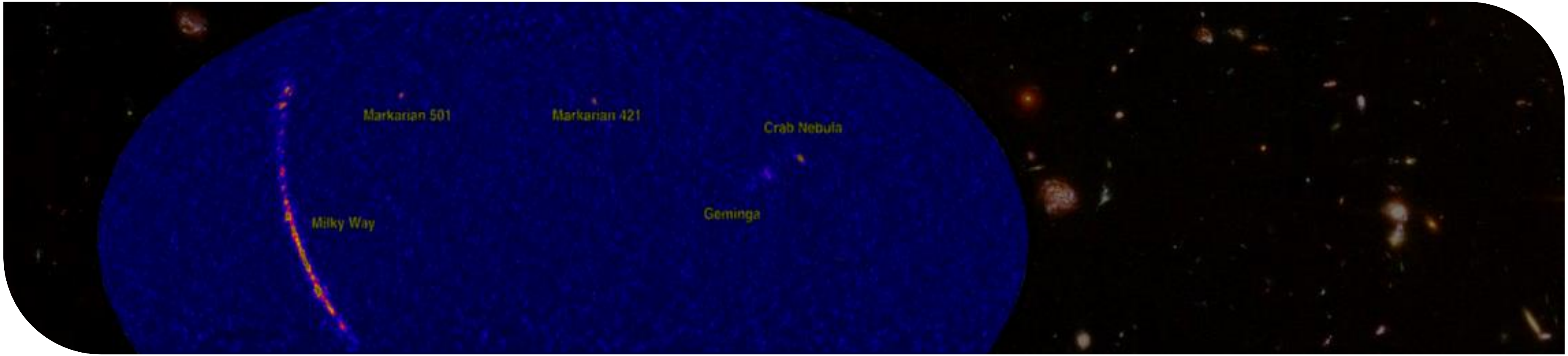
The HAWC-Observatory

High Altitude Water Cherenkov Gamma-Ray Observatory

Talk by Paul Filip (presentee), Markus Roth (supervisor), Maximilian Stadelmaier (supervisor)



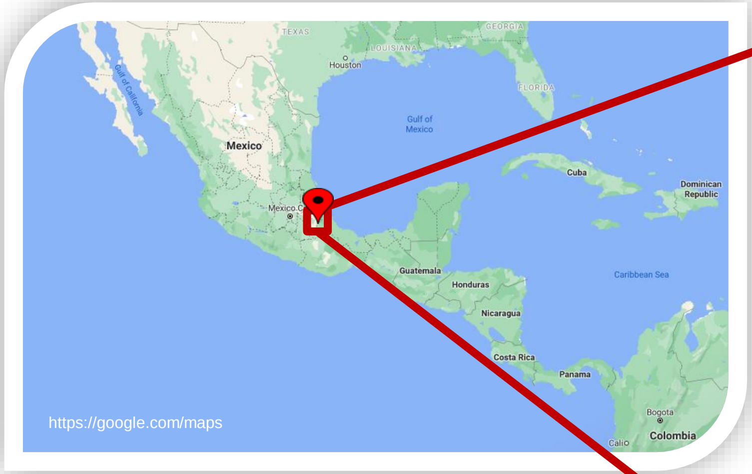
Outline

- **HAWC collaboration, location & goals**
- **The HAWC observatory in detail**
  - Measurement principle
  - Experimental setup
  - Event reconstruction
  - Sensitivity & Uncertainty
  - Data analysis & Hadron rejection
- **Results (so far!)**

A multinational collaboration

- **And many more!**
  - 37 universities and institutes
  - eight different countries, four continents

Location of the experiment



- Puebla, Mexico
- Located in national park
- Next to radio telescope LMT
- 4100 m above sea level **(!)**

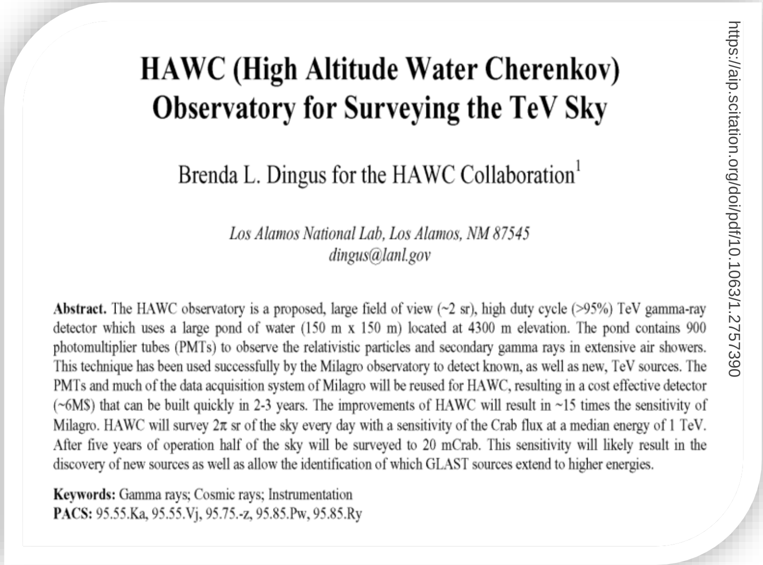
Scientific goals

- Observe TeV gamma-rays
- Sensitivity of 50 mCrab at 5σ over 1 yr.
  - $1\,\mathrm{mCrab} = 10^{-3}\ \times$ 
  - $50\,\mathrm{mCrab} \approx 1.2 \times 10^{-12}\,\frac{\mathrm{J}}{\mathrm{m^2 s}}$
- 2π sr instantaneous field of view
- Angular resolution 0.2° – 2° of events

➡ Observe new astronomical phenomena

➡ Gather information on origin of cosmic rays

➡ Improve understanding of cosmic accelerator mechanisms



HAWC (High Altitude Water Cherenkov) Observatory for Surveying the TeV Sky

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Abstract. The HAWC observatory is a proposed, large field of view (~2 sr), high duty cycle (>95%) TeV gamma-ray detector which uses a large pond of water (150 m x 150 m) located at 4300 m elevation. The pond contains 900 photomultiplier tubes (PMTs) to observe the relativistic particles and secondary gamma rays in extensive air showers. This technique has been used successfully by the Milagro observatory to detect known, as well as new, TeV sources. The PMTs and much of the data acquisition system of Milagro will be reused for HAWC, resulting in a cost effective detector (~6M$) that can be built quickly in 2-3 years. The improvements of HAWC will result in ~15 times the sensitivity of Milagro. HAWC will survey 2π sr of the sky every day with a sensitivity of the Crab flux at a median energy of 1 TeV. After five years of operation half of the sky will be surveyed to 20 mCrab. This sensitivity will likely result in the discovery of new sources as well as allow the identification of which GLAST sources extend to higher energies.

Keywords: Gamma rays; Cosmic rays; Instrumentation
PACS: 95.55.Ka, 95.55.Vj, 95.75.-z, 95.85.Pw, 95.85.Ry

https://aip.scitation.org/doi/pdf/10.1063/1.2757390

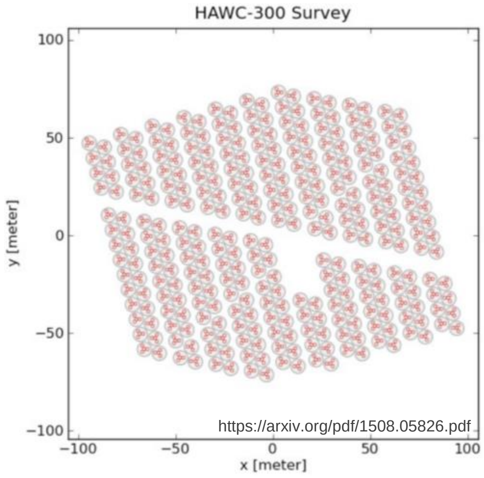
Measurement principle

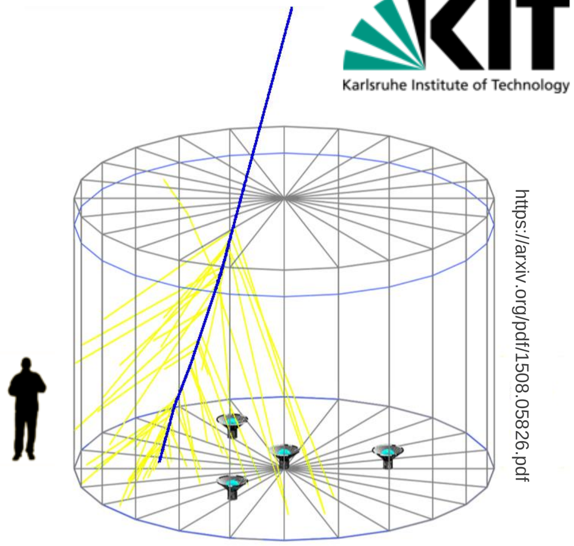
- High energy ($\approx 10^{12}$ eV) γ introduces EM-shower in air
- Electrons produce Cherenkov radiation in water tanks
- Cherenkov light detected by Photomultipliers (PMT)
- Use arrival time to reconstruct incident particle direction

- Signal amplitude holds information about incident particle energy

Experimental setup

- 300 tanks with $200\,000\ \mathrm{l}$ purified water (each)
- Every tank equipped with four PMTs
- Roughly $12\,000\ \mathrm{m}^2$ active detector area
- Outrigger array with 345 small water tanks





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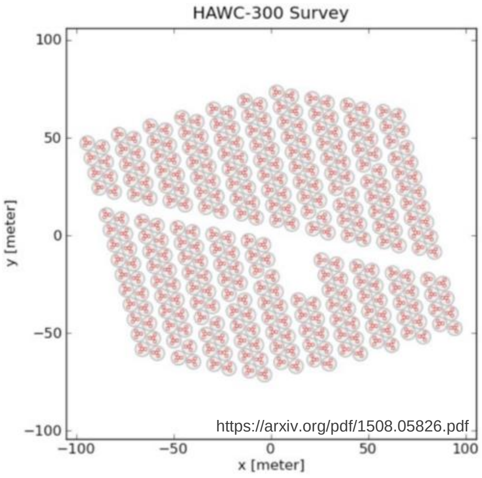
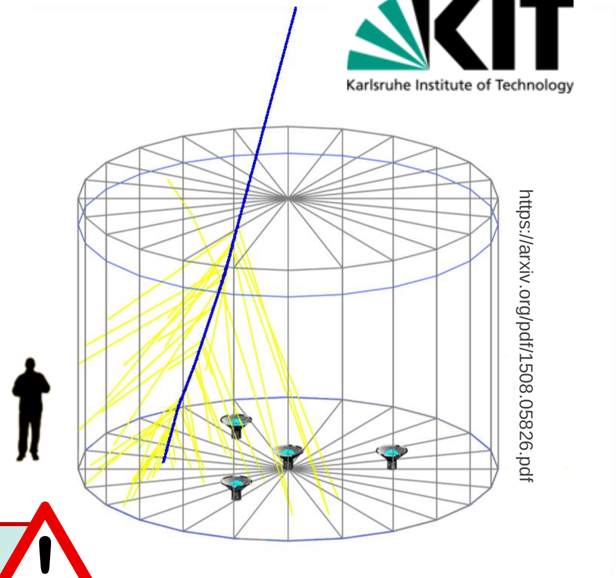




Why only four PMTs ?

$$\theta = \arccos\left(\frac{1}{n_{H_2O}\ \beta}\right) \approx \arccos\left(\frac{1}{1.33}\right) = 43^\circ$$

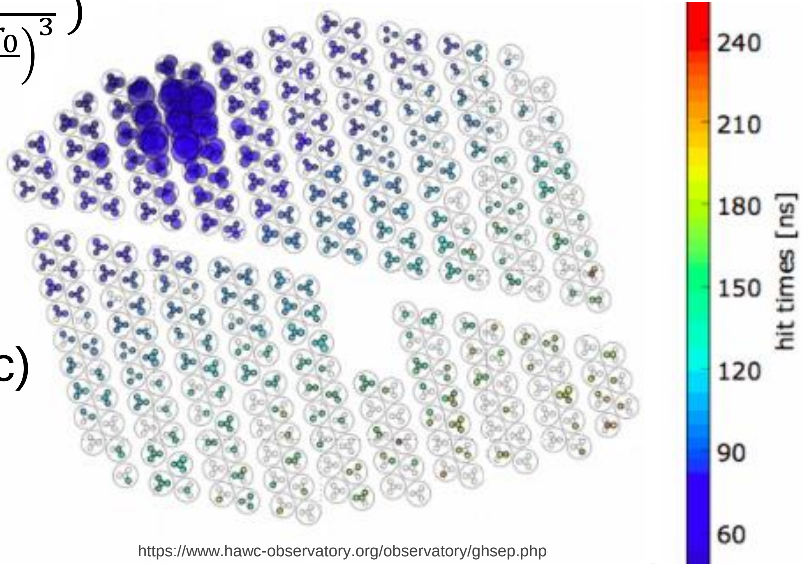
Large Cherenkov cone reaches at least one PMT regardless of incident particle direction

Event Reconstruction

- Consider signals in > 15 PMTs within $150\ \mathrm{ns}$ an „event“
- Fit lateral shower distribution to signal shape to find „shower core“

$$S_i(A, r_0, r_i) = A \cdot \left(\frac{1}{2\pi\sigma^2}\, e^{-\left(\frac{r_i - r_0}{2\sigma^2}\right)^2} + \frac{N}{\left(0.5 + \frac{r_i - r_0}{r_\mathrm{M}}\right)^3} \right)$$

  - Signal amplitude A (correlates with E_0)
  - Shower core location r_0
  - Photomultiplier location r_i
  - Molière radius $r_\mathrm{M} \approx 120\ \mathrm{m}$ (material specific)
  - Gaussian shower width $\sigma \approx 10\ \mathrm{m}$
  - Tail normalisation $N \approx 5 \times 10^{-5}$

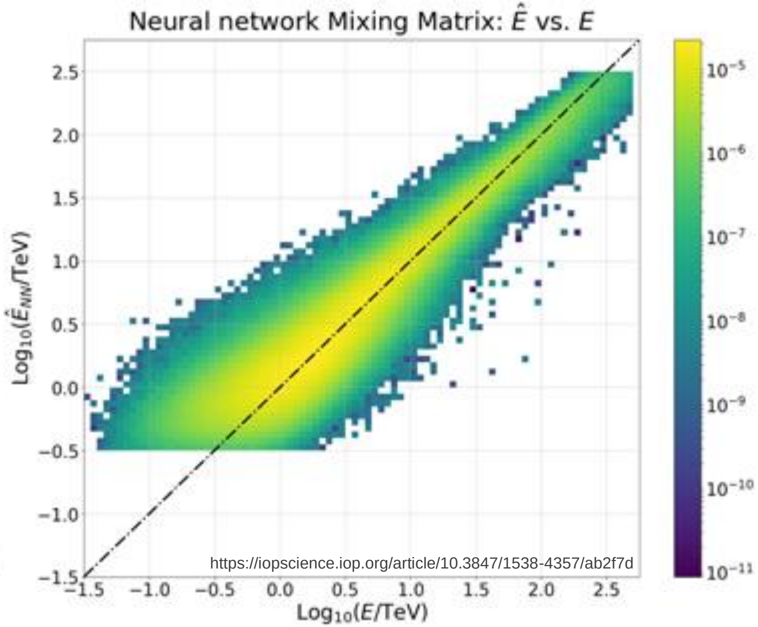


https://www.hawc-observatory.org/observatory/ghsep.php

Event Reconstruction

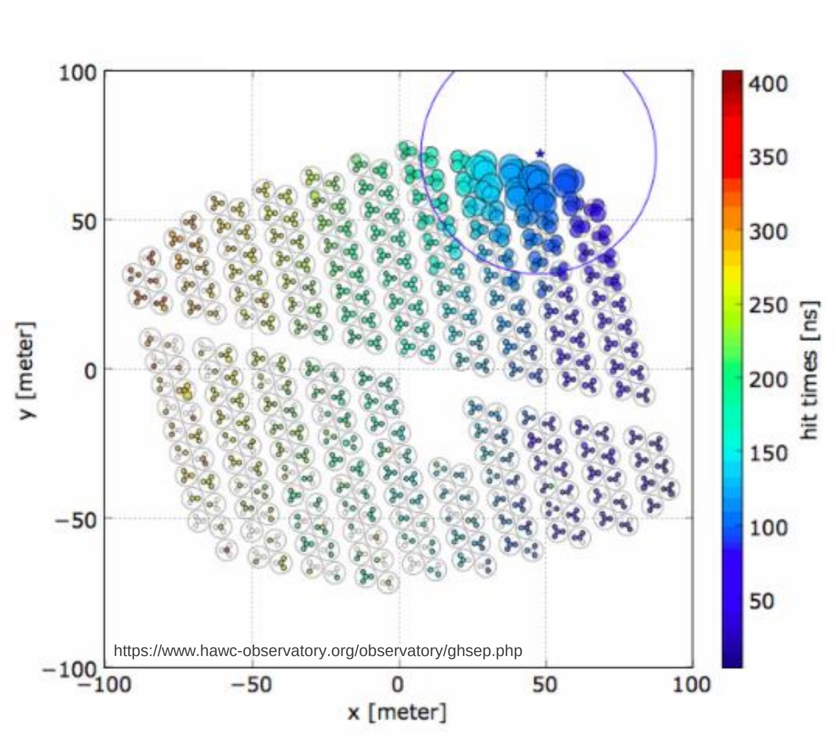
- Fit signal arrival times to shower plane hypothesis* to collect information about origin and direction of the incident particle

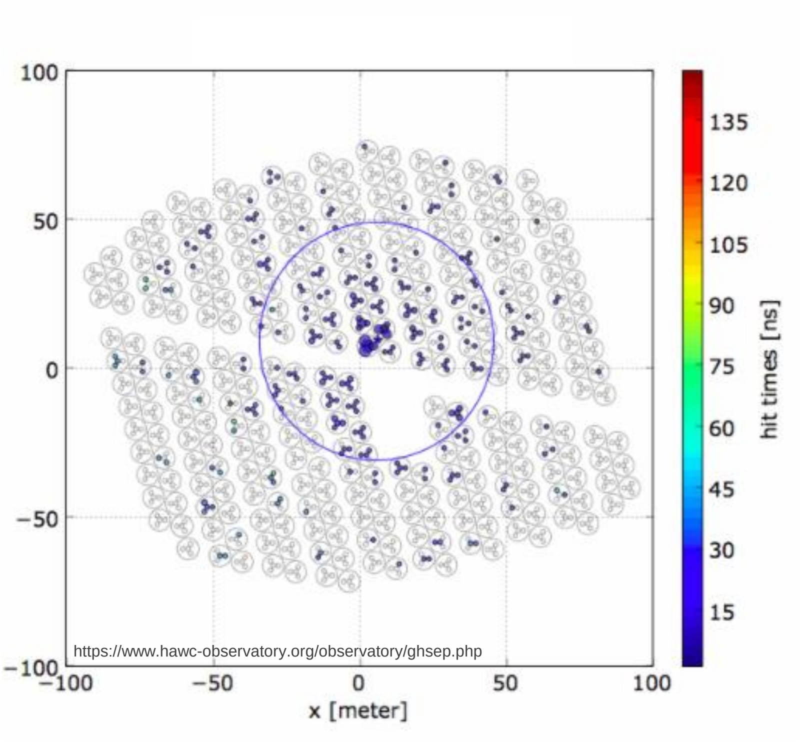
- Use artificial neural network to estimate E_0
  - Two hidden layers, 14 and 15 nodes
  - Train neural network with MC simulations
  - Rely on three input parameters:
    - Energy deposited in detectors E_{dep}
    - Ratio of shower footprint contained in HAWC
    - Attenuation of shower by atmosphere



* After correcting for shower curvature + sampling

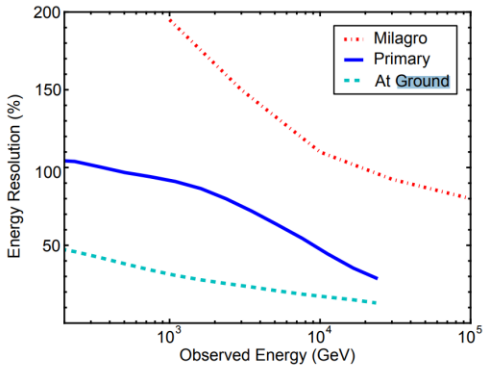
Event Reconstruction

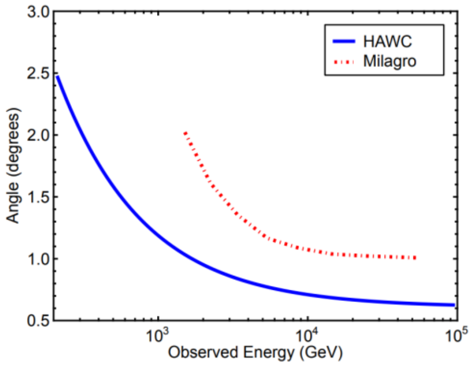




Sensitivity & Uncertainty

https://iopscience.iop.org/article/10.1088/1742-6596/375/1/052026





Energy resolution

- Primary energy is reconstructed to $\pm$X % of true E_0
- Energy resolution shrinks with higher energy
- Major improvement to previous experiments

Angular resolution

- Standard deviation on plane wave fit
- Decreases with energy as well ➡ **Why**
- Sensitivity on γ-ray point sources
- Comparable to IACTs like H.E.S.S. or VERITAS

Data Analysis & Hadron rejection

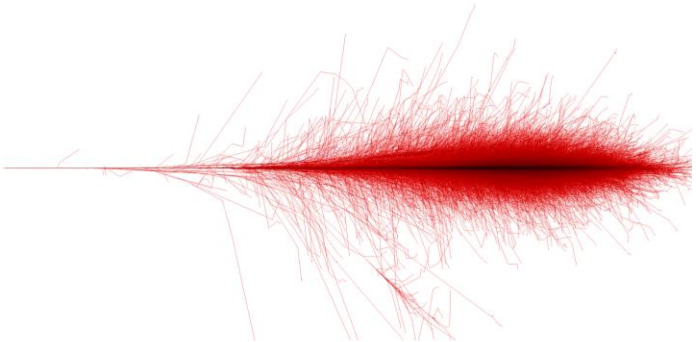
- Expected trigger rate from **Cosmic rays**

$$R(1\ \mathrm{TeV}) = \int \frac{\mathrm{d}\Phi_{\mathrm{CR}}}{\mathrm{d}\Omega}\bigg|_{1\ \mathrm{TeV}} \mathrm{d}\Omega \times A_{\mathrm{D}} \approx 1\ \mathrm{m}^{-2}\mathrm{s}^{-1} \times 12\,000\ \mathrm{m}^2 \geq \mathbf{10\ kHz}$$

- Events introduced by all sorts of incident particles
- Desire to distinguish between γ- and hadron showers
- Need to filter hadronically induced showers

Hadron Rejection

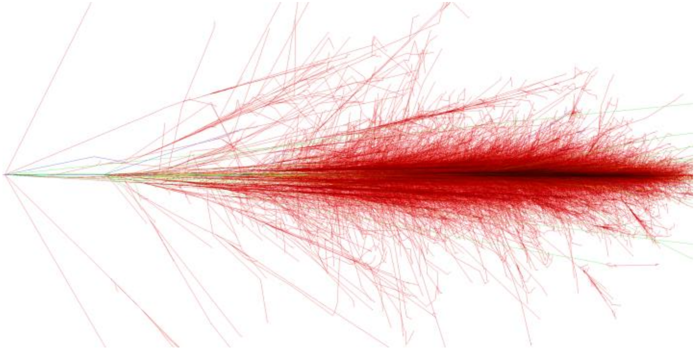
https://www.iap.kit.edu/corsika/



Photon induced air-shower

- no muons, hadrons, mesons
- Smooth(er) transversal shape
- Expect smooth signal shape

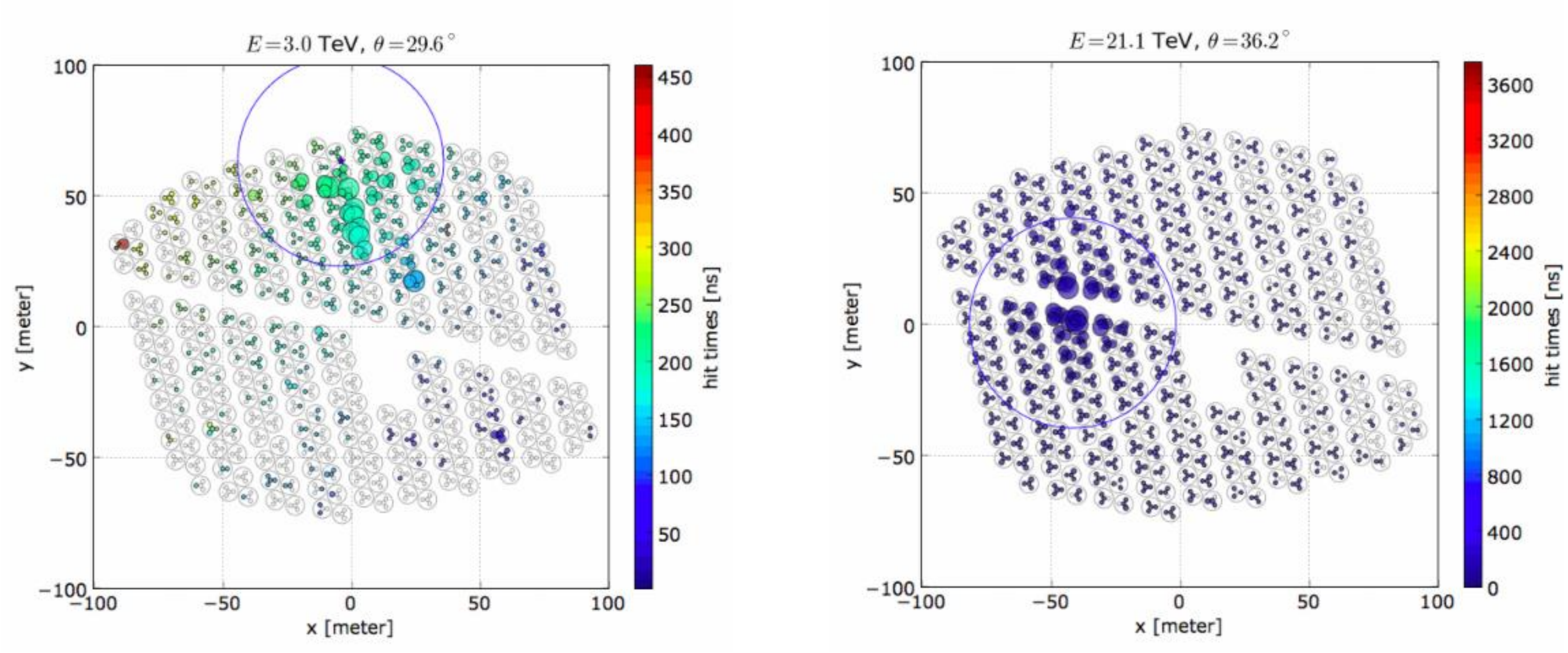
https://www.iap.kit.edu/corsika/



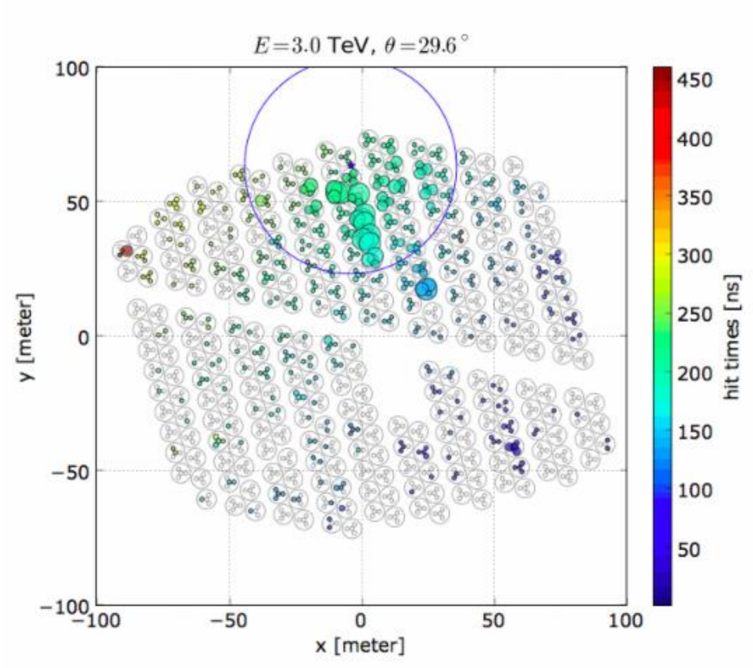
Proton induced air-shower

- Many muons, hadrons, mesons
- „patchy“ shower footprint
- Expect far away muon signals

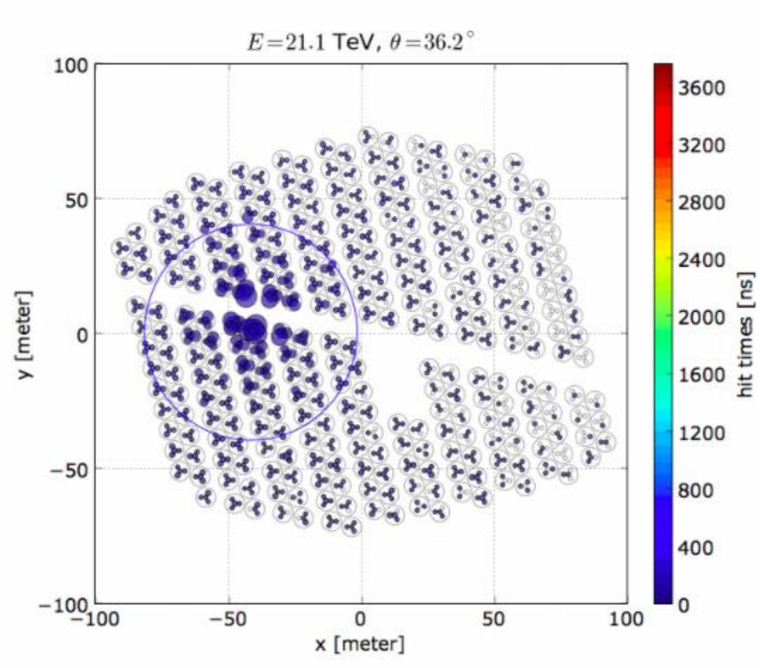
Hadron Rejection



Hadron Rejection

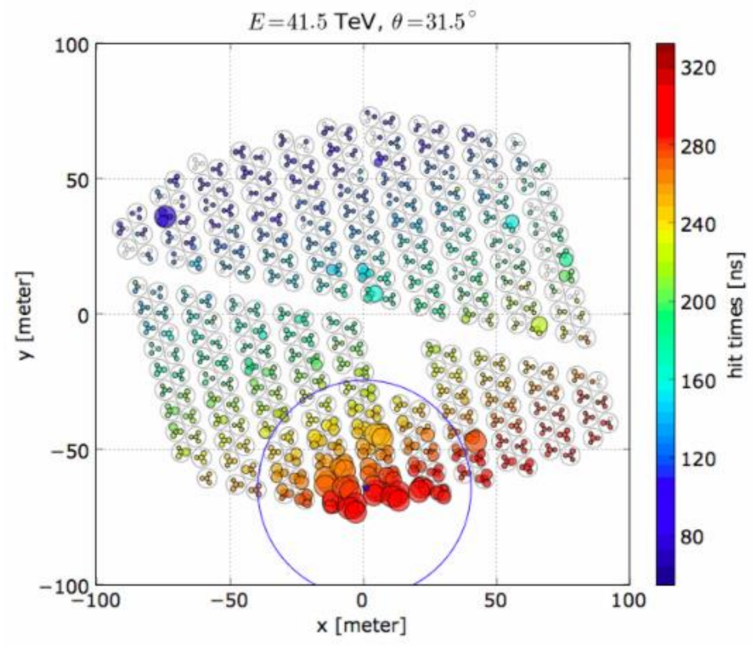


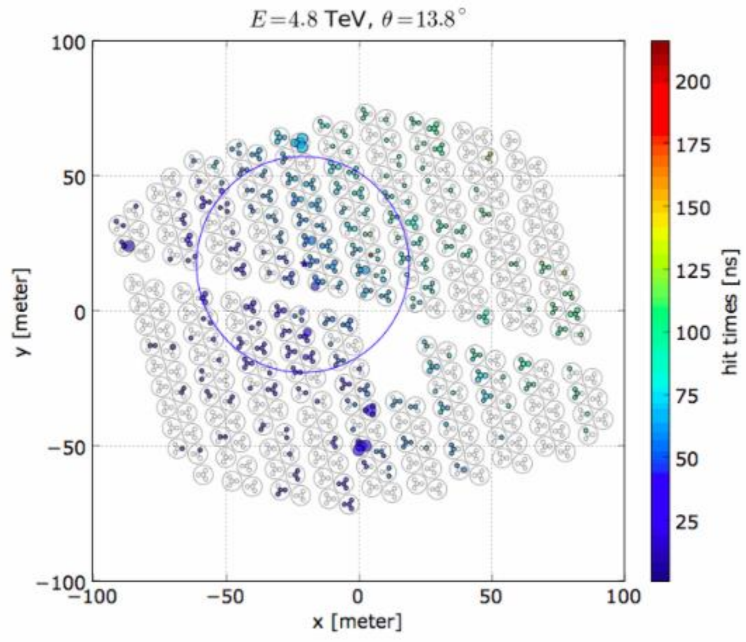
➡ Hadron shower



➡ Gamma shower

Hadron Rejection





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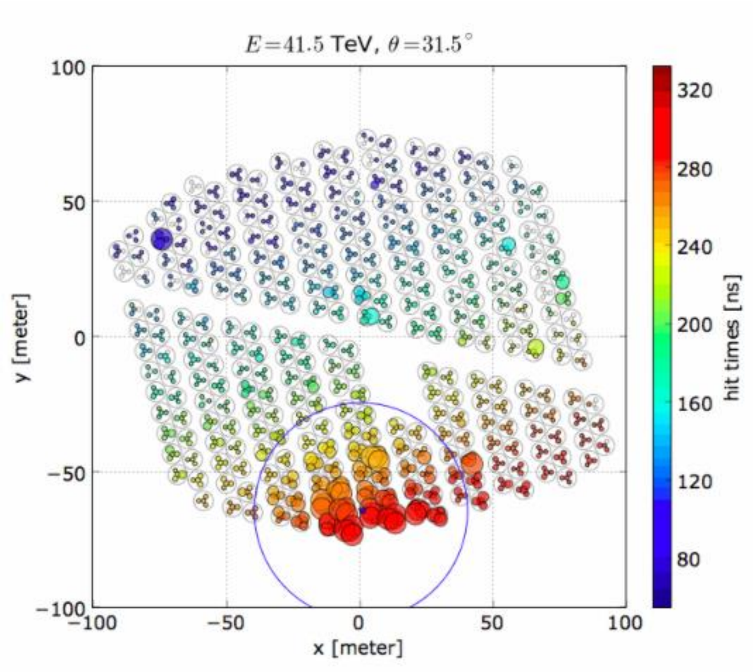

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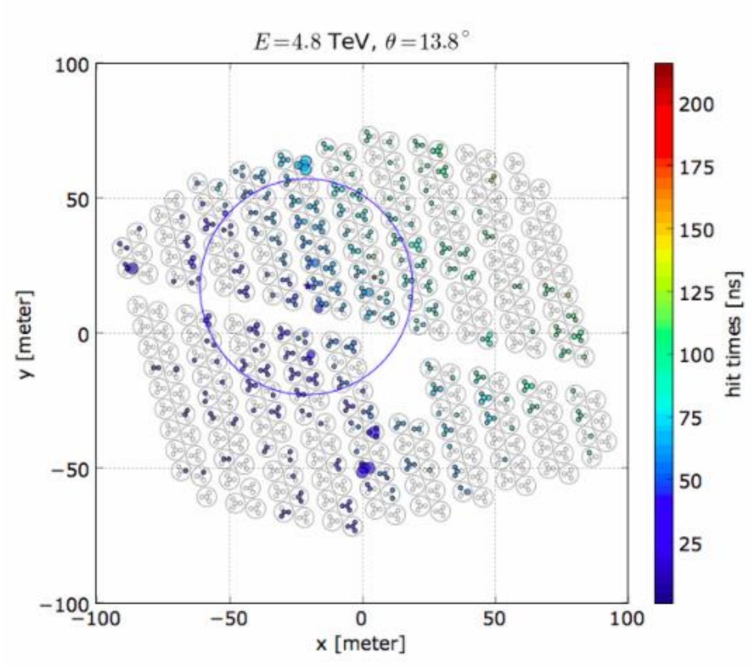


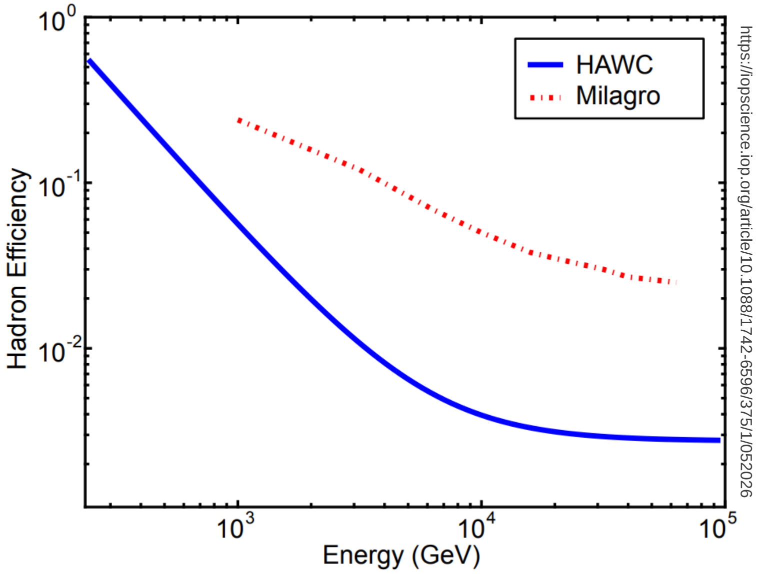
➡ Hadron shower

Hadron Rejection

- Try it out yourself on the HAWC **website** [1]
- Identify „uncompact“ and „clumpy“ events

$$\mathcal{C} = \frac{N_{\text{hit}}}{\text{CxPE}_{40}} \qquad \mathcal{P} = \frac{1}{N}\sum_{i=0}^{N} \frac{(\xi_i - \langle \xi_i \rangle)^2}{{\sigma_{\xi_i}}^2}$$

- Cuts reliably identify hadron events with $> 99\%$ efficiency above ~ 3 TeV
- Major improvement from predecessors



[1] - https://www.hawc-observatory.org/observatory/ghsep.php

Results (so far)

Karlsruhe Institute of Technology

Link	Paper	Comment
Science	"Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth"	Rule out pulsars Geminga, PSR B0656+14 as possible sources for CR positron excess
Arxiv	"All-particle cosmic ray energy spectrum measured by the HAWC experiment from 10 to 500 TeV"	Measure CR flux and confirm power law dependancy as well as existence of „knee"
ArXiv	"Constraints on Lorentz invariance violation from HAWC observations of gamma rays above 100 TeV"	Improve energy below which Lorentz invariance holds up to 2.2×10^{31} electronvolts
ApJ	"Observation of the Crab Nebula with the HAWC Gamma-Ray Observatory"	Observe Crab nebula and confirm analysis methods employed by HAWC are up to par
ArXiv	"Multi-messenger observations of a flaring blazar coincident with neutrino IceCube-170922A"	First multi-messenger detection of extrasolar neutrinos (ignoring SN1987A) with IceCube

- See full list of HAWC results (Articles, papers, theses) on their **website** [1]

[1] - https://www.hawc-observatory.org/publications/