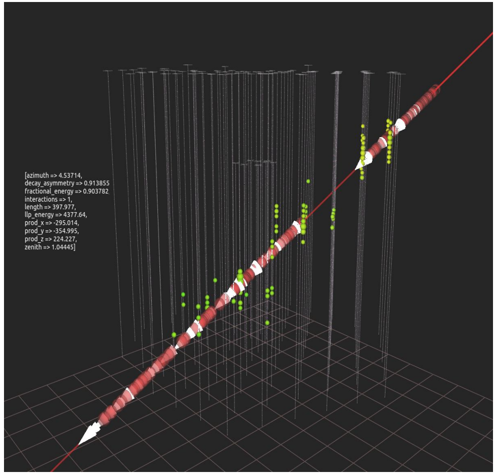
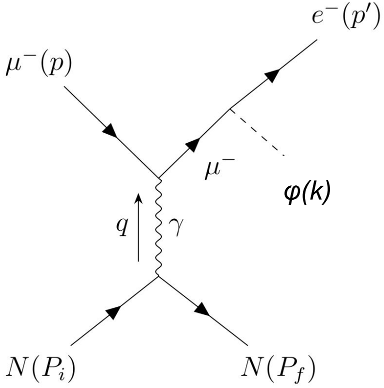
Search for Long Lived Particles at the IceCube Neutrino Observatory





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Partikeldagarna

Nov 24th 2025

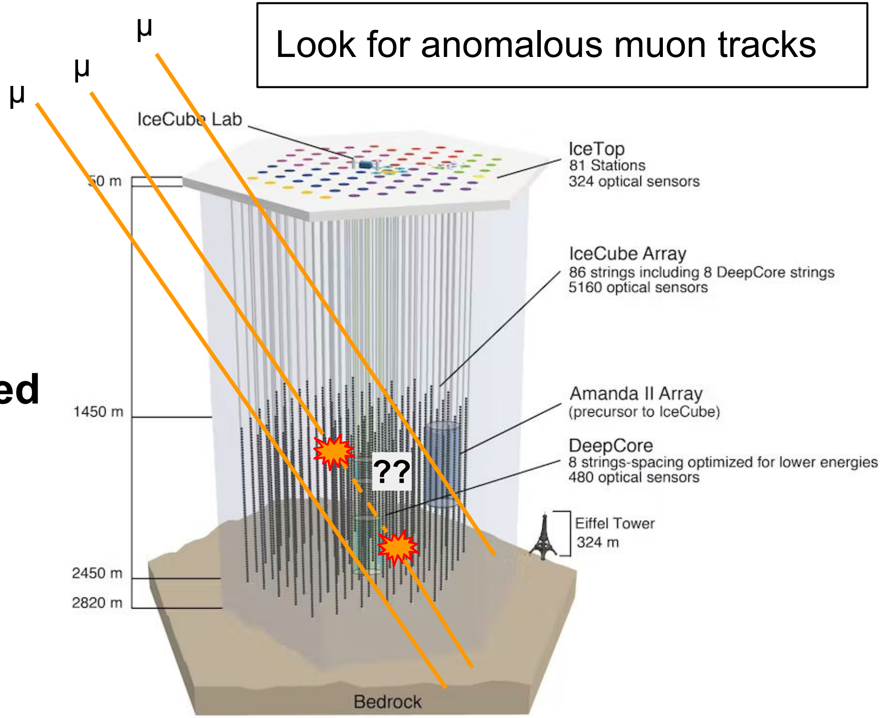
ICECUBE NEUTRINO OBSERVATORY

UPPSALA UNIVERSITET

Is there hidden physics in the abundant atmospheric muon flux at IceCube?

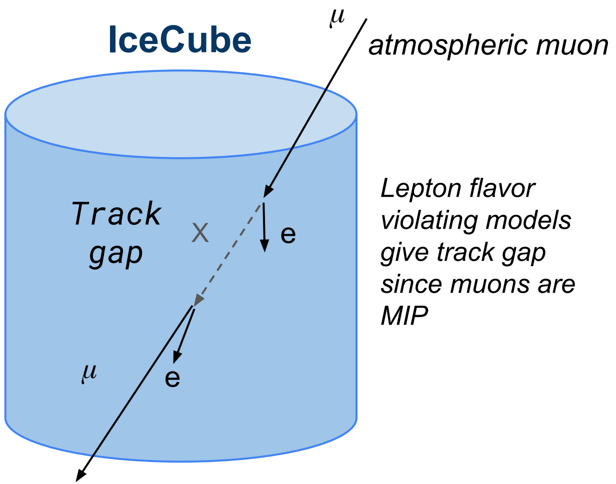
- 1.5 kHz muon rate
  - $\sim 10^{10}$ muons per year
  - Most are discarded as bkg
- Rare BSM physics coupling to muons?
  - Modified in-ice signature of muons
  - **Gaps in muon tracks from Long Lived Particles with displaced vertex?**
- Can IceCube complement accelerator searches for LLPs?

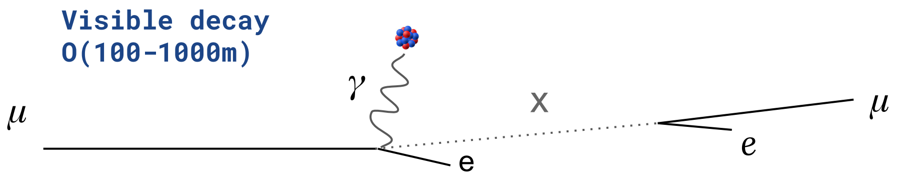
Look for anomalous muon tracks

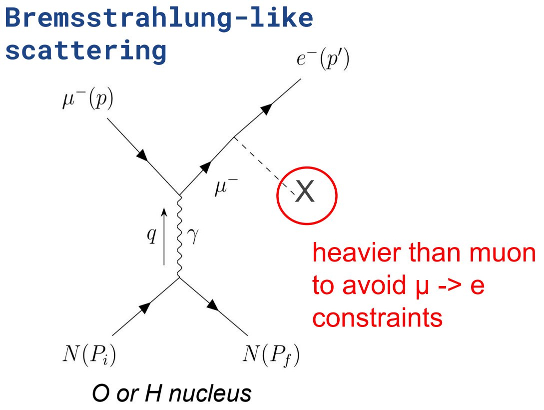


The Idea

- **Long Lived Particles from atmospheric muons**
  - Produced in exotic muon-nucleus scattering
  - Decays into visible SM particles
- **Event signature -> muon track with gap**
  - No Cherenkov light during LLP propagation
- **Advantage over accelerator searches**
  - Many nuclei in 1 km3 of ice: **very thick target**
  - No fixed decay length: **large decay volume**







Long Lived Particles (LLPs)

- Light particles with very weak coupling to the SM
  - Dark photon, Dark Z', ALPs, Dark Higgs, Heavy Neutral Leptons, etc.
- Produced in rare scattering or decays
- Decays visibly with macroscopic decay lengths
  - Displaced production and decay vertices
- Searched for at ATLAS, CMS, NA62, FASER, etc.

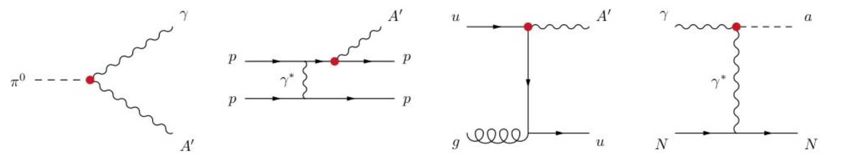
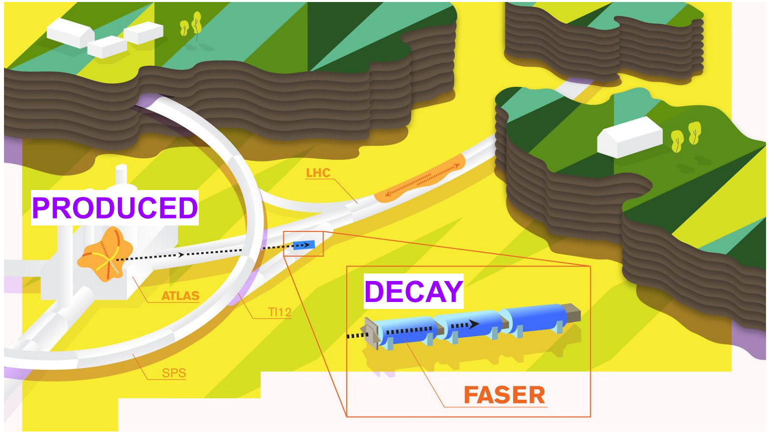


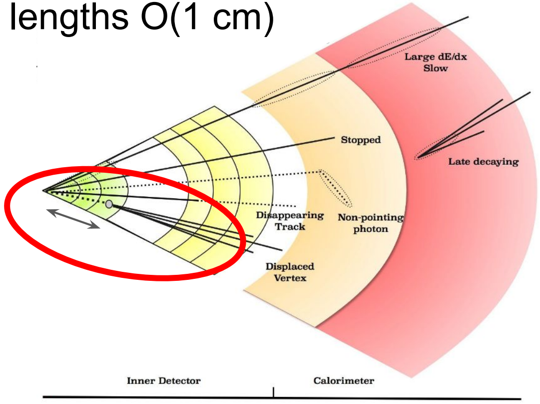
FIG. 4. Representative Feynman diagrams for the LLP production processes outlined in this section: dark photon production from pion decay (left), dark photon production via dark bremsstrahlung (center left), dark photon production in hard scattering (center right), and ALP production via the Primakoff process from photons scattering in the TAN (right).

arXiv:1811.12522v3

Decay lengths O(100 m)



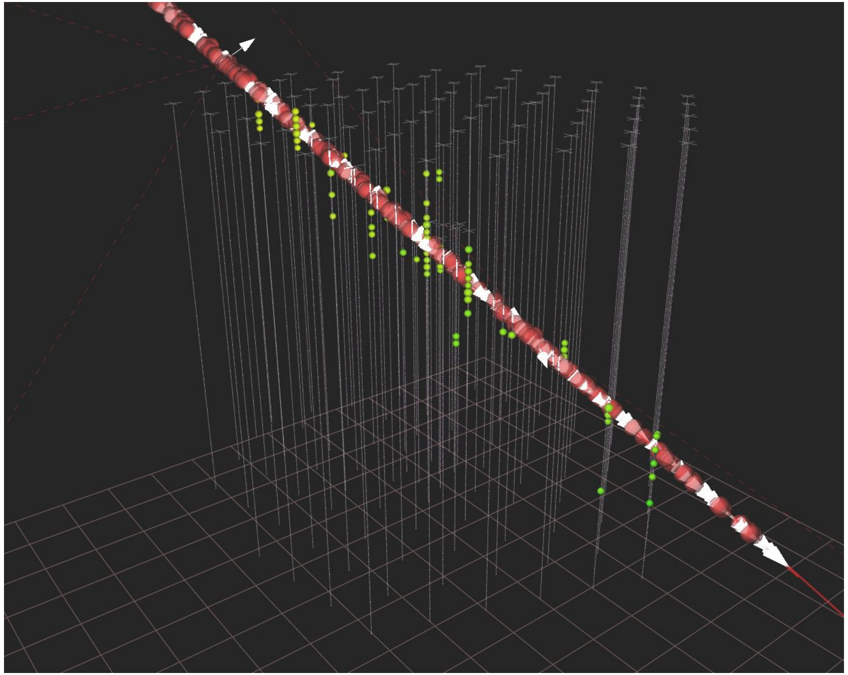
Decay lengths O(1 cm)



Signal vs. Background

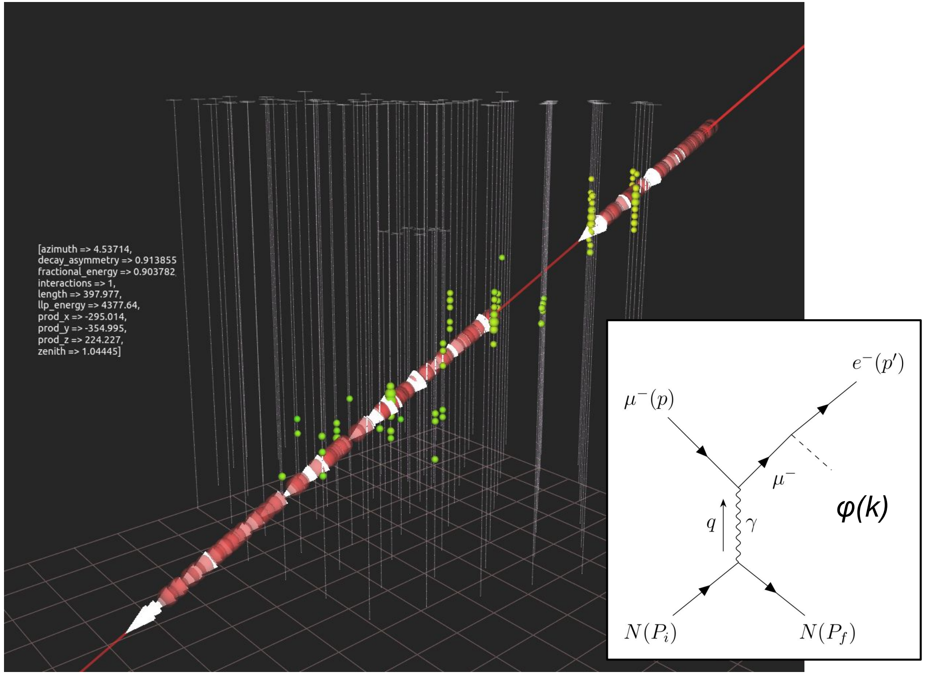
MC Simulation

Atmospheric muon



Red spheres and white arrows are MC energy losses which yield Cherenkov photons that hit the DOMs. Those pulses are the only event observables.

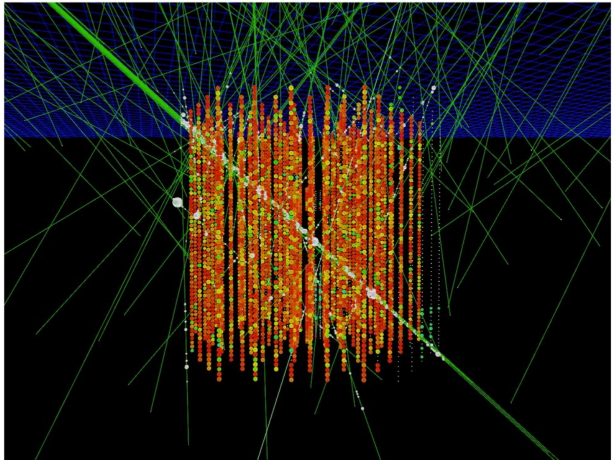
Atmospheric muon with Long Lived Particle

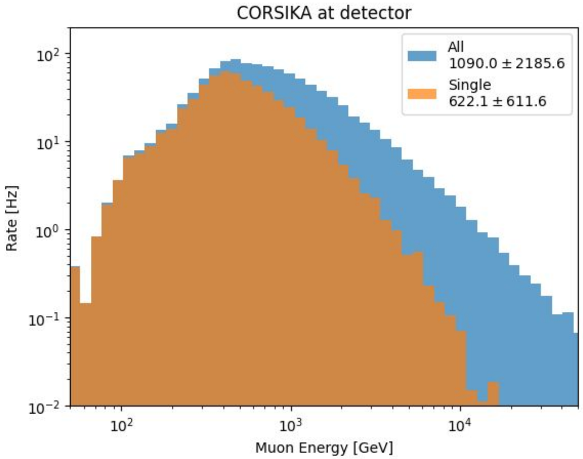


Benchmark model: Dark Leptonic Scalar
arXiv:2202.04410v3

Beam: Atmospheric Muon Flux at IceCube

- 1.5 kHz muon trigger rate (vs. 10 mHz neutrino rate)
- Complex and correlated covering orders of magnitude in energy!
  - Energy, zenith, length in detector, multiplicity etc.
  - Characterizing the “beam” is hard! No prior info
- Compare to e.g. fixed-target experiments with monochromatic beams hitting the same target from same direction

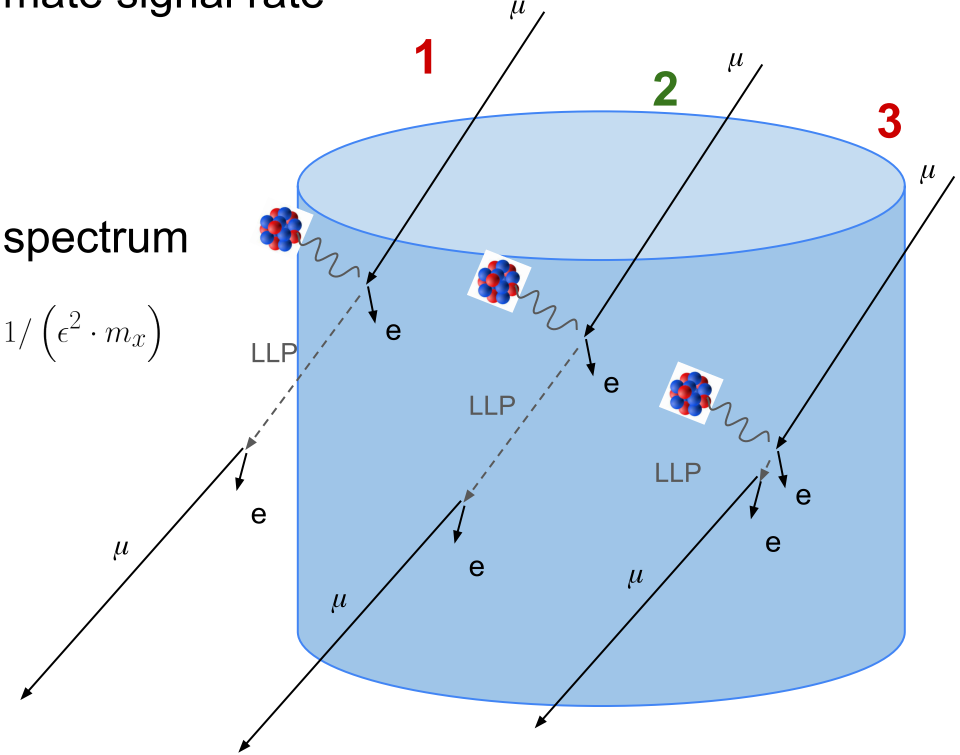




Production Estimation : Event-by-event LLP probability

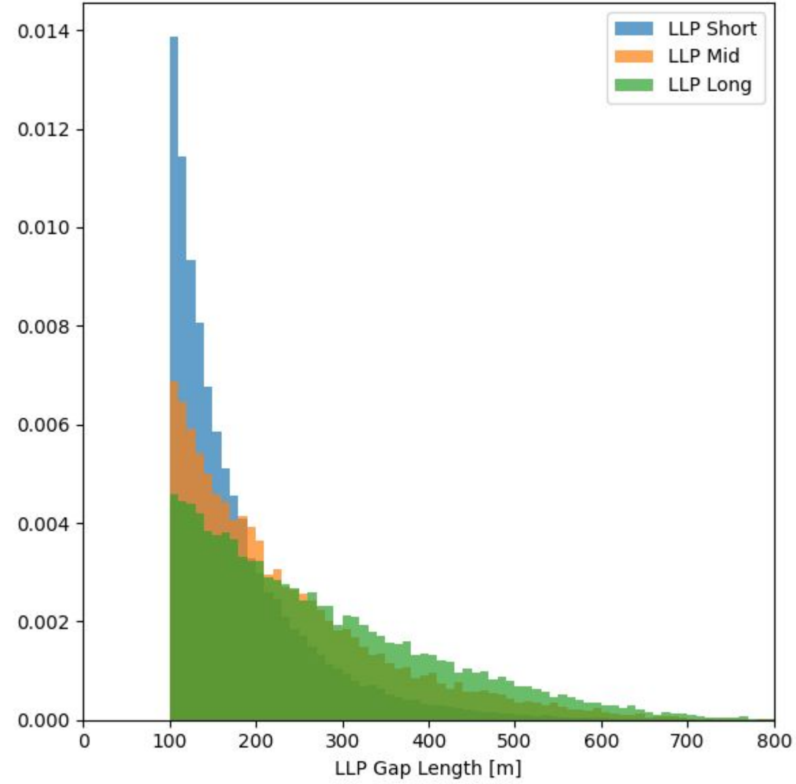
- Muon spectrum is complex
  - Need full MC simulation to estimate signal rate
- Single muons only!
  - Bundles cover gap
  - Limits us to low energy end of spectrum
- Production and decay compete $\tau \propto 1/\left(\epsilon^2 \cdot m_x\right)$

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



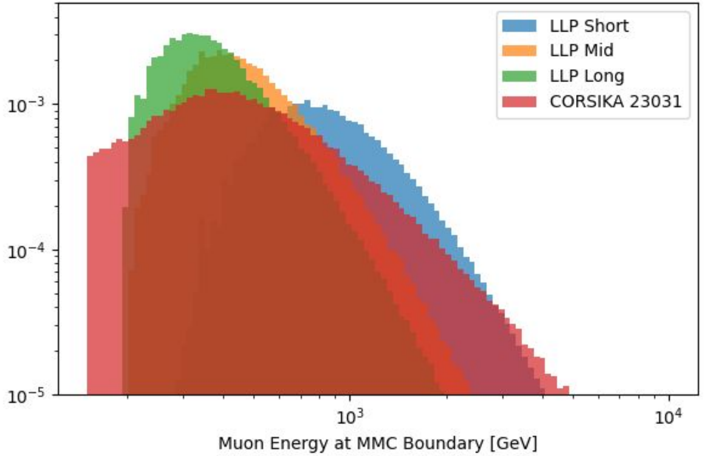
LLP energy spectrum is model dependent!

Gap needs to be short enough to be contained and long enough to be detectable -> [~100m, 1000m]

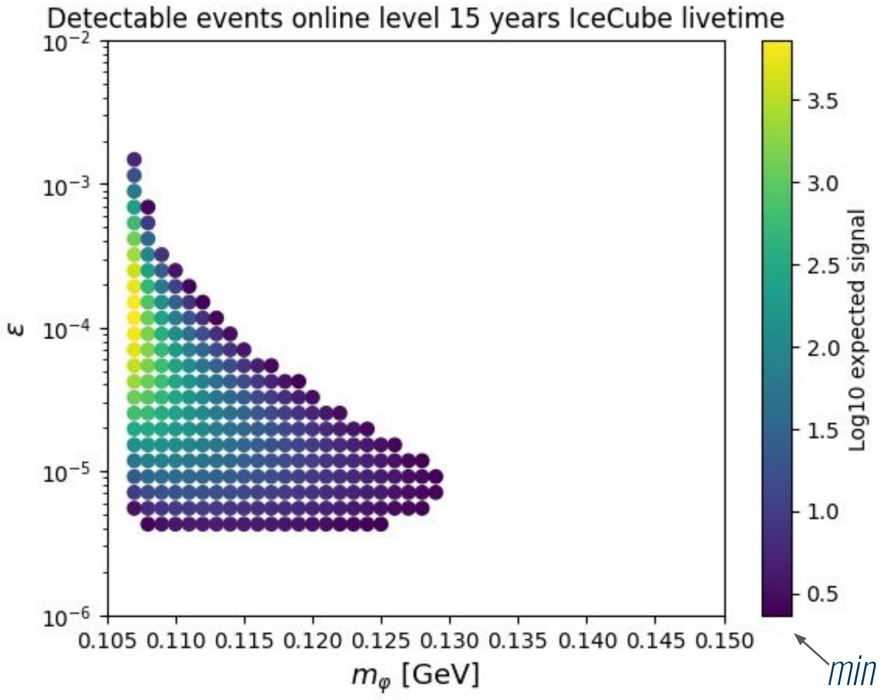


Sample	LLP Short	LLP Mid	LLP Long
Mass	110 MeV	110 MeV	108 MeV
Coupling	3e-5	1e-5	8e-6
Lifetime	5.62e-11 s	5.06e-10 s	2.67e-9 s
Decay length @1TeV	153 m	1380 m	7416 m

Energy (short lifetimes need larger Lorentz Boost)

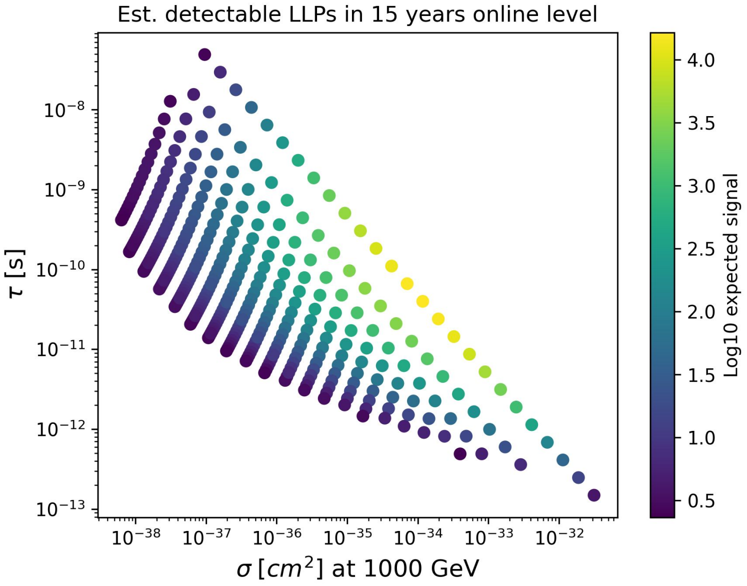


Estimate signal rate using CORSIKA single muon spectrum

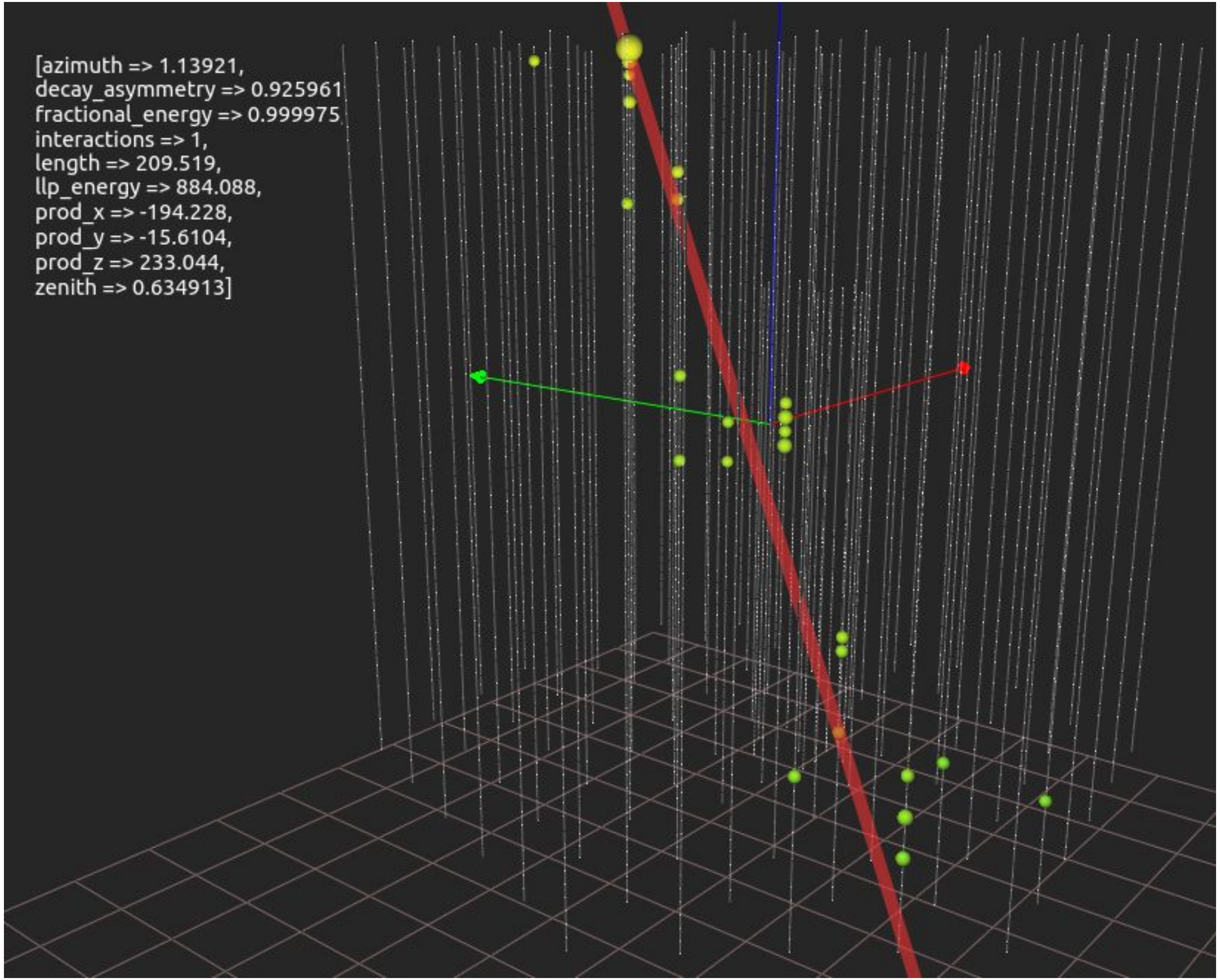


min = 2.3 events

Recast



Game!
Find the Long Lived Particle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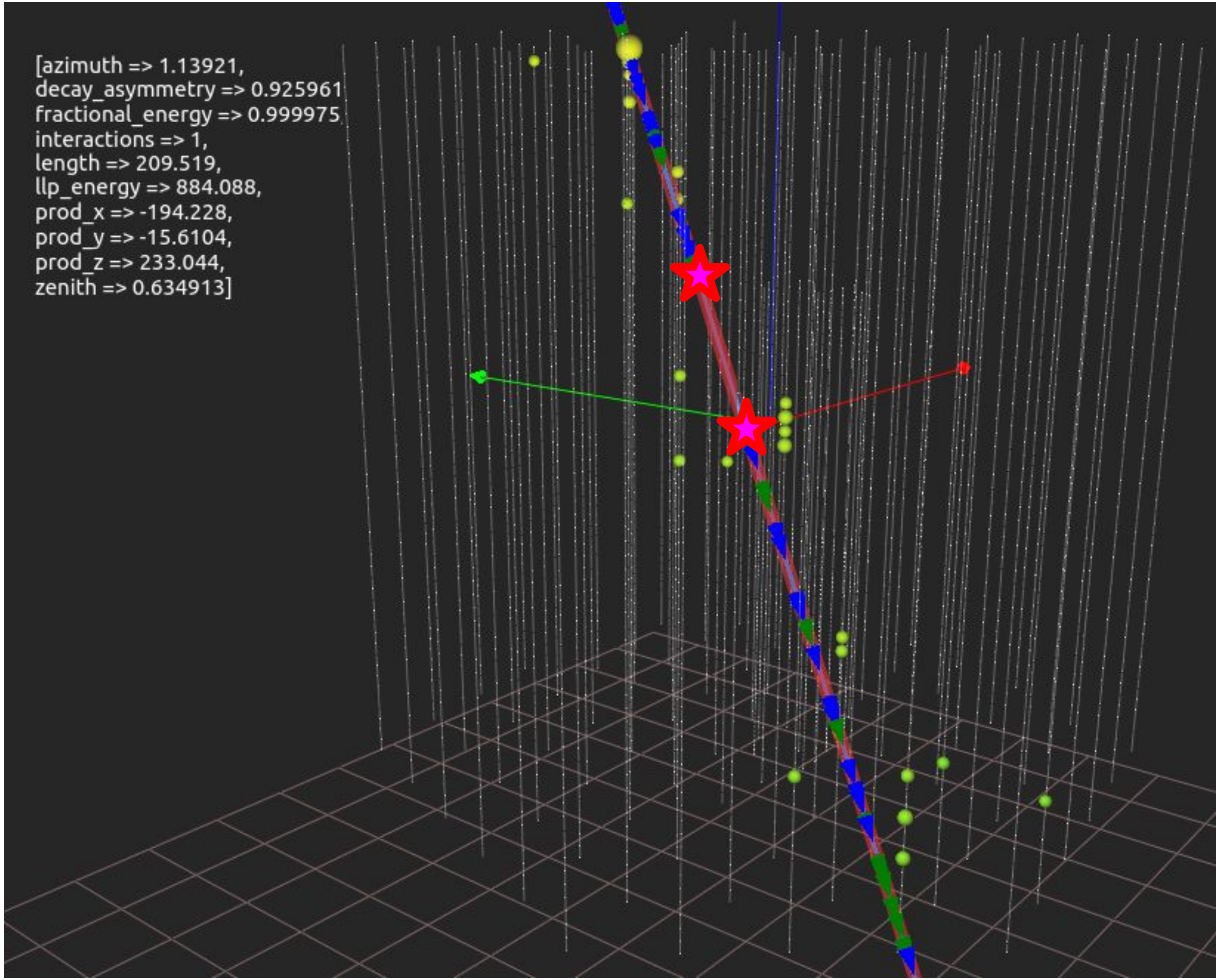
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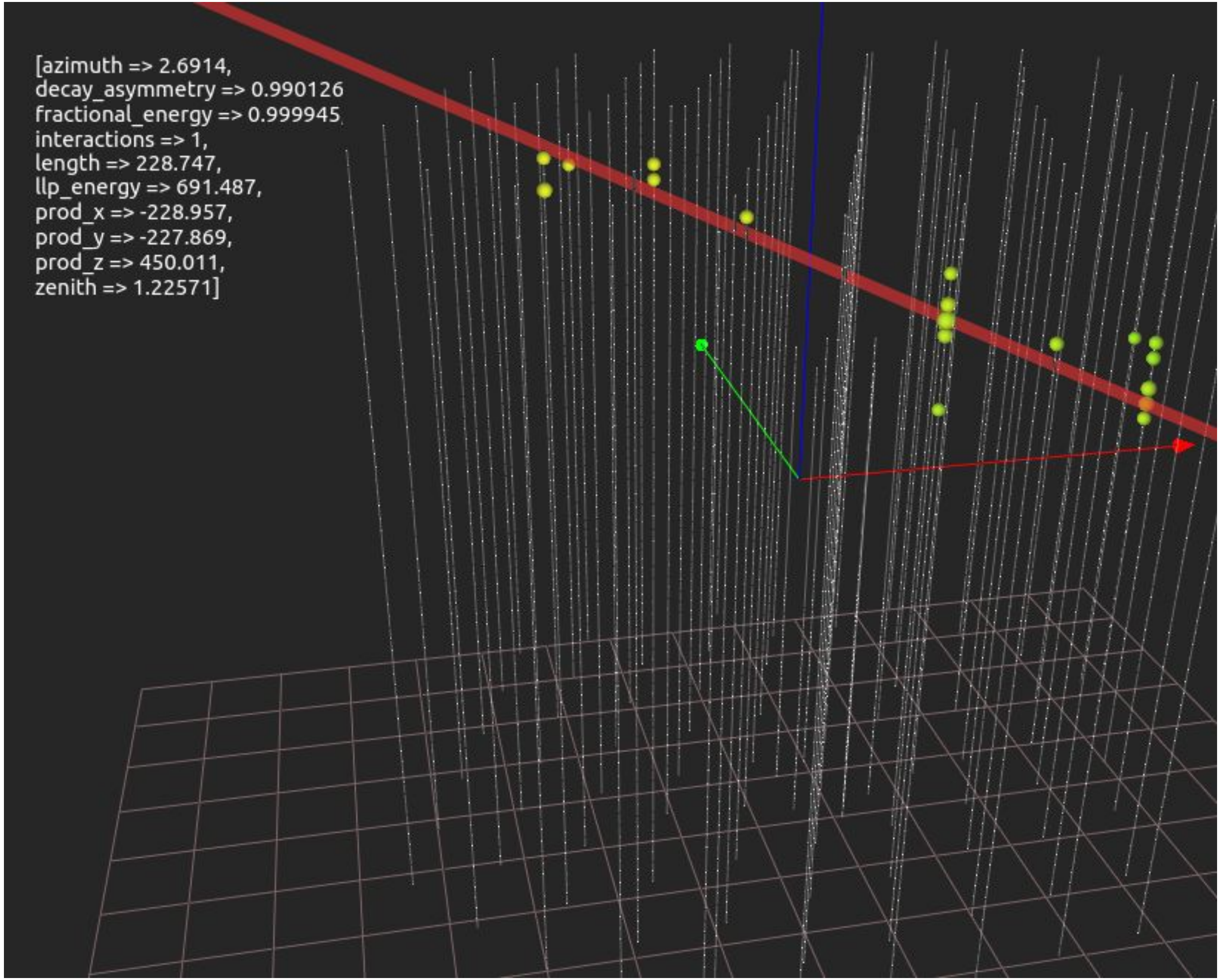
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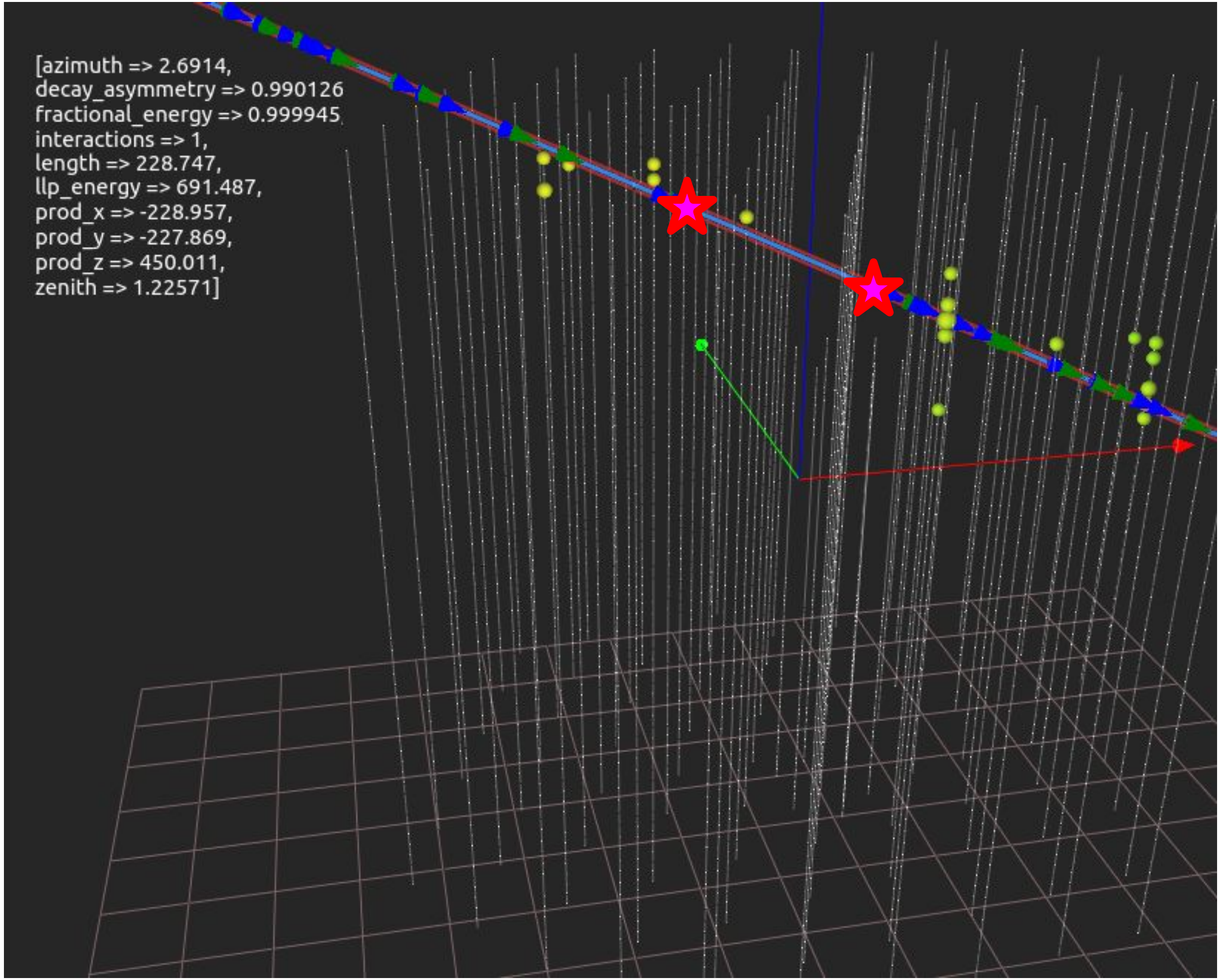
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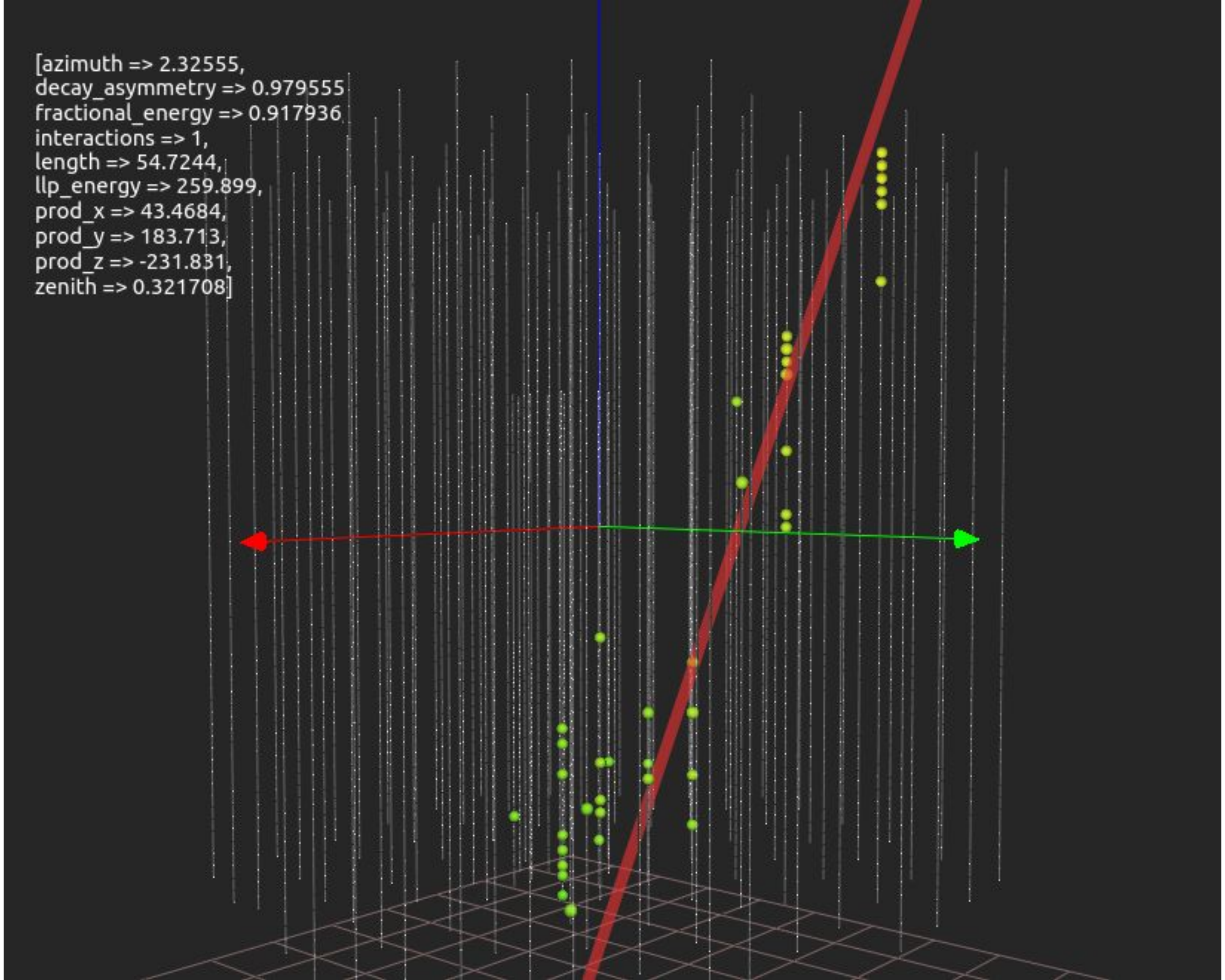
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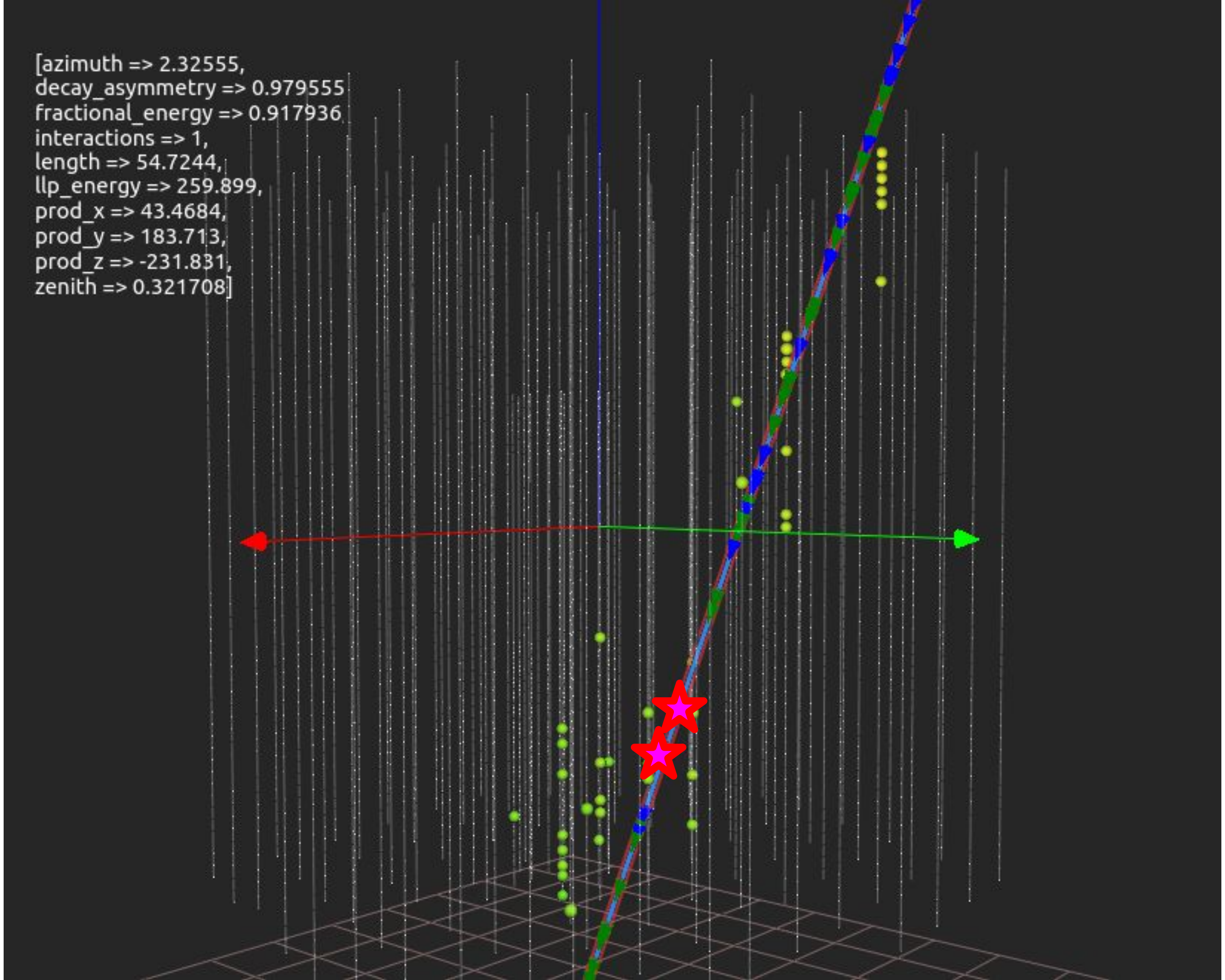
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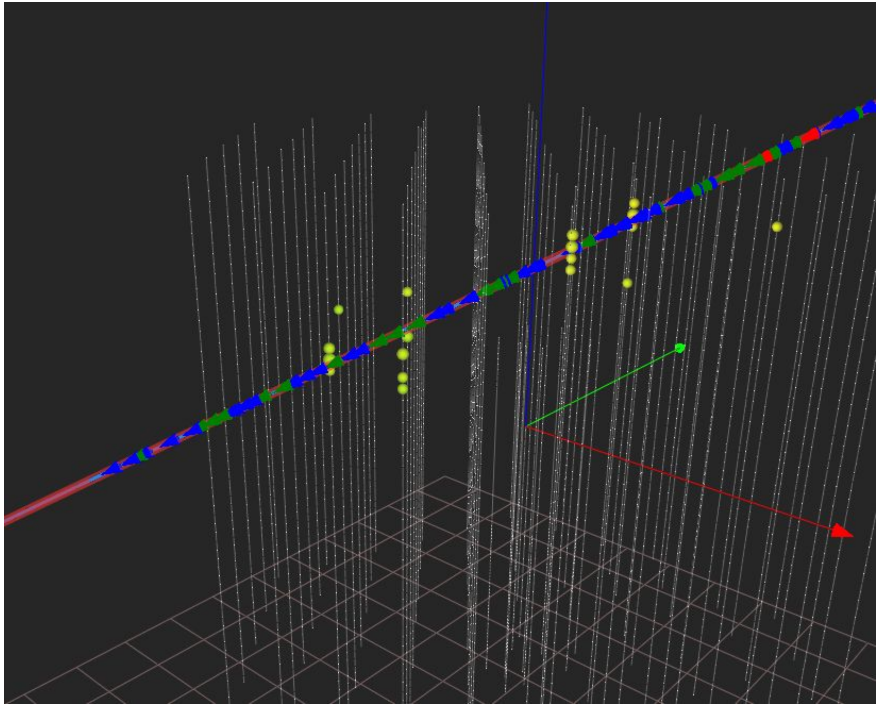
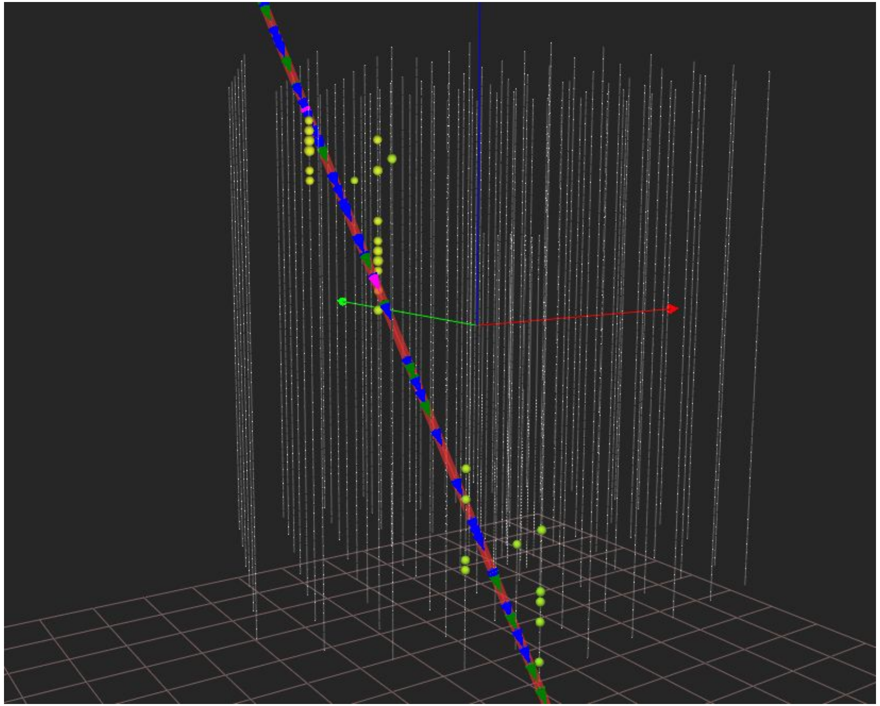
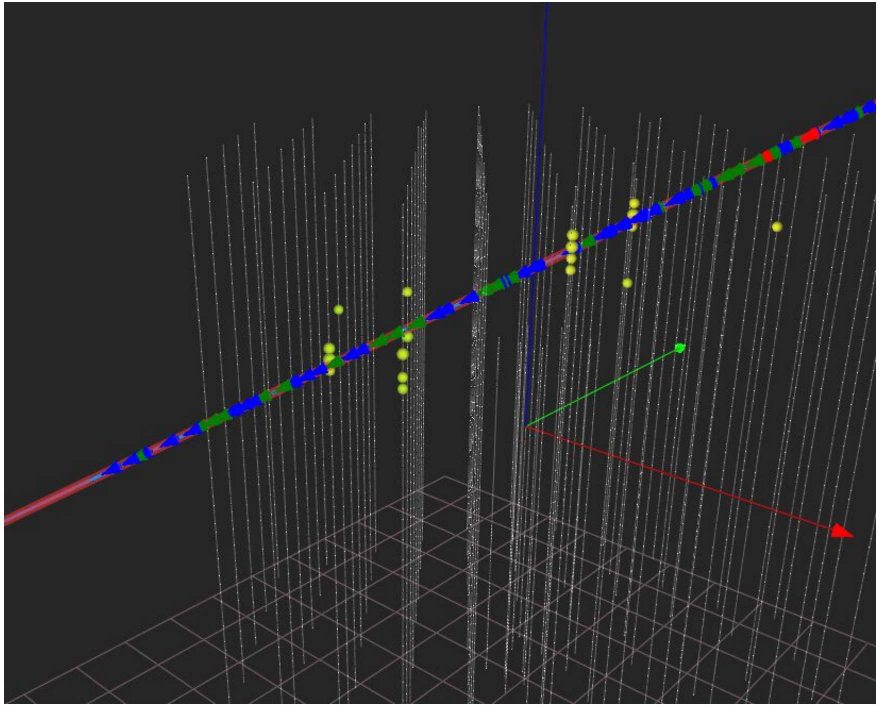
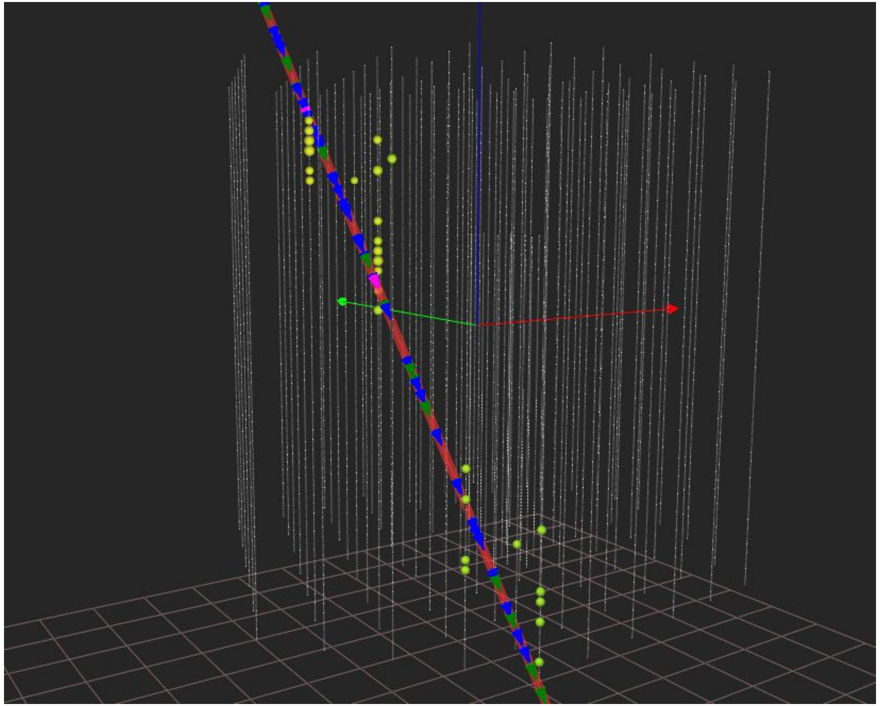




Regular atmospheric muons…



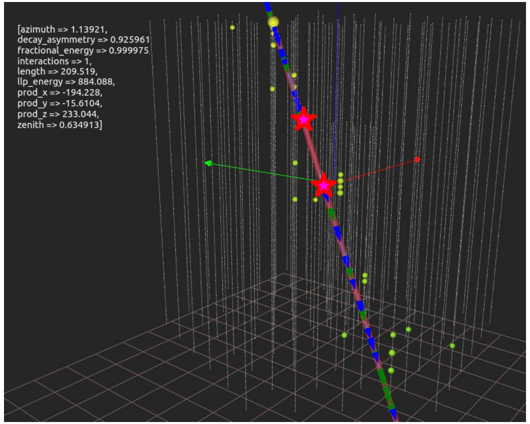


Gap in photon hits is common

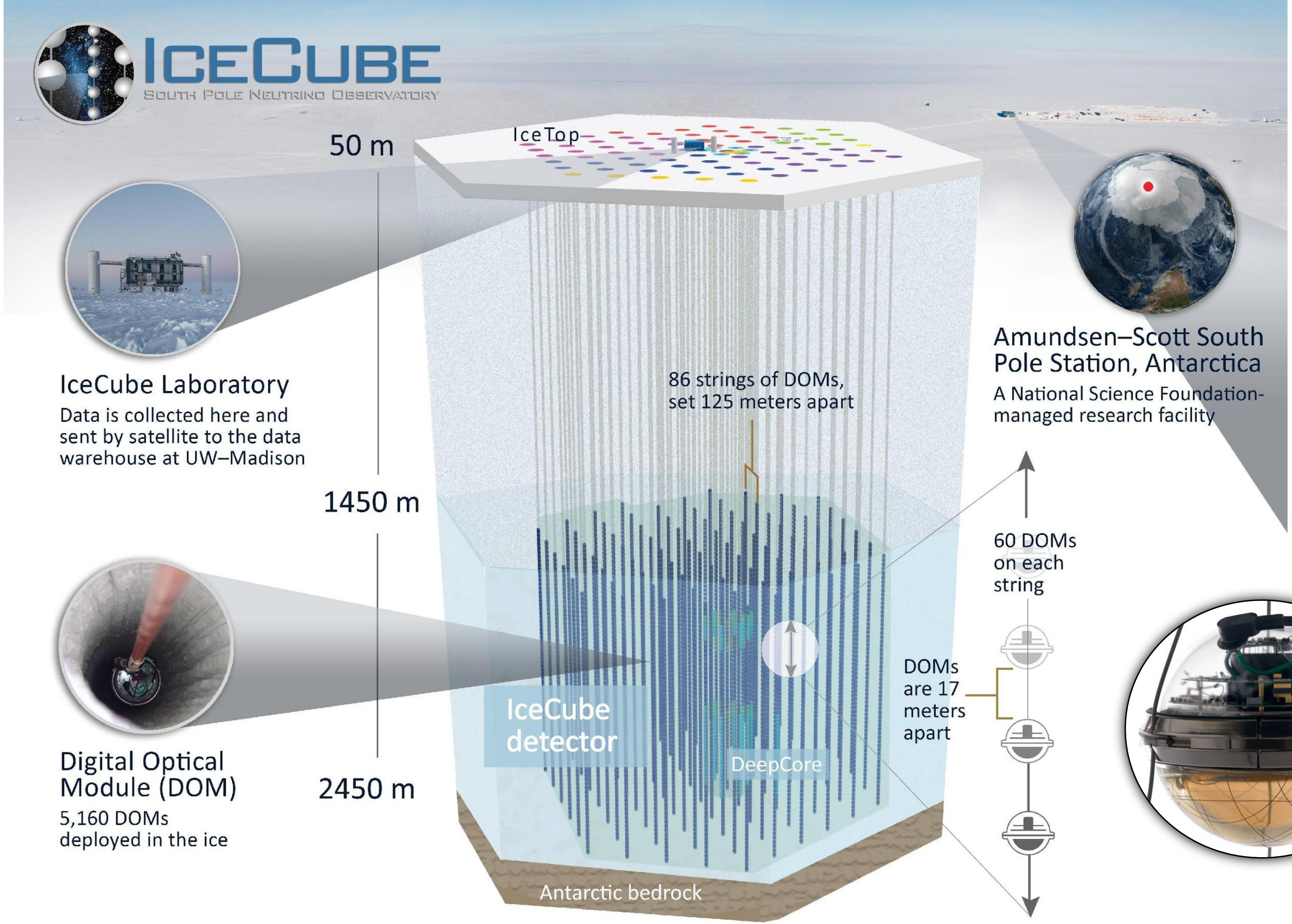
- Detector is sparse (~17-125 m resolution) and light travels far
- Gaps in Cherenkov emission is not always gap in detector hits, and vice versa

Summary and Outlook

- IceCube could potentially complement accelerator searches for Long Lived Particles
  - Pros: Very thick target, enormous decay volume
  - Cons: Low statistics, low spatial resolution
  - No one has done this type of analysis at a neutrino telescope!
- **Hard** to distinguish from background due to sparse detector
- LLP MC simulation chain finished, event selection chain in progress
- Next up:
  - Finish event selection
  - Simulate other event topologies (e.g. cascade at decay point)
  - Analyze data



Backup


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
Antarctic bedrock

Detector signatures mainly limited to two topologies

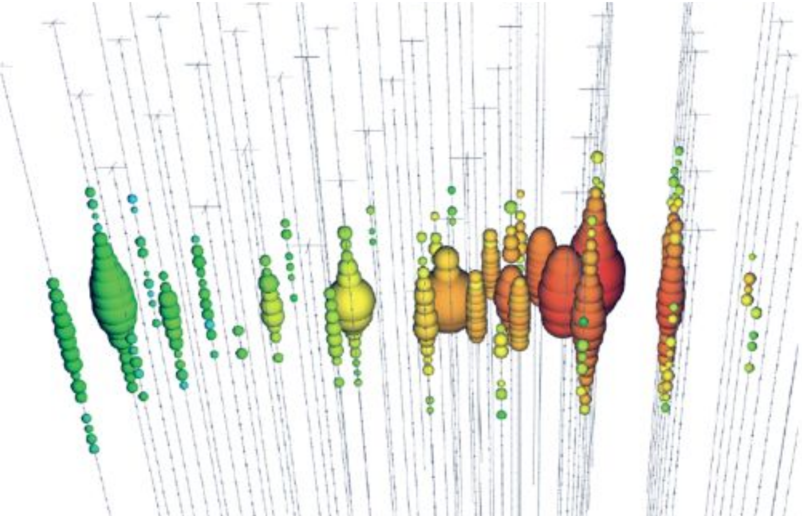
Tracks

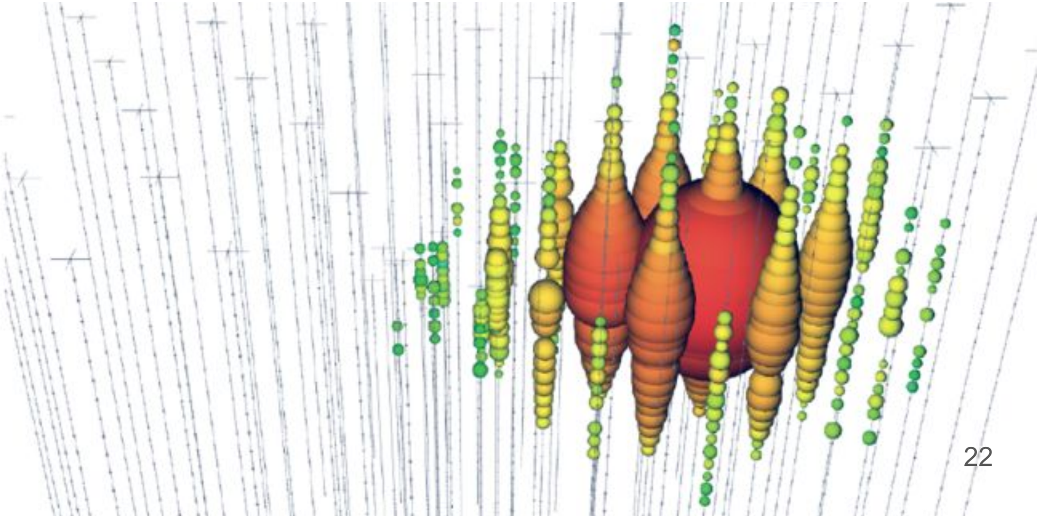
Downgoing tracks almost exclusively atmospheric muons

- ~x2 energy resolution
- Sub-degree angular resolution
- Minimum Ionizing Particles

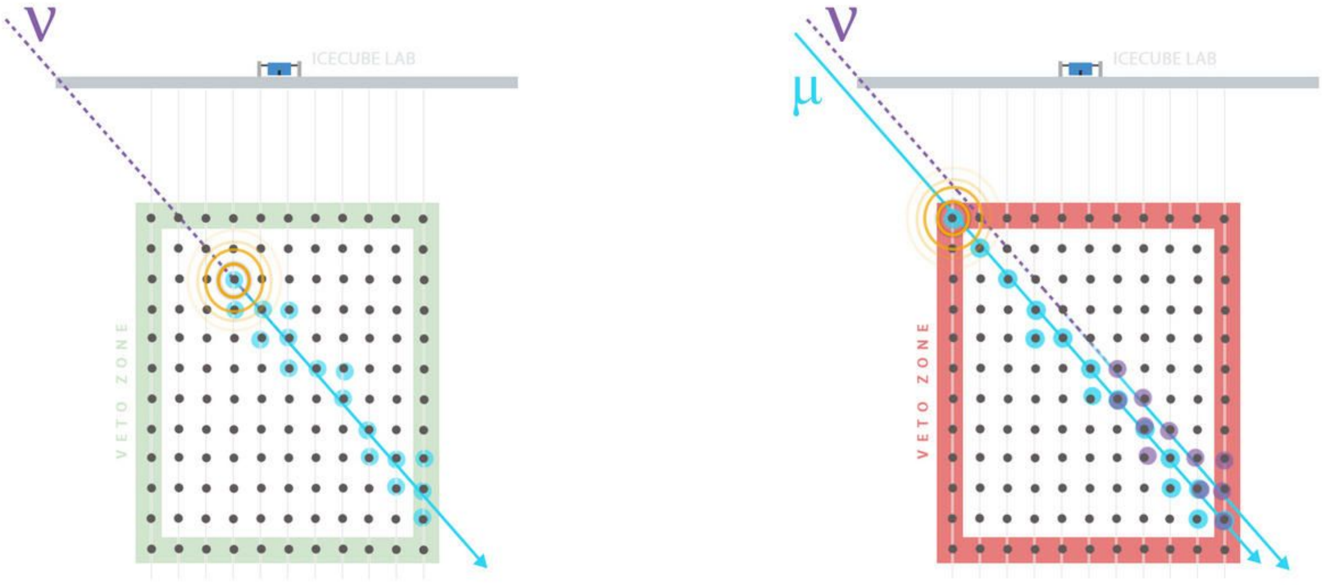
Cascades

- 10-20% energy resolution
- 10 degree angular resolution (at high energies)





Atmospheric muons are background to neutrino searches



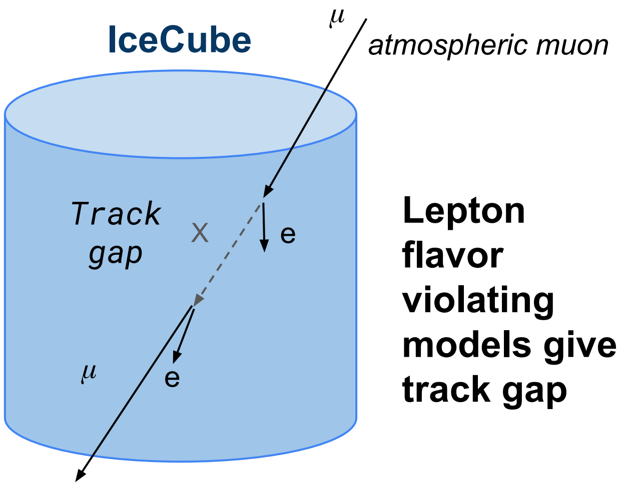
Most IceCube analyses try to remove them

⇩

Atmospheric muon flux might hide new physics

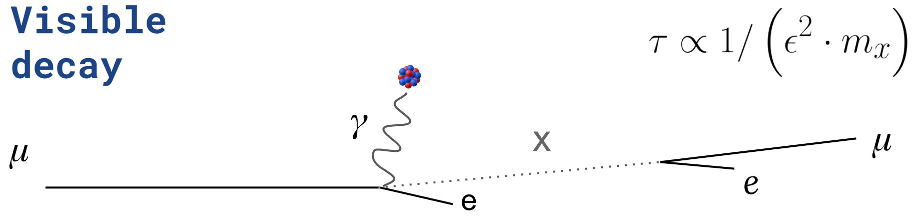
Production & Decay

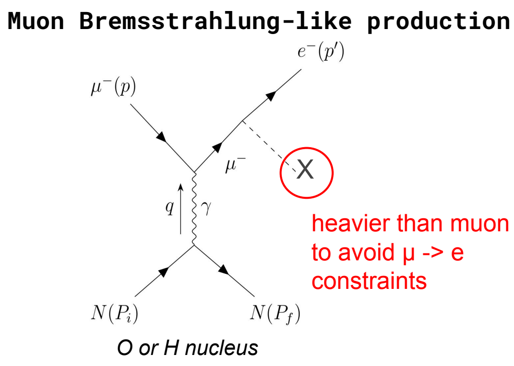
- Exotic bremsstrahlung-like muon-nucleus scattering
- IceCube - low spatial resolution but **enormous** volume
- No fixed distance between production and decay
  - Unlike accelerator experiments



Lepton flavor violating models give track gap

Decay lengths O(100 - 1000 m) -> IceCube

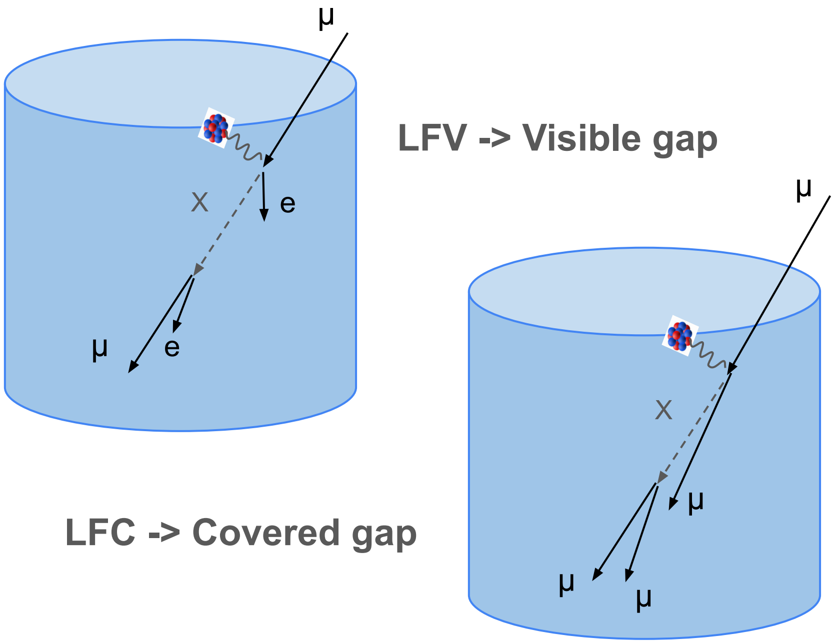




Can IceCube complement LLP searches at collider experiment?

If the model gives visible gaps!

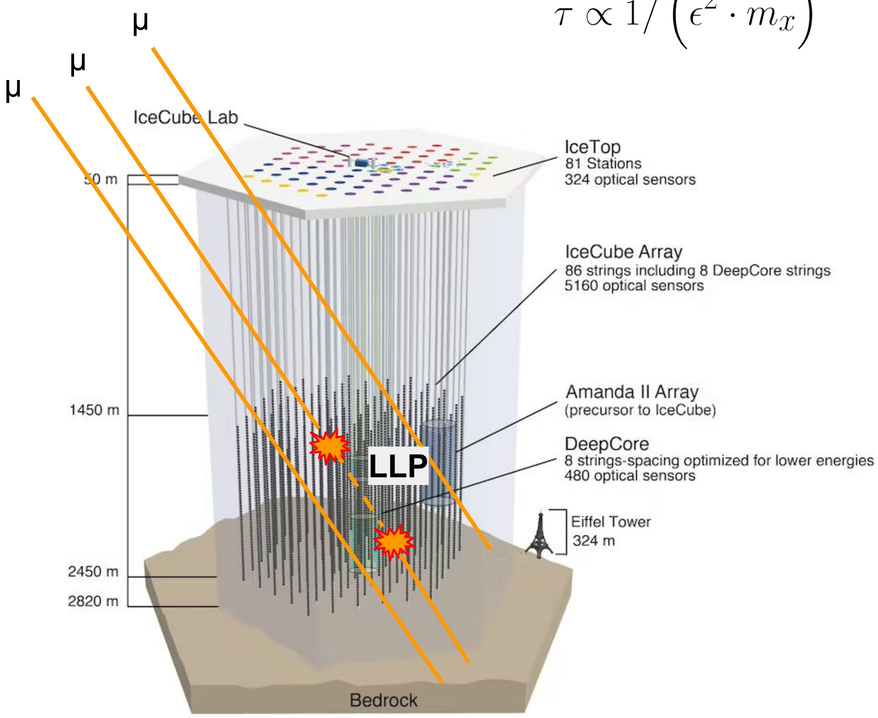
- No Cherenkov light between production and decay vertices
- Lepton flavor violation ensures gap

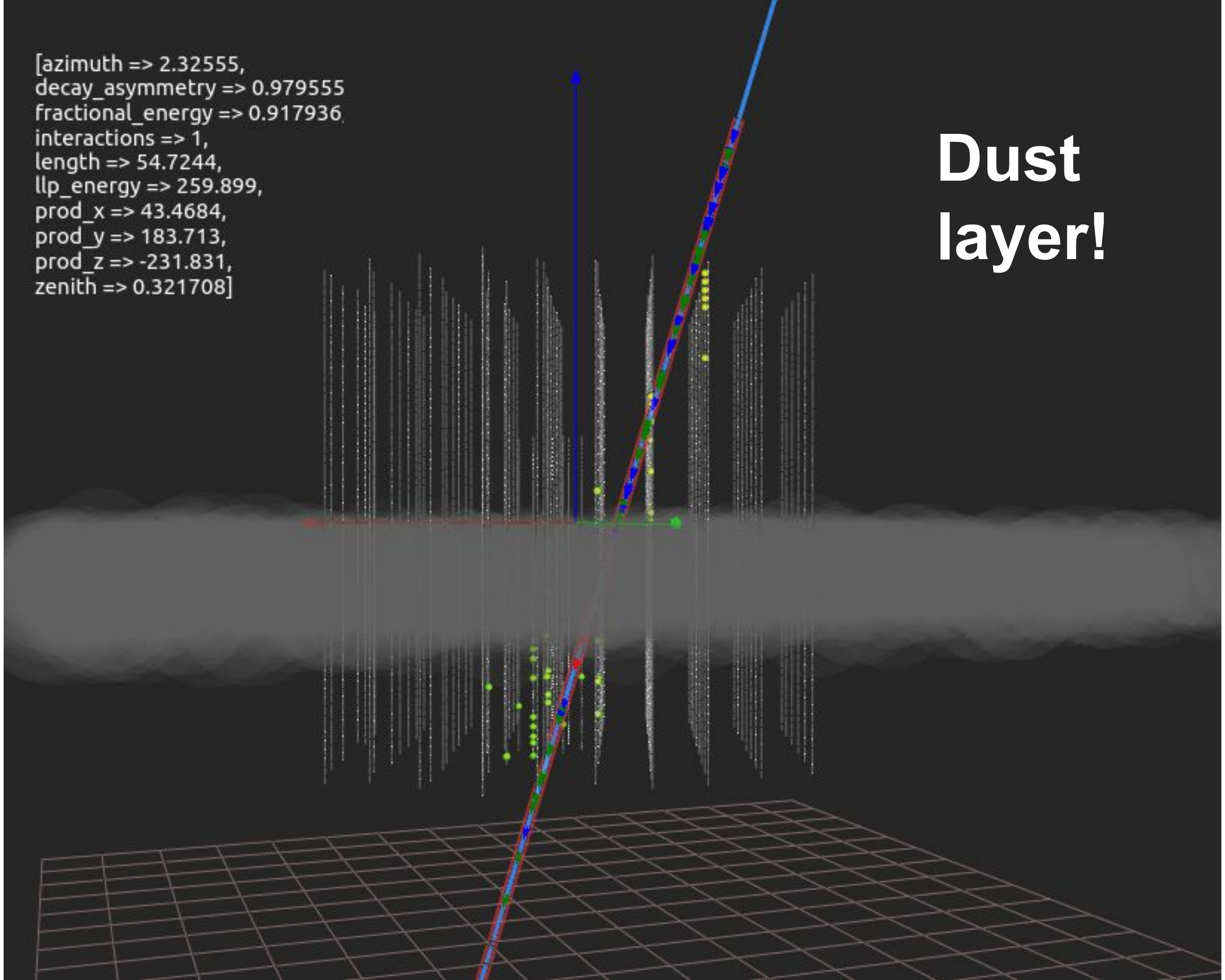


If we have enough statistics, rare events!

- Production & decay compete
- Is 10^{10} muons enough?

$$\tau \propto 1/\left(\epsilon^2 \cdot m_x\right)$$

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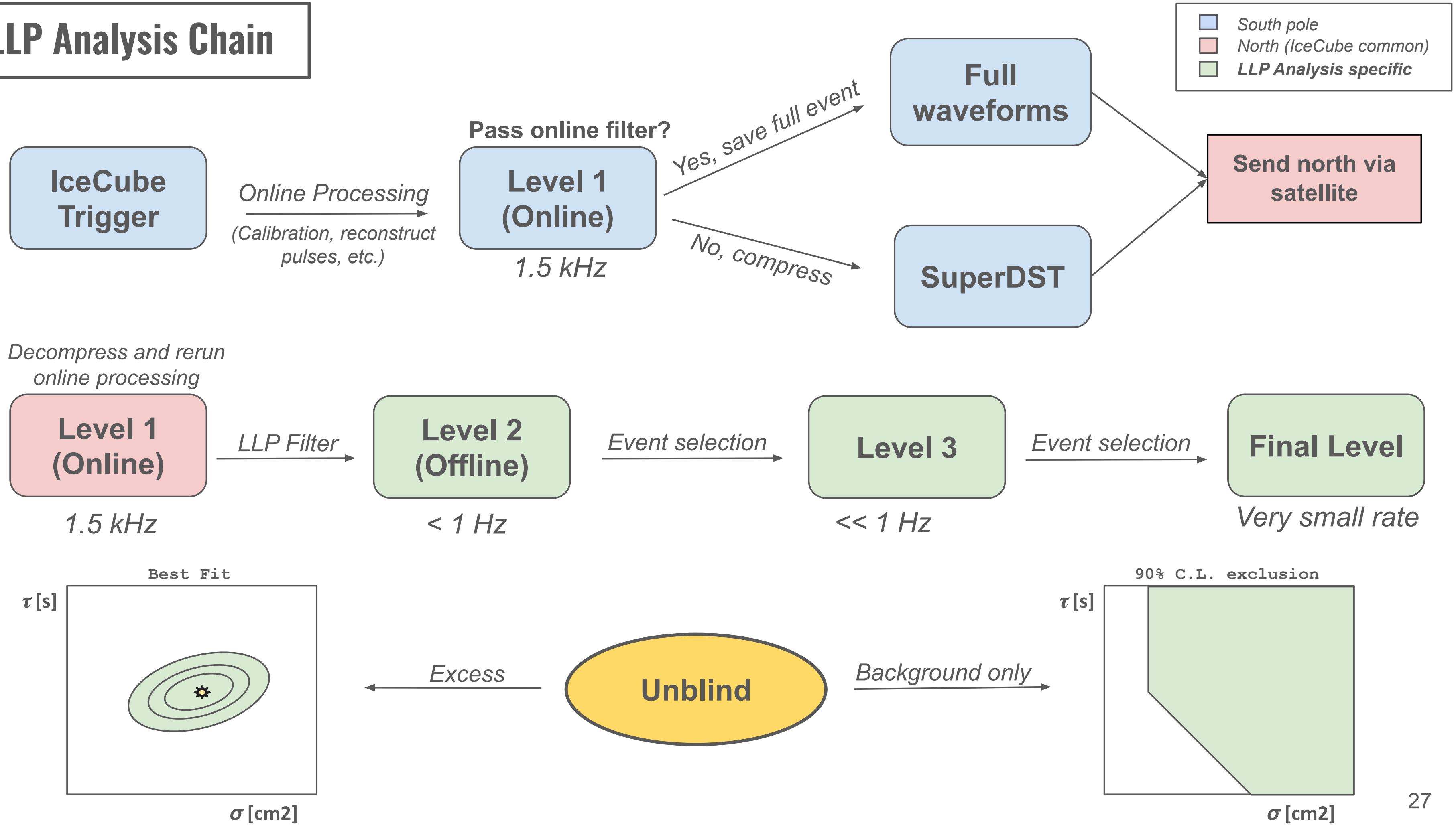
Dust layer!

LLP Analysis Chain



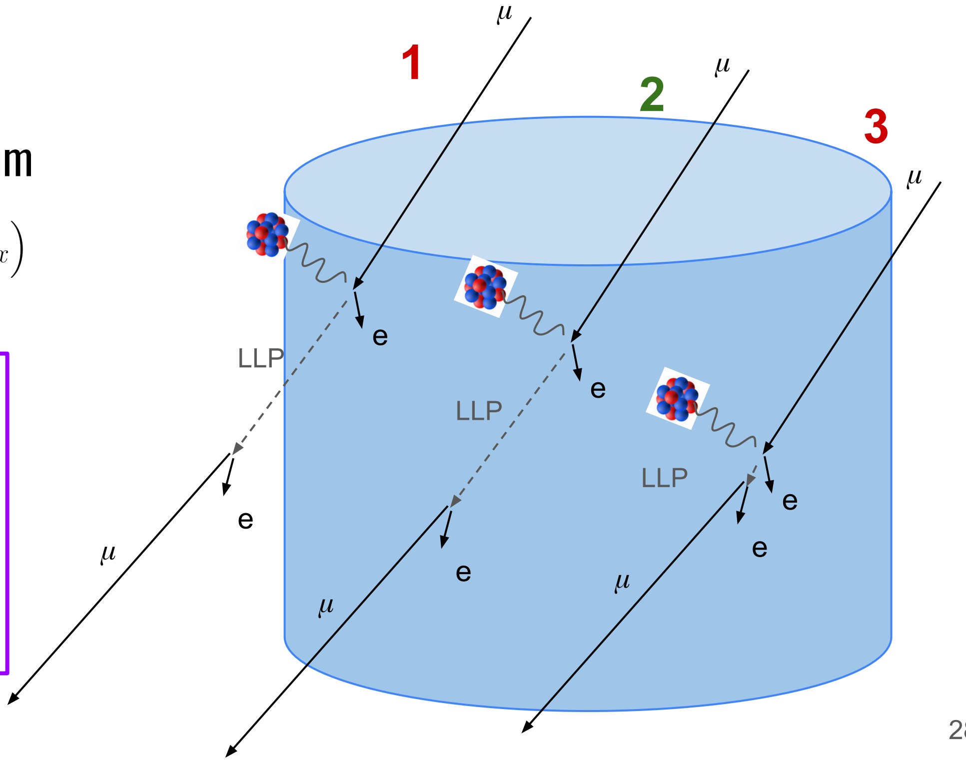
Production Estimation : Event-by-event LLP probability

- Muon spectrum is complex, use MC simulation to estimate production!
- Single muons only!
  - Bundles cover gap
  - Limits us to low energy end of spectrum
- Production and decay compete $\tau \propto 1/\left(\epsilon^2 \cdot m_x\right)$

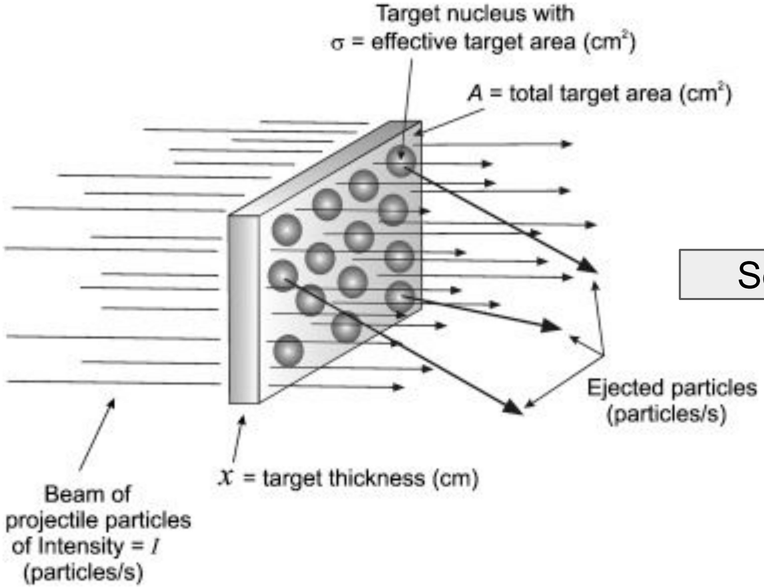
Segmented thin target approximation with decay

1. Chop up track into many segments
2. Probability of LLP production, thin target approx
3. Multiply by decay factor at each point [0, 1]
4. Sum together

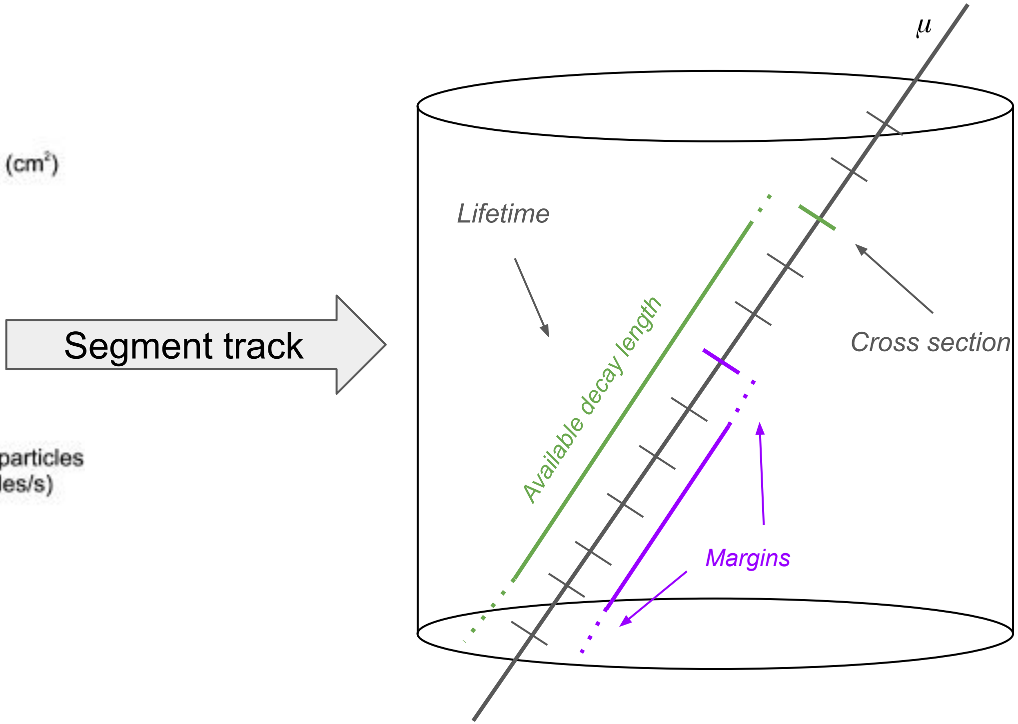
1. Decay outside detector :(
2. Detectable LLP :)
3. Gap too small :(



Modified thin target approximation: segment + decay factor



https://www.sciencedirect.com/topics/physics-and-astronomy/target-thickness



Chop up track -> Sum probability of LLP production + decay in the detector at each point

Final formula detectable LLP probability

Segment track

Event probability

$$P_{LLP} = \Sigma_i^{steps} \left[f_{decay}(E_i) \Delta L \cdot \Sigma_j^{O,H} \left[\sigma_j(E_i) \cdot n_j \right] \right]$$

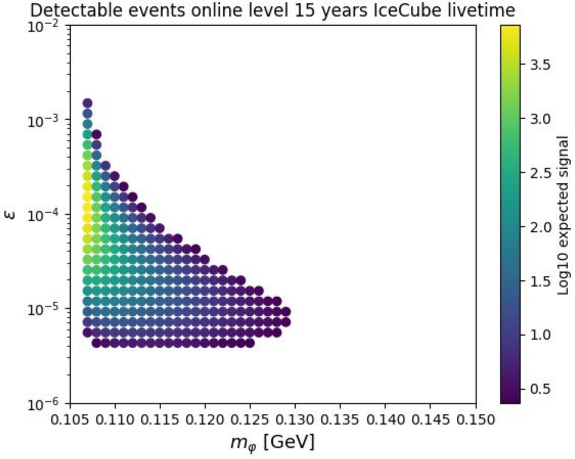
Probability to decay with good decay length

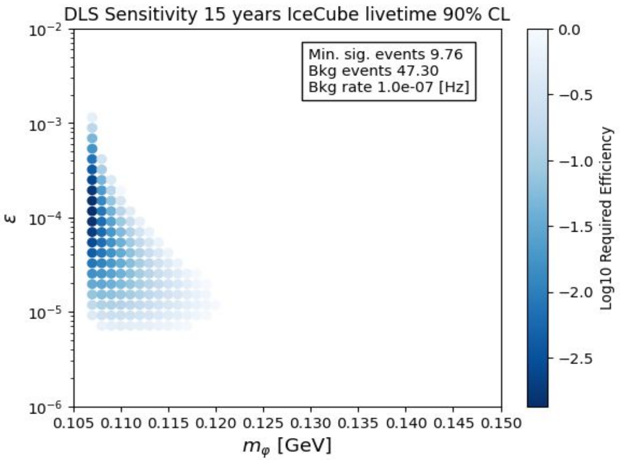
Thin target approximation (for H and O in ice)

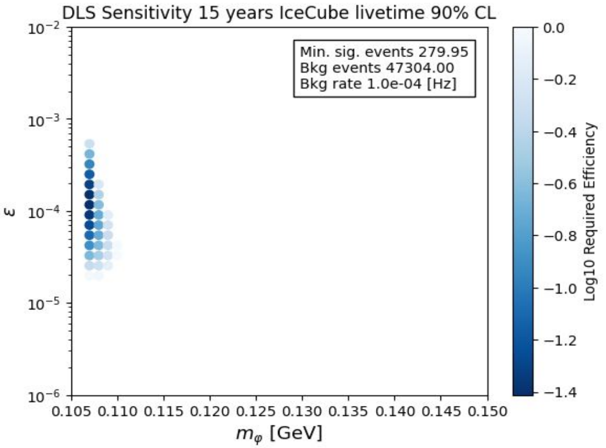
$$f_{decay}(E_i) = e^{\frac{-l_{min}}{c\gamma\tau}} - e^{\frac{-l_{max}}{c\gamma\tau}}$$

Need energy of muon along track -> Use MC truth energies of CORSIKA simulated muons

If background only, what signal efficiency is required to exclude Dark Leptonic Scalar at 90% C.L.?







Benchmark model: Dark Leptonic Scalar

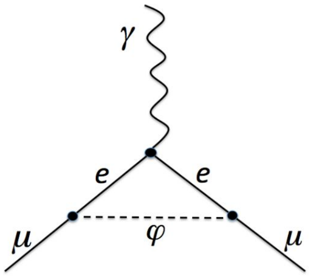
arXiv:2404.15931
arXiv:2202.04410v3

- Scalar boson with flavor violating coupling
- Heavier than muon to avoid μ -> e constraints
- Produced in brehmstrahlung-like process
- Decay to SM or DM particles
- Could contribute to muon g-2 anomaly

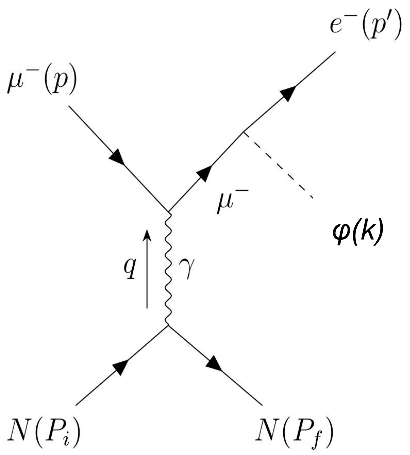
$$L_{\varphi\mu e} = -h_{\mu e}\bar{e}_L\mu_R\varphi + H.c.$$

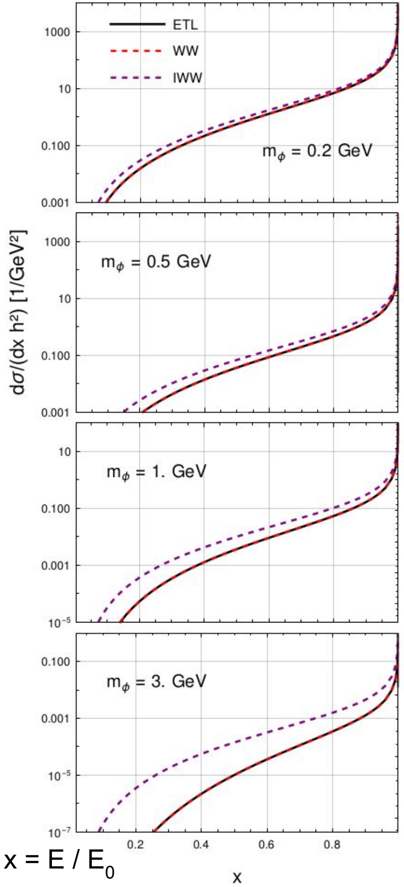
effective lagrangian, not gauge invariant or renormalizable

Muon g-2 contribution



Production cross section



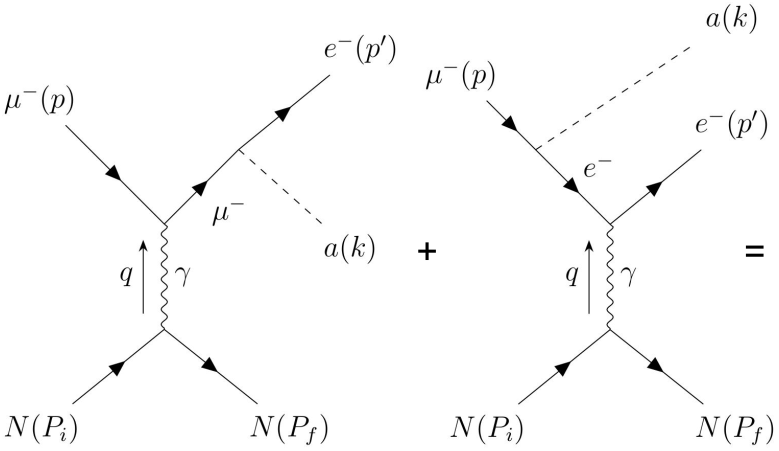


x = E / E_0

Dark Leptonic Scalar

Production μ + N -> e + a + N’

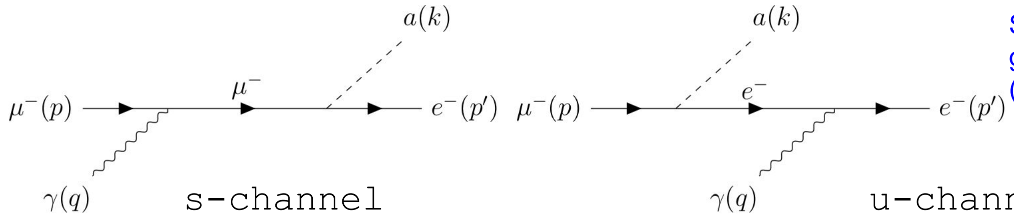
Tree Level 3-body final state



$$= \; i\mathcal{M}_{ETL} = ihe^2\frac{F(q^2)}{q^2}P_\mu \bar{u}_e(p')\left[P_R\frac{(\not{p}'+\not{k})+m_\mu}{\tilde{s}}\gamma^\mu + \gamma^\mu\frac{(\not{p}-\not{k})+m_e}{\tilde{u}}P_R\right]u_\mu(p)$$

Note: different fermion propagator in the two channels due to LFC

William Weiszäcker phase space approx.



See appendix D for generalized WW approx. (PhysRevD.8.3109)

$$\tilde{s} = (p'+k)^2 - m_\mu^2$$

$$\tilde{u} = (p-k)^2 - m_e^2$$

$$t_2 = (p'-p)^2$$

$$t = -q^2$$

$$m_a^2 = \tilde{s} + t_2 + \tilde{u} + t.$$

LFC

(I perform these integrals numerically)

ETL cross section

$$\left(\frac{d^2\sigma}{dx\,d\cos\theta_k}\right)_{ETL} = \frac{h^2\alpha^2}{4\pi}\frac{E_\mu|\mathbf{k}|}{|\mathbf{p}|V}\int_{t_{min}}^{t_{max}} dt\,\frac{F^2(t)}{t^2}\int_0^{2\pi}\frac{d\phi_q}{2\pi}\frac{|A_{2\to3}|^2}{8M^2}$$

↓

$$\left(\frac{d\sigma}{dx}\right)_{ETL} = \frac{h^2\alpha^2}{4\pi}\frac{E_\mu|\mathbf{k}|}{|\mathbf{p}|}\int_0^{\theta_{max}} d\cos\theta_k\,\frac{1}{V}\int_{t_{min}}^{t_{max}} dt\,\frac{F^2(t)}{t^2}\int_0^{2\pi}\frac{d\phi_q}{2\pi}\frac{|A_{2\to3}|^2}{8M^2}$$

↓

Total cross section: calculate ds/dx for an array of x-values, interpolate those values, and integrate the result from xmin to xmax

Weizsäcker-Williams cross section

$$\left(\frac{d^2\sigma_{2\to 3}}{dx\,d\cos\theta_k}\right)_{WW} = \frac{\alpha\chi^{WW}}{\pi(1-x)} E_\mu |\mathbf{k}| \left.\frac{d\sigma_{2\to 2}}{d(p\cdot k)}\right|_{t_{min}}$$

$$\frac{d\sigma_{2\to 2}}{d(p\cdot k)} = 2\frac{d\sigma_{2\to 2}}{dt_2} = \frac{1}{8\pi\tilde{s}^2}\langle|\mathcal{M}|^2\rangle = \frac{\alpha h^2}{2\tilde{s}^2}|A_{2\to 2}|^2.$$

$$|A_{2\to 2}|^2 = -\frac{(\tilde{s}+\tilde{u})^2}{2\tilde{s}\tilde{u}} + \Delta m^2\left[\frac{(\tilde{s}+\tilde{u})(\tilde{s}m_e^2+\tilde{u}m_\mu^2)}{\tilde{s}^2\tilde{u}^2} - \frac{t_2}{\tilde{s}\tilde{u}}\right]$$

from FeynCalc

evaluate at tmin

$$|A_{2\to 2}|^2_{t_{min}} = \frac{x^2}{2(1-x)} + \Delta m^2 \cdot \frac{\tilde{u}x + m_a^2(1-x) + x\left[m_e^2 + m_\mu^2(x-1)\right]}{\tilde{u}^2}.$$

Mandelstam at t_{min}

$$\tilde{s} \approx -\frac{\tilde{u}}{(1-x)}$$

$$t_2 \approx \frac{x\tilde{u}}{(1-x)} + m_a^2$$

$$\tilde{u} \approx -xE_\mu^2\theta_k^2 - m_a^2\frac{1-x}{x} + m_\mu^2(1-x) - m_e^2$$

$$m_a^2 \approx \tilde{s} + t_2 + \tilde{u}.$$

Extra term due to m_i != m_f

Weiszäcker-Williams cross sections

Double differential cross section

$$\left(\frac{d^2\sigma_{2\to 3}}{dx\,d\cos\theta_k}\right)_{WW} = \frac{\alpha^2 h^2 \chi^{WW}}{2\pi} E_\mu^2 x \beta_k \frac{(1-x)}{\tilde{u}^2}\left[\frac{x^2}{2(1-x)} + \Delta m^2 \cdot \frac{\tilde{u}x + m_a^2(1-x) + x\left[m_e^2 + m_\mu^2(x-1)\right]}{\tilde{u}^2}\right]$$

Fractional energy differential cross section

$$\left(\frac{d\sigma}{dx}\right)_{WW} = \frac{h^2\alpha^2}{2\pi} E_\mu^2 x \beta_k (1-x) \int_0^{\theta_{max}} dcos\theta \; \frac{\left|A_{2\to 2}\right|^2_{t_{min}}}{\tilde{u}^2} \chi^{WW}.$$

- ❖ Integrate above expression from xmin to xmax for total cross section
- ❖ Can solve integral over cos(θ) analytically in Improved Weizsäcker-Williams by assuming photon flux independent of θ.

Improved Weiszäcker-Williams cross sections

$$\left(\frac{d\sigma}{dx}\right)_{WW} = \frac{h^2\alpha^2}{2\pi} E_\mu^2 x \beta_k (1-x) \int_0^{\theta_{max}} dcos\theta \, \frac{|A_{2\to2}|^2_{t_{min}}}{\tilde{u}^2} \chi^{WW}.$$

Change variables and move photon flux outside

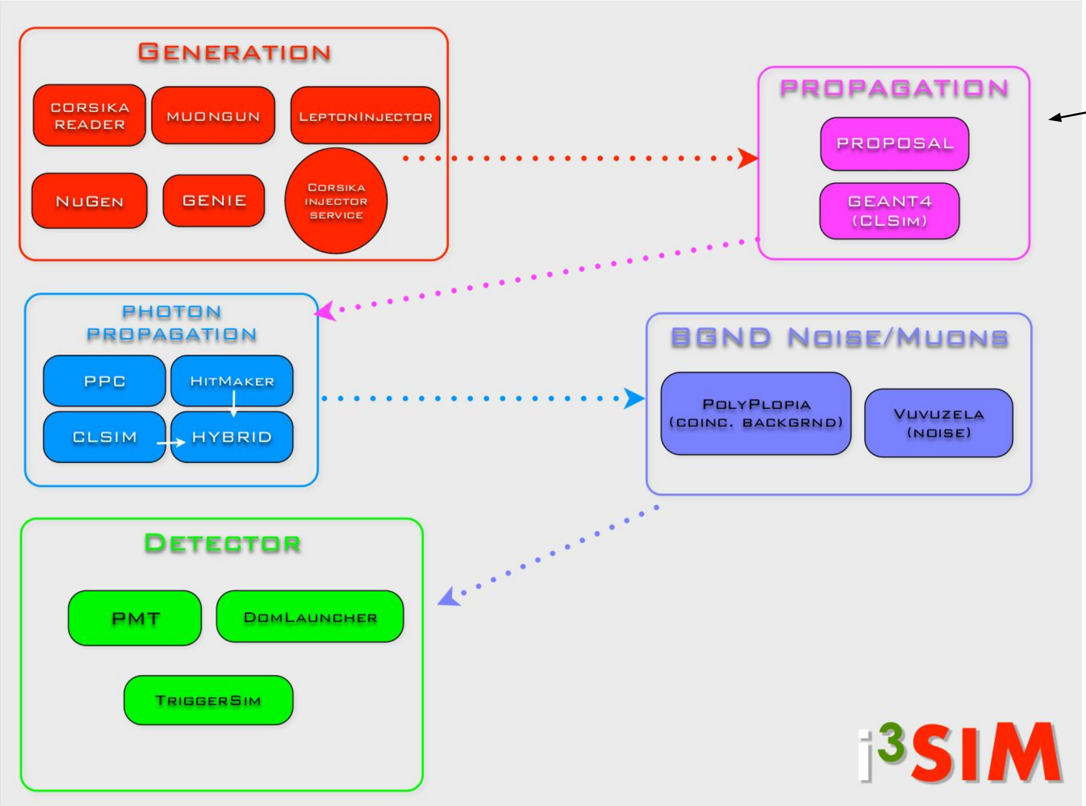
$$\chi^{WW} \to \chi^{IWW}$$

$$d\tilde{u} = -2xE_\mu^2 \theta_k d\theta_k = 2xE_\mu^2 d\cos\theta_k$$

$$\int_{\tilde{u}_{min}}^{\tilde{u}_{max}} d\tilde{u} \, \frac{\langle |A_{2\to2}|^2\rangle_{t_{min}}}{\tilde{u}^2} = \int_{\tilde{u}_{min}}^{\tilde{u}_{max}} d\tilde{u} \left[\frac{x^2}{2(1-x)\tilde{u}^2} + \frac{\Delta m^2 x}{\tilde{u}^3} + \Delta m^2 \frac{m_a^2(1-x) + x\left[m_e^2 + m_\mu^2(x-1)\right]}{\tilde{u}^4}\right]$$
$$= \left[\frac{x^2}{-2(1-x)\tilde{u}} + \frac{\Delta m^2 x}{-2\tilde{u}^2} + \Delta m^2 \frac{m_a^2(1-x) + x\left[m_e^2 + m_\mu^2(x-1)\right]}{-3\tilde{u}^3}\right]_{\tilde{u}_{min}}^{\tilde{u}_{max}}$$

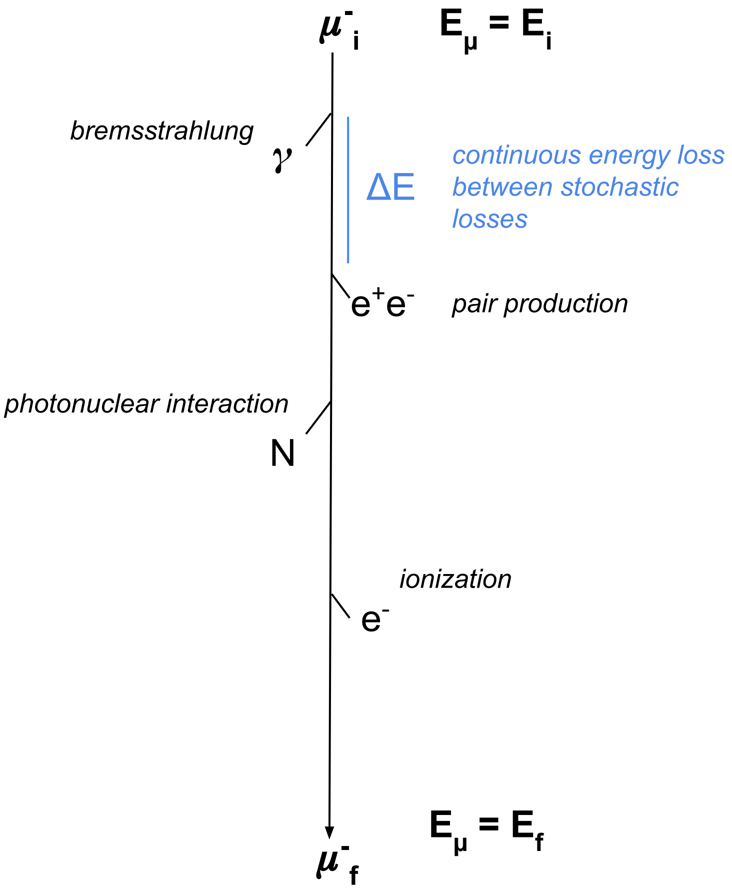
LLP Simulation in IceCube

Branch with LLP modified PROPOSAL: https://github.com/icecube/icetray/tree/axelpo/main/PROPOSAL

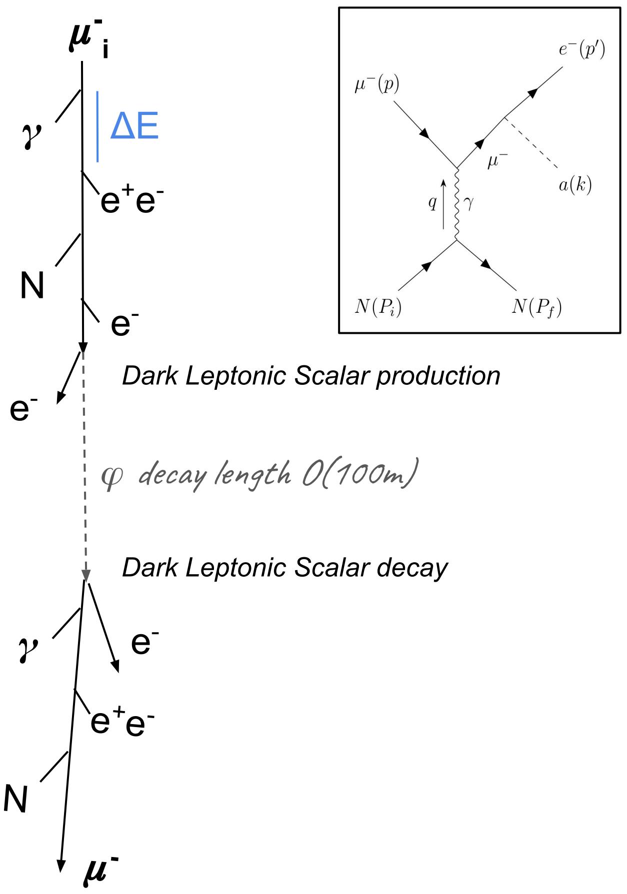


Add LLP production during muon propagation

Standard PROPOSAL

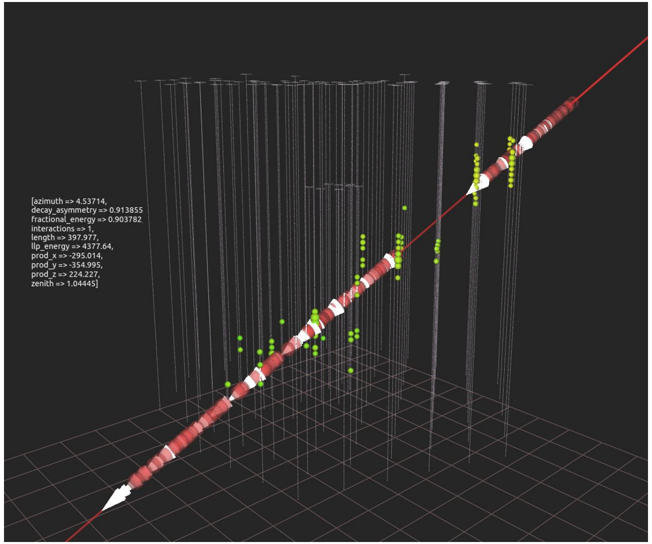


Standard PROPOSAL + LLP production

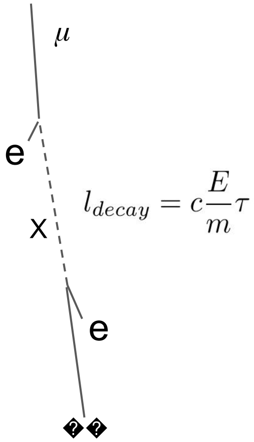


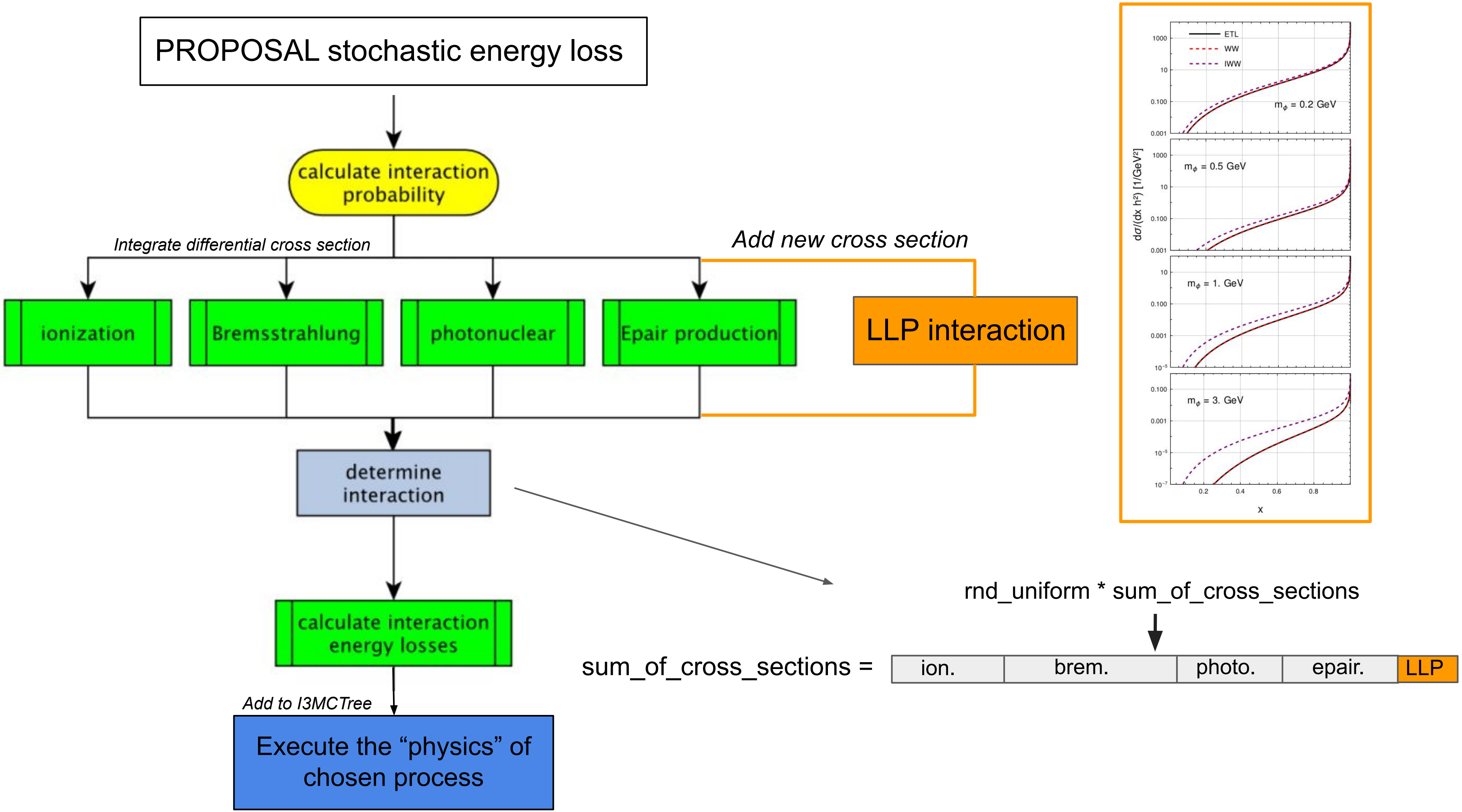
If LLP interaction happens

1. **Sample decay length**
   a. Exponential distribution of lifetimes in rest frame
   b. Multiply by speed of light and Lorentz boost
2. **Create daughter particles**
   a. One lepton at production point
   b. Two leptons at decay point
3. **Set time, energy, position and direction of product particles**
4. **Propagate the products**



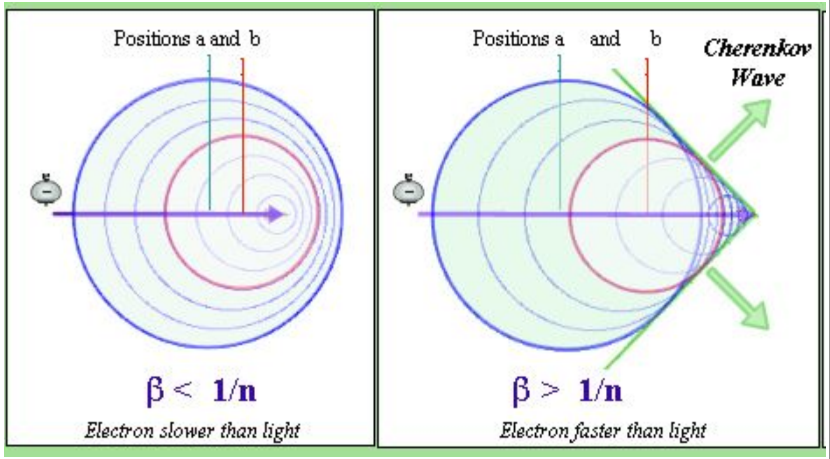
MC LLP Event



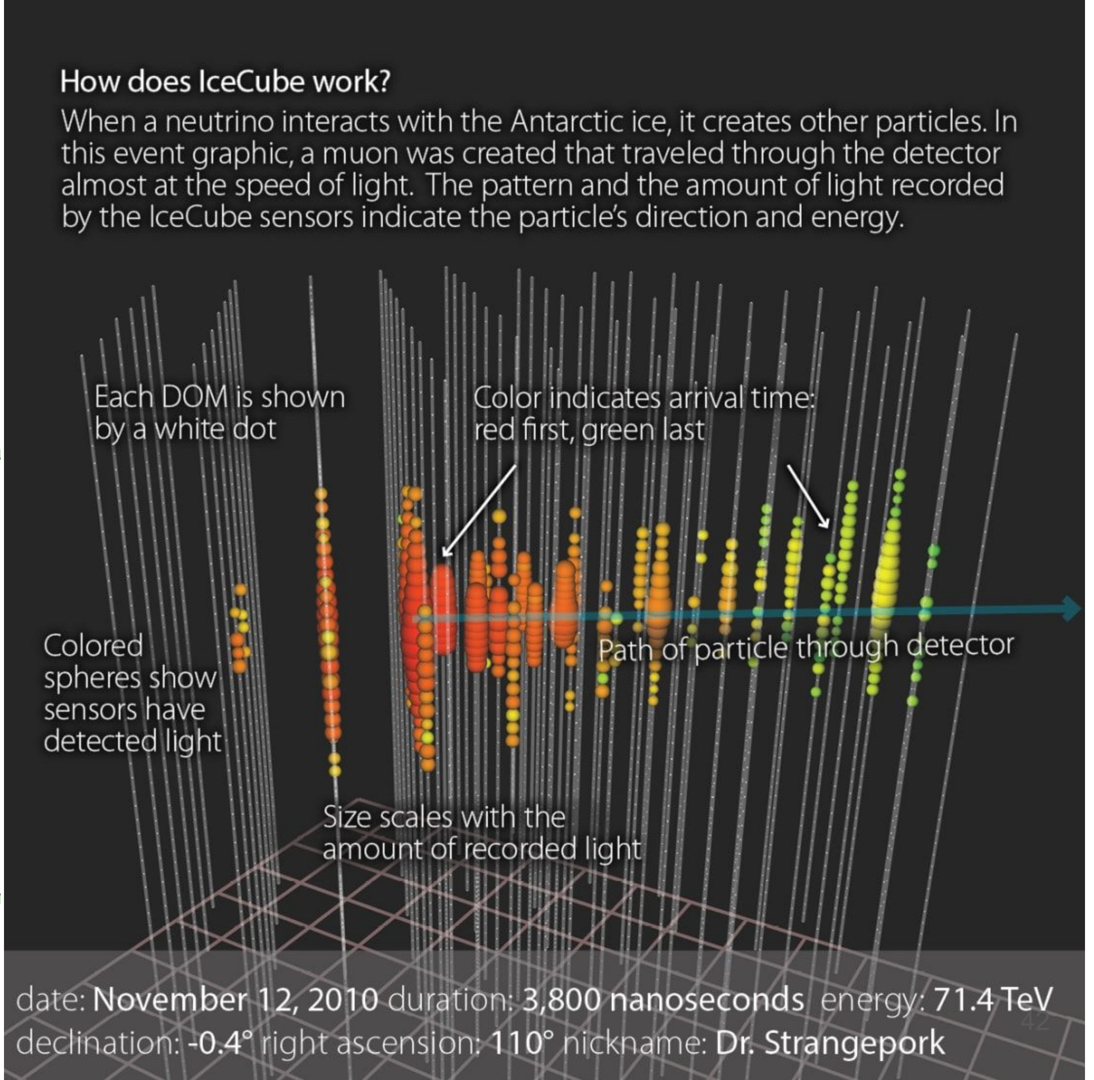

PROPOSAL stochastic energy loss
calculate interaction probability
Integrate differential cross section
ionization
Bremsstrahlung
photonuclear
Epair production
Add new cross section
LLP interaction
determine interaction
calculate interaction energy losses
Add to I3MCTree
Execute the "physics" of chosen process
rnd_uniform * sum_of_cross_sections
sum_of_cross_sections =
ion.
brem.
photo.
epair.
LLP
ETL
WW
IWW
m_φ = 0.2 GeV
m_φ = 0.5 GeV
m_φ = 1. GeV
m_φ = 3. GeV
dσ/(dx h²) [1/GeV²]
x

Detection principle

IceCube detects Cherenkov light

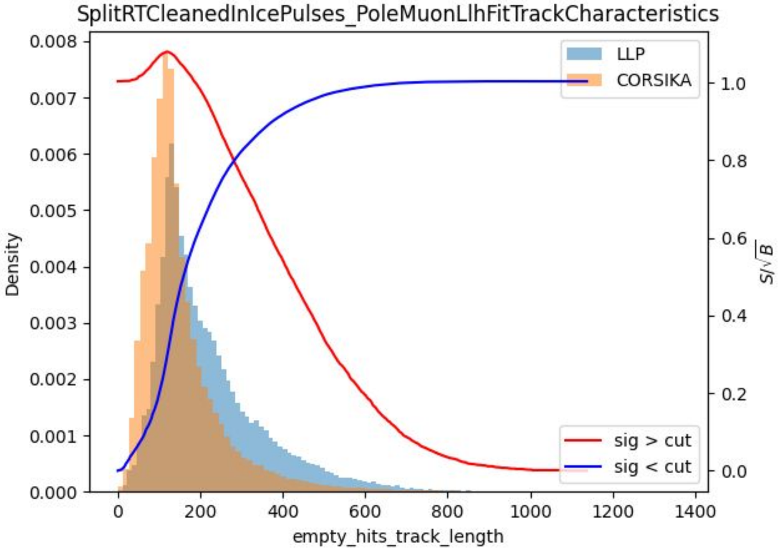


https://radioactivity.eu.com/articles/phenomenon/cherenkov_effect

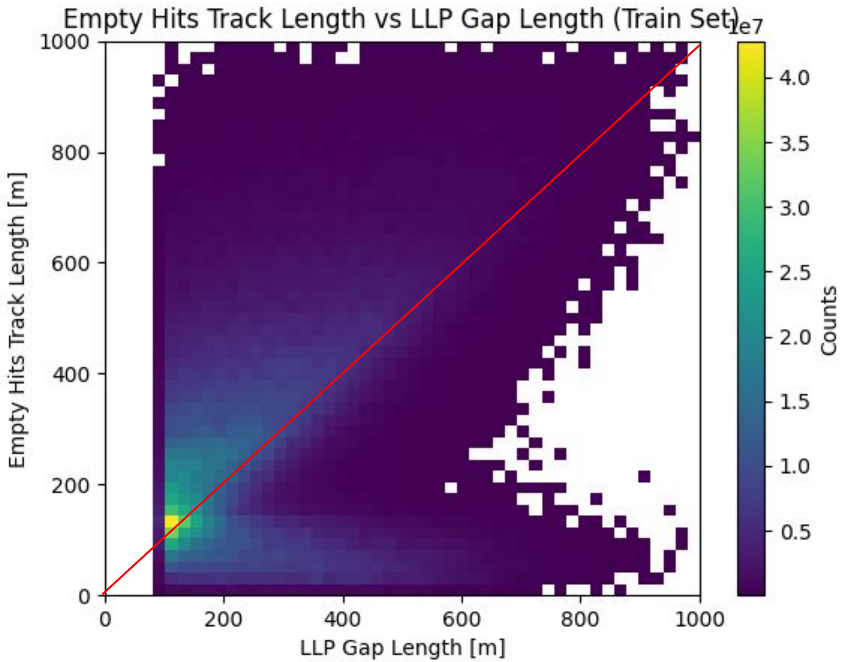


LLP Gap Length != Gap in photon hit distribution

- Detector is very sparse (~17-125 m resolution) and light travels far
- Gaps in photon emission not always gap in photon hits, and vice versa

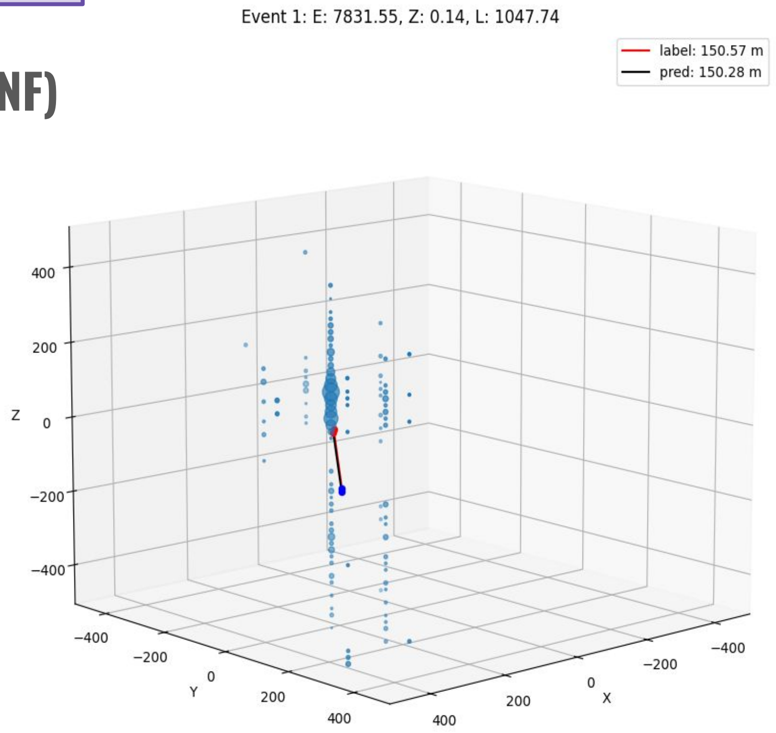


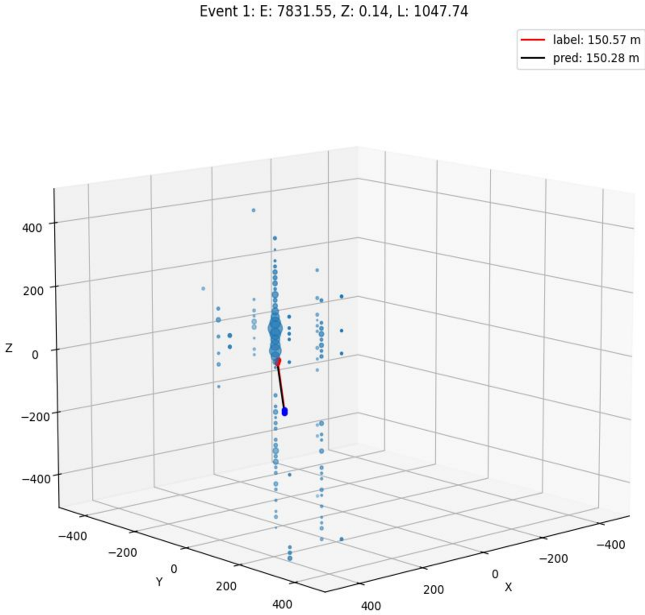
empty hits track length: The maximal track length of the track, which got no hits from hit DOMs within the specified cylinder radius around the track.



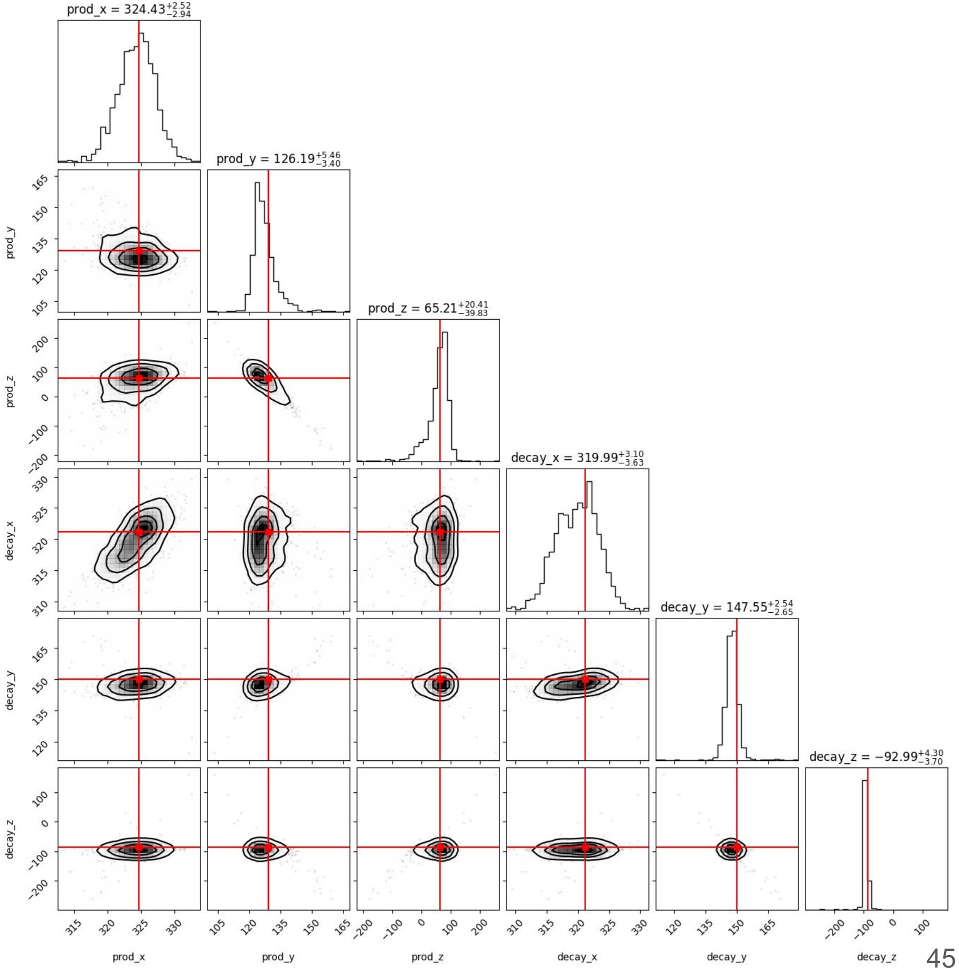
LLP Gap Reco with Deep Learning

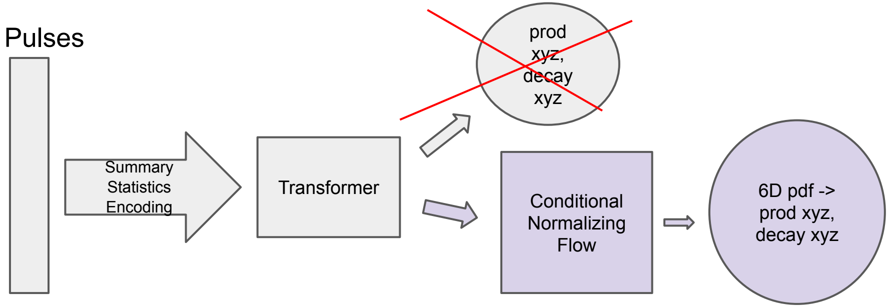
- **Transformer + Conditional Normalizing Flow (TNF)**
  - Input -> Pulses
  - Output -> Gap Position
- **Trained only on MC signal**
- Conditional normalizing flow (CNF)
  - Probability density functions instead of single values
  - Event-by-event uncertainty on gap position

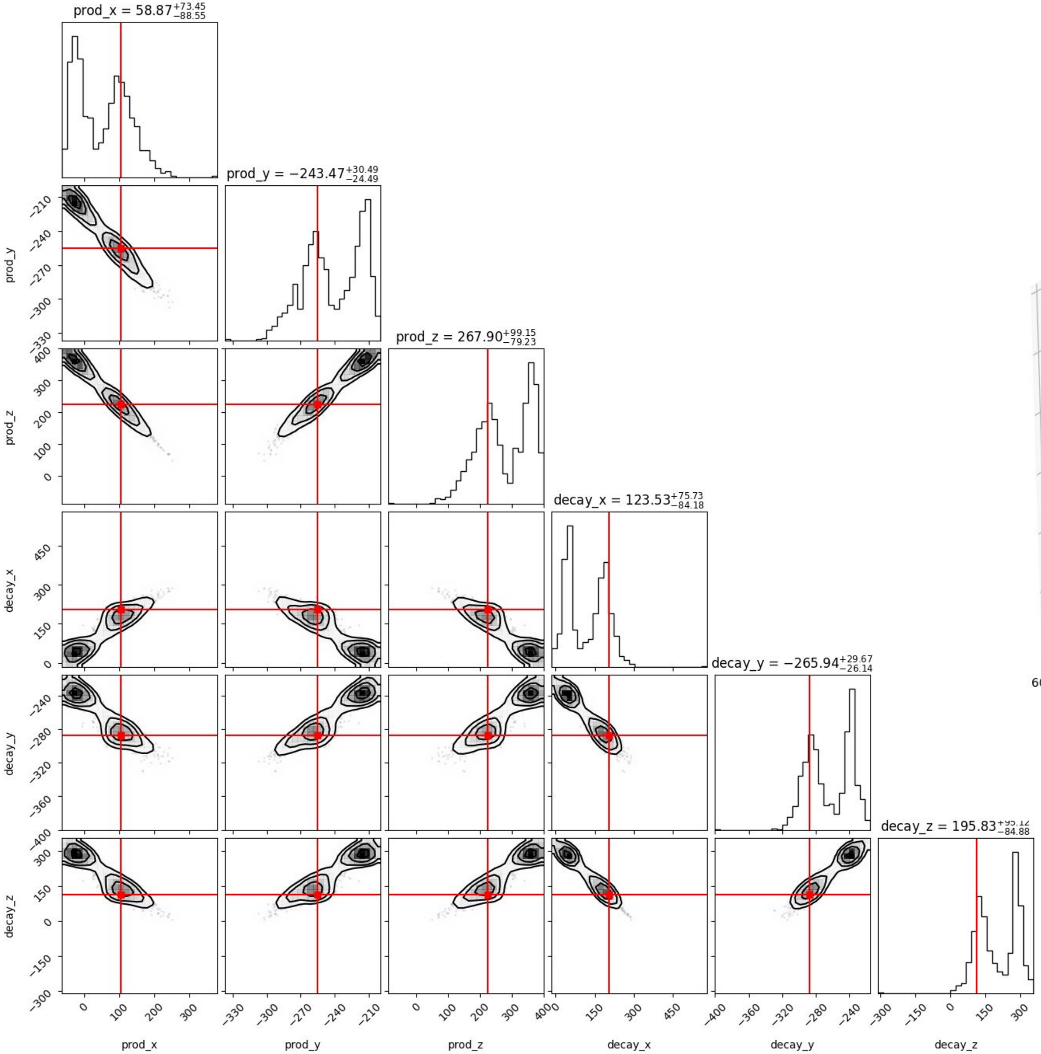



Event 1: E: 7831.55, Z: 0.14, L: 1047.74
label: 150.57 m
pred: 150.28 m
Z
Y
X

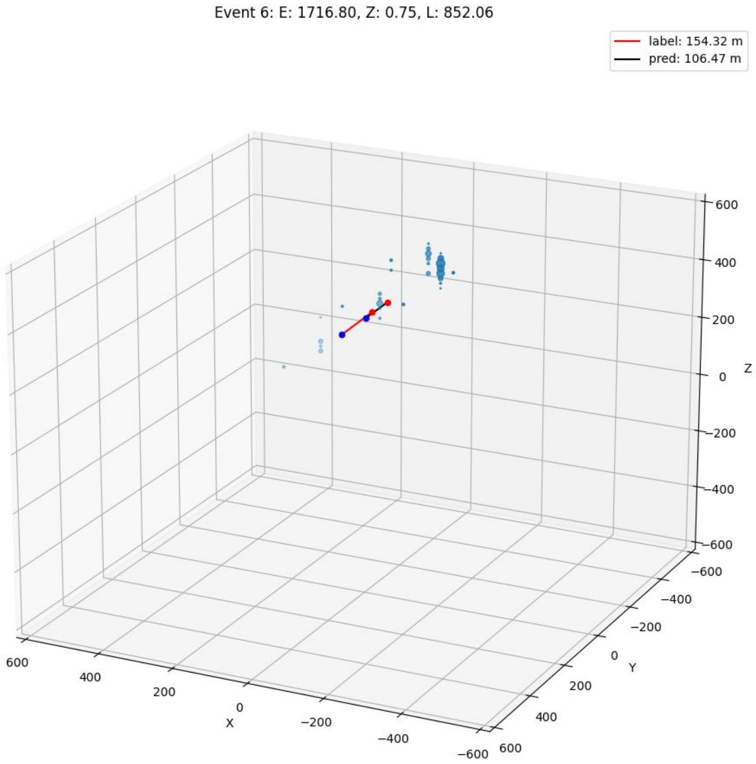

CNF


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



prod_x = $58.87^{+73.45}_{-88.55}$
prod_y = $-243.47^{+30.49}_{-24.49}$
prod_z = $267.90^{+99.15}_{-79.23}$
decay_x = $123.53^{+75.73}_{-84.18}$
decay_y = $-265.94^{+29.67}_{-26.14}$
decay_z = 195.83
prod_x
prod_y
prod_z
decay_x
decay_y
decay_z

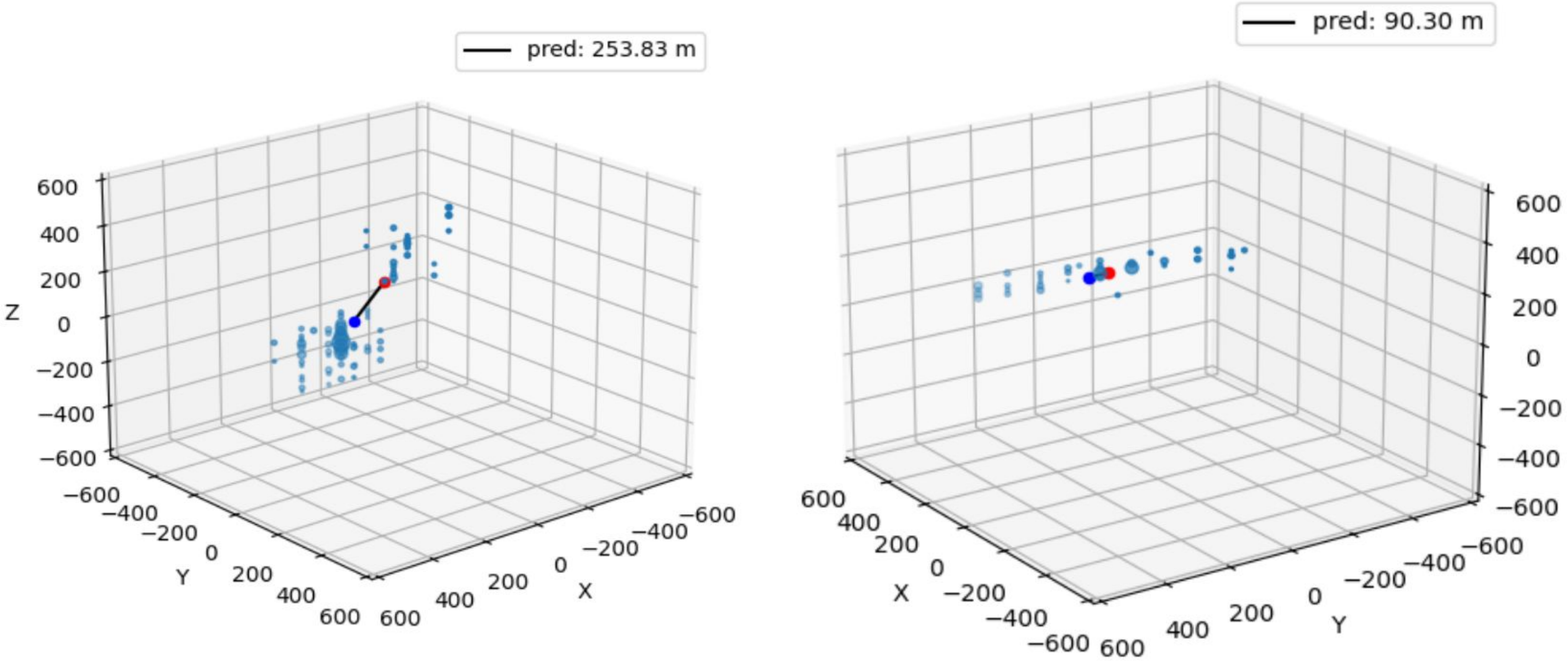


Event 6: E: 1716.80, Z: 0.75, L: 852.06
label: 154.32 m
pred: 106.47 m
X
Y
Z

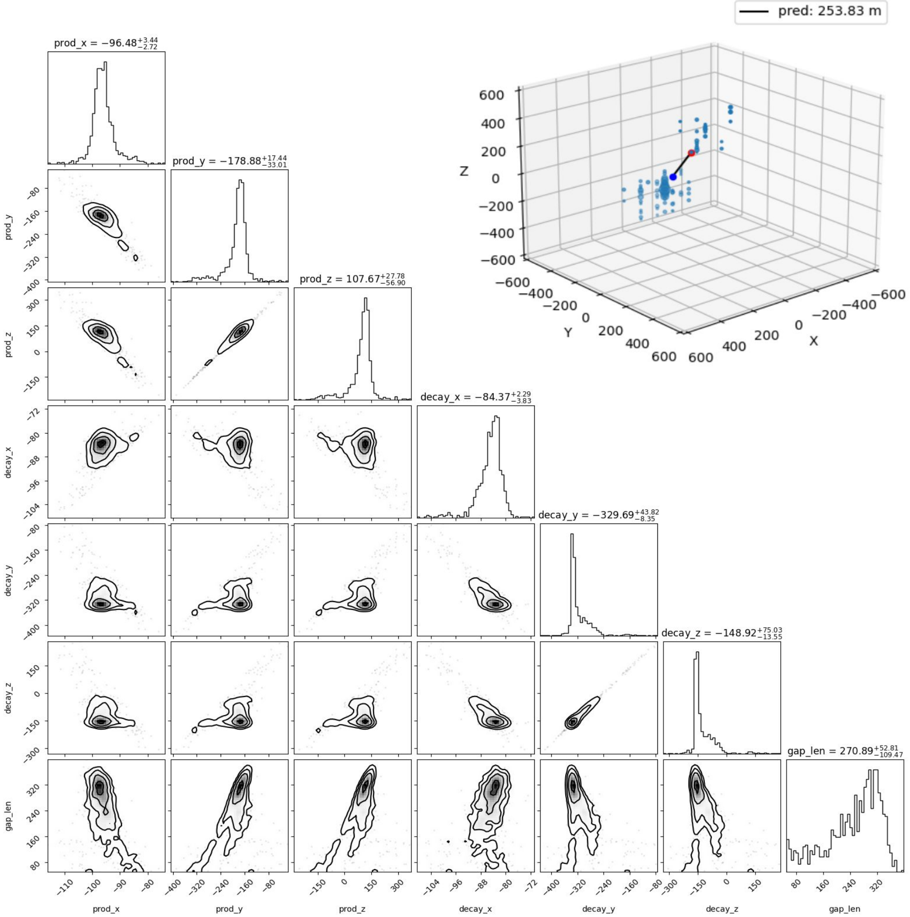
Is the TNF gap reco a reconstruction or classification tool?

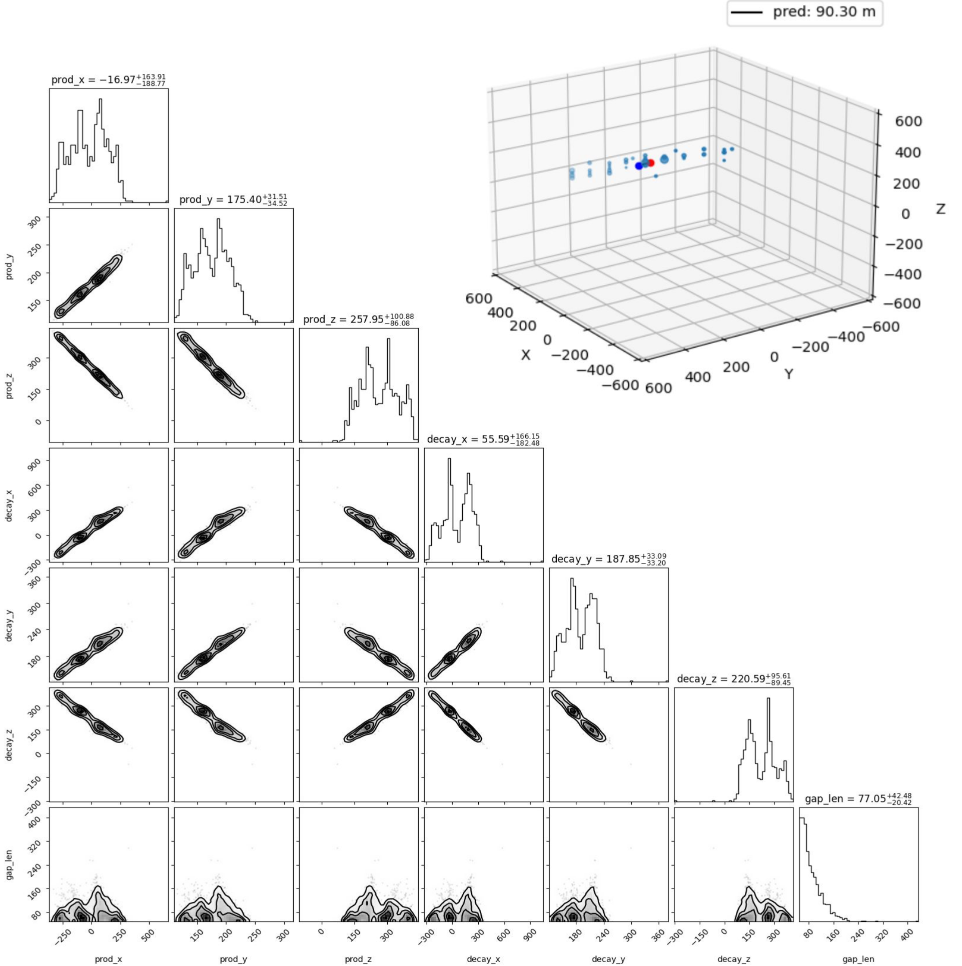
- Both, sort of.
- The output is nonsensical for non-signal events. Only LLPs have gaps.
- Network is only trained on signal. Unfamiliar input (aka bkg) will give wonky pdf’s from the CNF.
- Probability density function metrics can be used for event selection!
    - Mean, std, covariance, entropy, etc.
- This wouldn’t work for networks without normalizing flows, need the pdf’s!

Applying on CORSIKA



Applying on CORSIKA



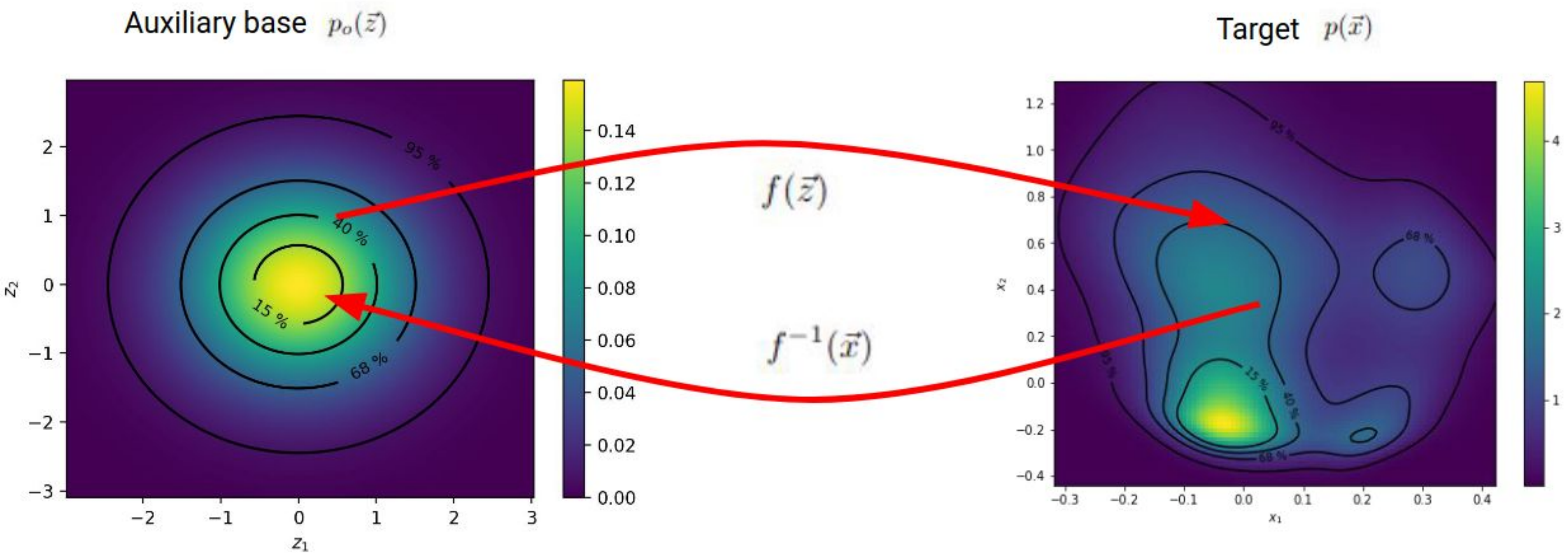


What is a normalizing flow?

(The following two slides are taken from Thorsten Gluesenkamp’s plenary talk at Grand Rapids 2023)
https://events.icecube.wisc.edu/event/168/contributions/9558/

https://events.icecube.wisc.edu/event/168/contributions/9558/

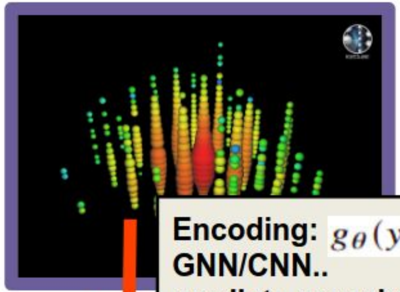
Normalizing flows: flexible PDFs



3

https://events.icecube.wisc.edu/event/168/contributions/9558/

Conditional NF structure



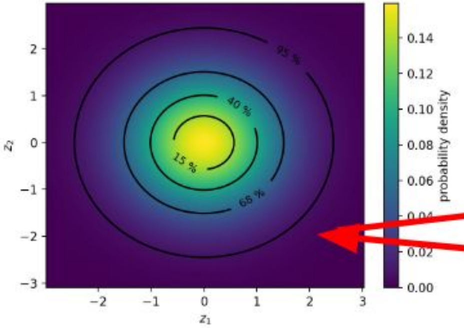
Auxiliary base space "z":

$$p_0(z) = \mathcal{N}(z; \mathbf{0}, \mathbb{1})$$

Encoding: $g_\theta(y)$
GNN/CNN..
predicts mapping

Target space "x":

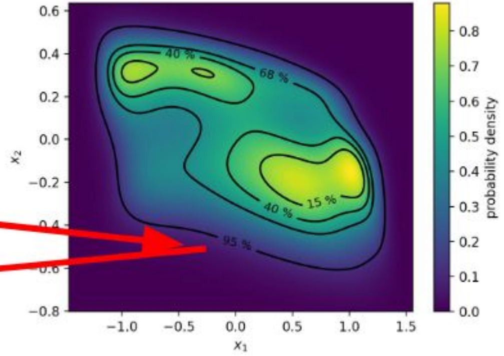
$$p_\theta(x|y) = p_0(f^{-1}_{g_\theta(y)}(x)) \cdot |\det J^{-1}_{g_\theta(y)}(x)|$$



affine: $x = \sigma \cdot z + \mu$

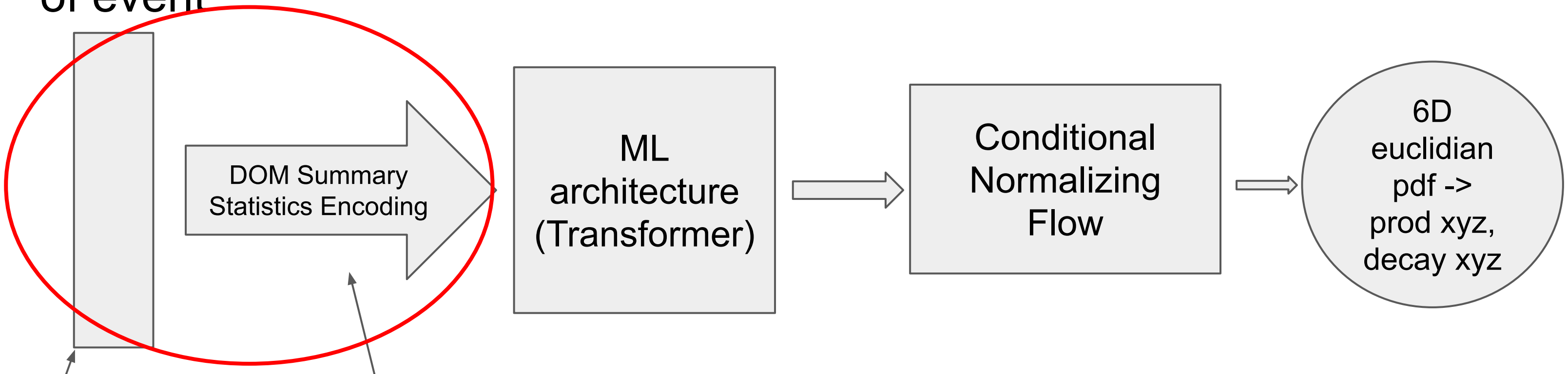
general: $x = f_\phi(z)$

bijective mapping



14

Pulse series of event

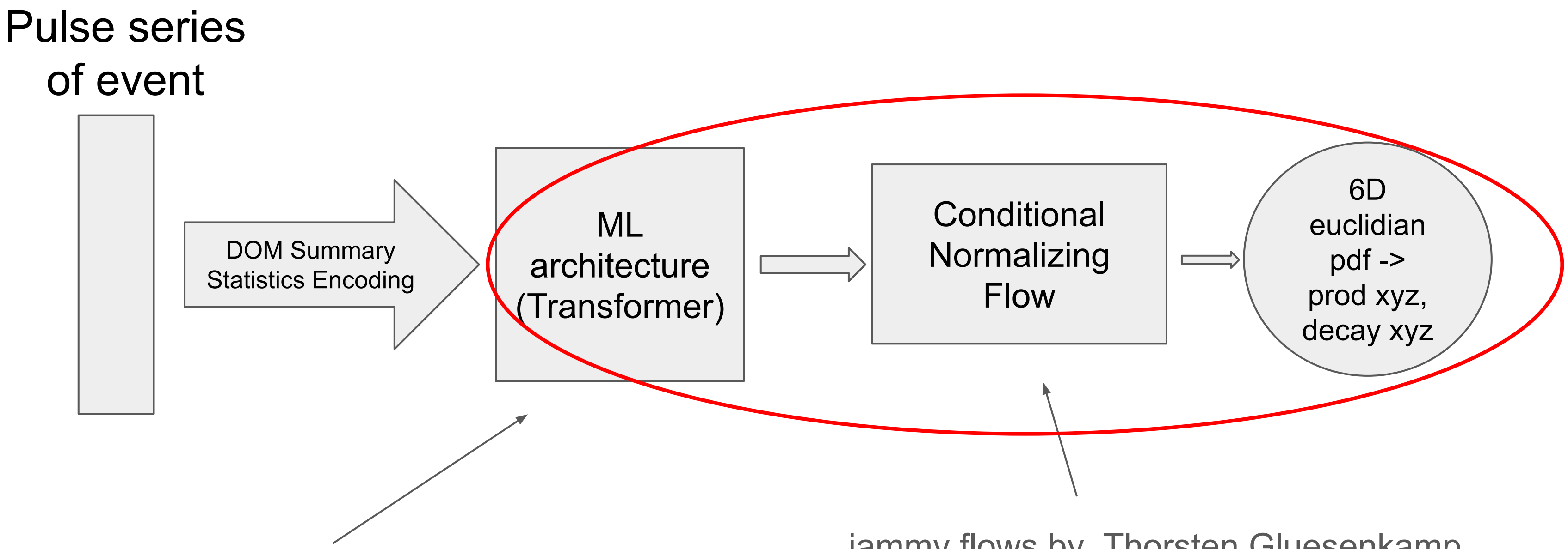


SRT Cleaned Pulses

Summary statistics: each DOM gives vector of same size no matter how many hits

Input features:

- Total charge
- Charge until time (10, 50, 100 ns)
- Time spread
- Charge weighted time std and mean
- Time of first pulse

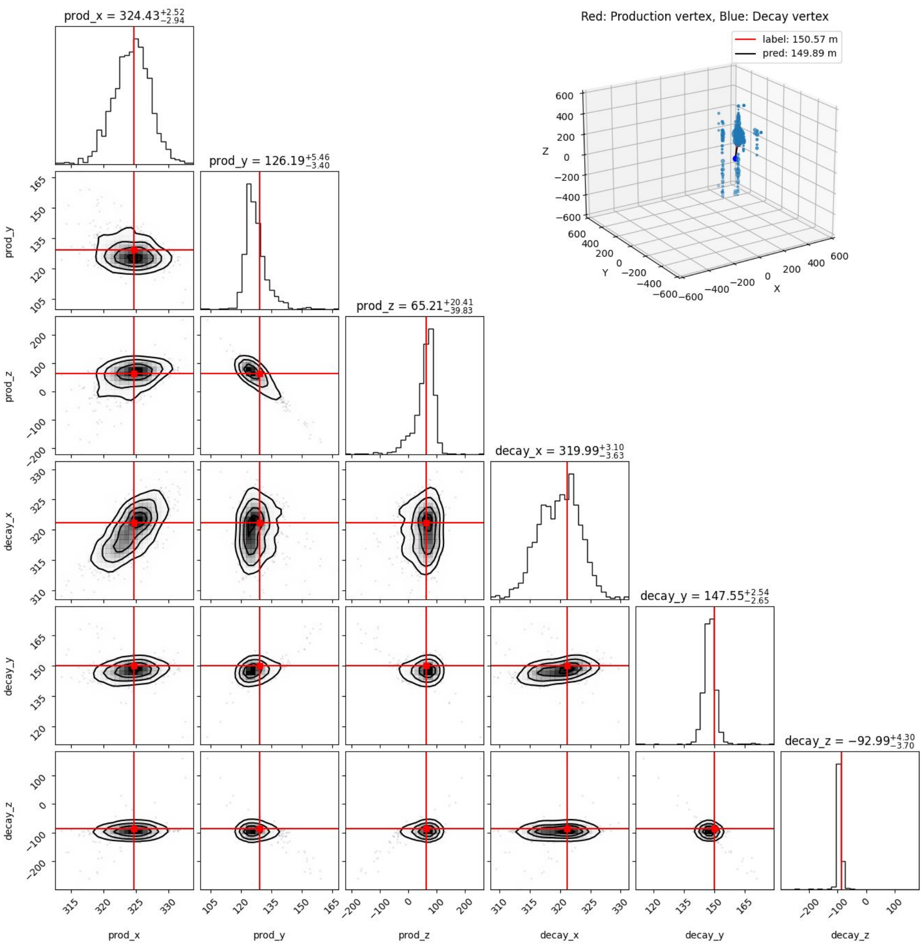


pytorch implementation of transformer architecture

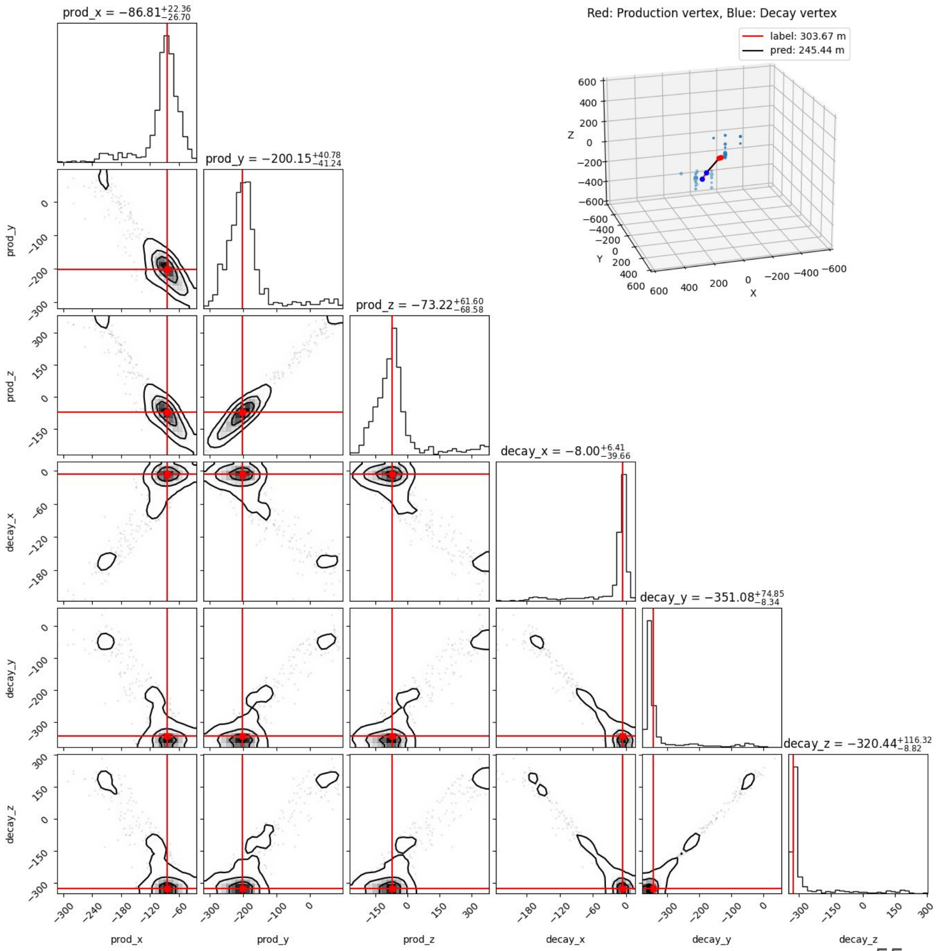
- Based on code by Thorsten Gluesenkamp
- Self attention algorithm is xFormers which allows variable sequence length (no. of hit DOMs) https://github.com/facebookresearch/xformers
- “Encodes” the event for the CNF, outputs 128 values per event

jammy flows by Thorsten Gluesenkamp
https://github.com/thoglu/jammy_flows

- Conditional input is 128 values from transformer encoder
- 6D euclidian base pdf mapped with five gaussianization flows and one affine flow -> final output is the 6D pdf of the gap positions



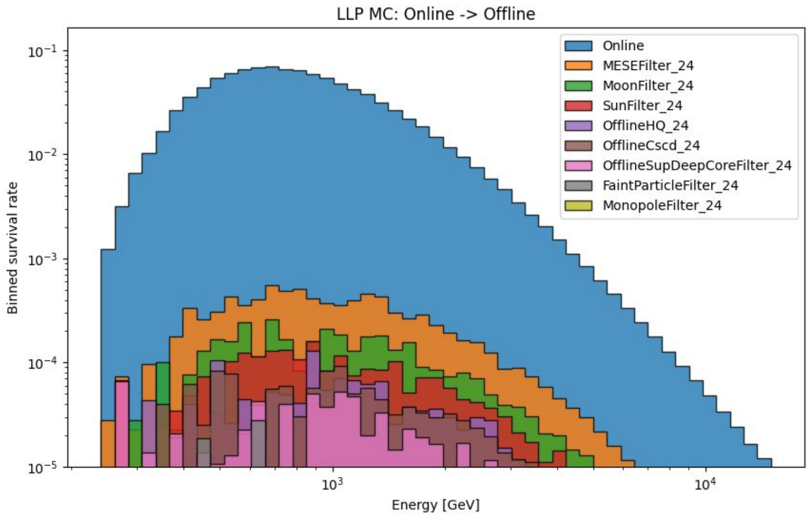
prod_x = 324.43$^{+2.52}_{-2.94}$
prod_y = 126.19$^{+5.46}_{-3.40}$
prod_z = 65.21$^{+20.41}_{-39.83}$
decay_x = 319.99$^{+3.10}_{-3.63}$
decay_y = 147.55$^{+2.54}_{-2.65}$
decay_z = −92.99$^{+4.30}_{-3.70}$
Red: Production vertex, Blue: Decay vertex
label: 150.57 m
pred: 149.89 m
X
Y
Z
prod_x
prod_y
prod_z
decay_x
decay_y
decay_z

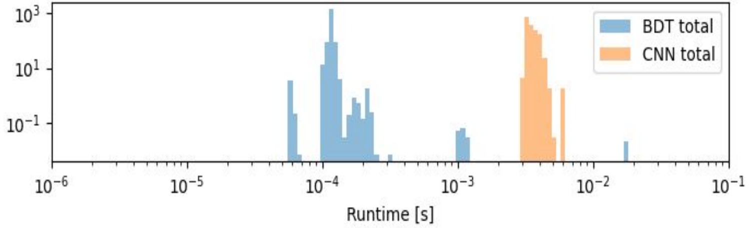


prod_x = −86.81$^{+22.36}_{-26.70}$
prod_y = −200.15$^{+40.78}_{-41.24}$
prod_z = −73.22$^{+61.60}_{-68.58}$
decay_x = −8.00$^{+6.41}_{-39.66}$
decay_y = −351.08$^{+74.85}_{-8.34}$
decay_z = −320.44$^{+116.32}_{-8.82}$
Red: Production vertex, Blue: Decay vertex
label: 303.67 m
pred: 245.44 m
X
Y
Z
prod_x
prod_y
prod_z
decay_x
decay_y
decay_z

LLPFilter_25 proposal for pass3

- 2024 filter scheme removes the LLP signal
  - No current data sample suitable for this analysis
- **Need to develop a new filter for pass3**
  - Boosted Decision Tree ~~+ Convolutional Neural Net (CNN)~~ **(not finished in time)**





Can't run deep neural nets on full online rate, reduce rate with Boosted Decision Tree (BDT)

Level 1

1.5 kHz

BDT with cheap variables →

LLP Filter Preselection

2 Hz

~~*CNN* →~~

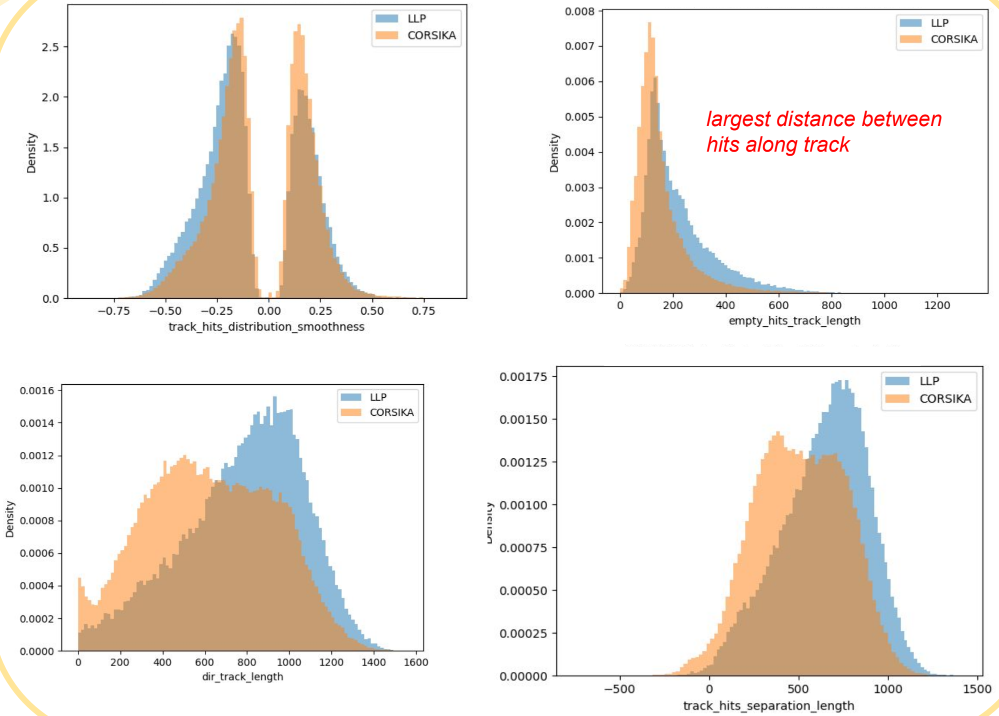
~~**LLP Level 2**~~

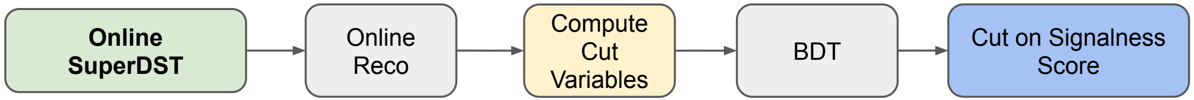
~~<1 Hz~~

Boosted Decision Tree (BDT)

- LLP MC vs CORSIKA classifier
- XGBoost https://xgboost.readthedocs.io/en/stable/#
- **Input Features**
  - PoleMuonLlhFit
  - PoleMuonLLhFitMuE
  - PoleMuonLlhFitDirectHitsBaseC
  - CommonVariables
    - HitStatistics
    - HitMultiplicity
    - TrackCharacteristics
    - TimeCharacteristics
    - *All computed with SplitRTCleanedInIcePulses + PoleMuonLlhFit*

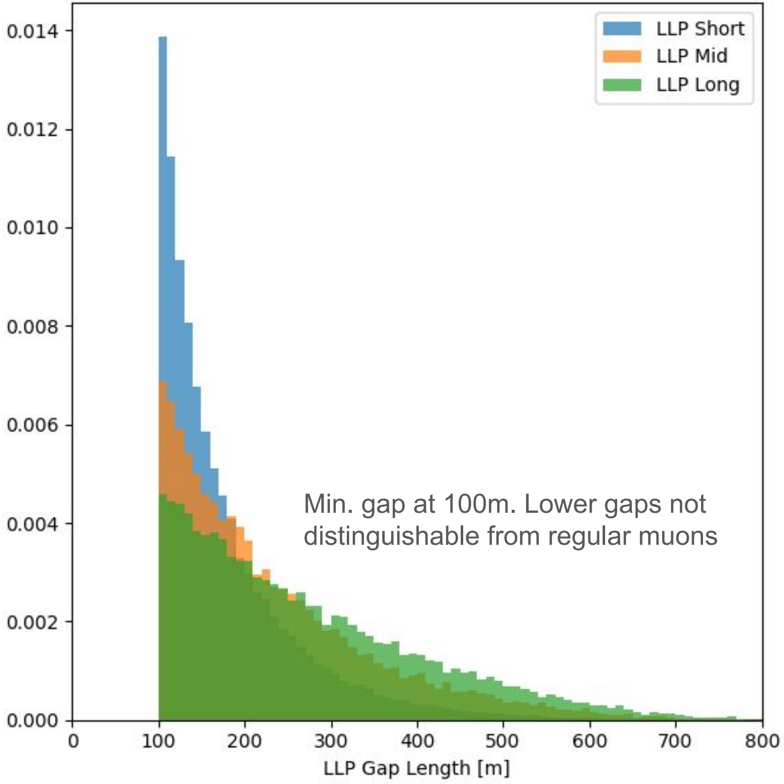
Feature examples





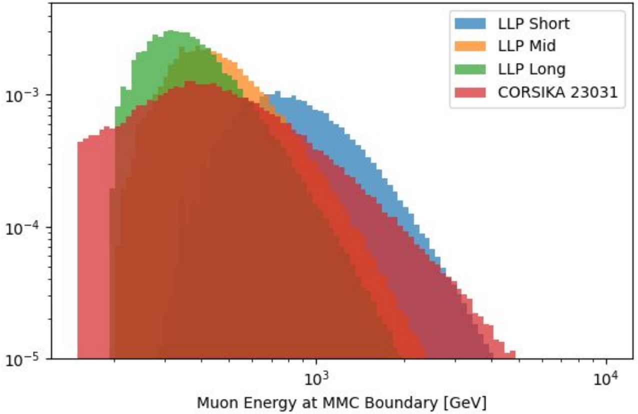
Three benchmark LLP Samples

Production and decay vertex distance



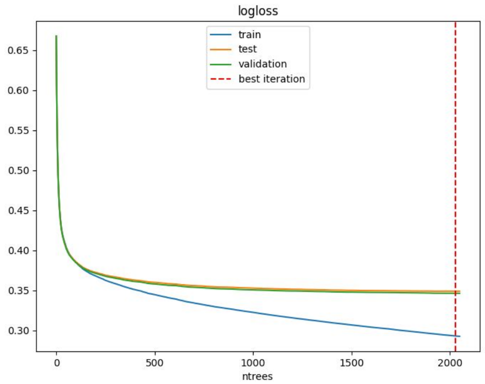
Sample	LLP Short	LLP Mid	LLP Long
Mass	110 MeV	110 MeV	108 MeV
Coupling	3e-5	1e-5	8e-6
Lifetime	5.62e-11 s	5.06e-10 s	2.67e-9 s
Decay length @1TeV	153 m	1380 m	7416 m

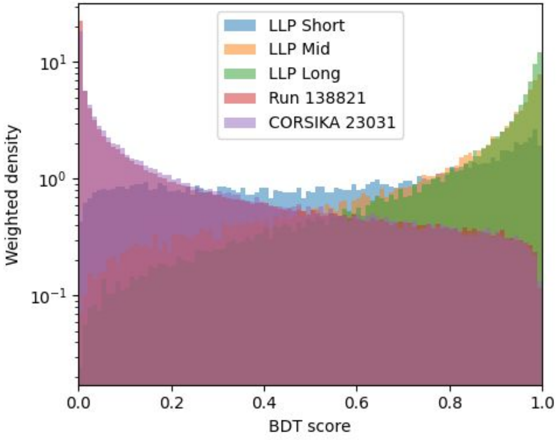
Energy (short lifetimes need larger Lorentz Boost)

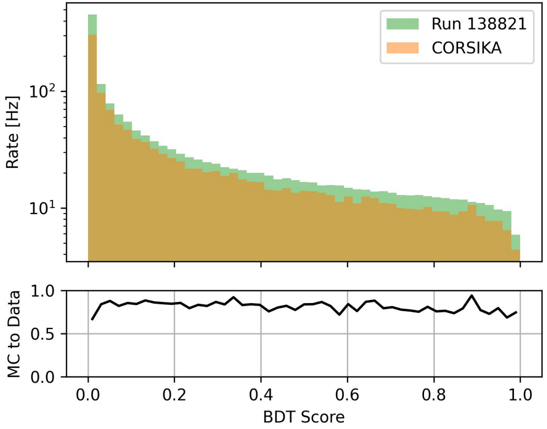


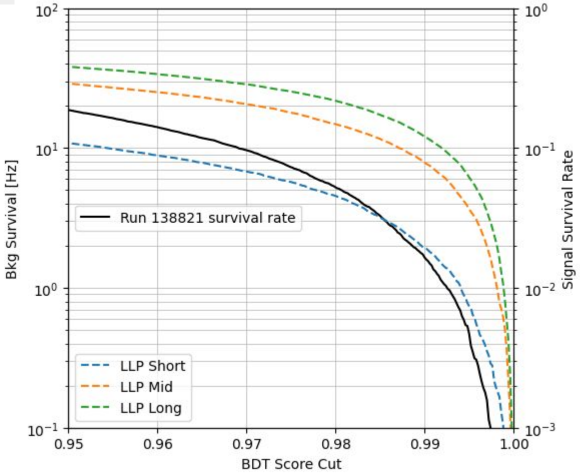
NEW LLPFilter_25: BDT Trained on LLP Long sample vs. CORSIKA 23031

- **Cut on BDT Score >= 0.988**
- **2.16 Hz data rate** (2.10 Hz exclusive) on one subrun of 138821
  - **/data/exp/IceCube/2024/filtered/PFFilt/0105/PFFilt_PhysicsFiltering_Run00138821_Subrun00000000_00000000.tar.bz2**
- Signal efficiency depend on sample (and min. LLP gap cut)
  - LLP Long ~15%, LLP Mid ~10%, LLP Short ~2.5%
  - *(total efficiency not as interesting as binned efficiency)*
- Good Data/MC agreement besides total rate
- Train/Test/Val samples found in:
  - **/data/user/axelpo/processed-MC/LLPFilter25_preprocess/LLP-filter_june25_230746441-230746453_vs_23031_142-202/**



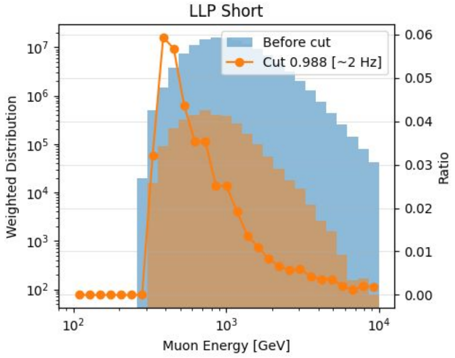


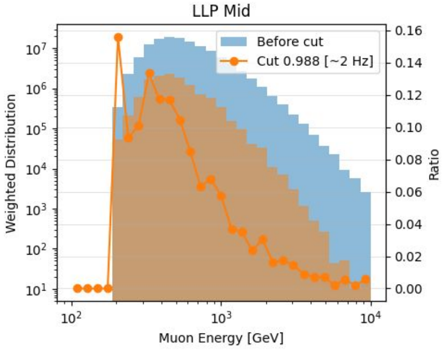


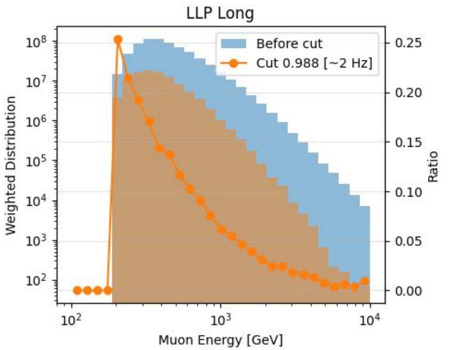


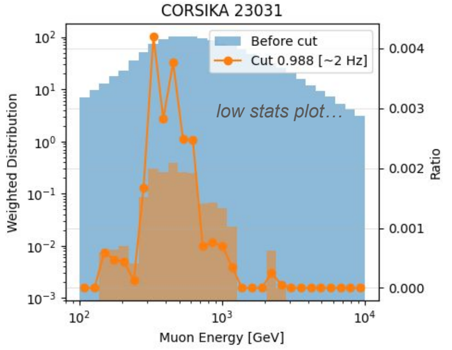
Binned Signal Efficiency: Muon Energy@MMC + Gap Length

BDT trained on LLP Long, which is lower in energy than the rest, due to Lorenz boost needed for a gap of sufficient size









Here including gaps down to 5 m!