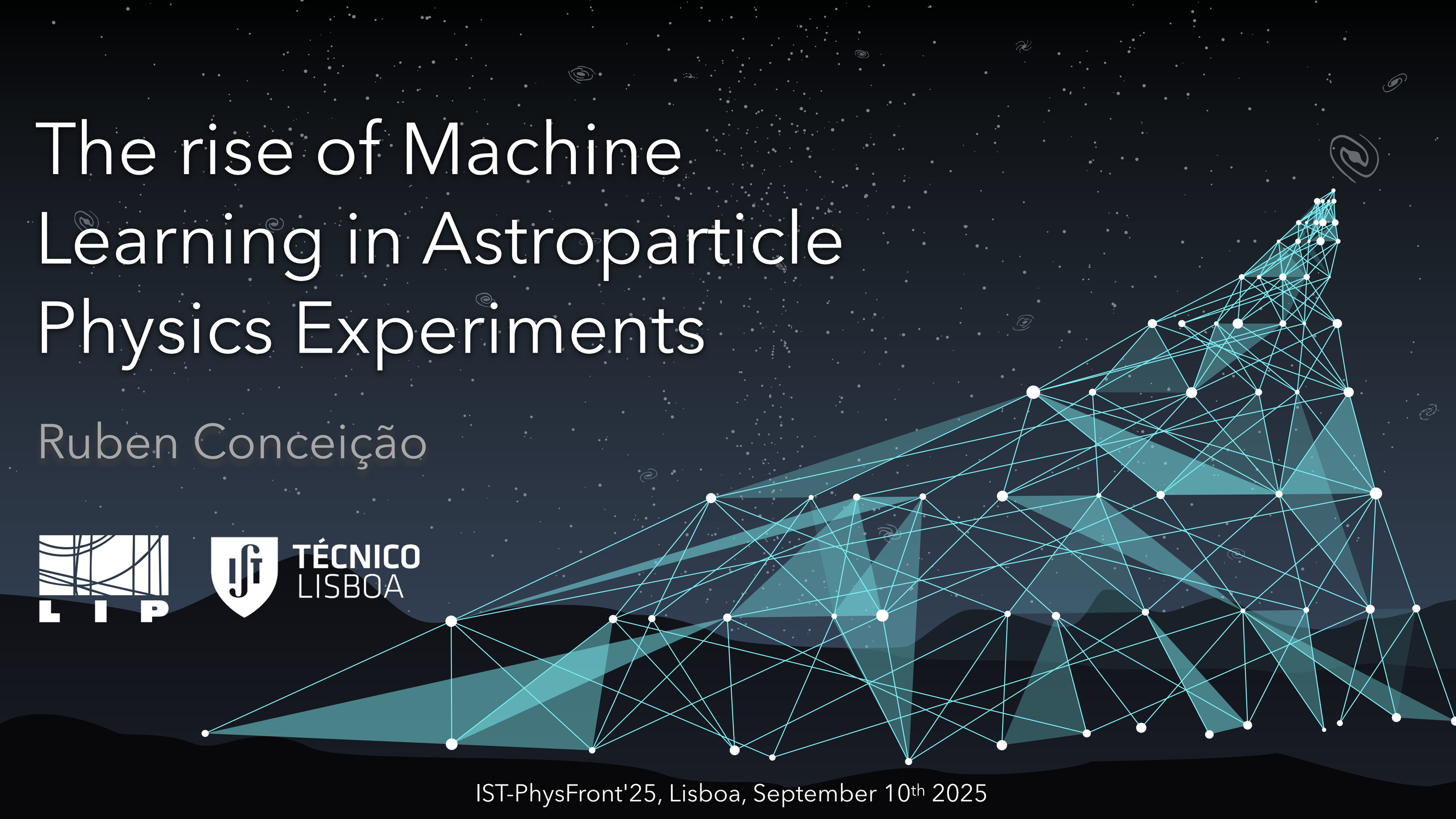
The rise of Machine Learning in Astroparticle Physics Experiments

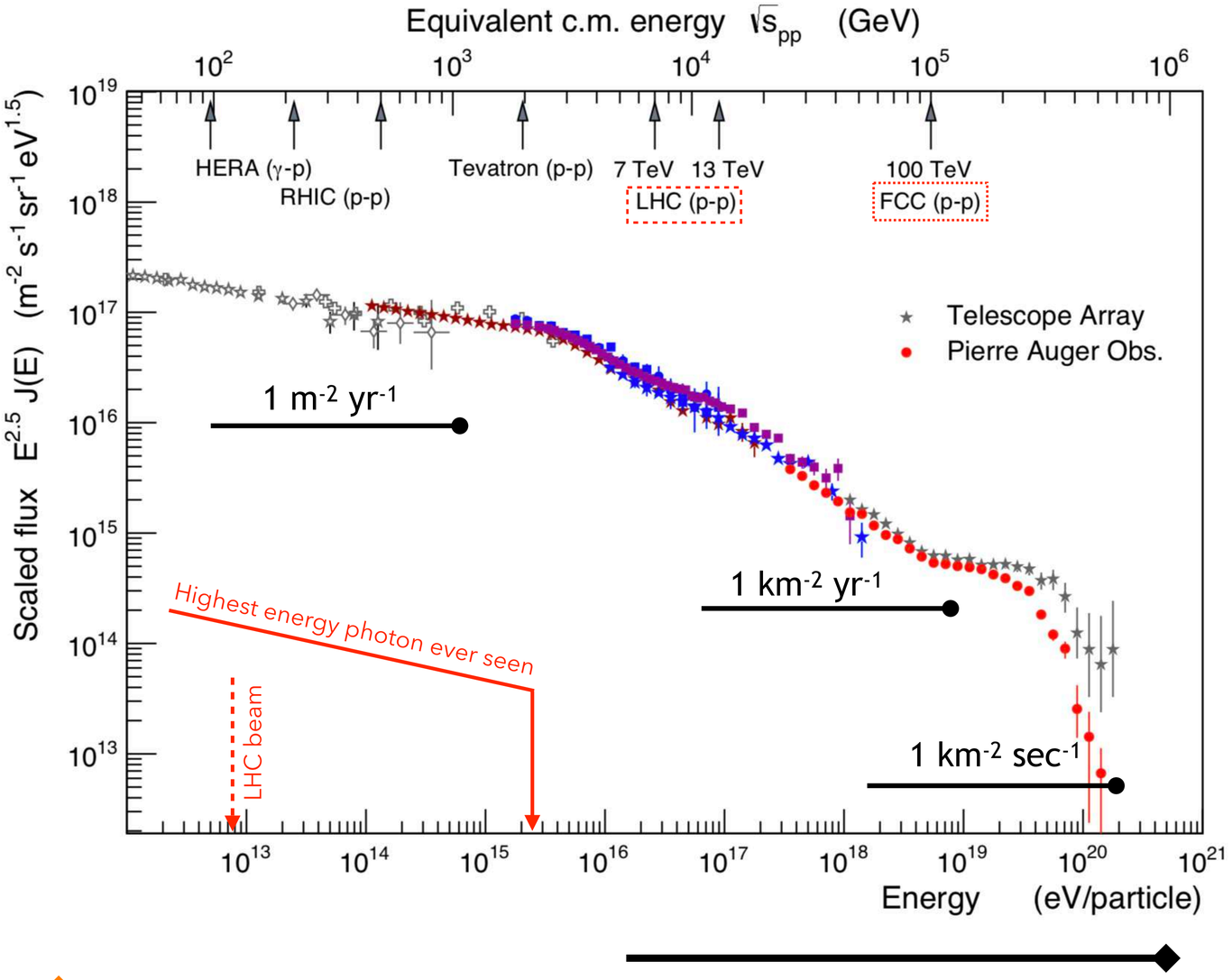
Ruben Conceição



IST-PhysFront'25, Lisboa, September 10th 2025

The extreme Universe

2026-2040



2004-2035

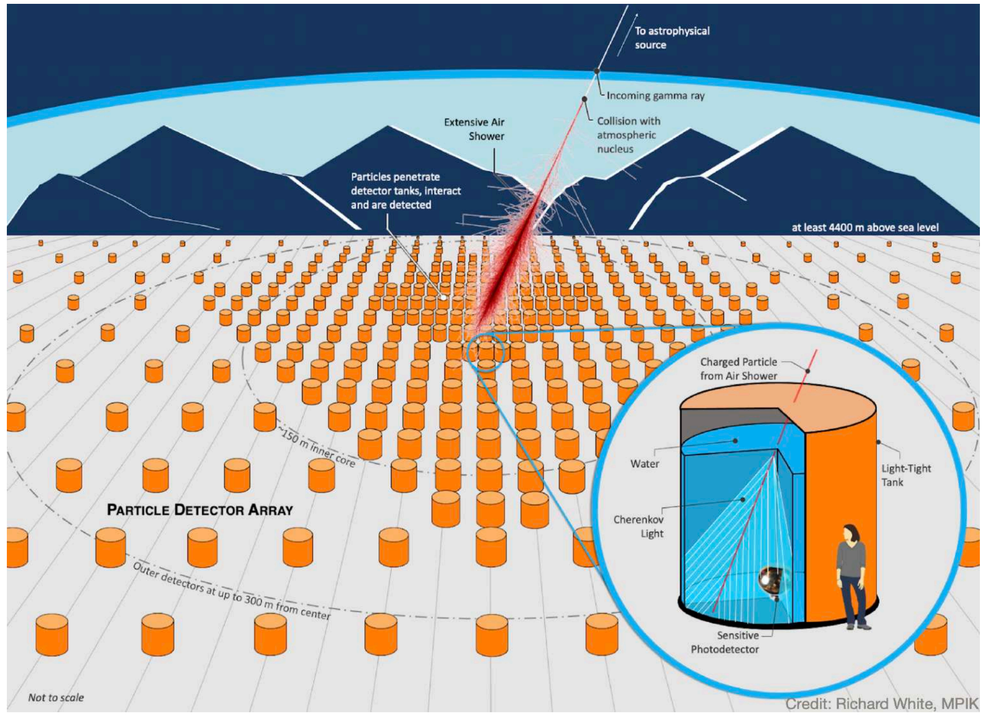
SWGO
The Southern Wide-field Gamma-ray Observatory

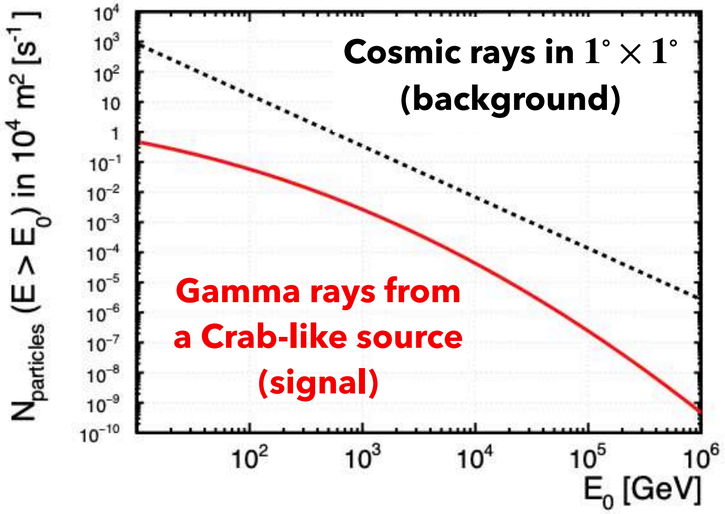
PIERRE AUGER OBSERVATORY

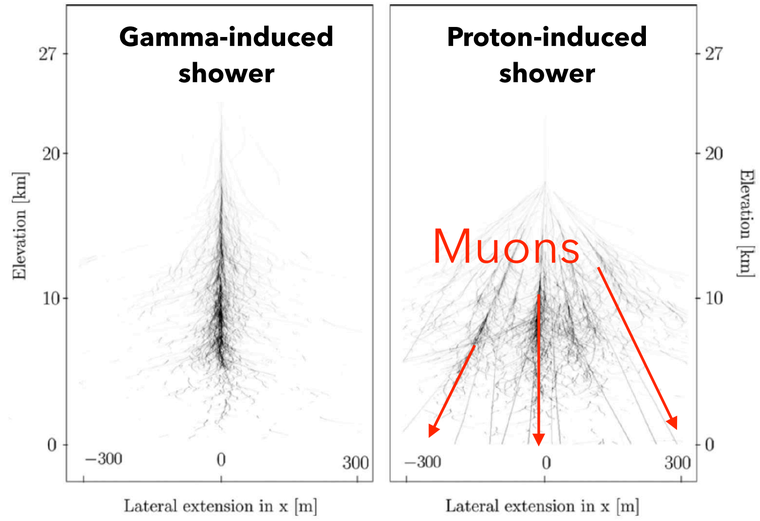
Find a needle in a haystack…

Gamma/hadron discrimination

SWGO
The Southern Wide-field Gamma-ray Observatory



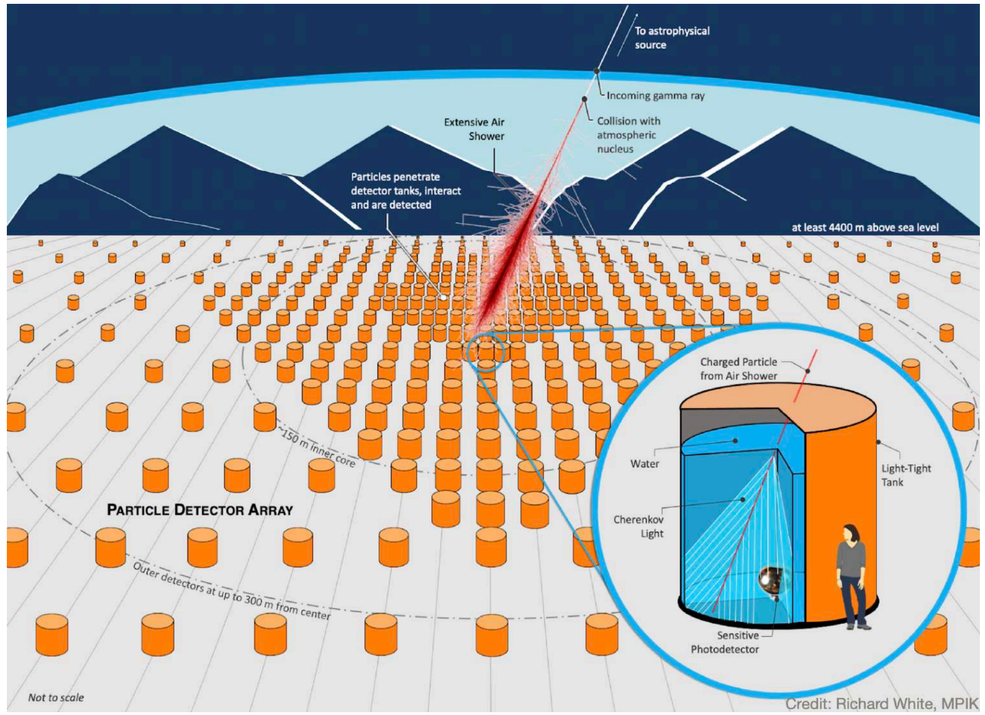




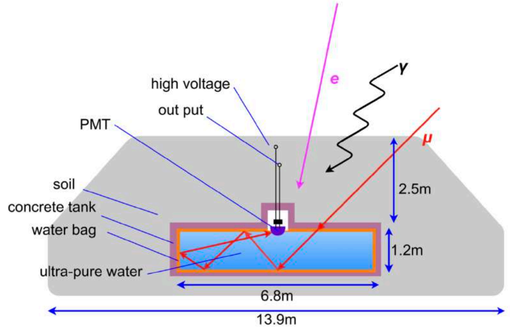
Find a needle in a haystack…

Gamma/hadron discrimination

The Southern Wide-field Gamma-ray Observatory



LHAASO experiment - Tibet - 4400 m



~2000 buried Water Cherenkov Detectors

Absorb e.m. shower component to detect muons

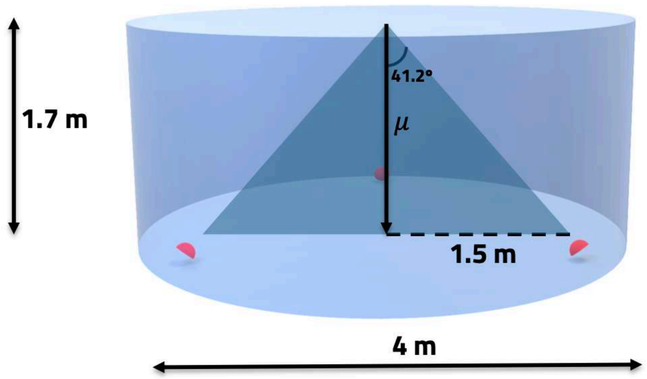
SWGO site

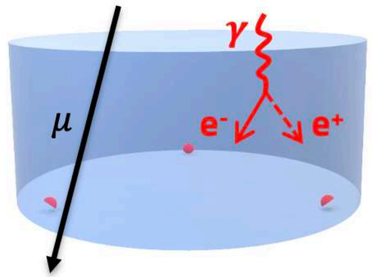
Atacama Natural Park - Chile - 4770 m a.s.l.

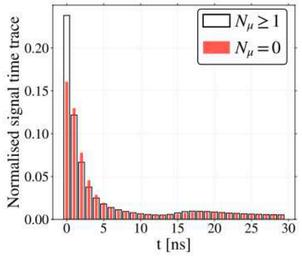
Burying detectors (LHAASO strategy) or building 5 m height water tanks (HAWC strategy)
is **costly**, **impractical**, and **environmentally unfeasible**

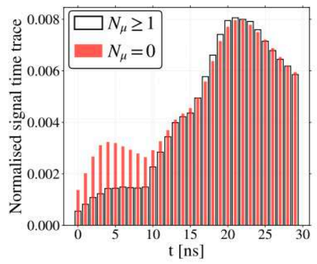
Looking for muons in shallow stations

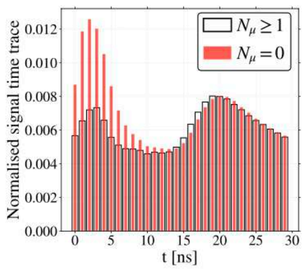
RC et al. Eur.Phys.J.C 81 (2021) 6, 542
González, **RC** et al. Neural Comput & Applic 34, 5715–5728
Assis, **RC** et al. Eur.Phys.J.C 82 (2022) 10, 899

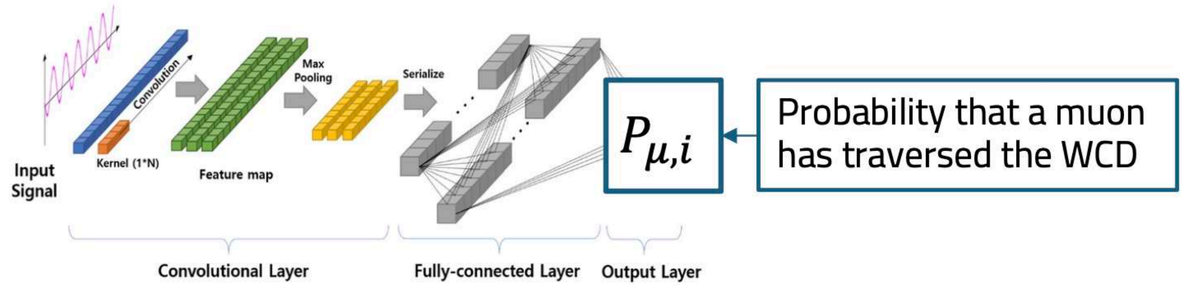












Looking for muons in shallow stations

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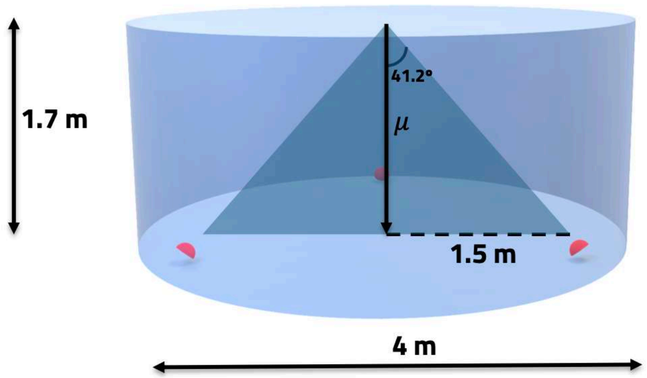
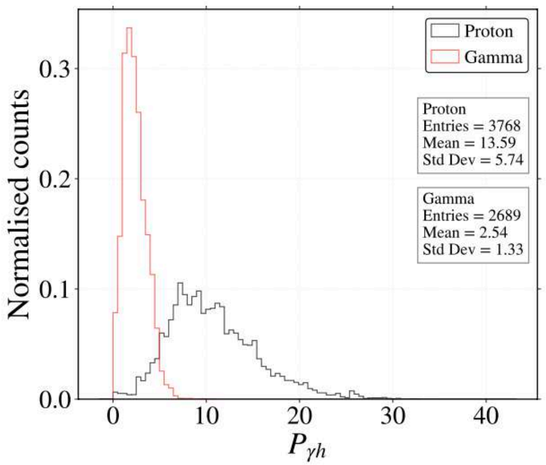
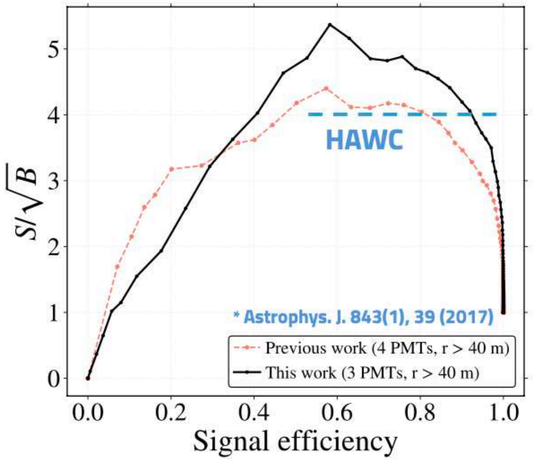


E~1 TeV, $\alpha = 1, r_{min} > 40$ m





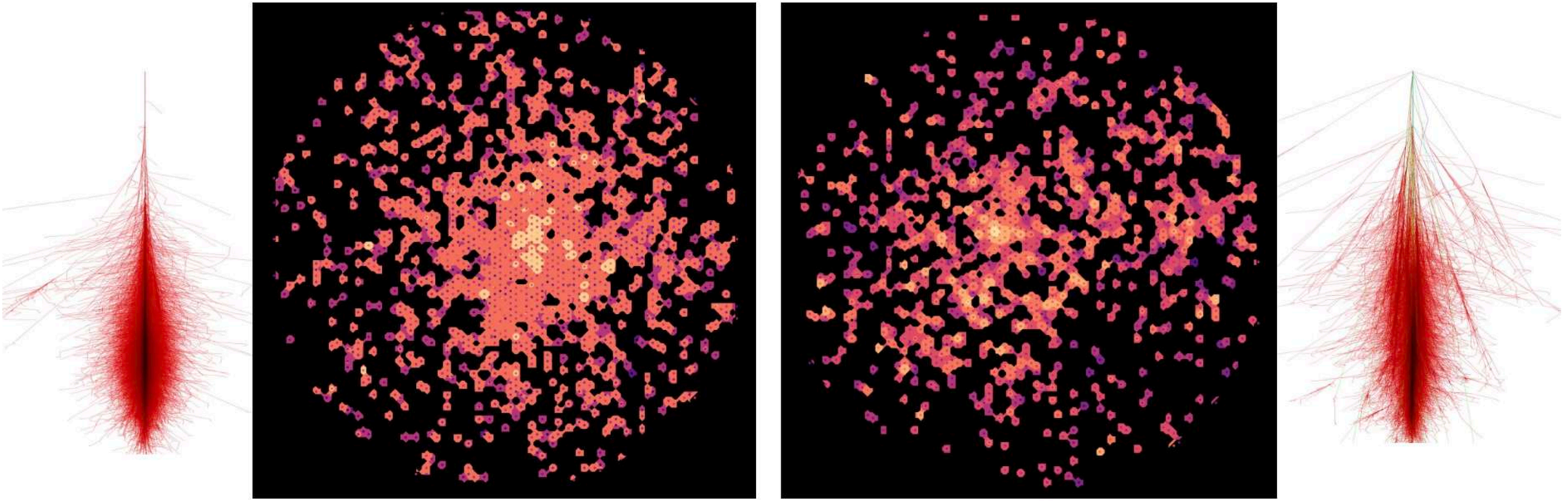
Gamma/hadron separation

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

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

Accessing sub-TeV shower energies…

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

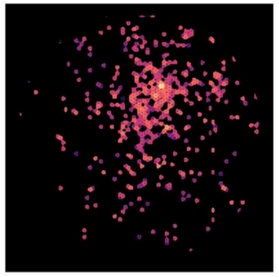


There's information in the shower footprint!

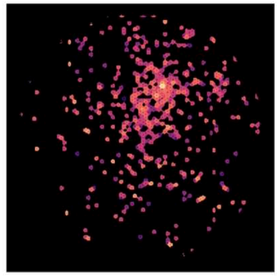
But the challenge lies in dealing with the overwhelming atmospheric muon background (~23 stations per event)

Exploring the shower footprint

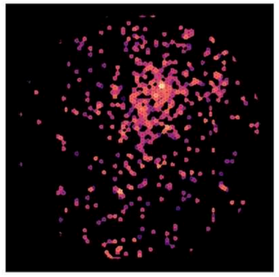
RC et al. Phys.Rev.D 111 (2025) 4, 043047



Shower
Noise-free



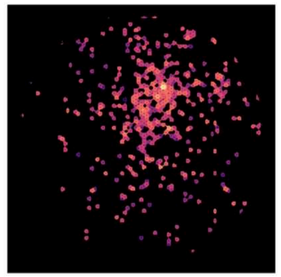
Shower
+
29 WCDs μ
(~6000 p.e.)



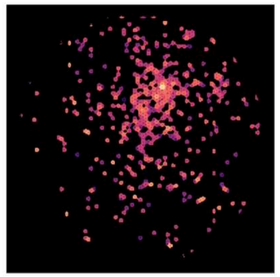
Shower
+
Proton shower
126 GeV
68 WCDs
(~2500 p.e.)

Exploring the shower footprint

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



Shower
Noise-free



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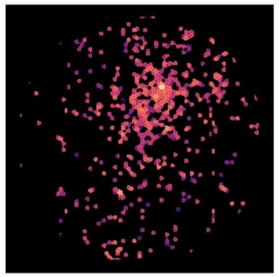

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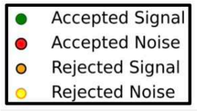
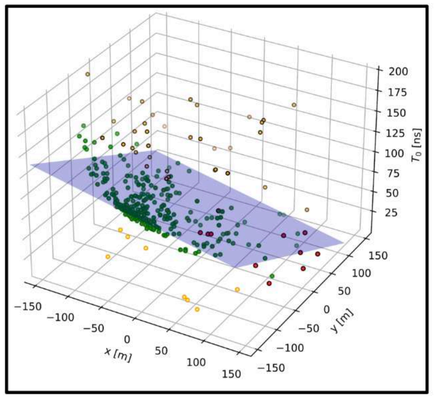
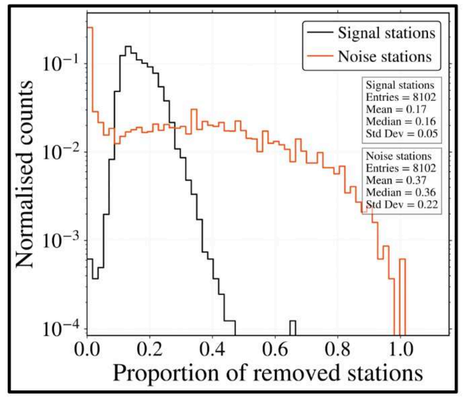
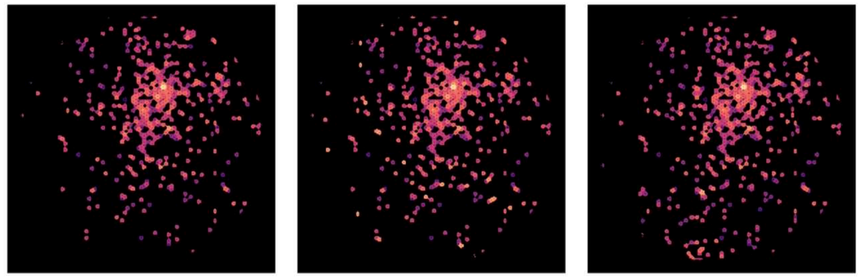






Exploring the shower footprint

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



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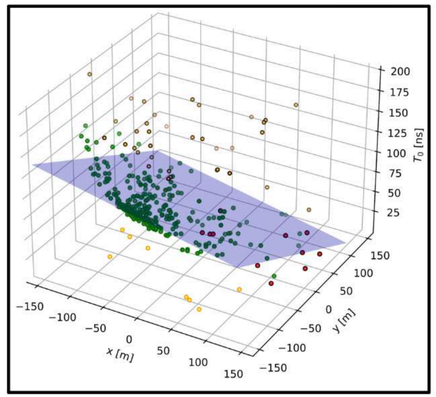
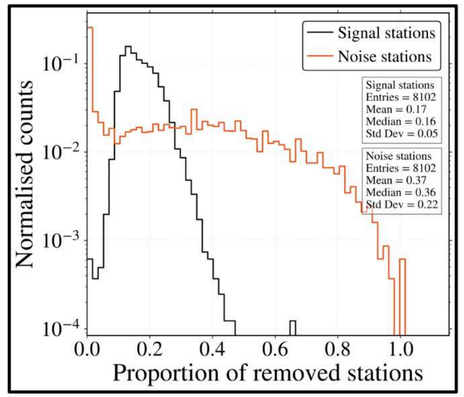
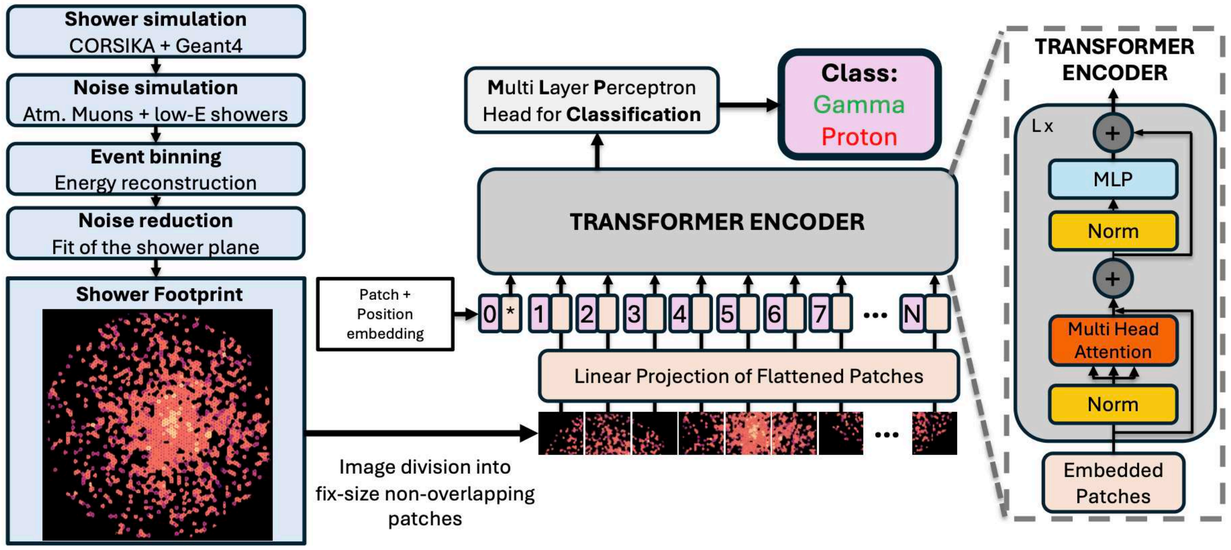
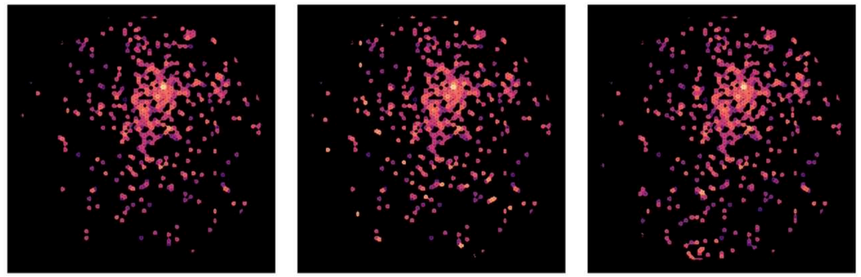






Exploring the shower footprint

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



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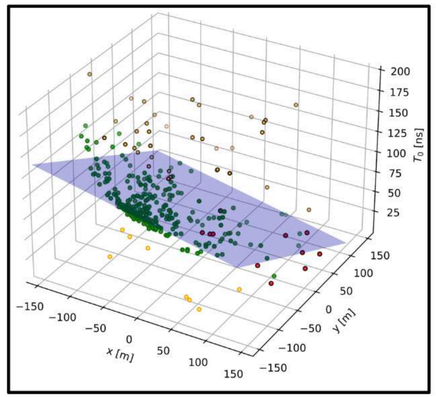
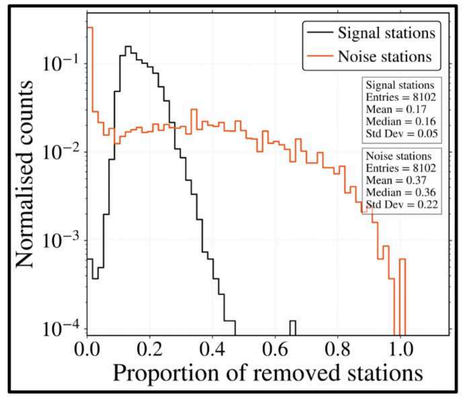
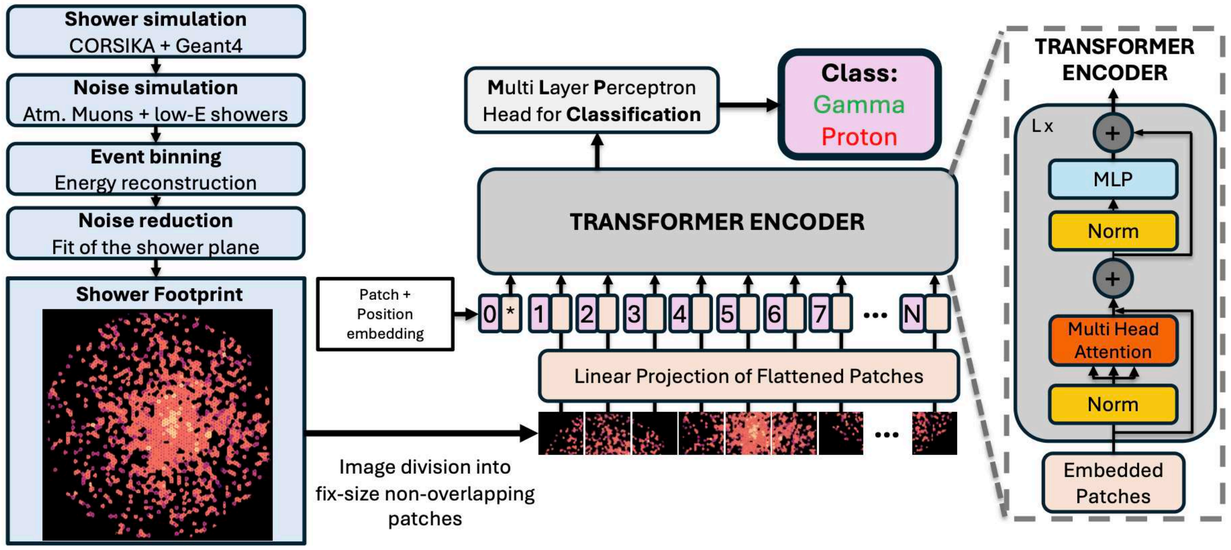
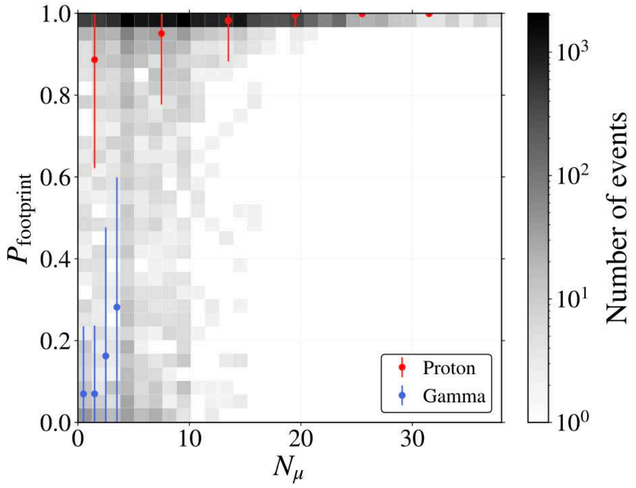


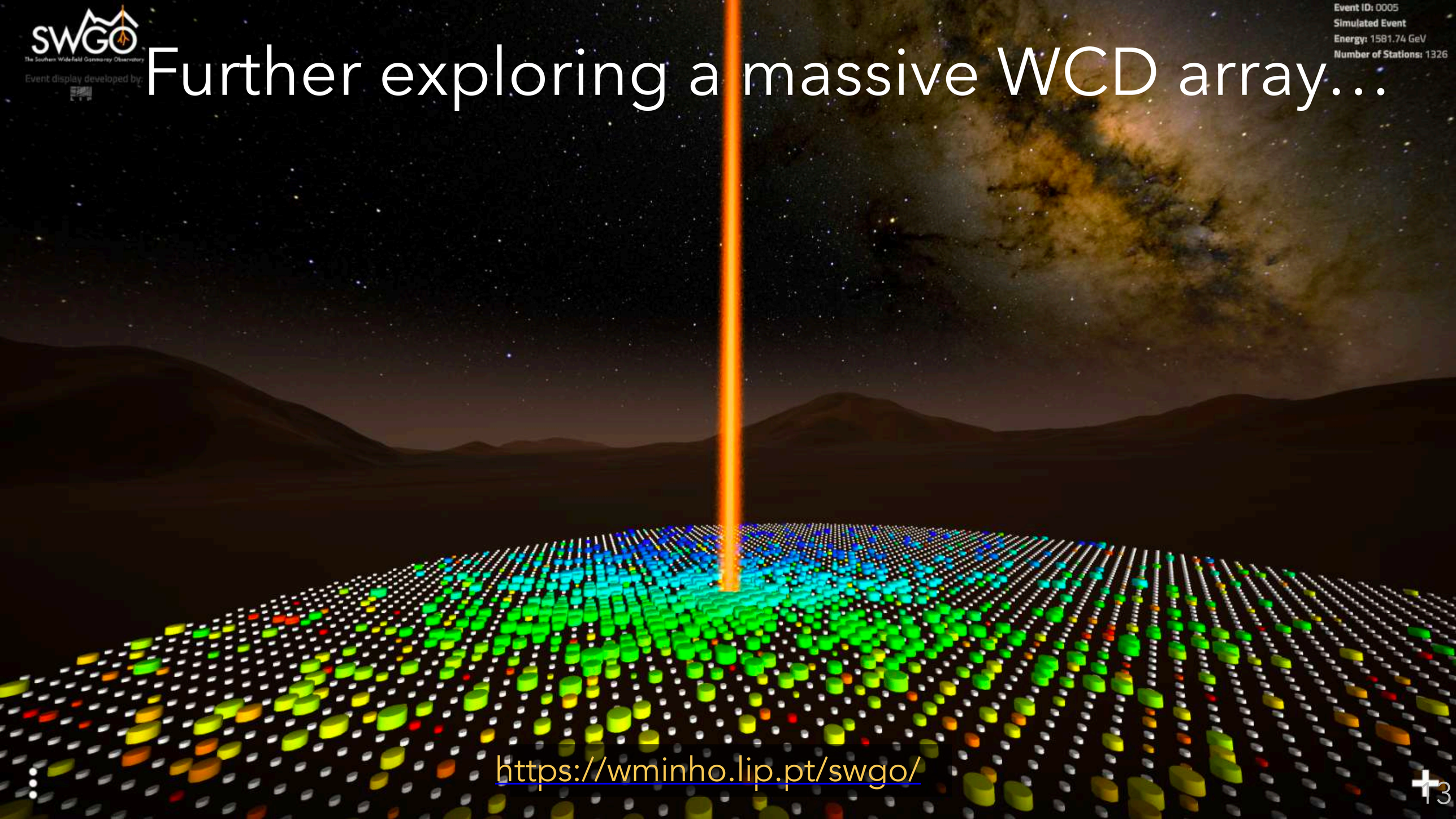






Excellent gamma/hadron separation even for proton showers with low muonic content

Further exploring a massive WCD array…

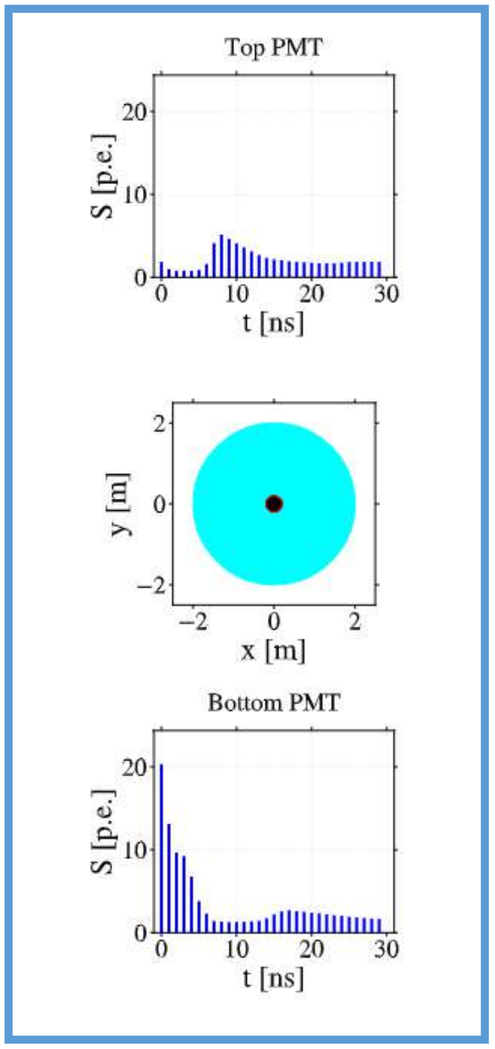


https://wminho.lip.pt/swgo/

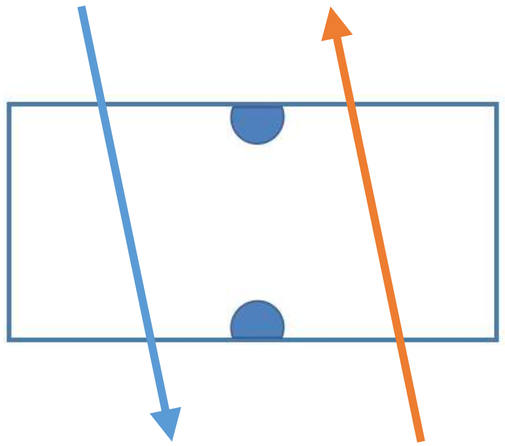
Detection astrophysical HE neutrinos

Alvarez-Muñiz, **RC**, et al. Phys.Rev.D 110 (2024) 2, 023032
Alvarez-Muñiz, **RC**, et al. Eur.Phys.J.C 85 (2025) 8, 842

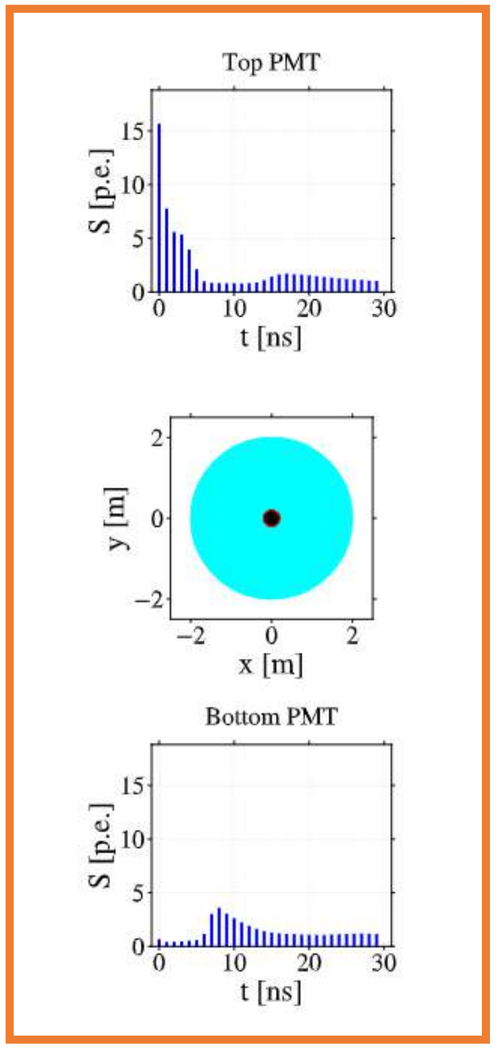
Background - cosmic ray events ($\theta < 40°$)



Down-going events



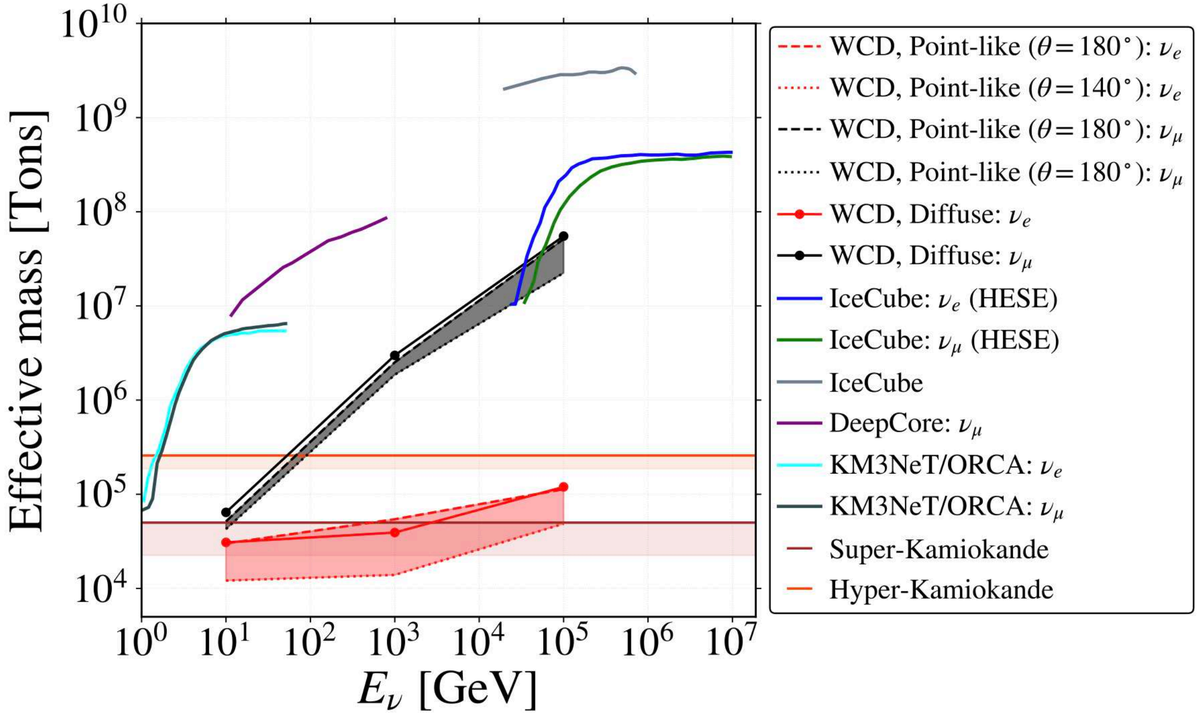
Signal - neutrino events ($\theta > 140°$)

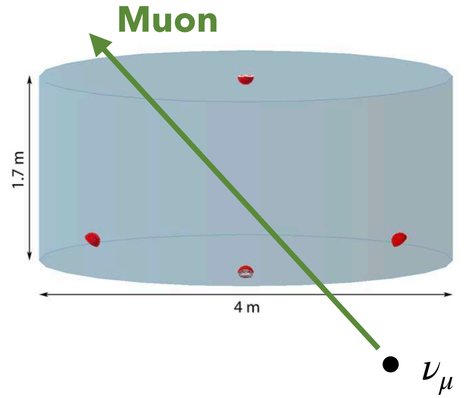


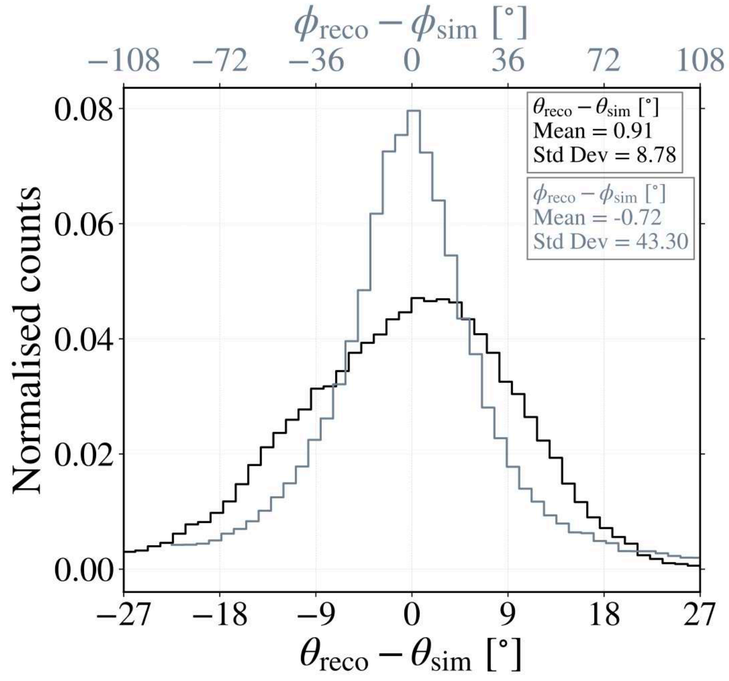
Up-going events

Catching neutrinos with a single WCD

Alvarez-Muñiz, **RC**, et al. Phys.Rev.D 110 (2024) 2, 023032
Alvarez-Muñiz, **RC**, et al. Eur.Phys.J.C 85 (2025) 8, 842



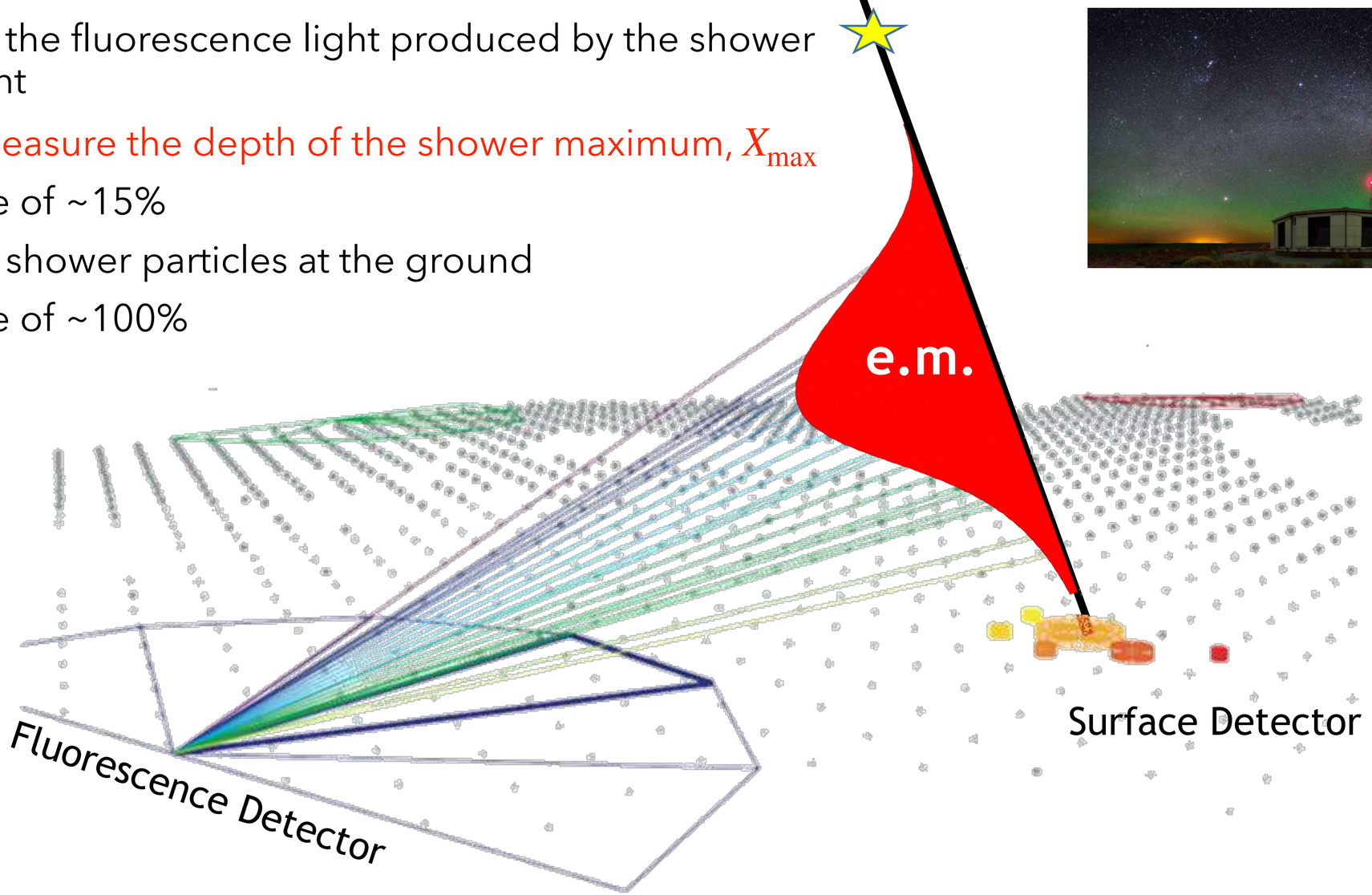




- Explore the PMT signal time trace structure recurring to ML algorithms (Transformer architectures based on self-attention mechanisms):
  - Identify up-going ν from cosmic ray background
  - Reconstruct the direction of the neutrino (i.e. the muon traversing the WCD)

Pierre Auger Observatory

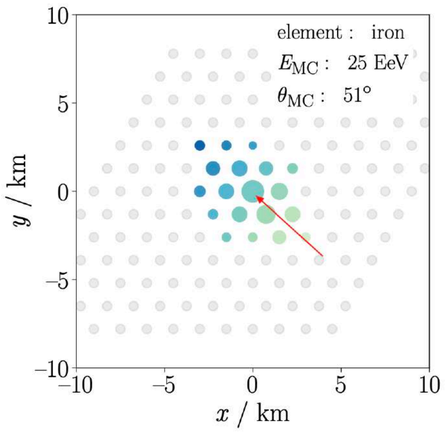
- FD: collects the fluorescence light produced by the shower development
  - Able to measure the depth of the shower maximum, $X_{\max}$
  - Duty cycle of ~15%
- SD: collects shower particles at the ground
  - Duty cycle of ~100%

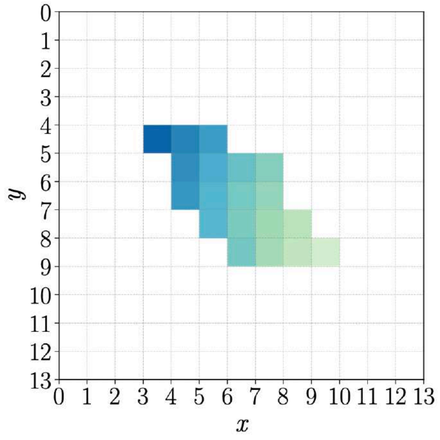


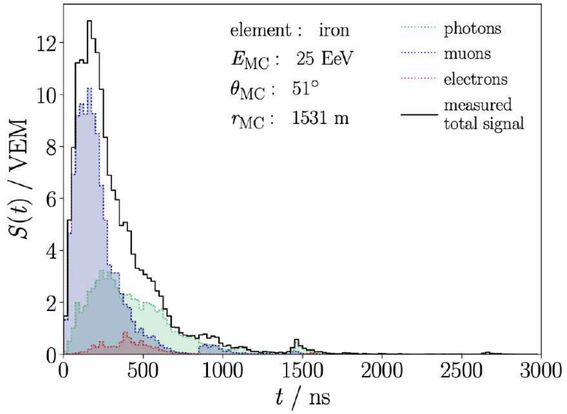
PIERRE AUGER OBSERVATORY

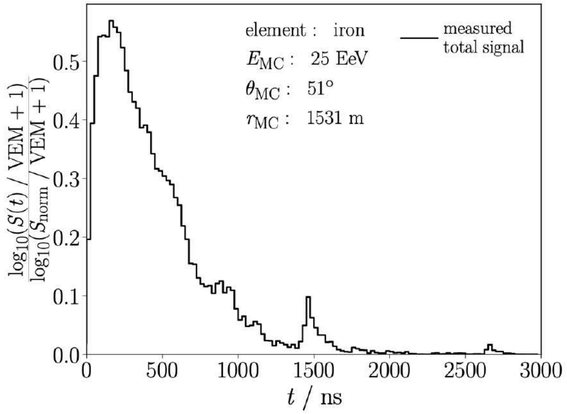
X_{max} from SD trace using a DNN

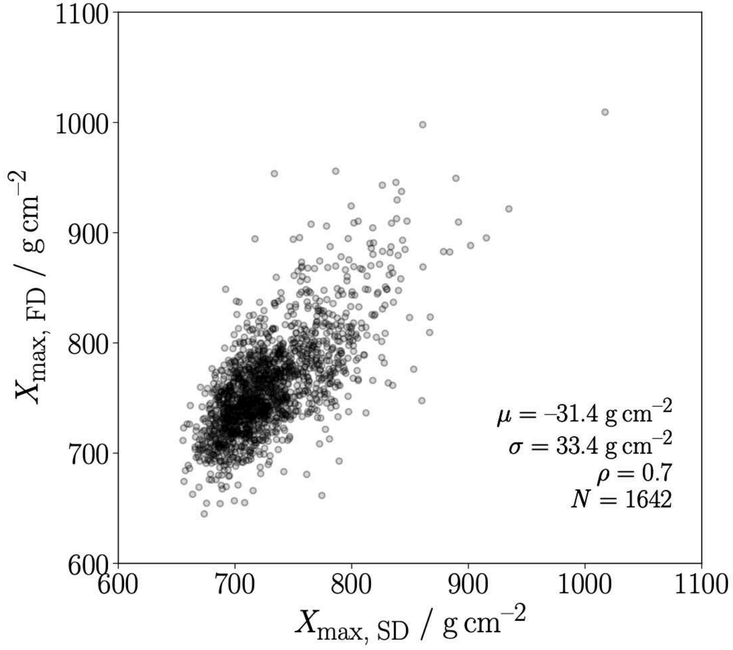
Pierre Auger Coll., Phys.Rev.Lett. 134 (2025) 2, 021001
Pierre Auger Coll., Phys.Rev.D 111 (2025) 2, 022003







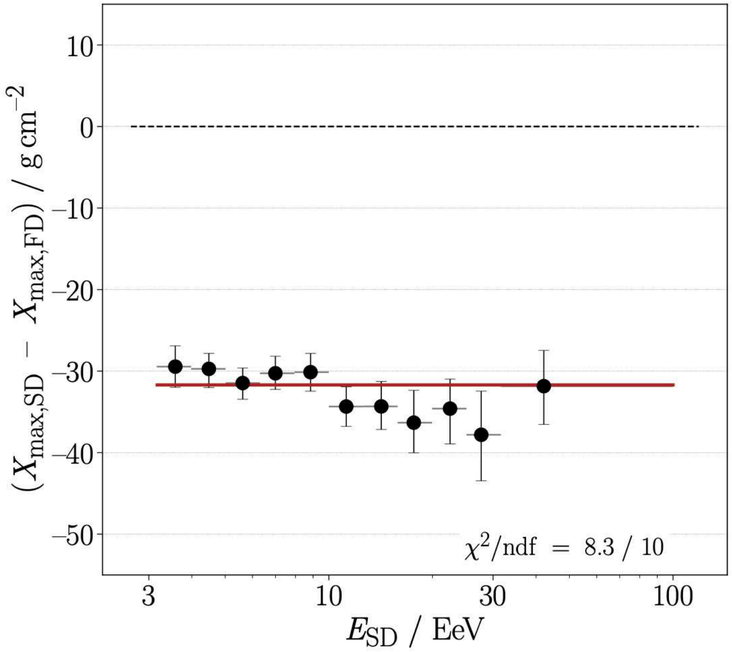




Extract the X_{max} from SD-only events

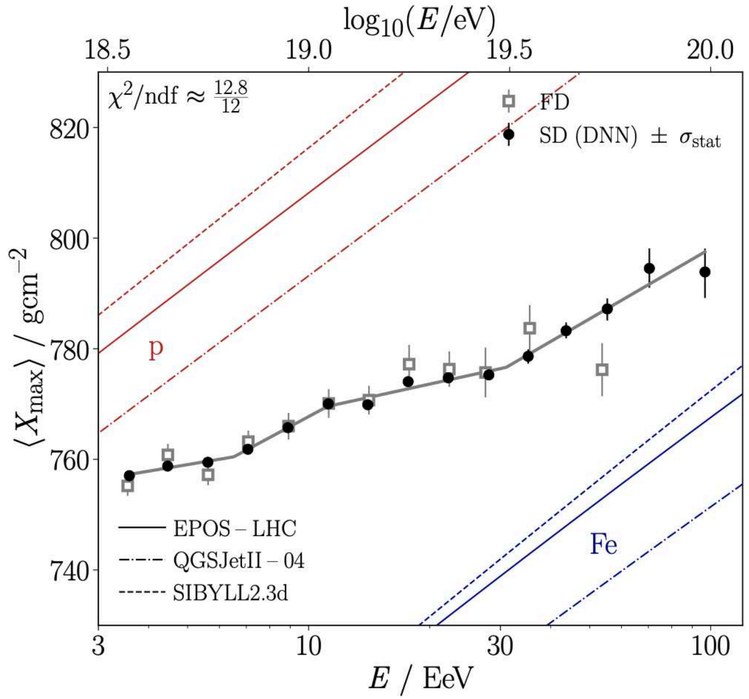
Exploit the SD traces using a Deep Neural Network

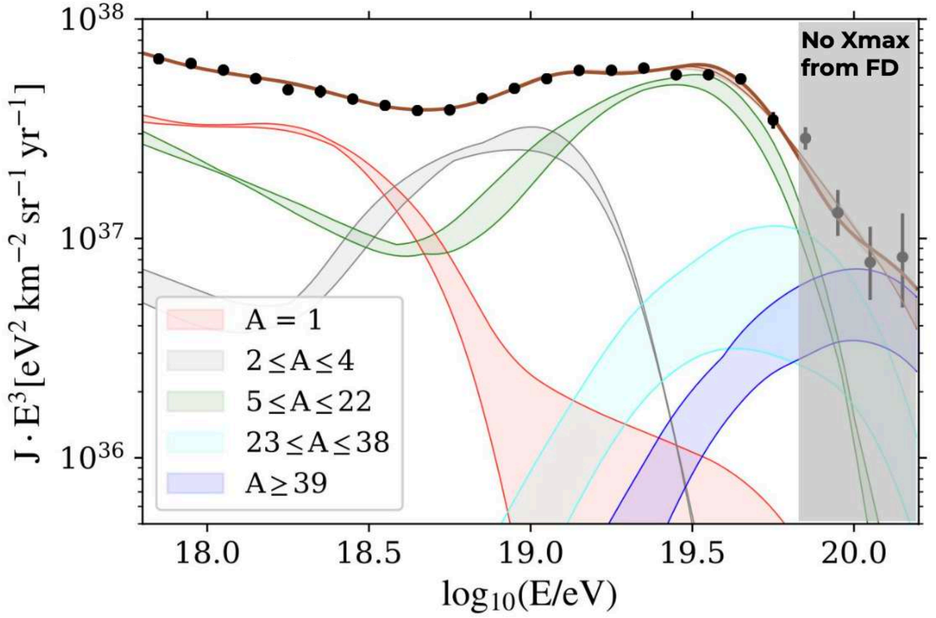
Test DNN performance using FD-SD **hybrid events**



Extraction of X_{max} from the SD ground signal

Pierre Auger Coll., Phys.Rev.Lett. 134 (2025) 2, 021001
Pierre Auger Coll., Phys.Rev.D 111 (2025) 2, 022003



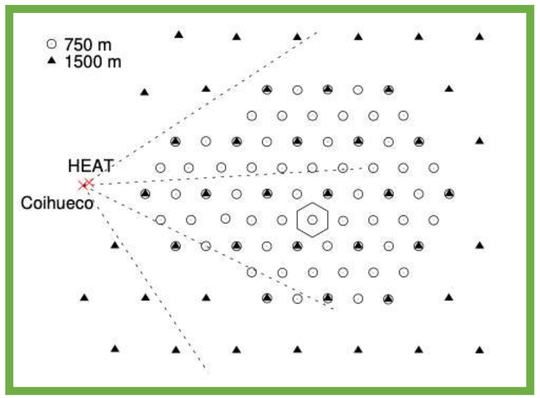


- **Resolutions** comparable to those achieved with **hybrid** (FD+SD) events but **factor nearly 7 of more events**
- Algorithms **rely heavily on simulations** and may be capturing uncontrolled or unknown shower features
- It is crucial to develop strategies that lead to self-consistent solutions

Multi-hybrid shower events

(Next years of the Pierre Auger Observatory)

HEAT

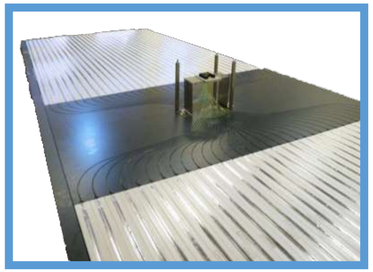


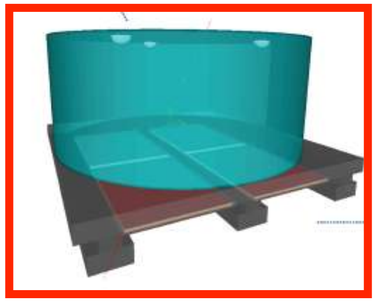
AMIGA

MARTA

Infill

Radio

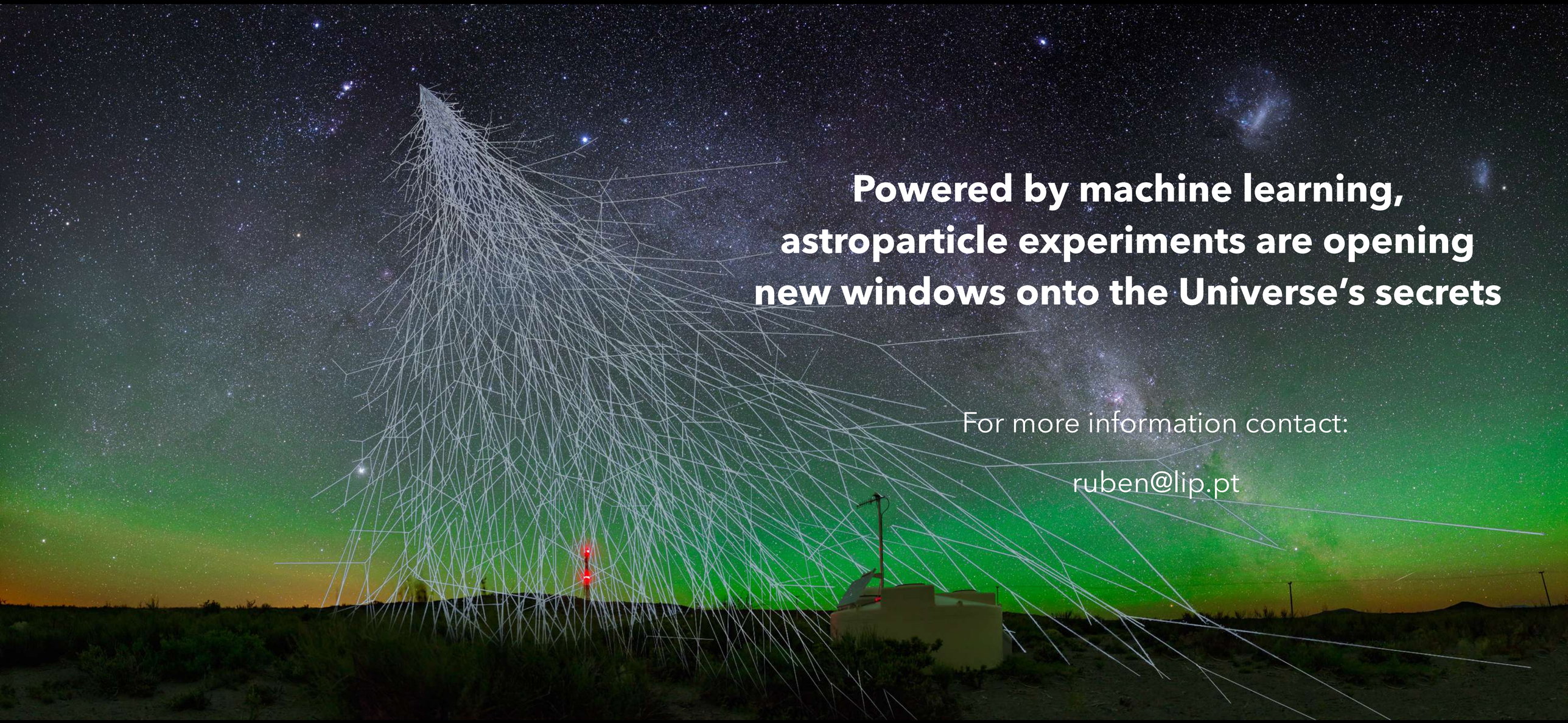




Auger Prime (SSD)

LHC c.m. energy equiv to first interaction

10^{16} 10^{17} 10^{18} 10^{19} 10^{20} Energy [eV]



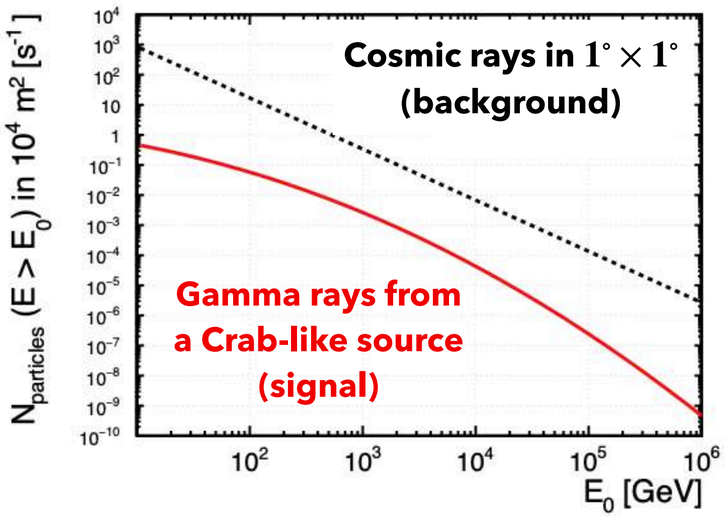
Powered by machine learning, astroparticle experiments are opening new windows onto the Universe's secrets

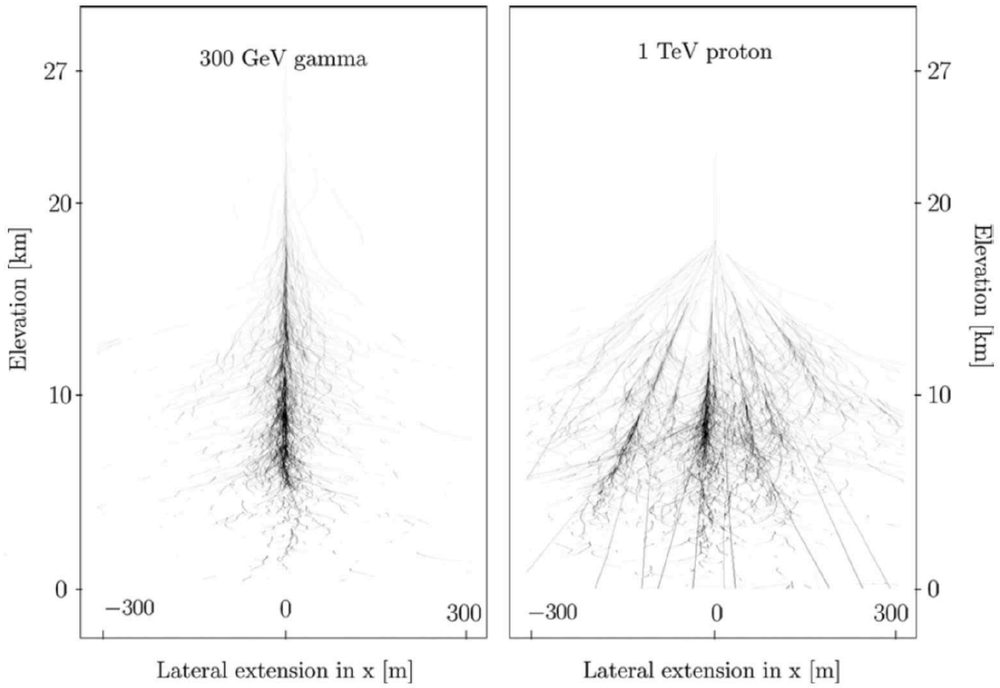
For more information contact:

ruben@lip.pt

BACKUP SLIDES

Uncertainties on EAS description at lower energies





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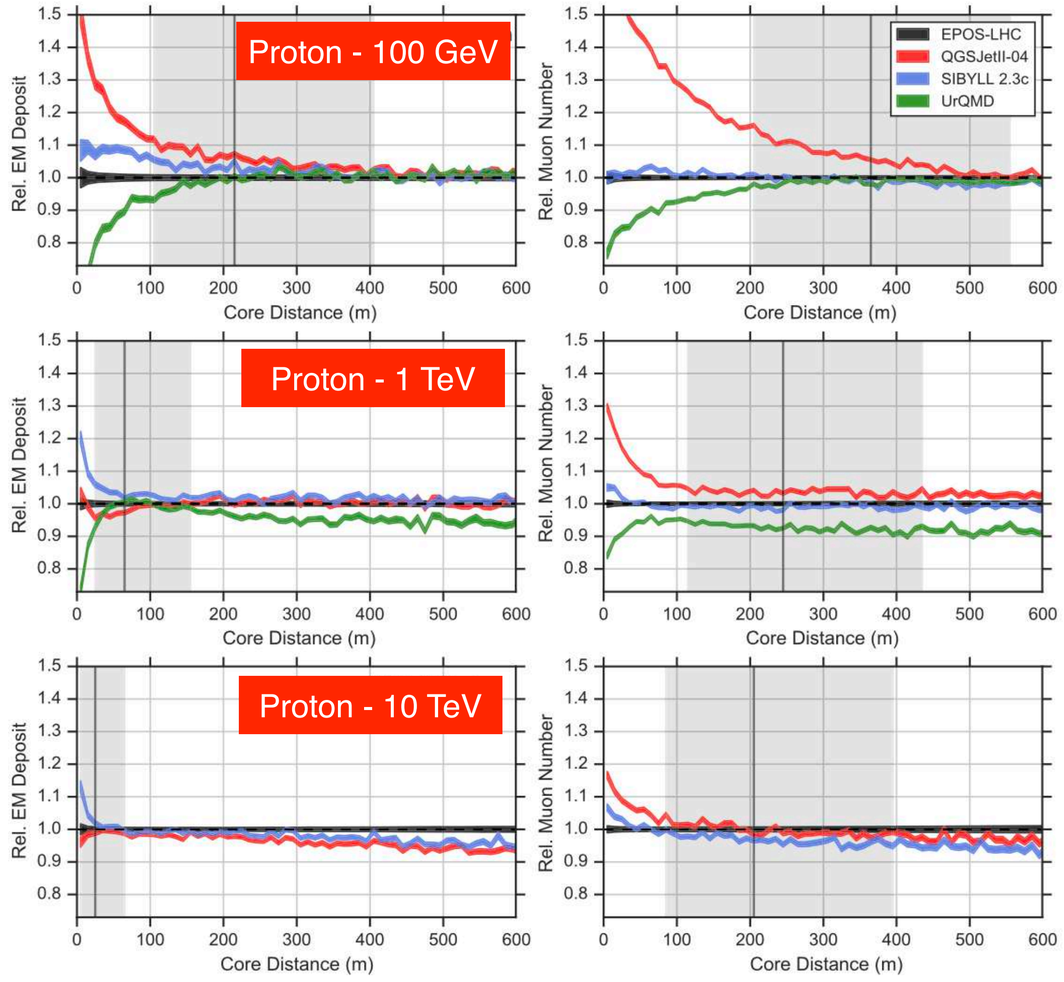
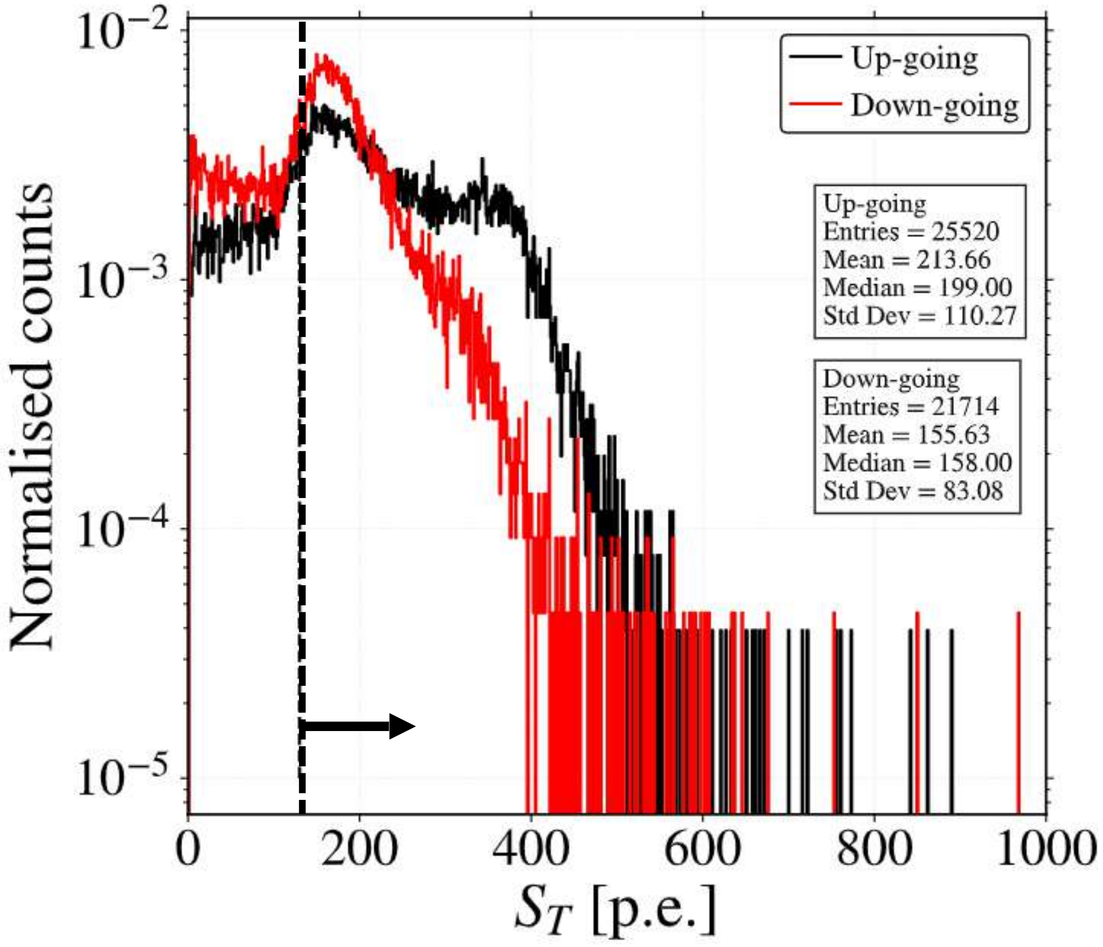
Differences between models at lower energies



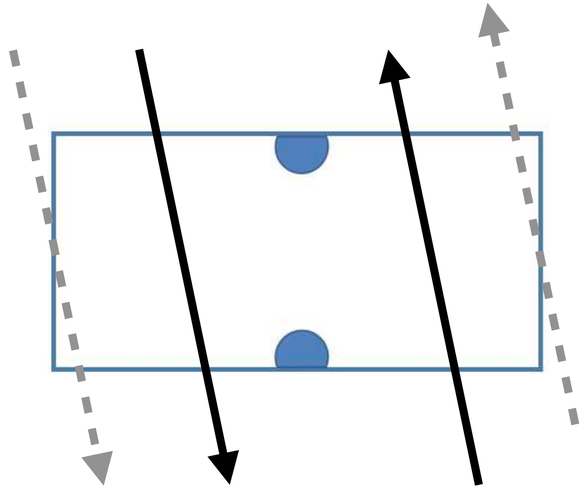
E.M. component

Muonic component

Cuts to select upward events



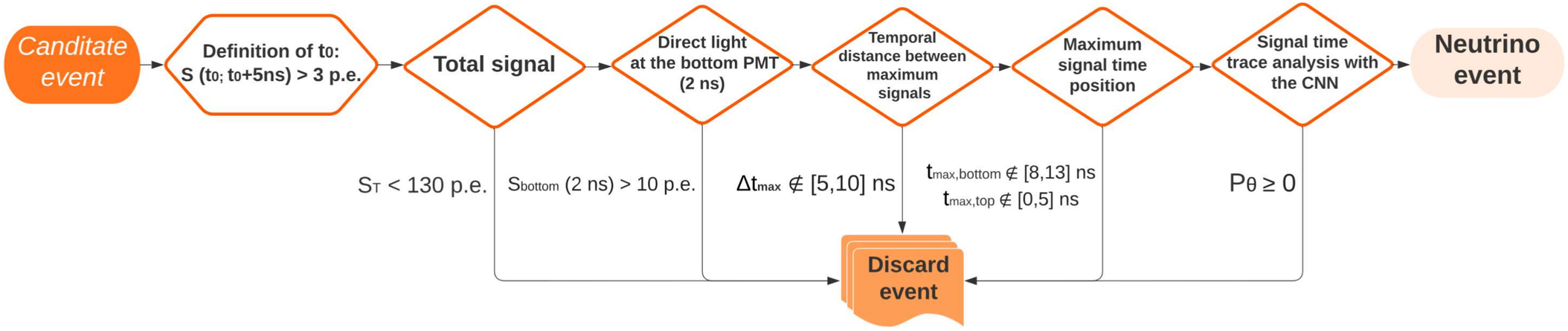
Accept only "good" geometries



Cut on the total signal based on the muons to discard clipping events.

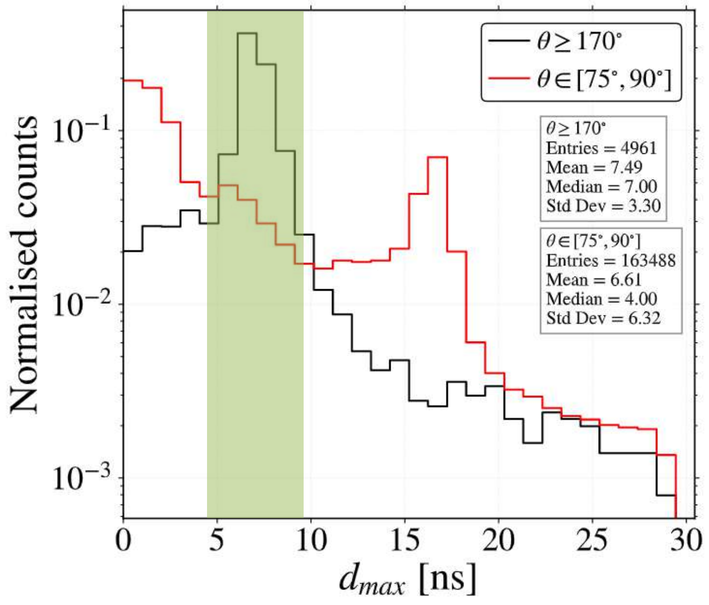
$$S_{\mathrm{T}} > 130\,\mathrm{p.e.}$$

Neutrino pipeline



Cuts to select upward events

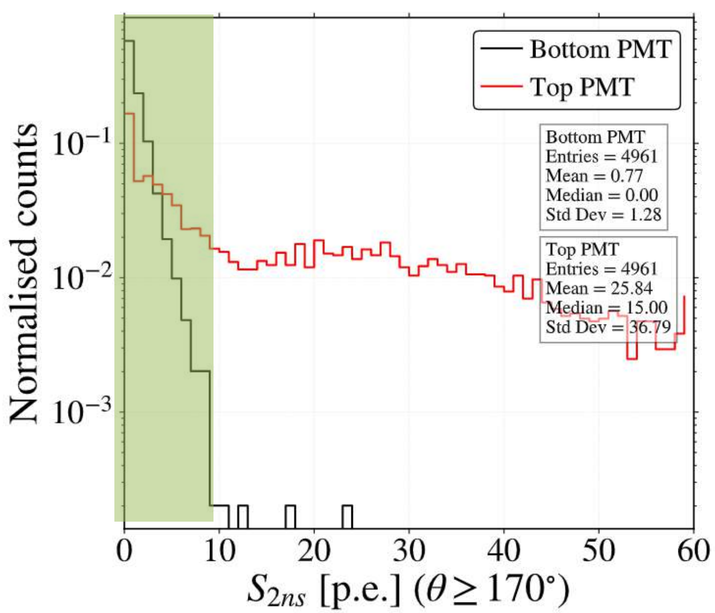
Rejection of horizontal events



Temporal distance in ns between the maximum of both PMTs:

$d_{\max} \in [5,10]\,\text{ns}$

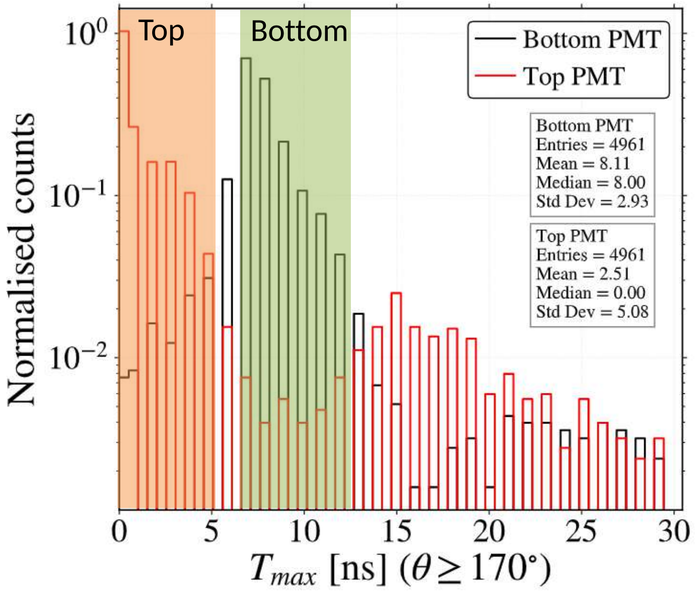
Rejection of vertical down-going events



Direct light at the bottom PMT:

$S_{\text{PMT}}^{\text{bottom}}(2\,ns) < 10\,\text{p.e.}$

Geometry for up-going events



Position of the maximum signal on both PMTs:

$T_{\text{max}}^{\text{bottom}} \in [8,13]\,\text{ns}$

$T_{\text{max}}^{\text{up}} \in [0,5]\,\text{ns}$

The application of these cuts removes 97% of the background events

Estimation of the effective mass

Effective mass for point-like sources

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

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