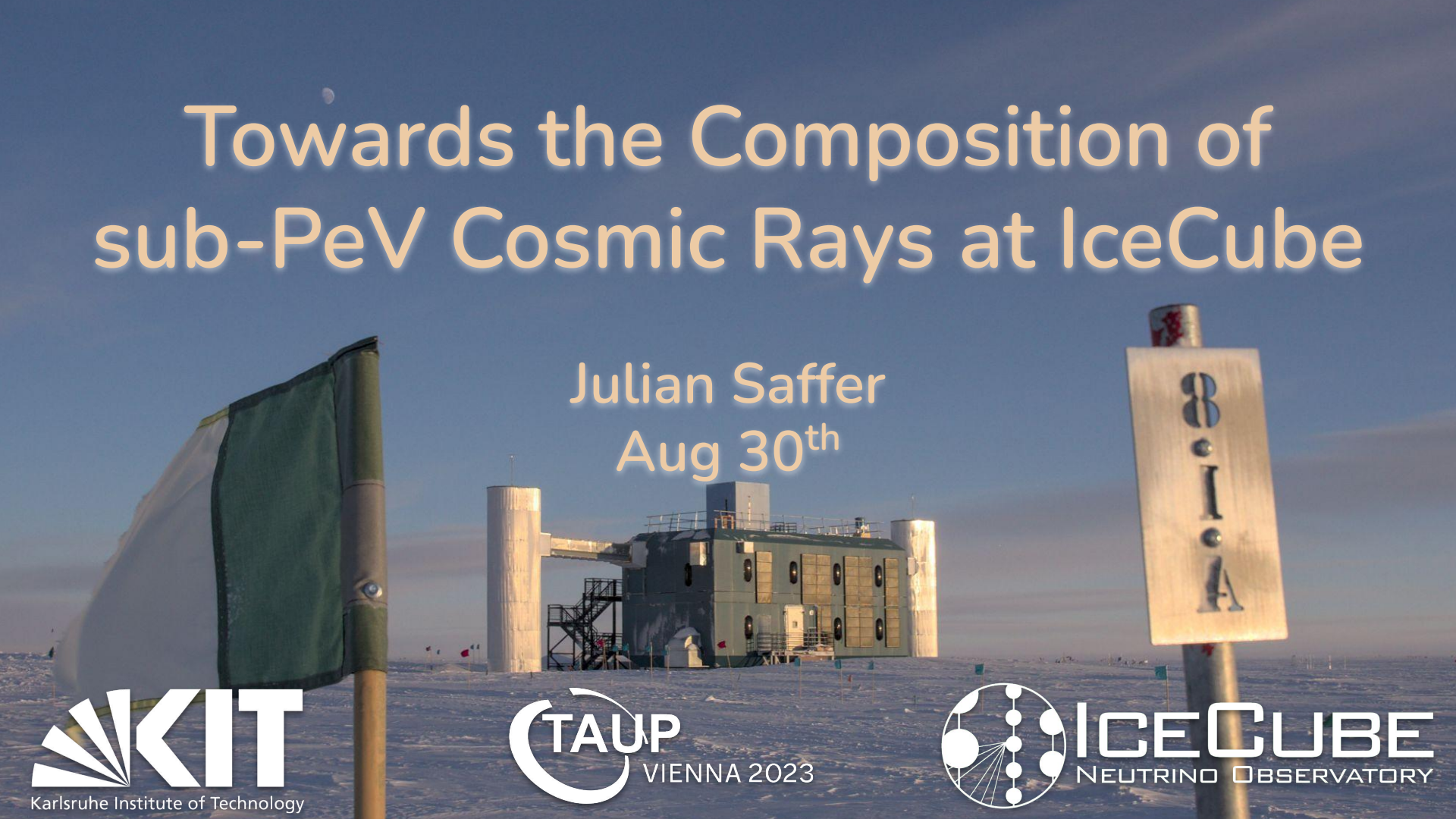
Towards the Composition of sub-PeV Cosmic Rays at IceCube

Julian Saffer

Aug 30th



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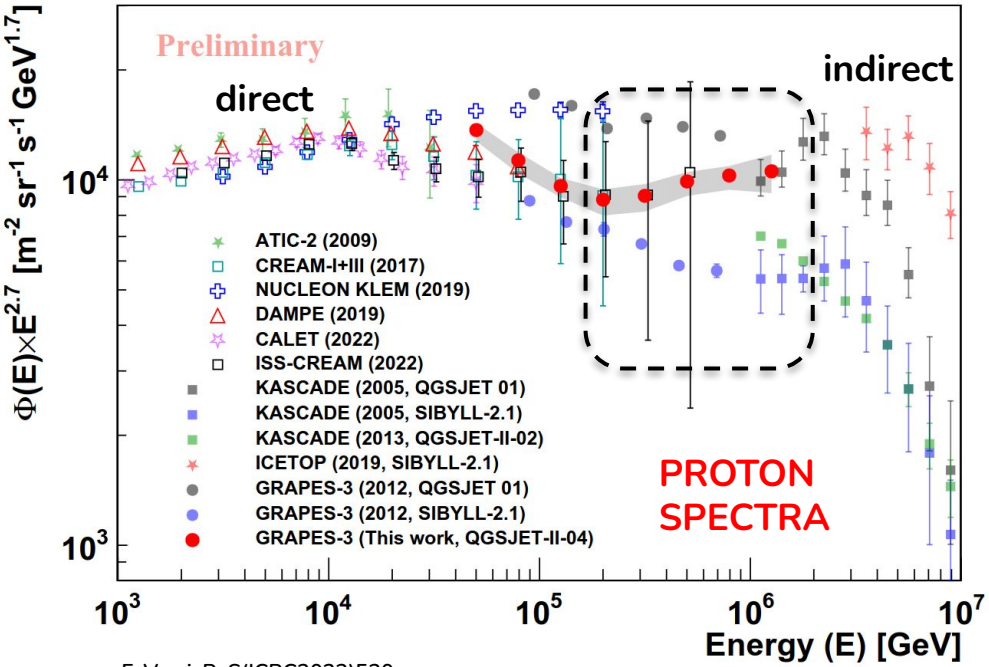
IceCube Neutrino Observatory

Below the Knee

- overlap region of direct and indirect CR measurements inconsistent (dependence on hadronic model)



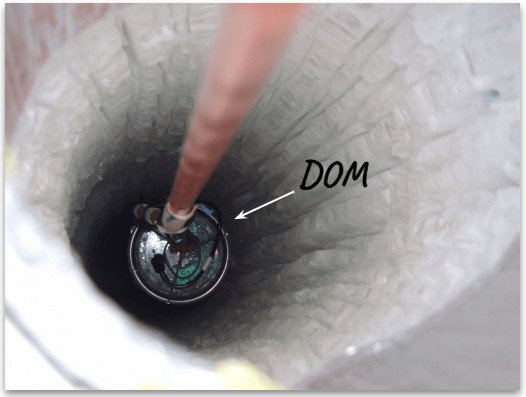
F. Varsi, PoS(ICRC2023)520

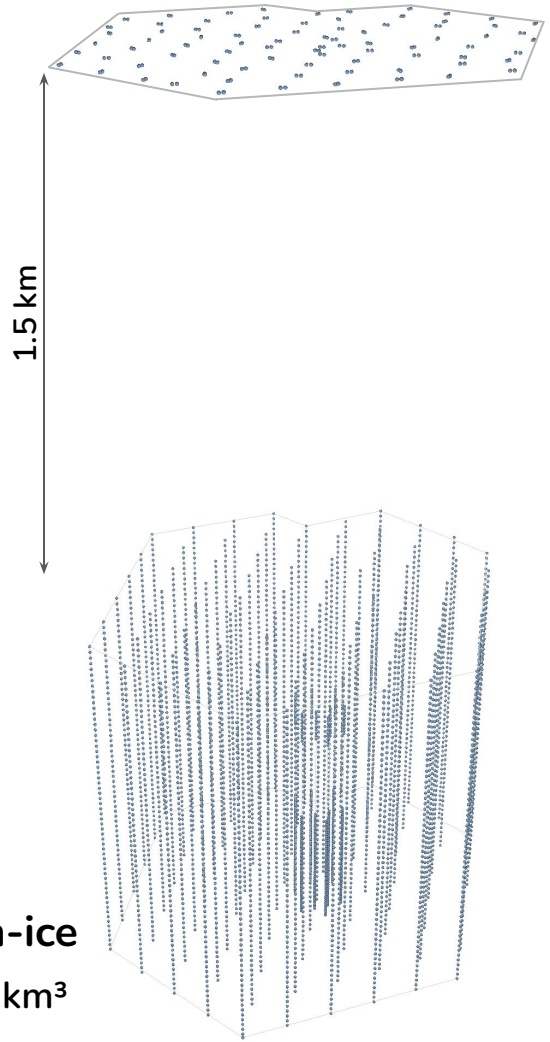
- IceCube has potential to lower its energy threshold for composition spectra to few hundred TeV
- everything I will show is Monte Carlo (proton & iron), unless stated explicitly otherwise

IceCube Neutrino Observatory

86 strings
60 DOMs per string

1.5-2.5 km below surface





in-ice

1 km³

IceCube Neutrino Observatory

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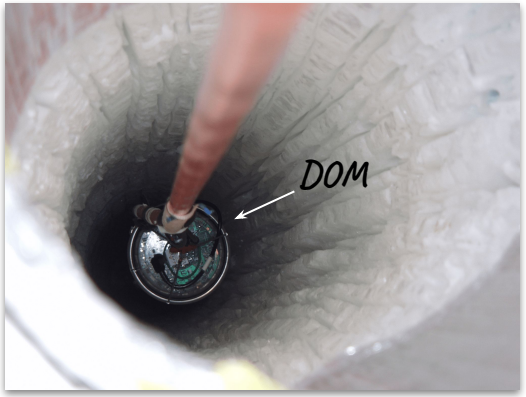
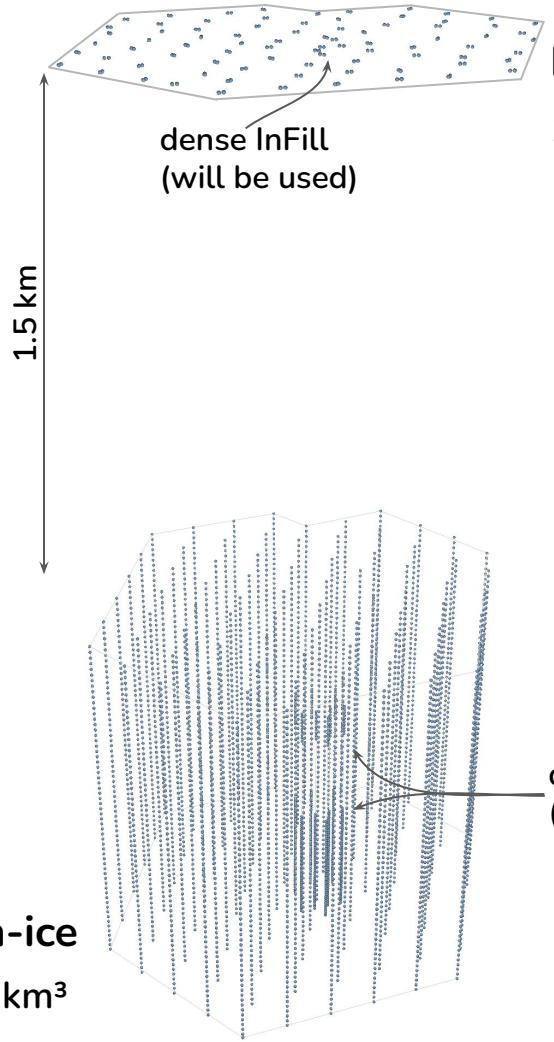




IceTop

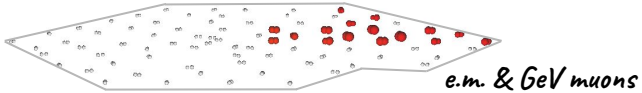
1 km²

in-ice

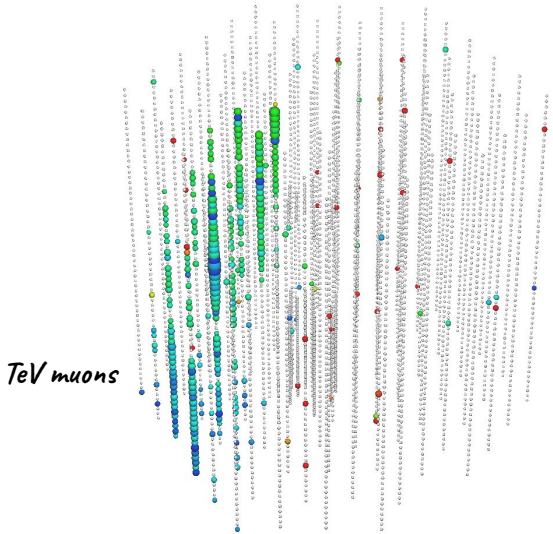
1 km³

81 stations
2 tanks per station
2 DOMs per tank

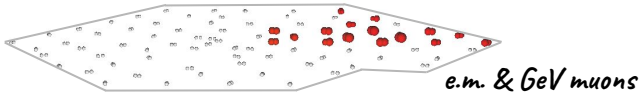
Coincident Events



small zenith angle:
shower can trigger IceTop + TeV muons penetrate in-ice



Coincident Events



small zenith angle:
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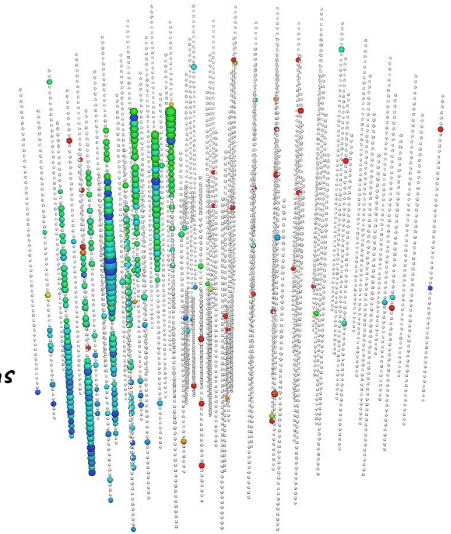
reconstruction of
primary energy
based on e.m. shower
component



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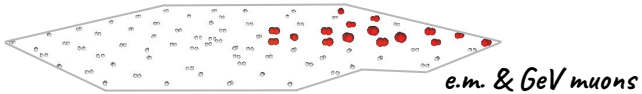
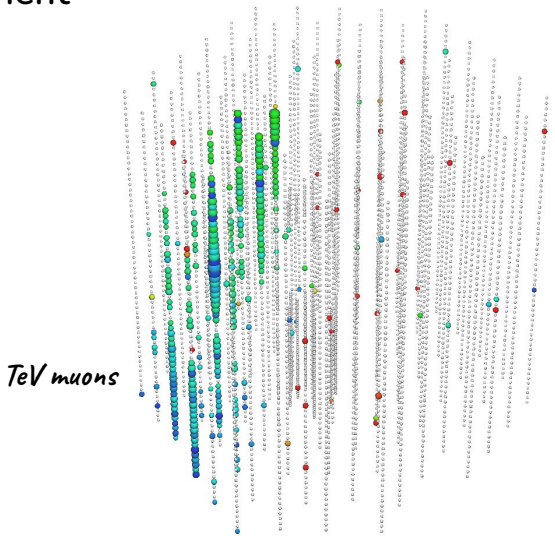


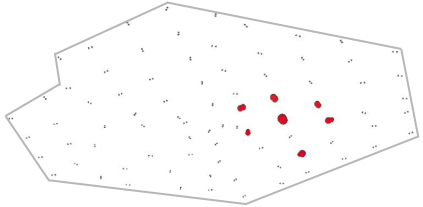
small zenith angle:
shower can trigger IceTop + TeV muons penetrate in-ice

reconstruction of **primary energy** based on e.m. shower component

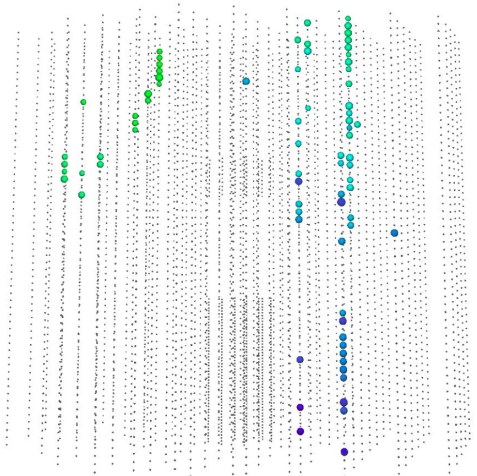
reconstruction of **primary type** (mass) based on muonic shower component



Background Cleaning



- unrelated background tracks can sneak in the readout window



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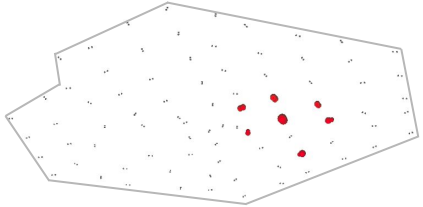
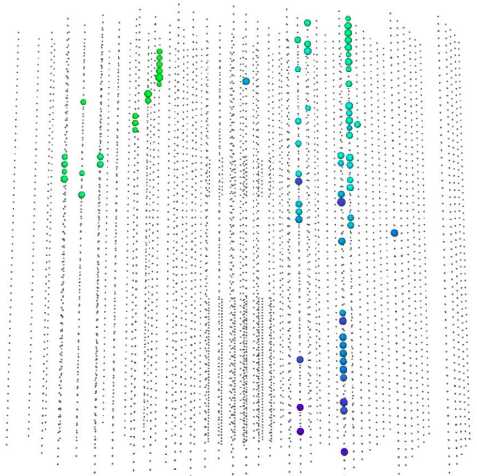


- unrelated background tracks can sneak in the readout window

- for low-energy air-showers, existing cleaning methods don’t always work (missing surface reconstruction)



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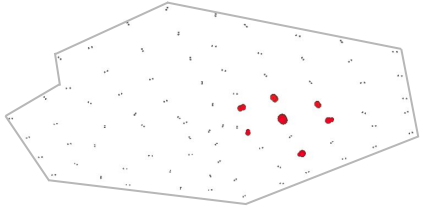
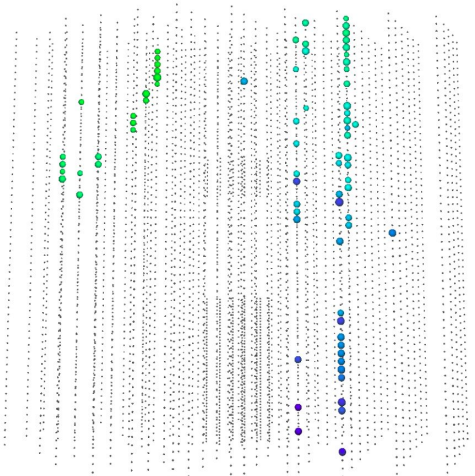
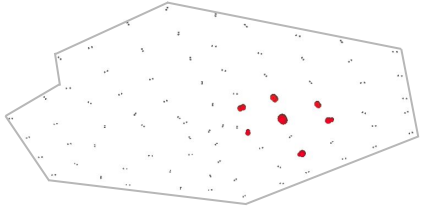


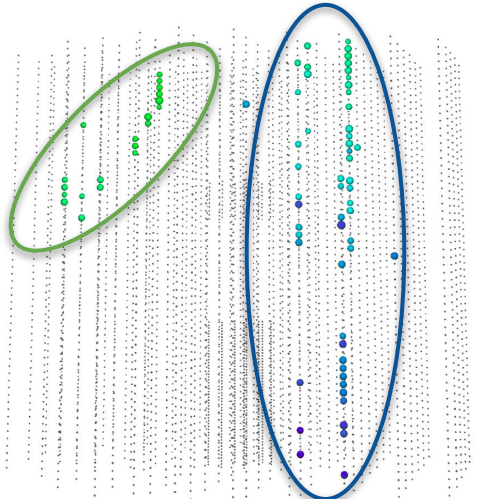
- unrelated background tracks can sneak in the readout window
- for low-energy air-showers, existing cleaning methods don’t always work (missing surface reconstruction)
- adopt established method ***pulse series splitting*** from in-ice analyses



Background Cleaning

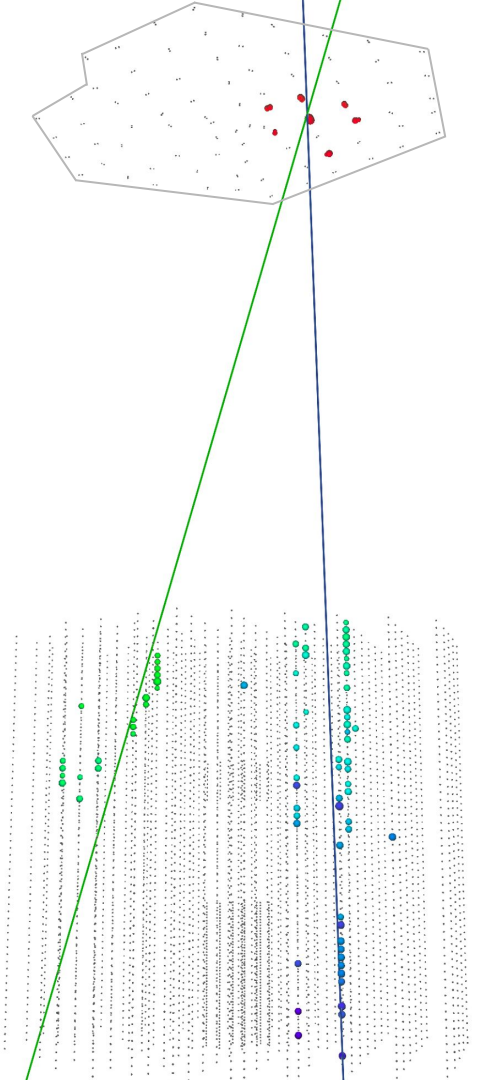


- topological splitting into independent pulse series



Background Cleaning

- topological splitting into independent pulse series
- fit pulse series separately combined with IceTop



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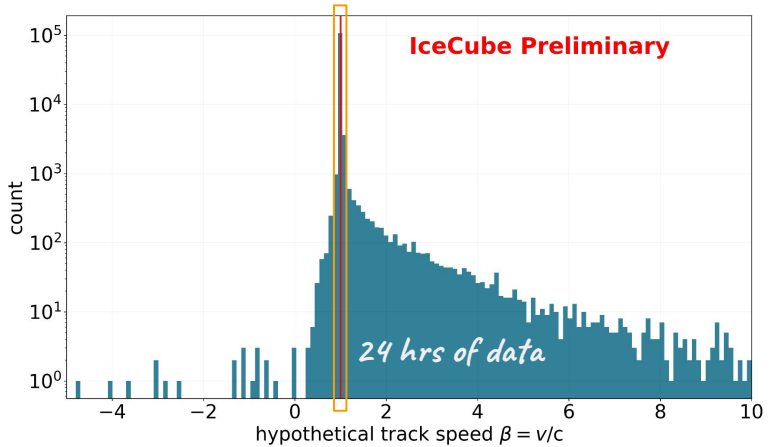
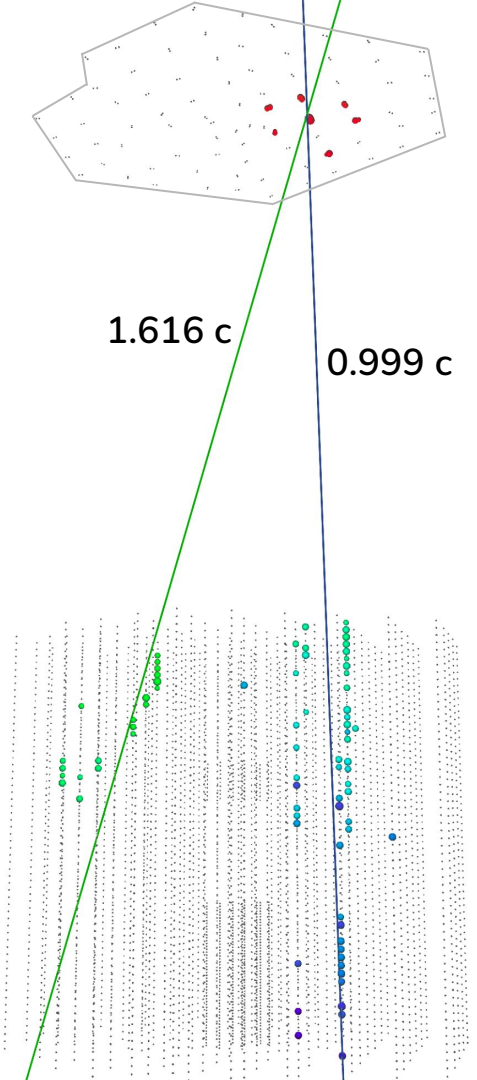
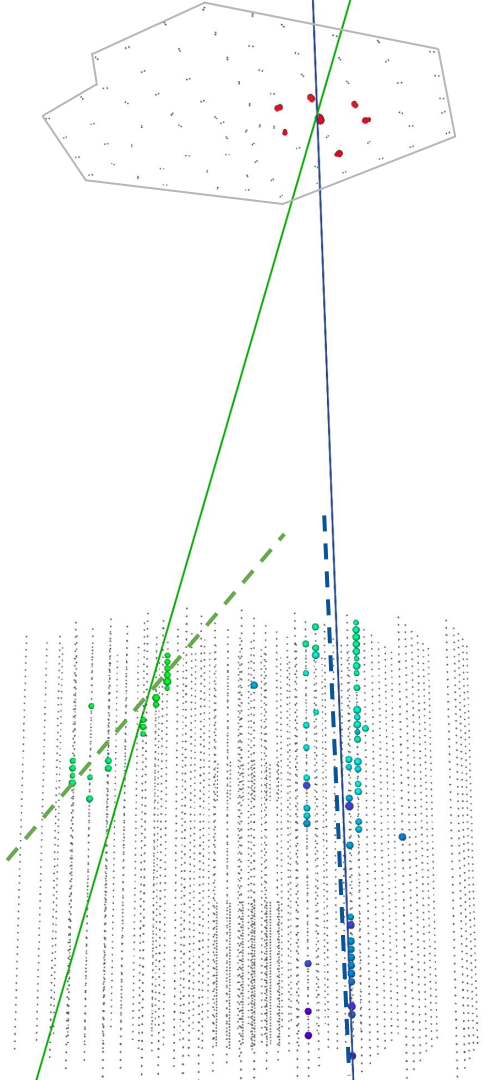




Background Cleaning

- topological splitting into independent pulse series
- fit pulse series separately combined with IceTop
- fit pulse series separately alone



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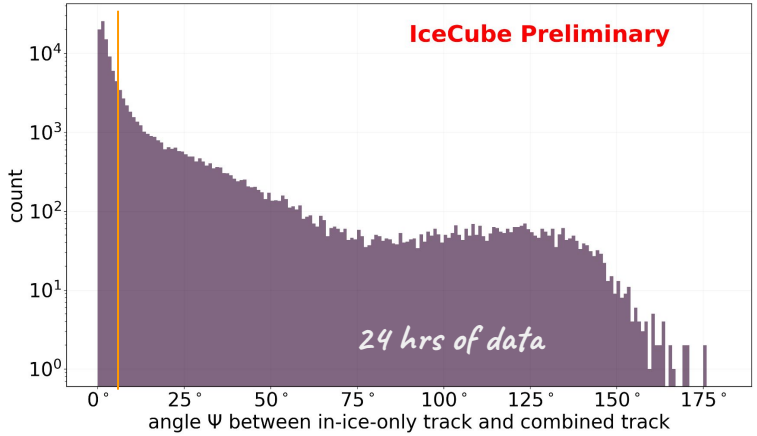
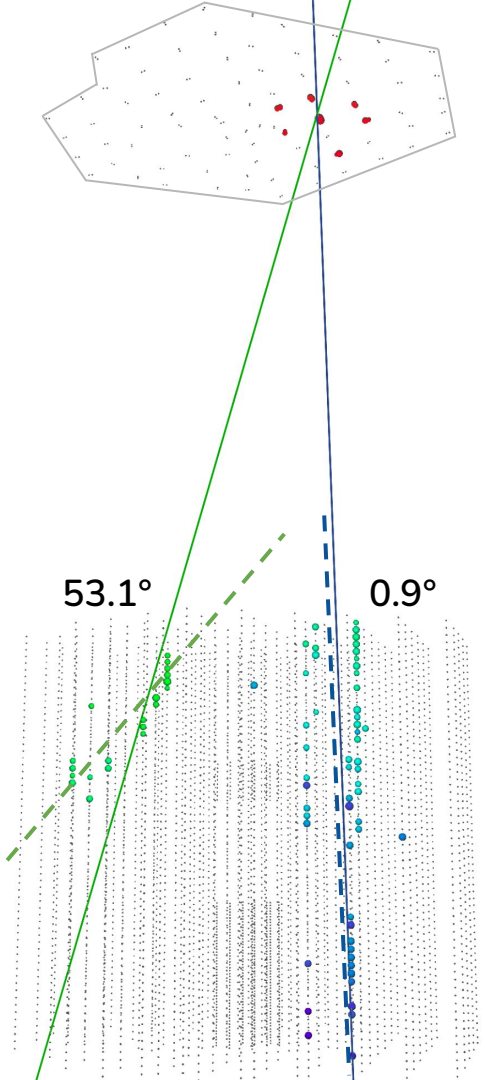
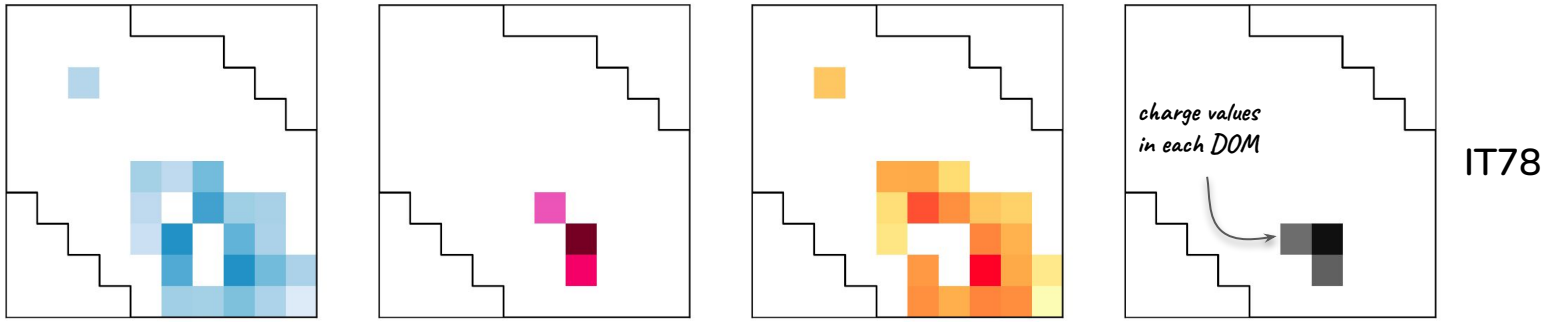
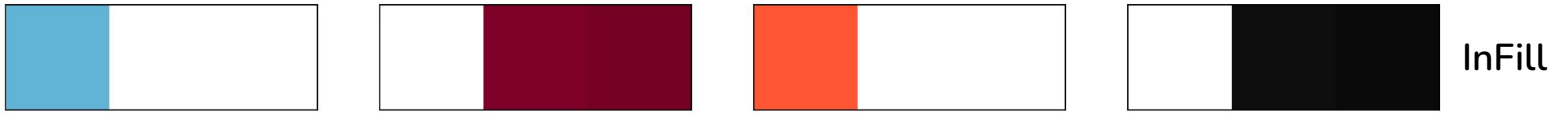




IceTop for Energy

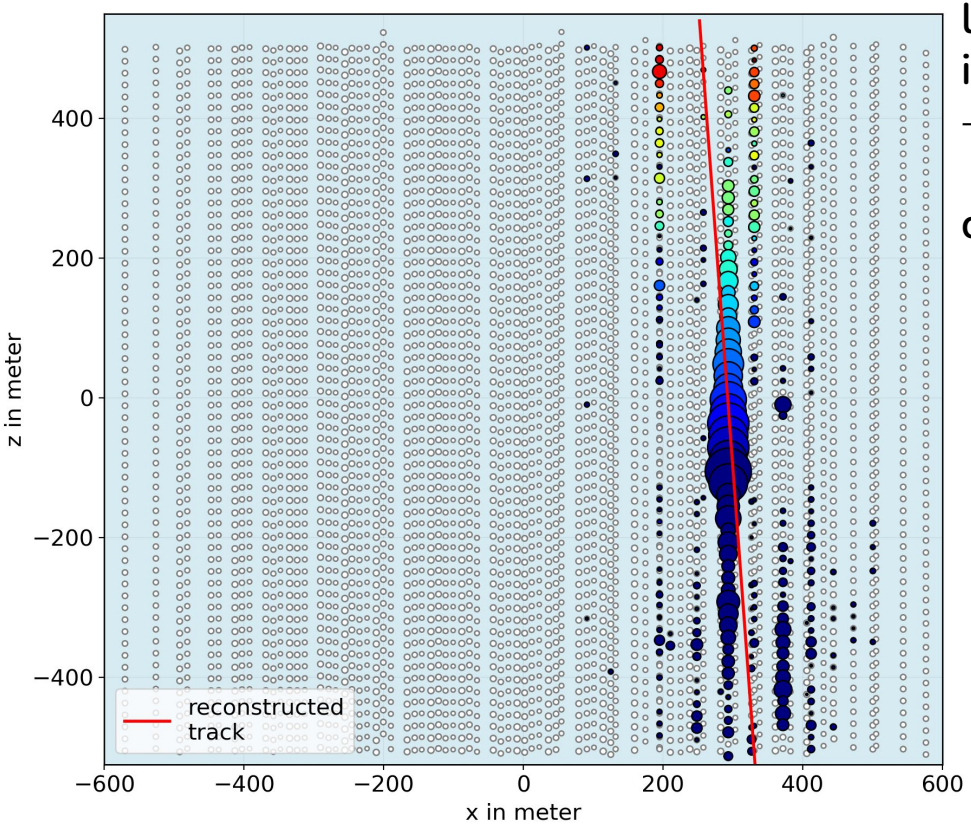


IceCube Preliminary



HG DOMs A | LG DOMs A | HG DOMs B | LG DOMs B

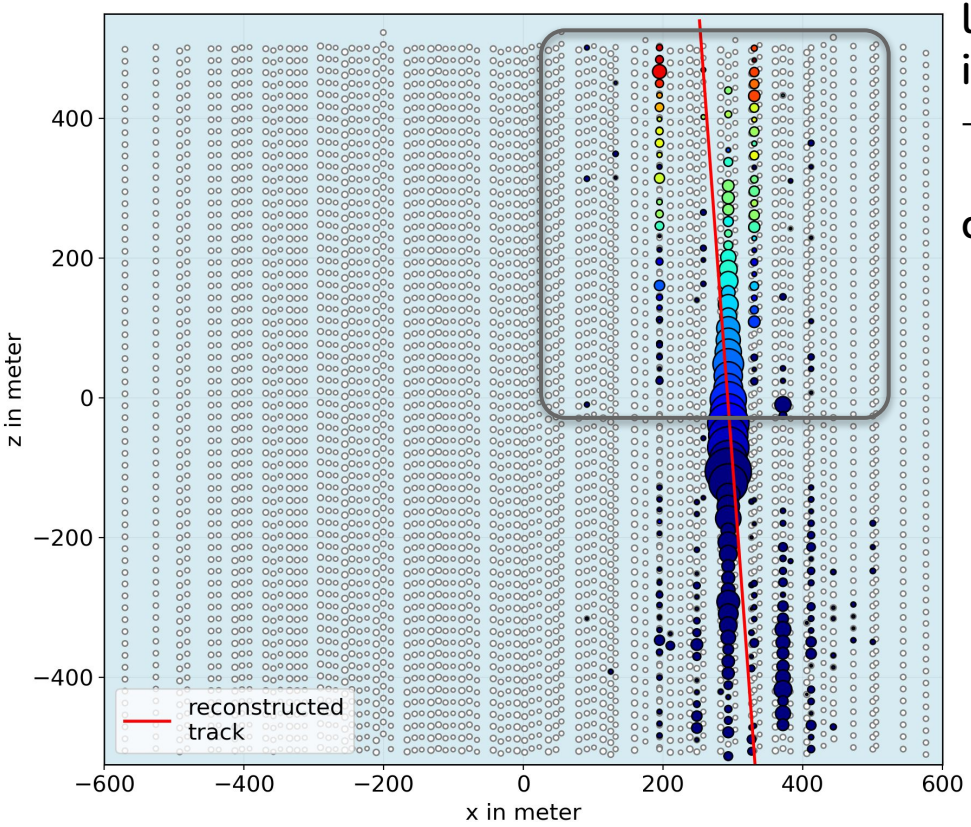
In-Ice for Mass



lateral spread and number of TeV muons
indicator for primary type
→ manifest in in-ice signal distribution

depth-dependent ice properties simulated

In-Ice for Mass



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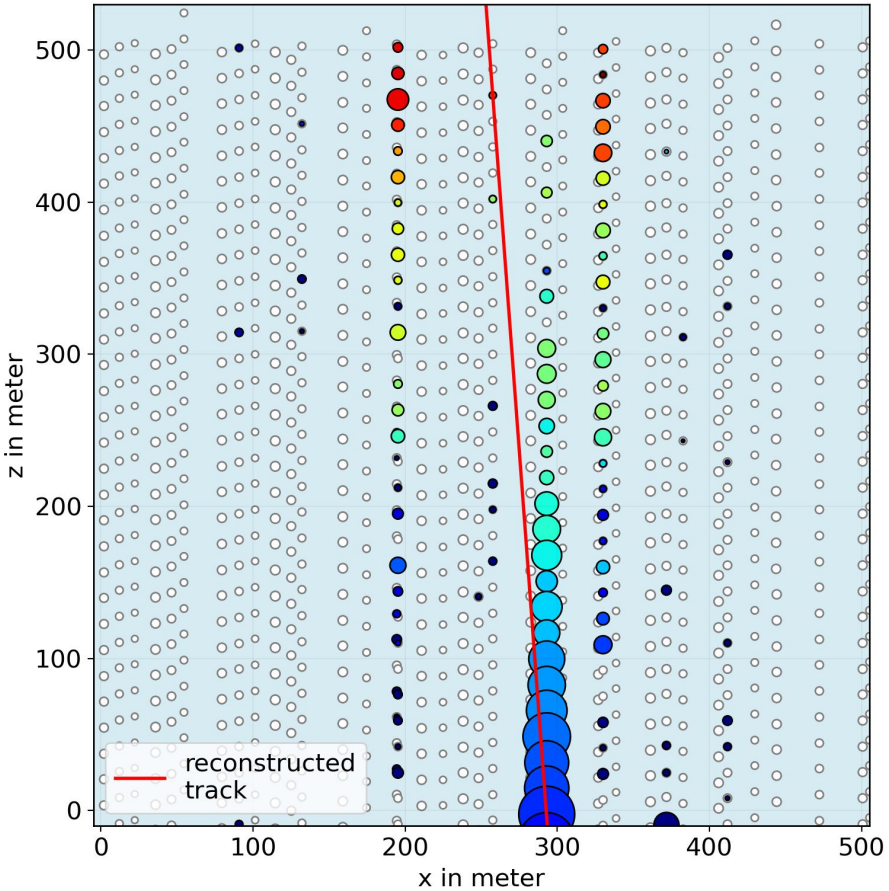

lateral spread and number of TeV muons
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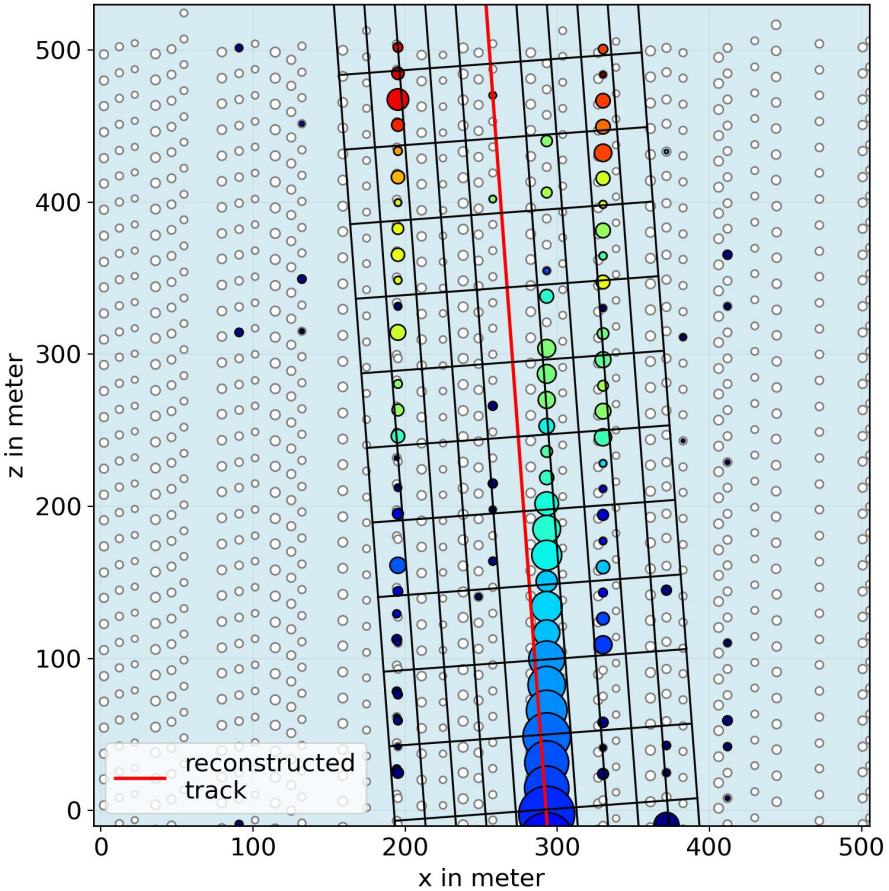
depth-dependent ice properties simulated

exploit radial symmetry around the track

In-Ice for Mass



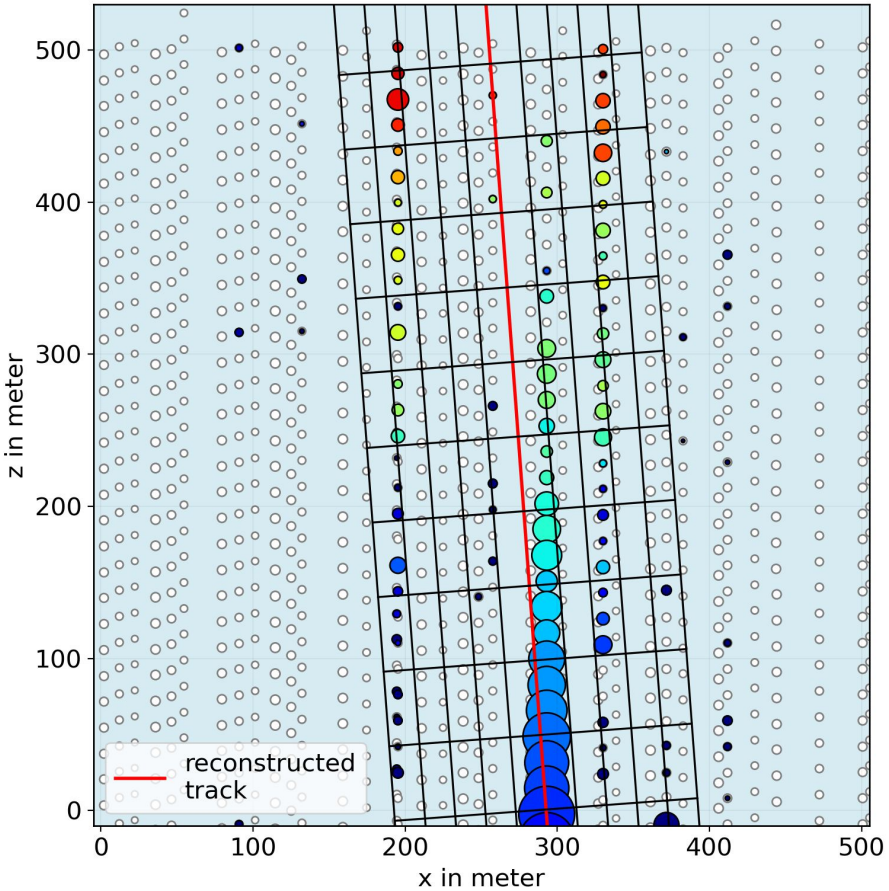
lateral spread and number of TeV muons indicator for primary type
→ manifest in in-ice signal distribution

depth-dependent ice properties simulated

exploit radial symmetry around the track

3D detector → 2D binning (“*slant depth along track*” and “*distance from track*”)

In-Ice for Mass



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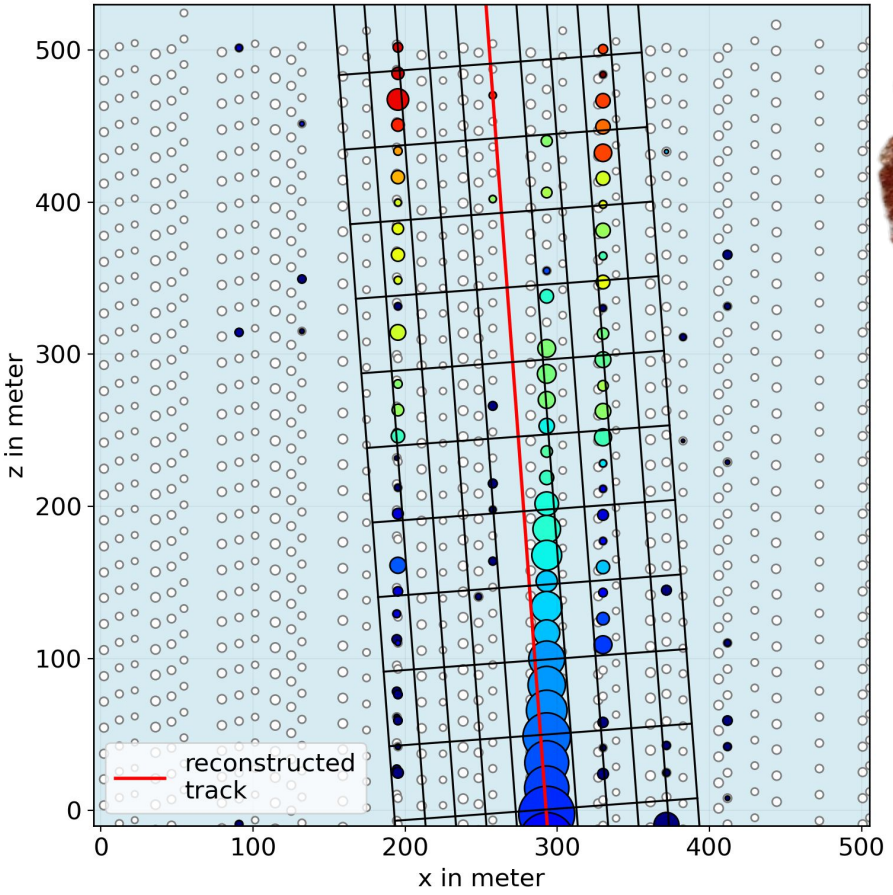
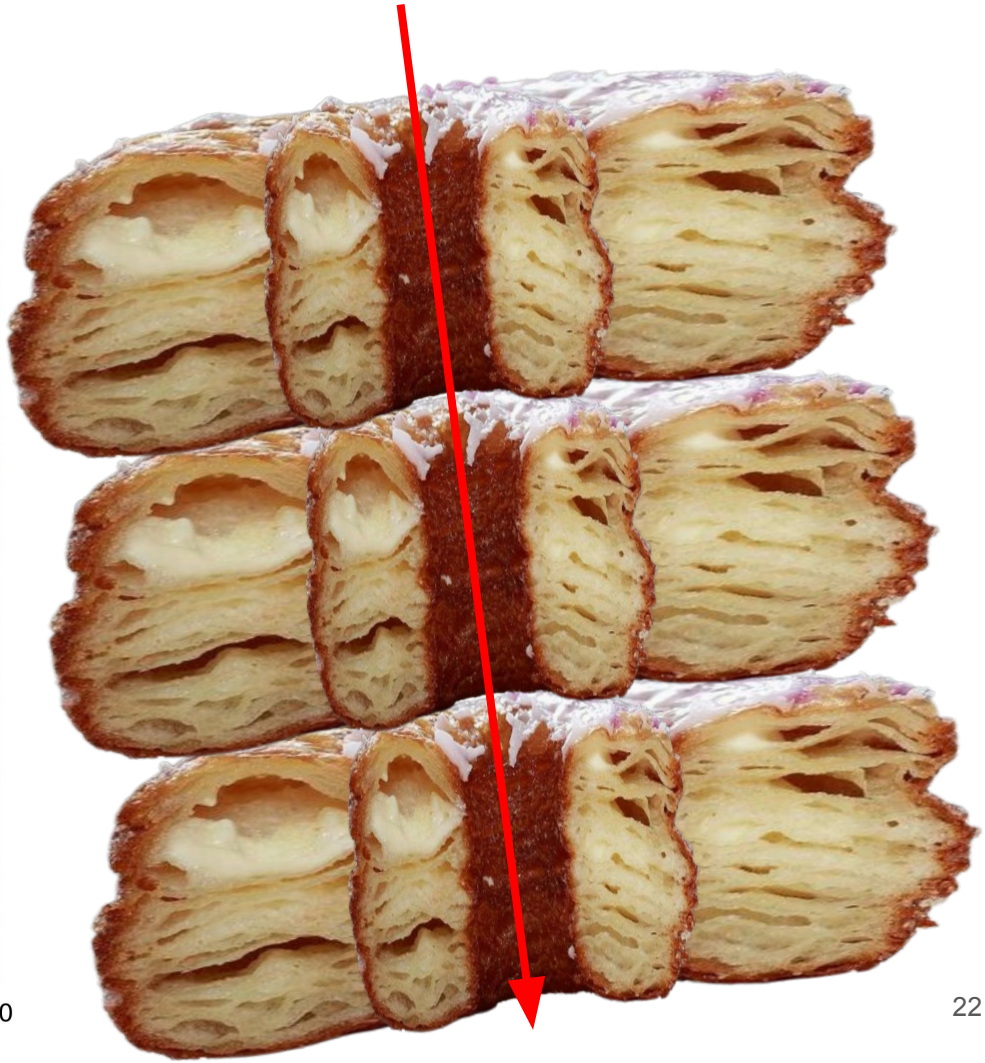
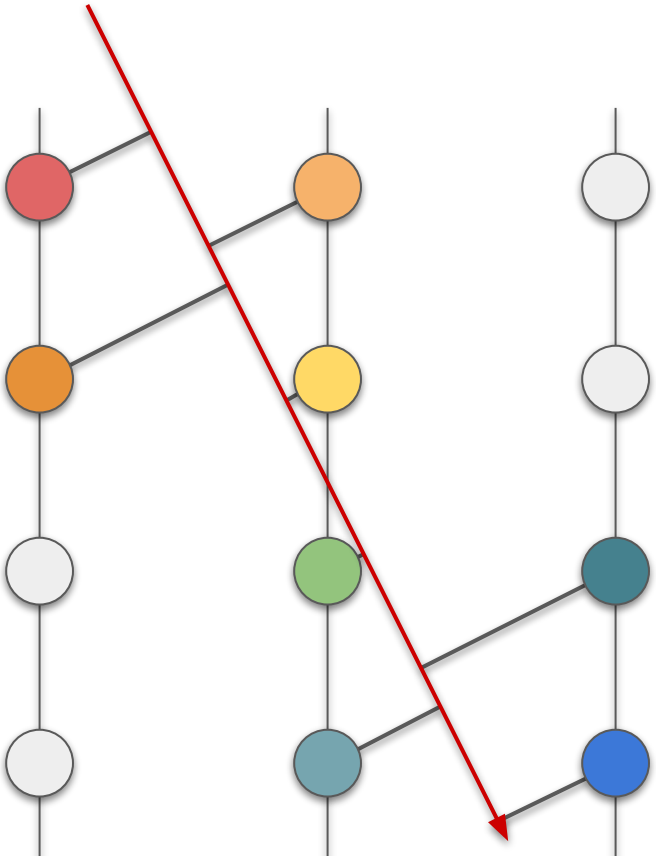
depth-dependent i

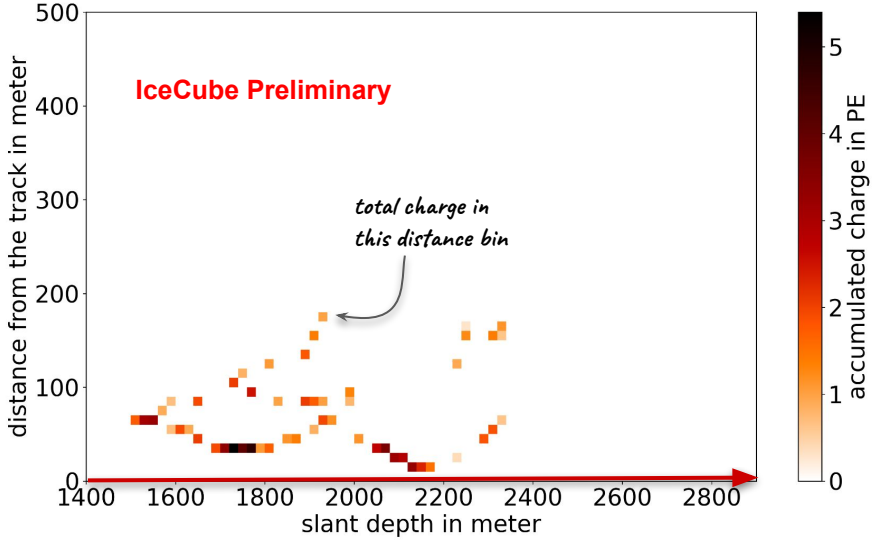
In-Ice for Mass



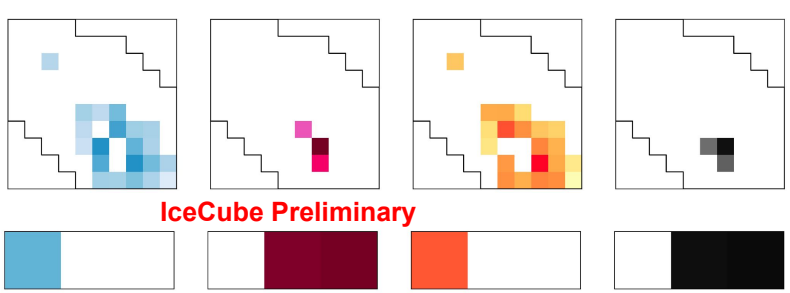


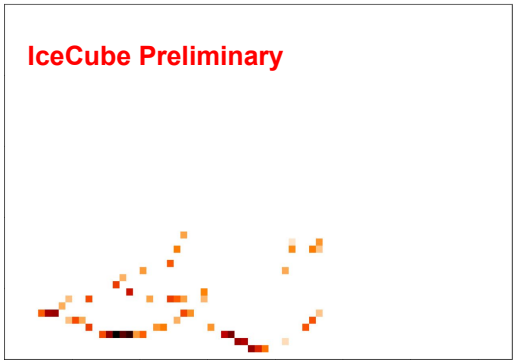
In-Ice for Mass





Combined Reconstruction



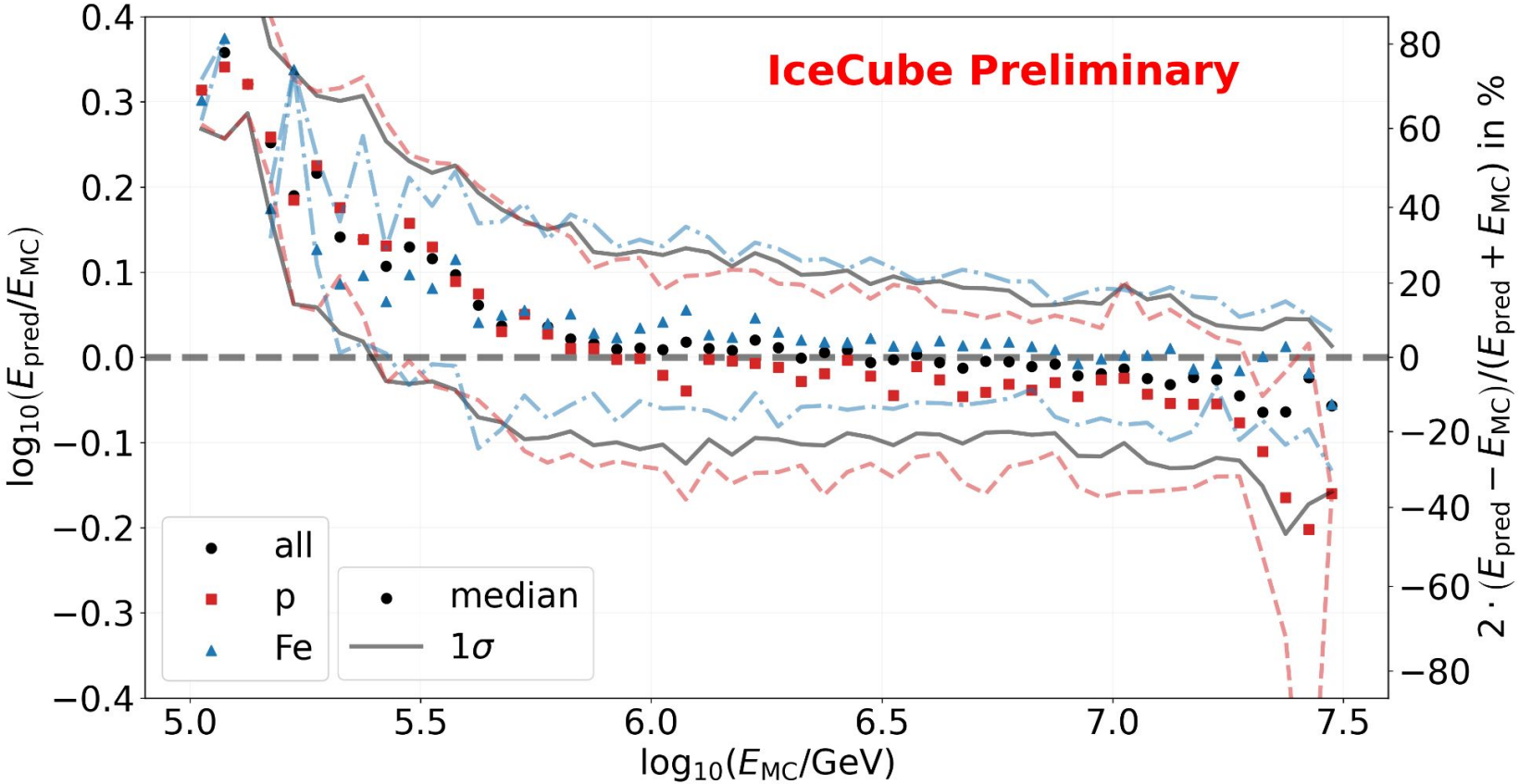


CNN

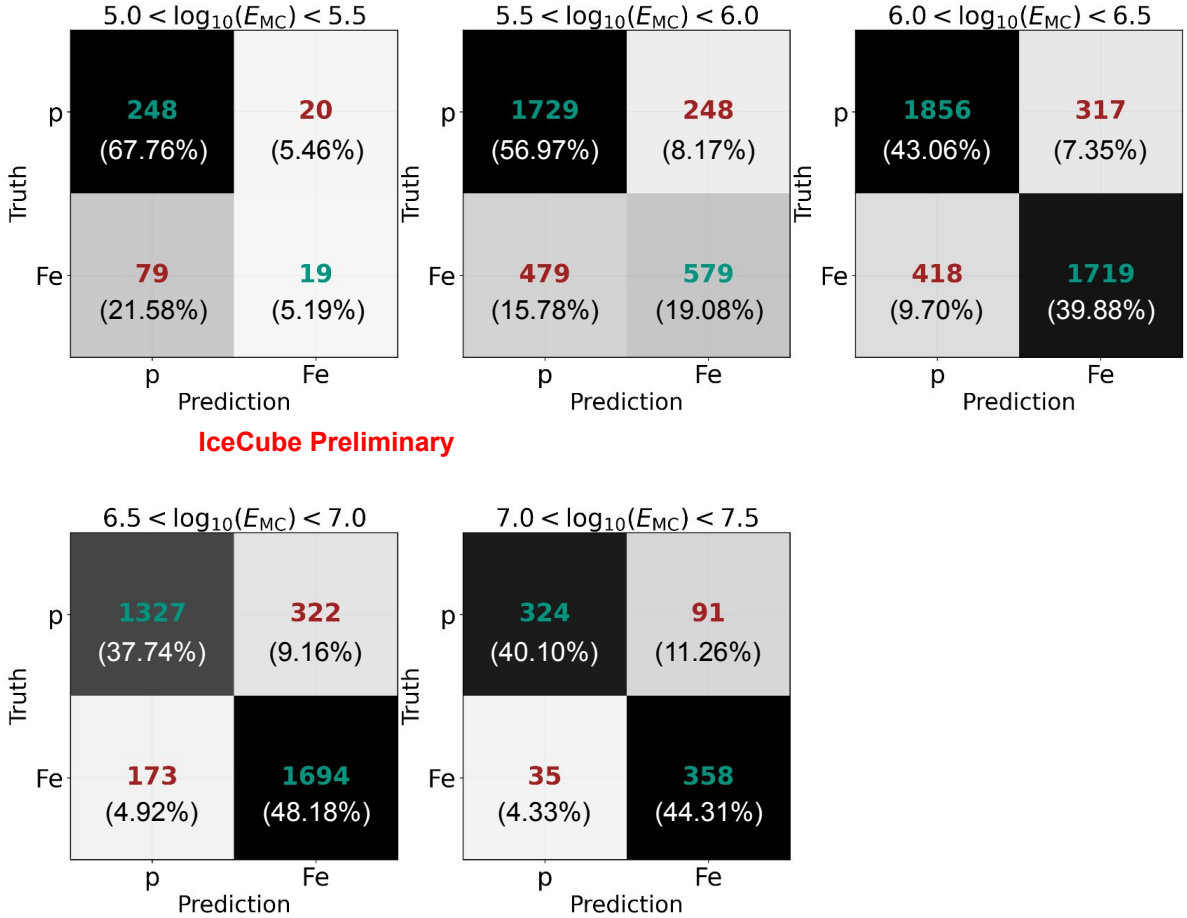
E_0

p/Fe

Reconstructing Energy



Reconstructing Primary Type



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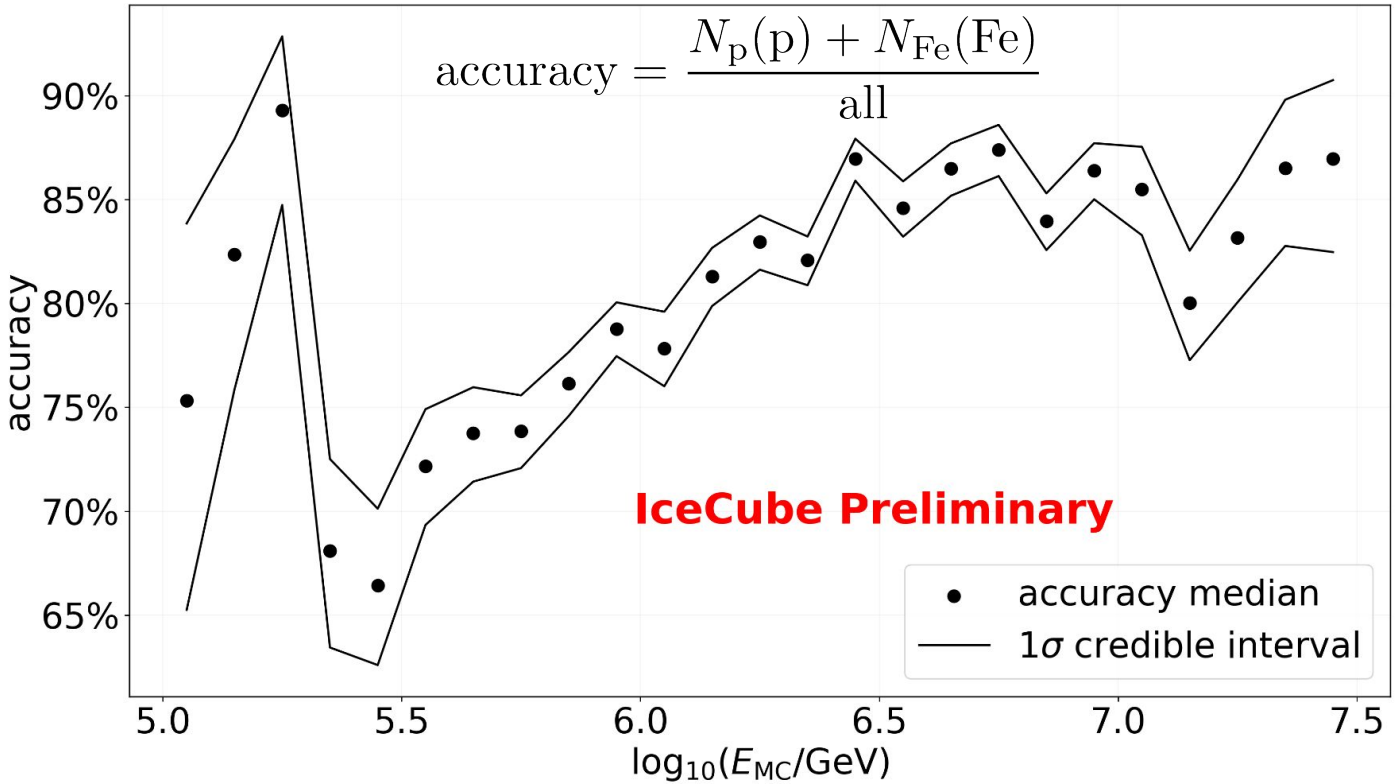
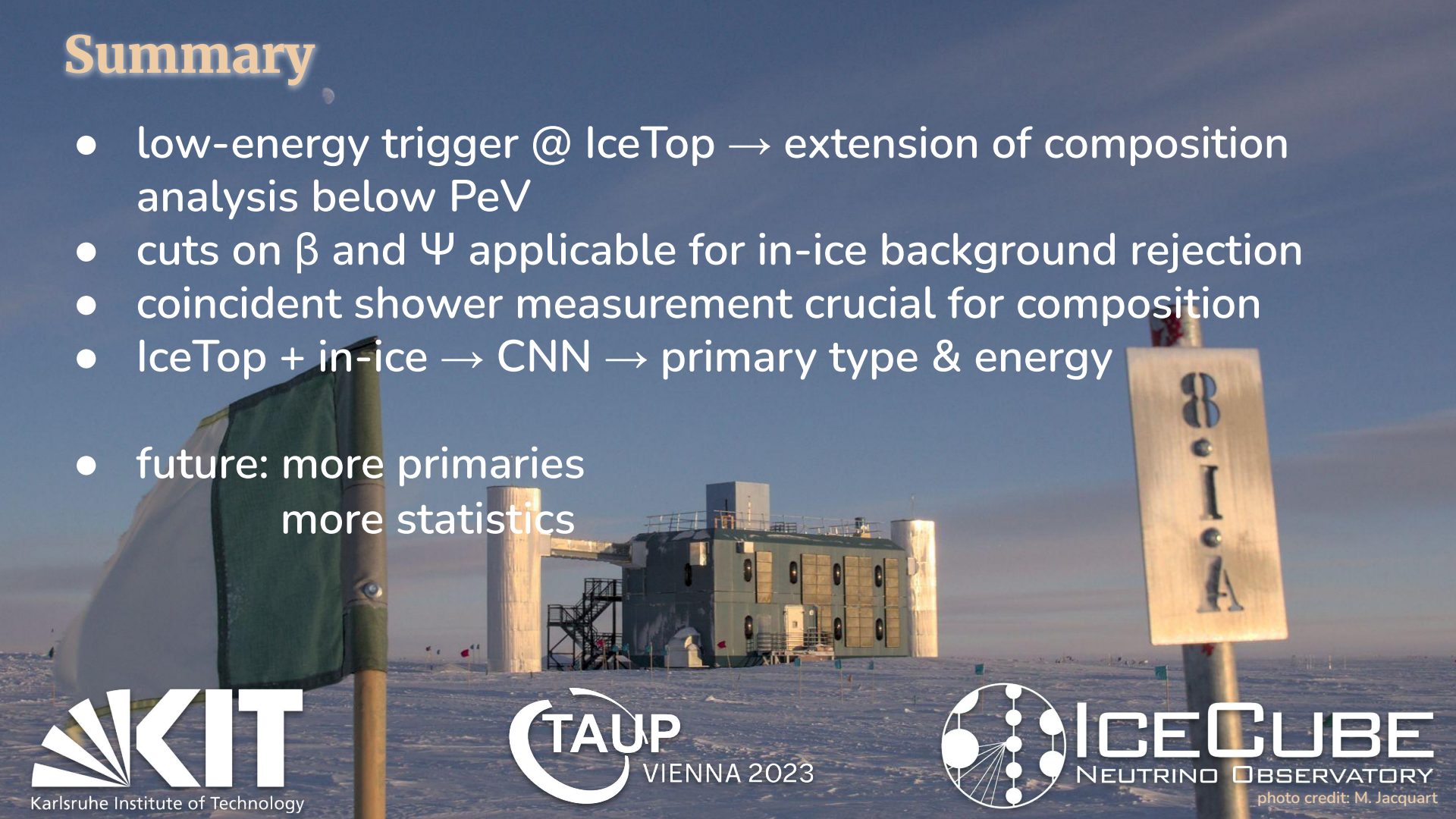


Summary

- low-energy trigger @ IceTop → extension of composition analysis below PeV
- cuts on β and Ψ applicable for in-ice background rejection
- coincident shower measurement crucial for composition
- IceTop + in-ice → CNN → primary type & energy

- future: more primaries
  more statistics



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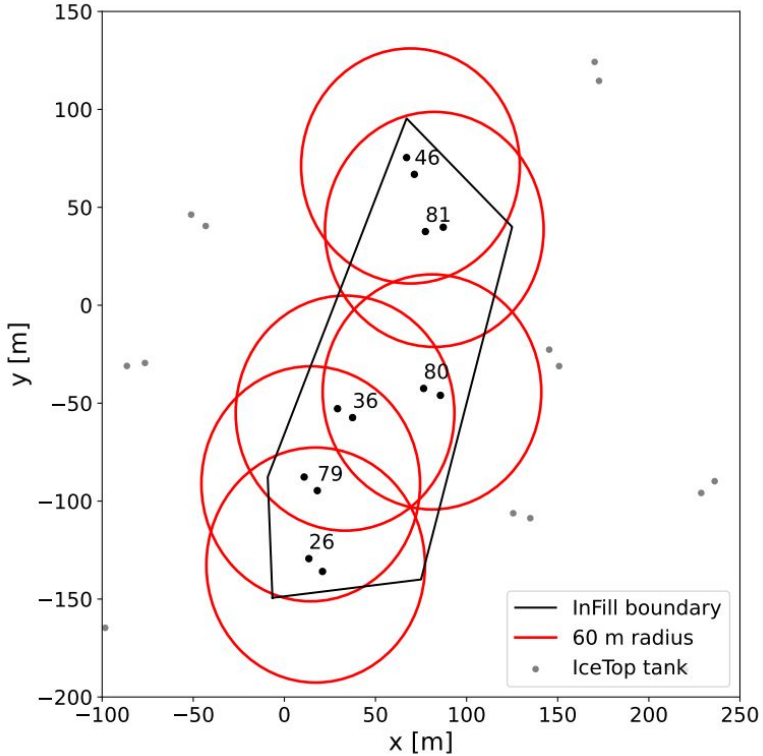
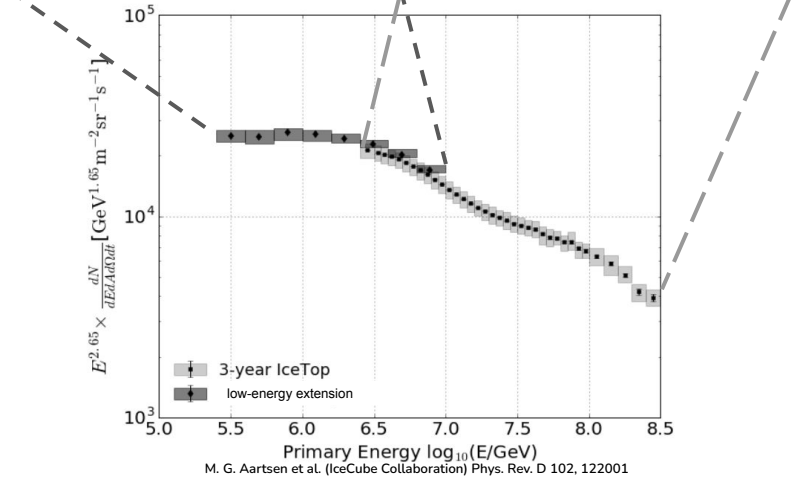
IceCube Neutrino Observatory

photo credit: M. Jacquart

Low-Energy Trigger for IceTop

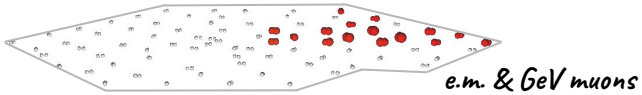


IceTop InFill	regular IceTop array
< 60 m spacing	~ 125 m spacing
~ 250 TeV threshold	~ 2.5 PeV threshold



M. G. Aartsen et al. (IceCube Collaboration) Phys. Rev. D 102, 122001

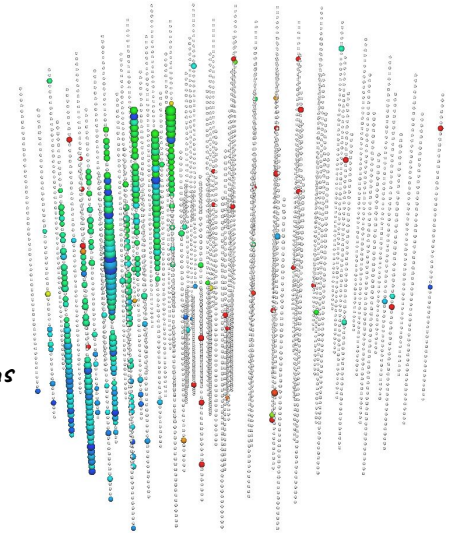
Coincident Events



small zenith angle:
shower can trigger IceTop + TeV muons penetrate in-ice

reconstruction of **primary energy** based on e.m. shower component

"the more surface signal, the higher the energy"

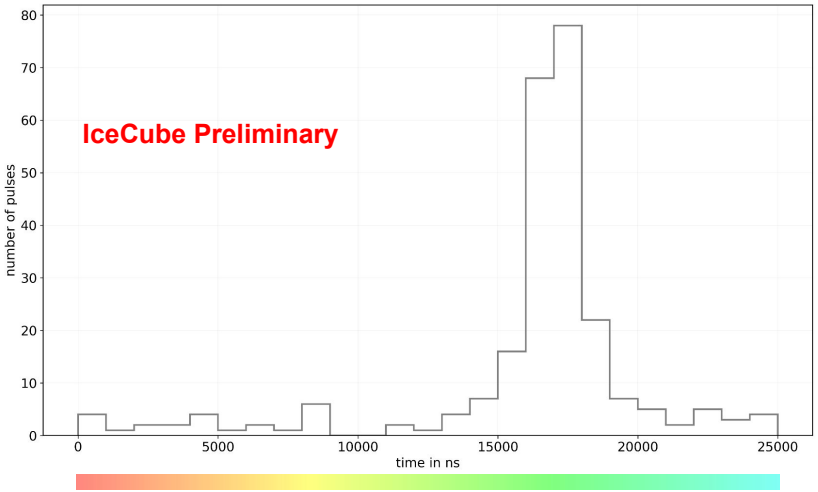


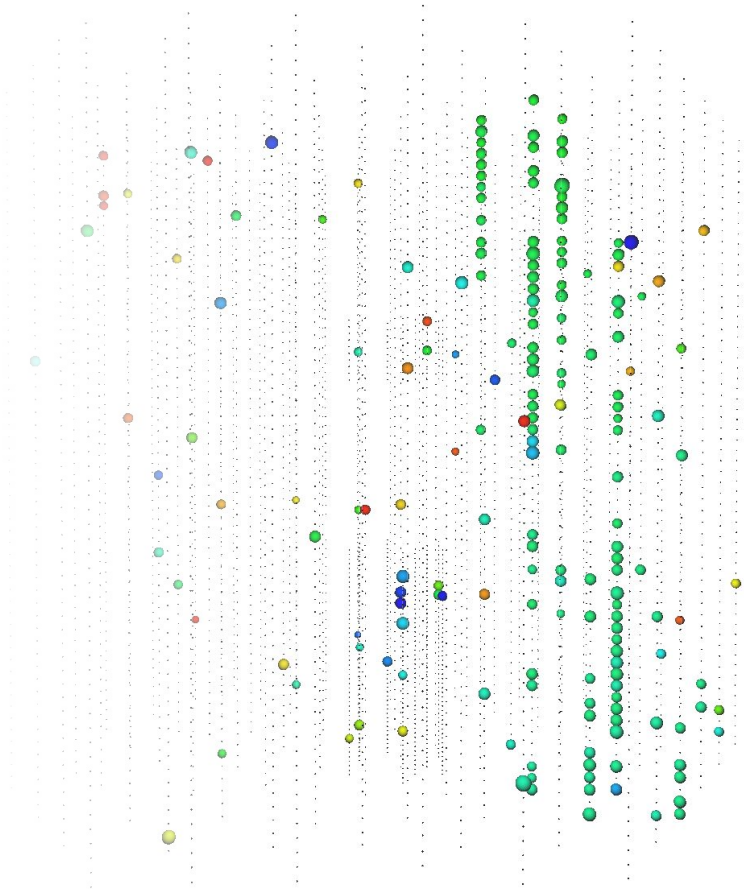
reconstruction of **primary type** (mass) based on muonic shower component

"the broader the bundle, the more high-p_T muons and the higher the point of first interaction"

Event Cleaning

"raw" in-ice pulses

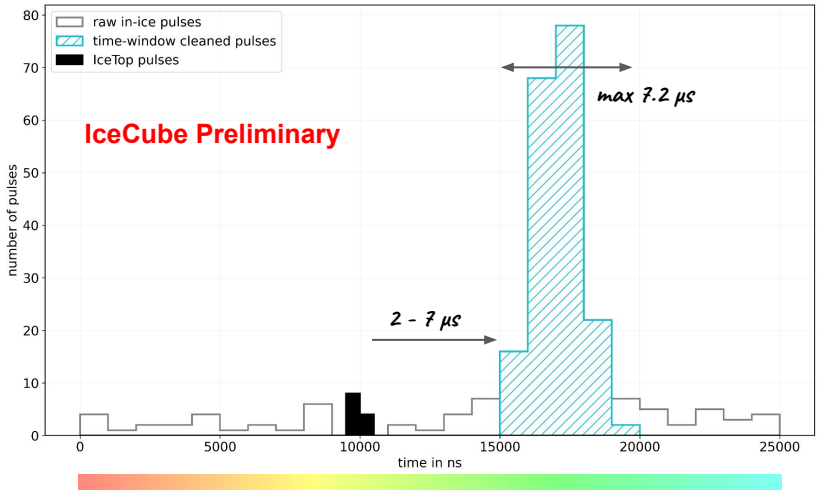


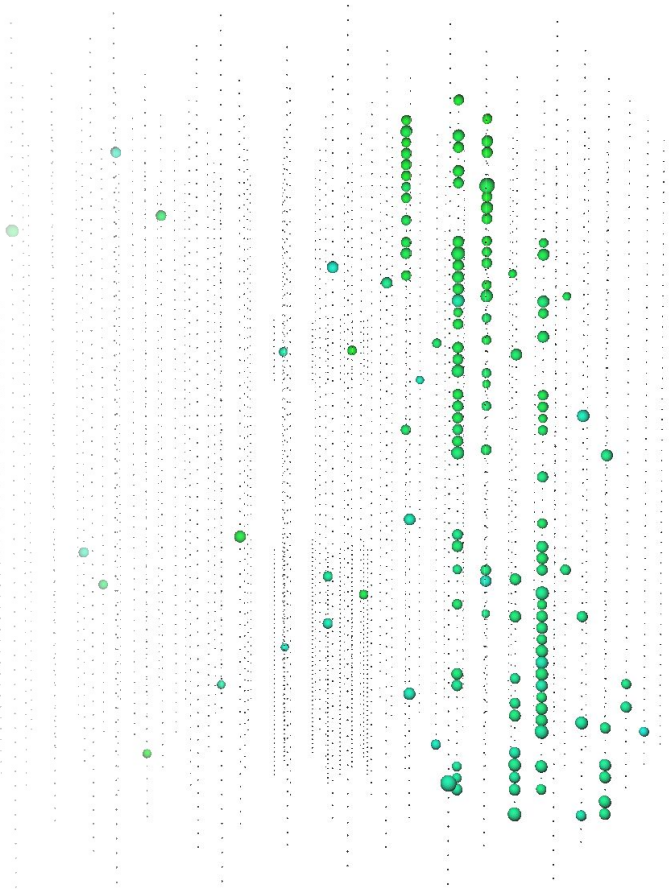


Event Cleaning

“raw” in-ice pulses

time-window cleaning



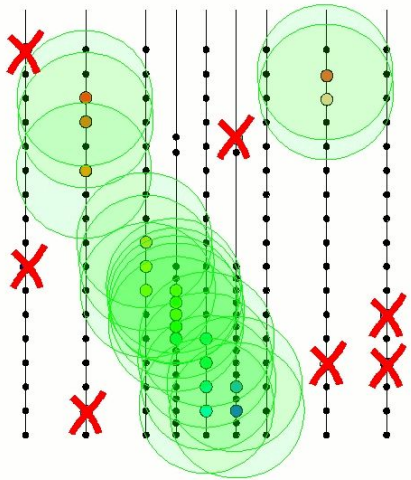


Event Cleaning

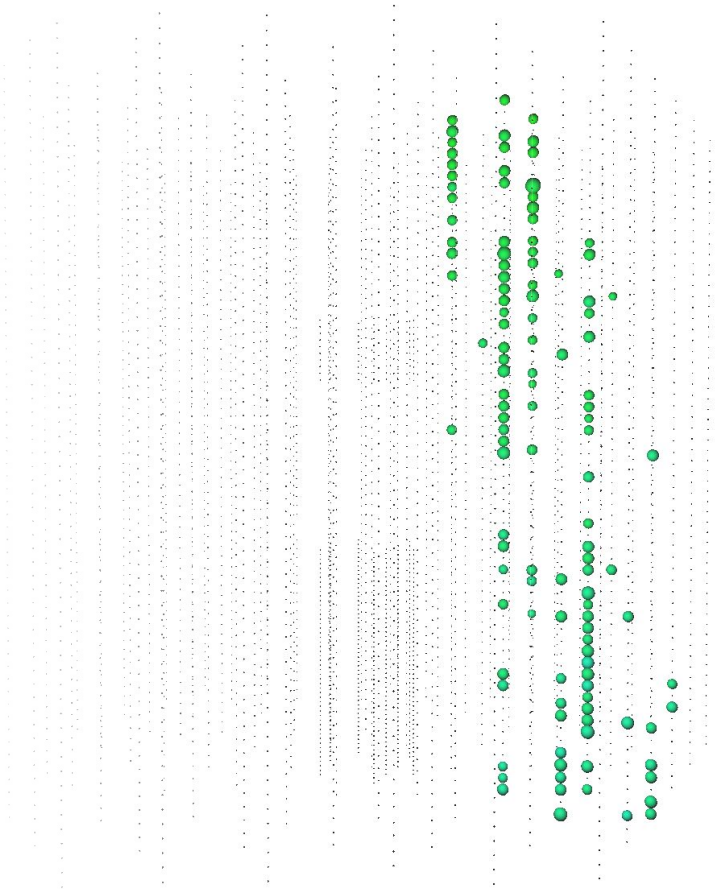
“raw” in-ice pulses

time-window cleaning

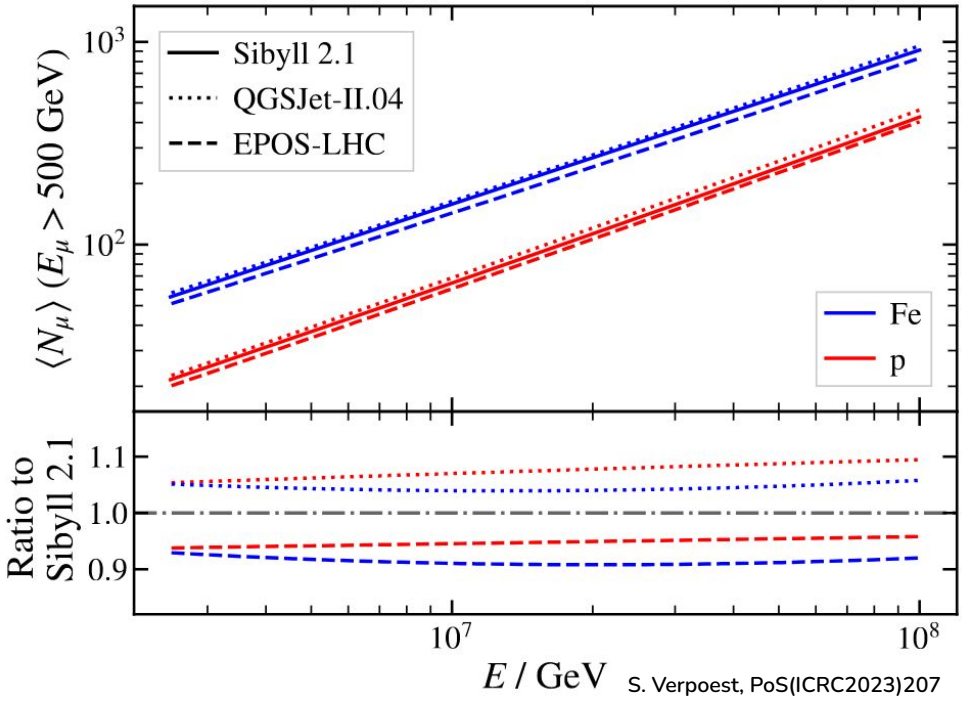
causality cleaning



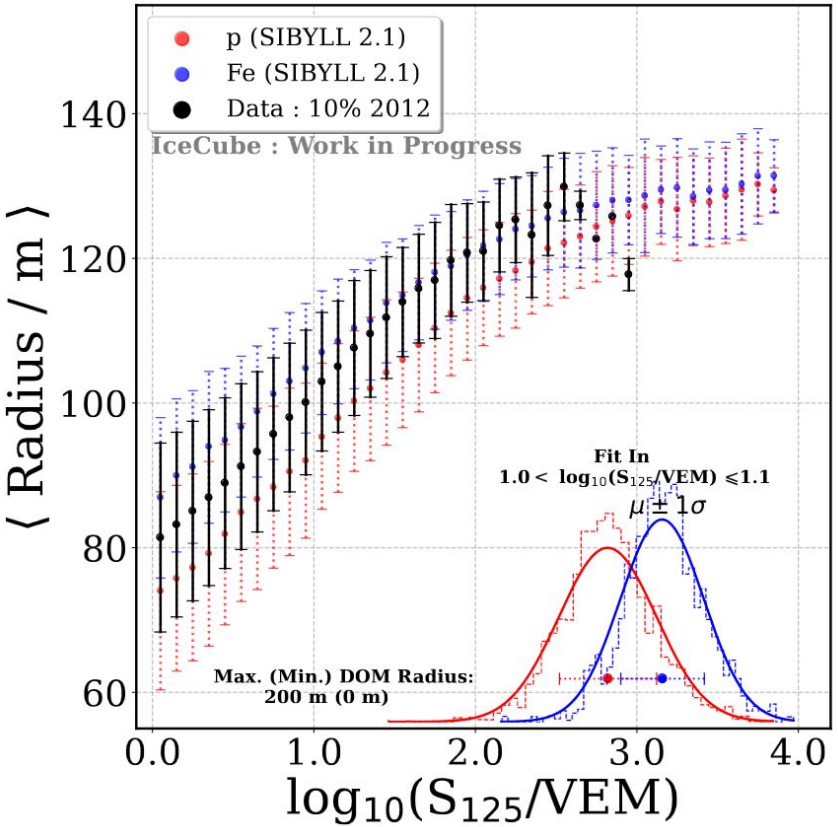
keep pulse if within distance (150 m) and time (1 μs) range of seed



Muon Bundle Width



S. Verpoest, PoS(ICRC2023)207



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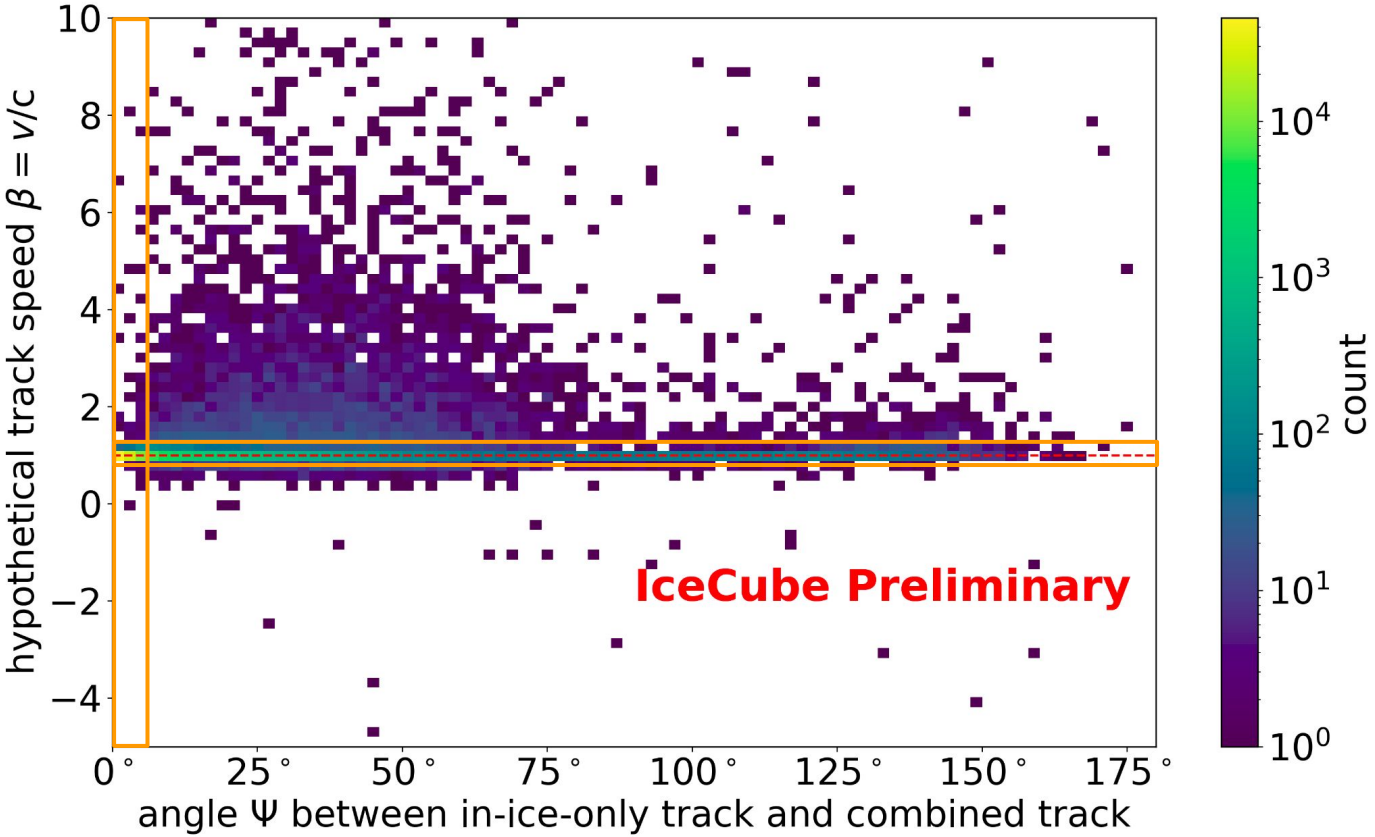
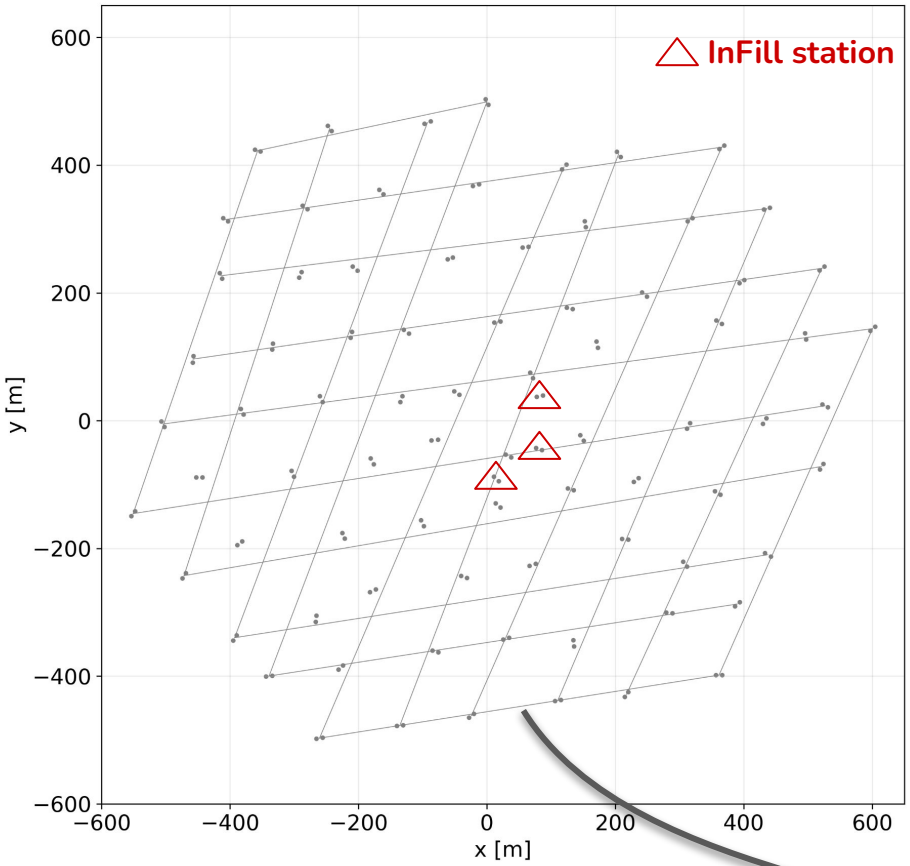
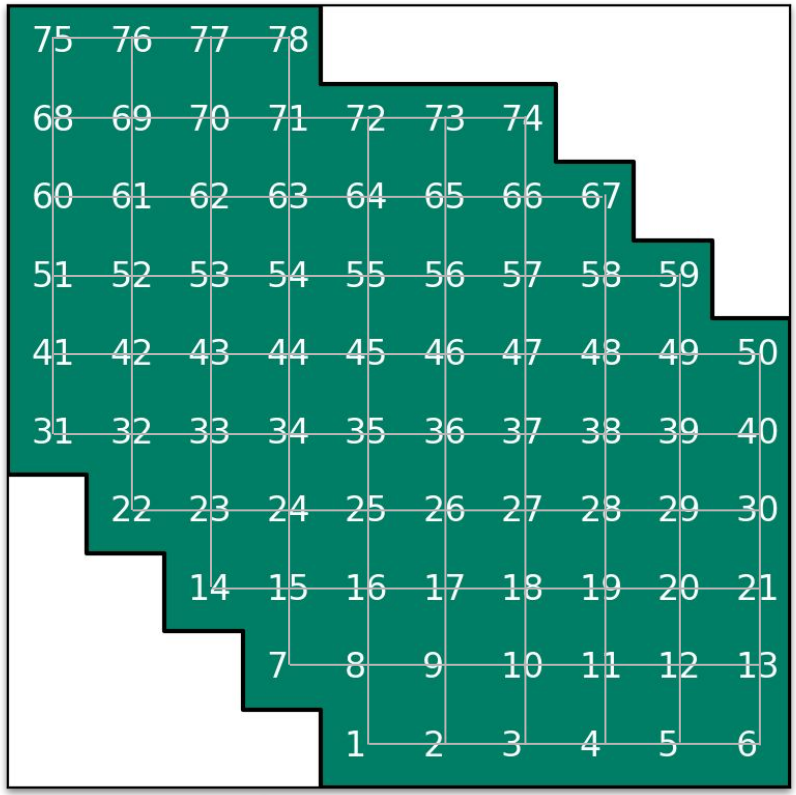
Are speed and angle cut both necessary? Or is one of them sufficient?

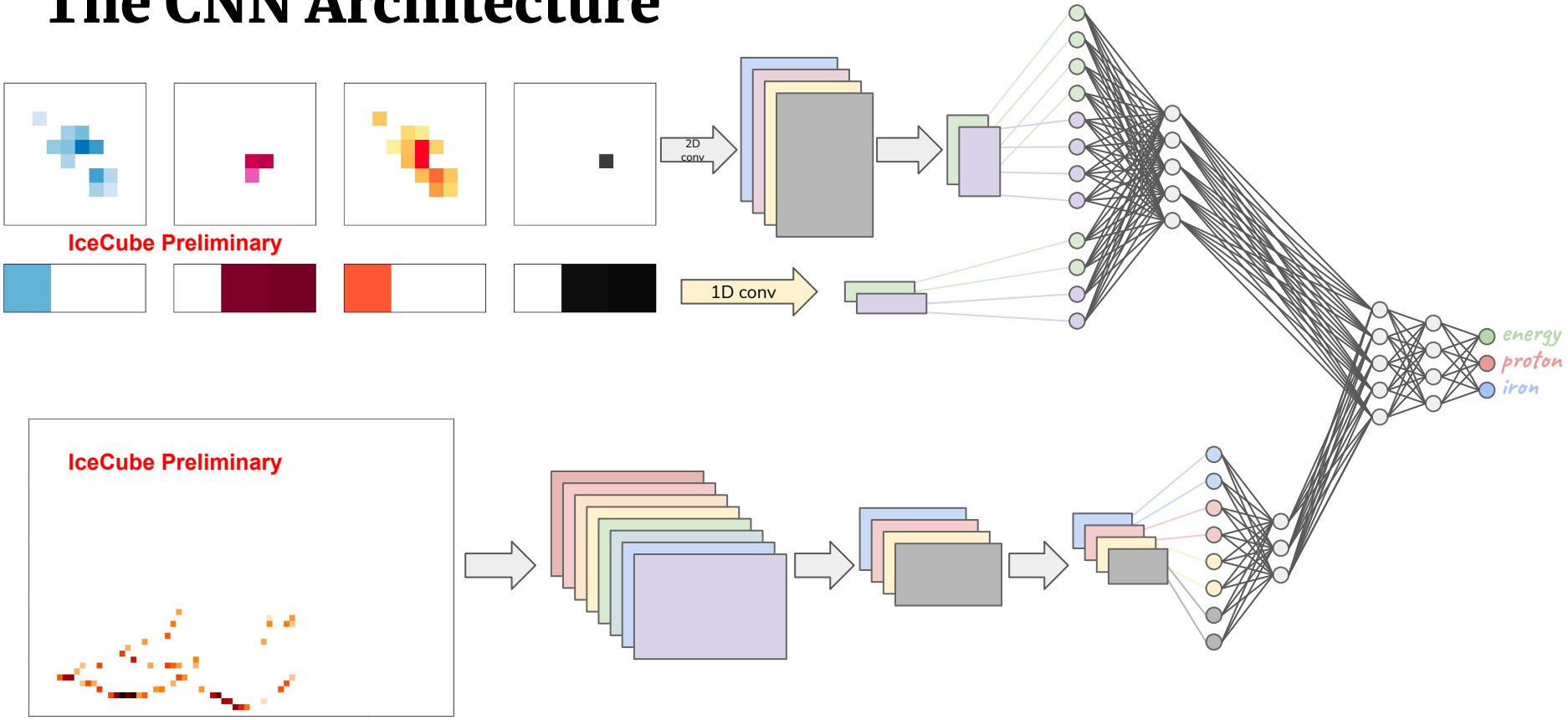


IceTop for Energy

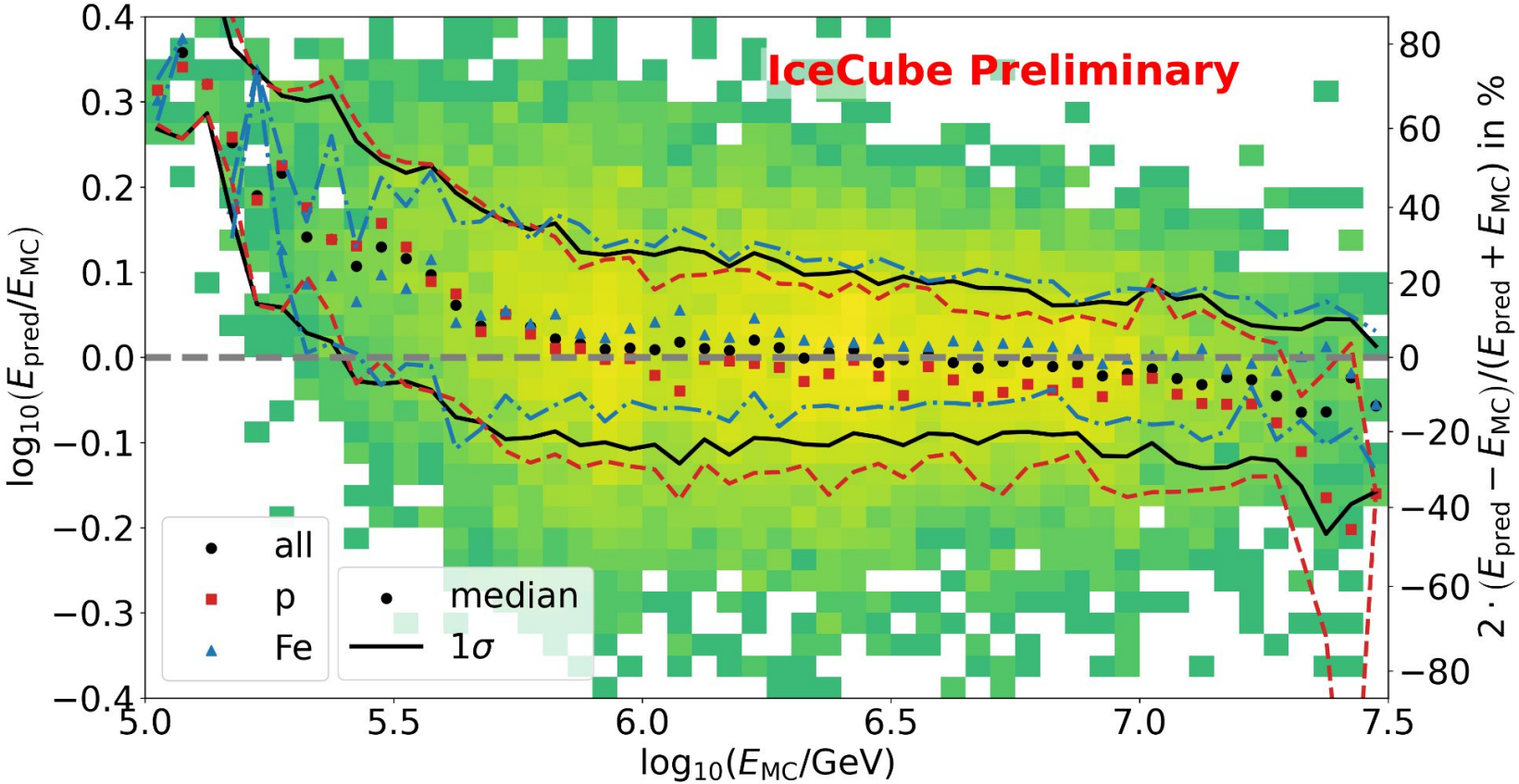




The CNN Architecture

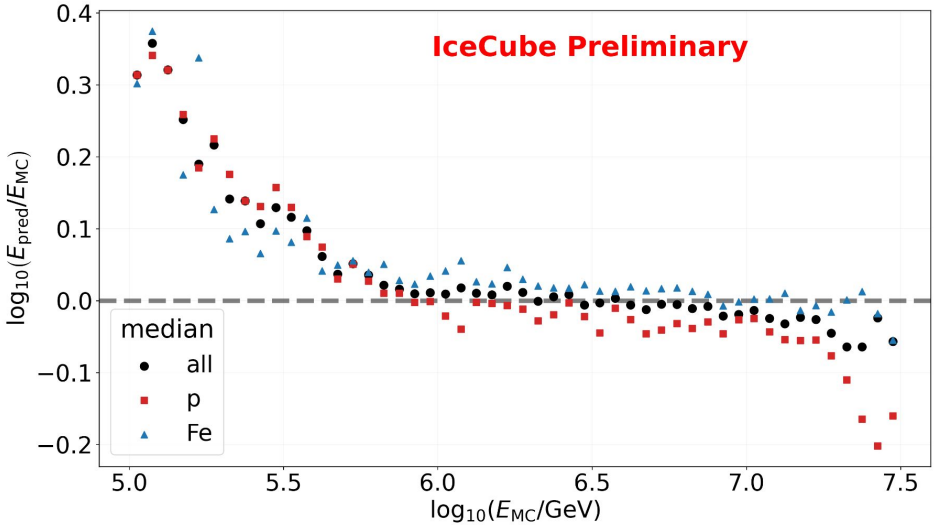


Reconstructing Energy

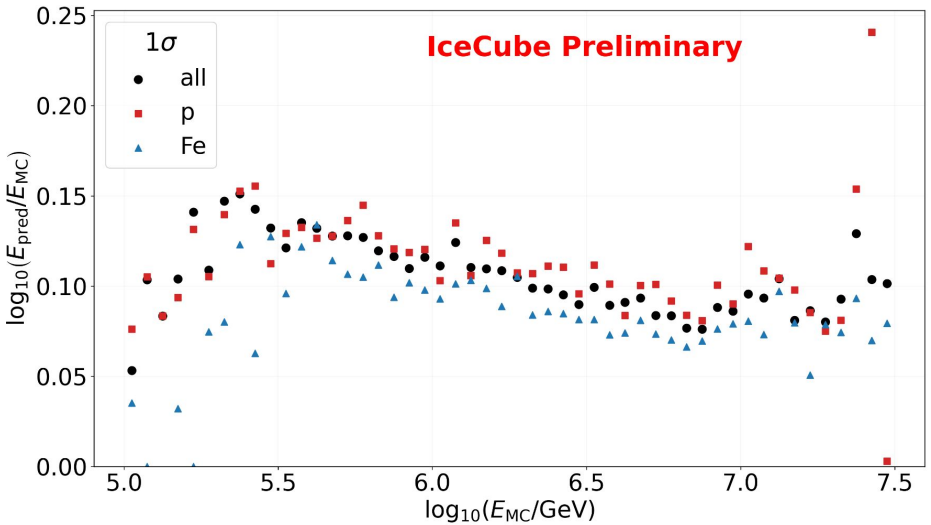


Reconstructing Energy

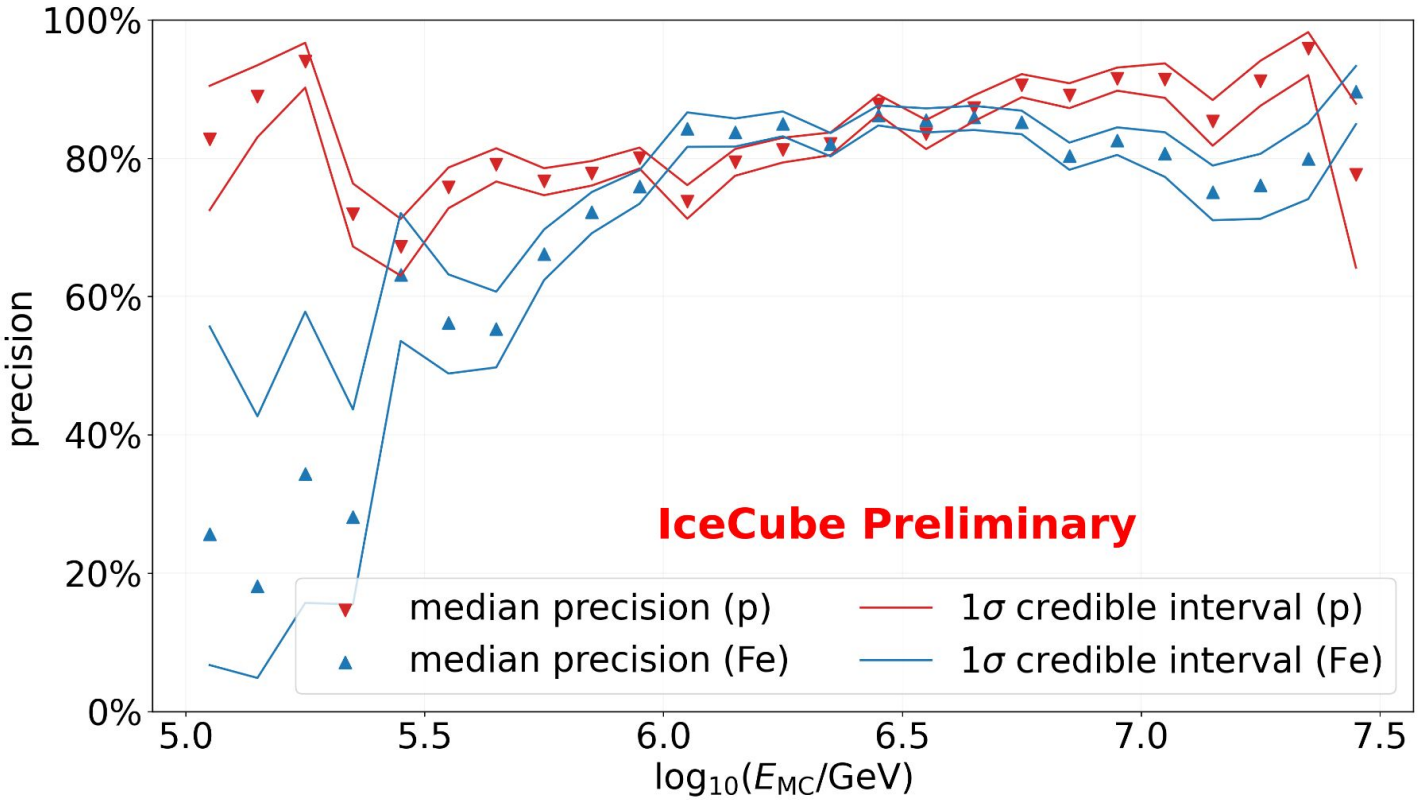
bias



resolution



Reconstructing Primary Type

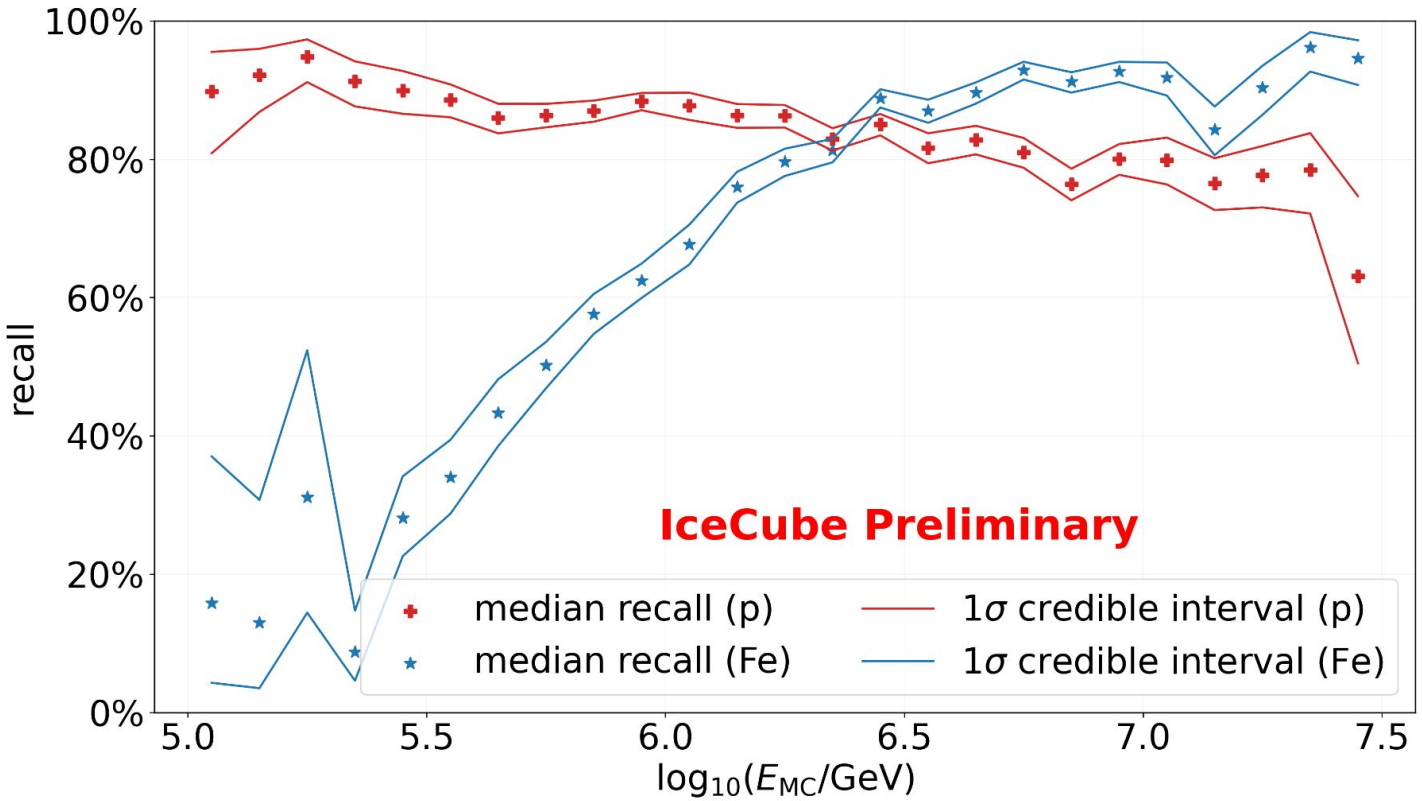


$$\text{precision}_{\text{p}} = \frac{N_{\text{p}}(\text{p})}{\text{N}_{\text{p}}}$$

out in

$$\text{precision}_{\text{Fe}} = \frac{N_{\text{Fe}}(\text{Fe})}{\text{N}_{\text{Fe}}}$$

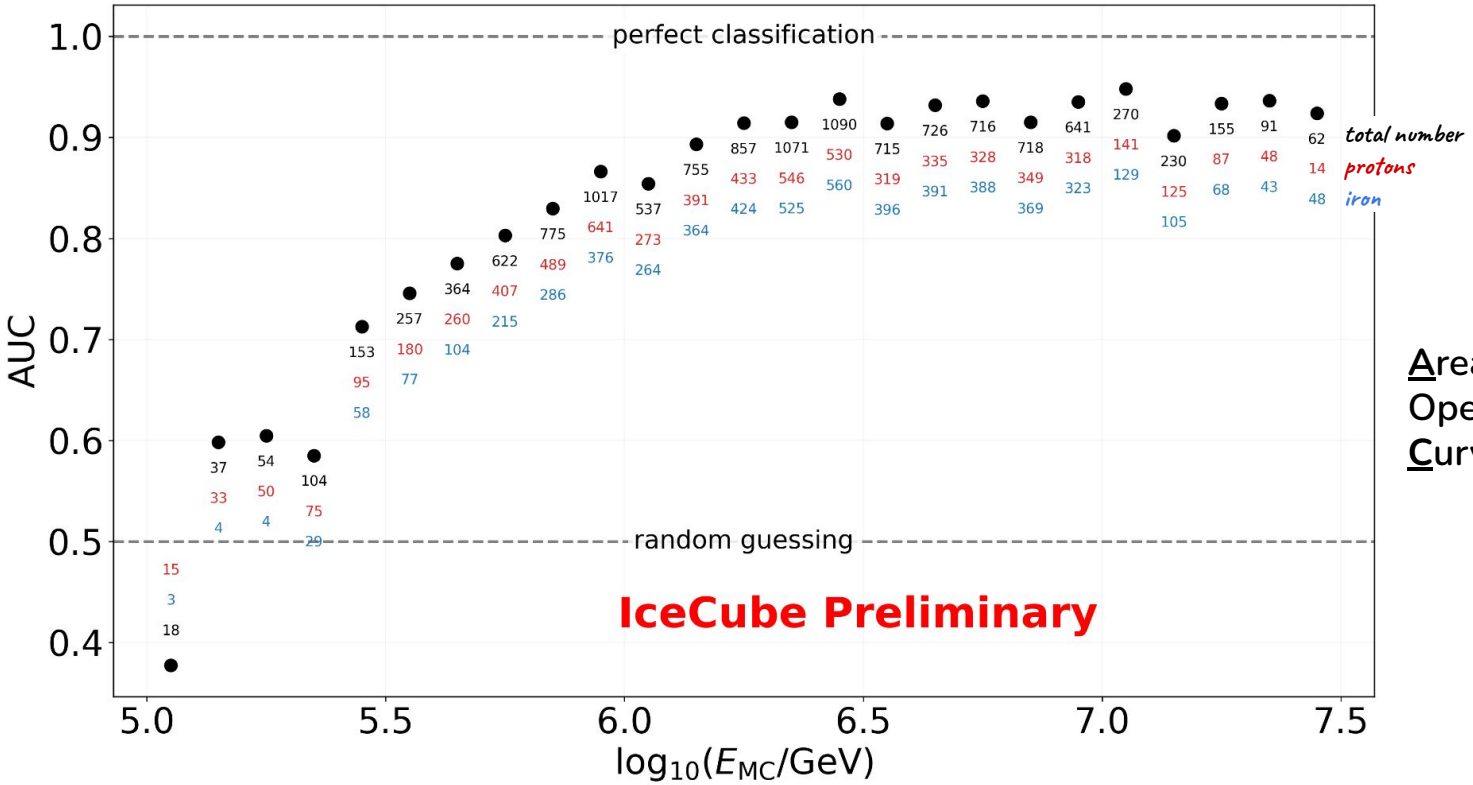
Reconstructing Primary Type



$$\text{recall}_{\text{p}} = \frac{N_{\text{p}}(\text{p})}{\text{N}(\text{p})}$$

$$\text{recall}_{\text{Fe}} = \frac{N_{\text{Fe}}(\text{Fe})}{\text{N}(\text{Fe})}$$

Reconstructing Primary Type



Area Under the Receiver Operation Characteristic Curve