IV PHD Neutrinos Summer School on Neutrinos Here, There & everywhere

July 10, 2025

Studying Muon Bundles for Improved EHE Neutrino Identification in IceCube

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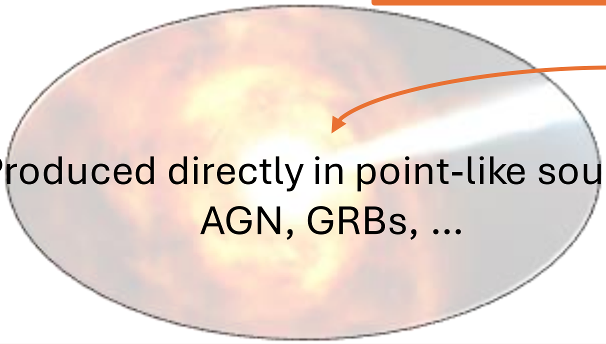
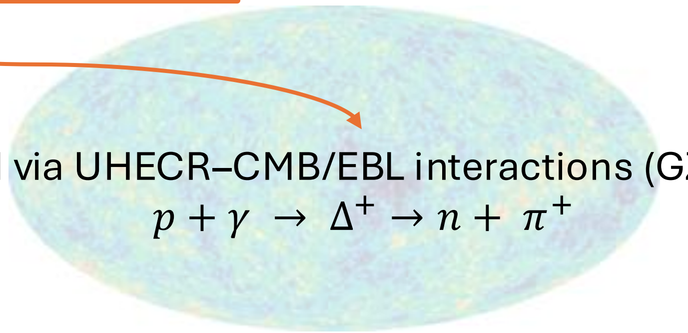
Astrophysical Goals

EHE neutrino = neutrino with energy > 10 PeV



Produced directly in point-like sources
AGN, GRBs, …



Produced via UHECR–CMB/EBL interactions (GZK process)

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$$

Astrophysical neutrinos
> 10 PeV

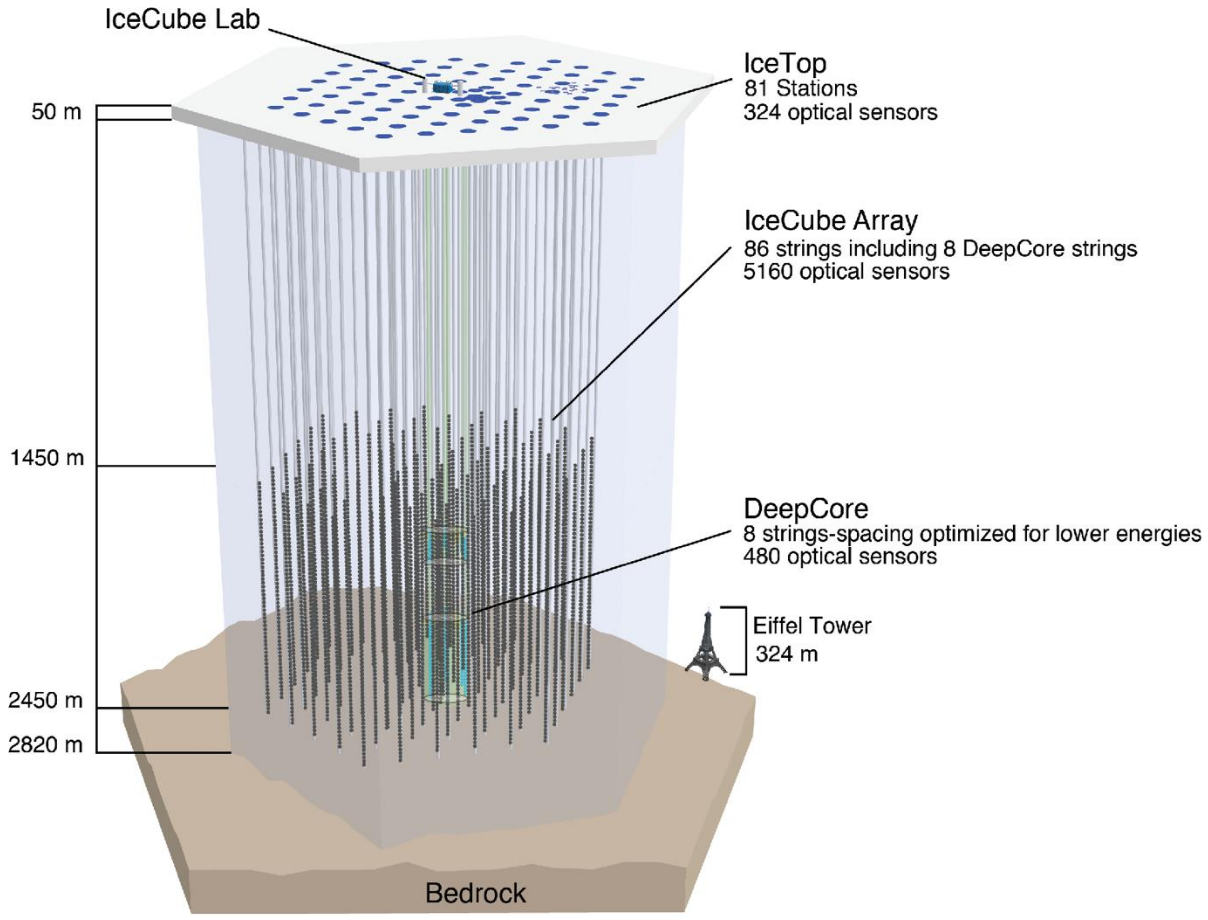
Cosmogenic neutrinos
> EeV

Study astrophysical sources
Production mechanism
Acceleration process
Source distribution

Trace the origin of UHECRs
composition (protons vs nuclei)
spectrum
source distribution

Constrain astrophysical models
Test fundamental physics at energies not accessible at Earth

IceCube Detector



[Yu, 2023]

Detection principle:

Detection of Cherenkov light produced by charged particles resulting from neutrino's deep inelastic scattering interaction with nucleon of the ice.

Main Target:

Neutrinos from Northern sky
(Earth = shield against atmospheric background)

Optimized Energy Range (In-Ice):

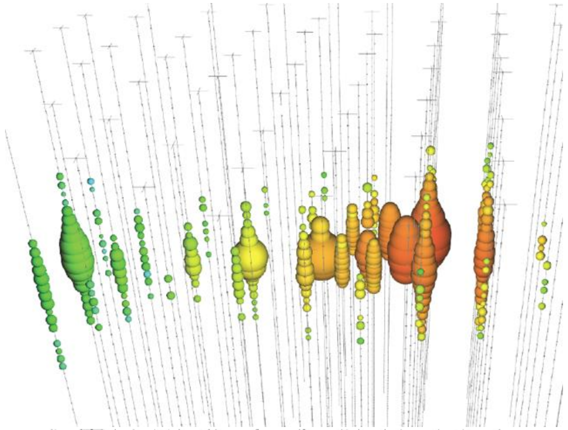
Main Detector: 100 GeV to 1 PeV
Deep-core: down to 10 GeV

➡ Possibility to probe higher energies: 1 PeV → 1EeV even if detected events are rare.

In-ice neutrino signatures

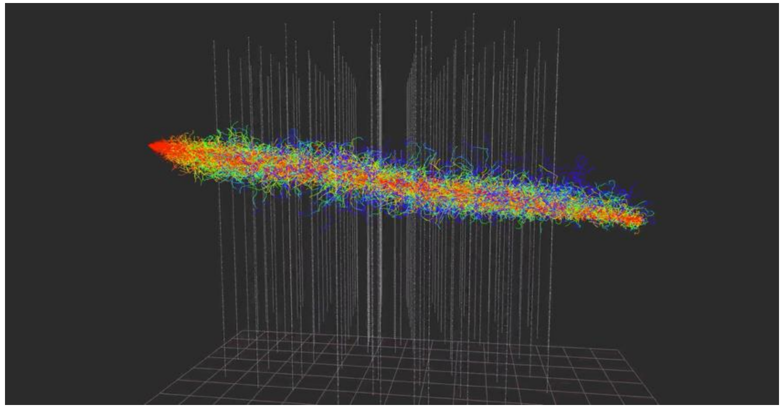
Events signature: total charge collected per DOM and photons arrival time create characteristic shapes in the detector.

Muon Track

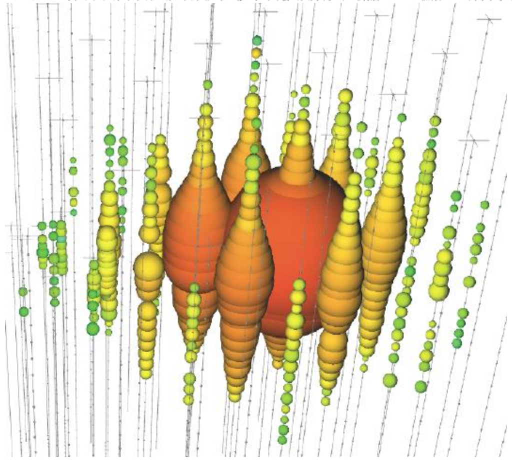


Angular resolution:
0.1° – 1°

Vertex can be outside detector: increased effective volume



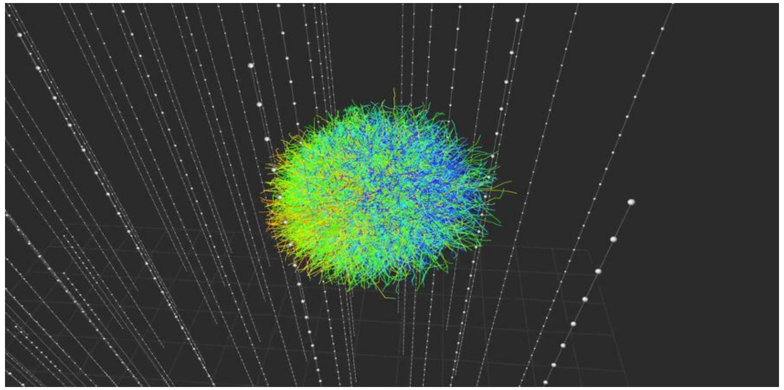
Cascade



[IceCube Masterclass, 2024]

Deposited energy resolution:
≈ 15%

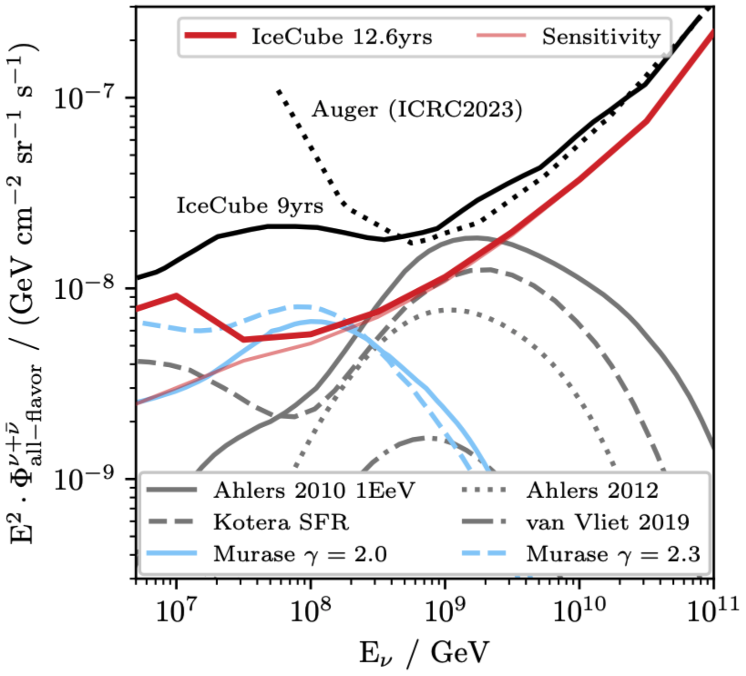
Angular resolution:
≈ 10° (E_ν > 100 TeV)



[IceCube Collaboration, 2024]

Extremely High Energy (EHE) Neutrinos

IceCube detector

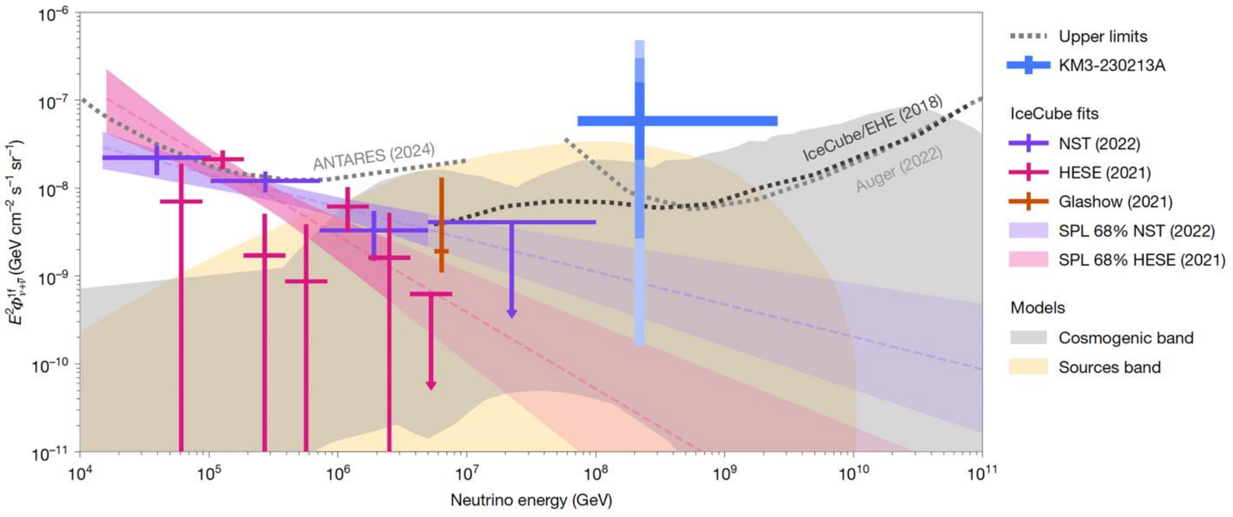


[Meier et al., 2025]

Flux dropping and no event beyond 10 PeV

KM3Net

KM3-230213A Event



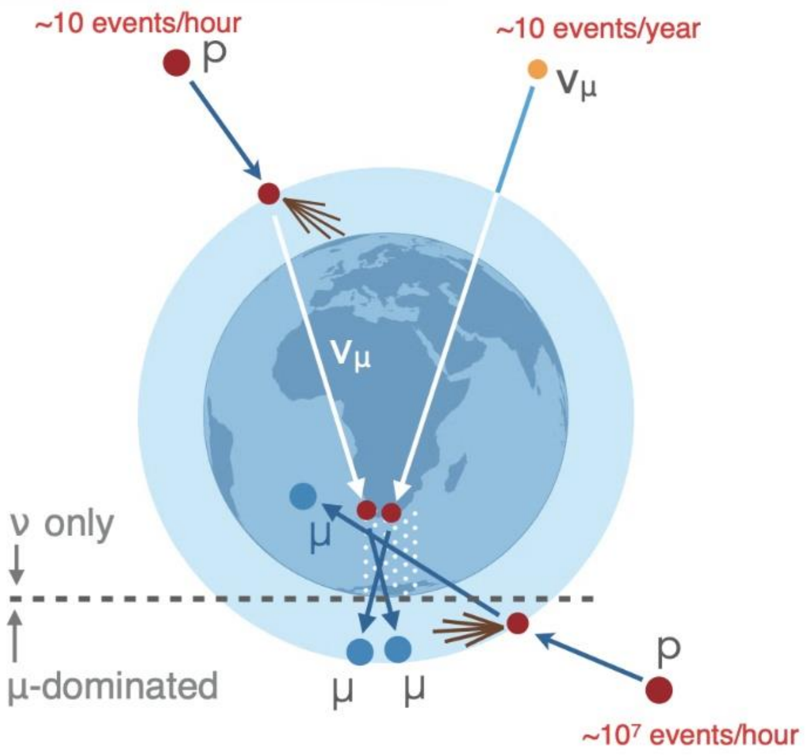
[KM3NeT Collaboration, 2025]

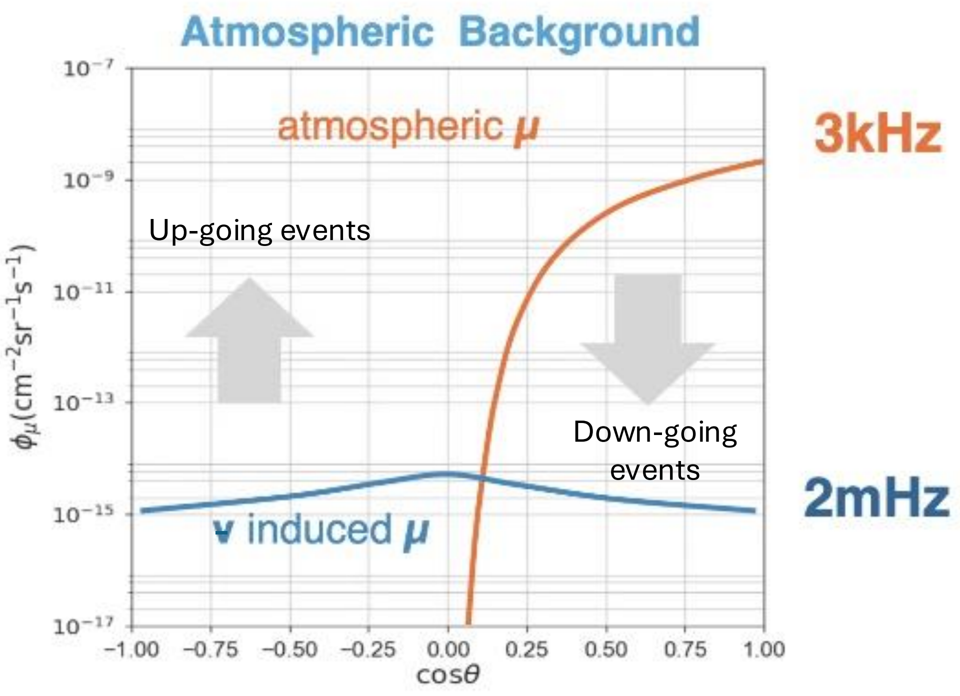
Muon: $E_\mu = 120^{+110}_{-60}\,PeV$

Estimated neutrino energy:
$E_\nu \approx 220\ PeV$

Atmospheric background

EHE increasing interaction cross-section → Earth becomes opaque to neutrinos → Focus on horizontal and down-going events NO Earth shield → Atmospheric background omnipresent





Credit: J.A. Aguilar

Muon Bundles

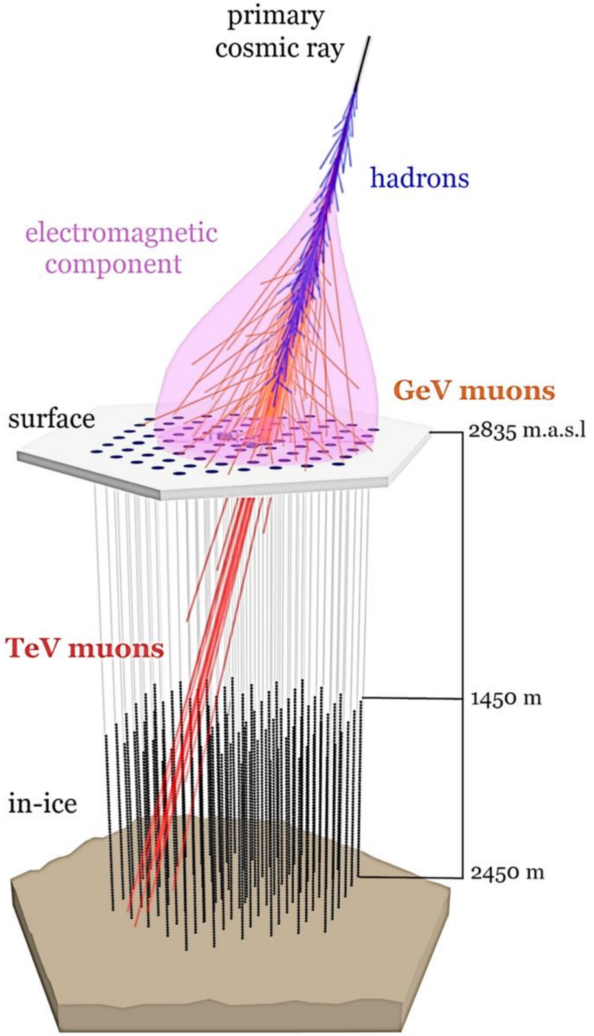
➡ Signal: Muon tracks from EHE neutrinos

Main background: Muon bundles

Muon groups from a single air shower caused by cosmic ray interactions in the atmosphere.

↳ Mimic the signal of a single muon

↳ Difficult to identify the signal



[IceCube Collaboration, 2021]

Research goal

Identify features that distinguish muon bundles from single muons to train a machine learning model and improve event selection.

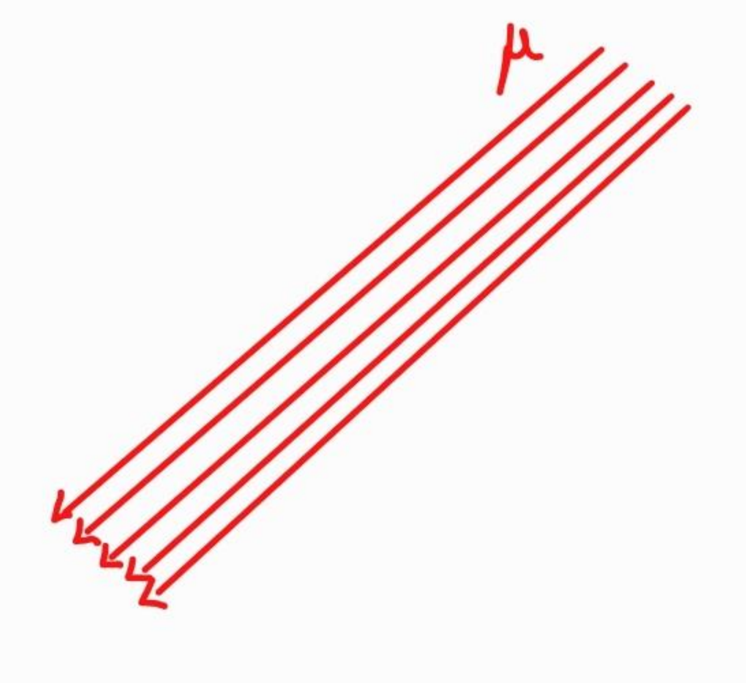
Simulations: charged current ν_μ interactions, only for throughgoing events

Muon Bundles Characteristics

Bundle Multiplicity: Number of secondary muons passing through the detector volume.

Lateral extension (at the detector level)

Radius of a cylinder along the track that contains a defined percentage of the collected light.



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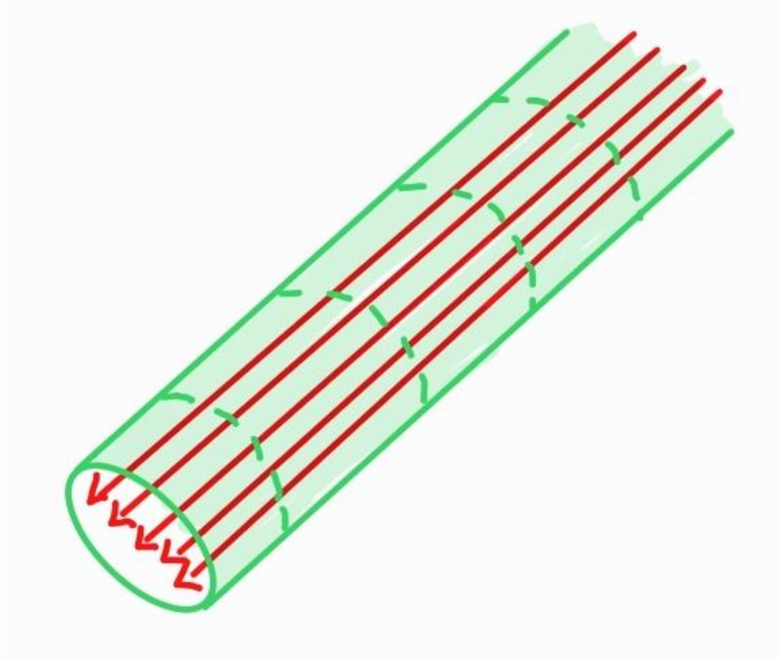

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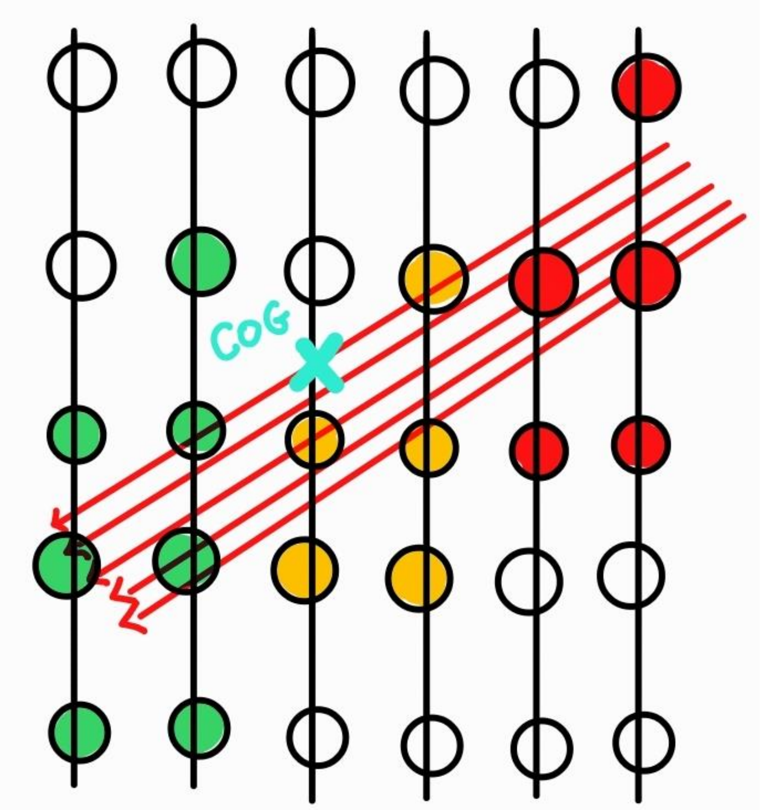

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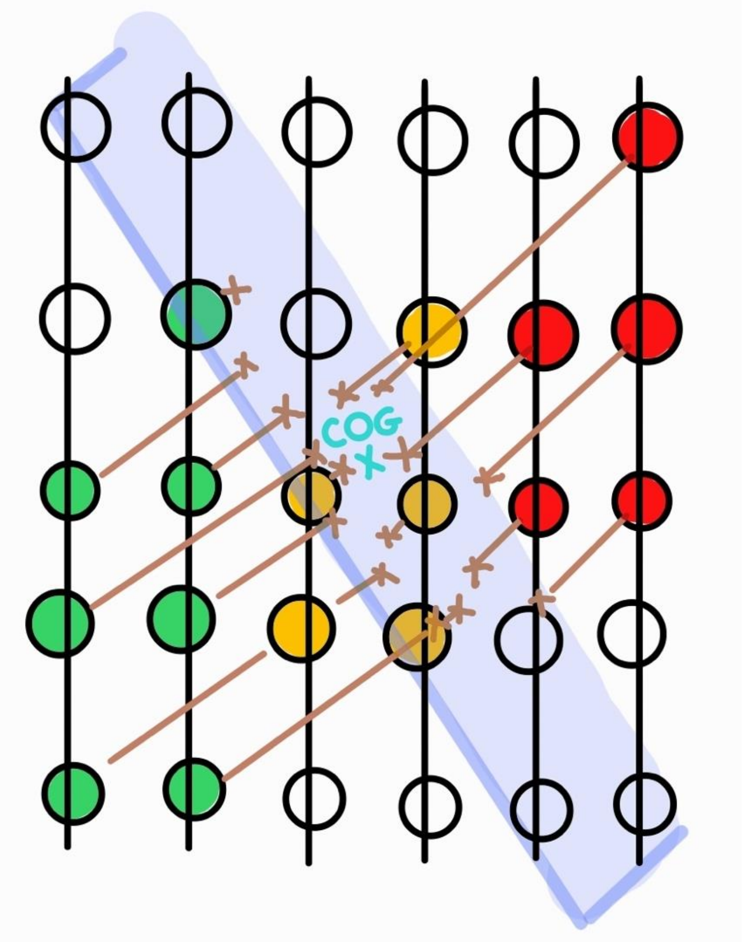
2. Project DOM charges into the plane perpendicular to the track at the COG



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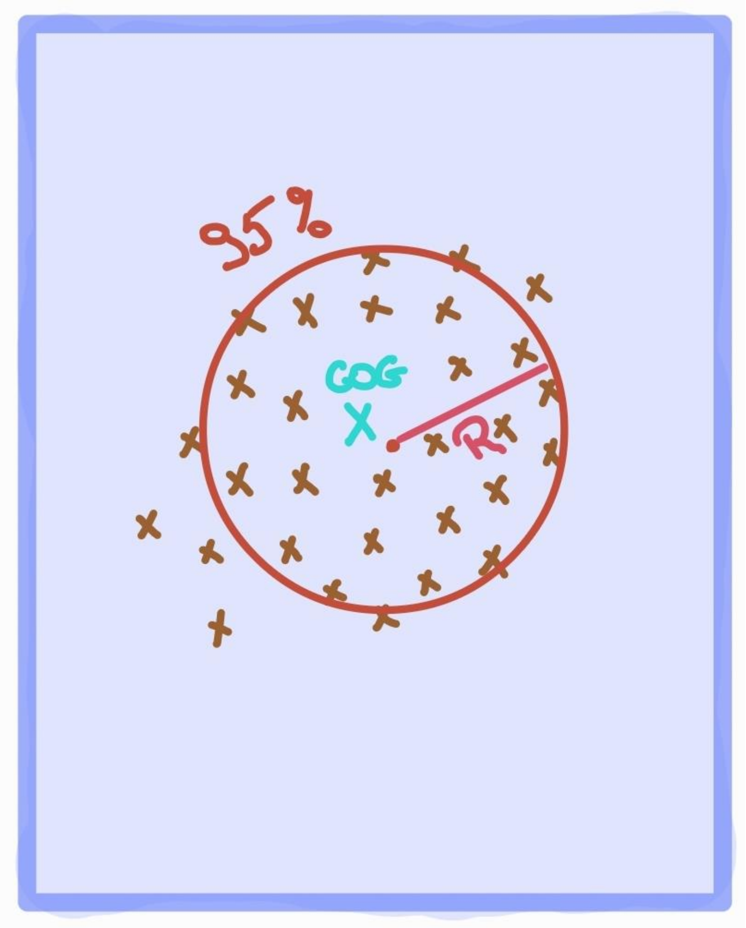
3. Draw a circle containing 95% of the total projected charge



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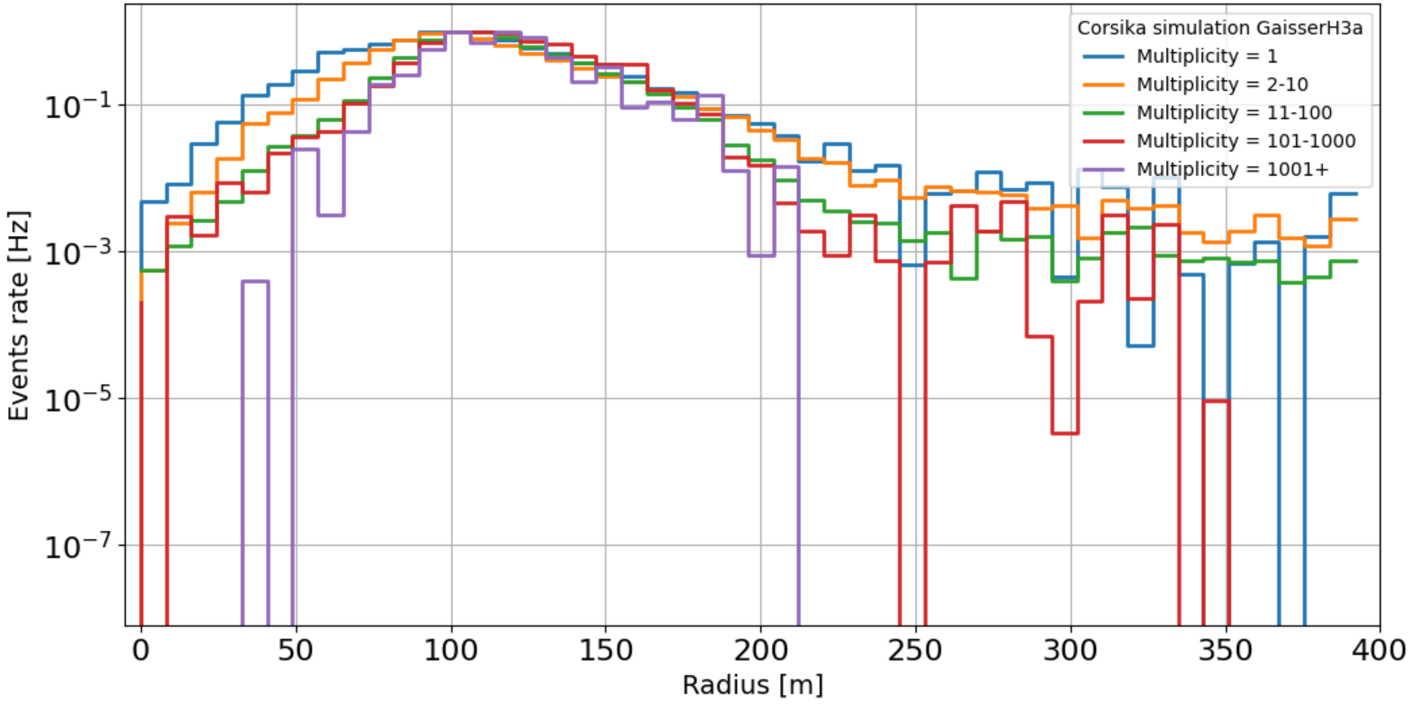
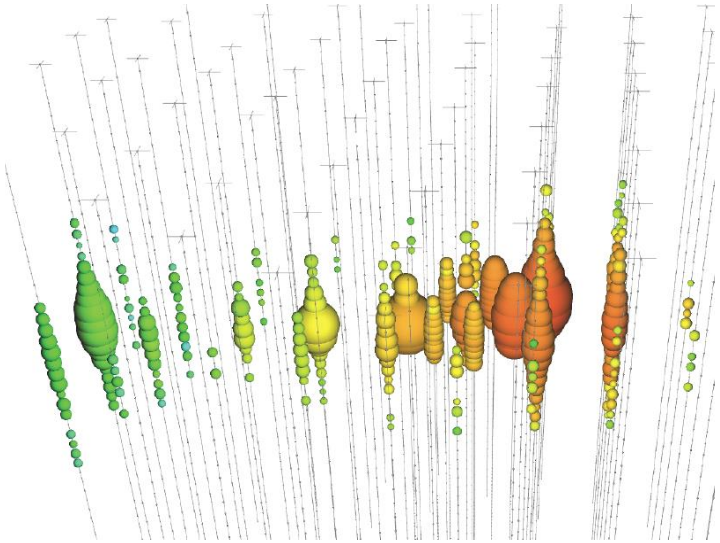


Muon Bundles Characteristics

Stochastic losses

Sudden energy deposits along a muon's track

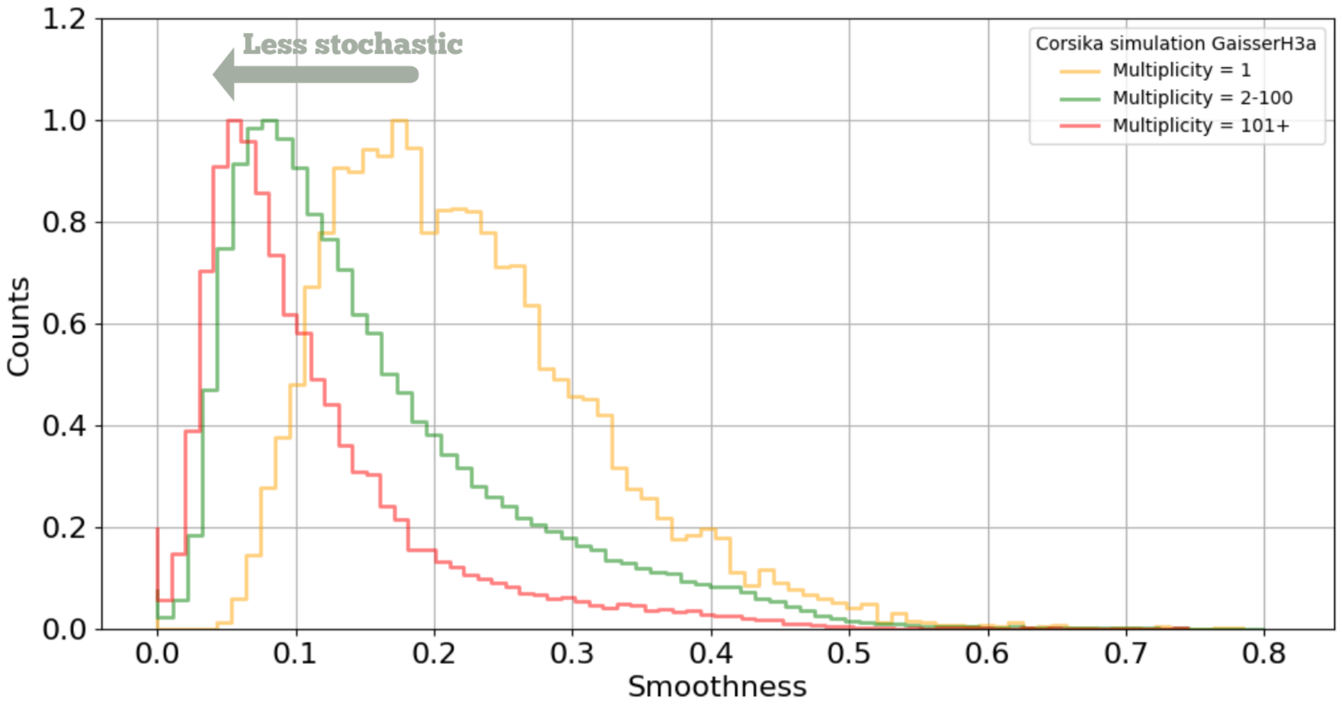
- ↳ Causing localized high energy deposition in the detector.
- ↳ Due to interactions like bremsstrahlung or pair production



[IceCube Masterclass, 2024]

Smoothness

Variable S that characterizes the difference between the observed energy distribution and a uniform one (S=0).

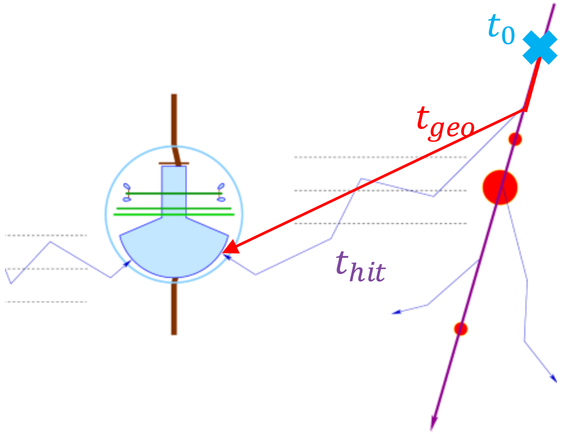


Muon Bundles Characteristics

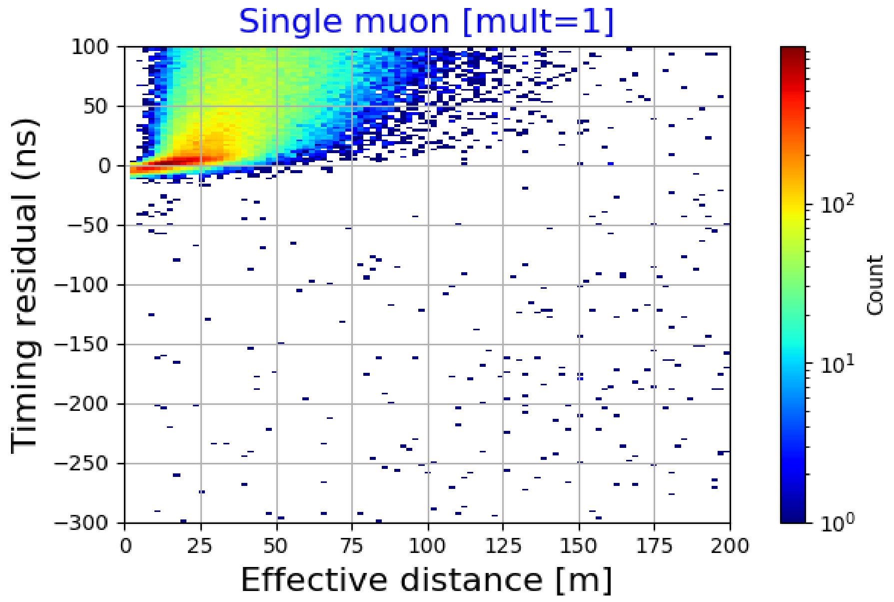
Residual time

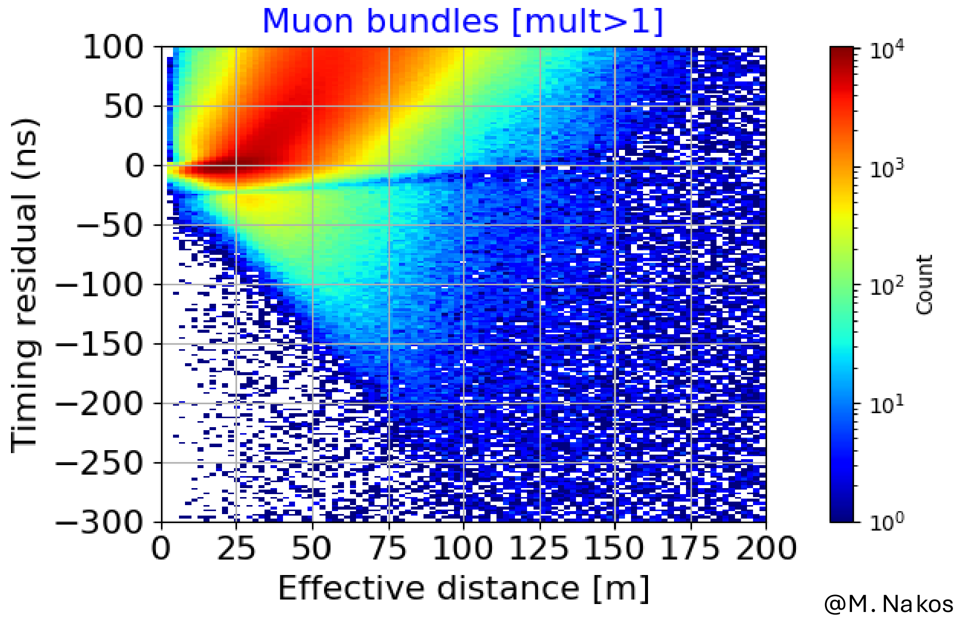
Difference between a photon's arrival time at the DOM and its expected arrival time assuming a direct, unscattered path.

$$t_{res} = t_{hit} - t_{geo} - t_0$$



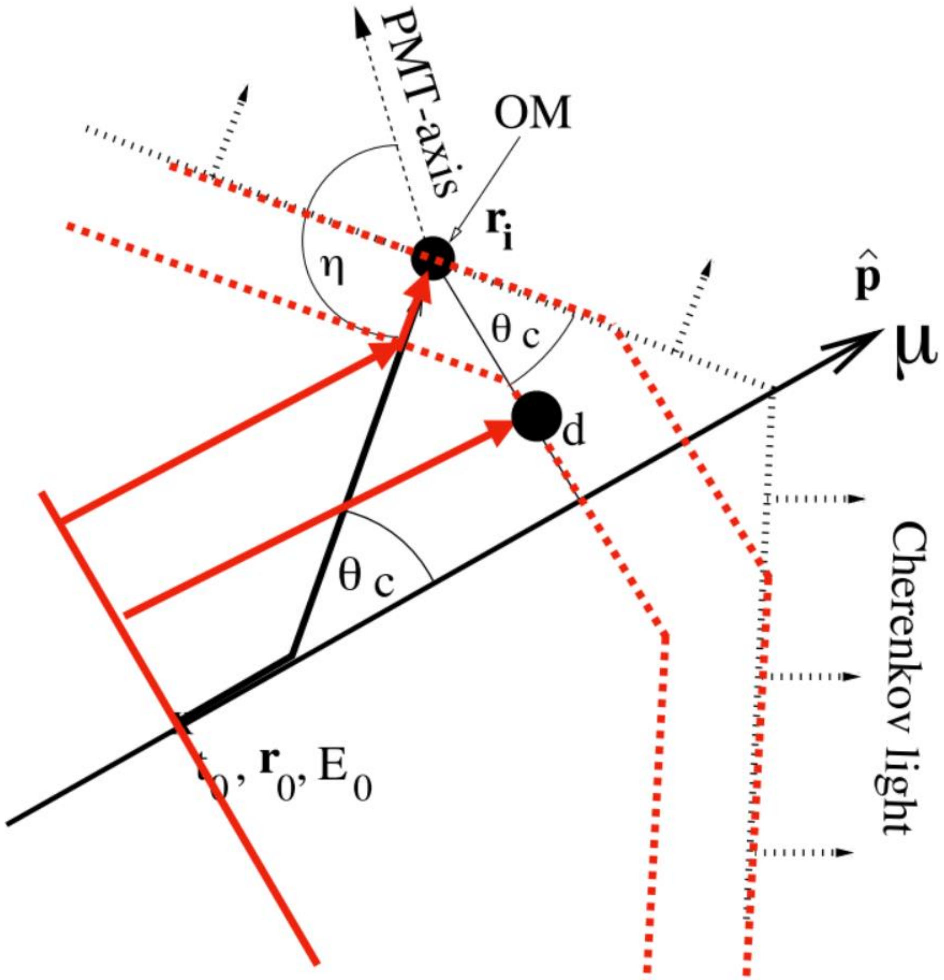
[Adapted from: Schwanekamp et al., 2022]





@M. Nakos display

Devil's Tower Model



[Rawlins, 2023]

Single muon = only one track

Cherenkov cone $\cos\theta = \dfrac{1}{n\beta}$

Muon bundle = multiple tracks

↳ Contained in a cylindrical volume around the track direction

Devils tower idea:

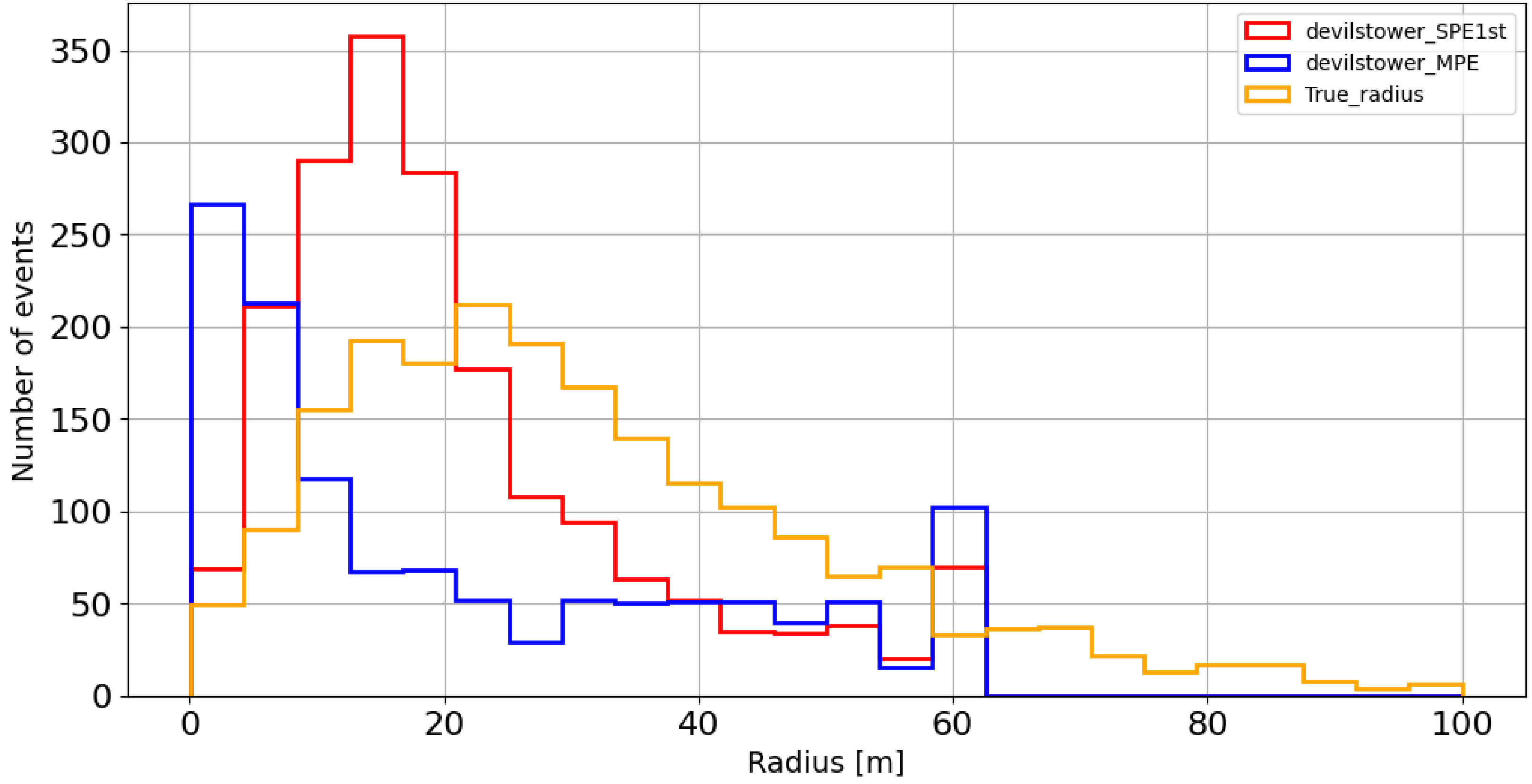
Truncate the Cherenkov cone to use a planewave to simulate the front of the bundle (developed by K. Rawlins)

Ligth emission depends on DOM position:

- Inside the cylinder: planewave Cherenkov emission
- Outside the cylinder: Cherenkov cone emission

Devil's Tower first result

Bundle radius



True bundle: estimated from the set of simulated muons intersecting the detector

Different reconstruction method:

- Multiple PhotoElectron (MPE)
- Single PhotoElectron (SPE)

Conclusion and Outlook

Research Goal

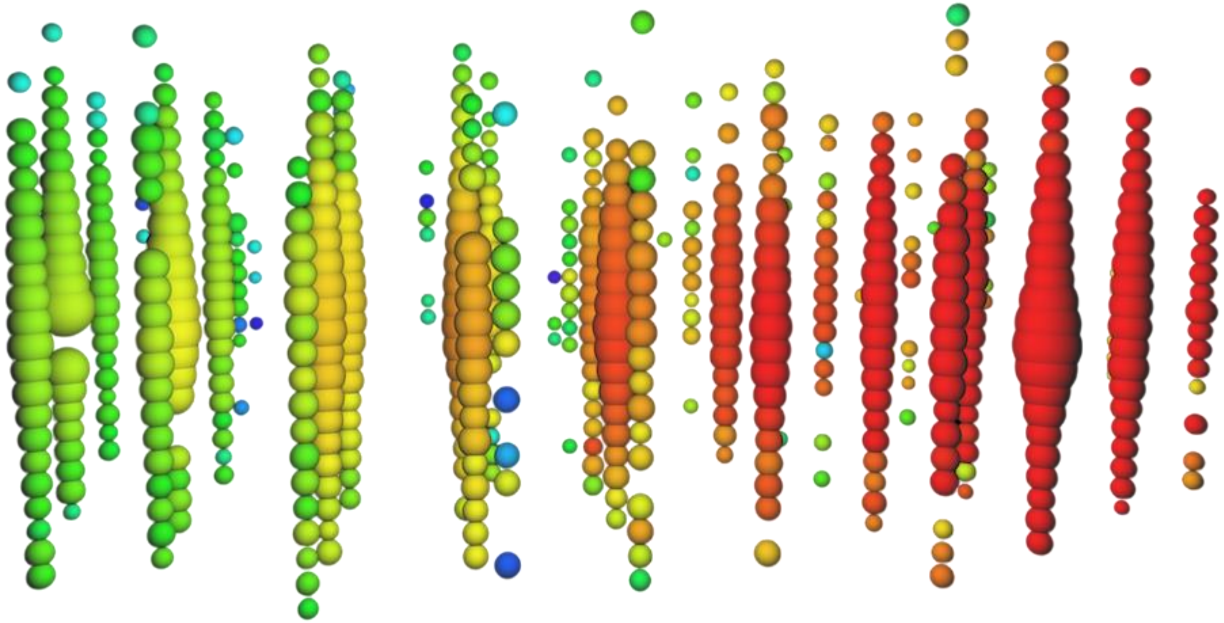
Study muon bundles to improve the identification of Extremely High Energy (EHE) neutrinos in IceCube

Muon bundle characterization
lateral extension, residual time, smoothness

Devil's Tower Geometry
Development of the new Event reconstruction model to refine track analysis

Outlook
Use these features to train a machine learning model (e.g., Graph Neural Network) for better event classification

Thank you



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Smoothness

1. List of the projected position of the hit DOMS:

   $distAlongTrack(DOM_i, Track)$ = projected position of the i^{th} DOM on the line of the configured track

   where i $\in [1, N_{hit}]$
   N_{hit} = the total number of hits

   $$domDistList := \{distAlongTrack(DOM_i, Track)\}$$

2. The « distance » list is rated in ascending order

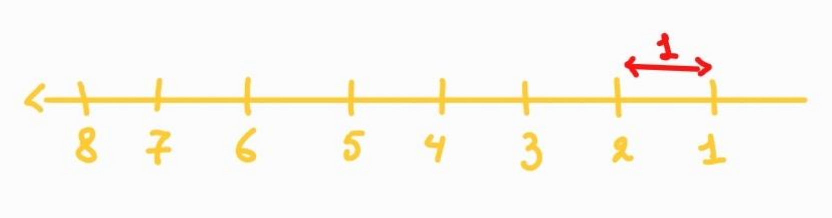
   $$ascDOMDistList := ascending\ Sort(domDistList)$$

3. l_i is the lenght of the track to the i^{th} pulse in regard to the first pulse in sorted distance list

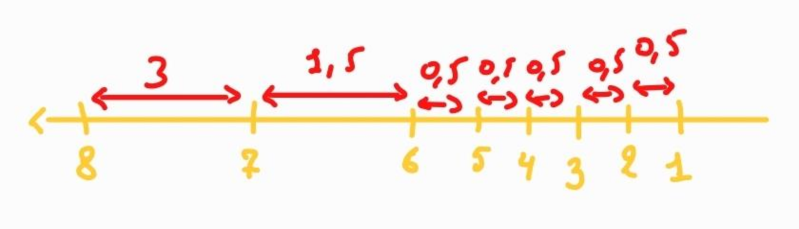
4. j is the pulse with: $max\left(\left|\frac{j}{n} - \frac{l_j}{l_n}\right|\right)$

5. Smoothness: $S = \frac{j}{n} - \frac{l_j}{l_n}$ where $S \in [-1, 1]$

$S = 0.1$



$S = 0.39$



$S = -0.34$