Sub-PeV Cosmic-Ray Measurements at IceCube

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DPG Frühjahrstagung

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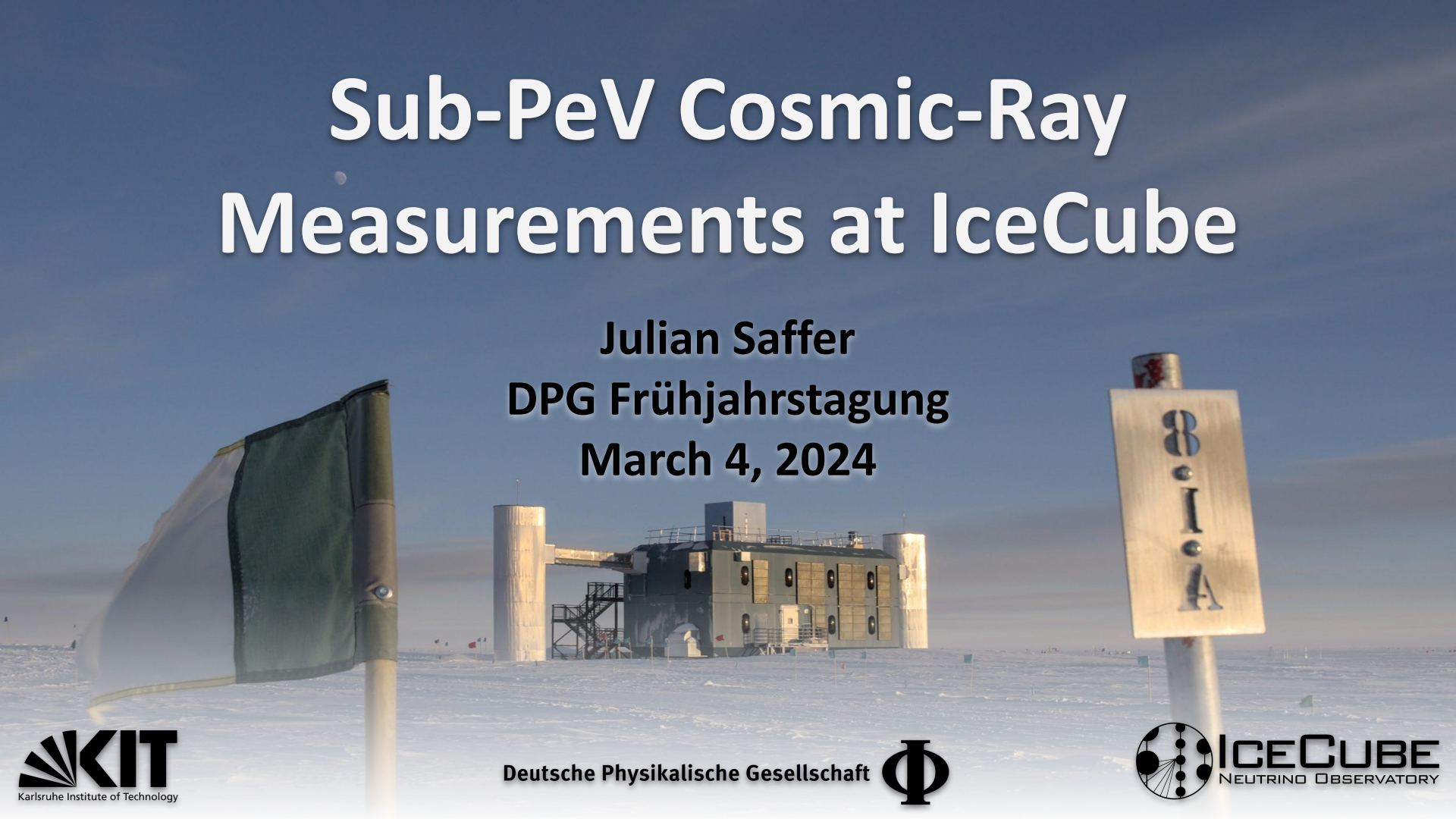


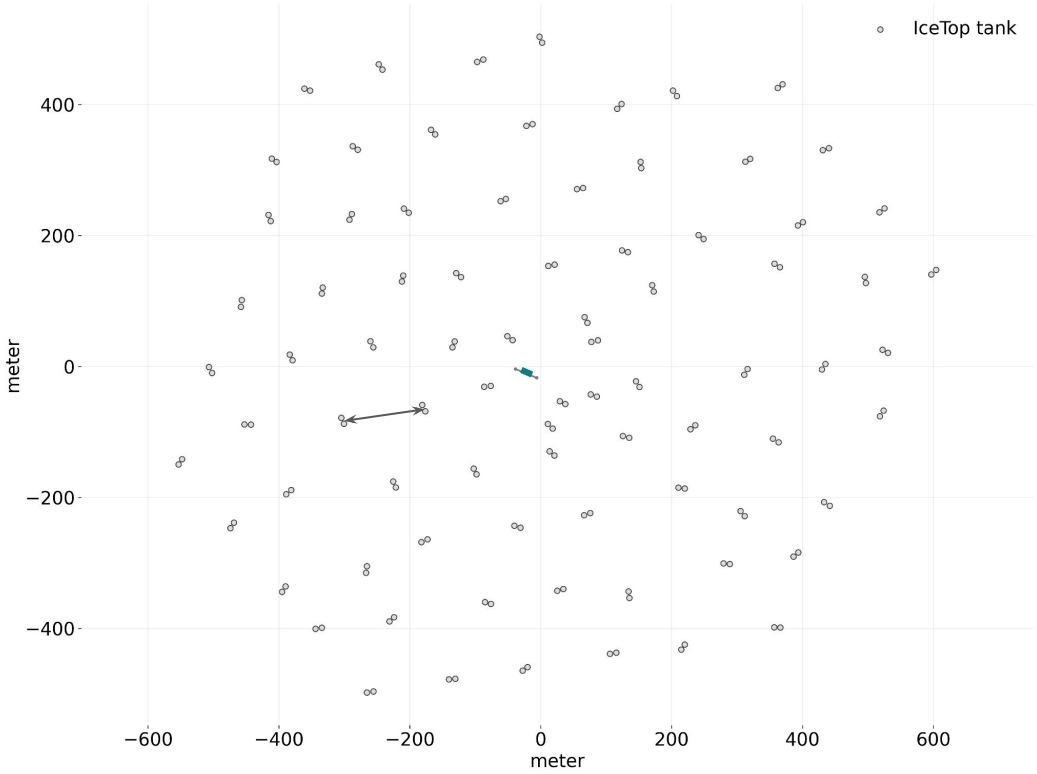
Karlsruhe Institute of Technology

Deutsche Physikalische Gesellschaft

IceCube Neutrino Observatory

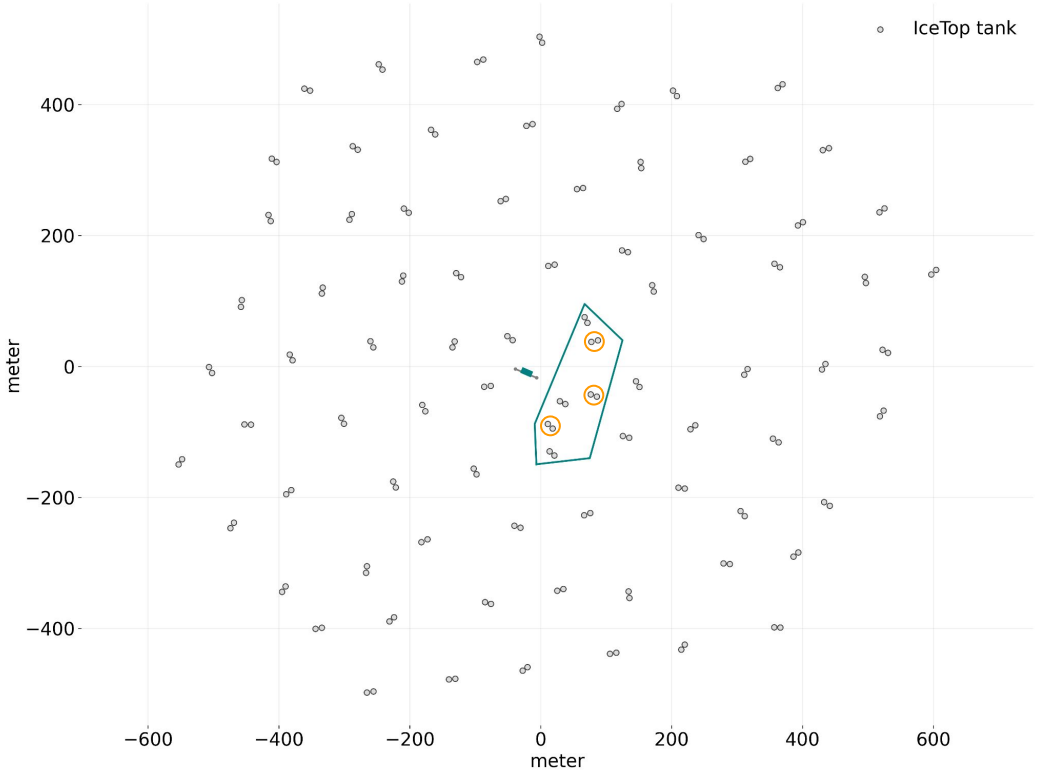
The Cosmic-Ray Detector IceTop

- 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

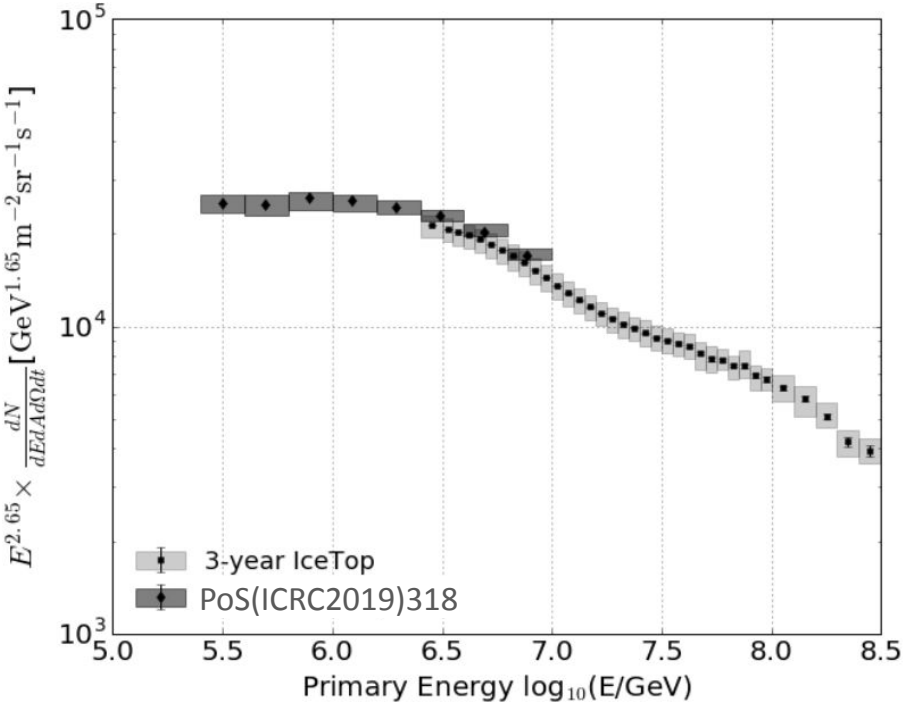
- Ice-Cherenkov tank array at the South Pole (680 g/cm²)
- Area of 1 km²
- Spacing between stations: 125 m in the in-fill: < 50 m
- air-shower energy range: 100 TeV – few EeV



The Cosmic-Ray Detector IceTop

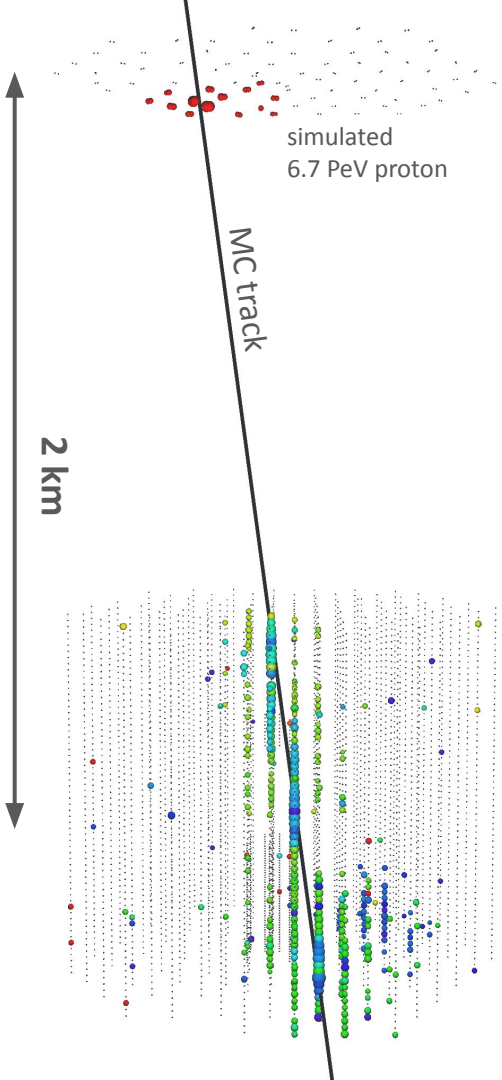
- Previous composition analyses started at full efficiency (3 PeV)

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



The Cosmic-Ray Detector IceTop

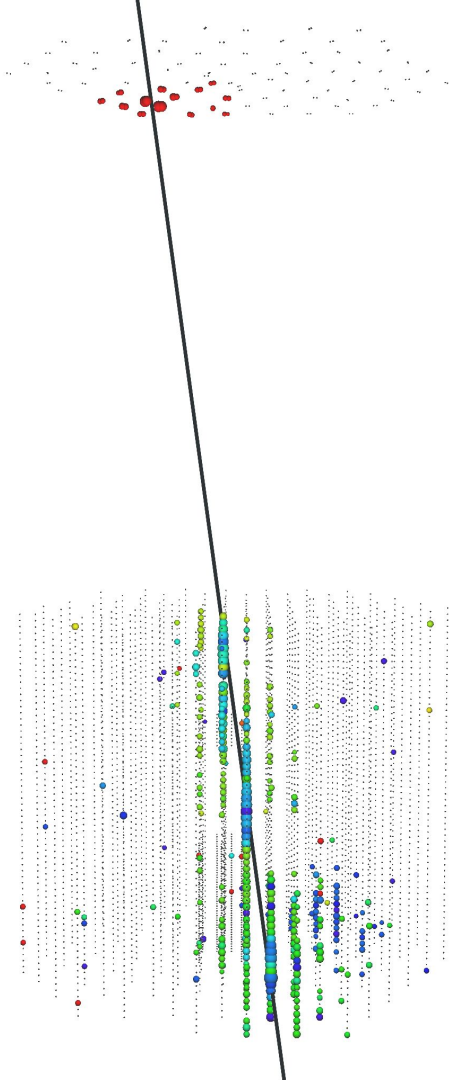
- Previous composition analyses started at full efficiency (3 PeV)
- All-particle energy spectrum with composition assumption starting at 250 TeV
- Coincidences with the in-ice array below
  - improve / enable directional reconstruction
  - in-ice muon bundle holds potential composition information



Event Selection & Processing

The new processing includes:

- Selecting coincident events



Event Selection & Processing

The new processing includes:

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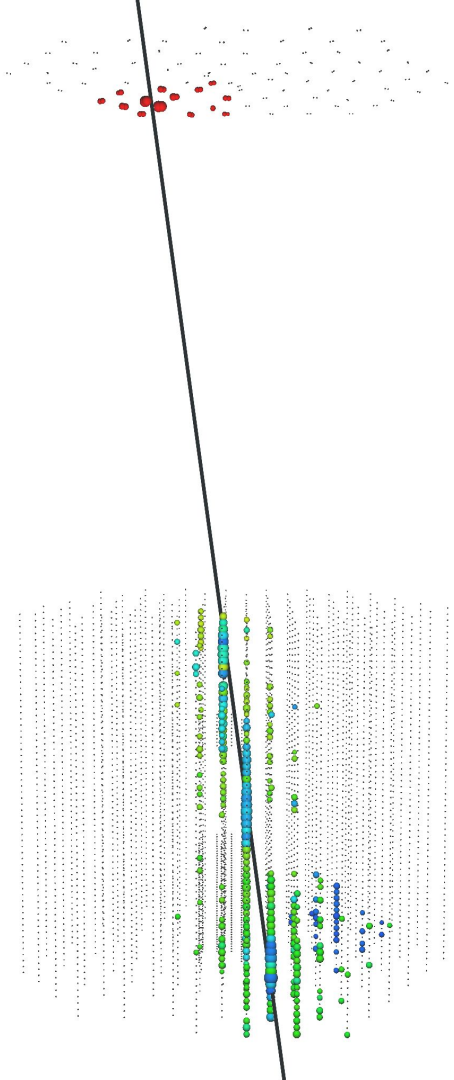
- Cleaning of in-ice pulses



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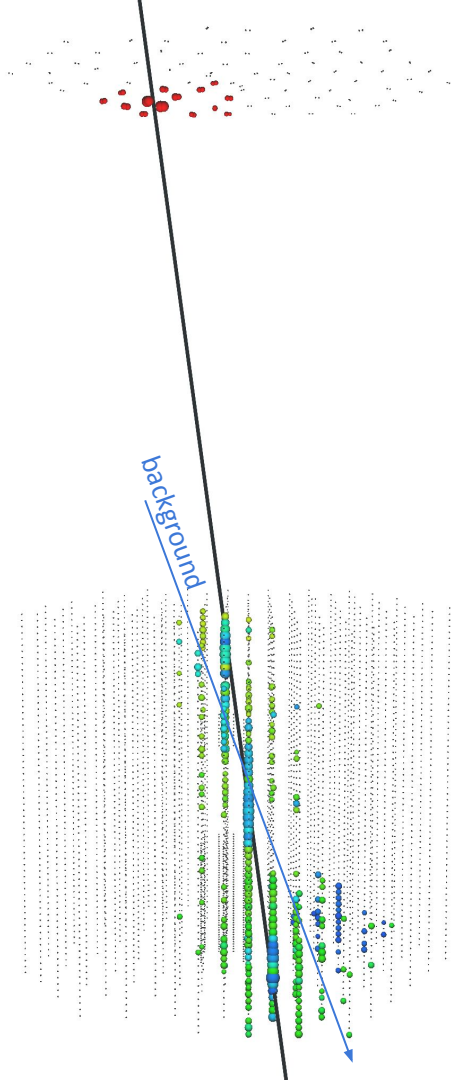

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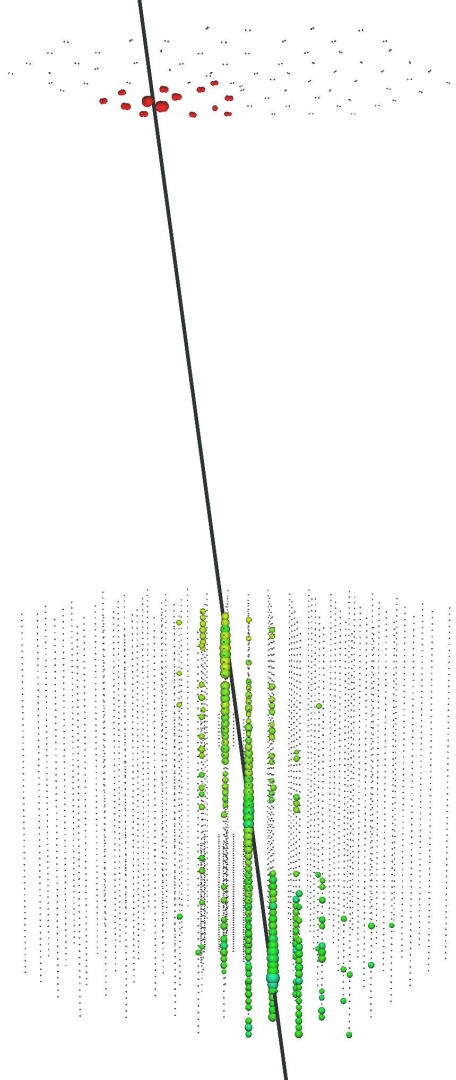


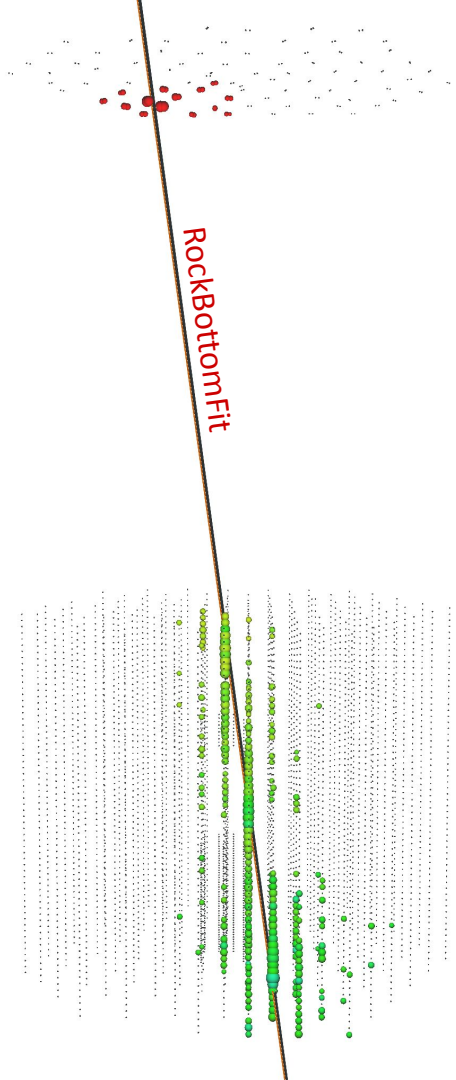
Event Selection & Processing

The new processing includes:

- Selecting coincident events
- Cleaning of in-ice pulses
- Removing coincident background
- Performing directional fit *“RockBottom”* to both surface and in-ice pulses

  → minimizing combined -log(*L*) with
  - in-ice pulses (track: infinite muon hypothesis) and
  - IceTop pulses (timing: Gaussian shower front hypothesis)

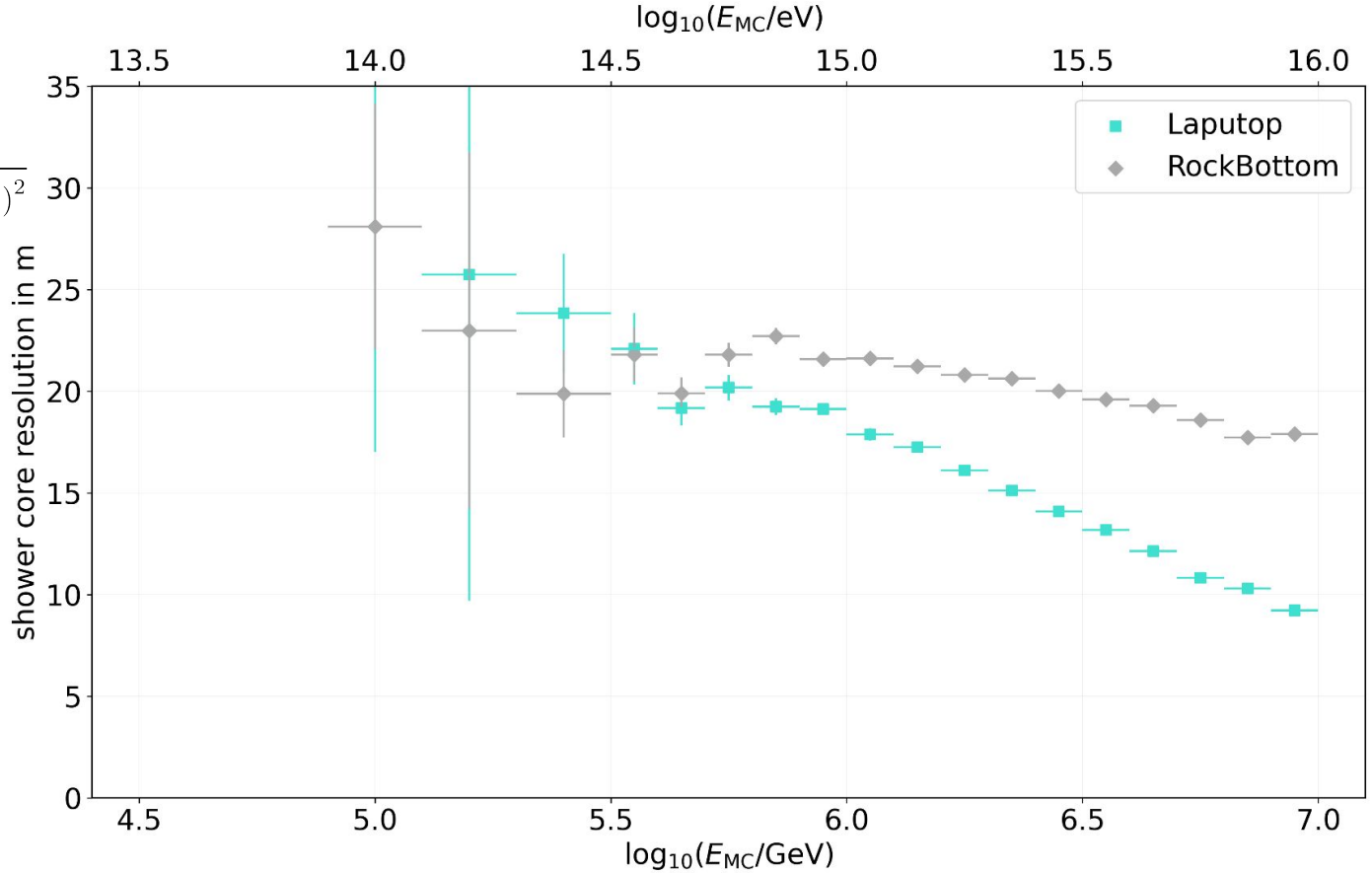
  keep shower core fixed around seed within a few meter



Shower Core Resolution

Defined as 68-percentile of $\sqrt{(x_{\mathrm{MC}} - x_{\mathrm{reco}})^2 + (y_{\mathrm{MC}} - y_{\mathrm{reco}})^2}$ distribution

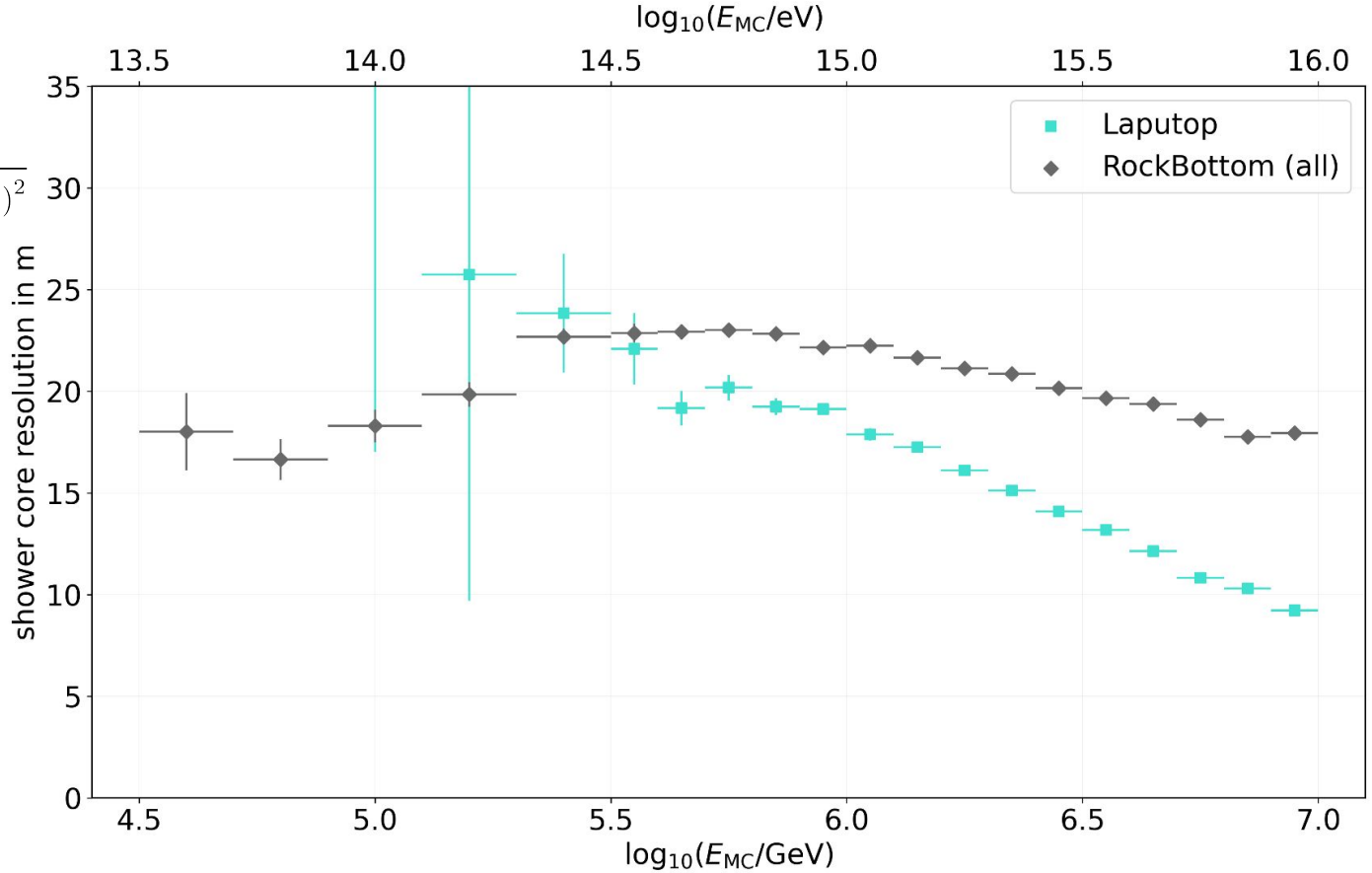
Only events that have successful standard reconstruction “Laputop” (surface only) and a “RockBottom” fit



Shower Core Resolution

Defined as 68-percentile of $\sqrt{(x_{\mathrm{MC}} - x_{\mathrm{reco}})^2 + (y_{\mathrm{MC}} - y_{\mathrm{reco}})^2}$ distribution

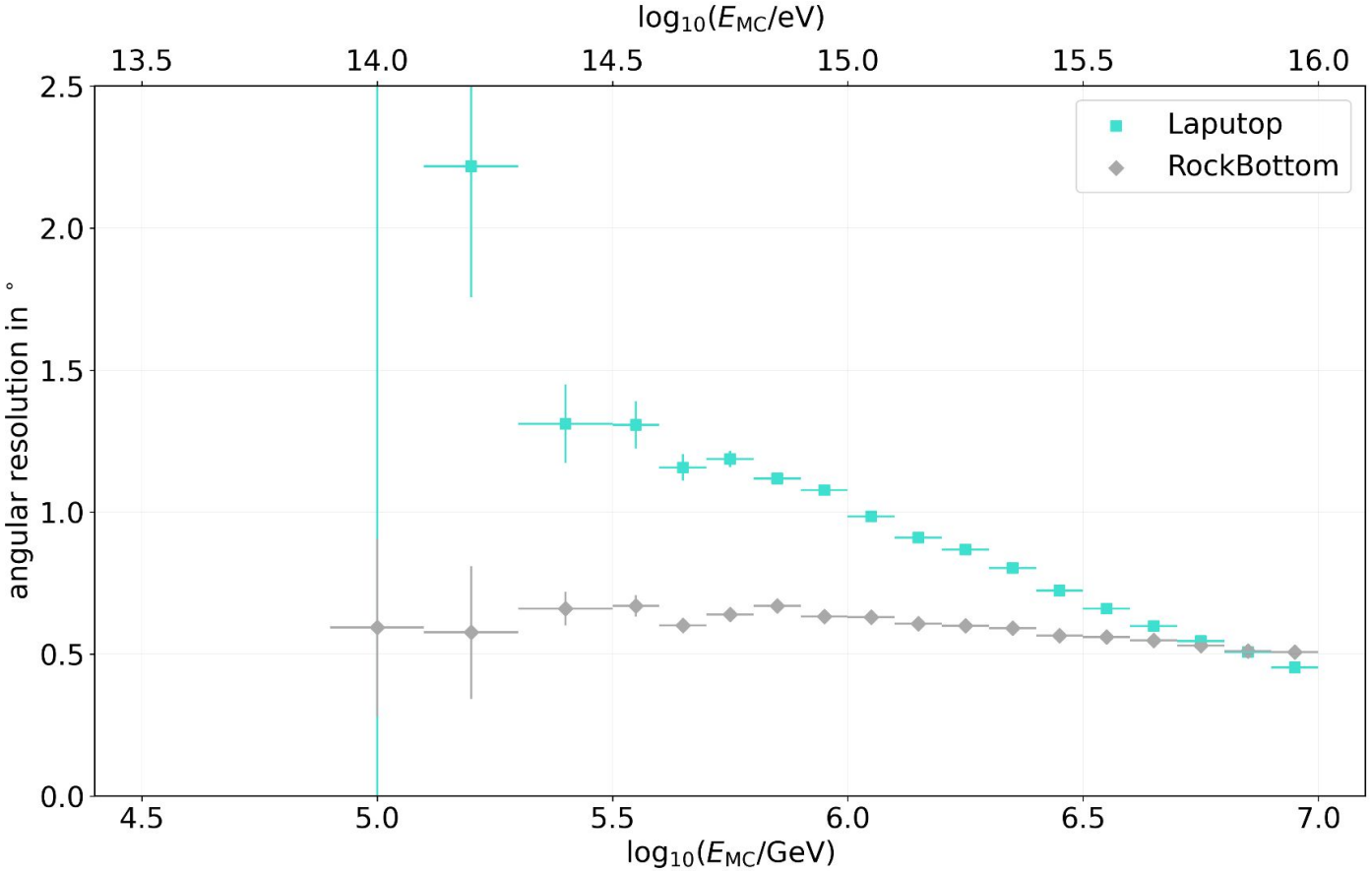
Even showers with just **40 TeV** have a decent core estimate



Angular Resolution

Opening angle between Monte Carlo and reco track

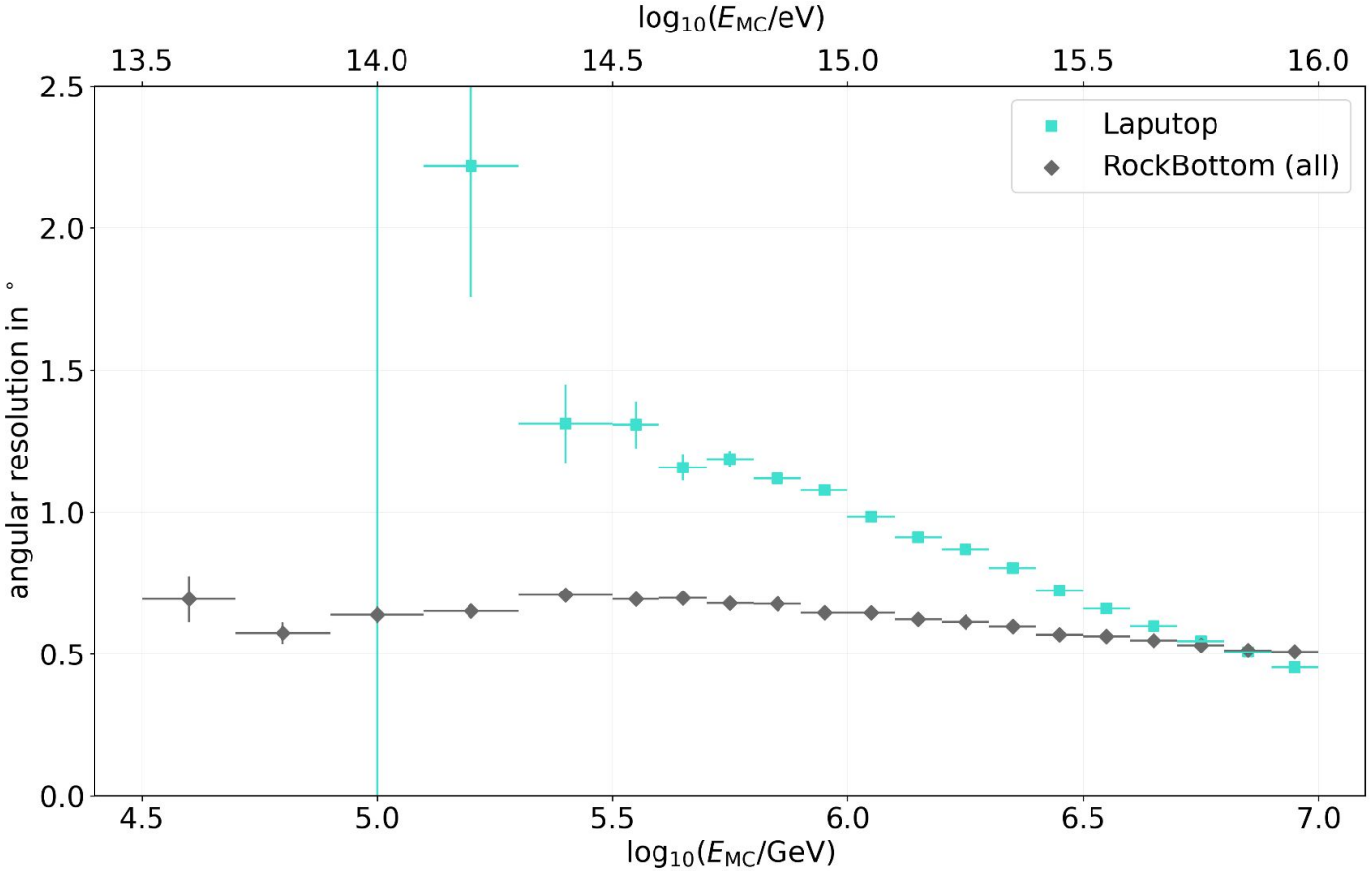
Below 6 PeV RockBottom has much better pointing



Angular Resolution

Opening angle between Monte Carlo and reco track

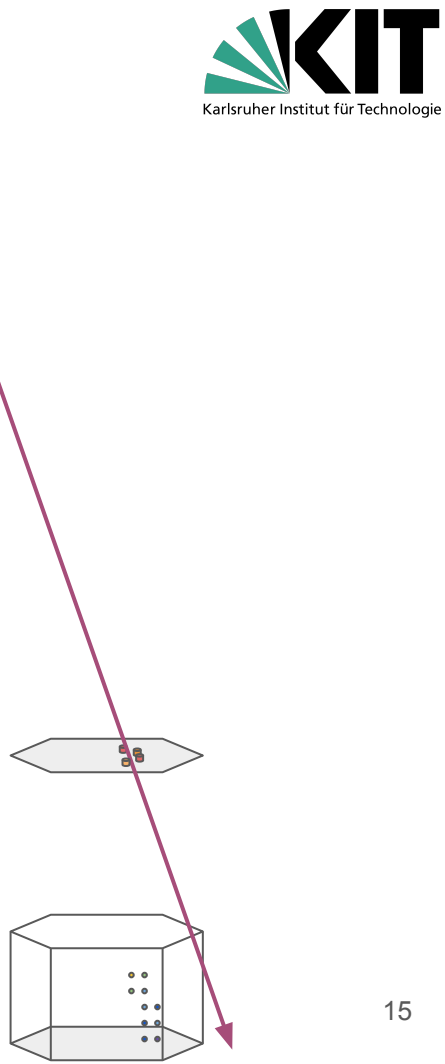
Below 0.7° angular resolution at 40 TeV



Why this Discrepancy?

How can the angular resolution improve so much while core resolution is very similar or even worse than Laputop?

	in-ice pulses	Lateral Distribution Function (LDF)
Laputop	no	yes
this RockBottom	yes	no



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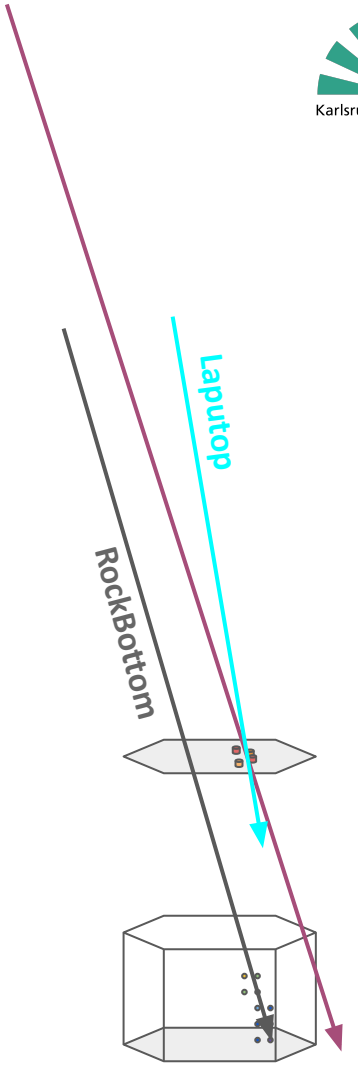

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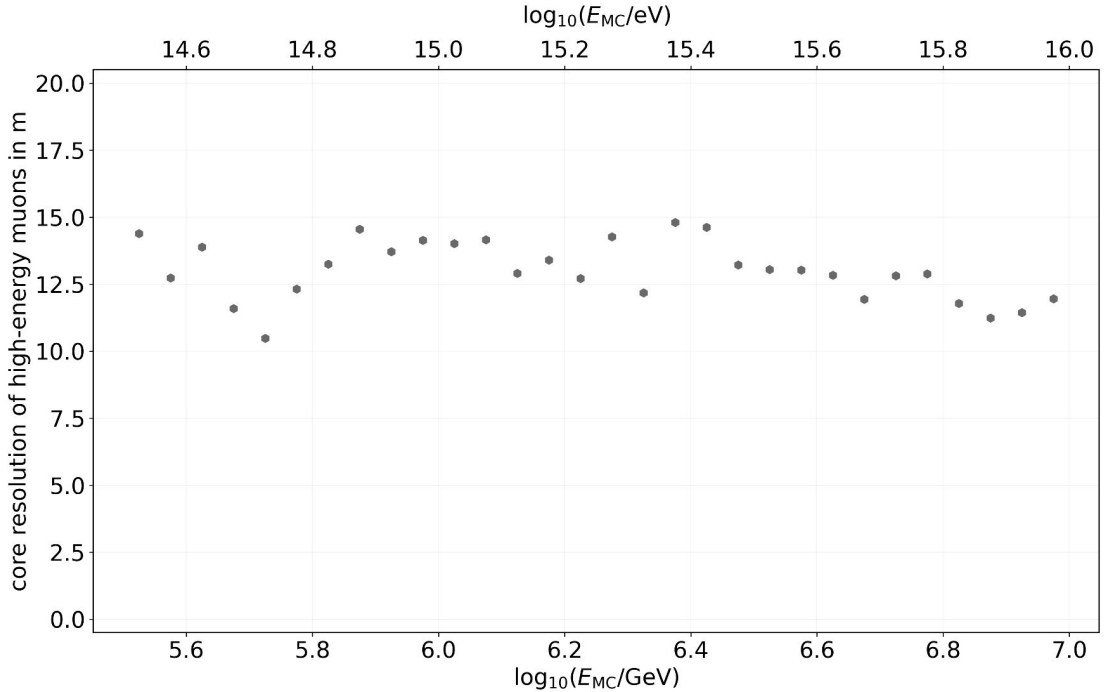
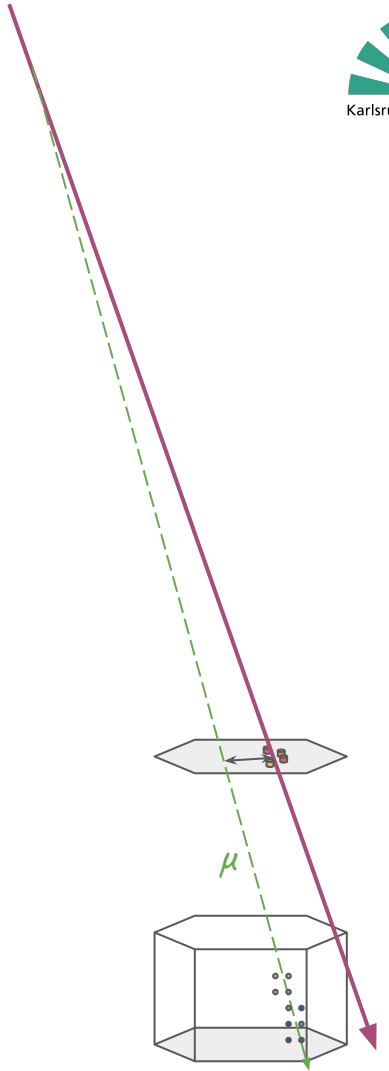
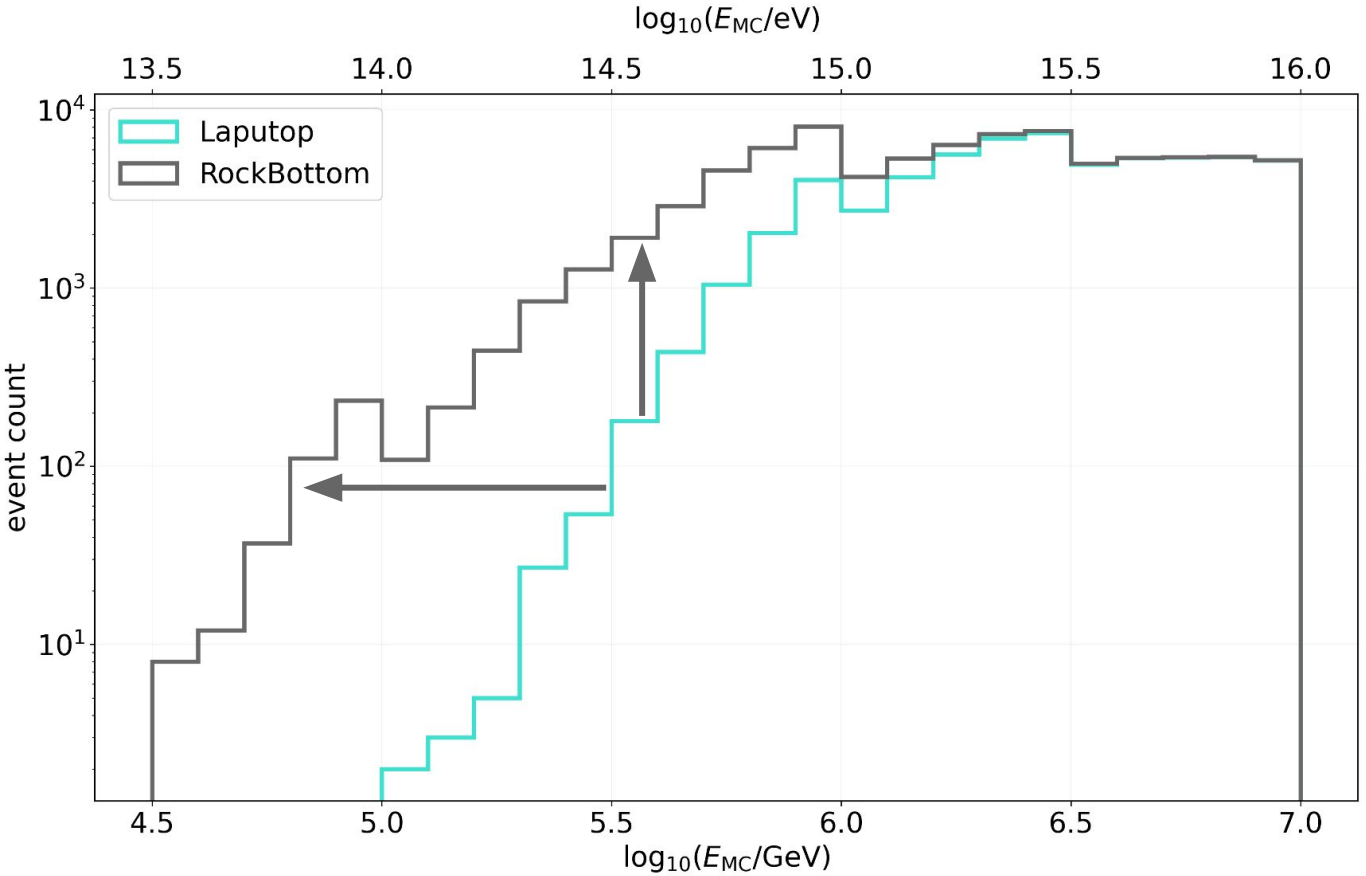




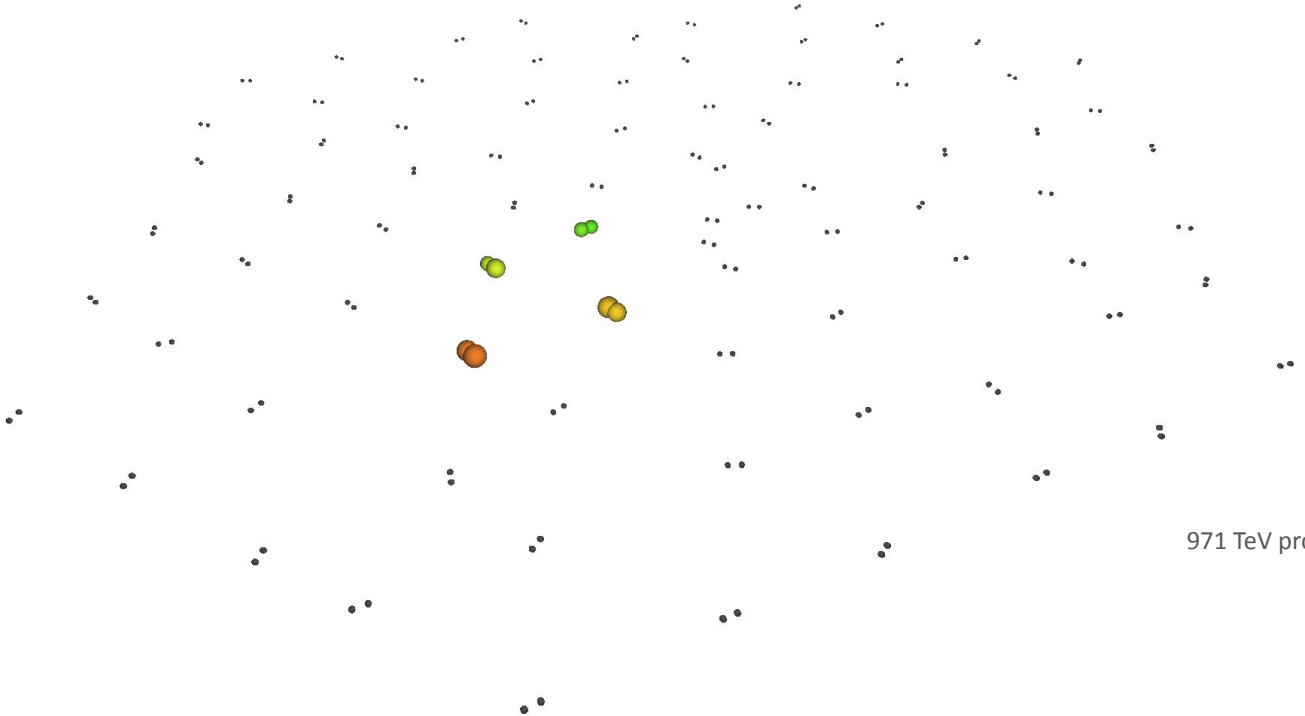
Increased Reconstructability below PeV Energies



Single-Tank Hits

Track reconstruction uses tank-pair hits, close to the shower core

Mostly electromagnetic particles

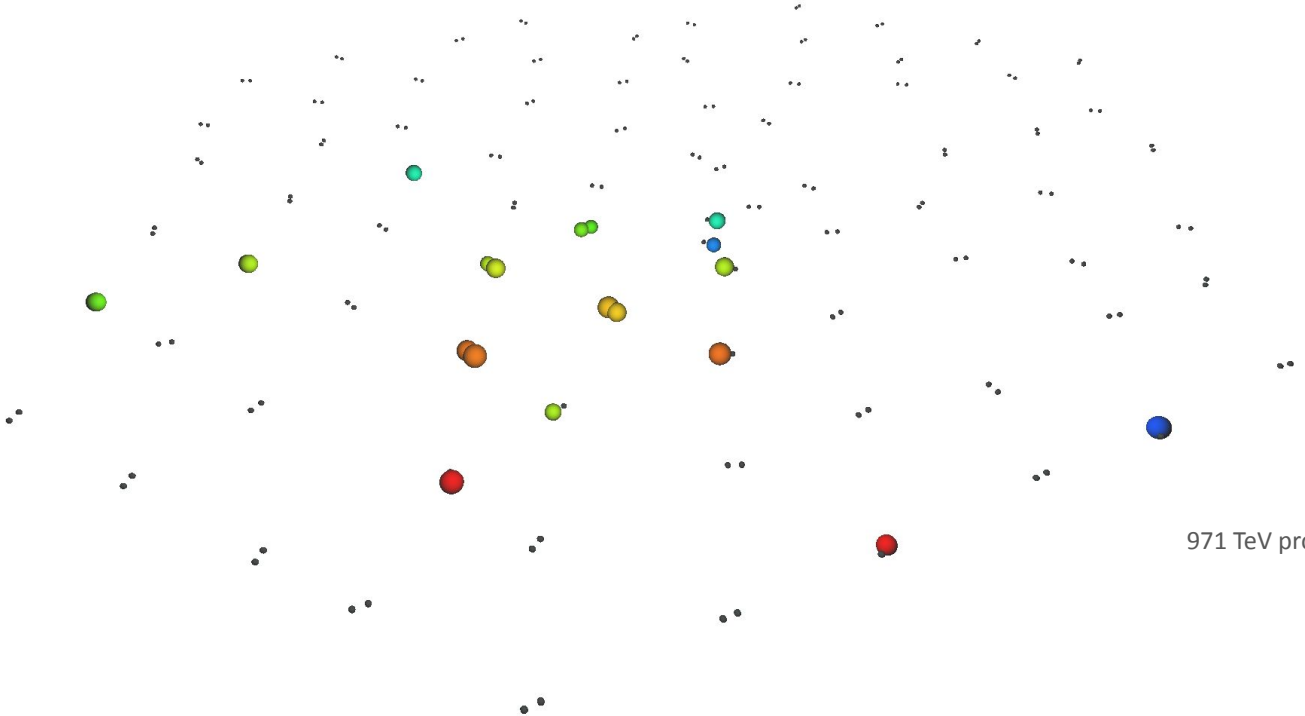


971 TeV proton

Single-Tank Hits

Single tank hits further away from the shower core

Predominantly triggered by GeV muons



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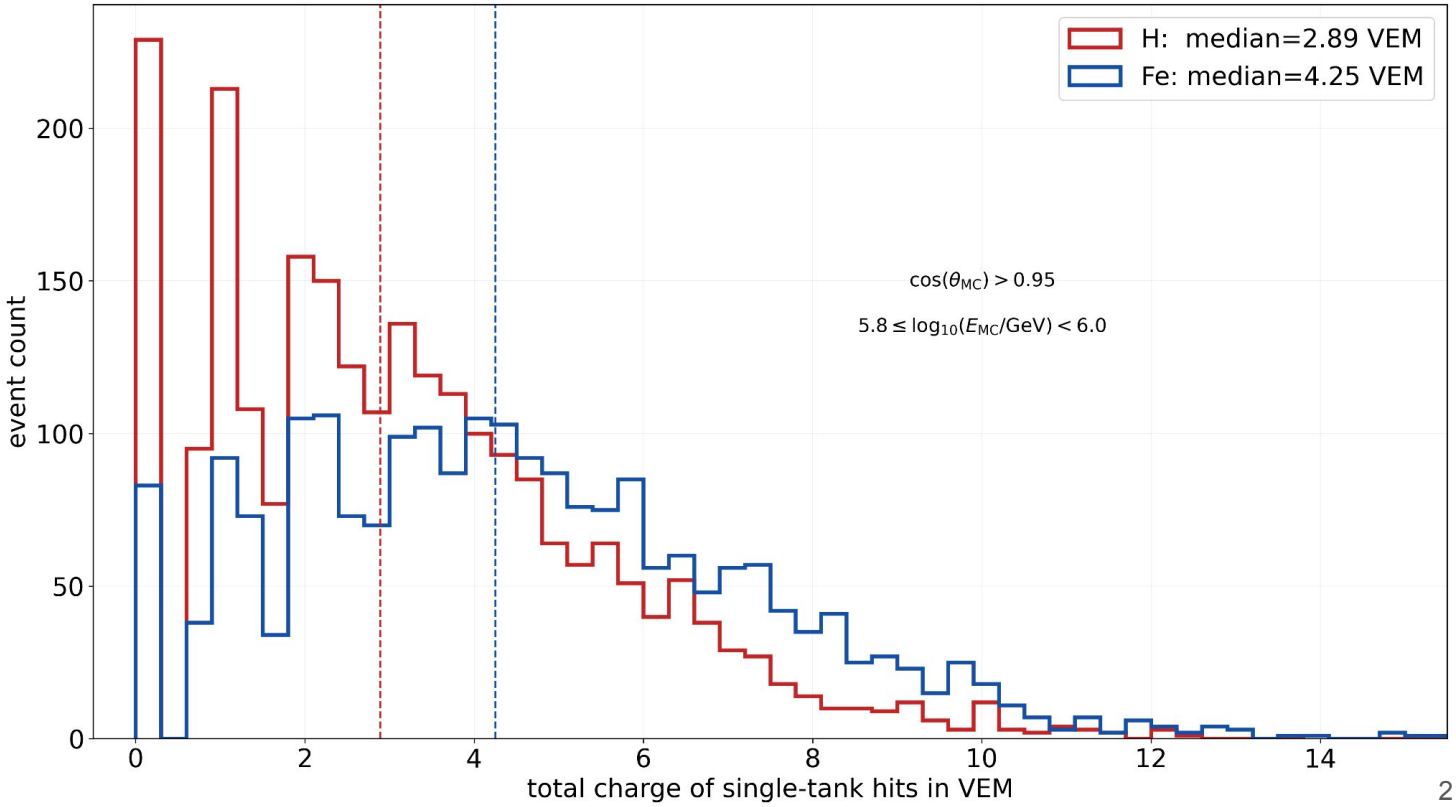
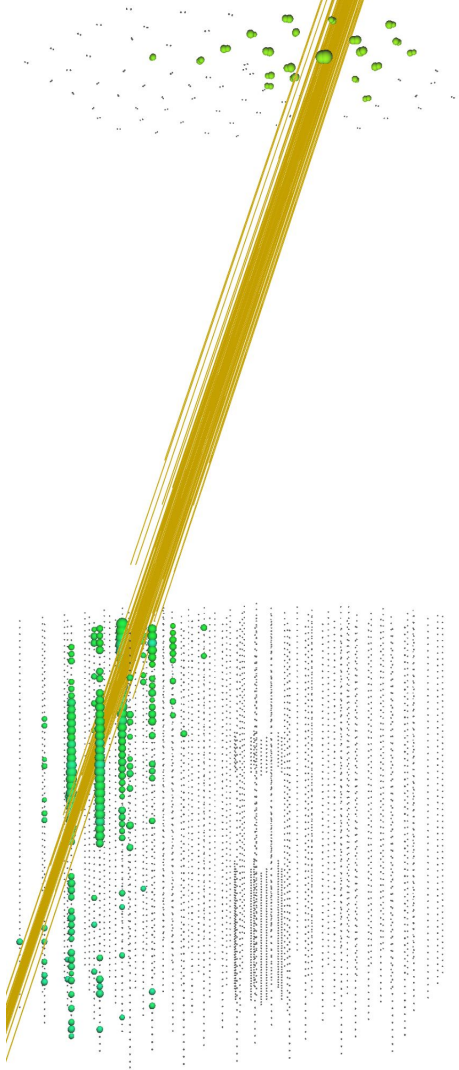


In-Ice Hits

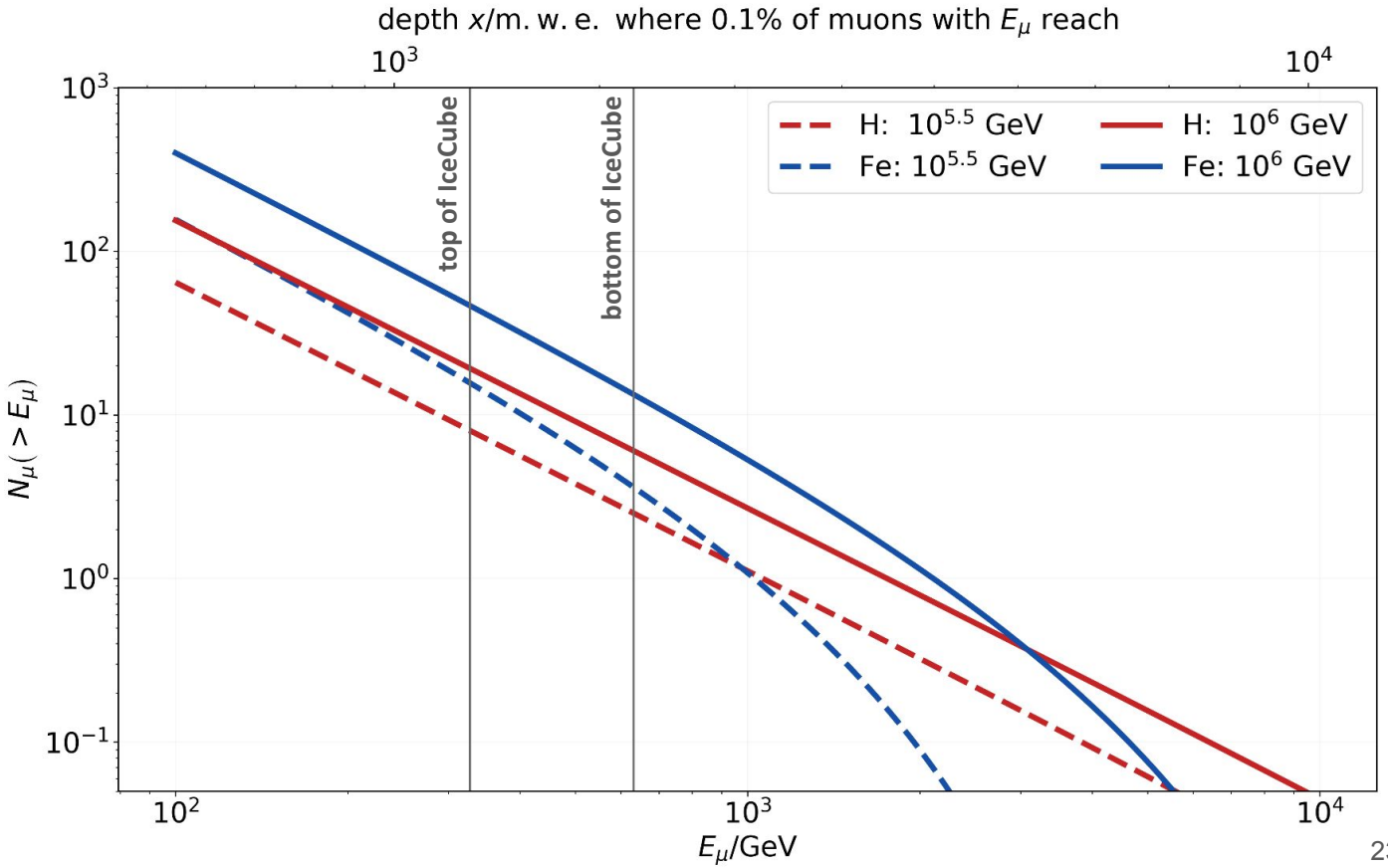
Muon bundle not only useful for directional fit, also composition dependence

Predominantly triggered by TeV muons



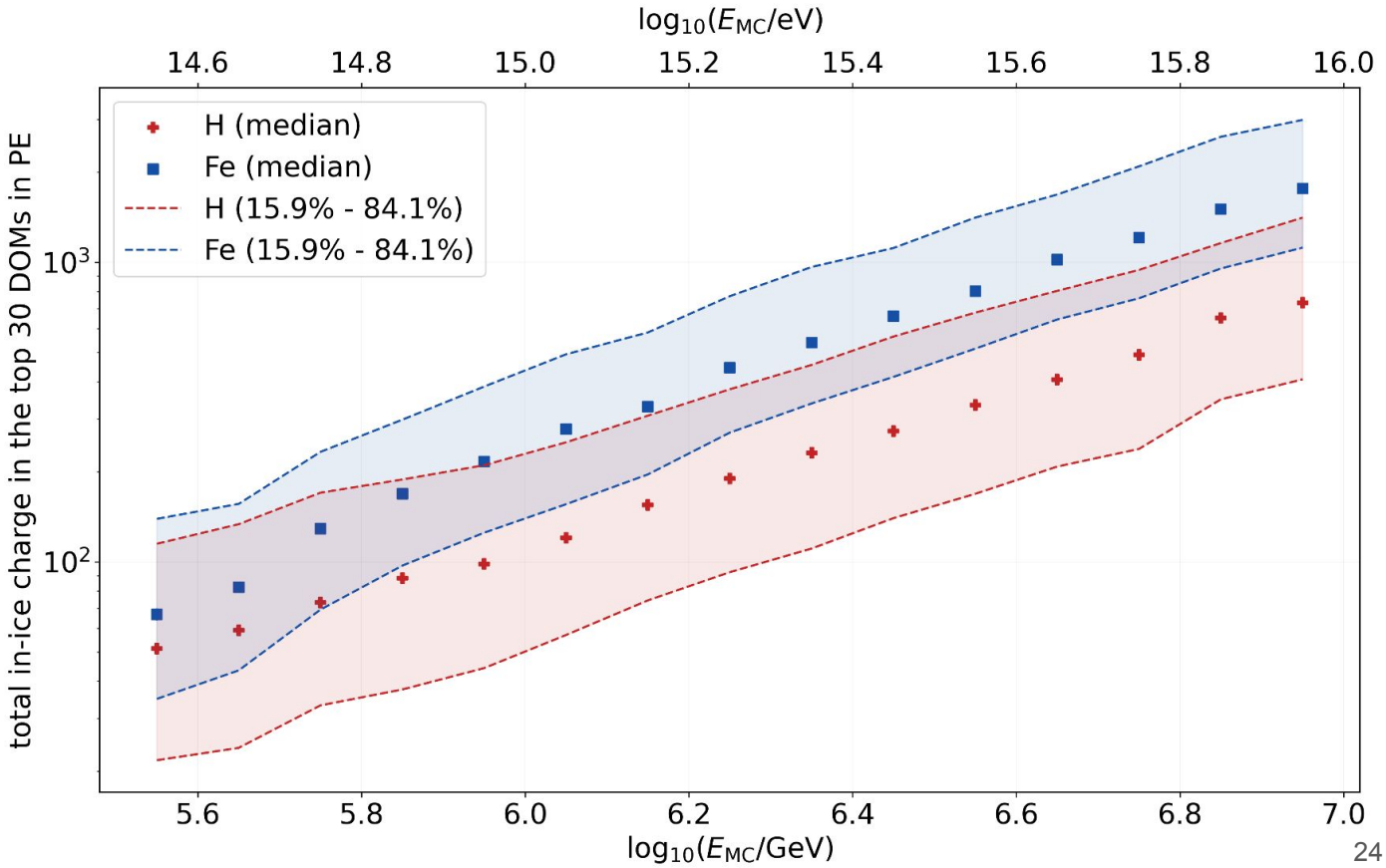
In-Ice Hits

Further down in the ice, muon number becomes less distinct



In-Ice Hits

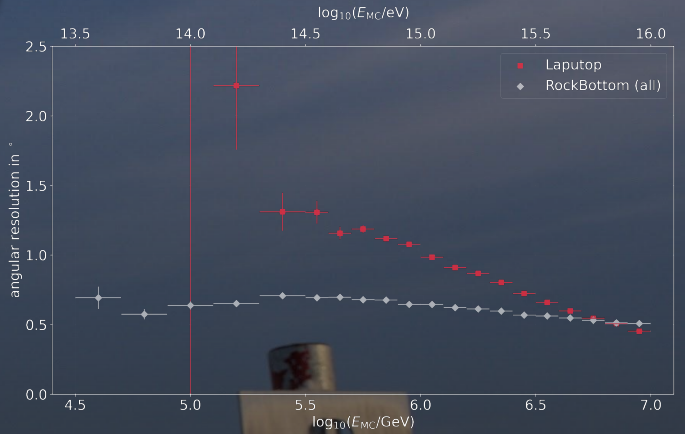
Collect charge in top half of in-ice array



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



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Outlook

- Use LDF fit in RockBottom 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

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Energy Estimation