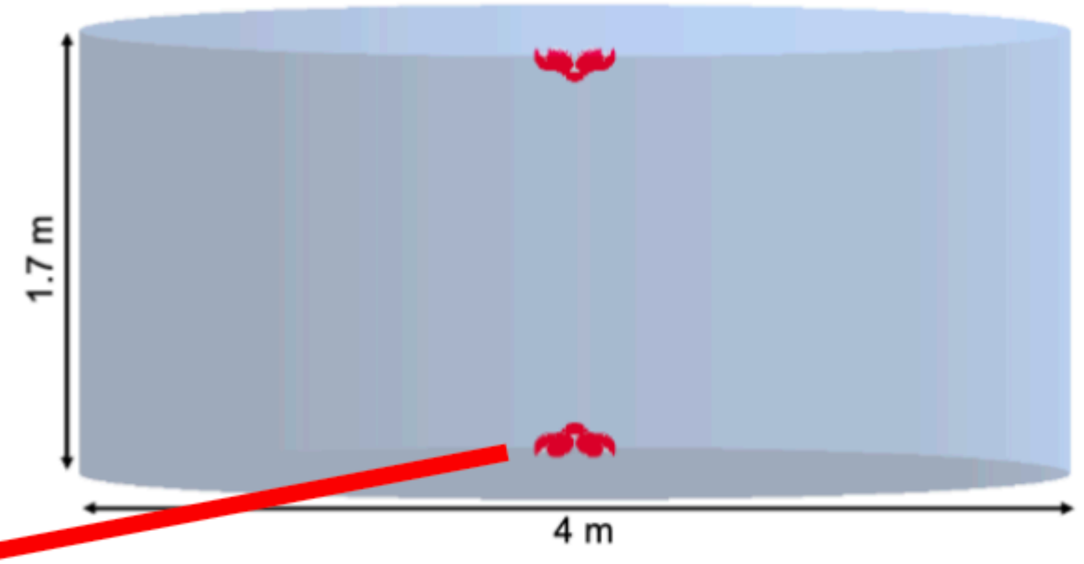


M3T1

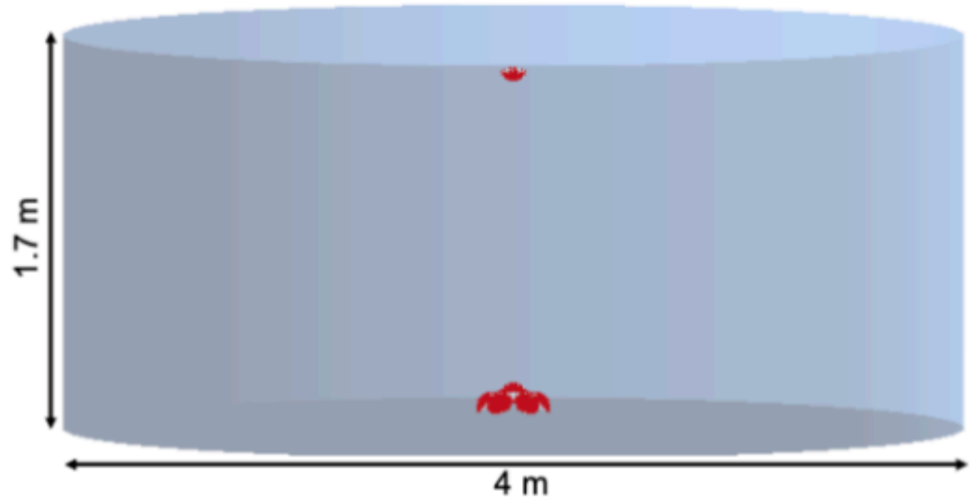


Prototype of the Mercedes station in SWGO

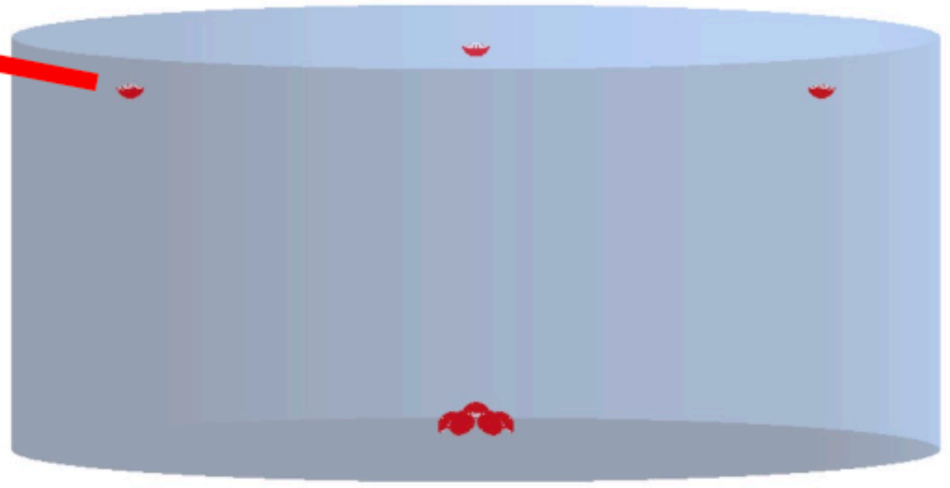
Multi-PMT based



M1mT1m



M1mT1s

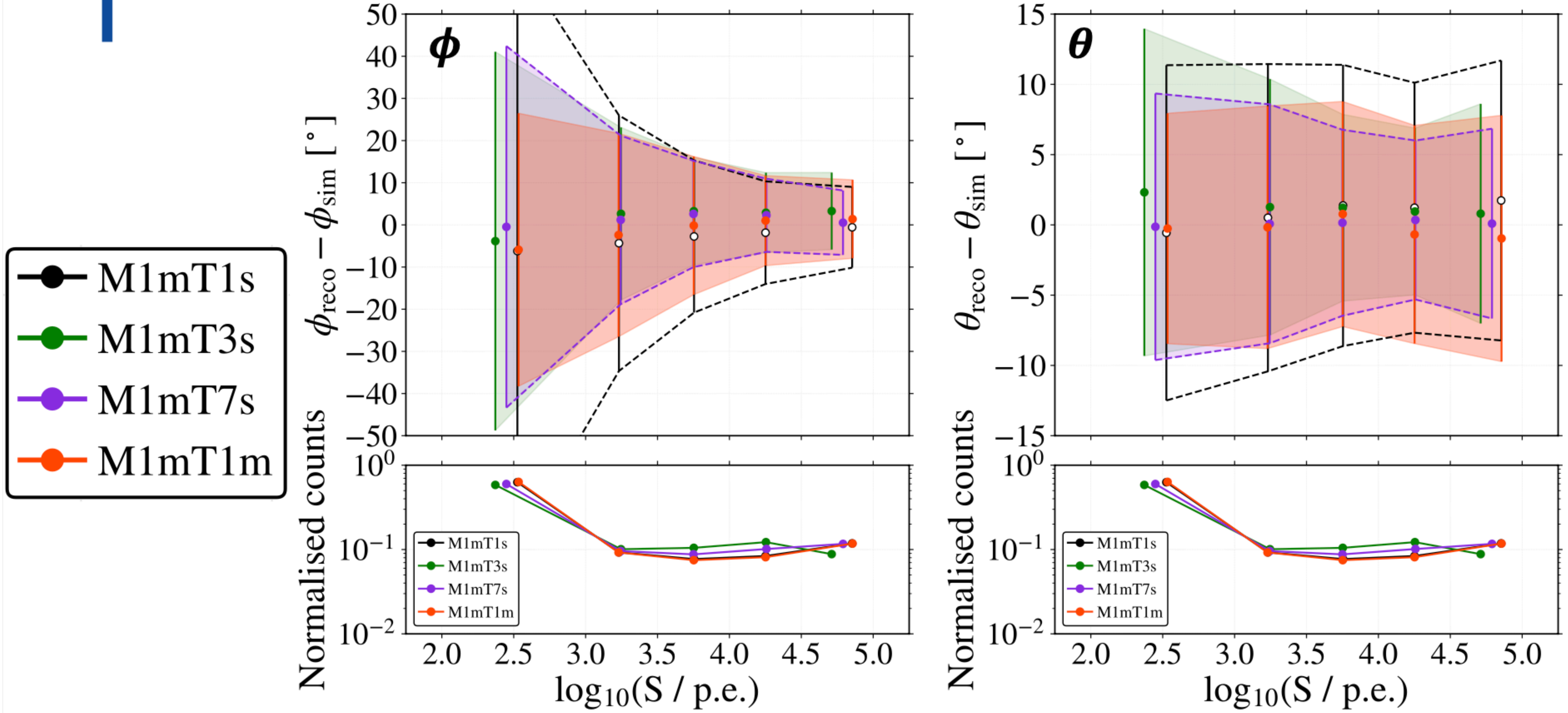


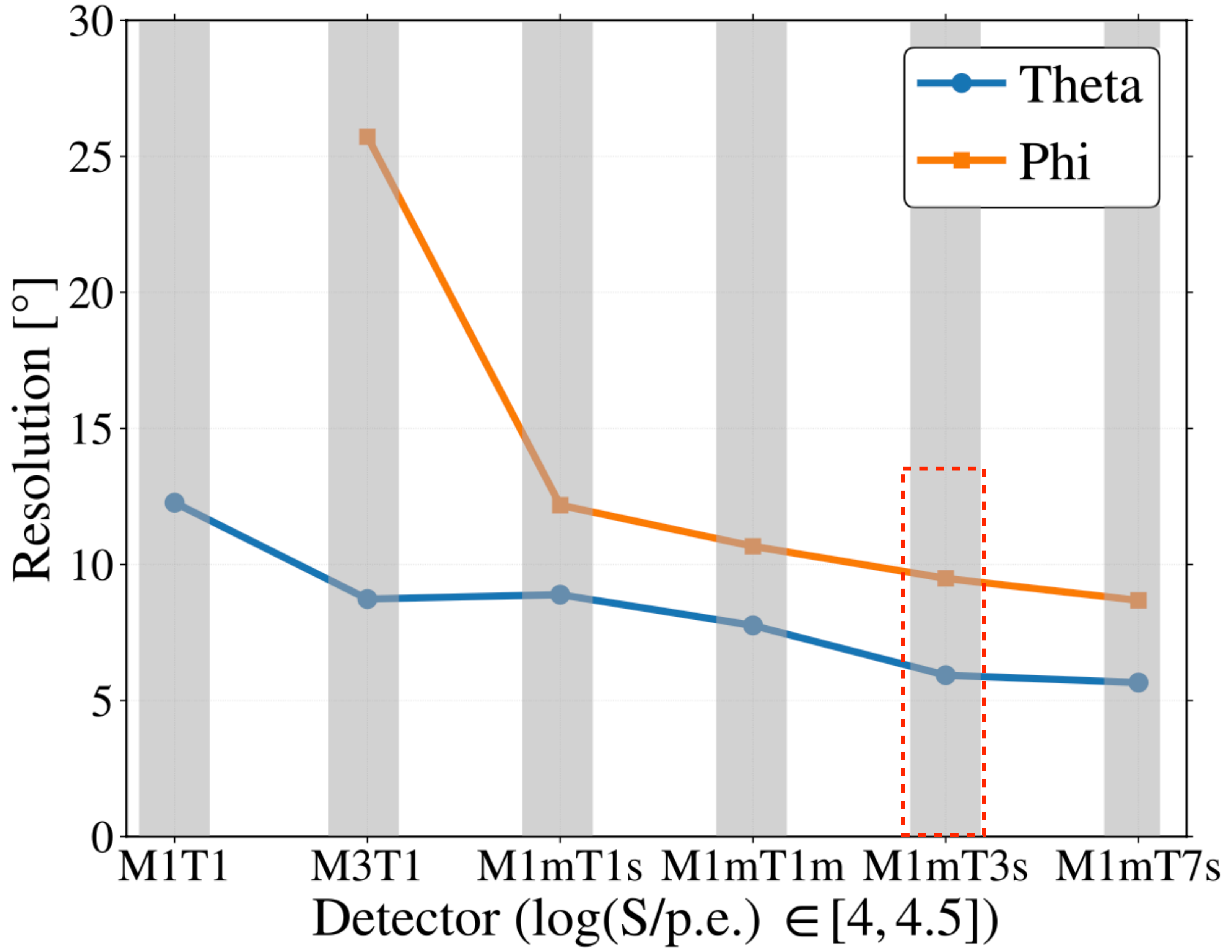
M1mT3s

Improving the ν direction reconstruction

Alvarez-Muñiz et al. Eur.Phys.J.C 85 (2025) 8, 842

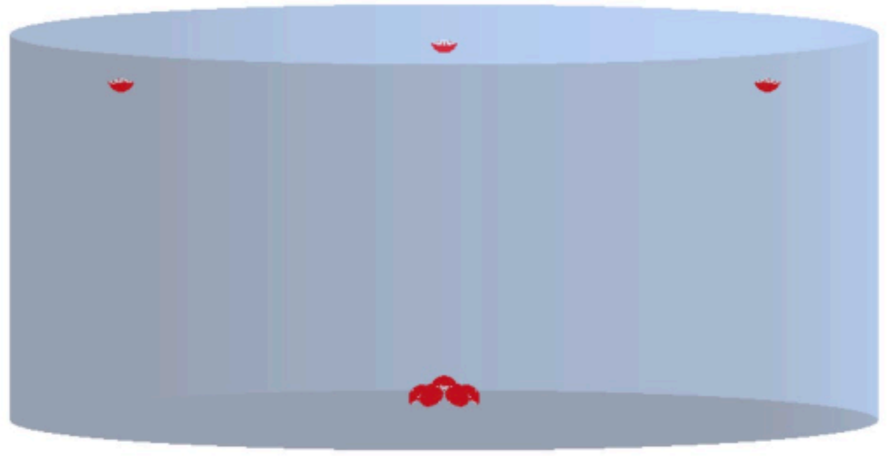
Angular reconstruction 1 TeV ν_μ





At the **top** surface, **multiple 3" PMTs** perform better than a single m-PMT.

M1mT7s: Negligible bias and resolution of ~**8.5° (azimuth)** and ~**5.5° (zenith)** for high-signal events

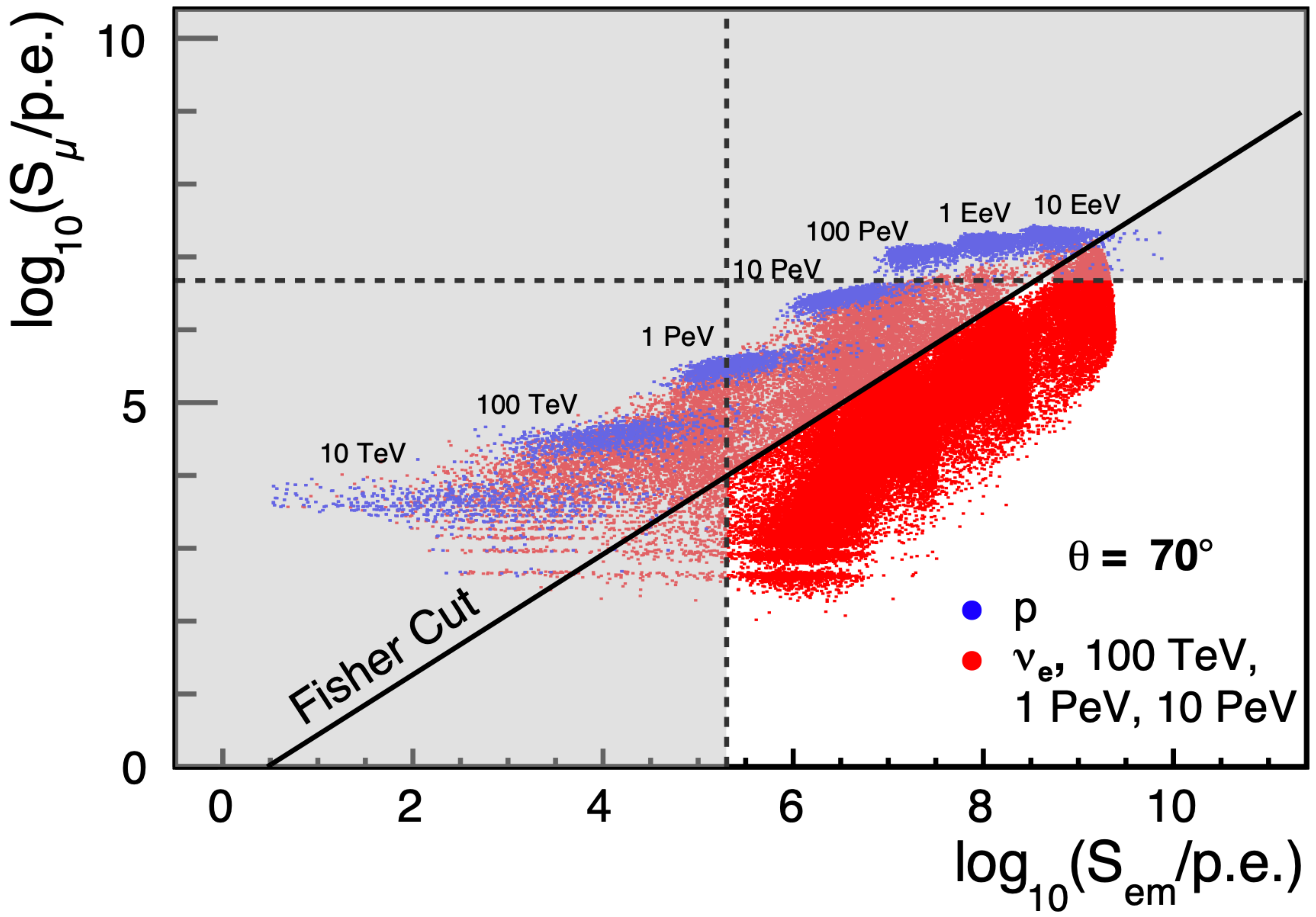


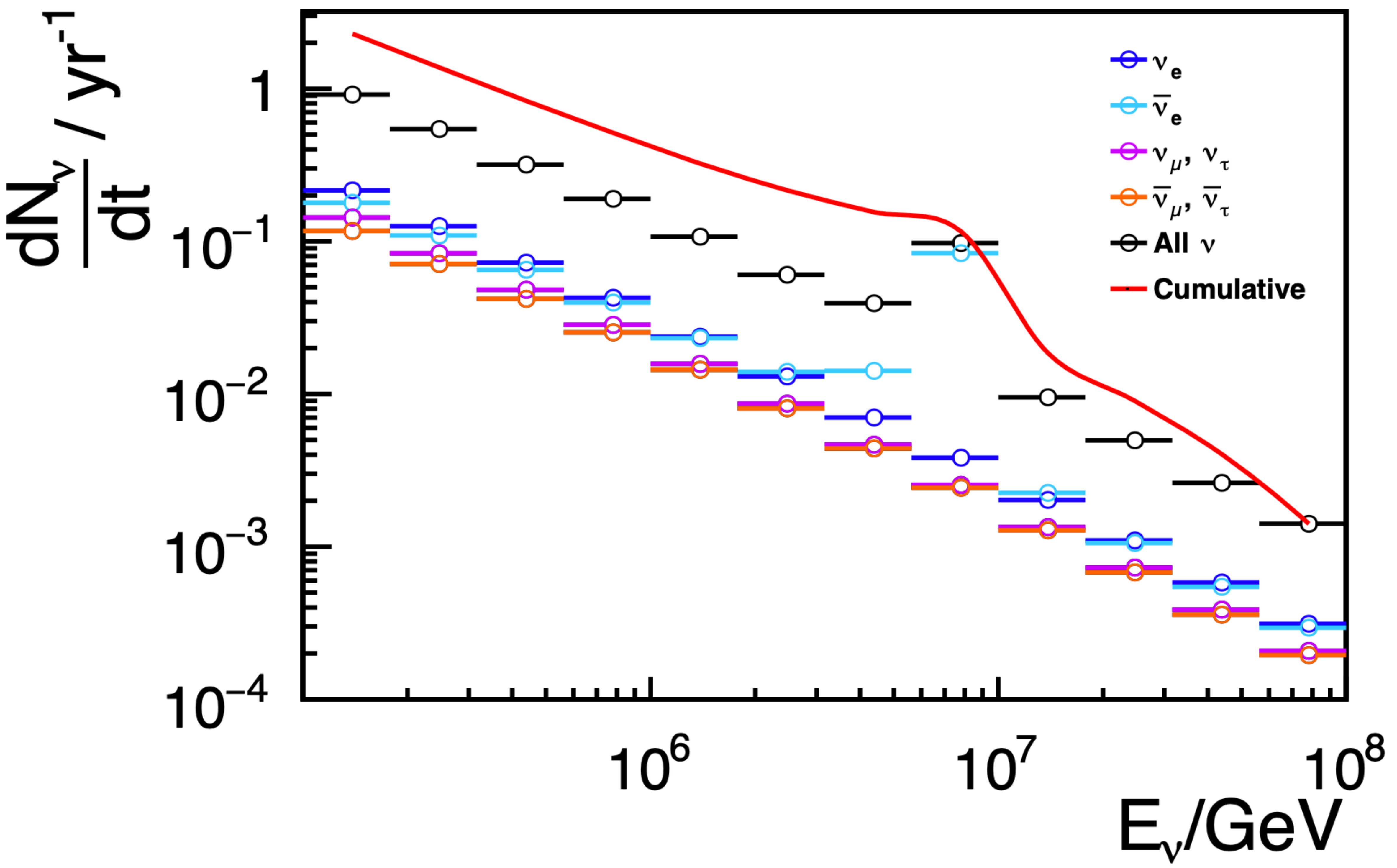
M1mT3s

Another way to detect neutrinos @ SWGO/LHASSO

Taking advantage of very inclined showers

Alvarez-Muñiz et al.Phys.Rev.D 106 (2022) 10, 102001

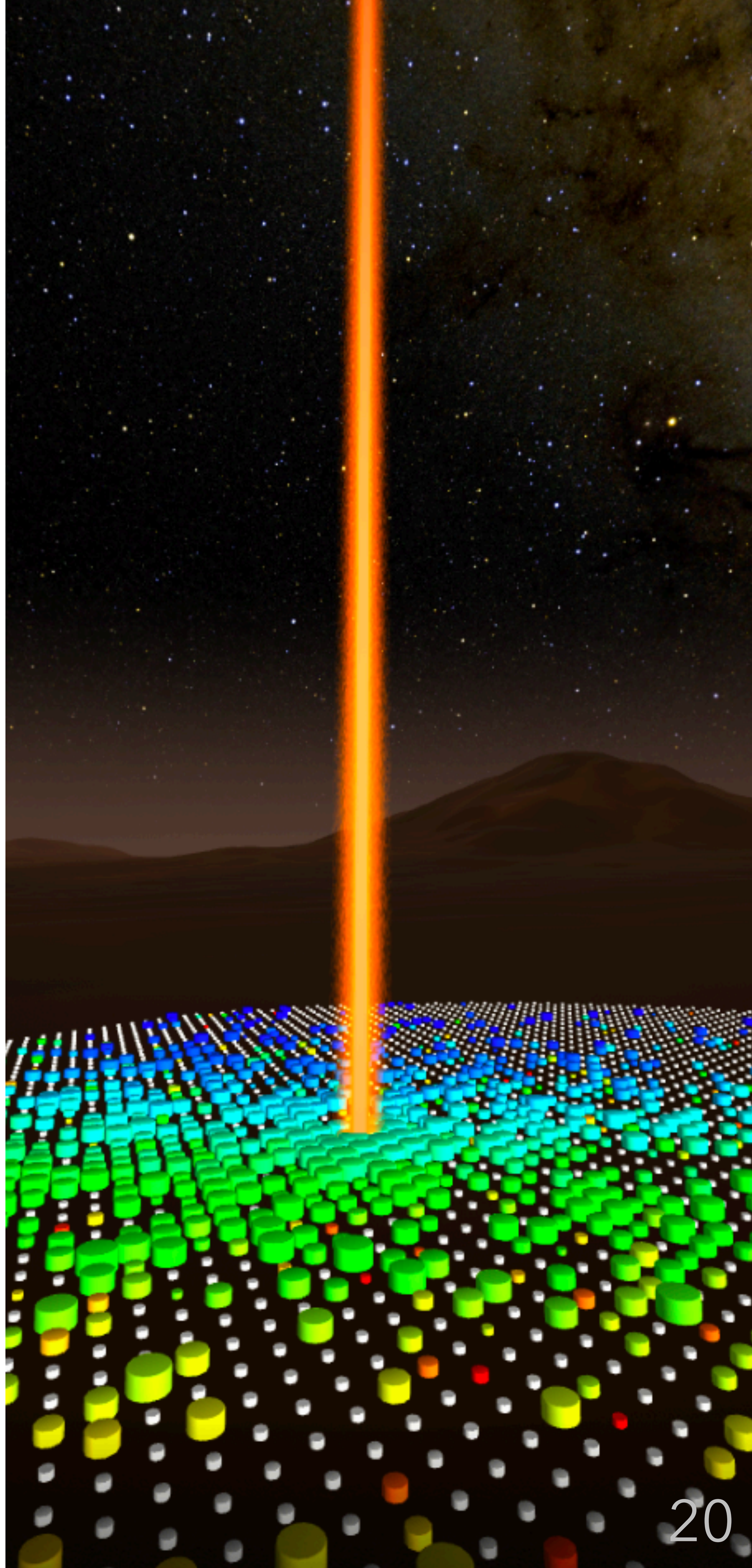




An experiment such as SWGO would be able to detect around 2 neutrinos with E>100 TeV per year

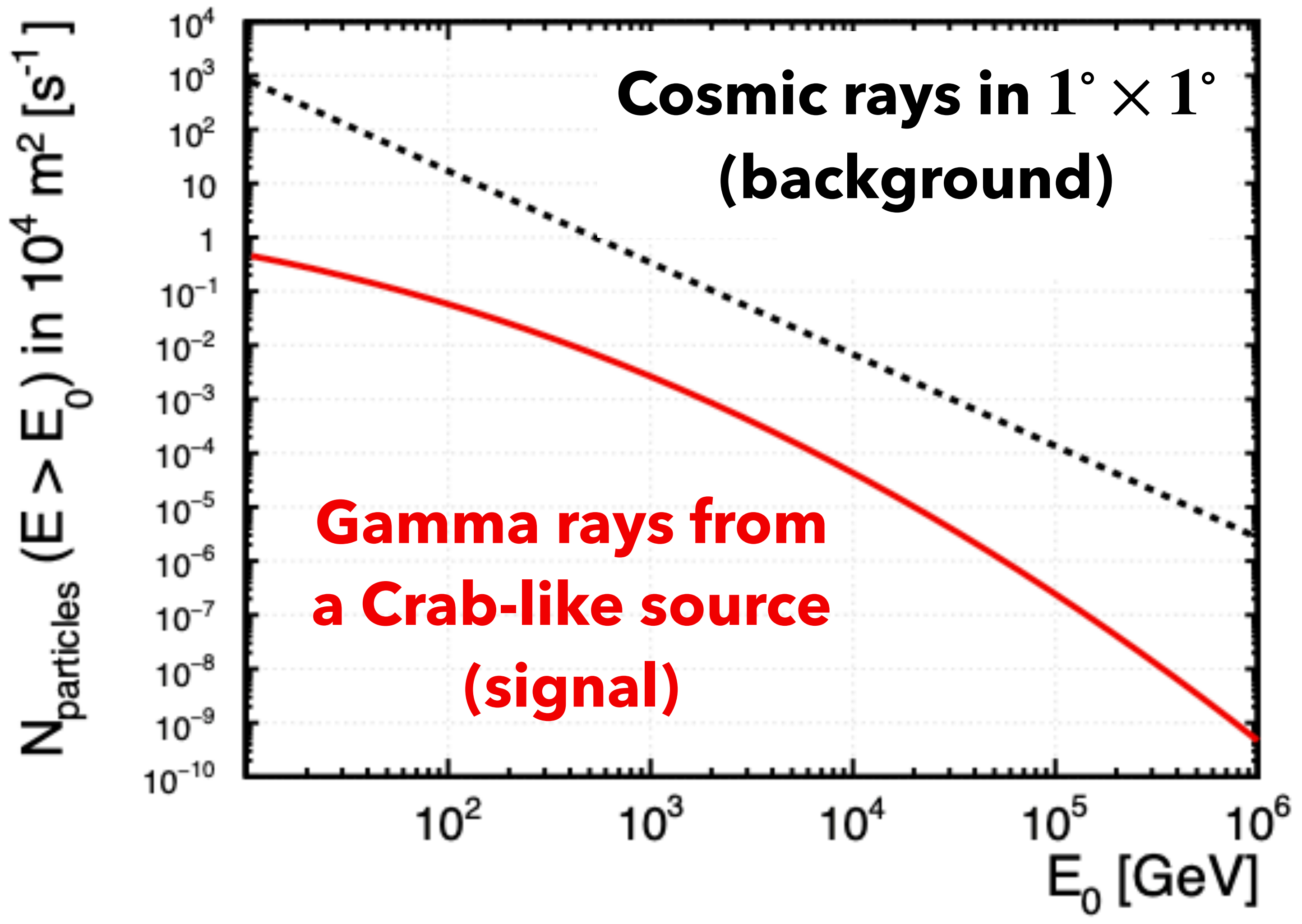
Summary

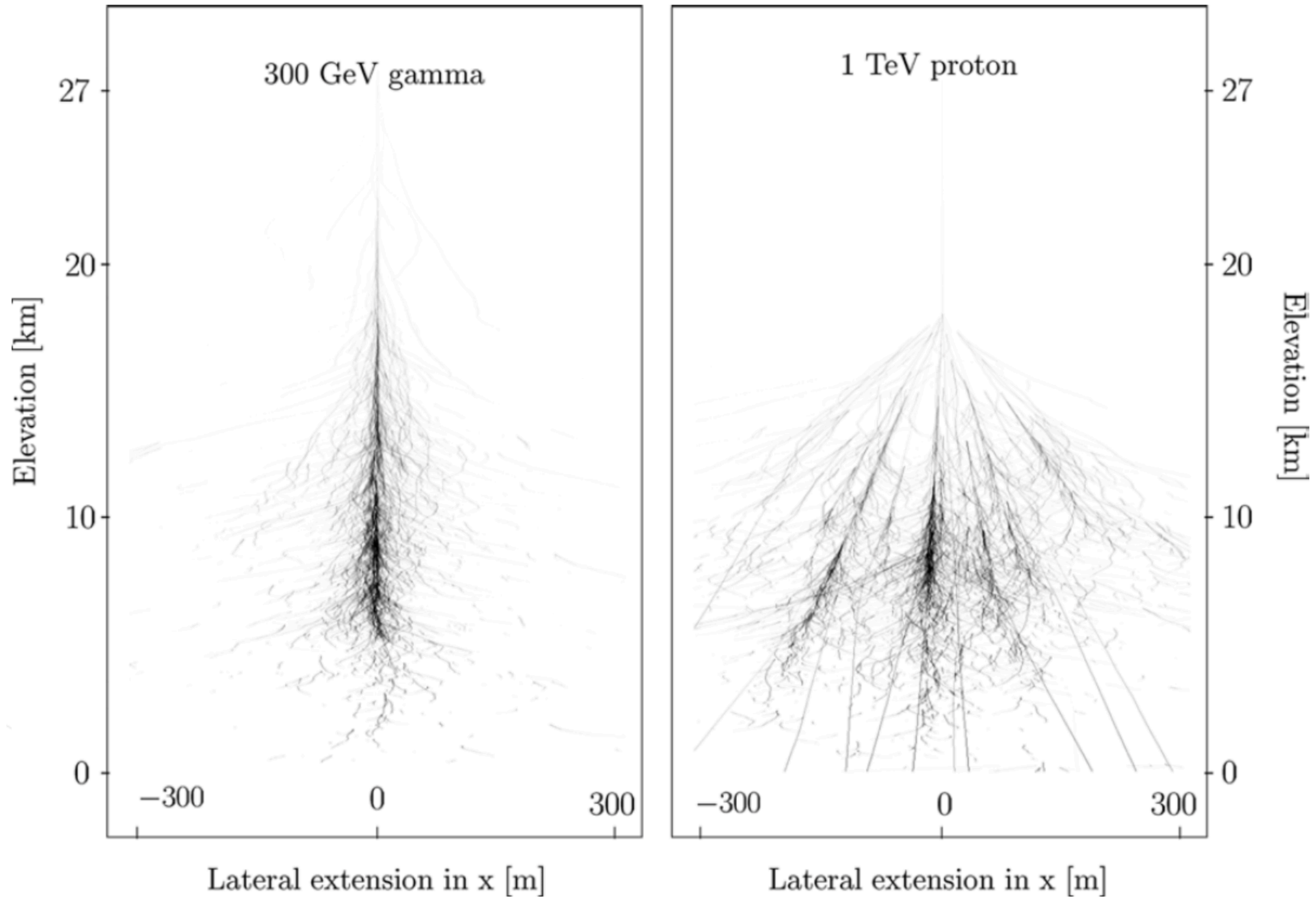
- By combining **machine learning** algorithms with the design of a **shallow WCD station**, we have demonstrated the potential to:
  - **Identify muons in TeV air showers**, enabling excellent gamma/hadron separation.
  - Distinguish gamma-induced from cosmic-ray showers using the footprint alone, **even in the absence of muons**.
  - Leverage a gamma-ray ground-based observatory to achieve **sensitivity to astrophysical neutrinos**.



BACKUP SLIDES

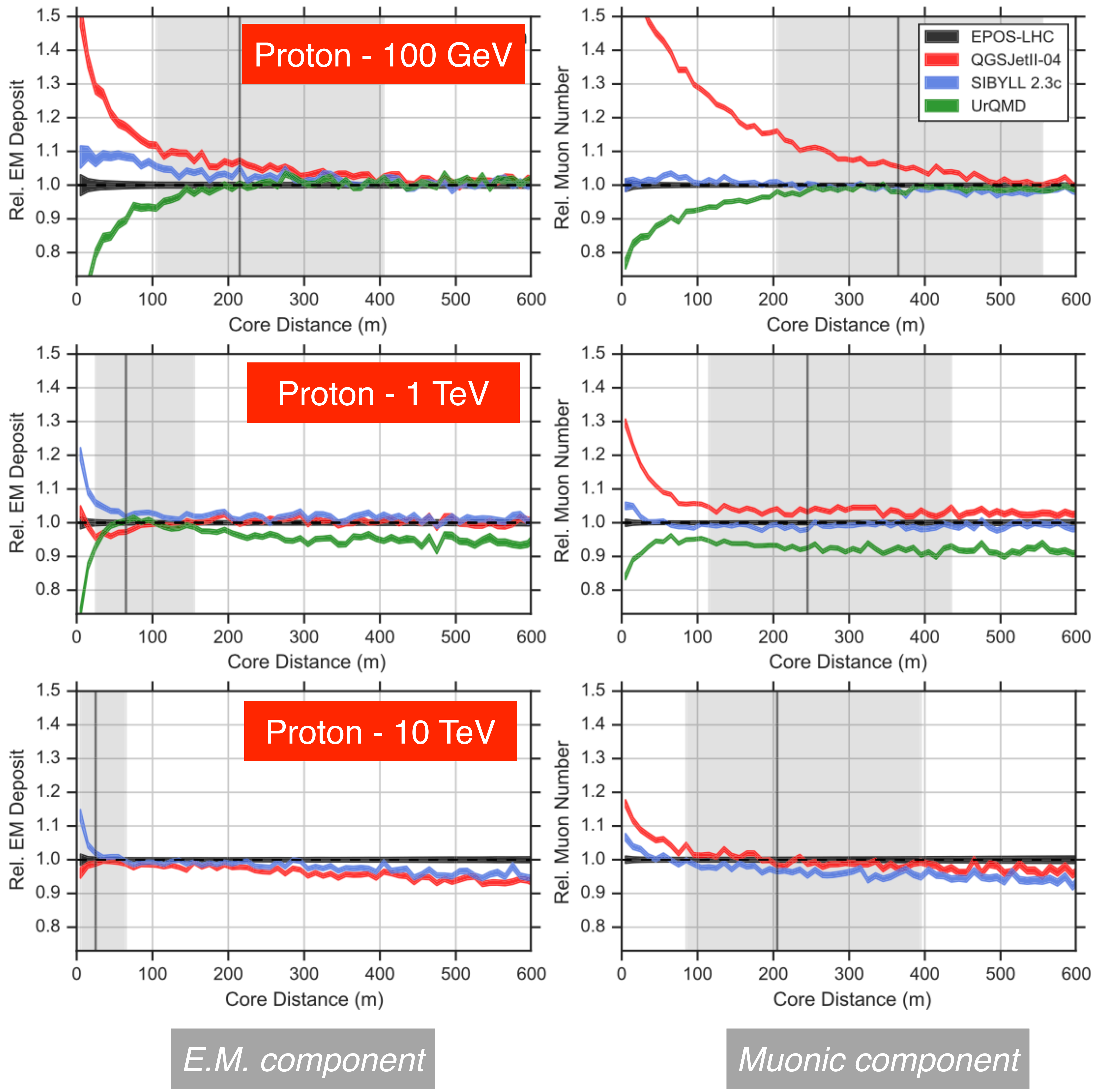
Uncertainties on EAS description at lower energies





Phys.Rev.D 100 (2019) 2, 023010

Differences between models at lower energies



Estimation of the effective mass

Effective mass for point-like sources

$$M_{\text{eff}}\,(E_\nu, \theta) = \int N_{\text{stations}}\ \varepsilon(x, y, D, \theta, \phi, E_\nu)\ dx\ dy\ dD\ [g]$$

$$\varepsilon(x, y, D, \theta, E_\nu) = \frac{\text{number of events selected as upgoing}}{\text{number of events simulated}} \in [0,1]$$