Improving Air Shower Reconstruction in HAWC Using the Outrigger Array

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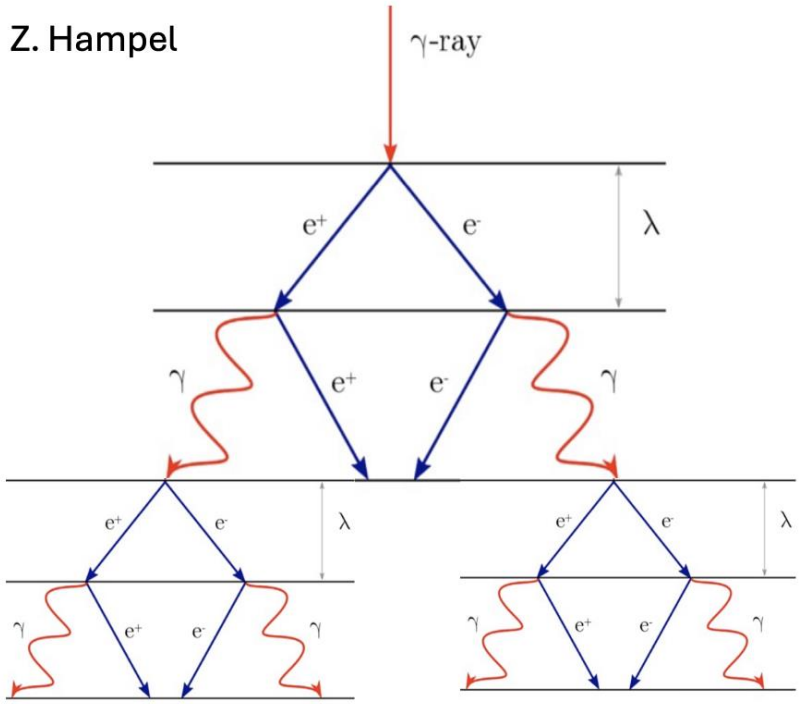
Extensive Air Shower



Schematic of an air shower

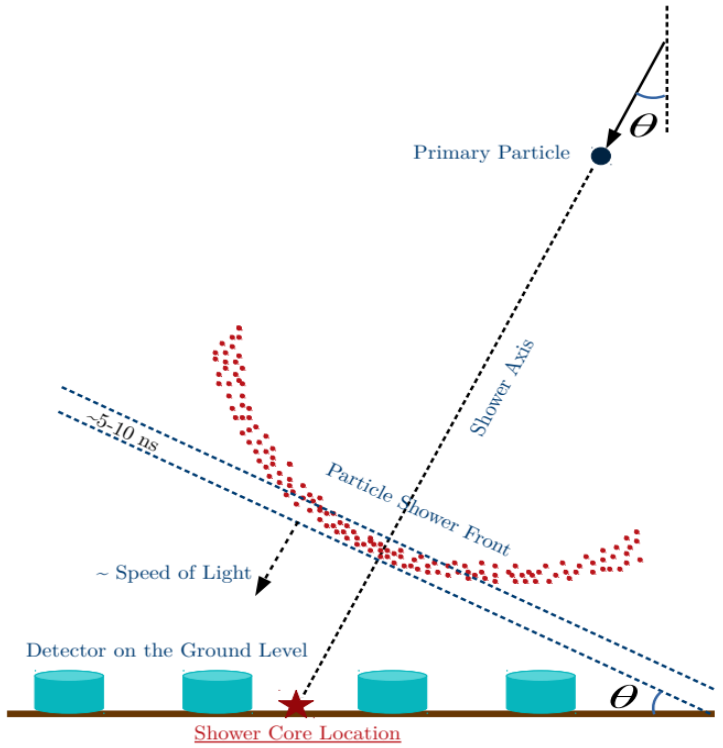
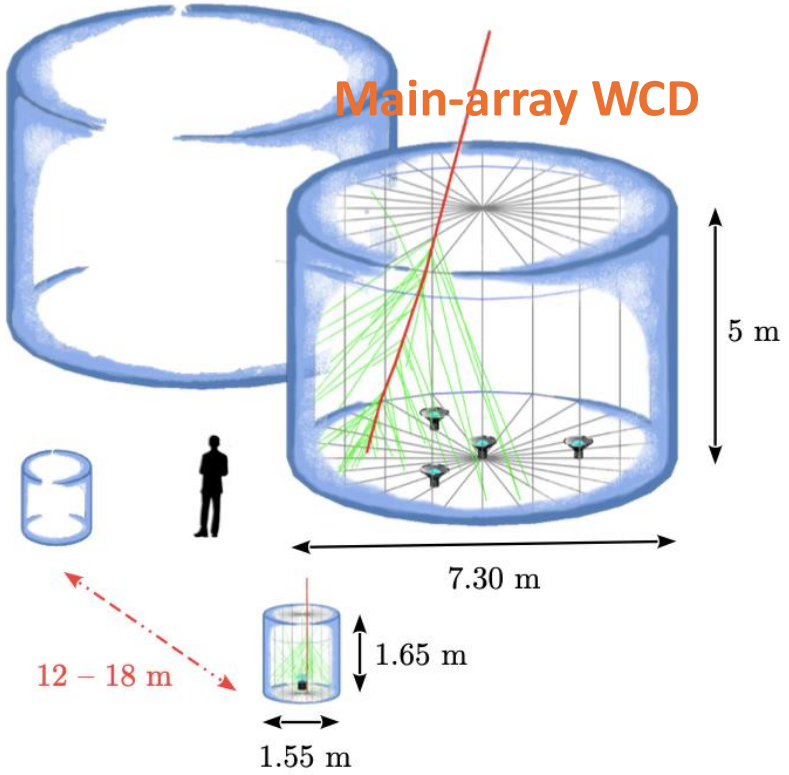


Illustration of a particle sampling array

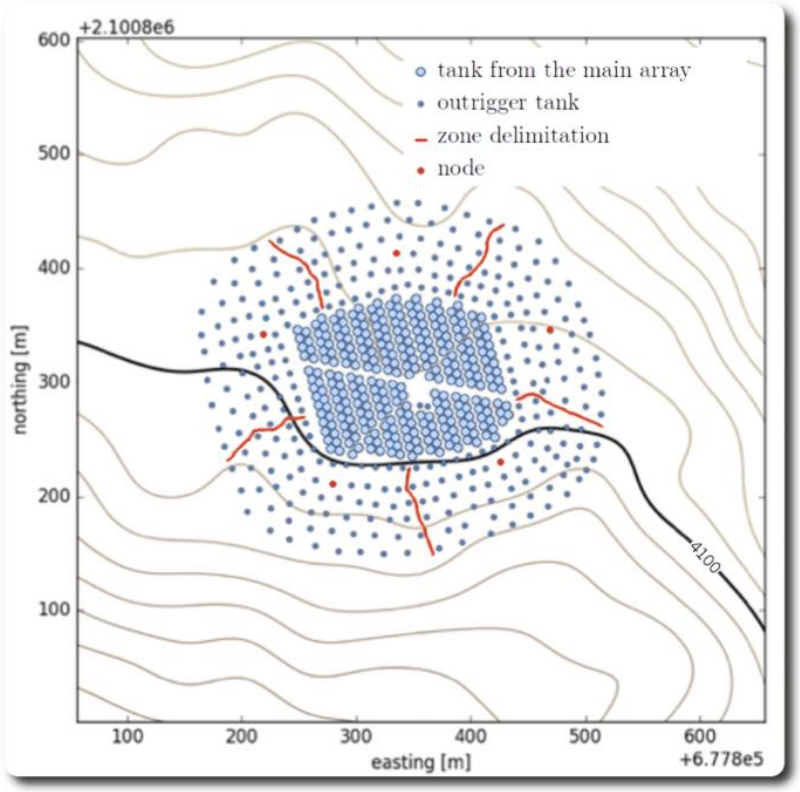
HAWC

- High-Altitude Water Cherenkov gamma-ray observatory (HAWC)
- Located in Mexico at an altitude of 4,100 m
- Particle sampling array
- Water Cherenkov detectors (WCDs)
- Wide field of view (~ 2 sr)
- High duty cycle (~ 92%)

HAWC Array

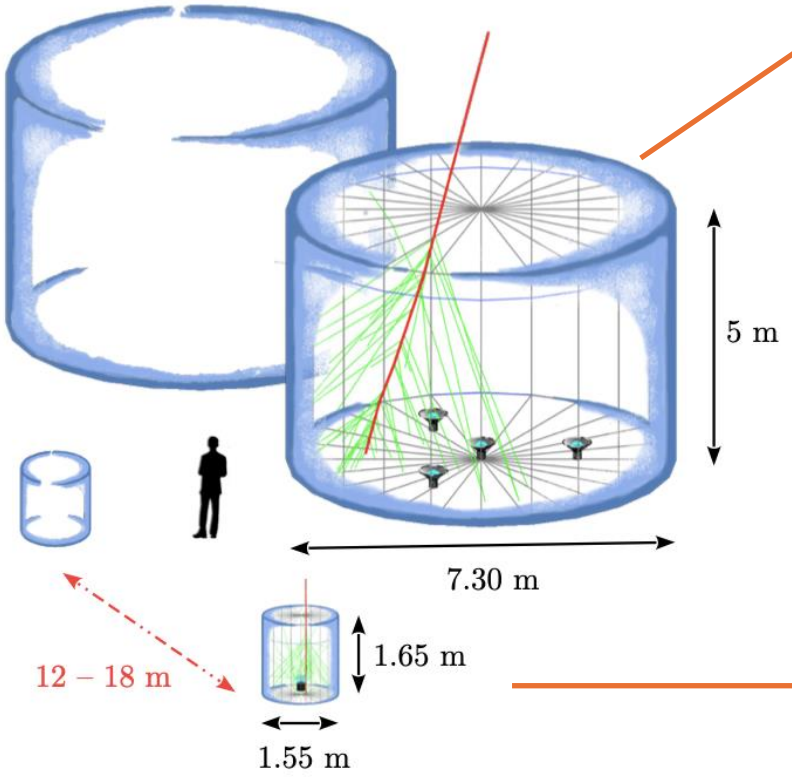


Outrigger tank (small WCD)



300 WCDs for the main array and 345 small WCDs for the outrigger array

Outrigger Tank



Main-array WCD

R5912 8” PMT

 × 3

R7081 10” PMT

 × 1

- 7.3 m diameter and 5 m height
- Three 8” PMTs and one 10” PMT
- 300 tanks in the dense central array

Outrigger WCD

R5912 8” PMT

 × 1

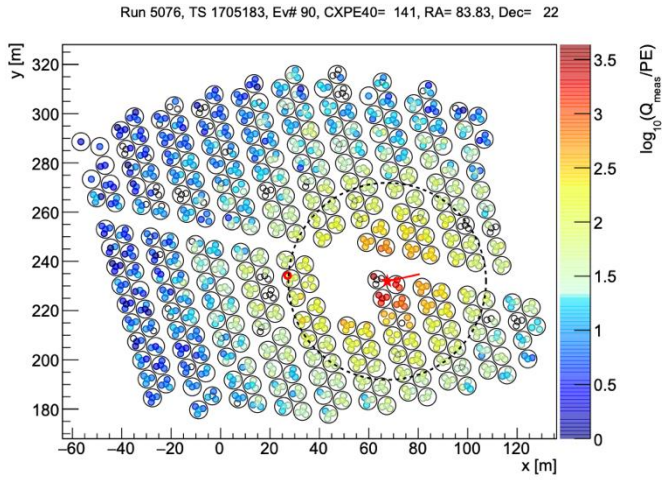
- 1.55 m diameter and 1.65 m height
- One 8” PMT
- 345 tanks in a sparse array surrounding the main array

Pass 6 Project

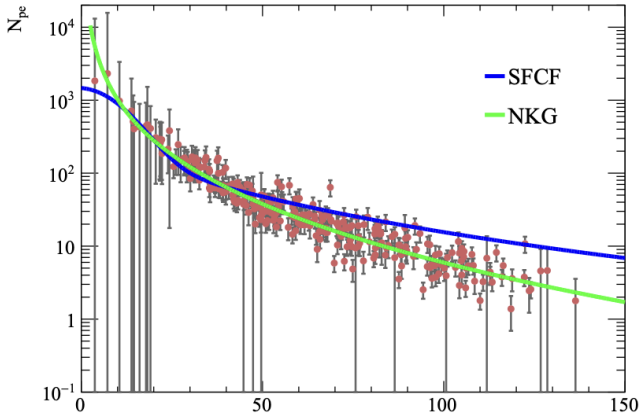
- Pass 5
  - Current standard HAWC reconstruction
  - Optimized for the main array only
  - Does not use outrigger information in the reconstruction
- Pass 6
  - New reconstruction framework for HAWC
  - Currently under development
  - Designed to incorporate outrigger information
  - Goal: Improve the reconstruction of high-energy and off-array events using outrigger information.

Air Shower Reconstruction in HAWC

COM core fit

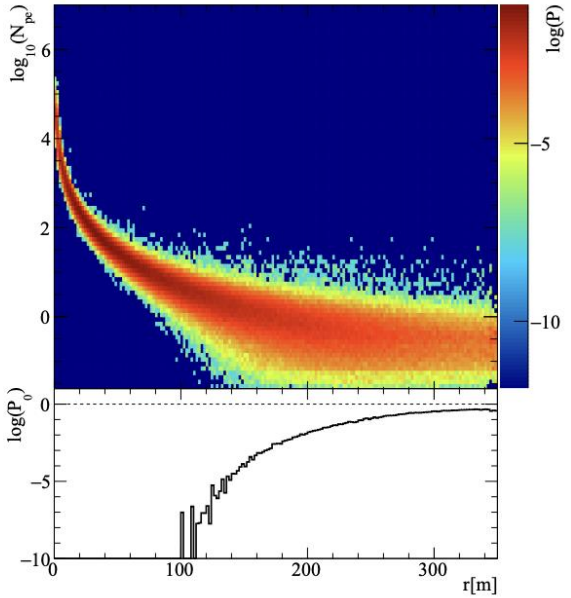


SFCF core fit

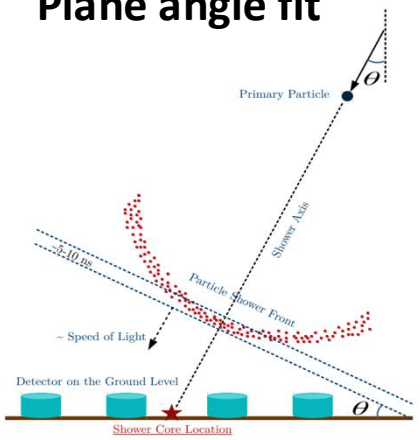


$$Q_i = A\left(\frac{1}{2\pi\sigma^2}\exp\left(\frac{-|\mathbf{x}-\mathbf{x_i}|^2}{2\sigma^2}\right)+\frac{N}{\left(0.5+\frac{|\mathbf{x}-\mathbf{x_i}|}{R_{\mathrm{Mol}}}\right)^3}\right)$$

Likelihood core fit



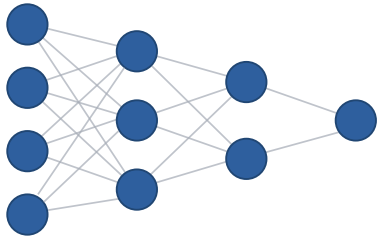
Plane angle fit



Neural network energy estimator

Reconstructed shower parameters

shower observables



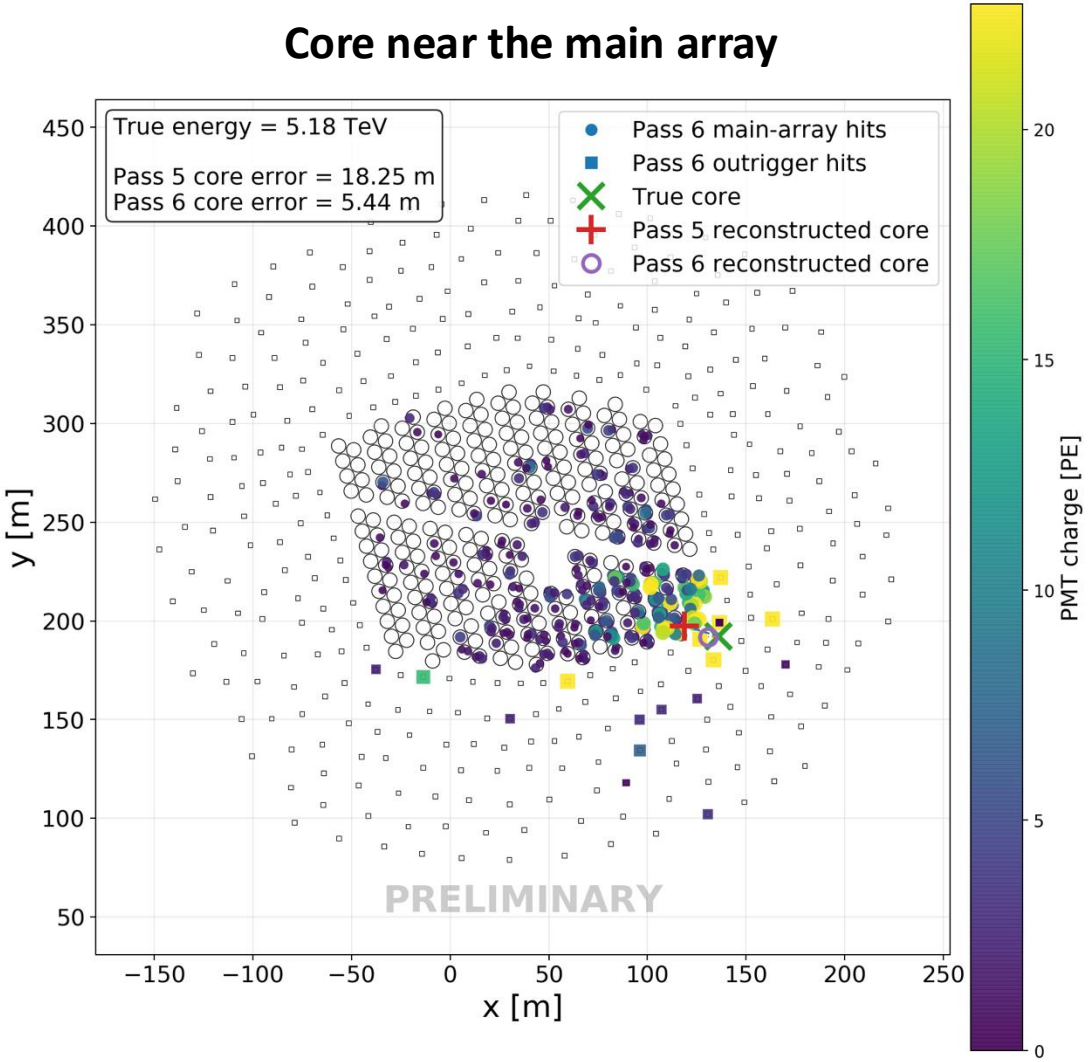
MLP

Estimated primary energy

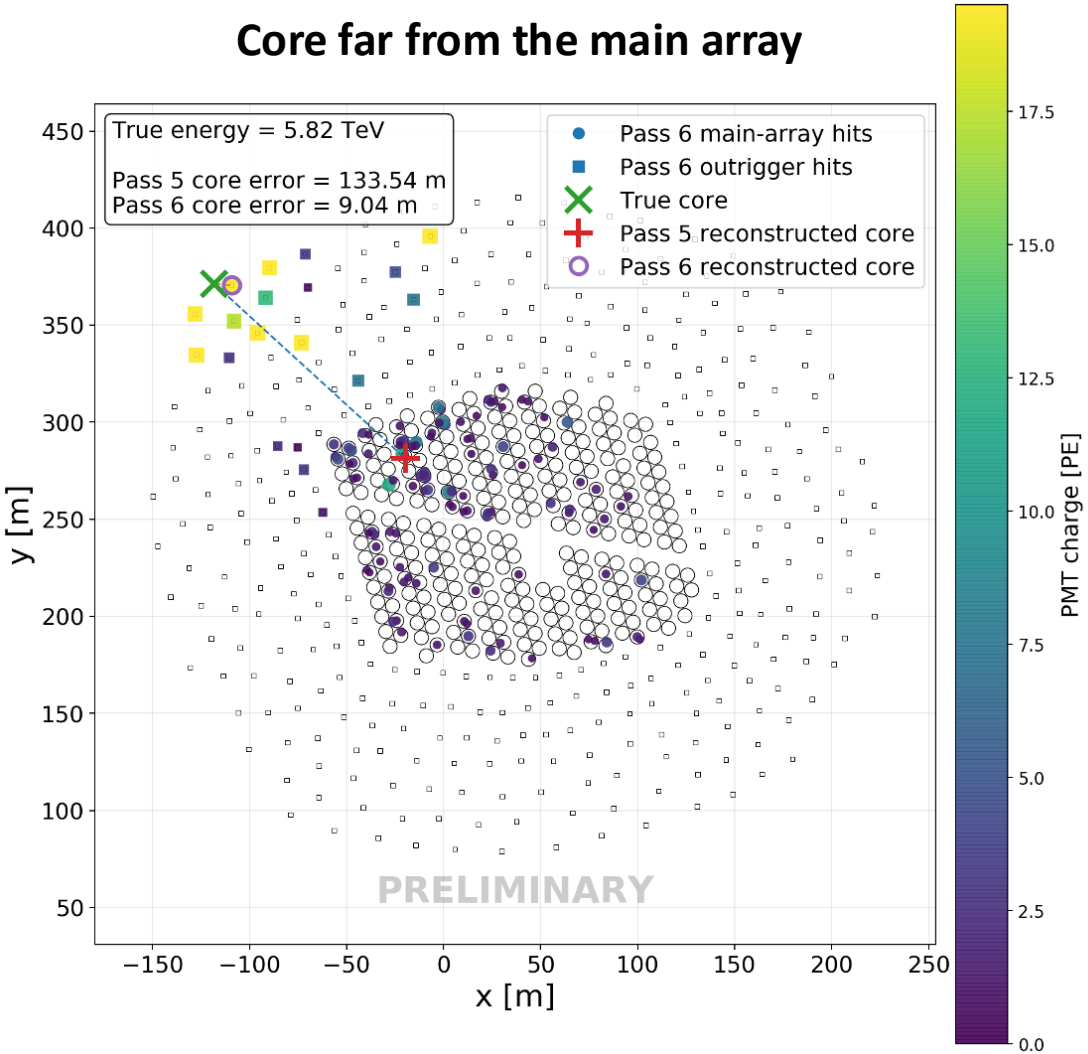
Shower observables → neural network → reconstructed energy

Examples of improved core reconstruction using outriggers

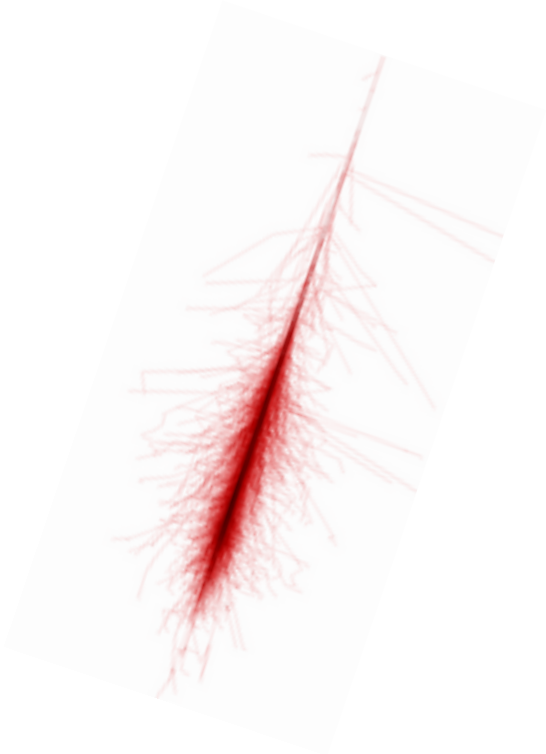
Core near the main array



Core far from the main array

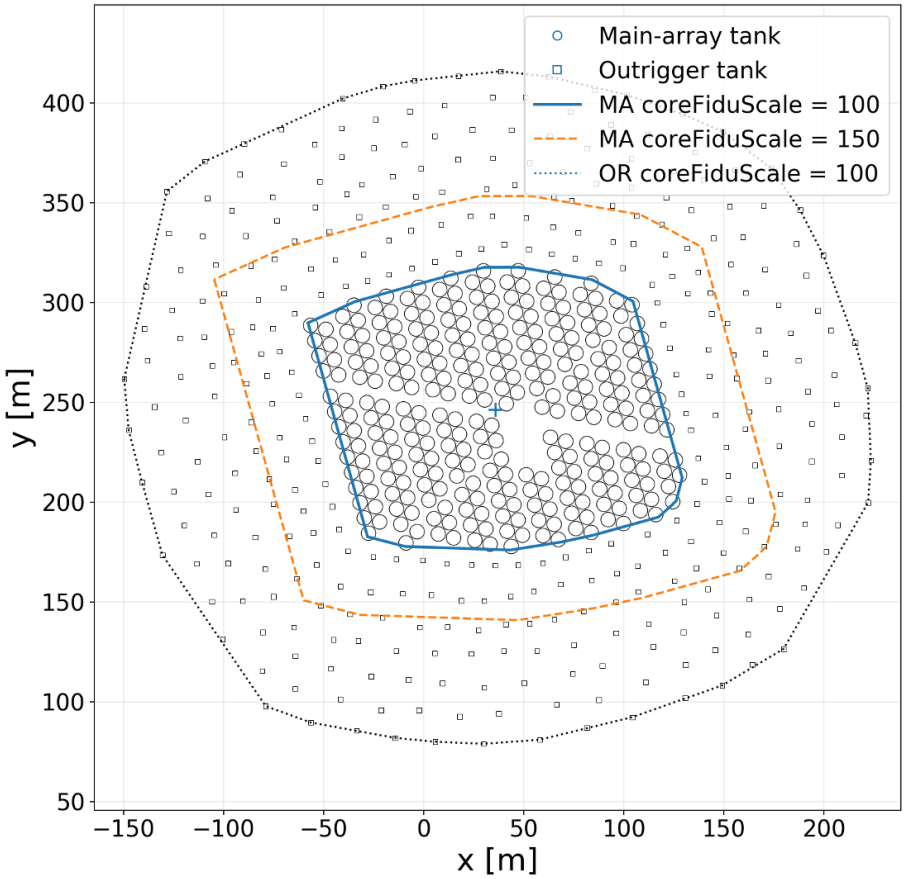


Simulations



- Air shower simulation
  - CORSIKA v7.7410
  - Zenith 0° – 65°
  - Low-energy gamma-ray simulations
    - Energy 5 GeV – 500 TeV
    - Spectral index: -2
    - Number of events: 10 million
  - High-energy gamma-ray simulations
    - Energy 500 TeV – 3 PeV
    - Spectral index: -2
    - Number of events: 200,000
- Detector simulation
  - Geant4-based simulations of the detector response at ground level
- Reconstruction
  - Custom HAWC software framework (AERIE)

Event Binning



HAWC detector positions and contours corresponding to different values of the core fiducial scale.

- Pass 6 event binning has not been optimized yet.
- For this analysis, we apply the Pass 5 binning scheme used in the HAWC Pass 5 performance study.

  (A. Albert et al 2024 ApJ 972 144)

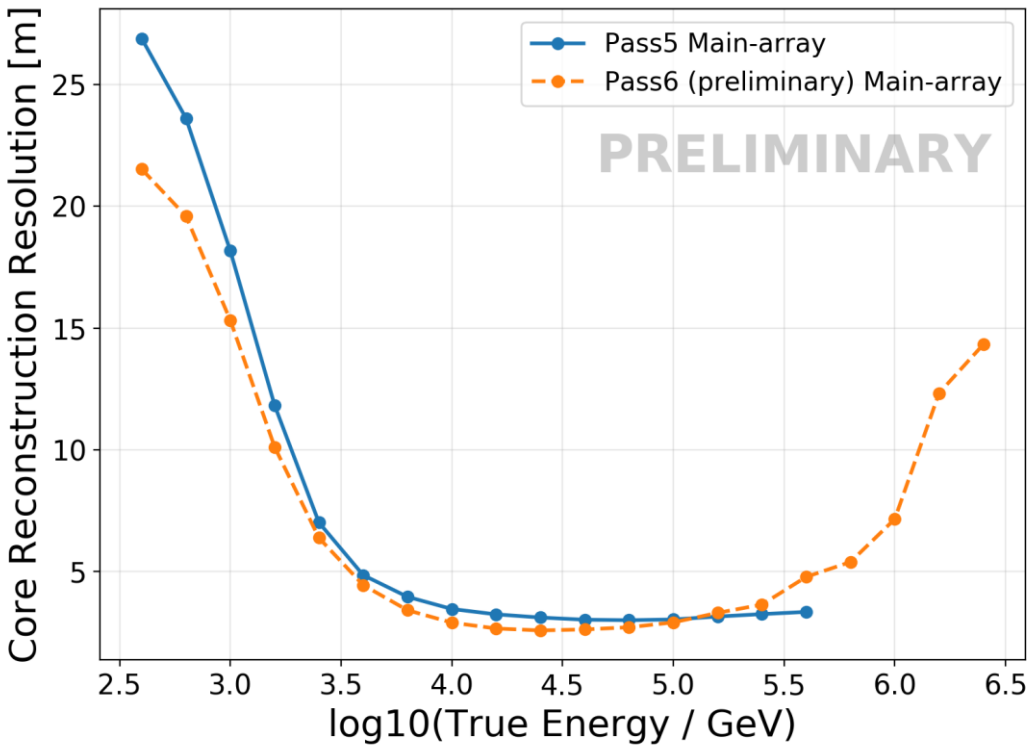
- The core fiducial scale characterizes the shower core location relative to the main array.
  - **Main-array events**: core fiducial scale < 100
  - **Off-array events**: $100 \leq$ core fiducial scale < 150

Performance Metrics

- Core resolution: The 68% containment of the distance between the reconstructed and true core positions.
- Angular resolution: The 68% containment of the angular separation between the reconstructed and true shower directions.
- Energy bias: The mean of the difference between the reconstructed and true log energies.
- Energy resolution: The RMS of the difference between the reconstructed and true log energies.

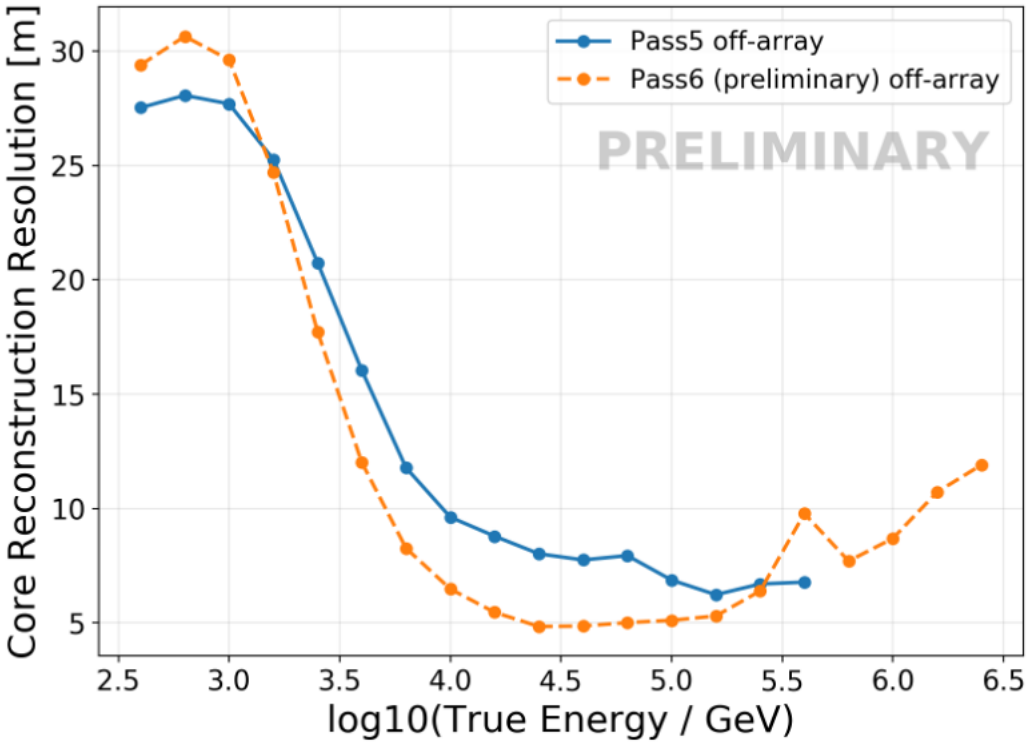
Core Reconstruction Performance

Core resolution (main array)



- Pass 6 shows slightly improved core resolution for main-array events. This is reasonable since these events already have the cores inside the central region.
- At the highest energies, saturated PMTs are excluded from the fit, leading to degraded core resolution. Nevertheless, Pass 6 can reconstruct events above 500 TeV, where Pass 5 cannot.

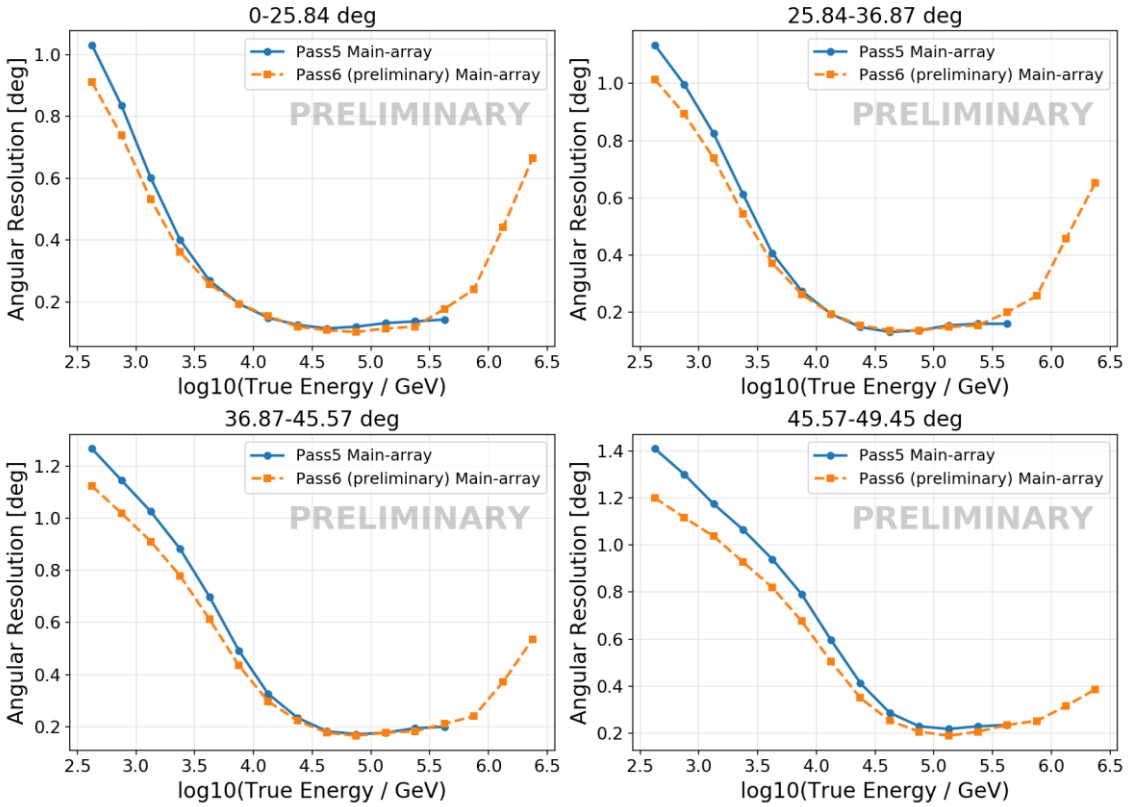
Core resolution (off array)



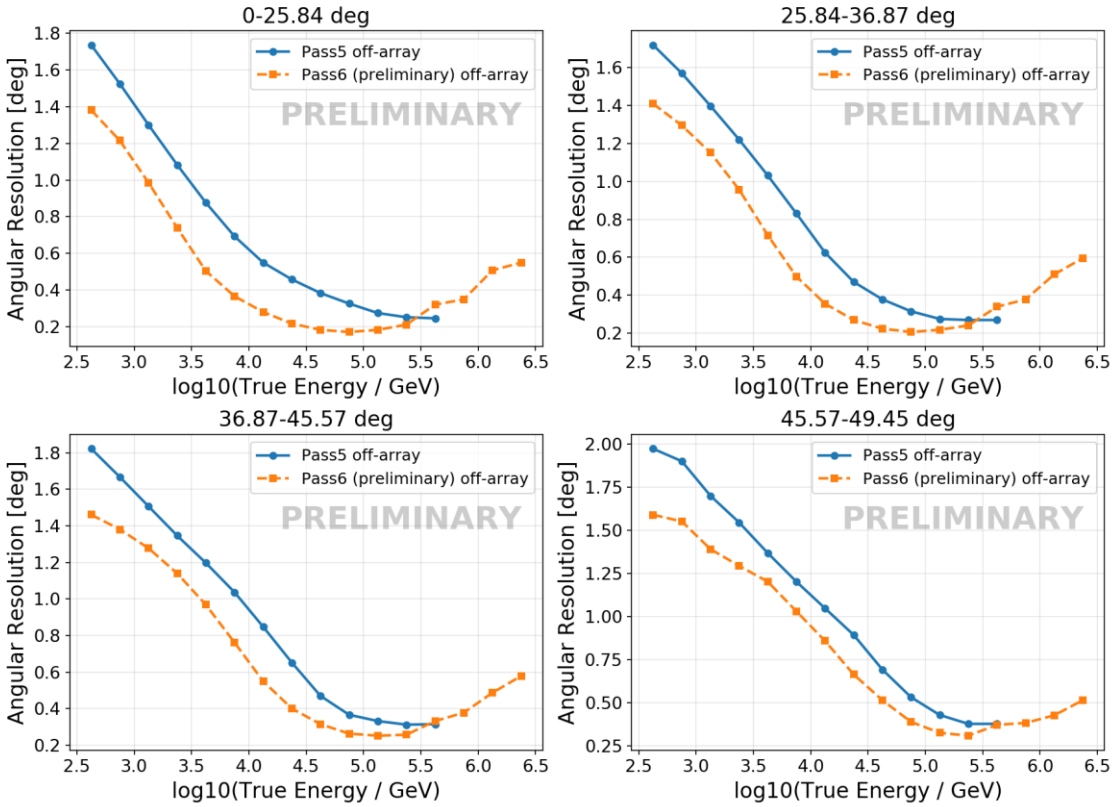
- Outrigger information significantly improves core reconstruction for off-array events.
- At low energies, Pass 5 appears to perform slightly better, mainly due to a selection effect. Pass 5 reconstructs only a small subset of off-array events, typically those closer to the main array and easier to reconstruct.

Direction Reconstruction Performance

Angular resolution (main array)



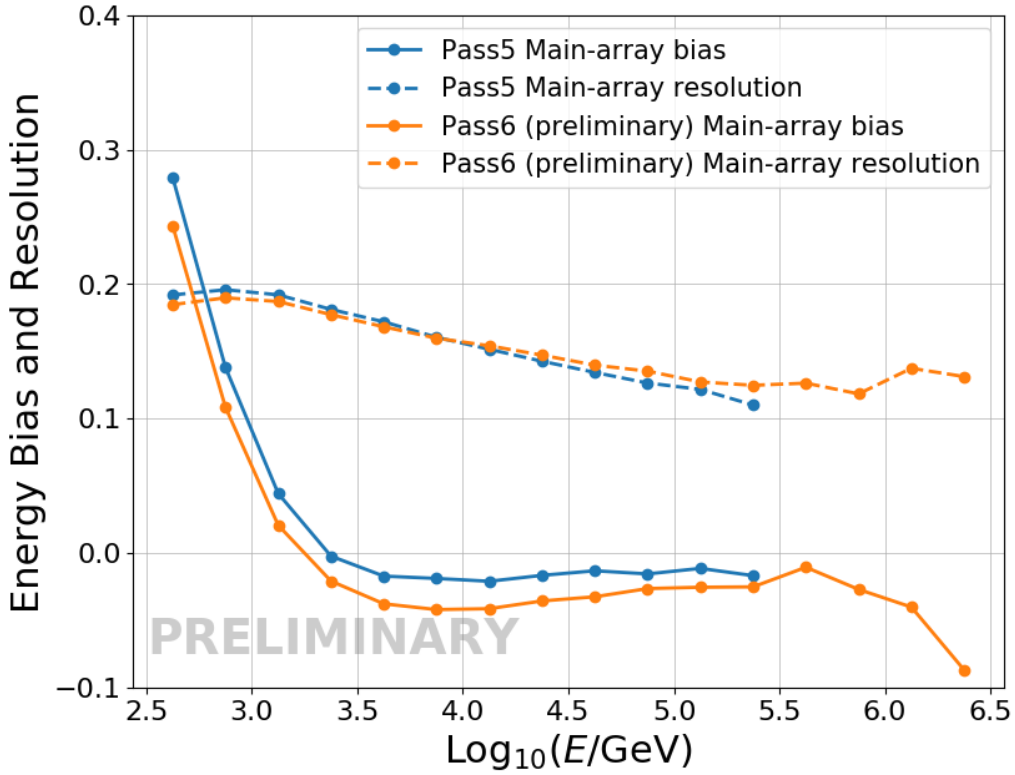
Angular resolution (off array)



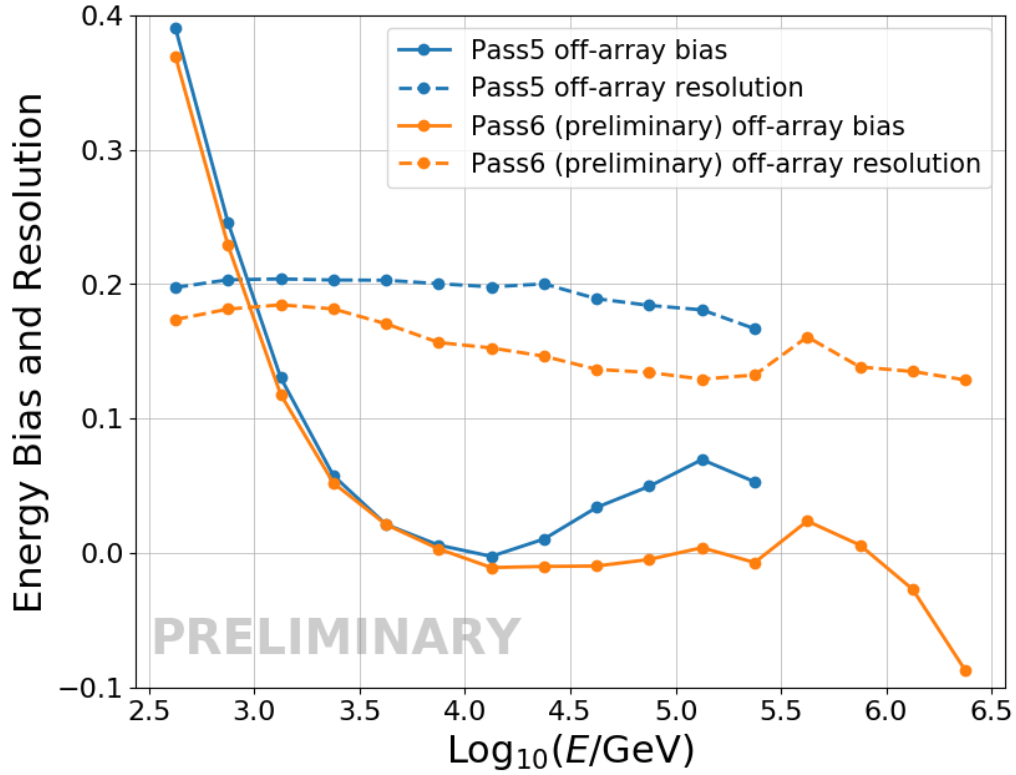
- Again, PMT saturation degrades the angular resolution at high energies.
- The impact of outrigger information becomes more pronounced at larger zenith angles.
- Pass 6 shows significantly better angular resolution for off-array events.

Energy Reconstruction Performance

Energy bias and resolution (main array)



Energy bias and resolution (off array)



- For main-array events, Pass 6 shows comparable energy reconstruction performance to Pass 5.
- For off-array events, Pass 6 shows substantially improved energy reconstruction performance.

Summary and Future Work

- **Summary**
  - Preliminary Pass 6 can successfully reconstruct events above 500 TeV.
  - Overall performance is improved, particularly for off-array events.

- **Future work**
  - Optimize the Pass 6 event binning.
  - Further investigate the reconstruction at the highest energies.

Thank you!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