Evaluation of the Potential of a Gamma-Ray Observatory to Detect Astrophysical Neutrinos

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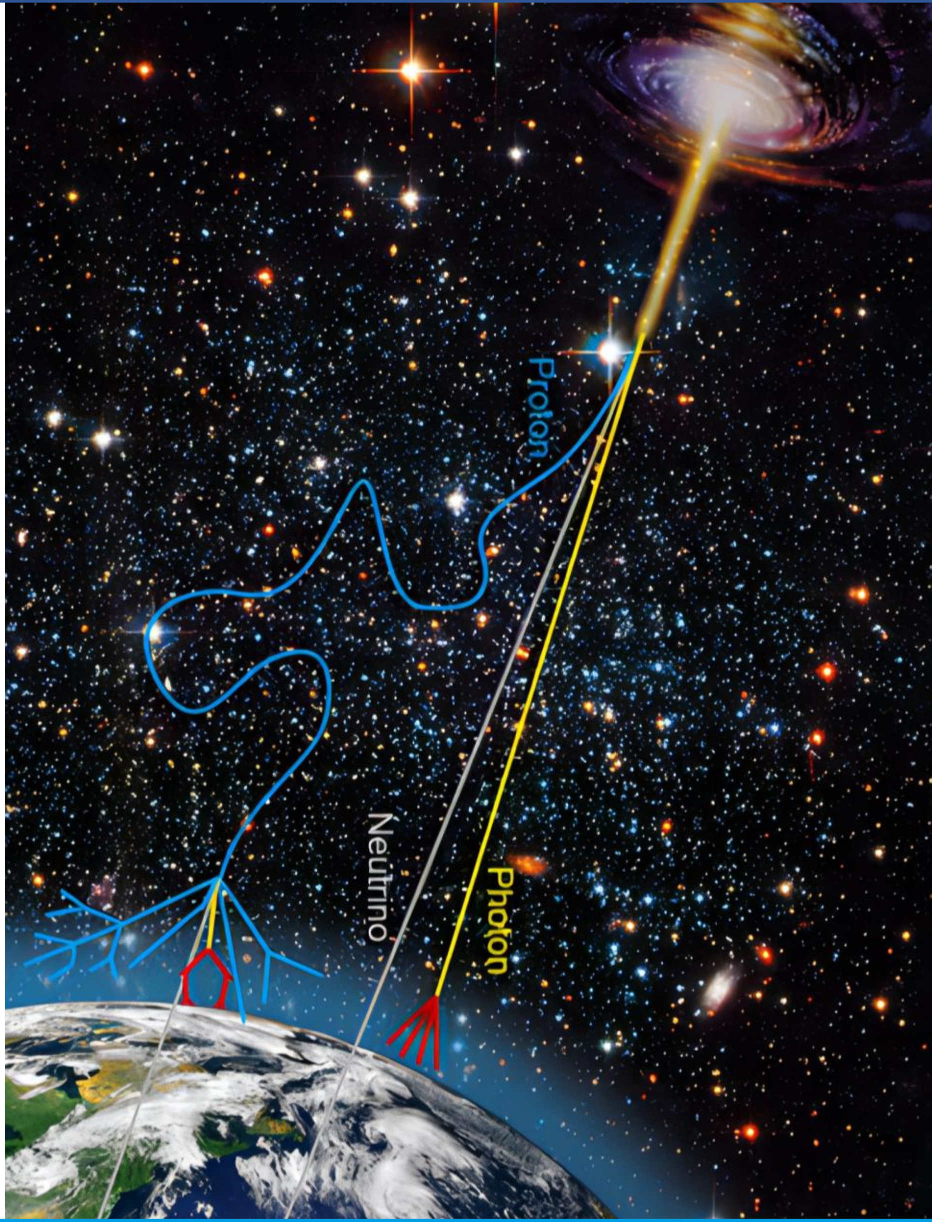
Motivation

- Astrophysical phenomena can emit different messengers: gamma-rays, gravitational waves, neutrinos, and cosmic-rays – **multi-messengers.**

- Experiments focusing on **VHE-UHE neutrinos** ($E_\nu \gtrsim 100$ TeV) need large volumes of target material (water or ice).

- Is it possible to use gamma-ray observatories to observe neutrinos?

- **Neutrino interactions** with nuclei in the atmosphere lead to **air showers**. **Interaction probability** is **extremely small.**



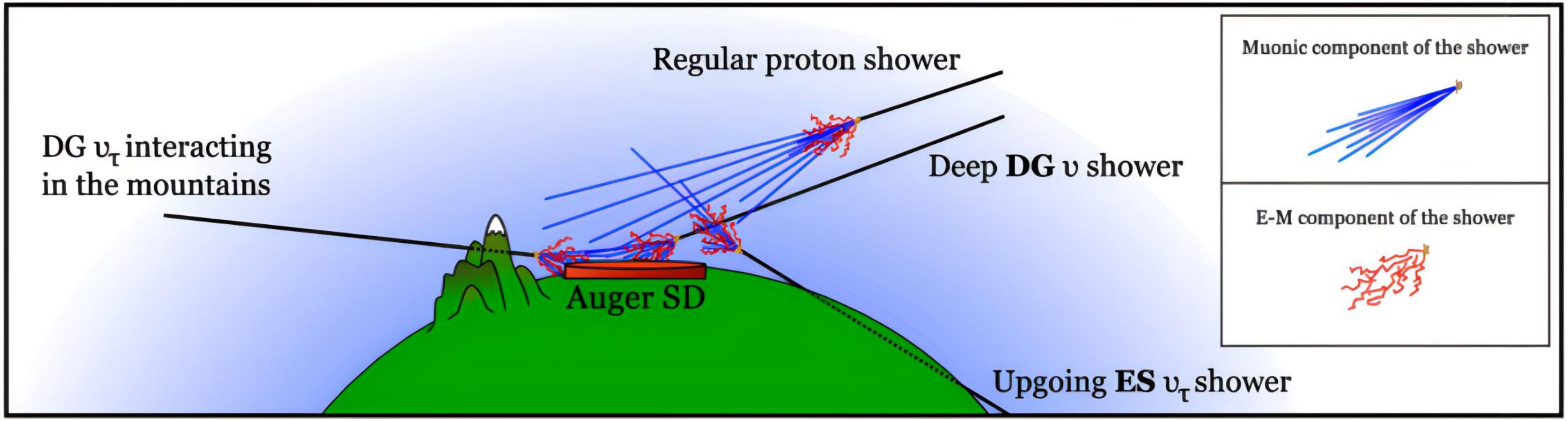
Strategies to detect neutrinos at VHE-UHE

Upward-directed shower

- Neutrino with trajectory emerging from beyond the horizon after traversing part of the Earth;
- Interacts before reaching the surface or shortly after entering the atmosphere .

Horizontal downward-going air showers (HAS)

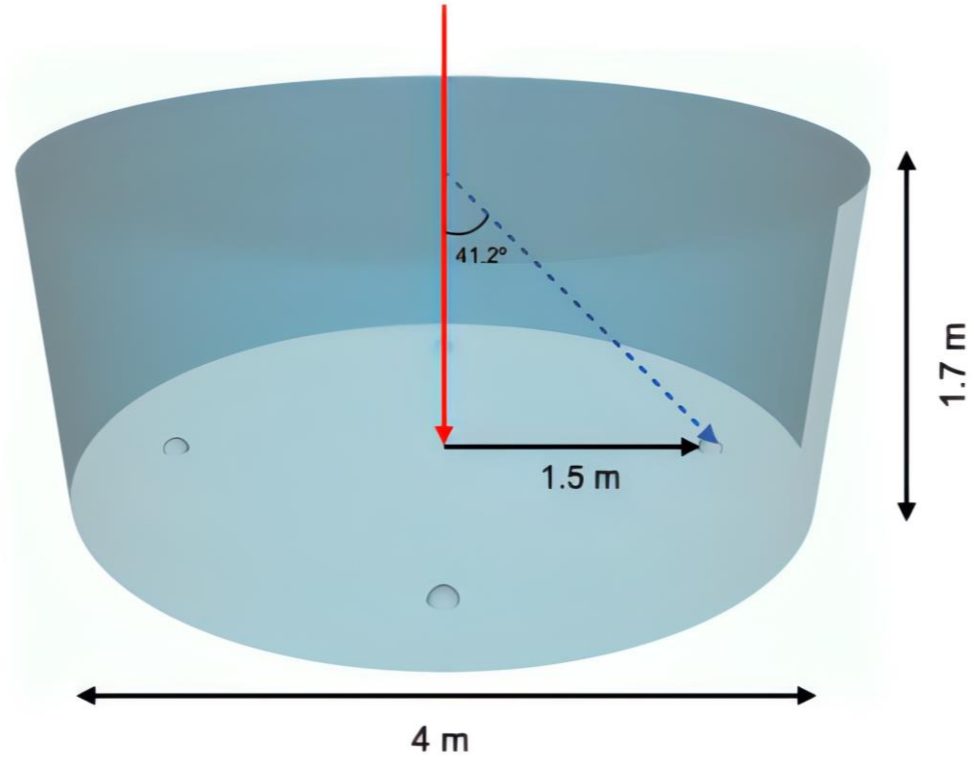
- Showers with large zenith angle ($\theta \gtrsim 60°$), induced by neutrinos in the atmosphere.



Simulation Framework

- Proton and neutrino showers simulated with **CORSIKA.**

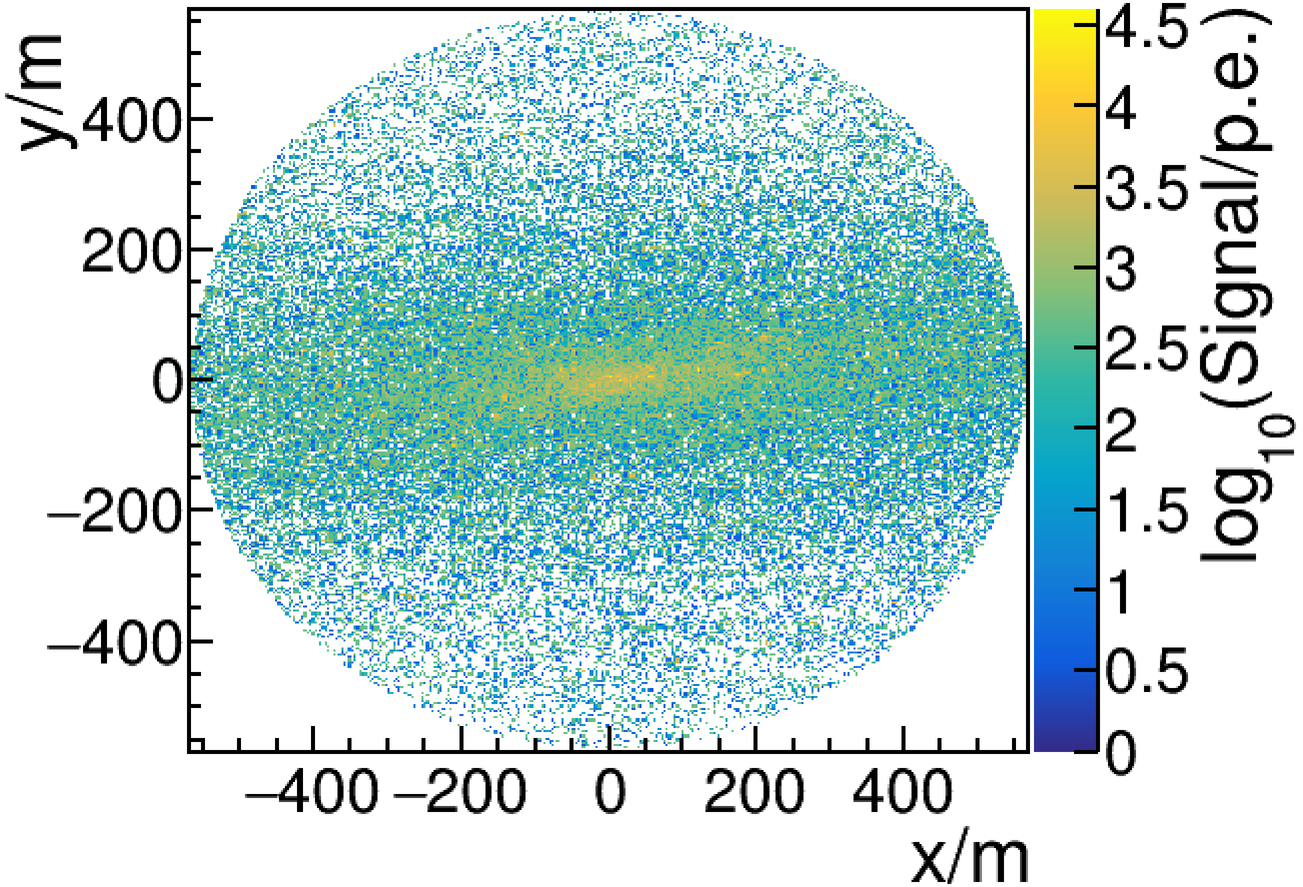
- Detector response emulated with **Geant4**.
  - Parametrisation of average signal as a function of the particle energy.
  - Detector Base Unit: **Single-Layered Water Cherenkov Detector (WCD) -** Tank filled with water, 4 PMTs at the bottom.



Taken from: ***Eur.Phys.J.C* 81 (2021) 6, 542**

Simulation Framework

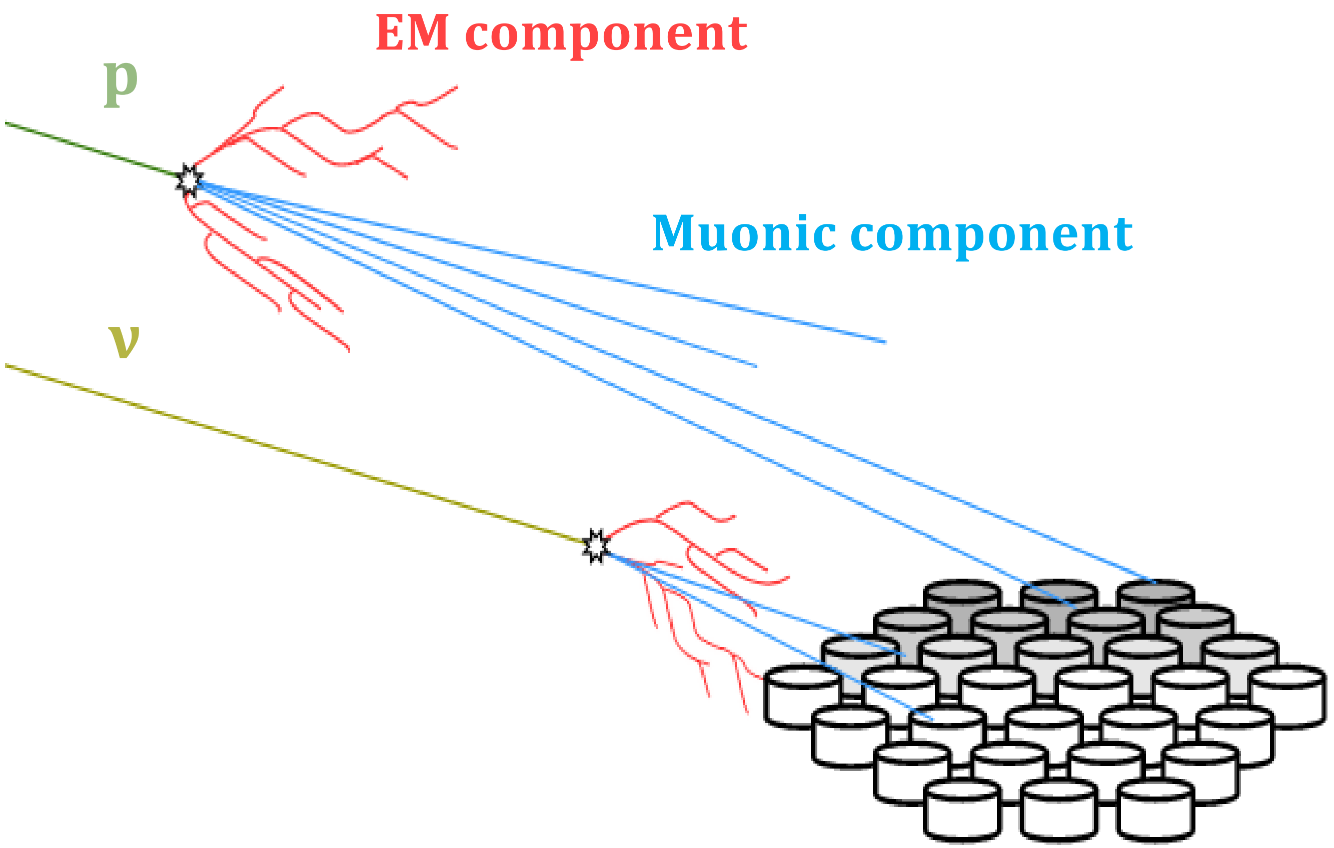
- Each station covers an **area of $\mathbf{12.6\ m^2}$**.
- **Homogeneous compact** array – **80% fill factor**.
- Detector array spanning a **circular surface area** of $\mathbf{1\ km^2}$
- Observation level remained unchanged in all simulations: **5 200 m**



Sum of signal at the ground, generated by 1000 proton-induced showers, $\mathrm{E_p} = 100\ \mathrm{TeV}$, $\theta = 75°$, $\phi = 0°$

Neutrino and Proton Induced Shower Discrimination

- **Background events:**
  - **Very-inclined proton-induced showers:** interaction at smaller grammages. EM component ⬇ Muonic component ⬆
- **Signal events:**
  - **Very-inclined showers induced by ν:** possibility of interacting near array. EM component ⬆ Muonic component ⬇
- Strategy successfully used by the **Pierre Auger Observatory**.



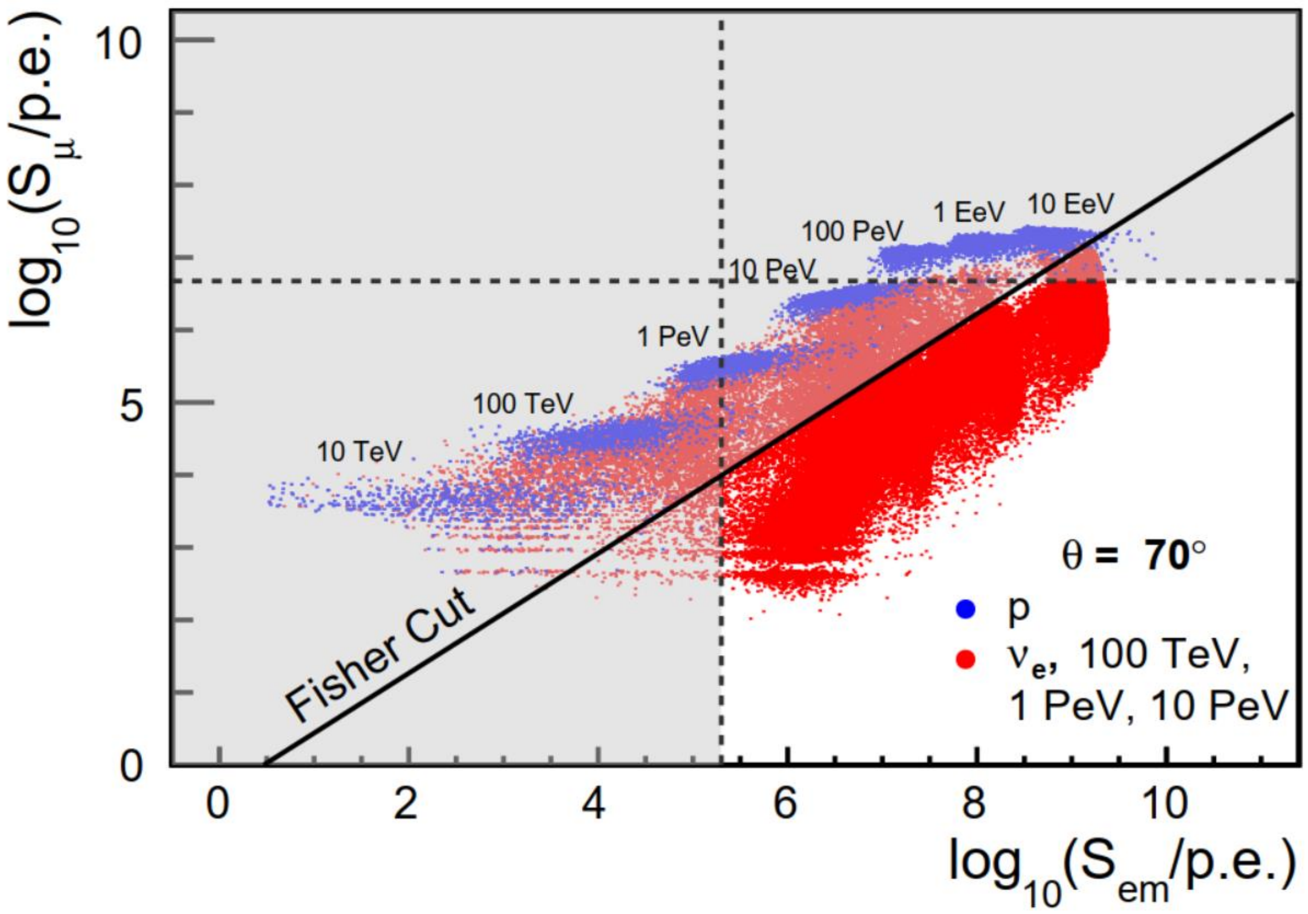
Neutrino and Proton Induced Shower Discrimination

- **Discrimination observables:**
  - Electromagnetic signal ($\boldsymbol{S_{EM}}$).
  - Muonic signal ($\boldsymbol{S_{\mu}}$).

- **ROI defined by 2 cuts:**
  - Cut in S_{EM} , fixed for all θ values
  - Cut in S_{μ} , varying with θ

- **Fisher discriminant** used to minimise background within ROI.

- **Efficiency**: ratio of neutrino events **within the ROI and below Fisher cut** with reference to total neutrino events simulated



EM and muonic signal of showers with $\theta = 70°$.

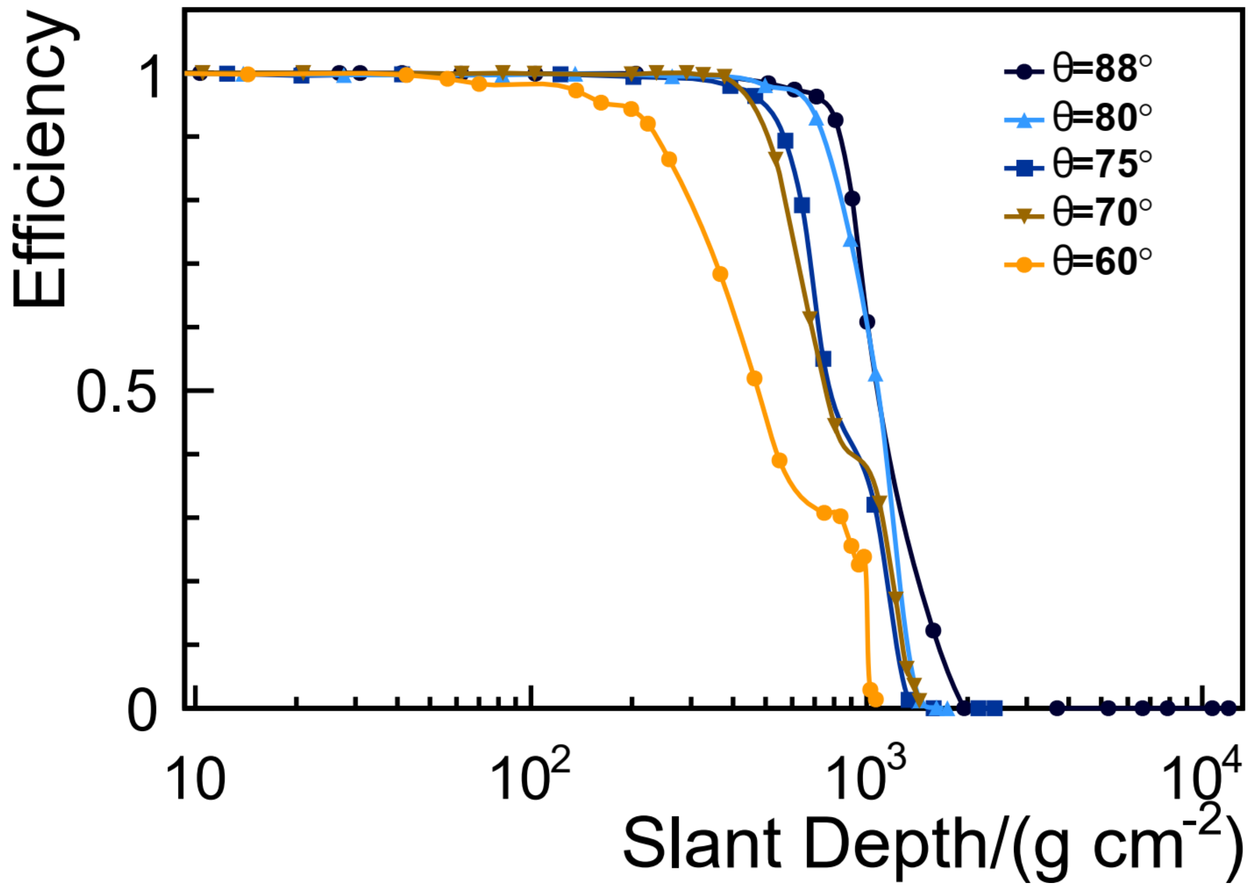
Event Rate Estimation

- Required parameters for computation:
  - **Integral** of **efficiency over slant depth;**
  - **Neutrino cross section;**
  - **Neutrino flux** (IceCube flux of VHE electron-neutrinos and anti-neutrinos):

$$\frac{d\phi}{dE_\nu} = k' \left(\frac{E_\nu}{E_0}\right)^{-2.53} ,$$

$$k' = 4.98 \times 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1},$$
$$E_0 = 10^5\ \mathrm{GeV}$$

- **Slant depth**: grammage between the observation level and point of first interaction.



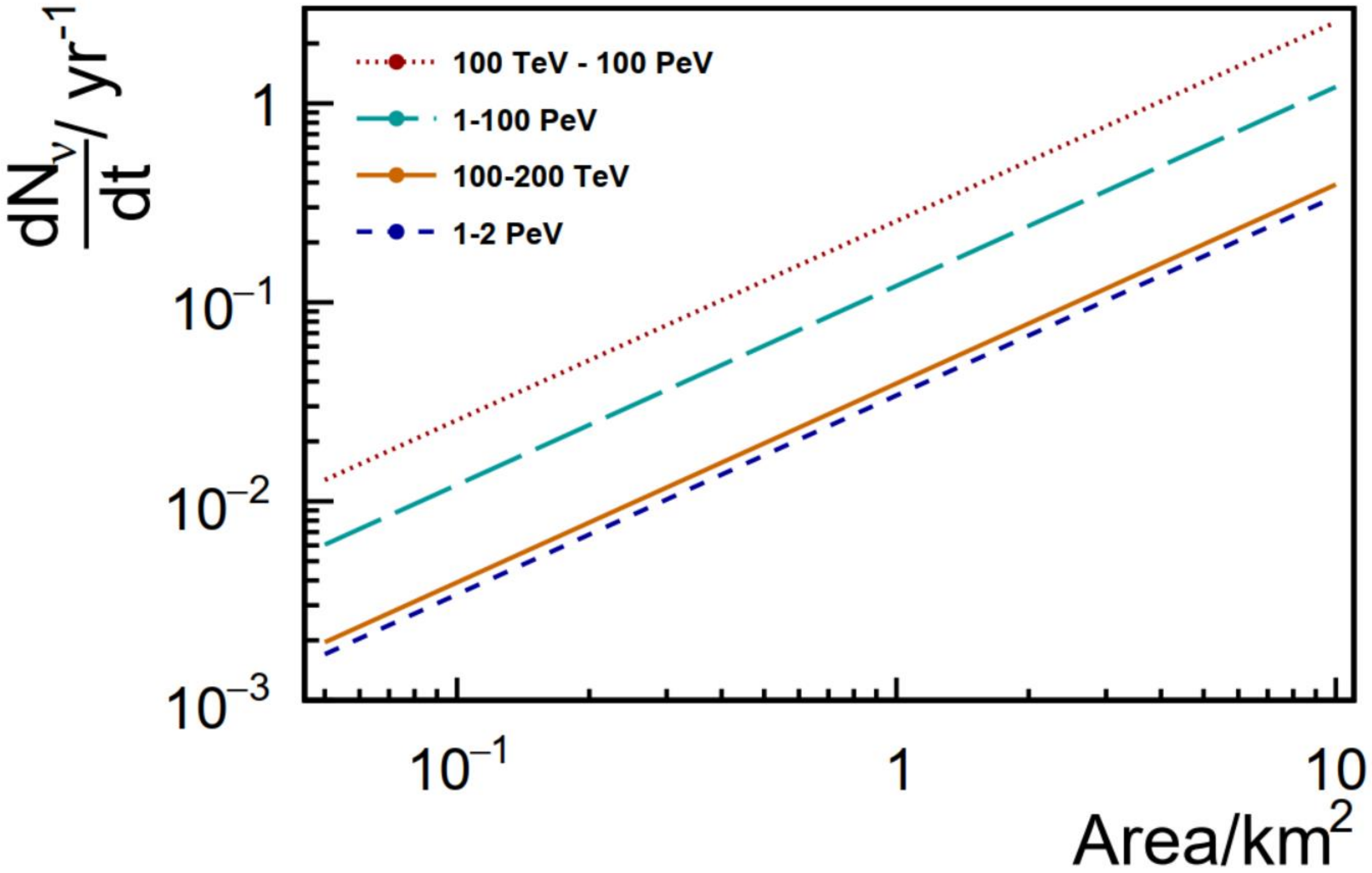
Signal-background discrimination efficiency curves for $E_\nu = 1$ PeV.

Measured Integral Electron Neutrino Flux

- **Electron neutrino** event rate as a function of **detector surface area** and **energy integration limits** ($A = 1\ \mathrm{km}^2$):

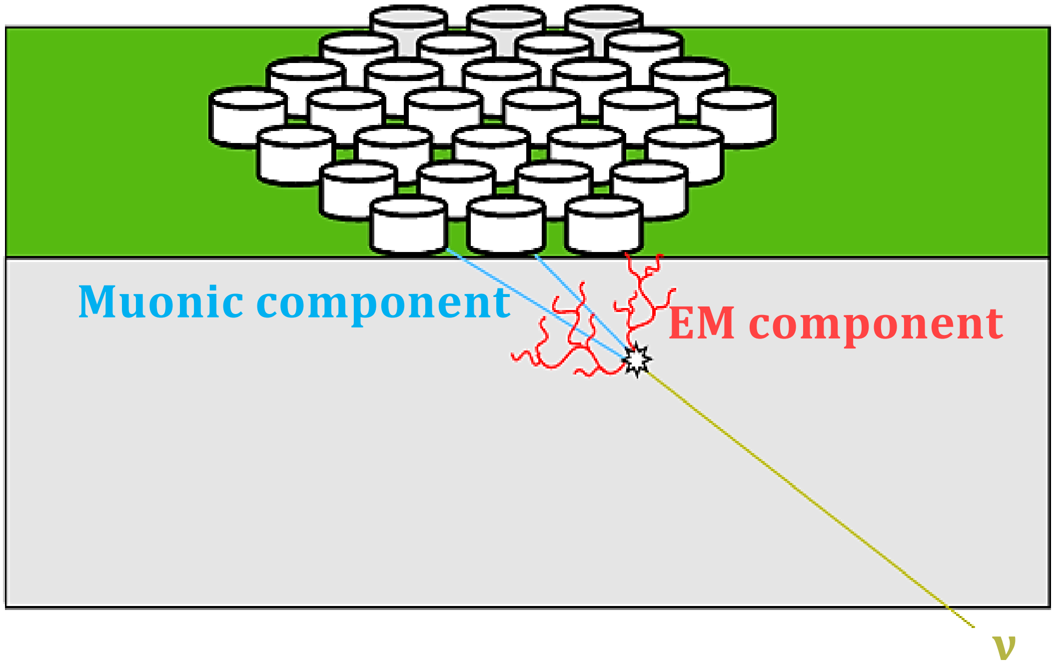
  - **1-2 PeV:** $3{,}12 \times 10^{-2}\mathrm{yr}^{-1}$

  - **100 TeV-100 PeV:** $3.01 \times 10^{-1}\mathrm{yr}^{-1}$,
    - 1 event every 3 years.



Sensitivity to Up-going Electron Neutrinos

- **Very inclined** showers, $\boldsymbol{\theta} \in [\mathbf{92°}, \mathbf{120°}]$.
- Primary energy, $E_\nu = 1$ PeV .
- Footprints have **small dimensions** – of the order of a few tens of m^2
- Small number of active stations. **Not enough individual detectors are triggered**.
- **Up-going neutrino** events are **not a viable addition** to the neutrino event rate.



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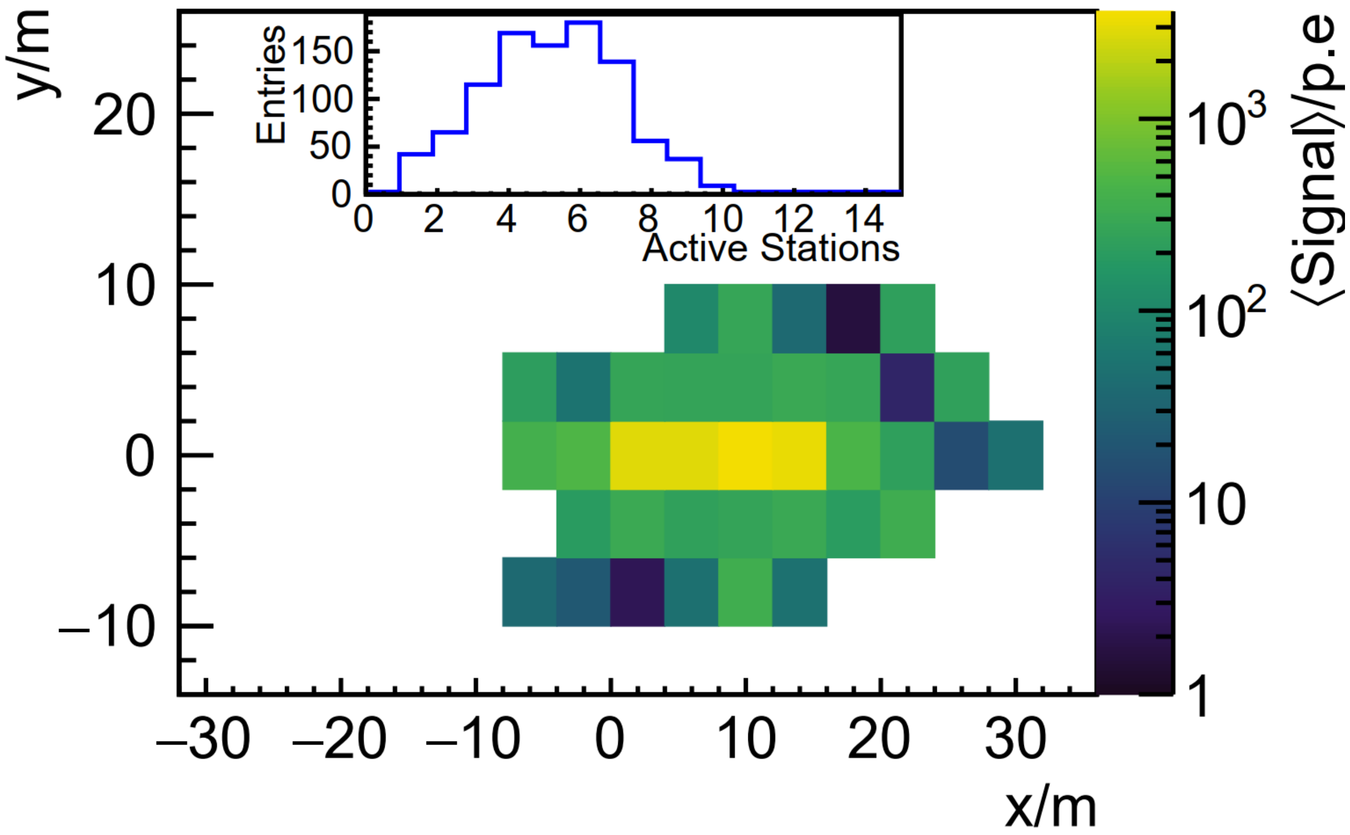
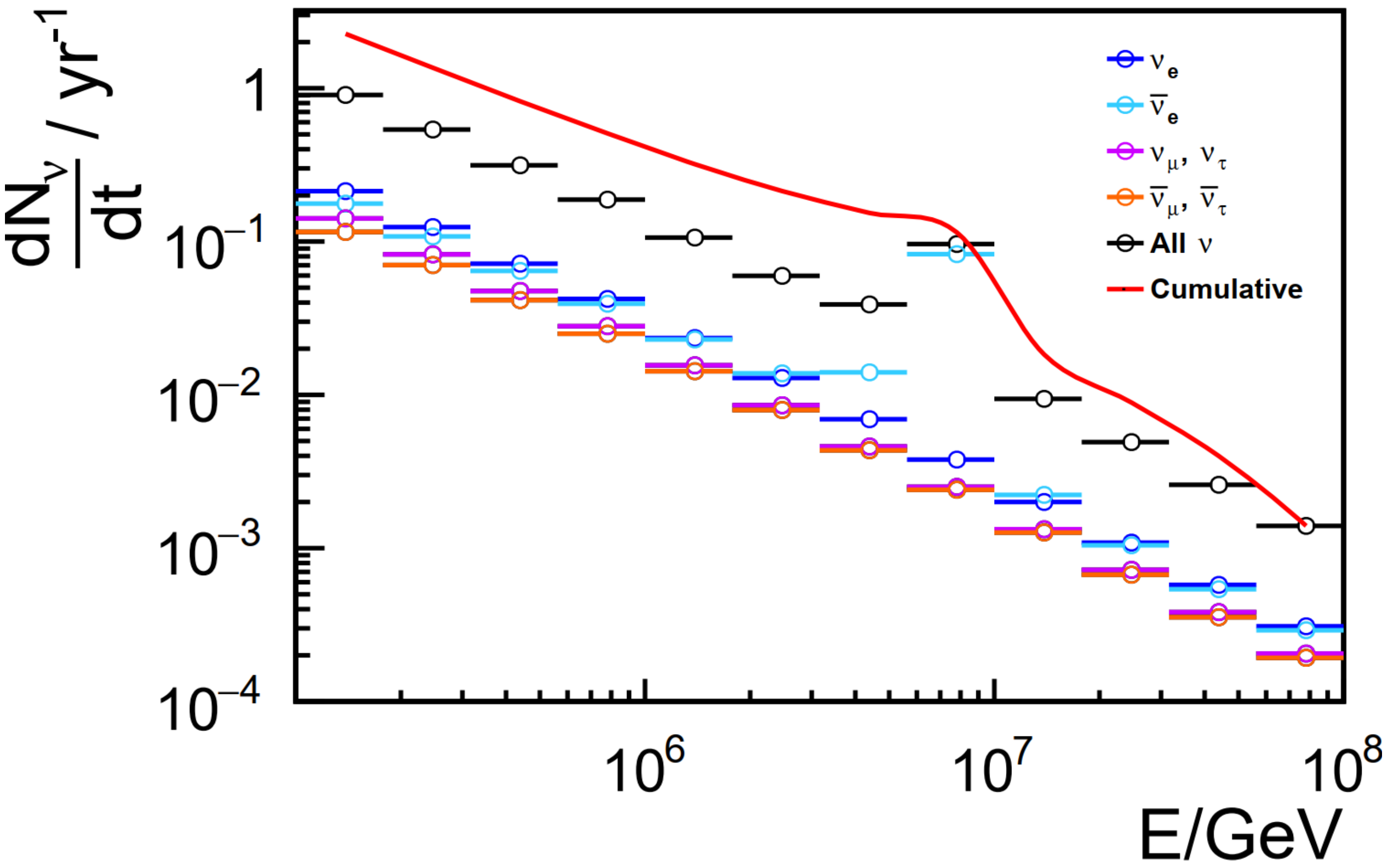


Average footprint for showers with $\theta = 100°$ and a fixed vertical height of first interaction of $3\ \mathrm{m}$.

All Neutrino Flavours

- Use the **efficiency computed for ν_e**, and analyses about **neutrino-air interaction properties** to conservatively extrapolate to other neutrino flavours.

- <u>**Red Line**</u> - Integrated number of events per year above a given energy.
  - Integrating from 100 TeV (10^5 GeV) $\sim$**2 neutrino events per year**.



Summary

- **Neutrino detection is viable** using a $\mathbf{km^2}$**-scale** wide-field ground-based gamma-ray observatory.

  - Potential to detect a **couple of VHE-UHE neutrino events per year** with a **reasonable pointing direction.**

- **Up-going neutrino** detection is **not viable.**

- Article detailing this work published in Physical Review D.

Link: https://journals.aps.org/prd/pdf/10.1103/PhysRevD.106.102001

PHYSICAL REVIEW D **106,** 102001 (2022)

Evaluation of the potential of a gamma-ray observatory to detect astrophysical neutrinos through inclined showers

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We assess the capabilities of a ground-based gamma-ray observatory to detect astrophysical neutrinos with energies in the 100 TeV to 100 PeV range. The identification of these events is done through the measurement of very inclined extensive air showers induced by downward-going and upward-going neutrinos. The discrimination of neutrino-induced showers in the overwhelming cosmic-ray background is achieved by analyzing the balance of the total electromagnetic and muonic signals of the shower at the ground. We demonstrate that a km^2-scale wide-field-of-view ground-based gamma-ray observatory could detect a couple of very-high- to ultrahigh-energy neutrino events per year with a reasonable pointing accuracy, making it an interesting facility for multimessenger studies with both photons and neutrinos.

DOI: 10.1103/PhysRevD.106.102001

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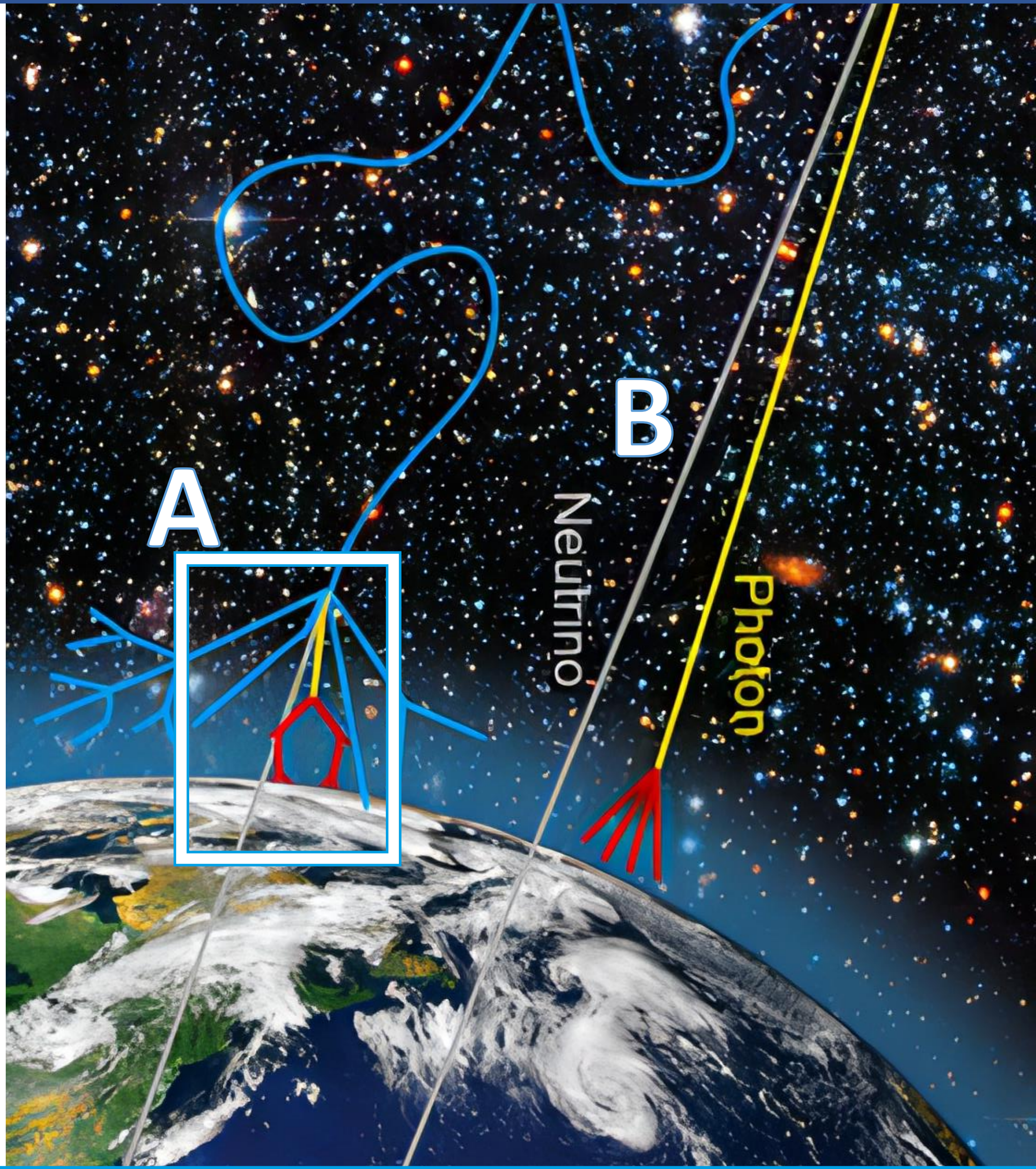
Thank you for your time

What neutrinos are we looking for?

- **VHE-UHE $\boldsymbol{\nu}$:** $E_\nu \gtrsim 100\ \mathrm{TeV}$.

- **Atmospheric neutrinos (A)**: resulting from interactions of other particles in the atmosphere.
  - Contribute to the neutrino flux at **100 TeV**.

- **Astrophysical neutrinos (B):** neutrinos produced in high energy phenomena, e.g.: AGN, GRBs, galaxy clusters, …
  - Dominate the neutrino flux **at and above 100 TeV**.

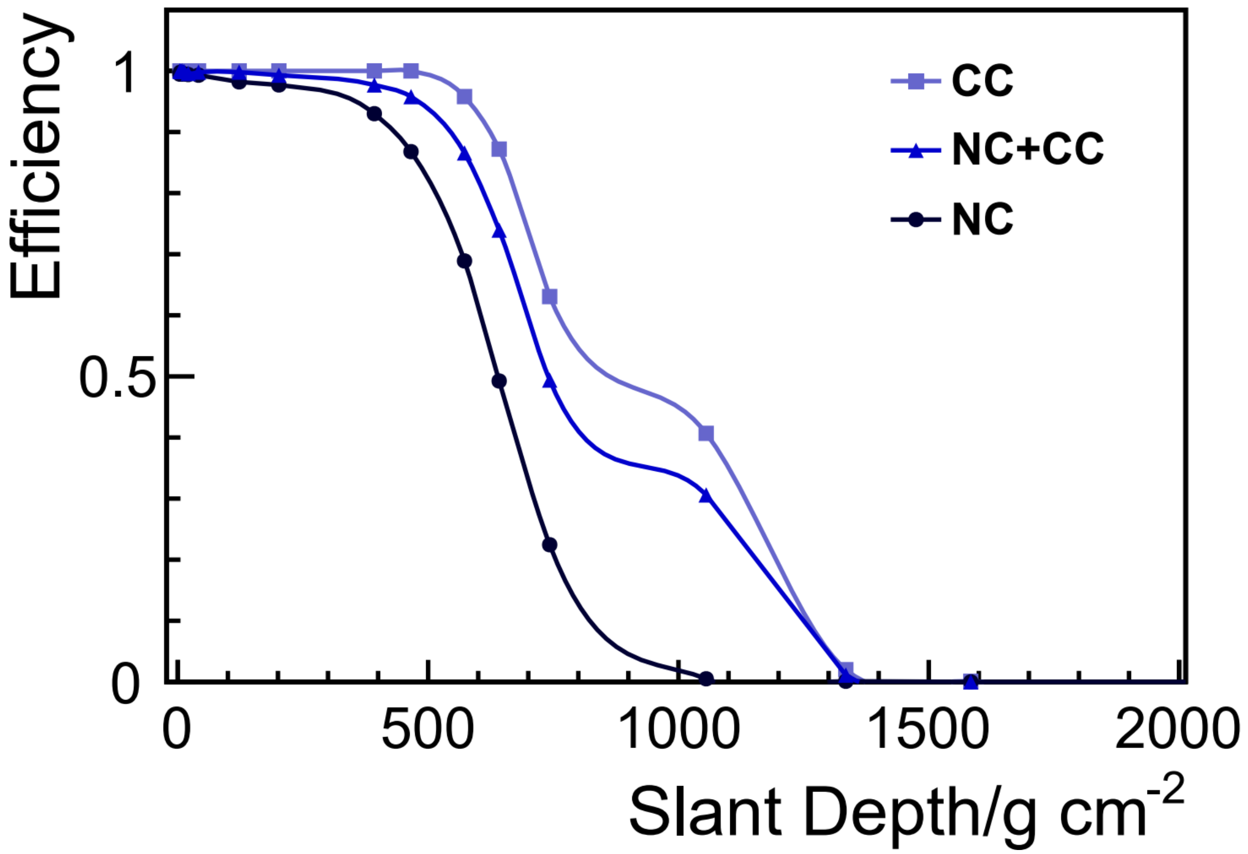


1 PeV Neutrinos – Interaction Current

- Impact of **neutrino interaction channel**:
  - Interaction type set in CORSIKA.
  - Charged current (**CC**).
  - Neutral Current (**NC**).
  - Interaction chosen according to relative weight in the total cross section (**NC+CC**).

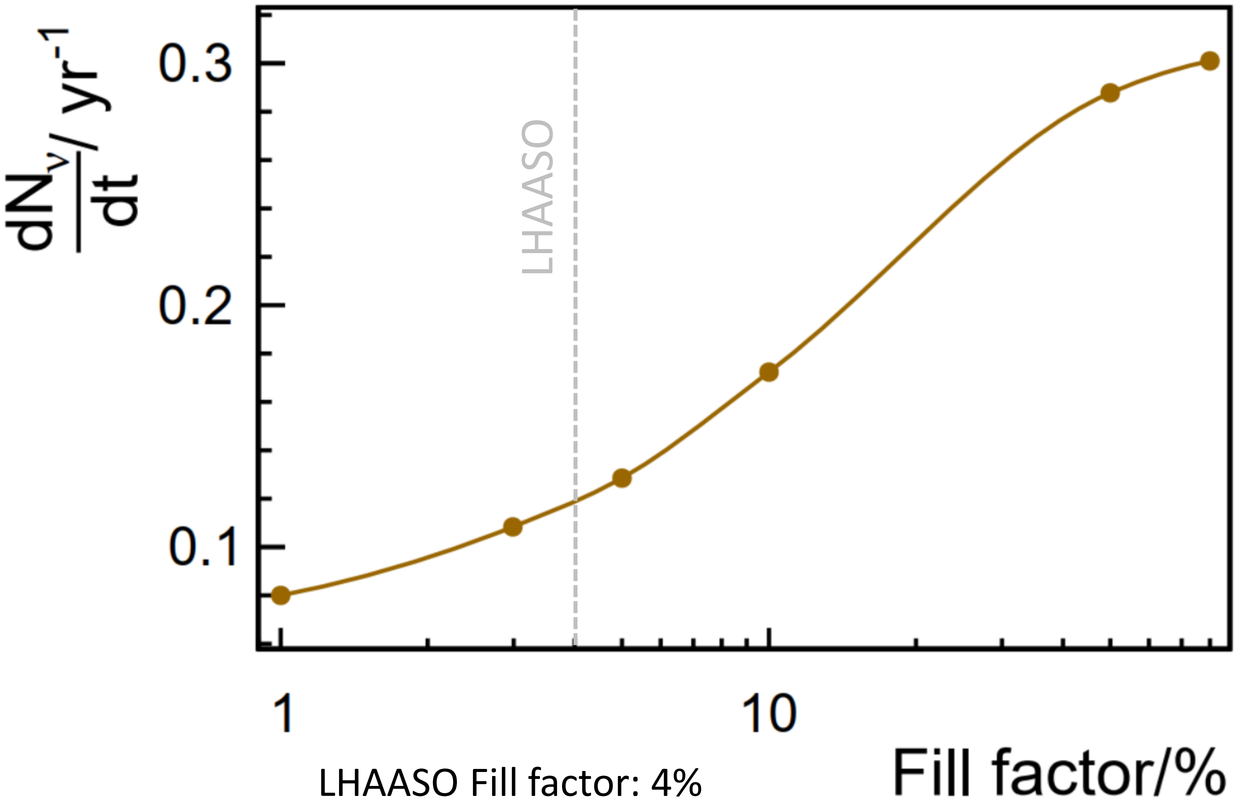
- Estimated event rate, **1-2 PeV bin**:
  - **CC**: $2.29 \times 10^{-2}\mathrm{yr}^{-1}$
  - **NC**: $2.50 \times 10^{-3}\mathrm{yr}^{-1}$
  - **NC+CC**: $3.12 \times 10^{-2}\mathrm{yr}^{-1}$

- Neutrino event rate maximised by **NC+CC.**



Impact of Fill Factor

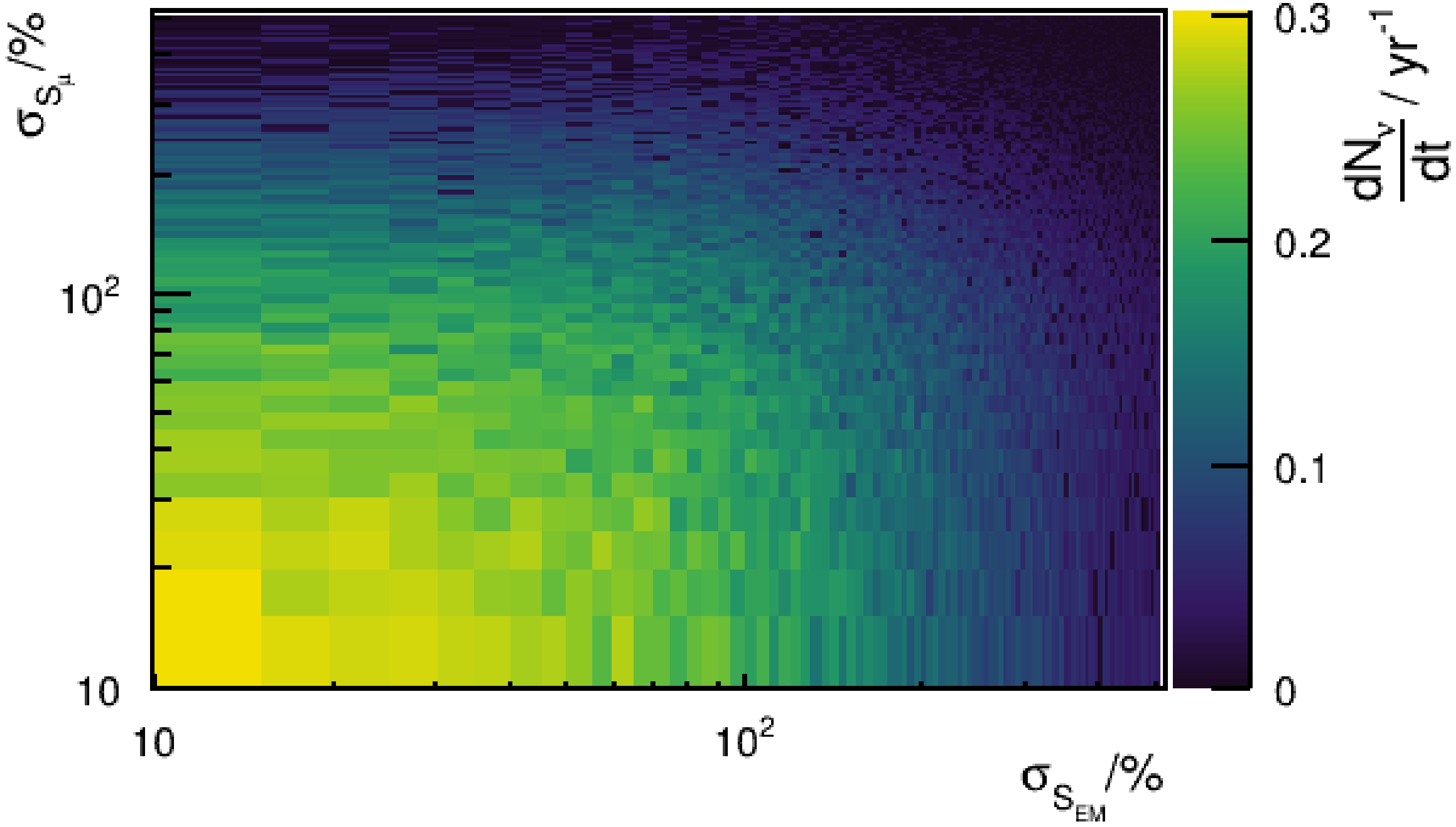
- **Fill factor**: ratio between detector area (histogram cell size) and total sampling area (array size).
- Decrease in fill factor from **80% to 3%** reduces event rate by a **factor of 3**.
- Neutrino detection by EAS arrays with lower fill factors still viable, although on a **larger timescale**.



LHAASO Fill factor: 4%
SWGO planned fill factor:
- 5% Compact Array
- 1.4% Sparse Array

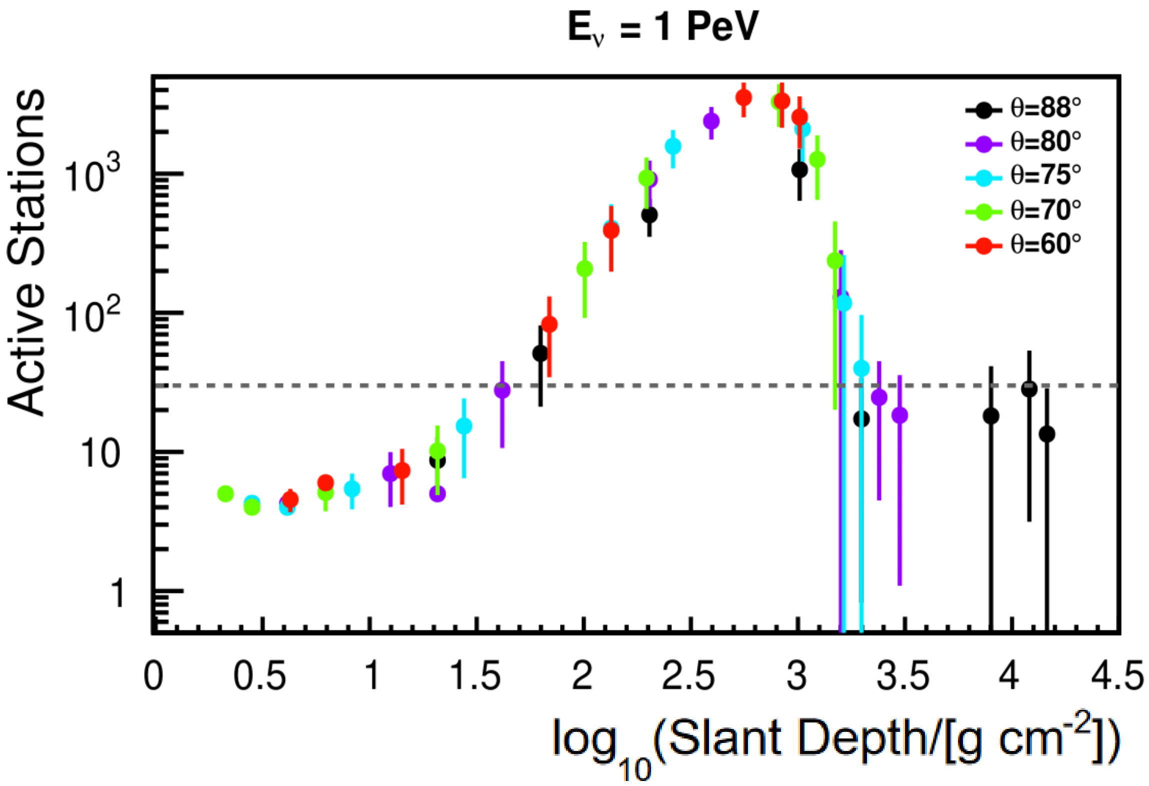
Experimental Resolution Impact• II/II

- Introduce fluctuations according to a **Gaussian distribution**:
- $\sigma_{S_{EM}}$ and $\sigma_{S_{\mu}}$ ranging from **0** to **500%.**
- Range of energies: **100 TeV-100 PeV**
- For a km^2-scale array with a 80% fill factor, the event rate decreased by a **factor of 2** for **fluctuations close to 200%.**



Experimental Resolution Impact• II/II

- Array with $1\ \mathrm{km}^2$ and fill factor of 5%.
- **Shower axis reconstruction** - Precision better than $\mathbf{5}°$, negligible bias if shower footprint has $\geq \mathbf{30}$ **active stations**.
  - Requirement met for showers with slant depths greater than $\sim 100\ \mathrm{g\ cm^{-2}}$.
  - Cut can be relaxed for very large slant depths ($\sim 2000\ \mathrm{g\ cm^{-2}}$).
- Condition leads to $\sim\mathbf{10\%}$ **decrease in effective mass**, and a proportionately lower neutrino event rate.



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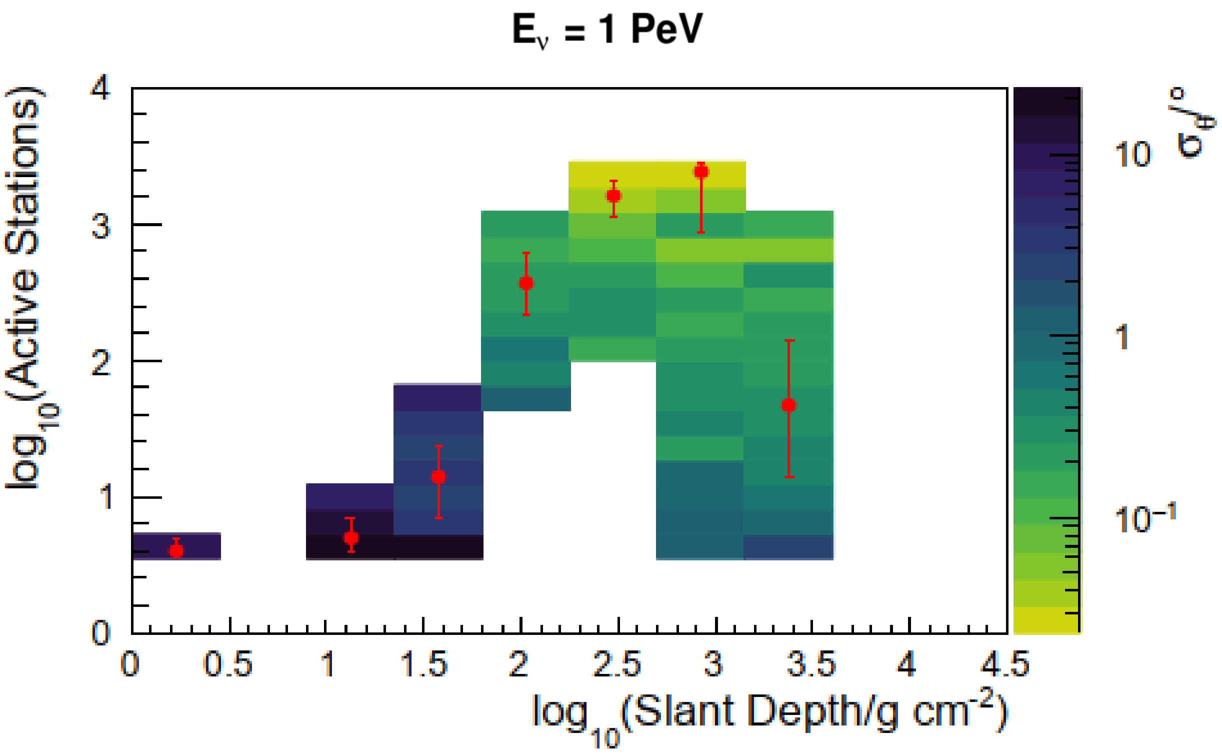
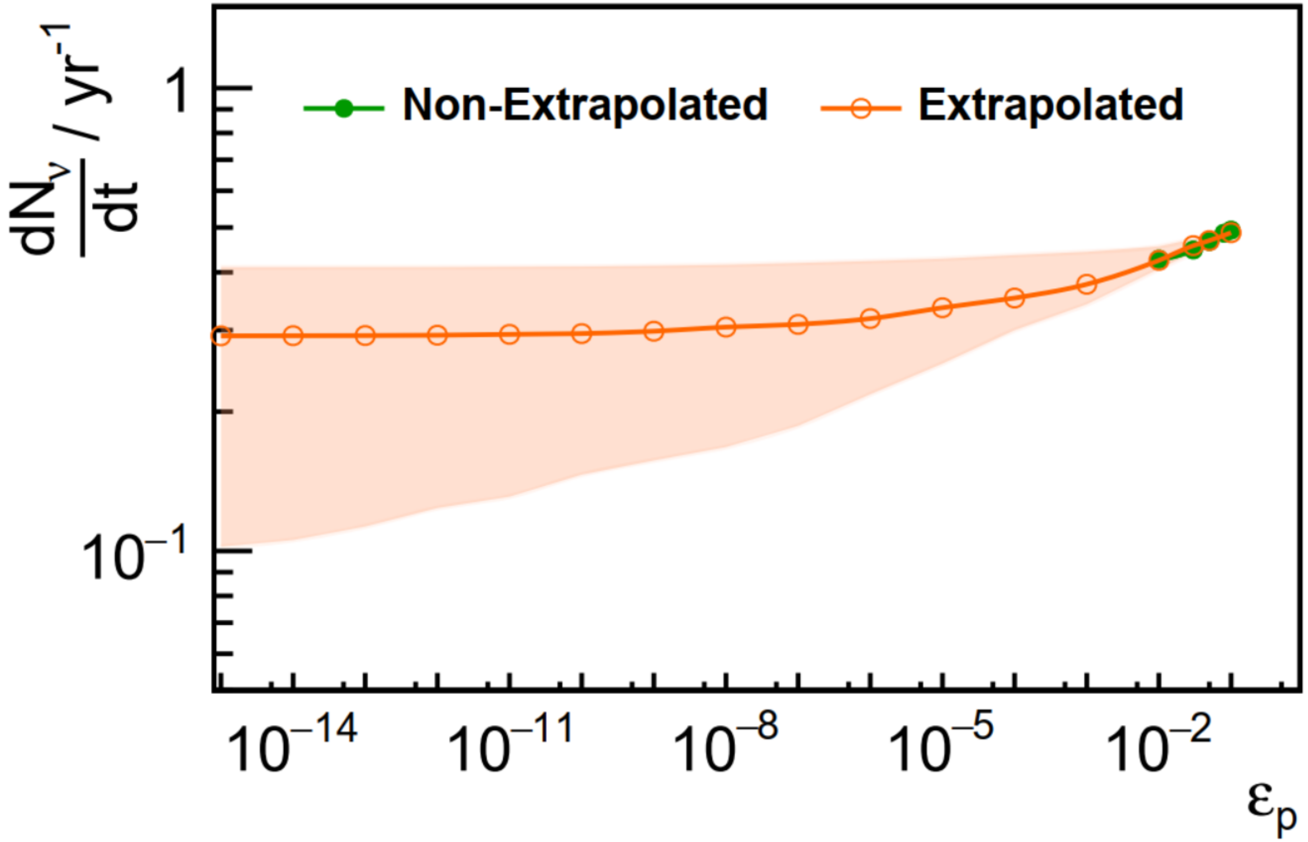


Impact of Limited Simulation Statistics

- **Background event rate ≫ expected electron neutrino event rate**.
  - Large proton background rejection factor required.

- Available simulations **limited in statistics**. **Extrapolation** to higher background rejection factors:
  - Fit exponential function to the tail of each Fisher Values cumulative.

- Uncertainty on number of expected neutrinos increases with ε_p,
  - Maximum factor of 4 for a background-free experiment.



Band: 1-sigma error of exponential fit to the tail