THE HENRYK NIEWODNICZAŃSKI
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"Fast Cascade Generator GAN in the P-ONE Experiment"

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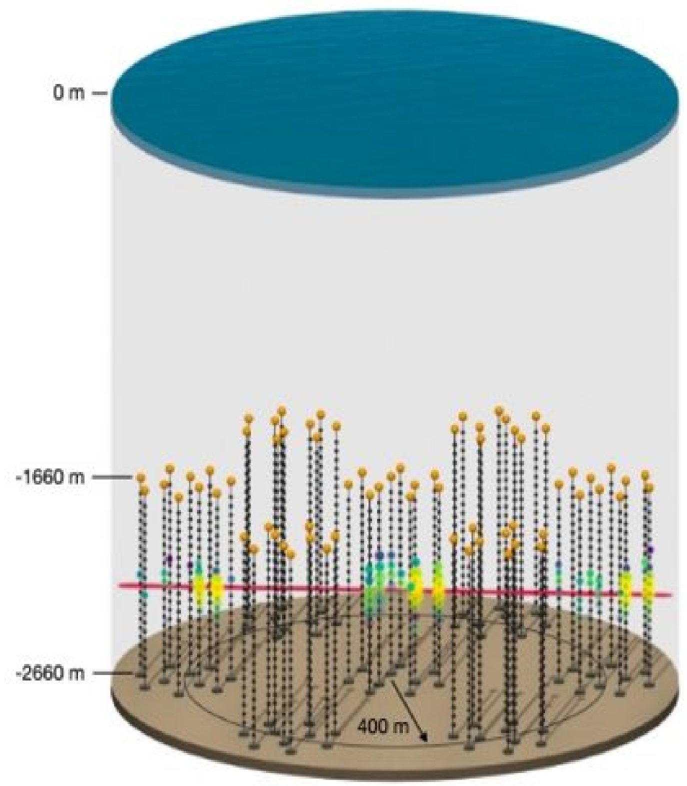
Introduction to the P-ONE Experiment

- P-ONE → Pacific Ocean Neutrino Experiment
- Location: Pacific Ocean, off the western coast of Canada
- It will be one of the largest very-high-energy cosmic neutrino observatories.
- P-ONE is part of the Global Neutrino Network (GNN).
- Aim: the observation of neutrinos arriving from the sky in the Southern Hemisphere
- A detection system composed of multiple Cherenkov detectors in water



Neutrino telescopes maps

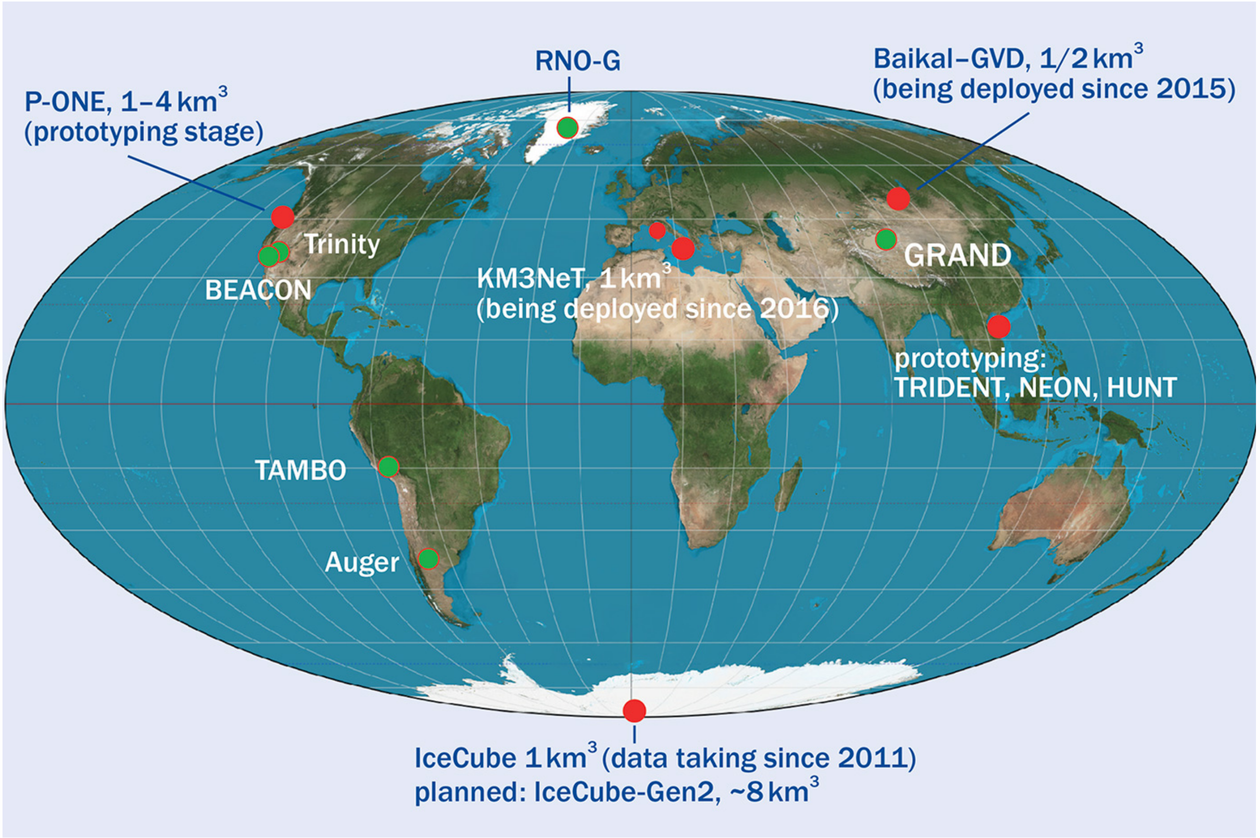


Fig 2. Map of neutrino telescopes maps [6]

GNN members:

- **P-ONE**
- **IceCube**: First to see cosmic neutrinos outside from Solar System (2013) and the blazar TXS 0506+056 (2018).
- **Baikal-GVD**: Large neutrino telescope in the deep water of Lake Baikal.
- **KM3NeT(**Cubic Kilometre Neutrino Telescope**).**: deep-sea detector
- **RNO-G (**Radio Neutrino Observatory Greenland) In build since 2021
- **ANTARES:**2006-2022, water Cherenkov 0,1km^3

Neutrino interactions and secondary particles

- Neutrinos interact only via the weak force
- We can only observe the secondary products of neutrino interactions with atomic nuclei
- Neutrinos interact with matter by both the charged-current (CC) and neutral-current (NC) interactions.
- The CC interactions can be expressed as:

$$\nu_l + N \rightarrow l + X$$

  where *N* is nucleus, *l* denotes a charged lepton corresponding to the neutrino flavor and X represents the hadronic final state produced in the interaction
- Neutrinos also interact via neutral-current (NC) interactions

$$\nu_l + N \rightarrow \nu_l + X$$

Cherenkov radiation

- Using a Cherenkov detector, we observe Cherenkov radiaton when electrically charged particles, e.g. electrons (e^-), moving faster than the speed of light in a given medium(in this case, water)
- Example of charged-current (CC) interaction:

$$\nu_e + n \rightarrow p + e^-$$

- The condition for the emission of Cherenkov radiation is given by:

$$\beta > \frac{1}{n},$$

where β is the velocity of the particle in units of the speed of light:

$$\beta = \frac{v}{c}$$

and n is the refractive index of the medium

What will we directly observe?

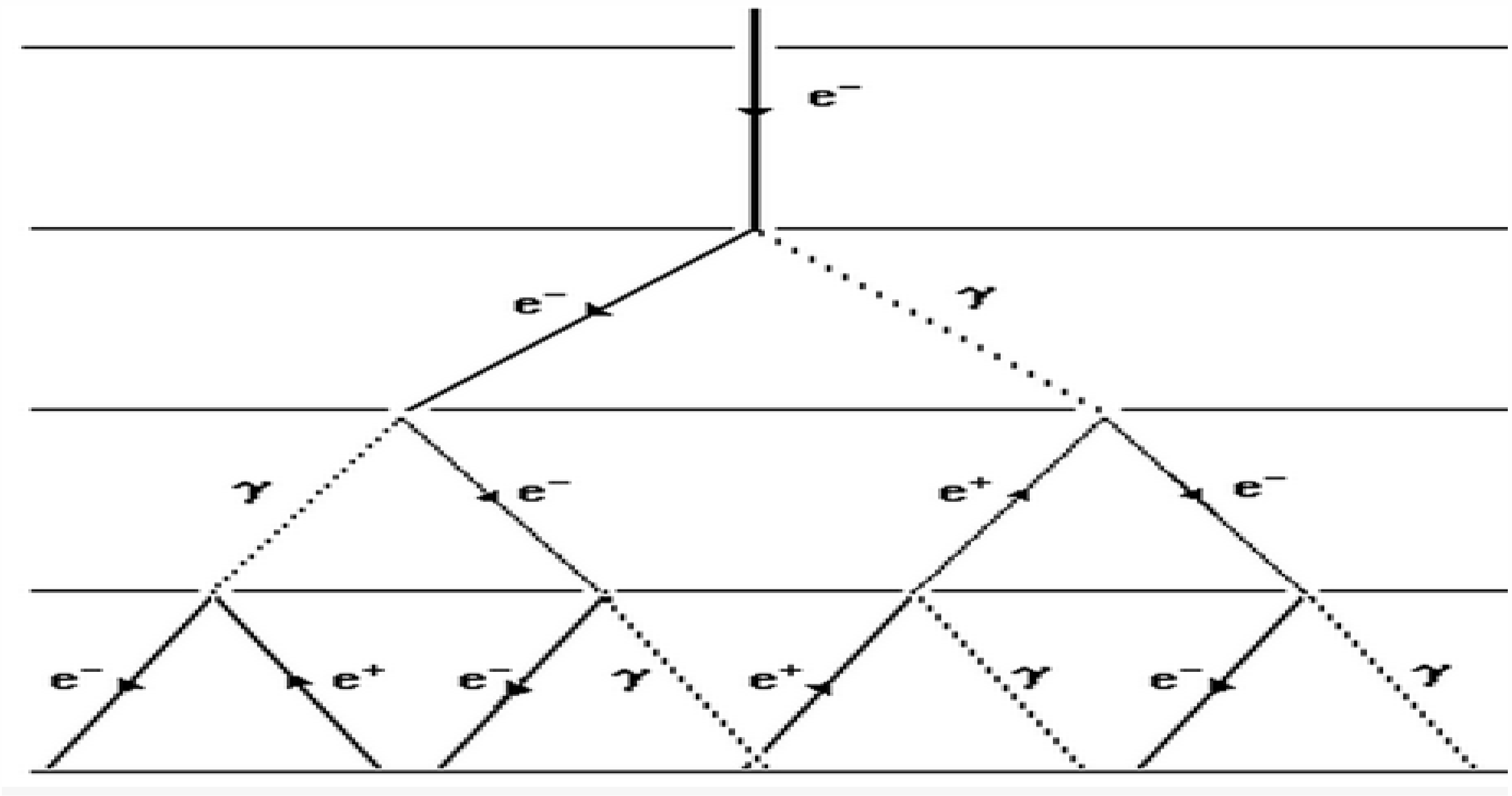


Fig. 2. An electromagnetic cascade initiated by an electron [2].

My involvement in the experiment

- My objective is to generate realistic Cherenkov photon data in water, much faster than classical Monte Carlo simulations (e.g. Geant4).
- Training of a GAN neural network model based on Geant4 simulation data, using Graphics Processing Units (GPUs).
- A GAN (Generative Adversarial Network) is a system of two neural networks – the Generator and the Discriminator – that compete with each other.
- GPU offers thousands of parallel computing operations

Geant4 vs GAN model

Geant4

- CPU
- Very high precision- full physic simulation (Monte Carlo)
- Time cosnuming process(slow, step-by-step tracking)
- Gold standard for data validation

GAN model

- GPU
- High fidelity approximation of physics distributions
- Extremelly fast: 100-1000x than CPU
- Primary use: Fast simulation of large-scale datasets

Adversarial training concept (Counterfeiter & Policeman Analogy)

- **Generative Model** (The Counterfeiter): Learns to create perfect replicas of "realistic" money
- **Discriminative Model** (The Policeman): Learns to distinguish between real and fake data by detecting the smallest flaws or anomalies.
- **The Adversarial Process:** This competition drives the training; the generator perfects its deception while the discriminator sharpens its detection.
- **Ultimate Goal:** Synthetic data becomes indistinguishable from the Geant4 samples.

My model details

- Model: Generative Adversarial Network (GAN) for Cherenkov photon cascades.
- Setup: 1 GeV electrons propagating in water.
- Training: 2.800 epochs.
- Output: Spatial coordinates (x, y, z) , wavelength and angle relative to the Z-axis of photon emission points.

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Comparison of preliminary Geant4 simulation results and the GAN model

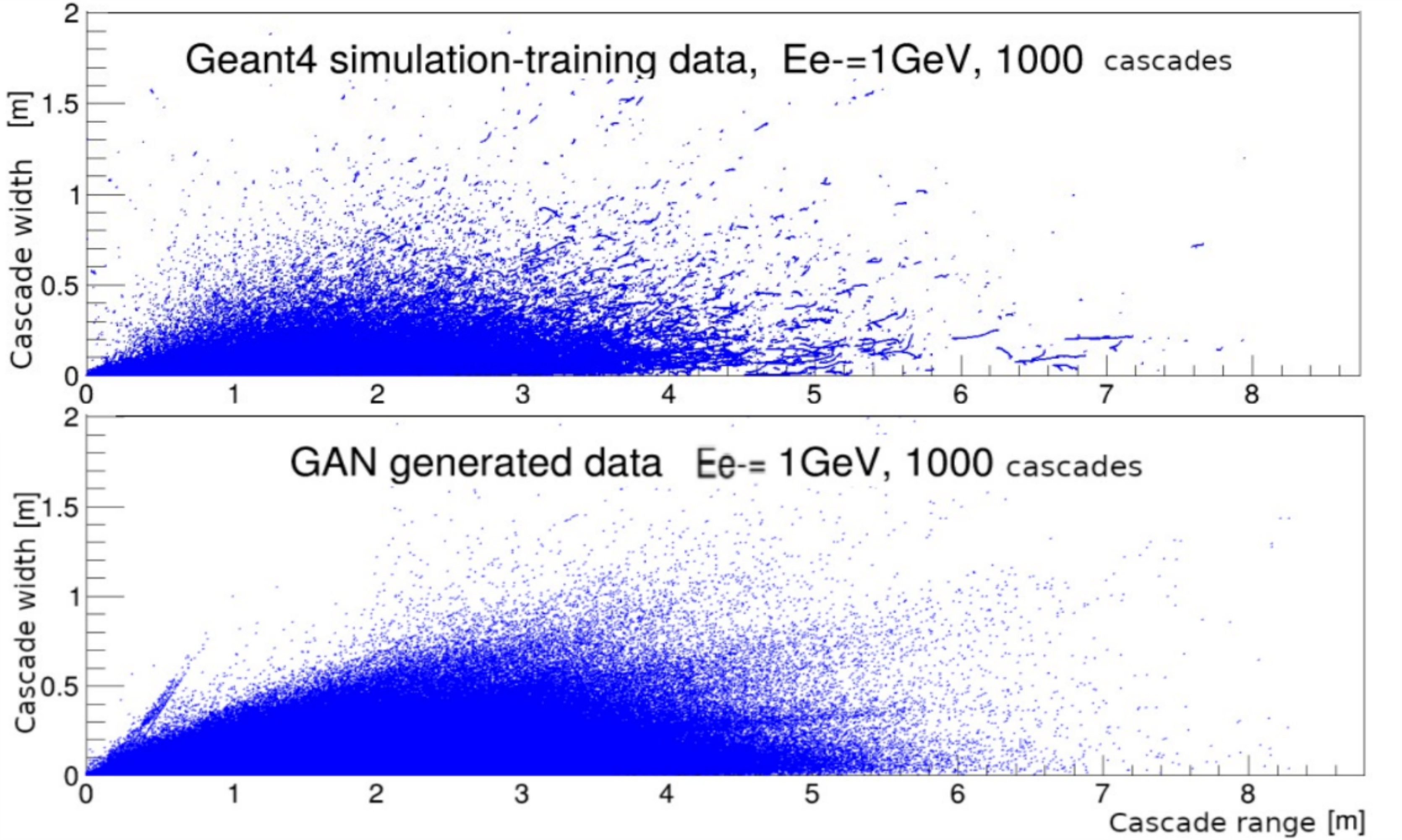

Fig. 3. Comparison of Geant4 simulation results and the GAN model.

Validation of the GAN-based Fast Simulation: X-coordinate Distribution

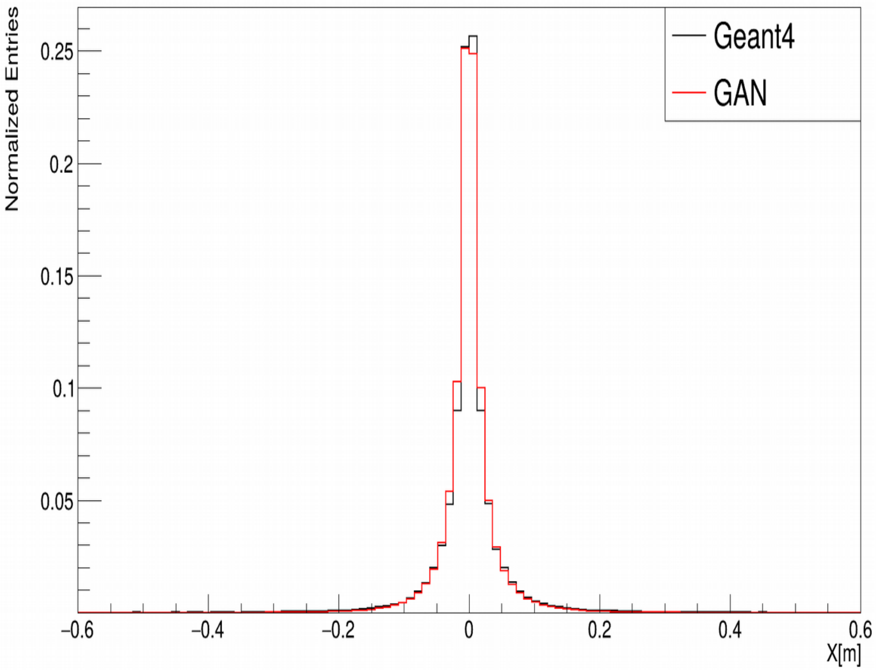

Fig. 4: GAN model validation: comparison of the X-coordinate distribution with Geant4 reference data. The model demonstrates excellent agreement in reproducing the central peak and the distribution symmetry. Statistics: 1.2×10^{7} events.

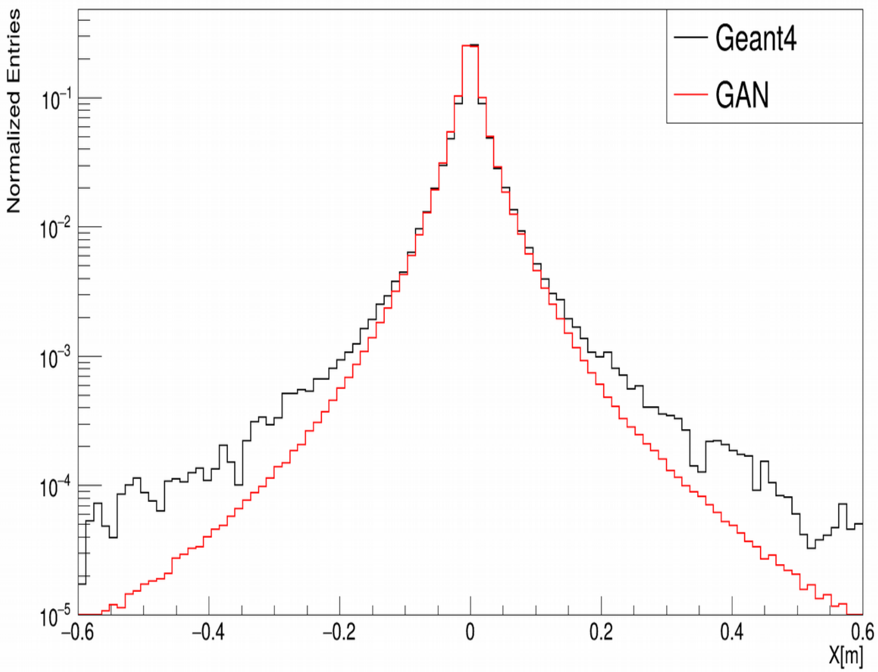

Fig 5 X: Validation of the GAN model against Geant4 simulation for the X-coordinate. The logarithmic scale illustrates the model's performance across several orders of magnitude. The GAN outputs are characterized by a clear underestimation of the distribution tails. Total statistics: 1.2×10^{7} events.

Validation of the GAN-based Fast Simulation: Y-coordinate Distribution

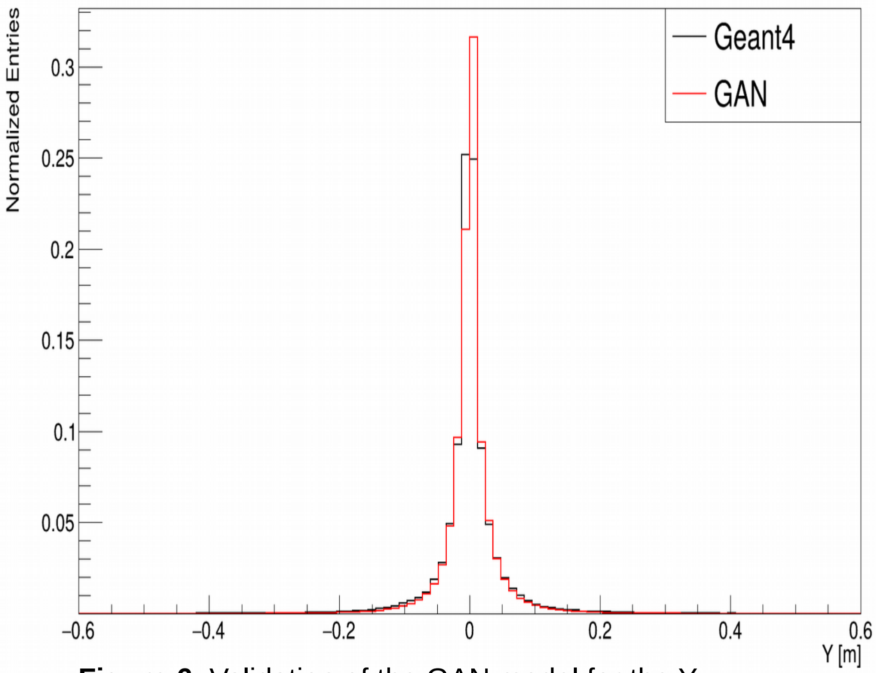

Figure 6: Validation of the GAN model for the Y-coordinate distribution. The generative model (red) accurately captures the symmetric nature of the distribution, with a slight overestimation observed in the central peak compared to the Geant4 baseline (black). Total statistics: 1.2×10^{7} events.

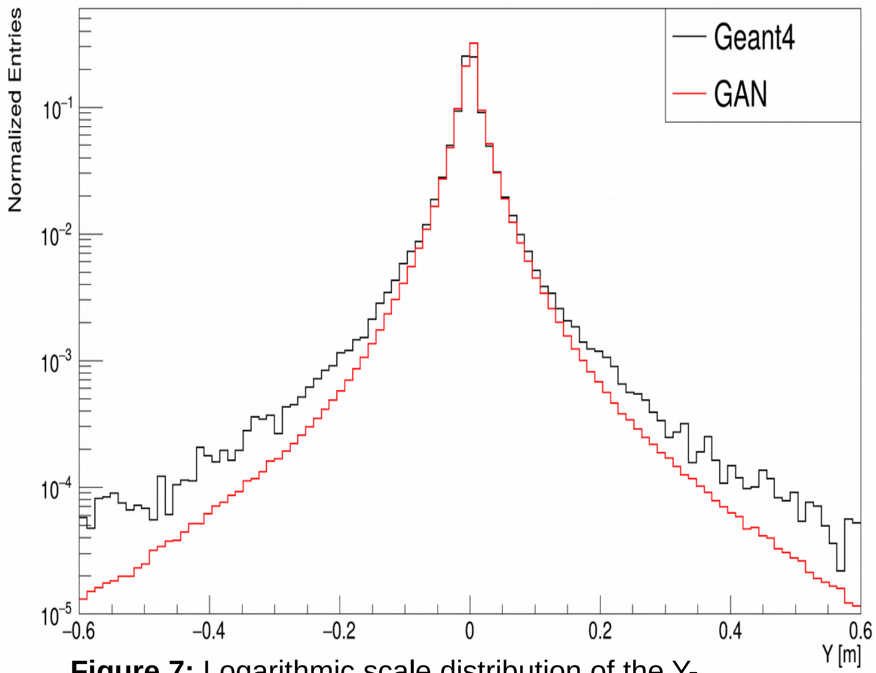

Figure 7: Logarithmic scale distribution of the Y-coordinate. The GAN model accurately reproduces the Geant4 reference within the high-statistics region. However, a systematic underestimation of the distribution width is observed in the tails (below 10^{-3}). Total statistics: 1.2×10^{7} events.

Validation of the GAN-based Fast Simulation: Z-coordinate Distribution

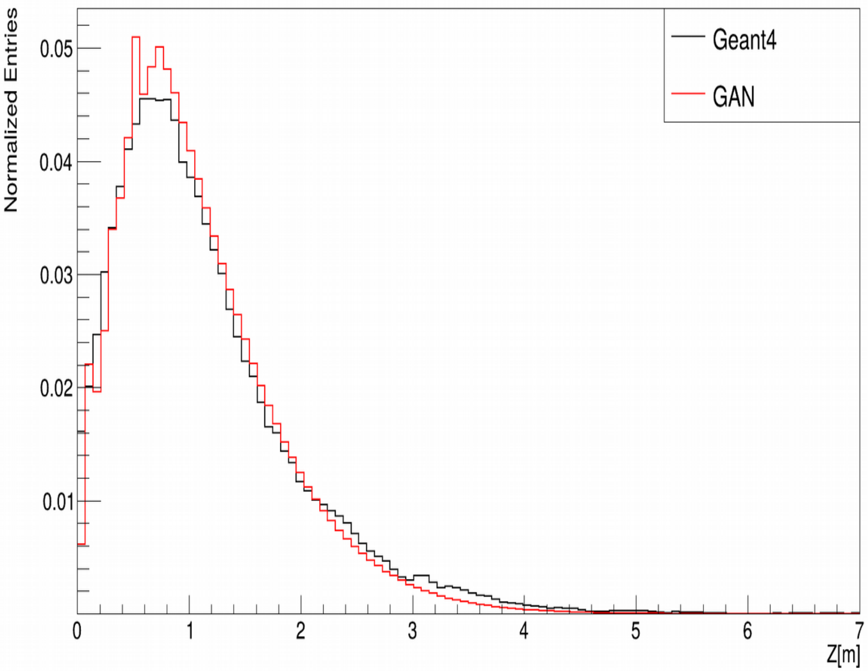

Fig. 8: Validation of the GAN model for the Z-coordinate distribution. The model successfully reproduces the asymmetric profile of the Geant4 reference data. A slight overestimation is observed in the peak region (Z≈0.7 m), while the long tail shows good overall agreement with minor deviations beyond Z=3 m. Total statistics: $1.2{\times}10^{7}$ events.

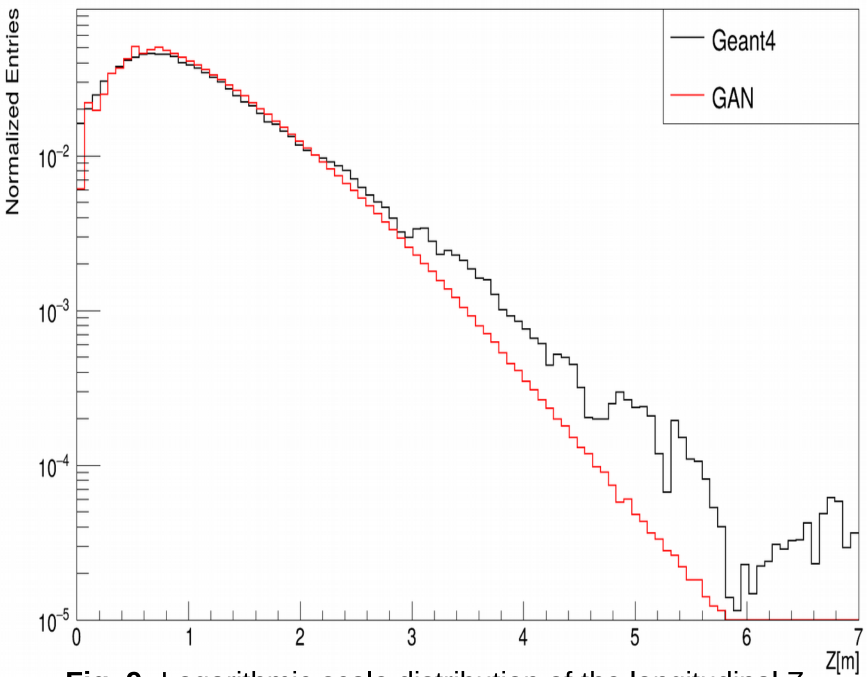

Fig. 9: Logarithmic scale distribution of the longitudinal Z-coordinate. The GAN model (red) accurately reproduces the peak and the initial slope of the Geant4 reference (black). The GAN outputs are characterized by a clear underestimation of the distribution tails. Total statistics: $1.2{\times}10^{7}$ events.

Comparative analysis of emission Angle(Z) against Geant4 baseline

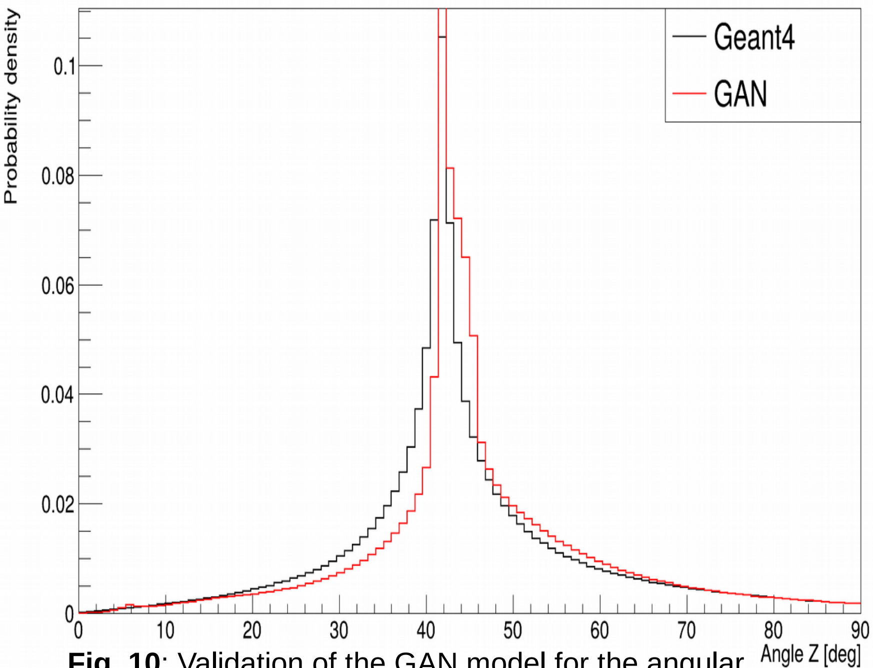

Fig. 10: Validation of the GAN model for the angular distribution (Angle Z).The graph shows a characteristic peak in the region of the so-called Cherenkov con.The GAN peak is shifted by ~1° relative to the Geant4 simulation. Total statistics: 1.2×10^{7} events.

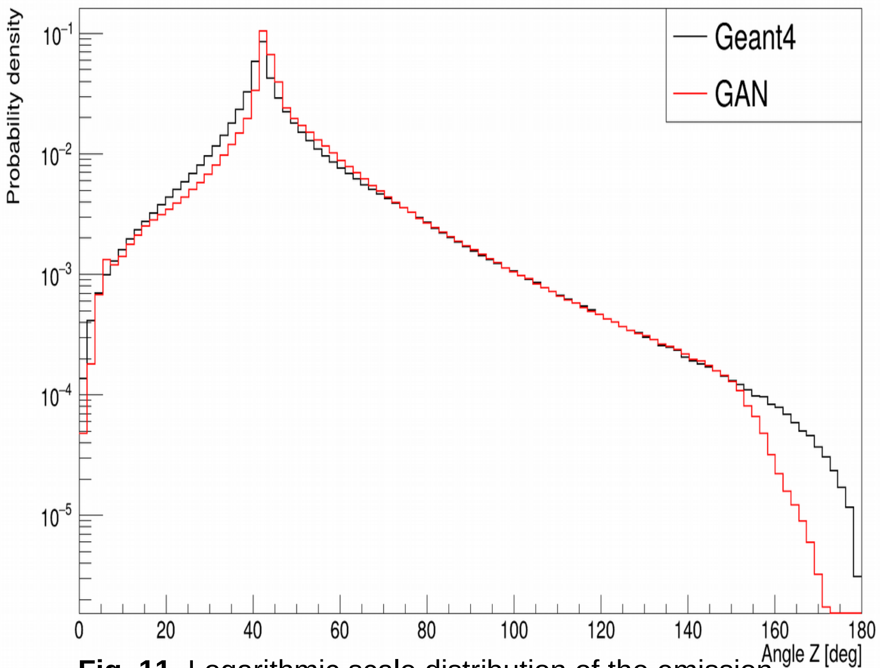

Fig. 11. Logarithmic scale distribution of the emission angle (Angle Z). The GAN (red) accurately reproduces the Cherenkov-like peak at 42°. A characteristic underestimation by the GAN can be observed in the tails of the distribution. Total statistics: 1.2×10^{7} events.

Comparative analysis of wavelength against Geant4 baseline

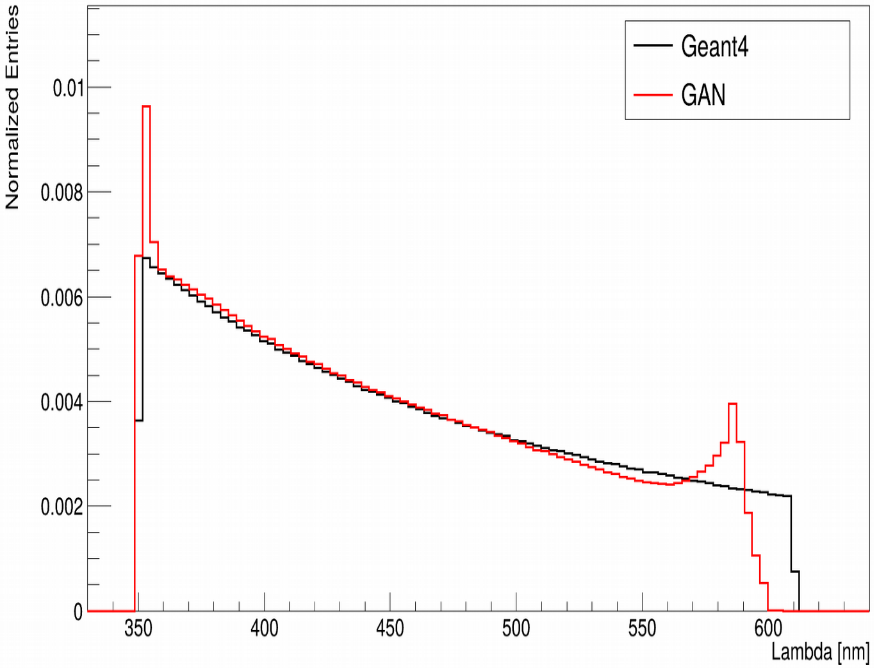

Fig. 12. The generative model successfully reproduces the overall spectral shape of the Geant4 reference (black) between 350 and 600 nm. However, characteristic "spikes" are observed at the spectrum boundaries, and the sharp cut-off at 610 nm is slightly shifted, indicating the generator's difficulty in modeling strict physical thresholds. Total statistics: 1.2×10^{7} events..

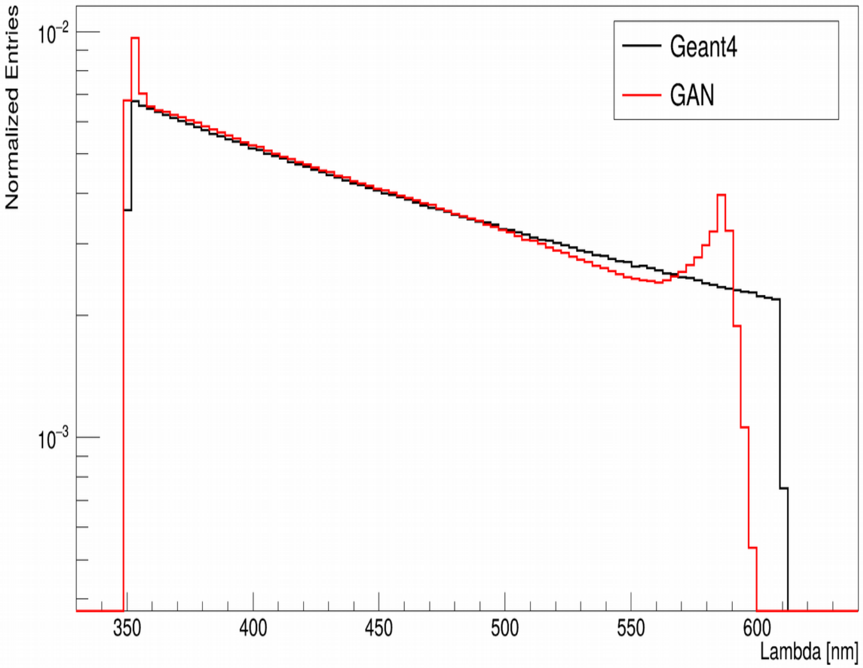

Fig. 13. The model accurately reproduces the central peak and distribution symmetry. The logarithmic scale demonstrates good agreement in the high-statistics region, with noticeable discrepancies emerging in the low-probability tails. Statistics: 1.2×10^{7} events.

Preliminary comparison of total user time between CPU and GPU

Number of photons	User Time (m,s) - GPU (NVIDIA Tesla V100)	User Time (m,s) - CPU (Intel Xeon E5-2683 v4)	**Ratio (CPU User Time / GPU User Time)**
10^7	0m2s	3m10s	**63.4 x**
10^8	0m7s	35m40s	**274.3 x**
10^9	0m56s	363m1s	**386.2 x**

User time in Linux is the CPU time spent executing a program's code in user mode, excluding input/output operations and system calls

Conclusion

- Based on preliminary results, we find that the GPU-based GAN model accelerates the simulation by up to 400 times compared to CPU-based execution
- Based on histogram analysis, it can be concluded that the GAN model faithfully reproduces the distributions in high-intensity regions.
- The GAN outputs are characterized by a clear underestimation of the distribution tails.

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The end

Thank you very much for your attention!