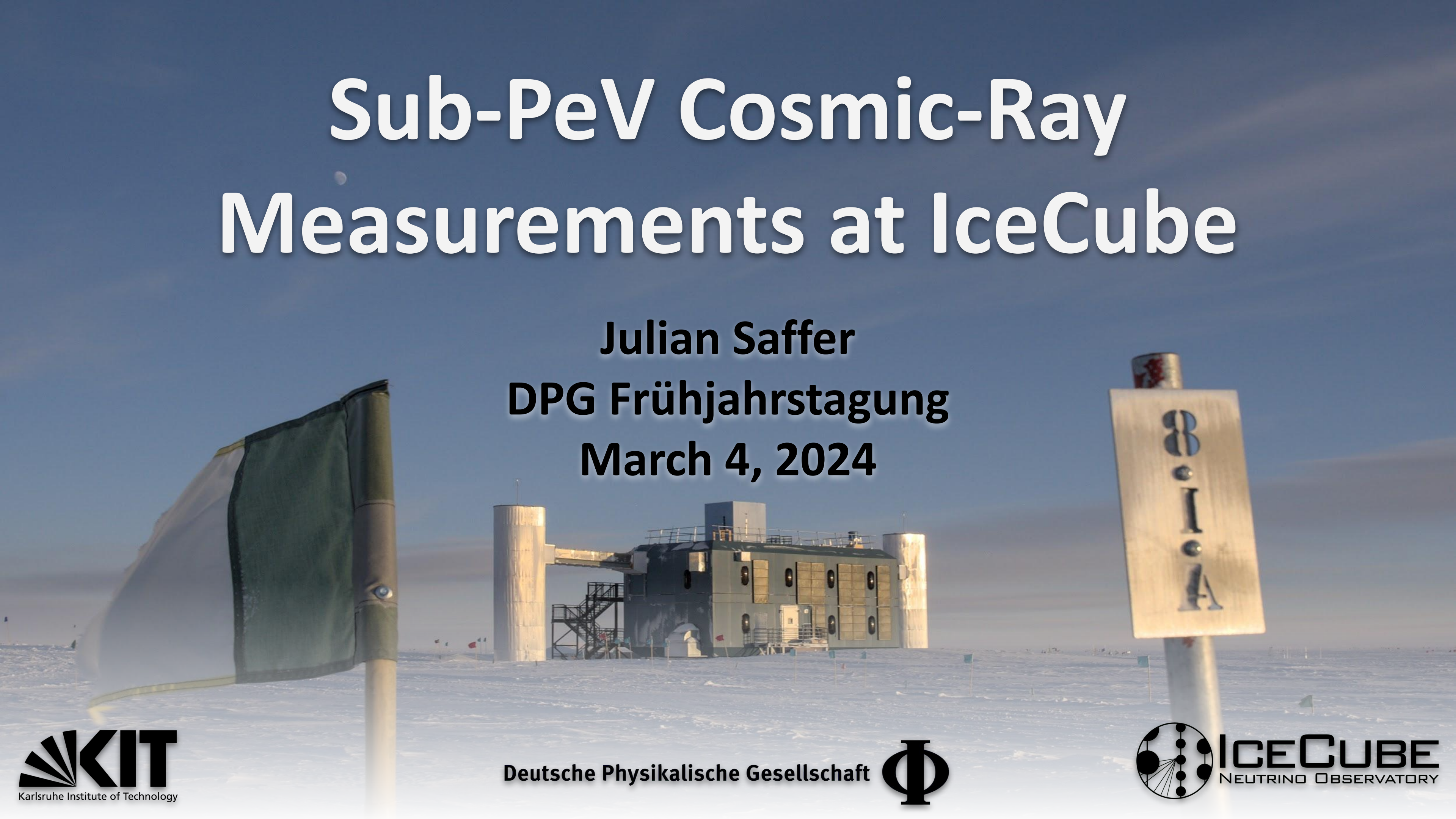
Sub-PeV Cosmic-Ray Measurements at IceCube

Julian Saffer

DPG Frühjahrstagung

March 4, 2024



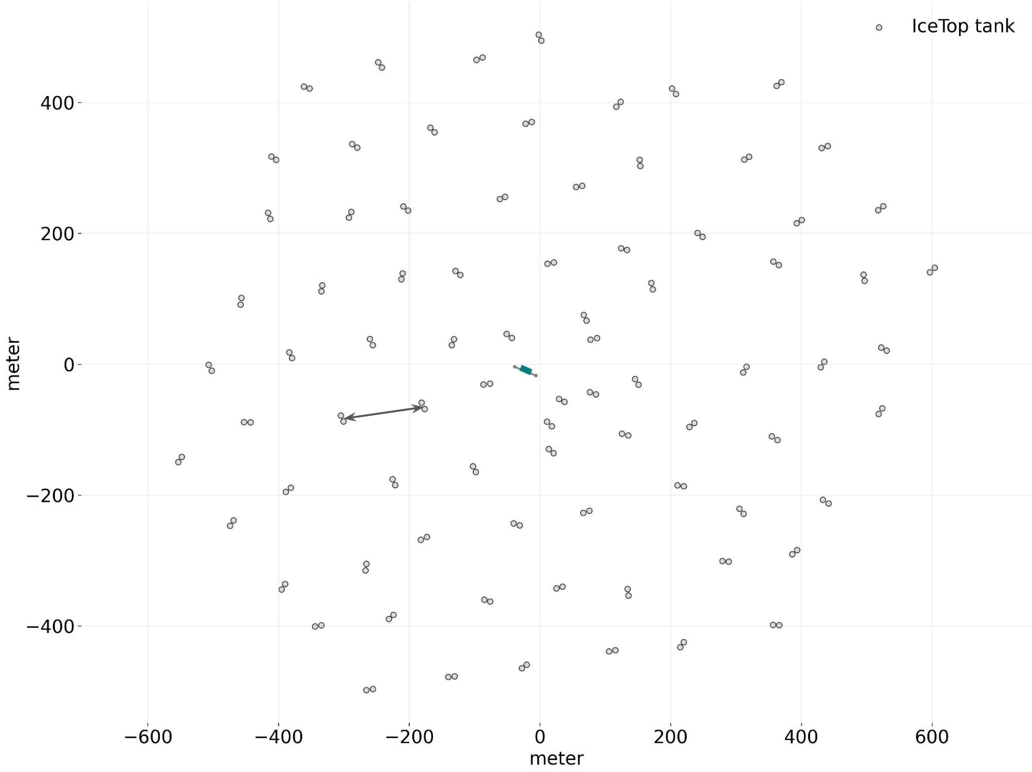
Karlsruhe Institute of Technology

Deutsche Physikalische Gesellschaft

ICECUBE NEUTRINO OBSERVATORY

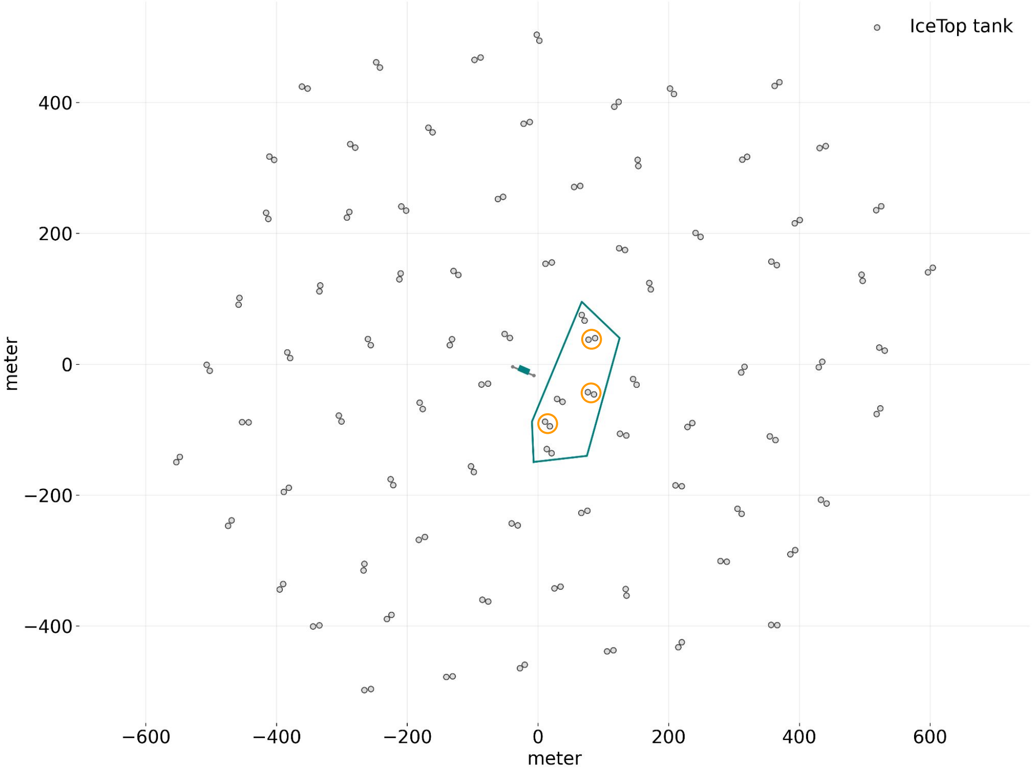
The Cosmic-Ray Detector IceTop

- Ice-Cherenkov tank array at the South Pole (680 g/cm²)
- Area of 1 km²
- Spacing between stations: 125 m



The Cosmic-Ray Detector IceTop

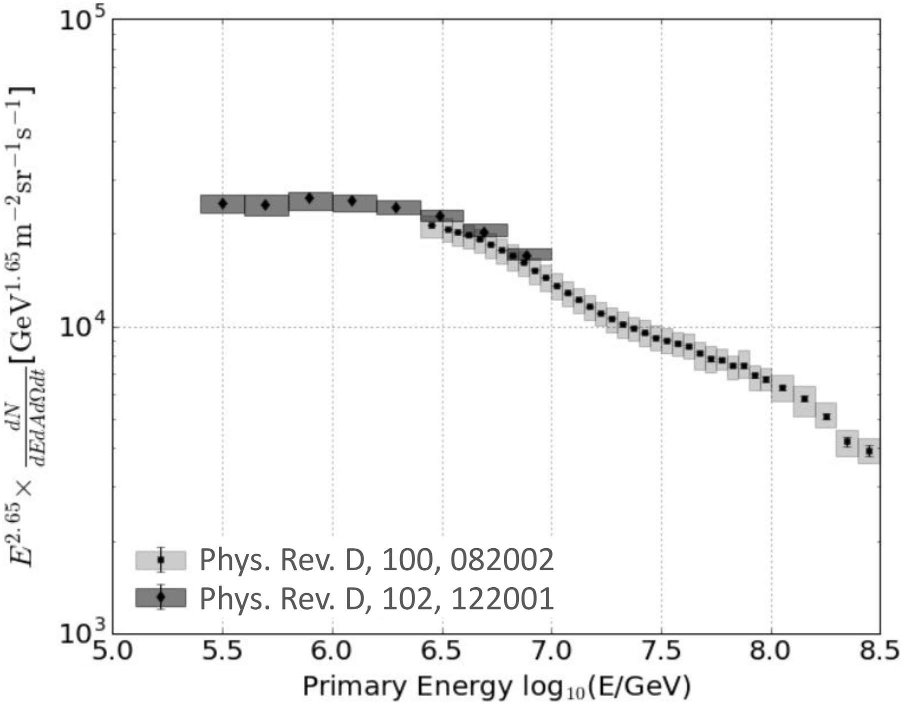
- Ice-Cherenkov tank array at the South Pole (680 g/cm²)
- Area of 1 km²
- Spacing between stations: 125 m in the in-fill: < 50 m
- air-shower energy range: 100 TeV – few EeV



The Cosmic-Ray Detector IceTop

- Previous composition analyses started at full efficiency (3 PeV)

- All-particle energy spectrum with composition assumption starting at 250 TeV

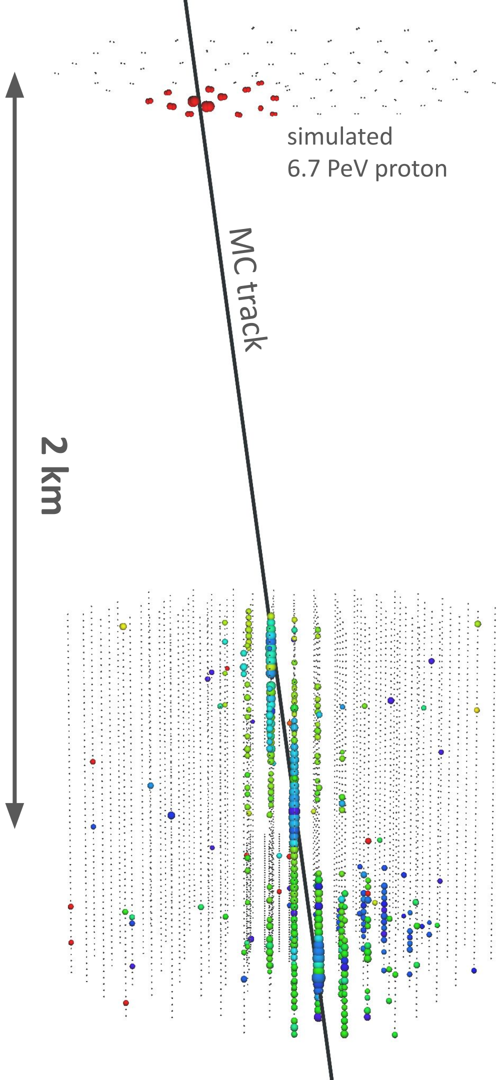


The Cosmic-Ray Detector IceTop

- Previous composition analyses started at full efficiency (3 PeV)

- All-particle energy spectrum with composition assumption starting at 250 TeV

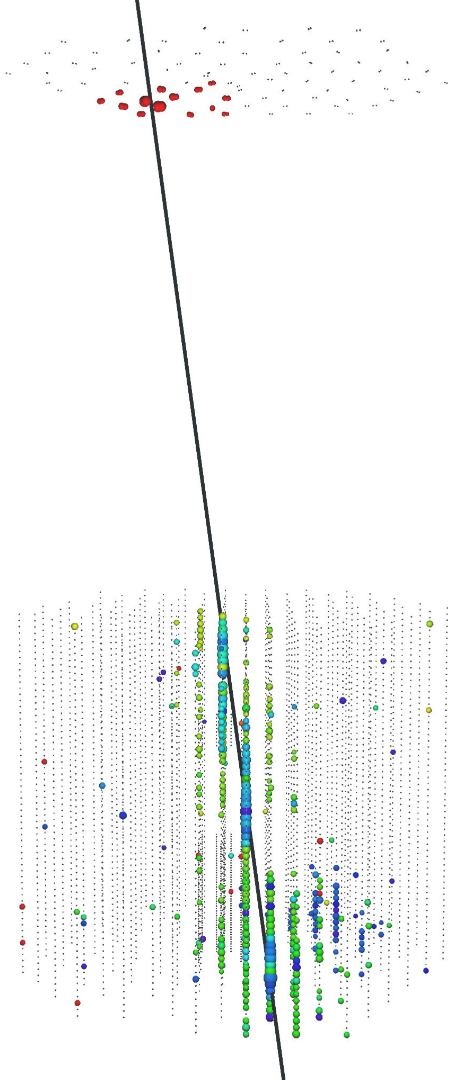
- Coincidences with the in-ice array below
  - improve / enable directional reconstruction
  - in-ice muon bundle holds potential composition information



Event Selection & Processing

The new processing includes:

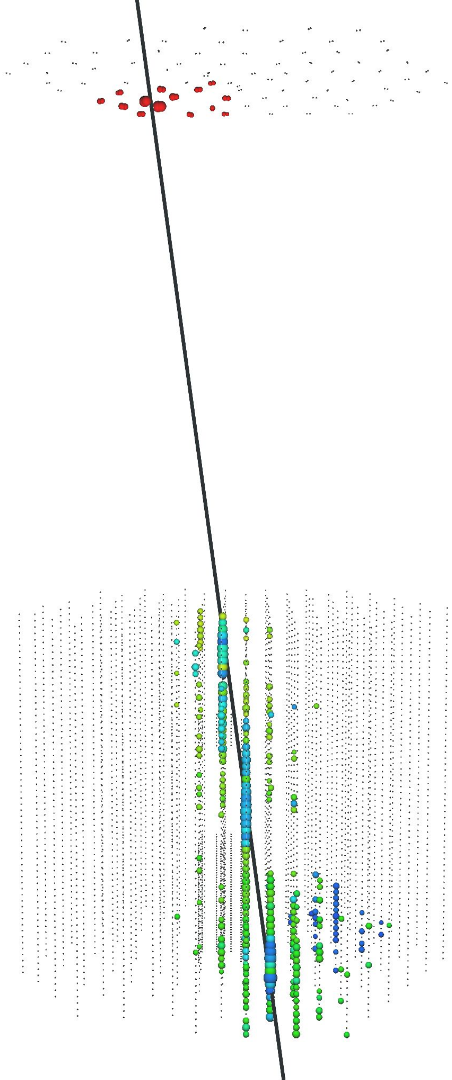
- Selecting coincident events



Event Selection & Processing

The new processing includes:

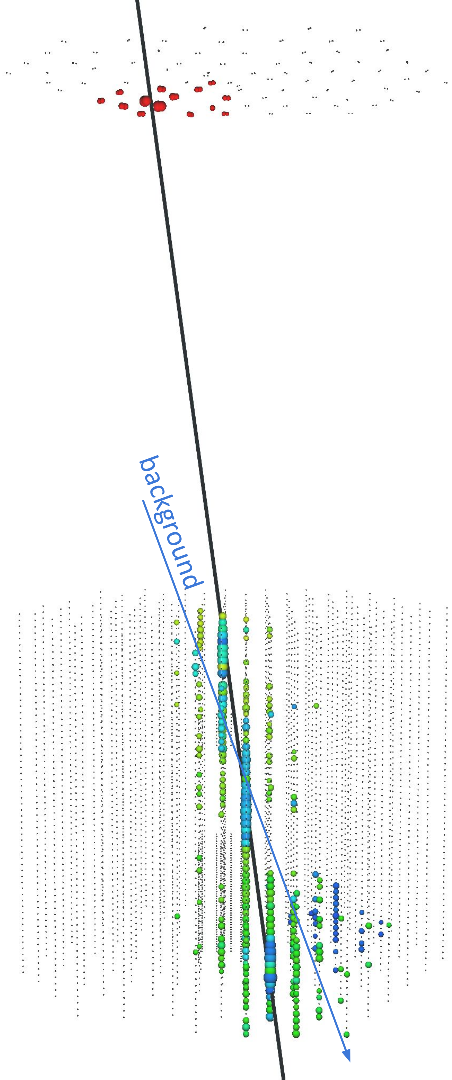
- Selecting coincident events
- Cleaning of in-ice pulses



Event Selection & Processing

The new processing includes:

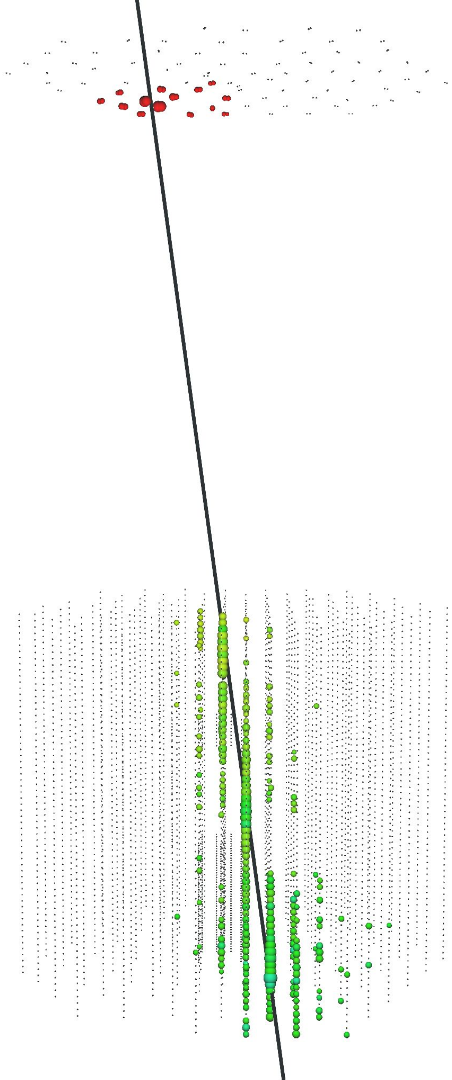
- Selecting coincident events
- Cleaning of in-ice pulses
- Removing coincident background



Event Selection & Processing

The new processing includes:

- Selecting coincident events
- Cleaning of in-ice pulses
- Removing coincident background

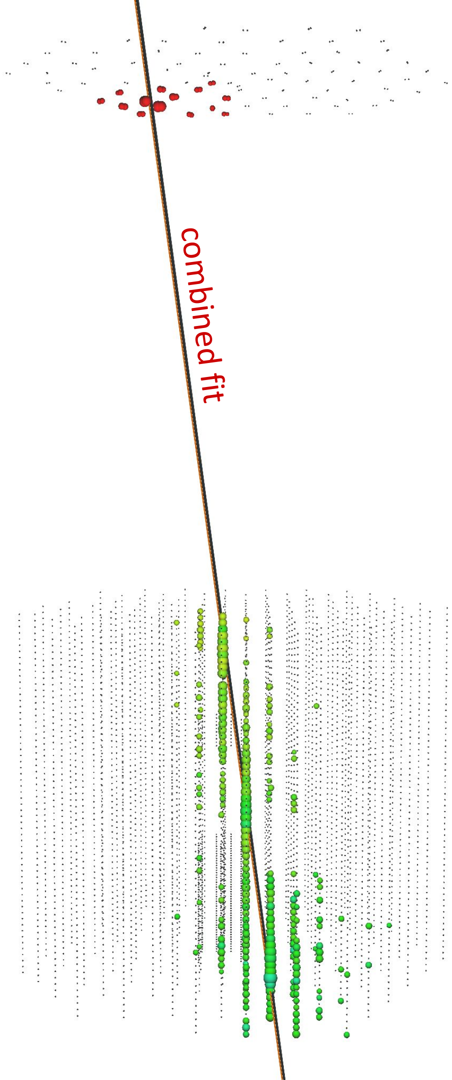


Event Selection & Processing

The new processing includes:

- Selecting coincident events
- Cleaning of in-ice pulses
- Removing coincident background
- Performing directional fit to both surface and in-ice pulses
  $\longrightarrow$ minimizing combined -log(L) with
  - in-ice pulses (track: infinite muon hypothesis) and
  - IceTop pulses (timing: Gaussian shower front hypothesis)

  keep shower core fixed around seed within a few meter



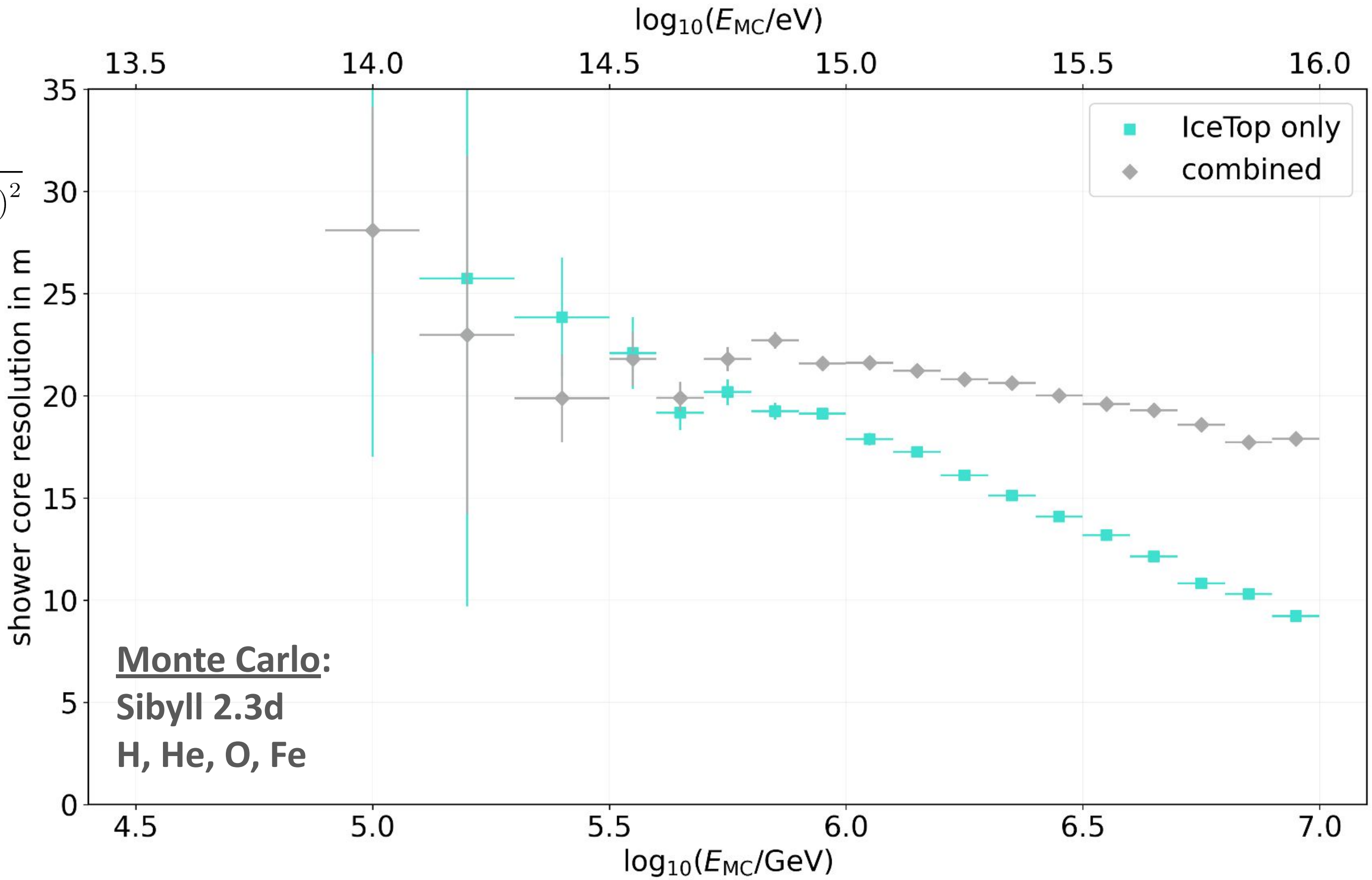
Shower Core Resolution

Defined as 68-percentile of

$$\sqrt{(x_{\mathrm{MC}} - x_{\mathrm{reco}})^2 + (y_{\mathrm{MC}} - y_{\mathrm{reco}})^2}$$

distribution

Only events that have successful IceTop-only reconstruction and a combined fit



Shower Core Resolution

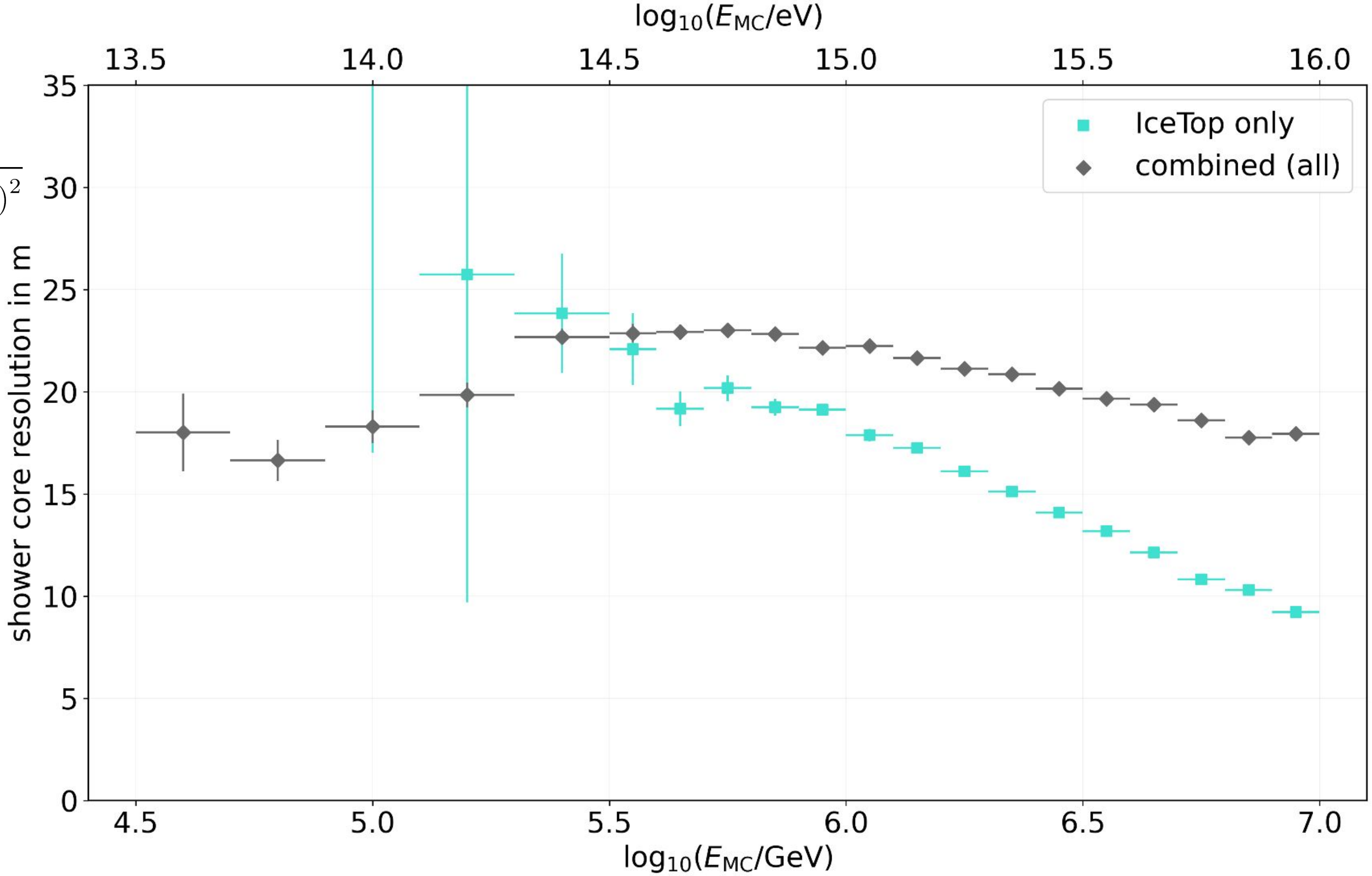
Defined as

68-percentile of

$$\sqrt{(x_{\mathrm{MC}} - x_{\mathrm{reco}})^2 + (y_{\mathrm{MC}} - y_{\mathrm{reco}})^2}$$

distribution

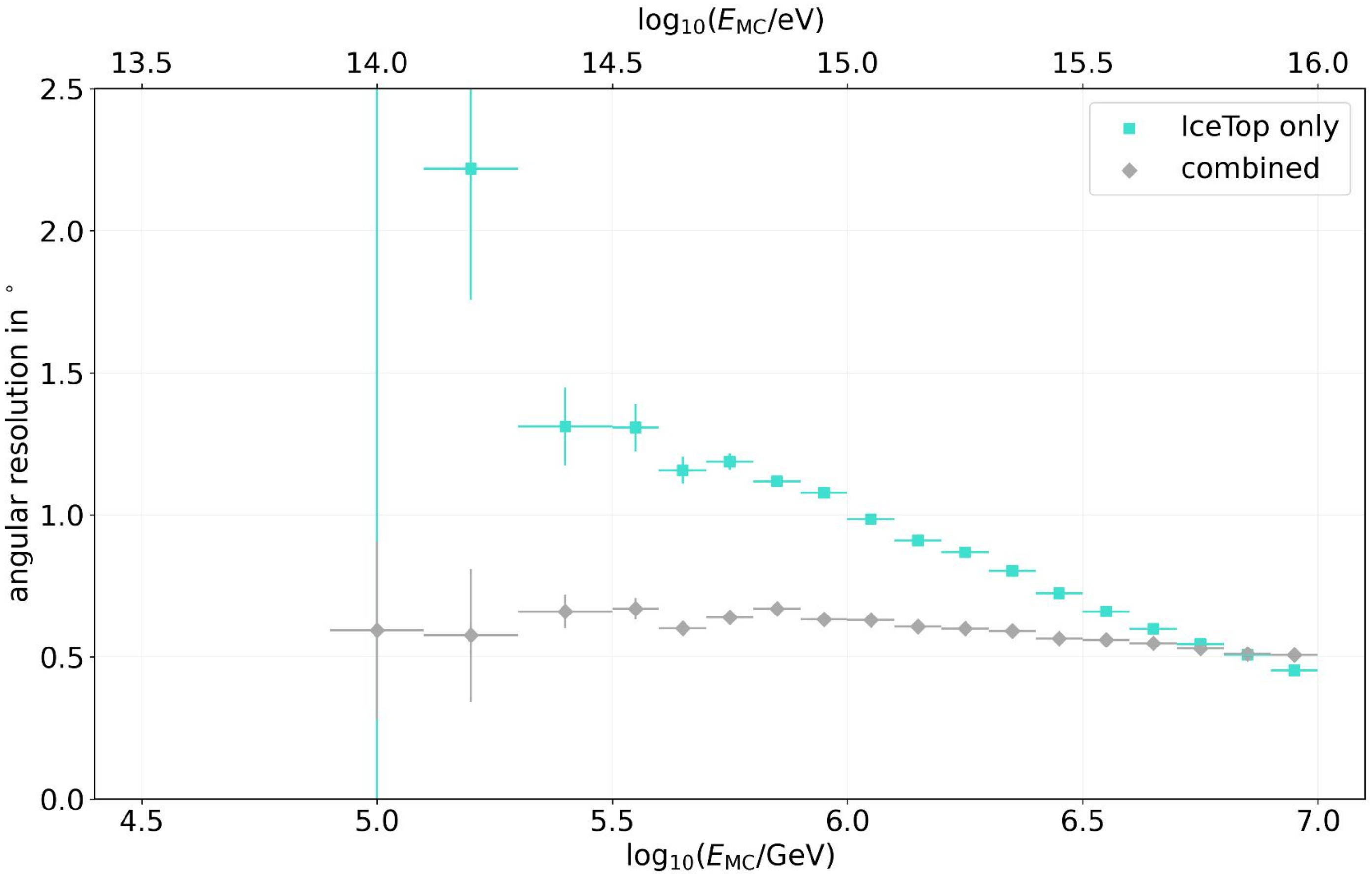
Even showers with just **40 TeV** have a decent core estimate



Angular Resolution

Opening angle between Monte Carlo and reco track

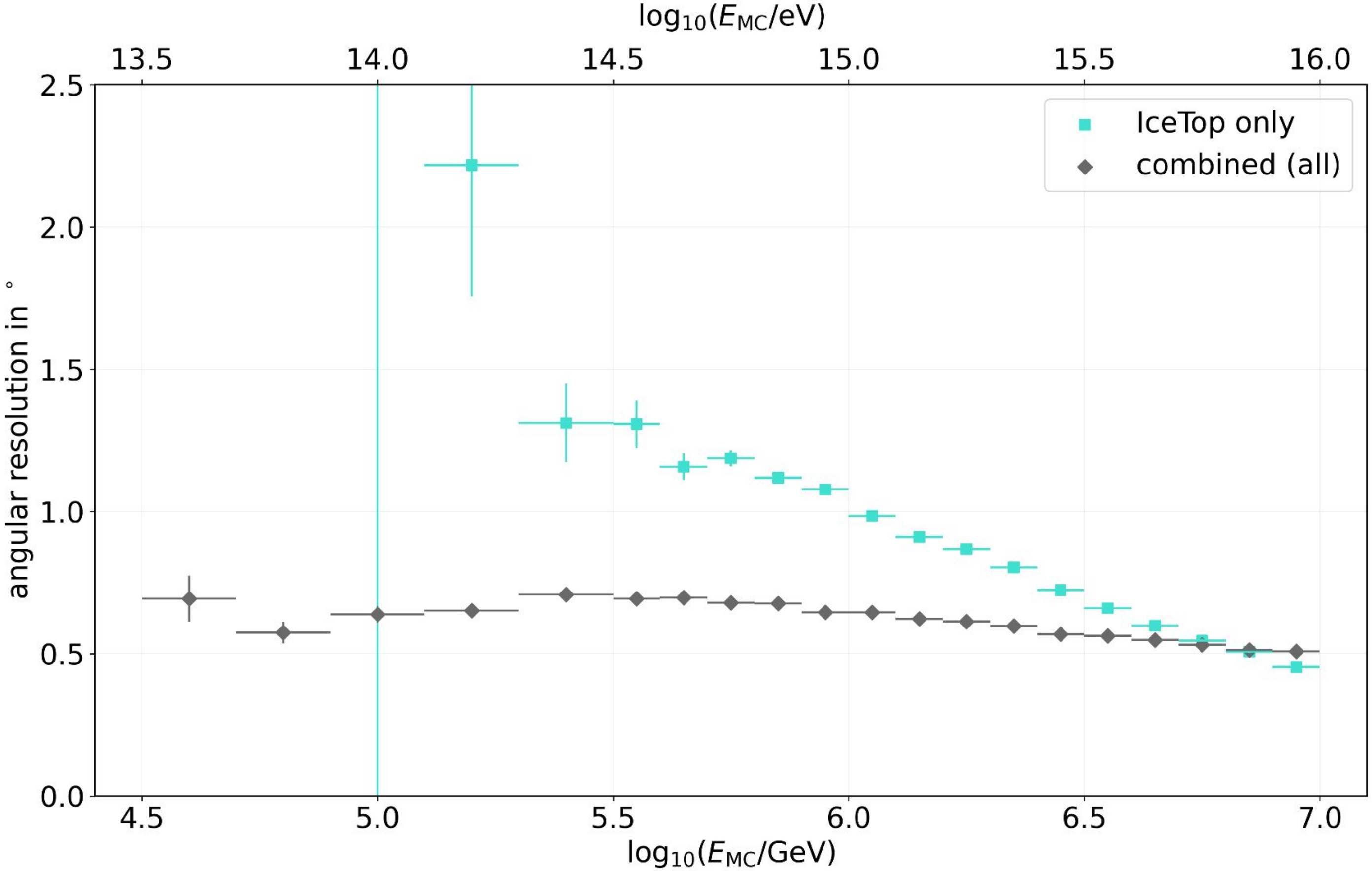
Below 6 PeV combined fit has much better pointing



Angular Resolution

Opening angle between Monte Carlo and reco track

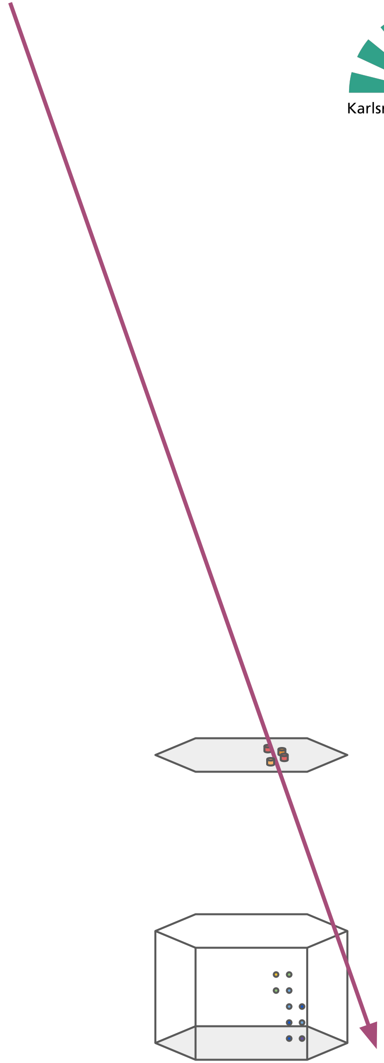
Below 0.7° angular resolution at 40 TeV



Why this Discrepancy?

How can the angular resolution improve so much while core resolution is very similar or even worse than the IceTop-only fit?

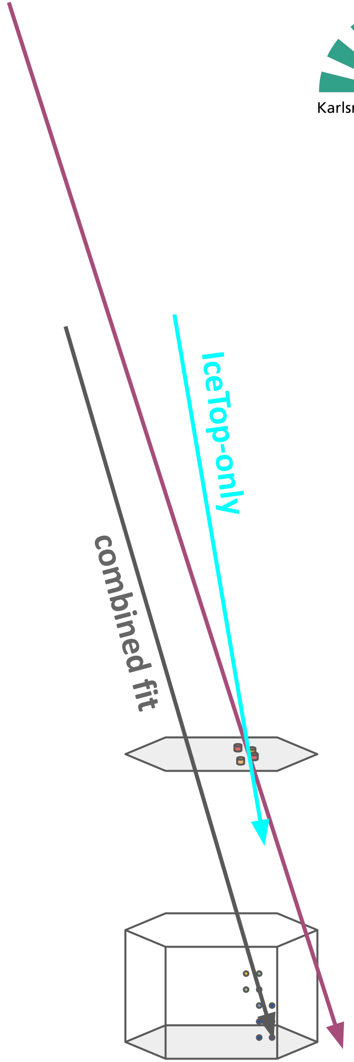
	in-ice pulses	Lateral Distribution Function (LDF)
IceTop-only	no	yes
combined fit	yes	no



Why this Discrepancy?

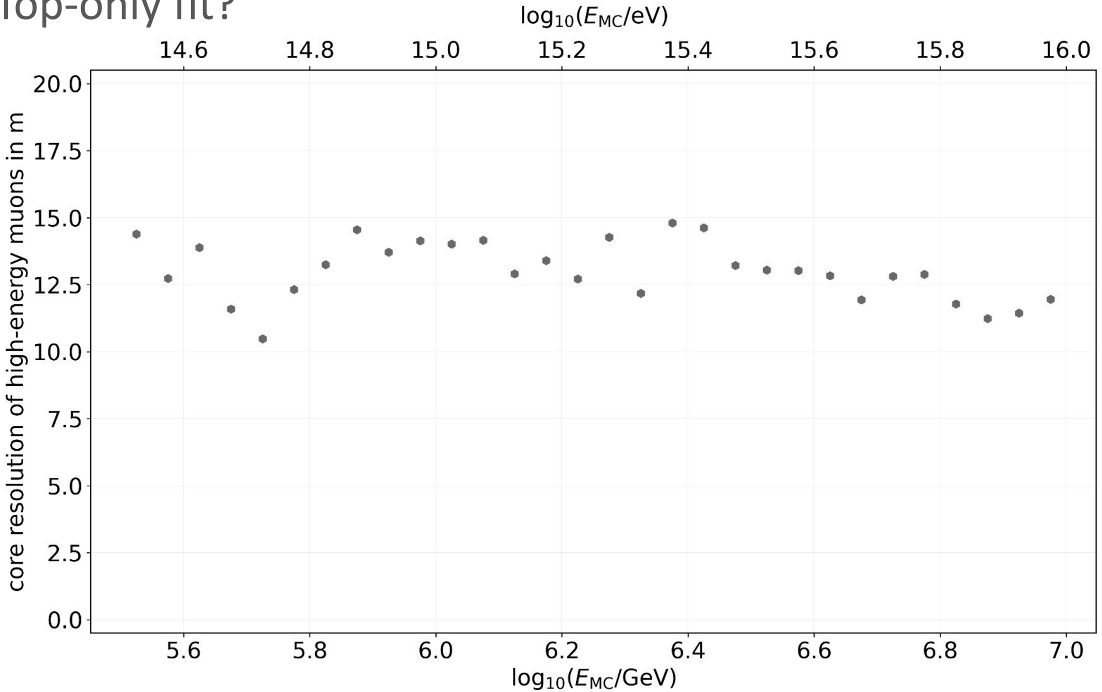
How can the angular resolution improve so much while core resolution is very similar or even worse than the IceTop-only fit?

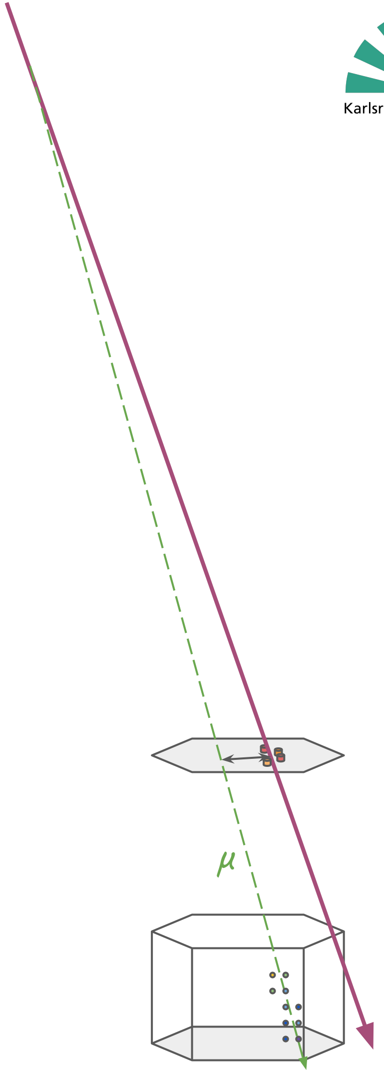
	in-ice pulses	Lateral Distribution Function (LDF)
IceTop-only	no	yes
combined fit	yes	no



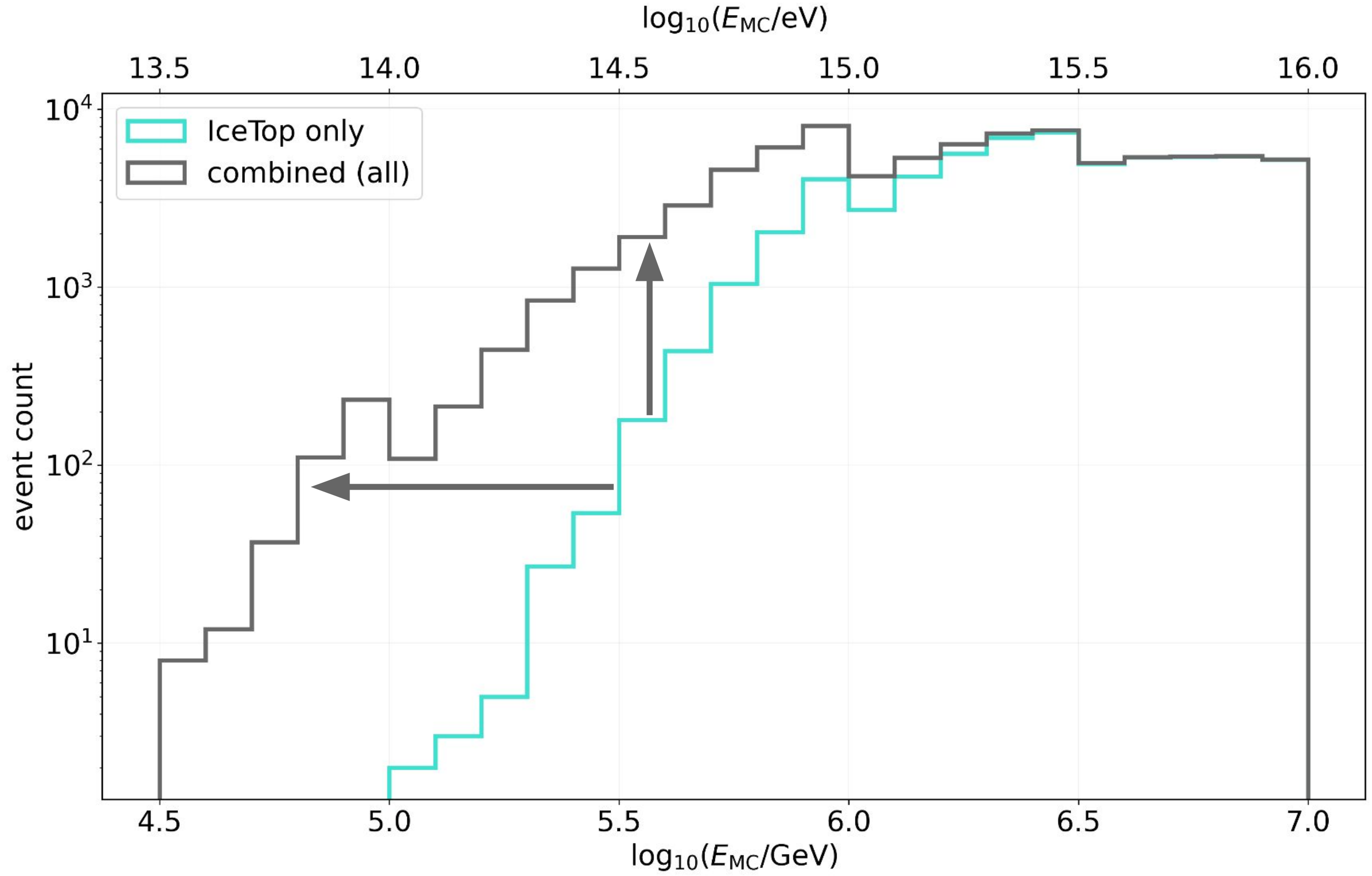
Why this Discrepancy?

How can the angular resolution improve so much while core resolution is very similar or even worse than the IceTop-only fit?





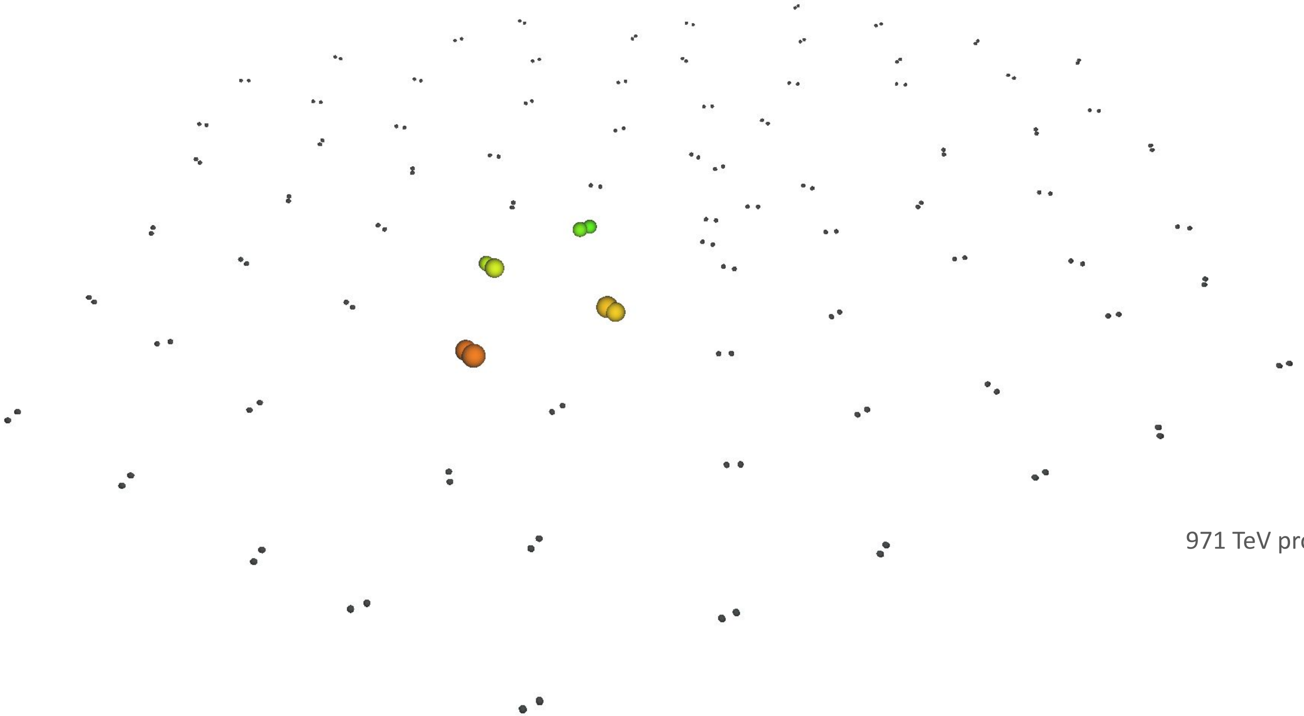
Increased Reconstructability below PeV Energies



Single-Tank Hits

Track recon-
struction uses
tank-pair hits
(HLCs), close to
the shower core

Mostly
electromagnetic
particles



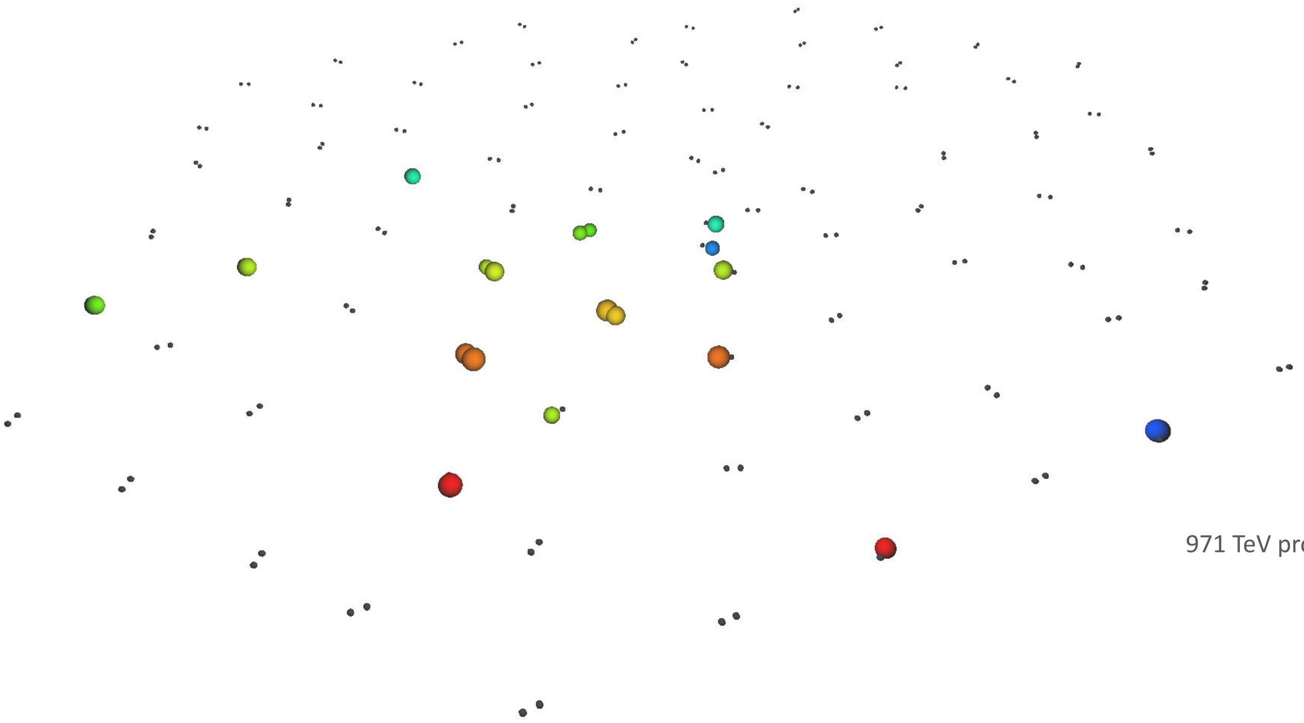
971 TeV proton

Single-Tank Hits

Karlsruher Institut für Technologie

Single tank hits (SLCs) further away from the shower core

Predominantly triggered by GeV muons

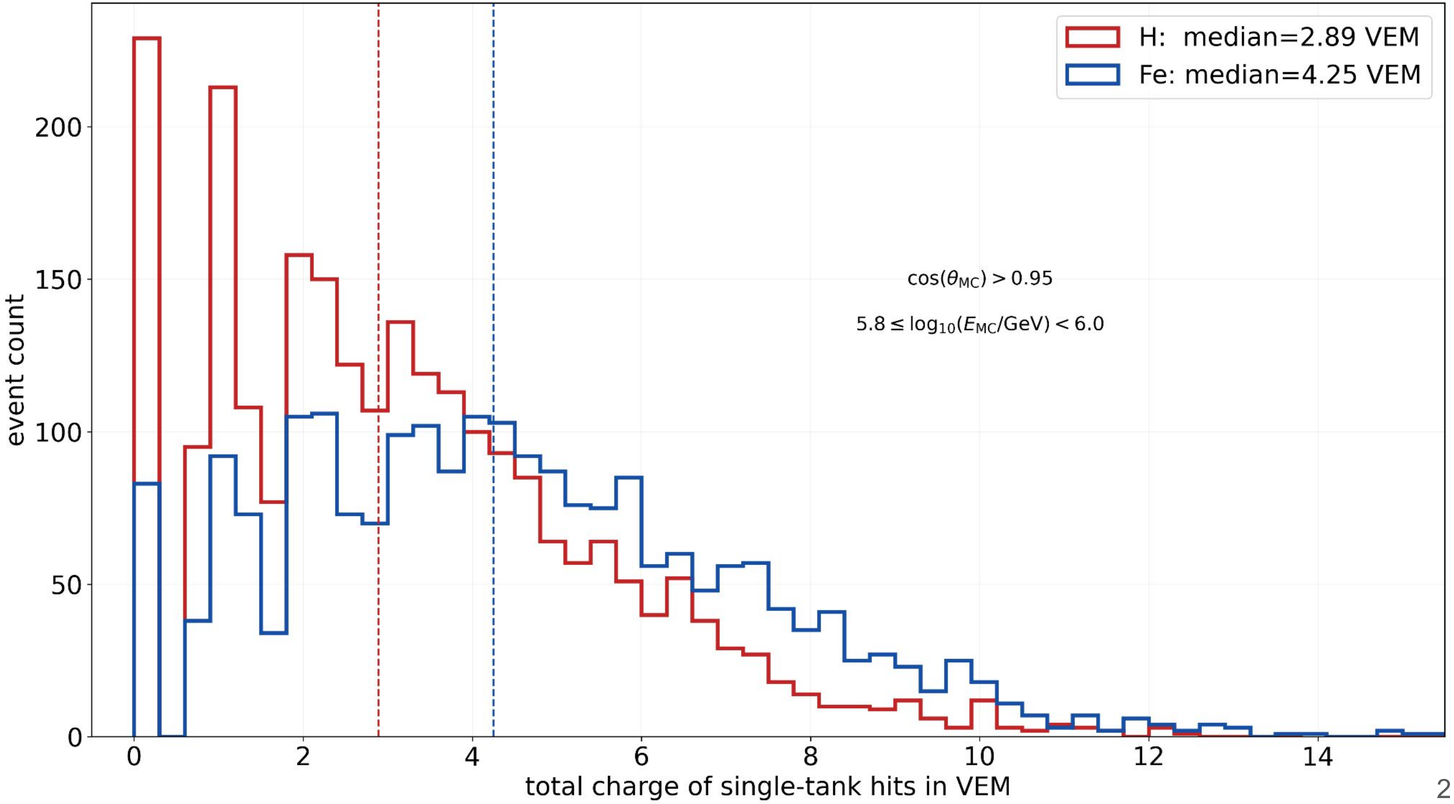


971 TeV proton

Single-Tank Hits

Single tank hits further away from the shower core

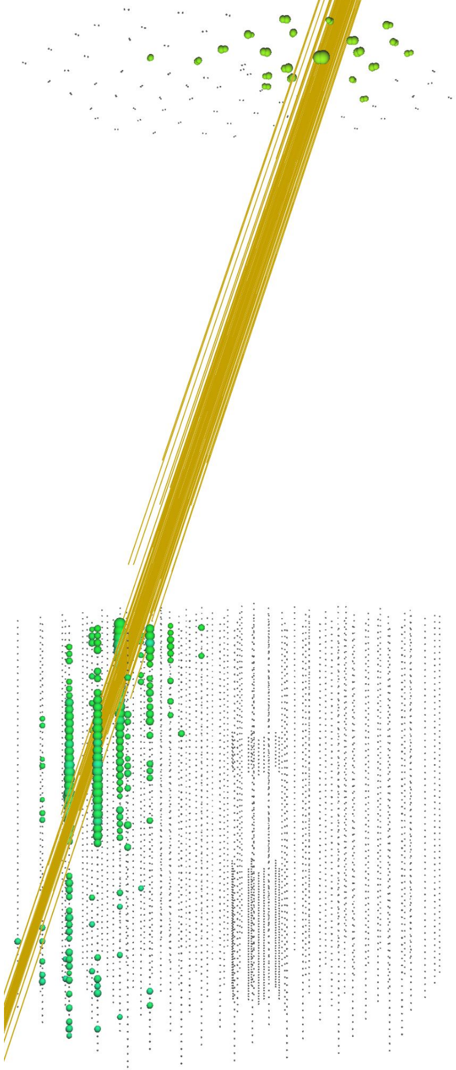
Predominantly triggered by GeV muons



In-Ice Hits

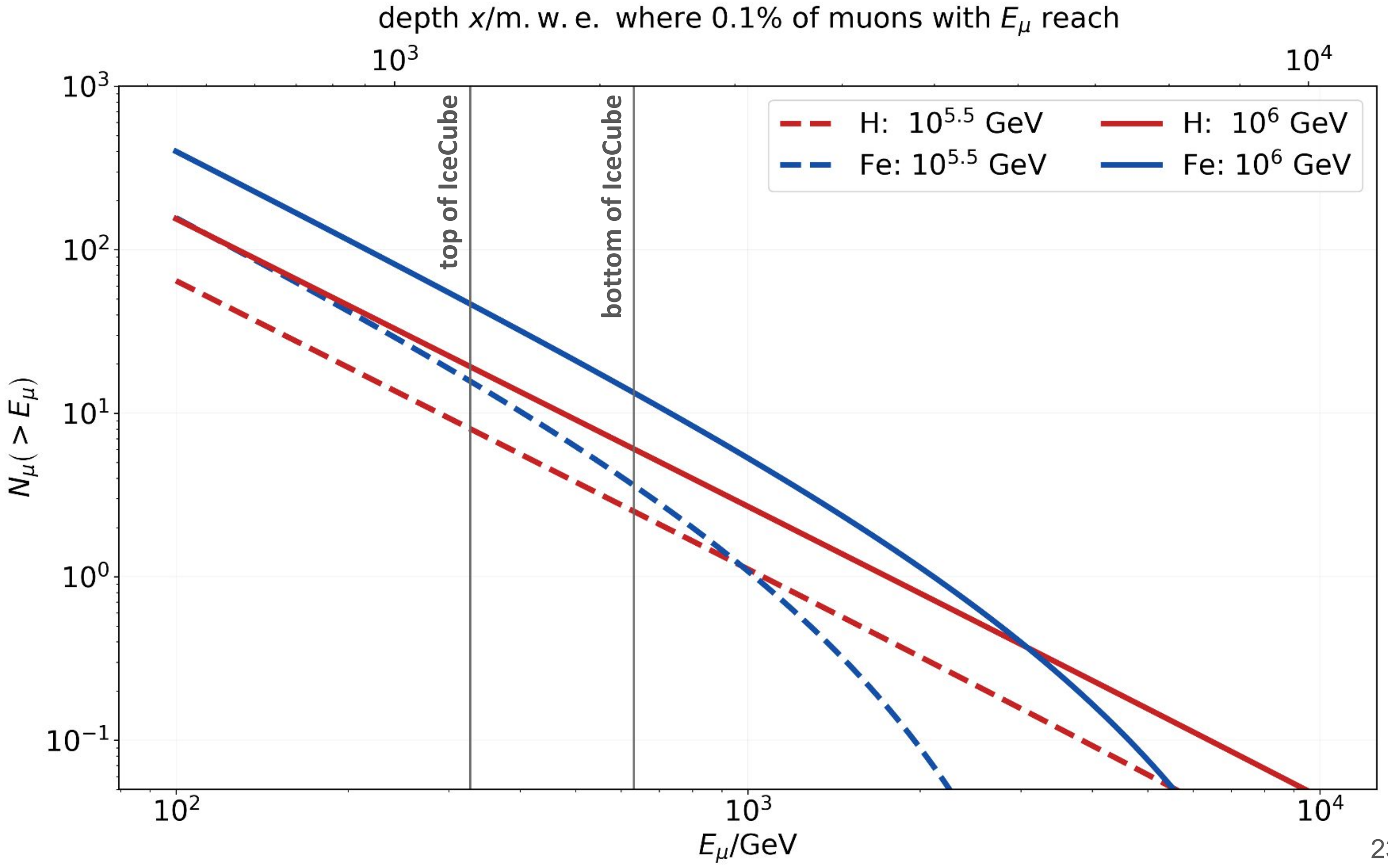
Muon bundle not only useful for directional fit, also composition dependence

Predominantly triggered by TeV muons



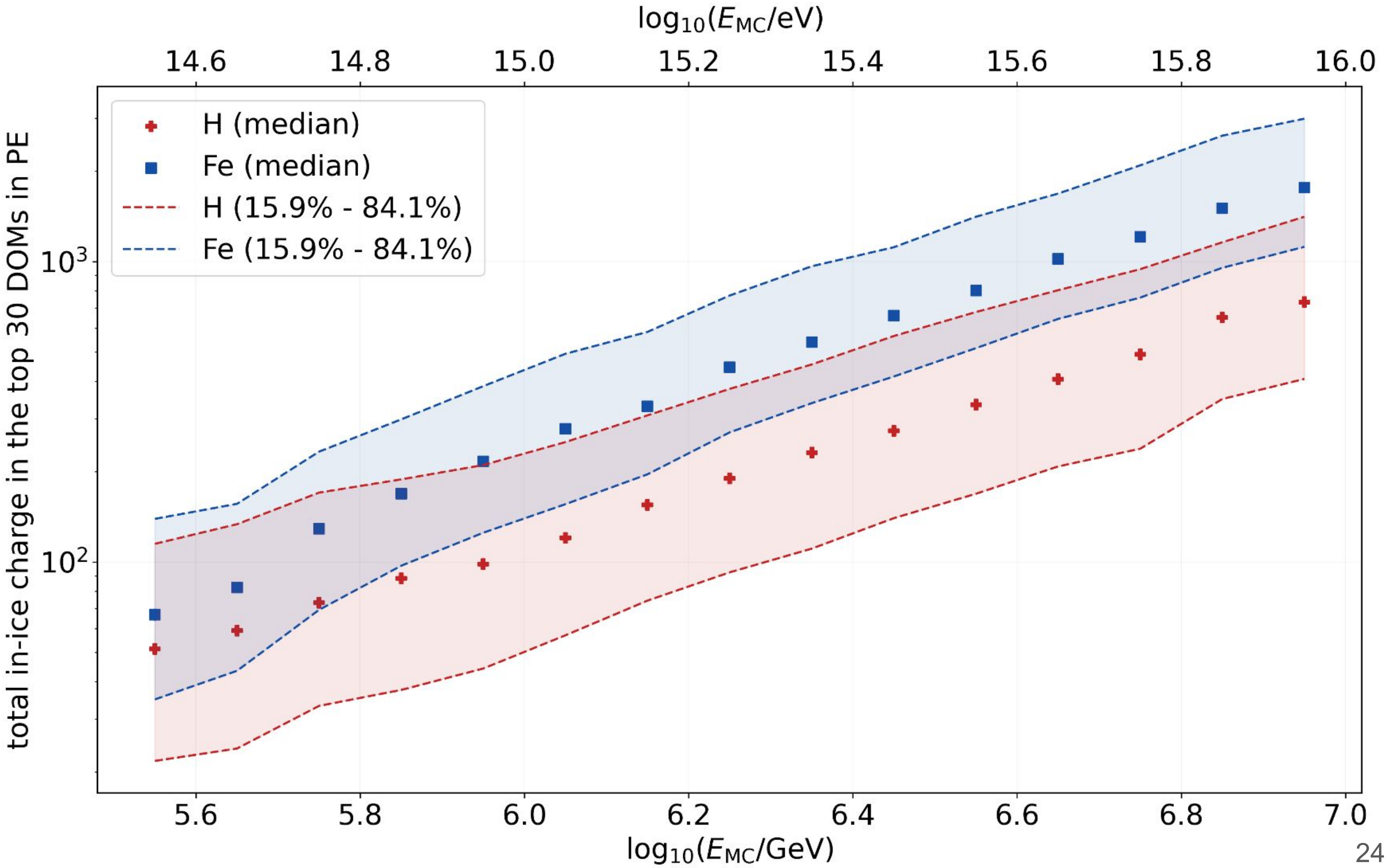
In-Ice Hits

Further down in the ice, muon number becomes less distinct



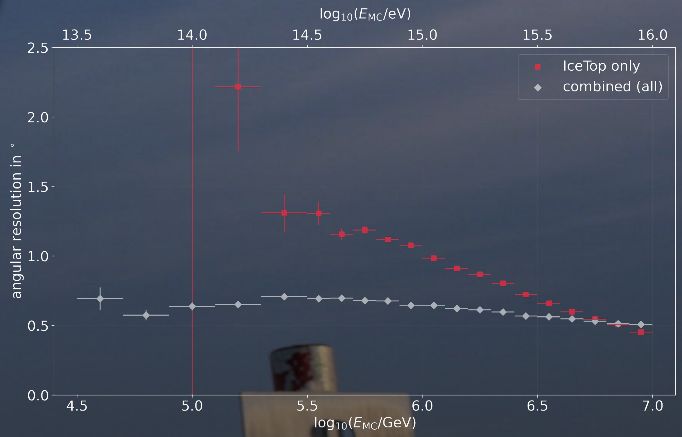
In-Ice Hits

Collect charge in top half of in-ice array



Summary

- Extended the shower track reconstruction below PeV energy with good angular resolution
- Surface muons and in-ice mouns accessible and valuable for composition analysis



Outlook

- Use LDF fit in combined fit to improve core resolution
- Neural network processing double-tank and single-tank pulses as well as aggregated in-ice charge in top of array
- With an unbiased energy estimate, primary classification is possible

Julian Saffer | julian.saffer@kit.edu

Energy Estimation

Karlsruher Institut für Technologie