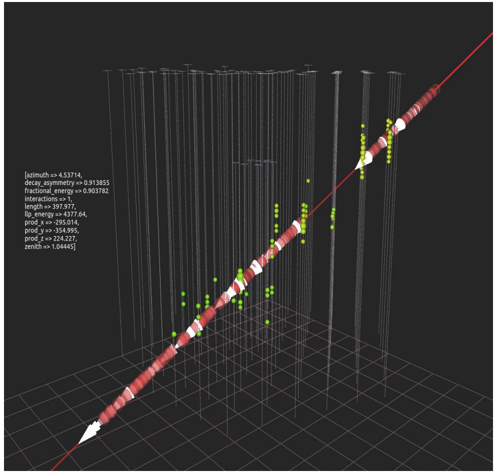
Search for Long Lived Particles with the IceCube Neutrino Observatory



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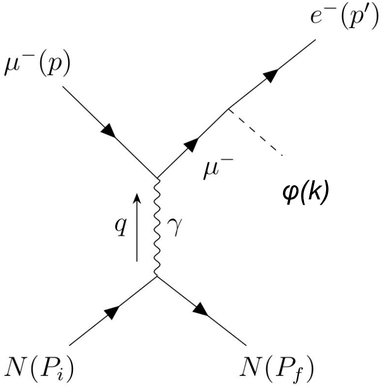


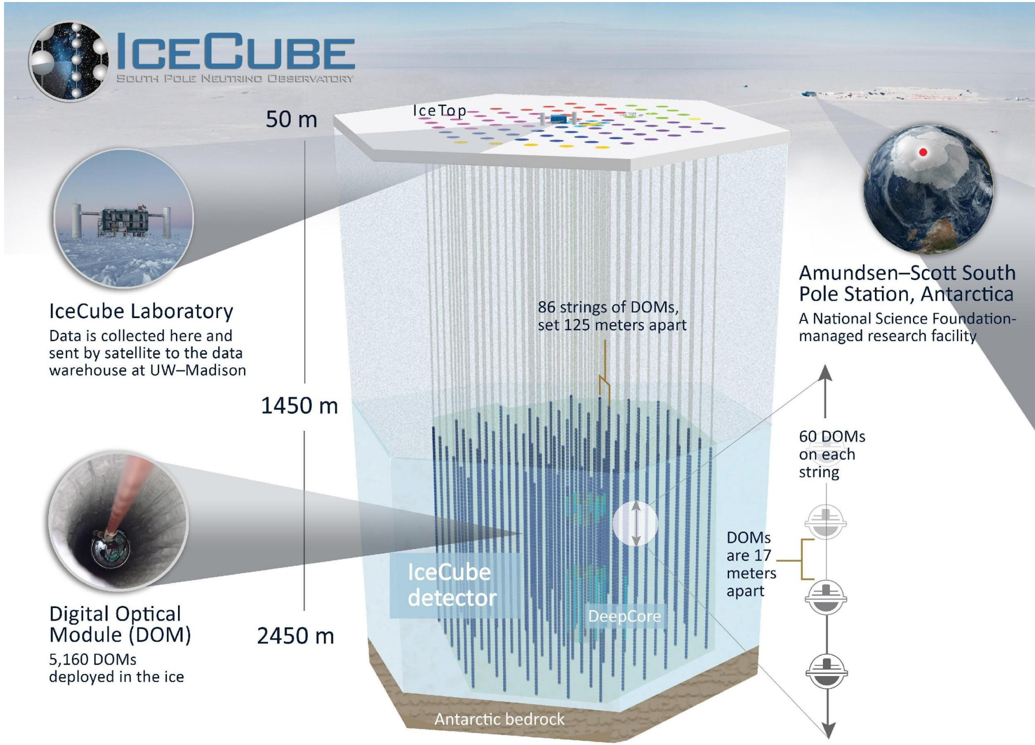
ICECUBE NEUTRINO OBSERVATORY

September 18th 2026 | Partikeldagarna-2026

UPPSALA UNIVERSITET

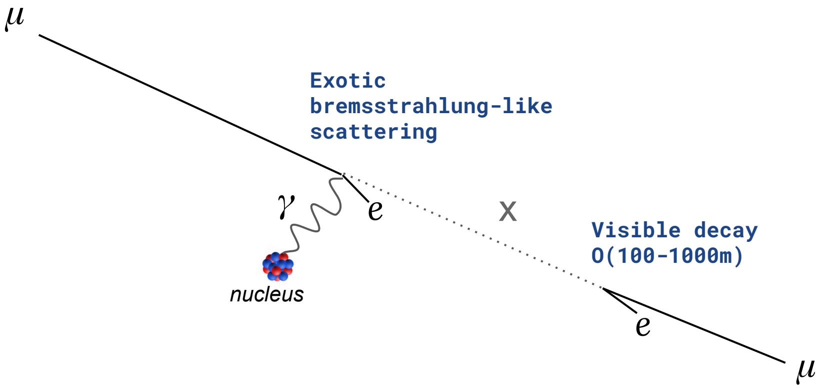
IceCube Neutrino Observatory

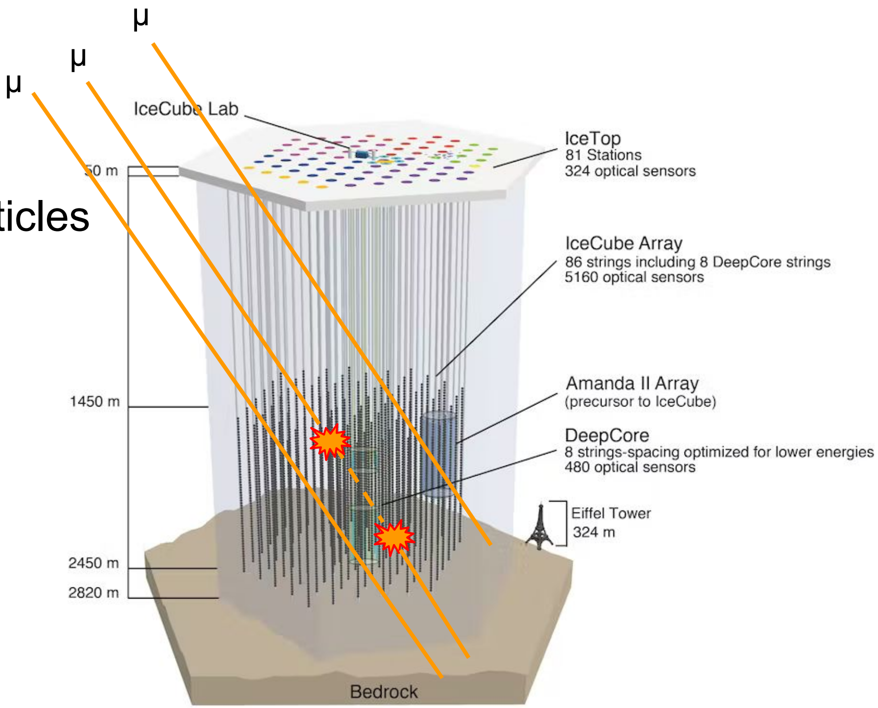
- Neutrino telescope buried 1.5km deep under the antarctic ice
- ~5000 optical modules over 1 km^3 measures Cherenkov light in the ice
- Events
  - Astrophysical neutrinos ~ few per year
  - Atmospheric neutrinos ~ mHz rate
  - Atmospheric muons ~ kHz rate
- Can do particle physics
  - Neutrino oscillations
  - Exotic BSM searches (e.g. monopoles, fractionally charged particles, **long lived particles**, etc.)
  - and more…



Is there hidden physics in the “unwanted” atmospheric muon flux?

- ~10^{10} muons per year (kHz rate)
  - Discarded in most analyses
- Anomalous muon tracks from rare BSM?
  - Displaced vertex from dark Long Lived Particles (LLPs)
  - Dark gap in otherwise bright muon track



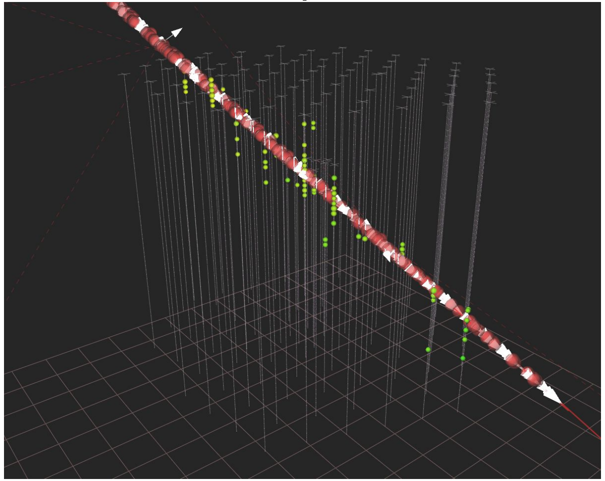


Long Lived Particles at IceCube

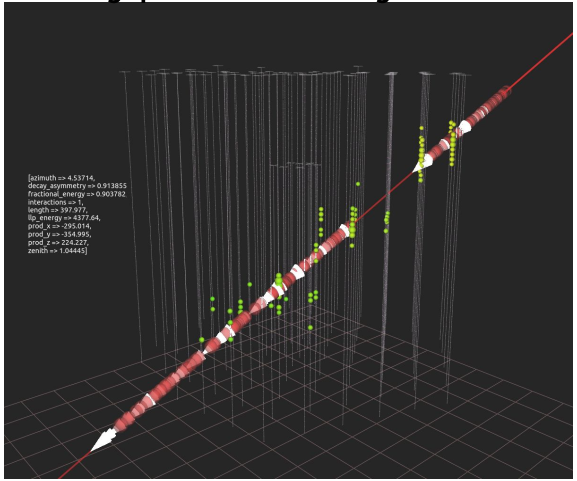
Requires a visible gap with production and decay inside detector

- Gaps 100m-1000m
  - Shorter looks like background
- <u>Only single muons!</u> Bundles cover gap
  - Low energy (peak below 1 TeV)
- Flavour changing coupling easier to distinguish
  - Secondary muon might cover gap (muons are MIP)

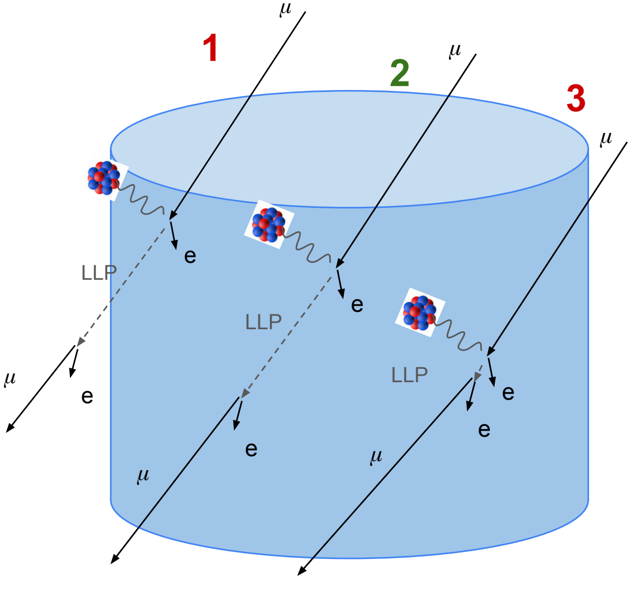
Continuous atmospheric muon track



Track gap from “dark” Long Lived Particle



1. *Decay outside detector :(*
2. *Detectable LLP :)*
3. *Gap too small :(*



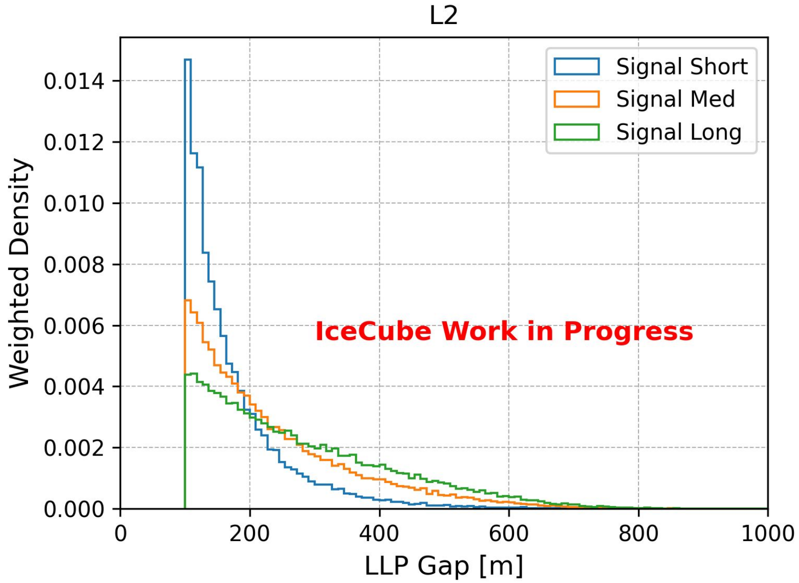
Benchmark model: Dark Leptonic Scalar arXiv:2202.04410v3

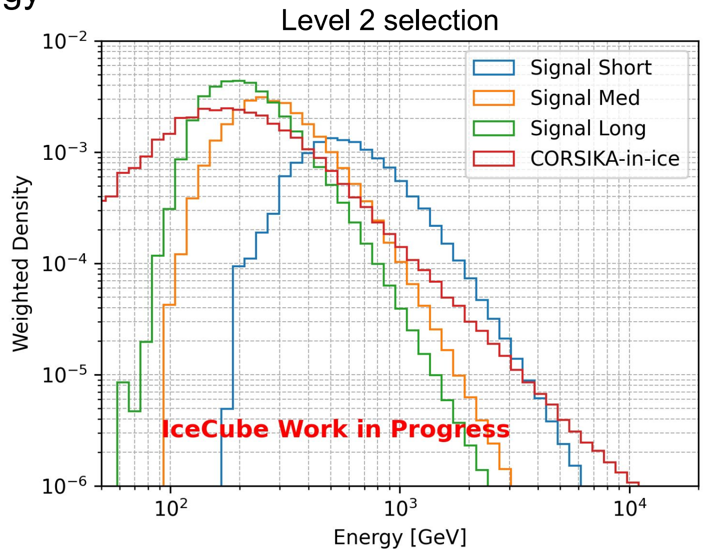
Benchmark Model

- Dark Leptonic Scalar as benchmark model arXiv:2202.04410v3
  - $\mu \rightarrow e$ coupling
  - Potential portal to dark sector
- Different lifetimes give difference in gap distribution and energy spectrum

Benchmark samples

	LLP Short	LLP Mid	LLP Long
Mass	110 MeV	110 MeV	108 MeV
Coupling	3e-5	1e-5	8e-6
Lifetime	0.06 ns	0.5 ns	3 ns
Decay length @1TeV	153 m	1380 m	7416 m

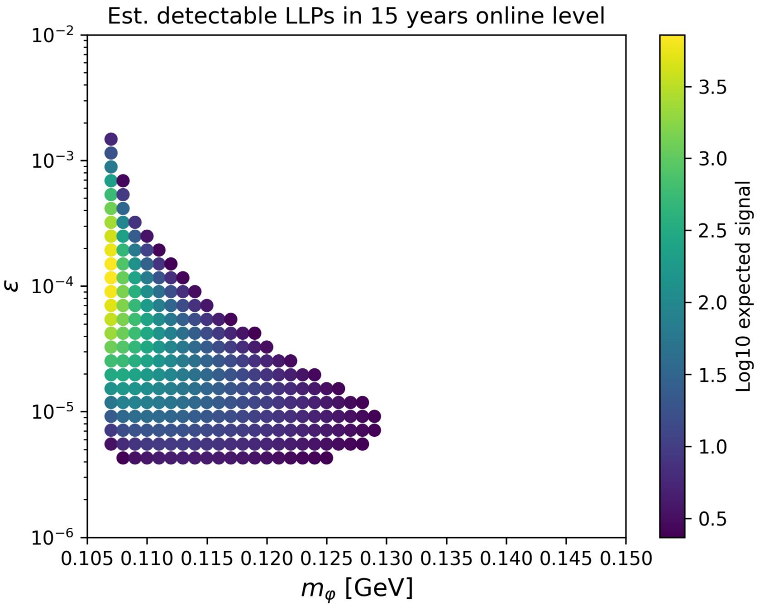




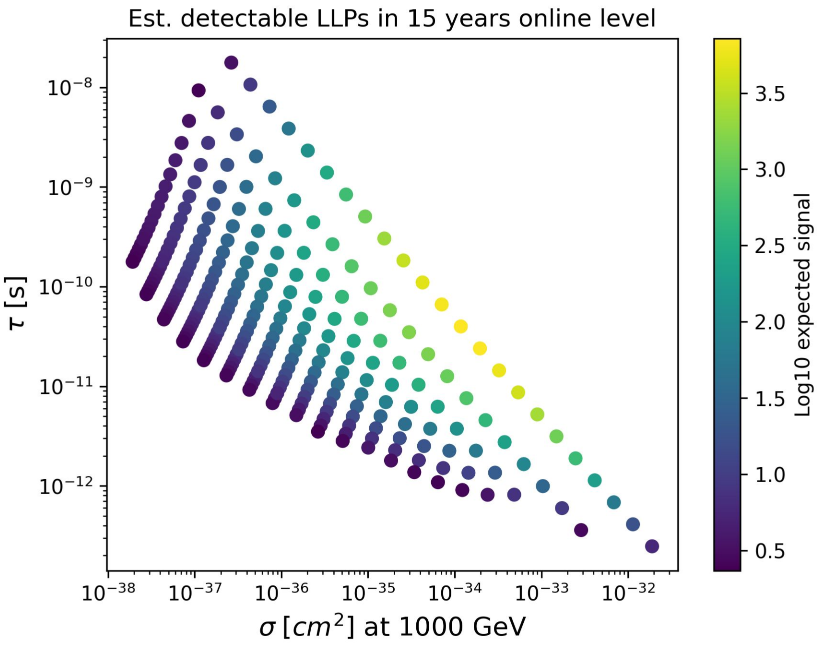
Lorentz Boost determines gap length!
Long lifetime needs low energy for containment
Short lifetime needs high energy for long enough gaps

Estimating signal rate @ trigger level

Muon spectrum is highly complex, use full MC simulation of single muons to estimate event-by-event probability



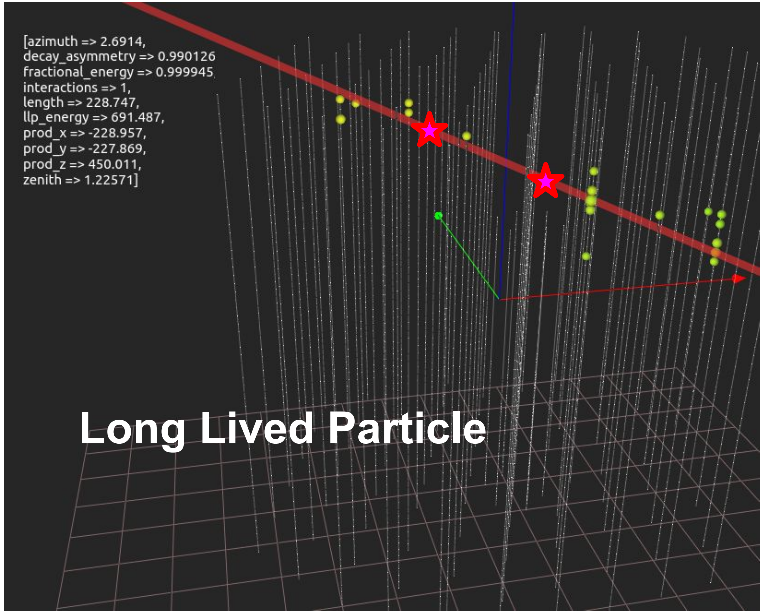
Recast

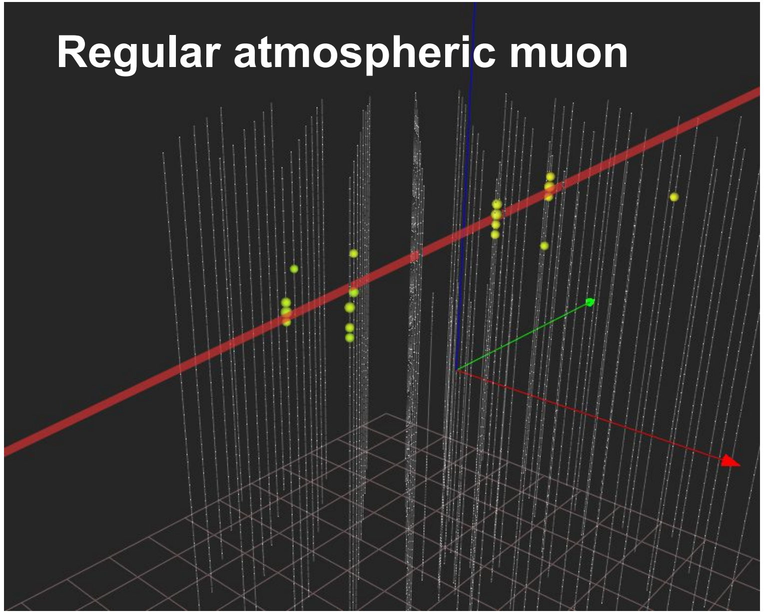


Min gap 100m
200m entry/exit margins

Low energy muons already have gaps

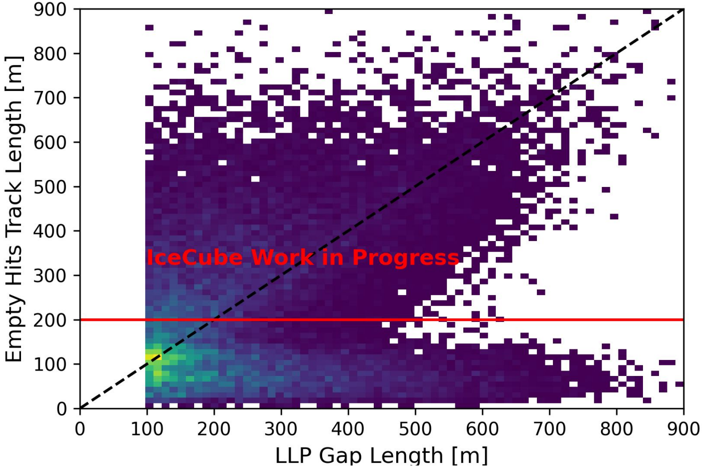
- Single muons are low energy
- Detector is sparse (~17-125 m resolution)
- Gaps in photon hits not always due to Long Lived Particle, especially at lower energies



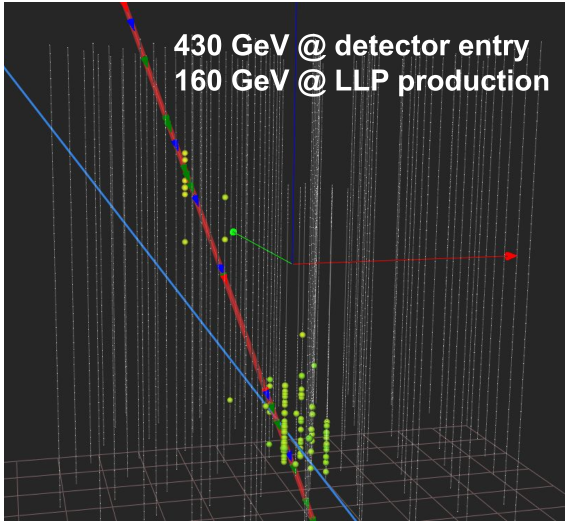


Many LLP Events Hard to Identify After Pulse Cleaning

Empty Hits Track Length = Longest distance between hits projected along track reconstruction

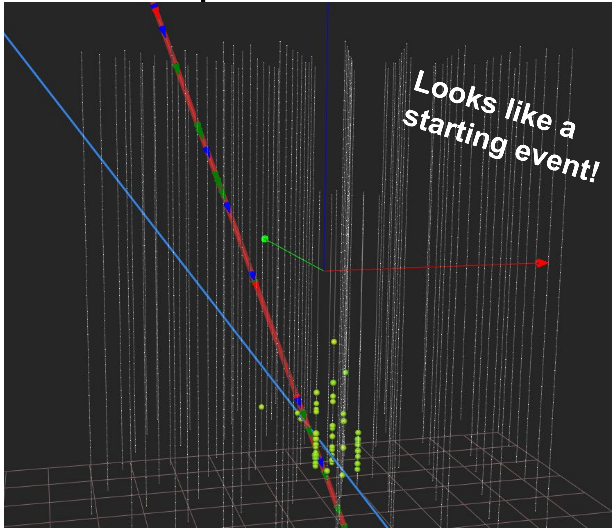


MC Truth (before noise gen.)



Generate noise hits then apply **standard** pulse cleaning algorithm

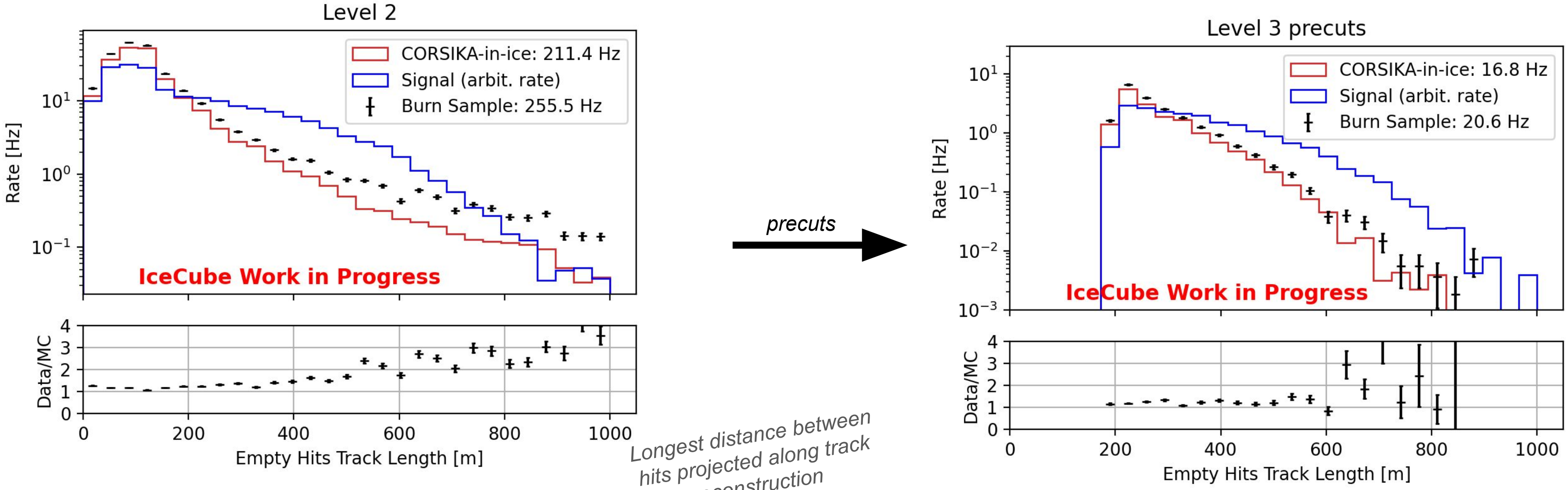
Cleaned pulses



Precuts

1. Track reco goodness of fit cut
2. Reco Zenith < 90deg
3. Empty hits track length > 200m
4. Estimated track length > 300m
5. Total hits > 12

1. Many signal events are diffuse or look like starting events
2. Background data/MC disagreement from difference in coincidence muon rate

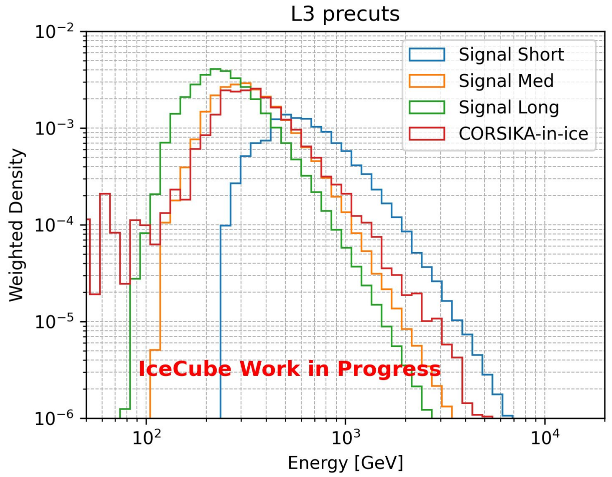


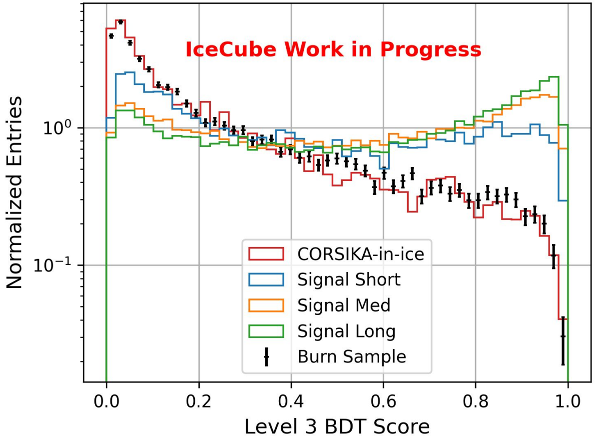
Longest distance between hits projected along track reconstruction

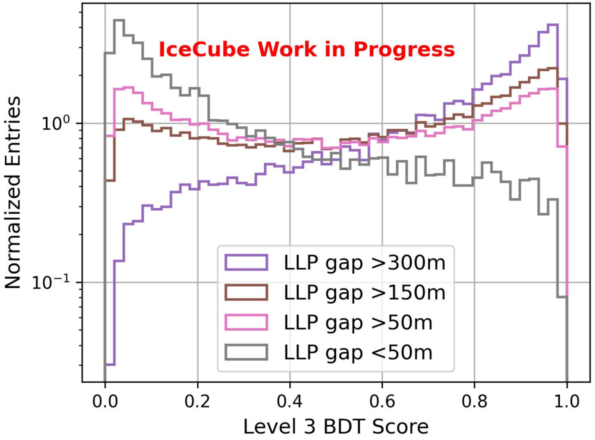
Boosted Decision Tree (BDT)

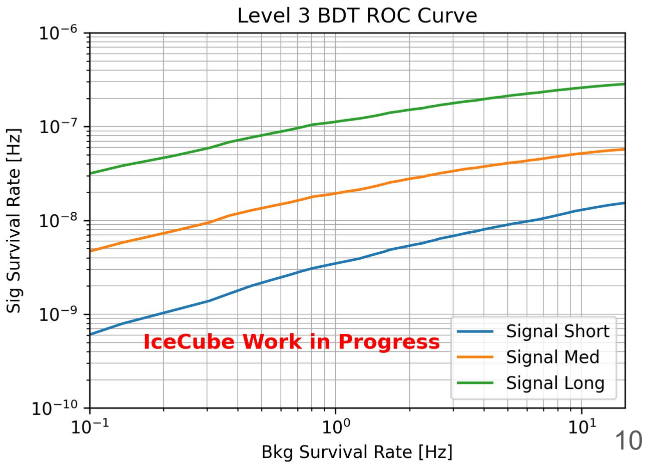
First classifier in event selection chain

- Trained on uniform gap signal vs. MC atmospheric muon background
- Event level variables related to hit distribution
  - *e.g. # of hits, estimated track length, empty hits track length, reco zenith, ...*
- **Careful!** BDT should find gaps, not pick out energy spectrum
  - *weight signal to background spectrum during training*
- Score Cut @ 0.80 gives ~1Hz data rate





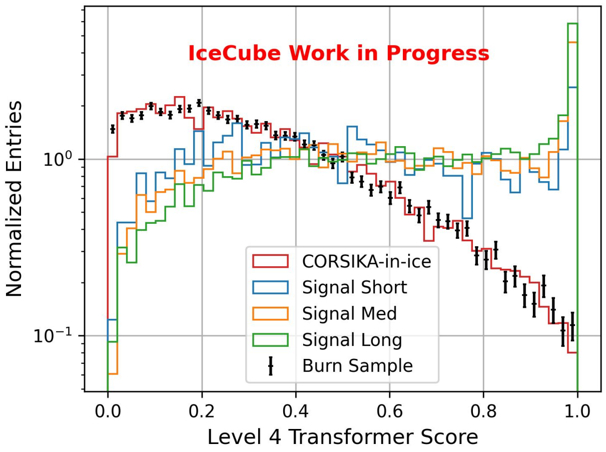


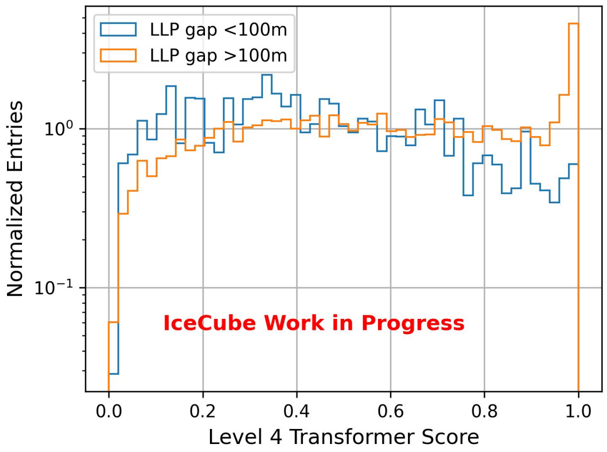


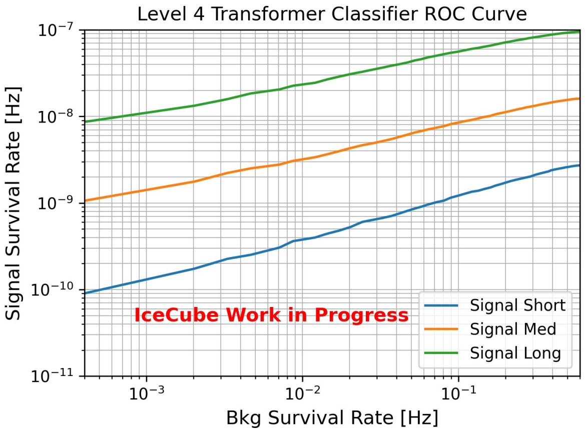
Transformer Classifier

Second classifier in event selection chain

- Trained on uniform gap signal vs. MC atmospheric muon background passing the BDT
- Trained directly on the photon hit pulses
  - *Summary statistics per optical module: time of first hit, position xyz, total PE charge, etc.*
- Score cut: work in progress

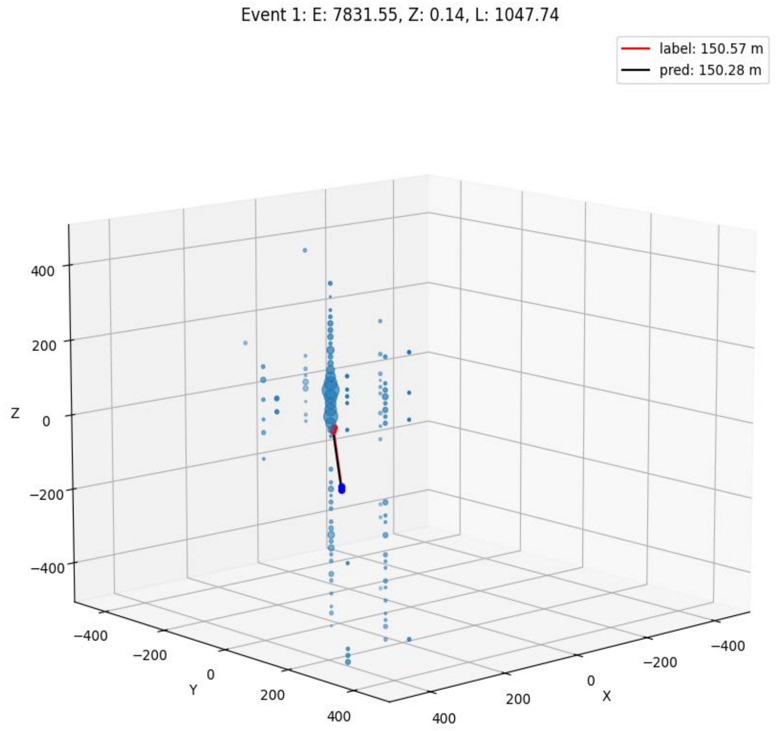


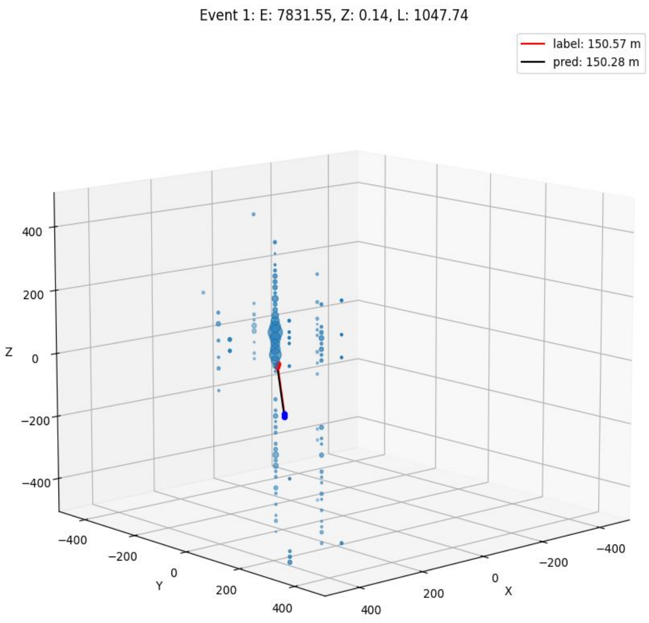




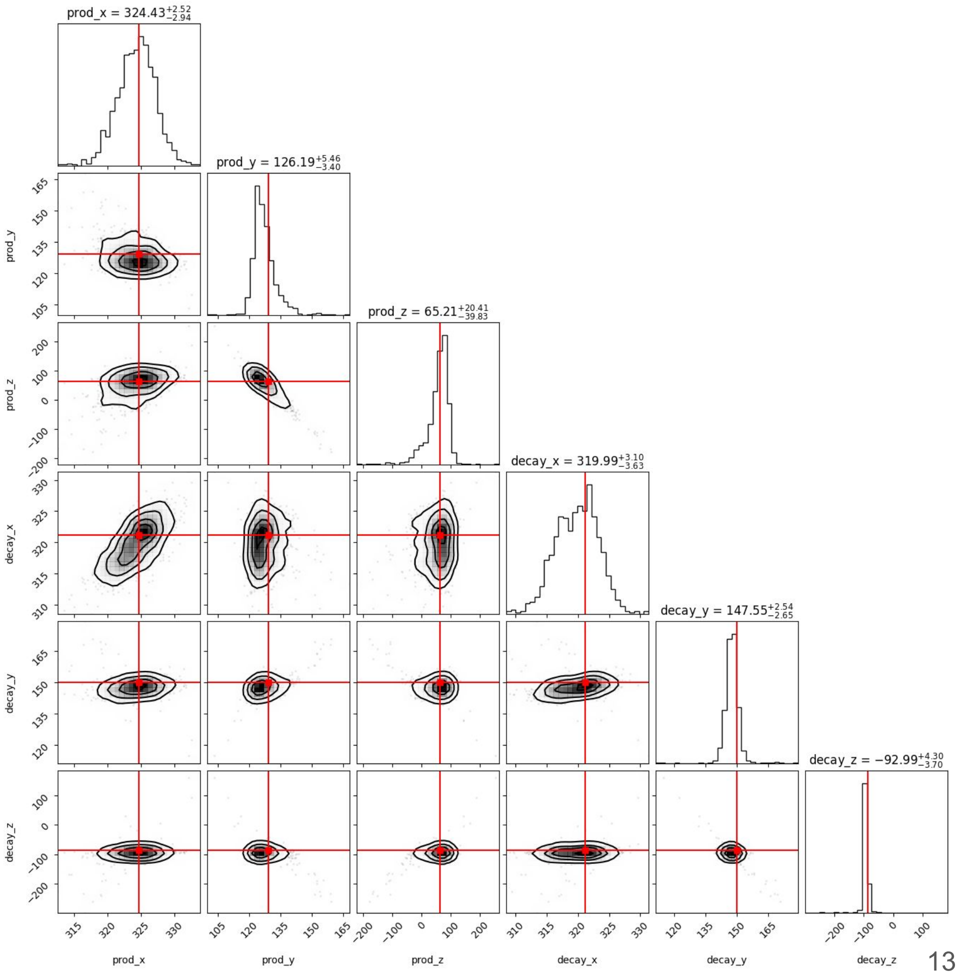
Gap Reconstruction with Deep Learning

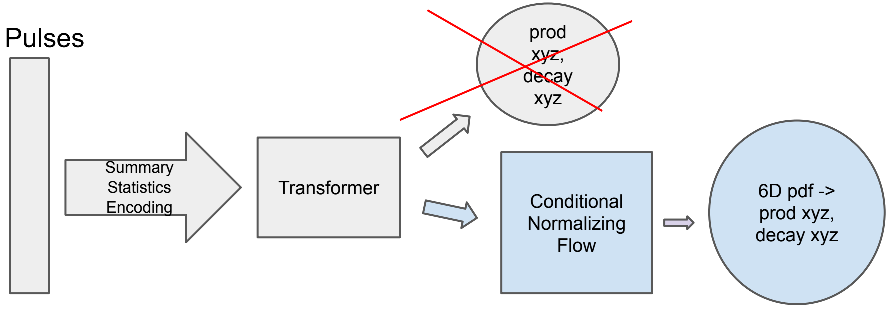
- **Transformer + Conditional Normalizing Flow**
    - Input -> Photon Hit Pulses
    - Output -> Gap Position pdf
- **Trained only on MC signal**
- Conditional normalizing flow (CNF)
    - Outputs ***probability density functions*** instead of numerical values
    - Event-by-event uncertainty on gap position
- Based on work by Thorsten Glüsenkamp
    - Package by him https://github.com/thoglu/jammy_flows/
    - Read more https://arxiv.org/abs/2008.05825
    - Find out more during his talk on Wed Sep 9th




Event 1: E: 7831.55, Z: 0.14, L: 1047.74
label: 150.57 m
pred: 150.28 m
Z
Y
X


CNF


prod_x = 324.43$^{+2.52}_{-2.94}$
prod_y = 126.19$^{+5.46}_{-3.40}$
prod_z = 65.21$^{+20.41}_{-39.83}$
decay_x = 319.99$^{+3.10}_{-3.63}$
decay_y = 147.55$^{+2.54}_{-2.65}$
decay_z = −92.99$^{+4.30}_{-3.70}$
prod_x
prod_y
prod_z
decay_x
decay_y
decay_z


Pulses
Summary Statistics Encoding
Transformer
~~prod xyz, decay xyz~~
Conditional Normalizing Flow
6D pdf -> prod xyz, decay xyz

Summary

- First search for Long Lived Particles in IceCube
- LLPs would give gaps in muon tracks at IceCube
  - Pros: Very thick target, enormous decay volume
  - Cons: Low statistics, low energy, low spatial resolution
- Signal **hard** to distinguish from background
- BDT and transformer classifiers help reduce the background
- Transformer + conditional normalizing flow for LLP gap reconstruction
- Results for Dark Leptonic Scalar can be recast to put limits on xsec/lifetime
- Stay tuned!