IceAct:

Hybrid cosmic ray measurements using the IceAct telescopes in coincidence with the IceCube and IceTop detectors

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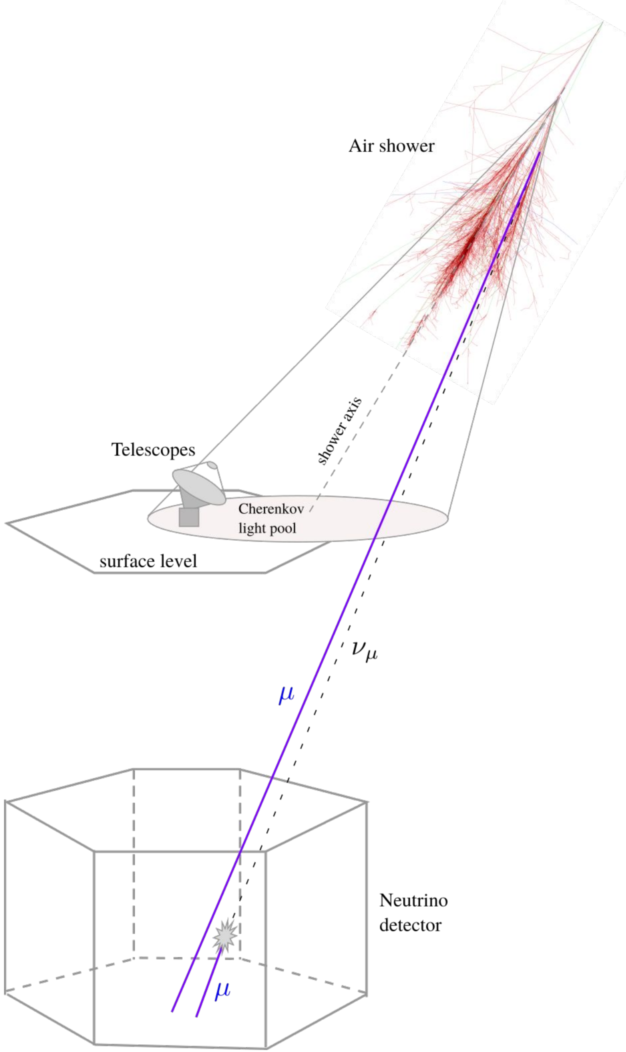
Science case and overview:

Hybrid detection provides:

- Electromagnetic component (IceAct telescopes)
- Particle footprint on ground (IceTop detector)
- In-Ice muon reconstruction (IceCube in-ice)

Science goals:

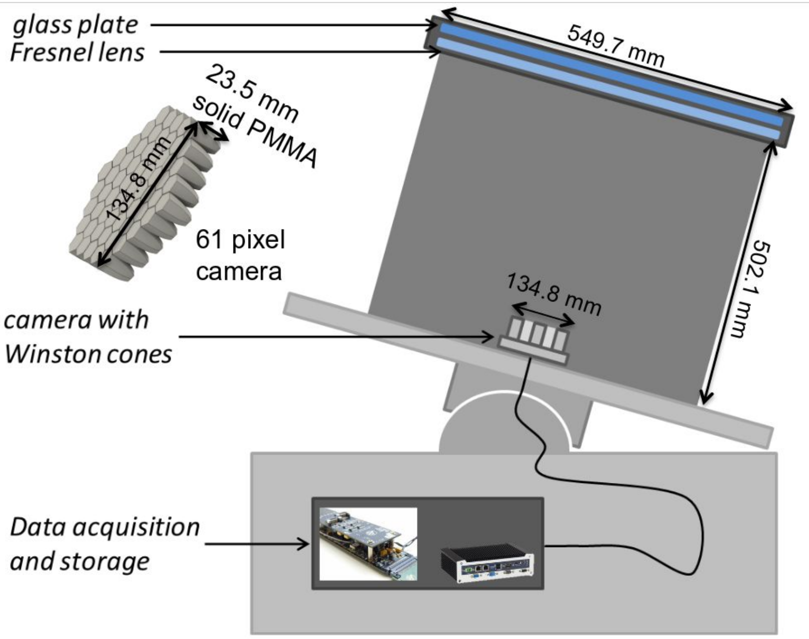
- Hybrid cosmic ray composition studies
- Calibration of IceCube/IceTop geometry and energy reconstruction
- Low energy cosmic ray veto capability for neutrino studies



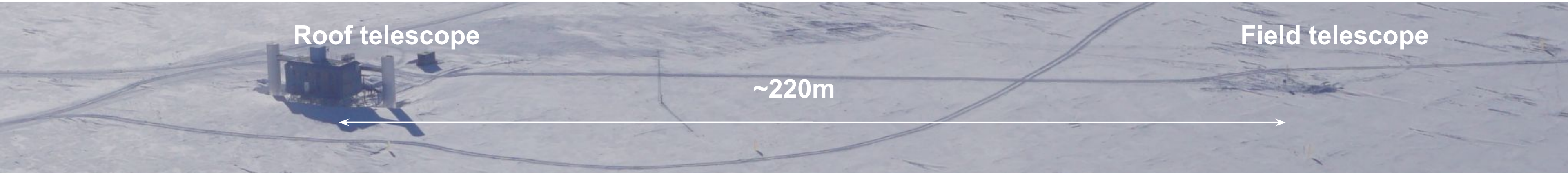
Baseline design:

IceAct telescope design:

- Fresnel lens, f~D~0.5m, fully enclosed design with heated front window (max. 100W)
- 61 SiPM based pixel (SensL J)
- Solid PMMA Winston cone light concentrators
- 1.5°/Pixel ~ 12° total Field-of-View
- TARGET-C/T5TEA based DAQ:
  - 1 GS/s 64 channel frontend
  - 4 Pixel sum-trigger (patch)
  - Next-Neighbor patch coincidence



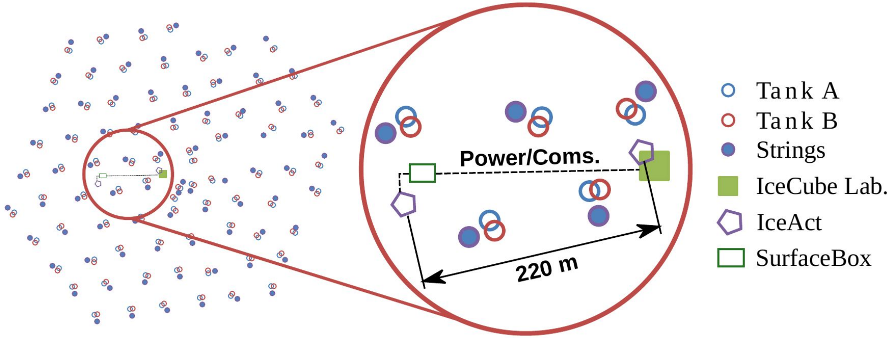
IceAct project status:



2019: Two IceAct telescopes with 61 pixel installed, both operate since then

2020: DAQ unification and heating upgrade, infrastructure installed for a full IceAct station featuring 7 telescope (~36 deg. Field of view)

2021: No pole activities (Covid-19), start to build 6 new telescopes (4 in Germany, 2 in the US) to complete the station when possible.

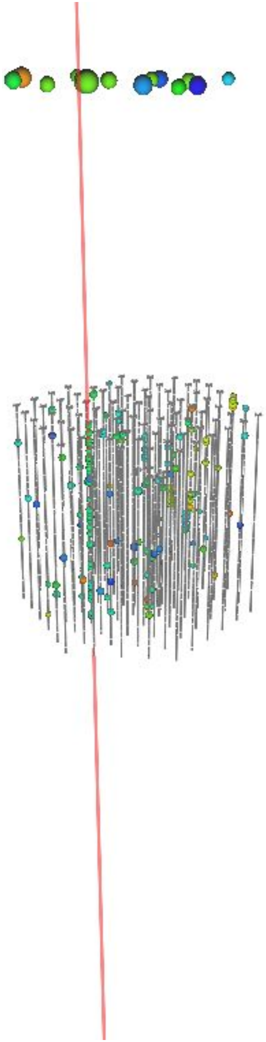


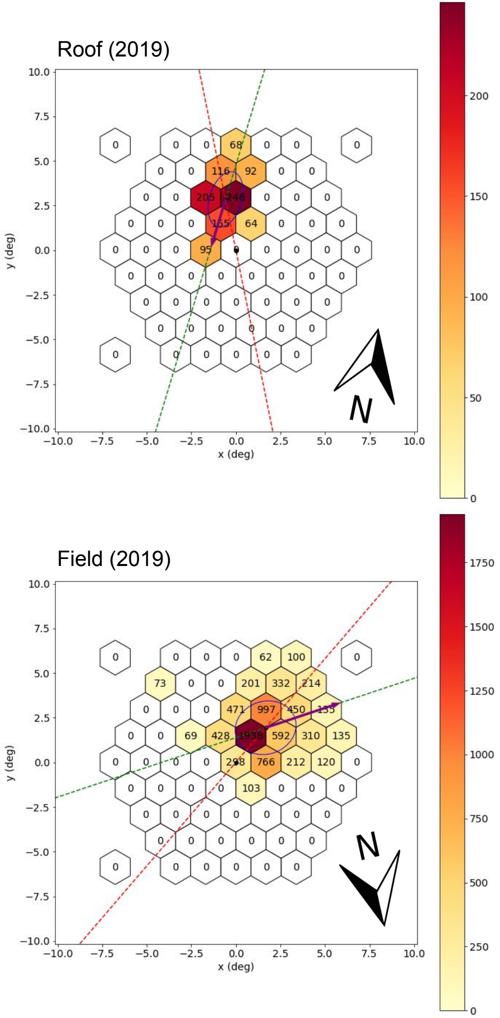
Data taking and Performance:

- Successful data taking since 2019 with different DAQ designs
- Former duty cycle estimation of >20% is realistic
- Aurora and moon light pose no major problem for the operation
- Snow and ice buildup on the lens is reduced due to a new heating concept but is still under investigation as the main technological challenge (High power budget)

- Coincident detection of air-shower and synchronization events as default operation:

  Right: Example event with a trigger in both telescopes, an IceTop signal and a reconstructed in-ice muon





Data/Analysis:

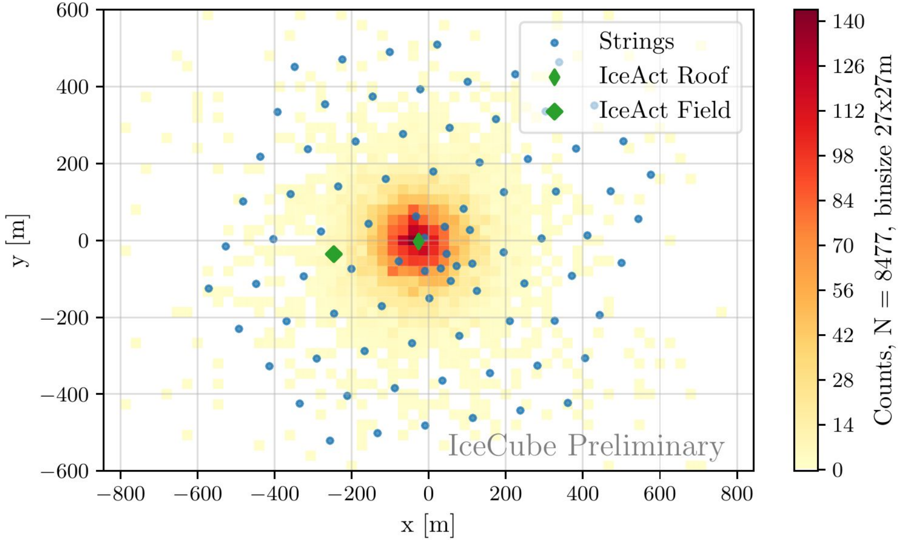
Data processing:

1. Event building: Detect coincidences over event timestamps and build hybrid events containing IceAct/IceTop/IceCube data.
2. Processing:
    a. IceAct: Image cleaning + simple Hillas center-of-gravity
    b. IceCube: In-Ice Muon log-likelihood reconstruction

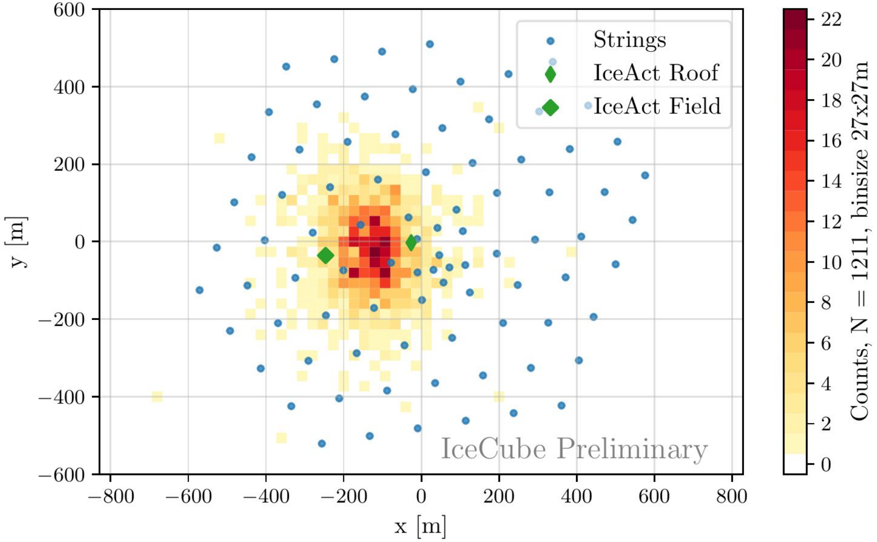
Data set for this study:

- Single day of data during good conditions with both telescope and IceCube
- No final analysis level reconstruction (loose IceCube quality cuts, simple Hillas image analysis), **proof-of-principle!**

In-Ice Muon surface positions:



Roof telescope, 24h (mono-)data



Roof + Field telescope, 24h stereo-data

- Extrapolation of the in-ice (online) muon reconstruction to the surface clearly shows the sensitive area of a single telescope (left) and the stereo telescope events (right) for one day of data. >1000 Coincident stereo events per day.

Directional correlation:

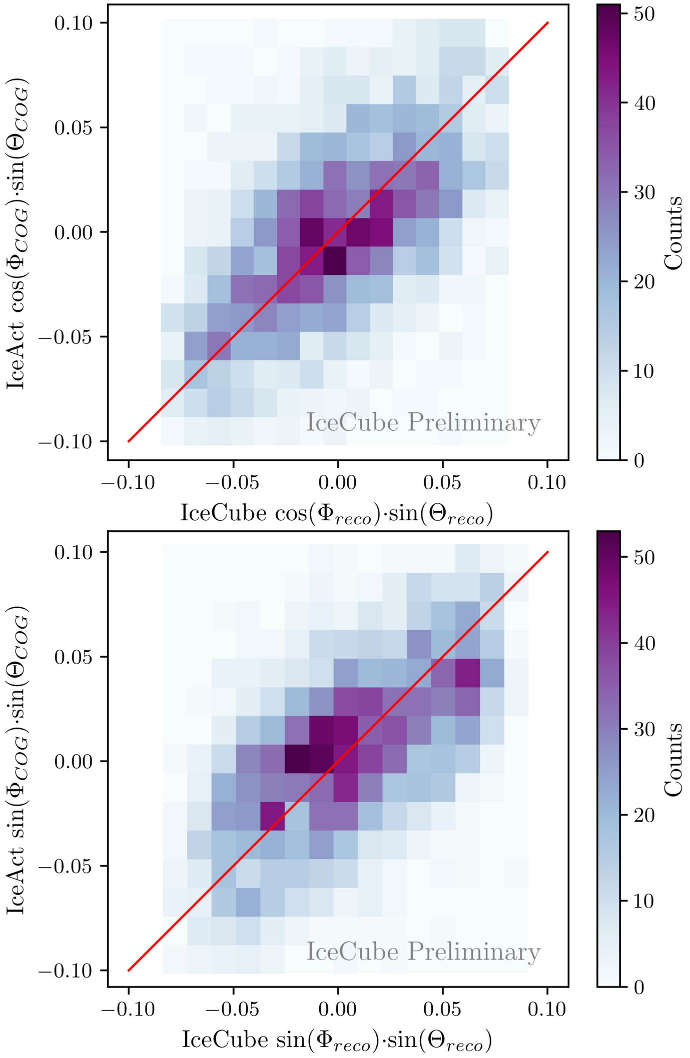
U/V Correlation

- 24h of data, one telescope (roof)
- IceAct direction:
  - Simple hillas image parameters:
  - Position of image COG:

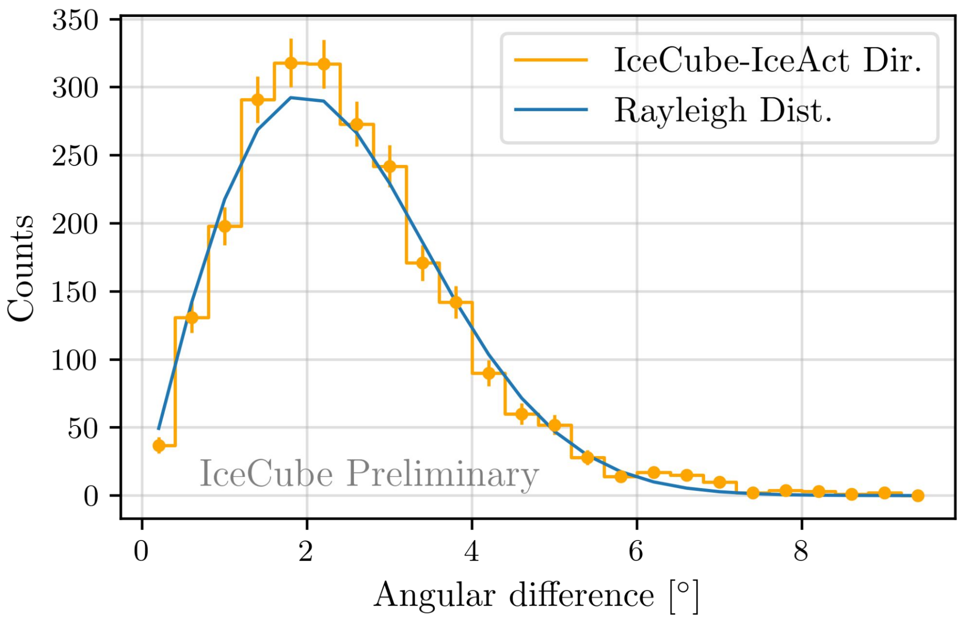
$$\Phi = tan^{-1}\left(\frac{Y_{COG}}{X_{COG}}\right) \qquad \Theta = \tan^{-1}\left(\frac{\sqrt{X_{COG}^2 + Y_{COG}^2}}{f_{len}}\right)$$

- IceCube reconstruction:
  - Online MuonLLH reconstruction
- Transformation to U and V coordinates to avoid edge and periodic effects

Clear correlation without optimized reconstruction and quality cuts!



Directional correlation:



Correlation differences

- Mean reconstruction difference is ~2°, which is as expected from the reconstruction methods:
- Online muon reconstruction >2° uncertainty
- Intrinsic uncertainty of the COG image analysis due to the Cherenkov cone width of >1°

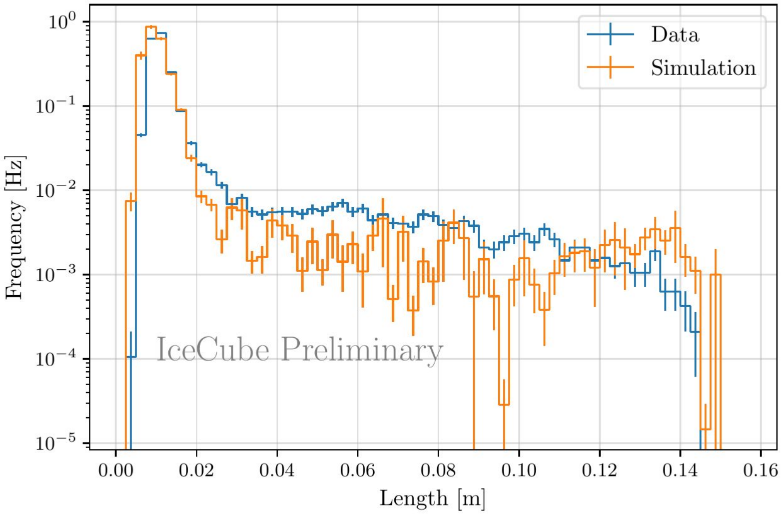
Outlook: Analysis with dedicated hybrid reconstruction very promising

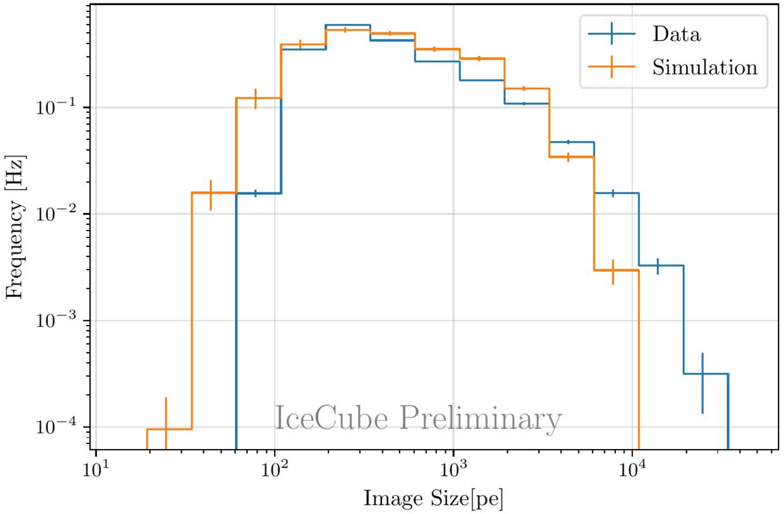
Simulation overview:

Dataset:

- CORSIKA (FLUKAS + SIBYLL-2.3c) air shower simulation
  - Protons, helium, nitrogen, aluminium and iron from 3 TeV to 1 PeV (E^{-1}) under the CORISKA standard atmosphere for the South Pole
  - Data/mc comparison 100k proton and iron shower and 40k helium, nitrogen and aluminium are reweighting the MC to an H4a
  - For the mass composition analysis 65k proton and iron are split into 66% training sample and 33% test sample
- Complete detector simulation including the wavelength dependent IceAct optics, the SiPM and a full electronic simulation. The IceCube/IceTop response is simulated using the IceCube simulation framework

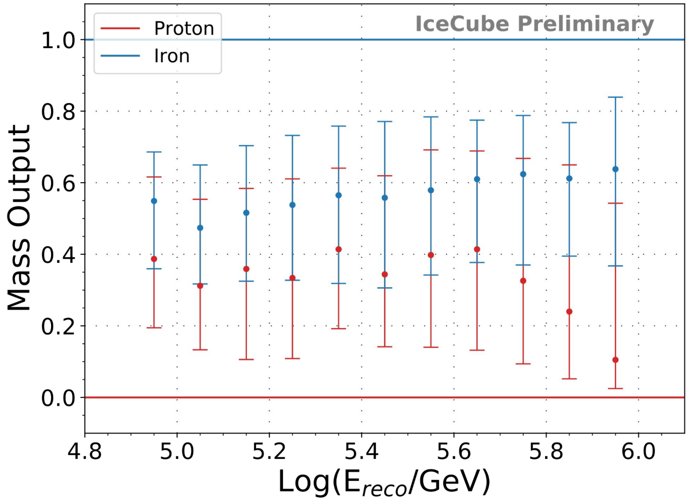
First data/MC comparison:

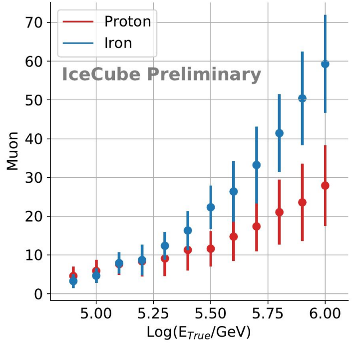




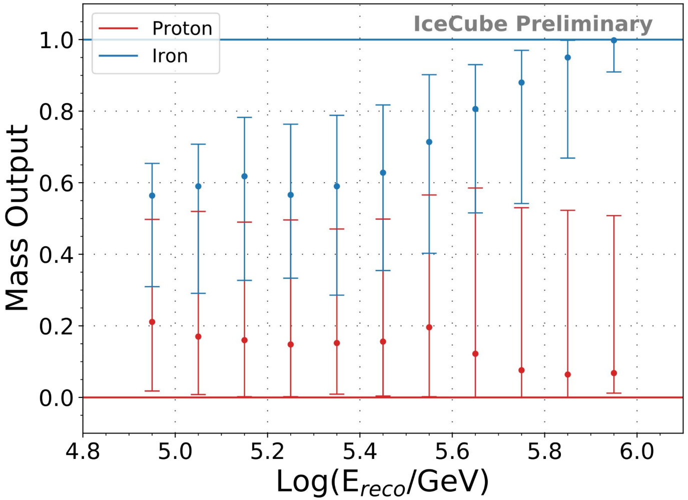
- General match is acceptable for almost no tuning
- Size match is improvable, different known factors are not yet fully calibrated:
  - Simulation energy range, simulated threshold, dynamic range calibration is slightly off
  - Obstruction through the heating system not yet implemented (~10%)

Hybrid composition simulation:





IceCube muon proxy



Method: Random Forest Regressor (3-Year IceCube composition analysis topology). Input parameter:

Hillas image parameter: Primary Geometry: In-Ice parameter:

Size, width, length, Distance to shower core, cos(zenith), Muon proxy

Summary and outlook:

Summary:

- Successful operation of two compact air-Cherenkov telescopes at the South Pole since 2019. Aurora and moon light due not severely impacting the experiment performance
- Coincident data showed a clear correlation between the reconstructed muon direction (IceCube) and the image center-of-gravity of the air shower detected by IceAct.
- First simulation results already show a decent Data/MC agreement and very promising capabilities for hybrid composition studies.

Outlook:

- Dedicated hybrid reconstruction (direction, energy, mass proxy) under development.
- All parts for the final simulation are tested, still fine tuning necessary
- Six new IceAct telescopes are currently in assembly or commissioning (Germany, USA) to complete a full seven telescope station (~36° FOV) at the south pole

Thank you for your attention! Any questions?