

Combining PYTHIA and Geant4 for High-Energy Event Simulation in Neutrino Telescopes

WNPPC 2026

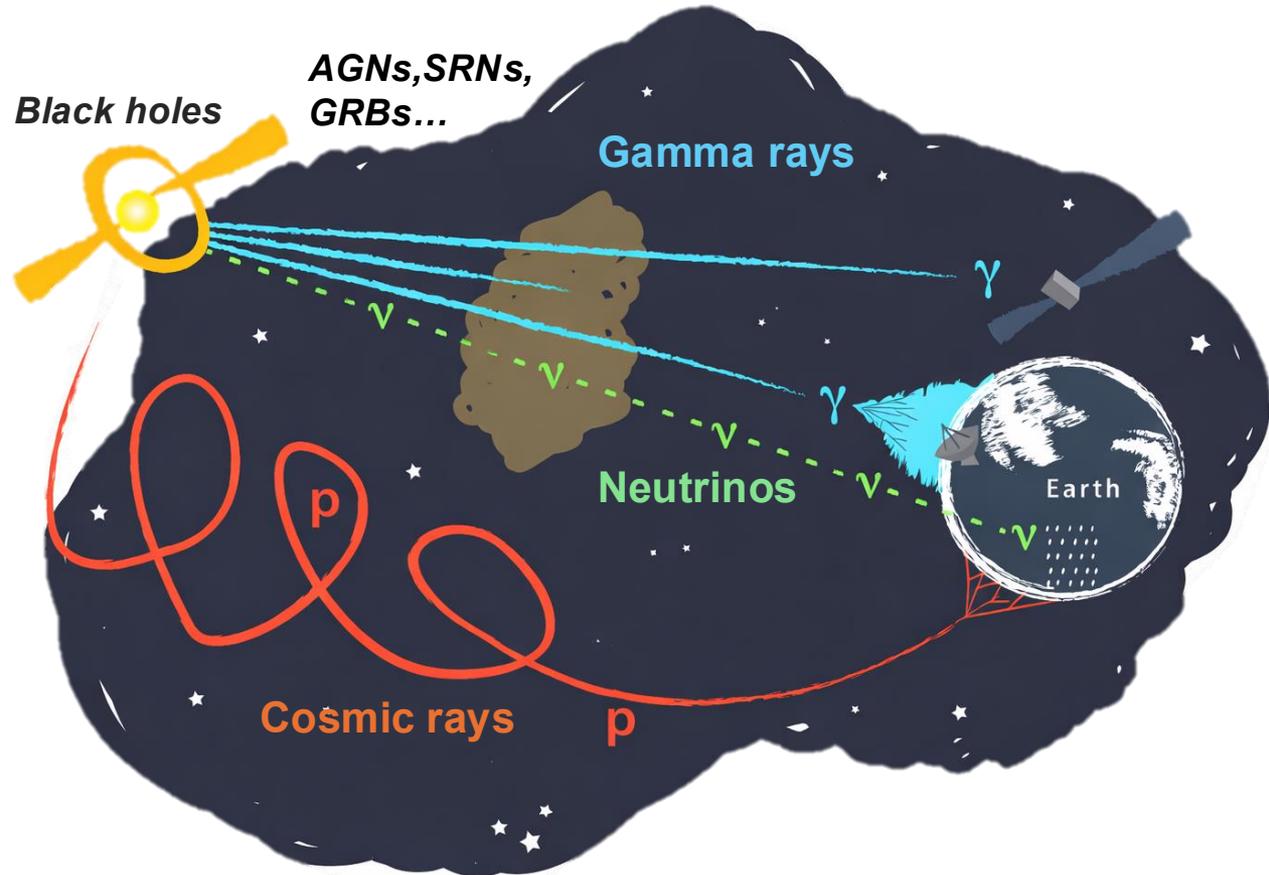
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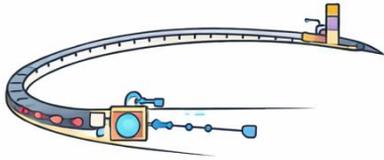
Neutrinos, Messengers From Cosmic Accelerators

Neutrinos can travel through space without experiencing deflection by magnetic fields, therefore they carry clean information from the universe.



Taken from <https://iccube.wisc.edu/news/research/2016/10/neutrinos-and-gamma-rays-partnership-to-explore-extreme-universe/> in Feb. 4/26

Why not in the lab?



GeV beams



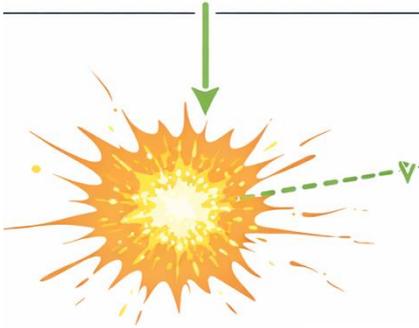
High-energy proton beams at targets of graphite or beryllium. (e.g., NuMI at Fermilab).



**Few TeV
collider
neutrinos**

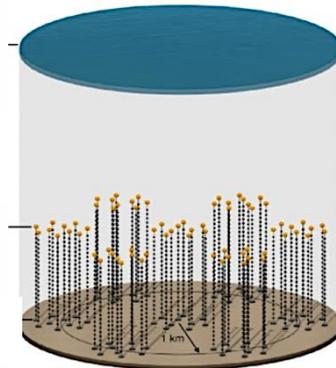


Neutrinos produced at colliders (e.g., forward neutrinos at the LHC).



**TeV+
neutrino
energies**

Cannot recreate in a lab!

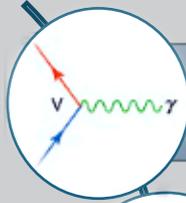


The regime
neutrino
telescopes probe.



Simulations Become Critical

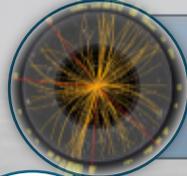
We can collide protons at multi-TeV energies, but we can't currently perform controlled laboratory measurements of neutrino-nucleon interactions at those energies.



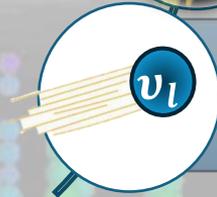
We rely on theoretical modeling.



We rely on event generators.



We rely on tools validated at collider energies.



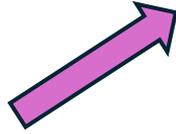
We extrapolate into this unexplored regime.

Whole Process

Neutrino Arrives
to the Detector



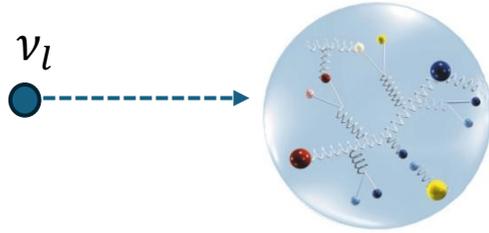
Whole Process



Neutrino Arrives to the Detector

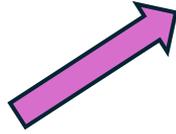


It Interacts with a Nucleon in the Ice

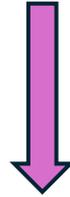
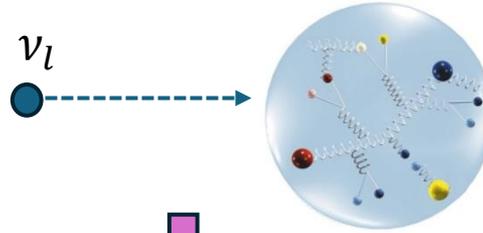


Whole Process

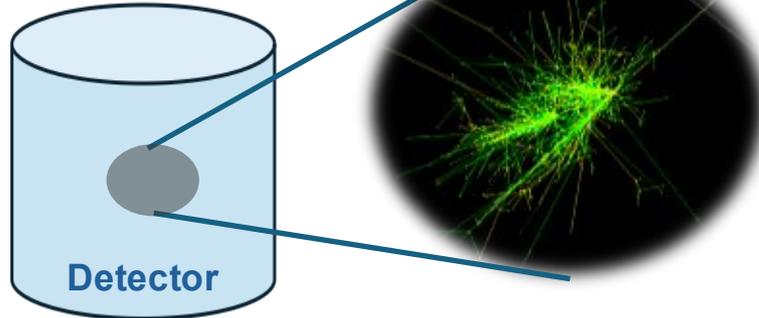
Neutrino Arrives to the Detector



It Interacts with a Nucleon in the Ice



Daughter Particles Propagate



Whole Process

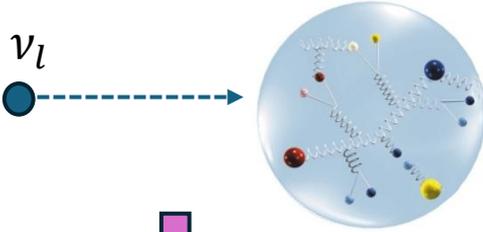
Neutrino Arrives to the Detector

ν_l



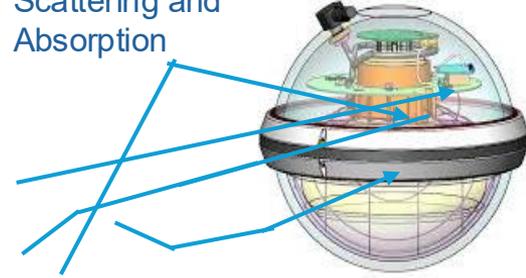
It Interacts with a Nucleon in the Ice

ν_l

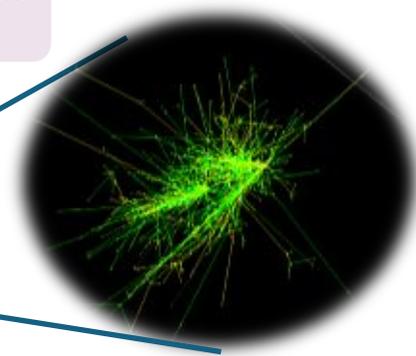
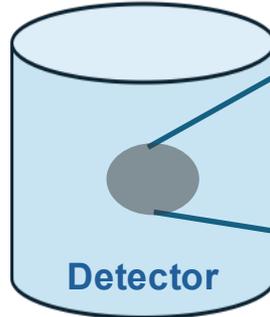


Cherenkov Light Reaches Sensors

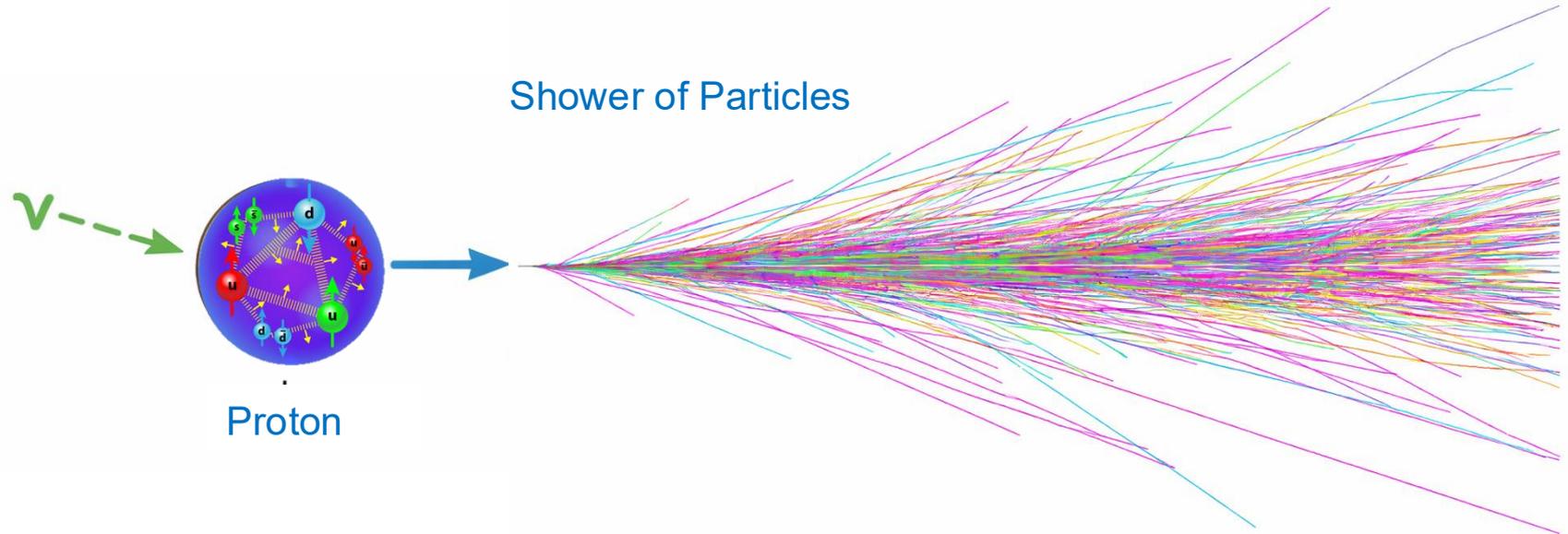
Scattering and Absorption



Daughter Particles Propagate



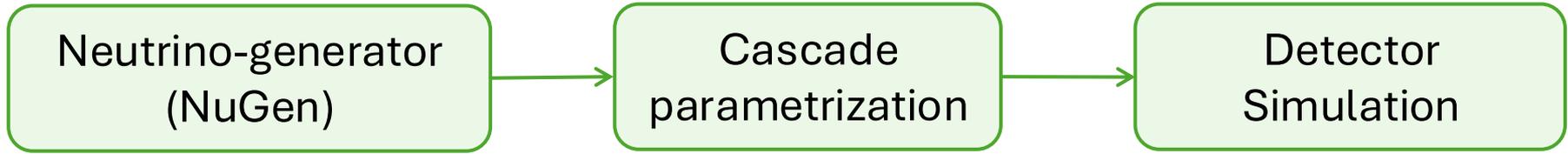
From a Single Neutrino to Millions of Particles



A high-energy neutrino interacts with the nucleon's internal structure and scatters off its constituent quarks.

At TeV+ energies, this interaction produces a whole shower containing millions of secondaries.

Current Simulation Workflow



It forces the interaction of the neutrino inside the detector producing an outgoing lepton and a "hadron blob".

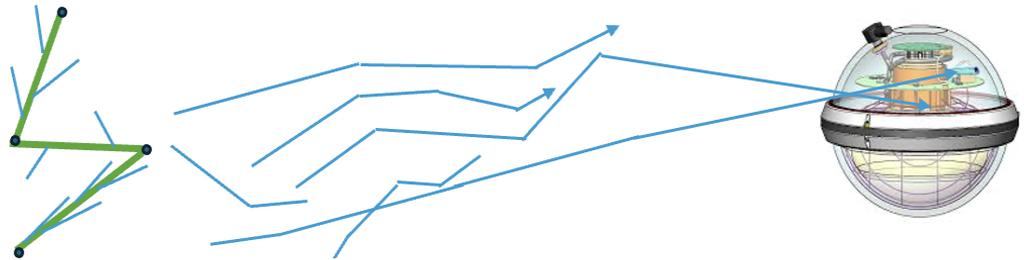


Hadron Blob



Outgoing leptons

It approximates shower development and estimates light production using simplified models.



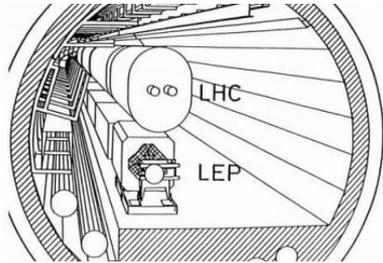
Components of the detectors are simulated.

Hadronic details are simplified in this chain.

My Proposed Workflow

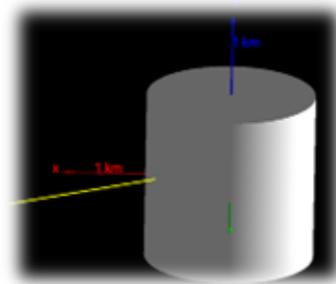


It simulates $\nu_l + N$ interaction using parton distribution functions (PDFs).



Pythia has been tuned using LHC-Data and is already validated at TeV energies.

It propagates all secondaries through matter until they reach a defined cutoff energy value.



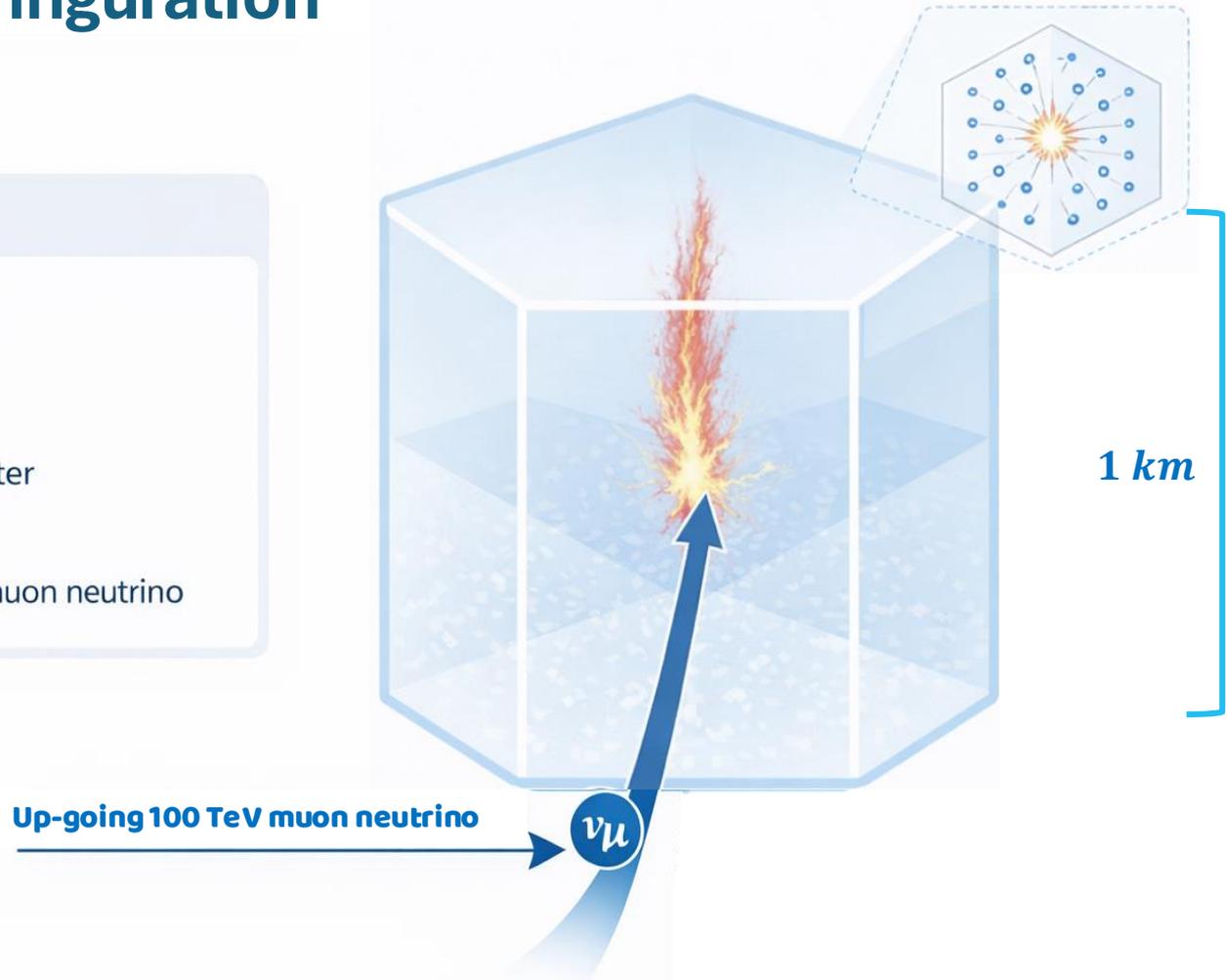
It's been widely used and tested in different areas in physics.

Output particles from Geant4 are passed to this module. No modifications made.

Simulation Configuration

Simulation Setup

- **Detector**
 - 1 km³ volume
- **Interaction**
 - Vertex fixed at center
- **Primary**
 - Up-going 100 TeV muon neutrino



Preliminary Results

Comparison types of particles produced 1 Event Example

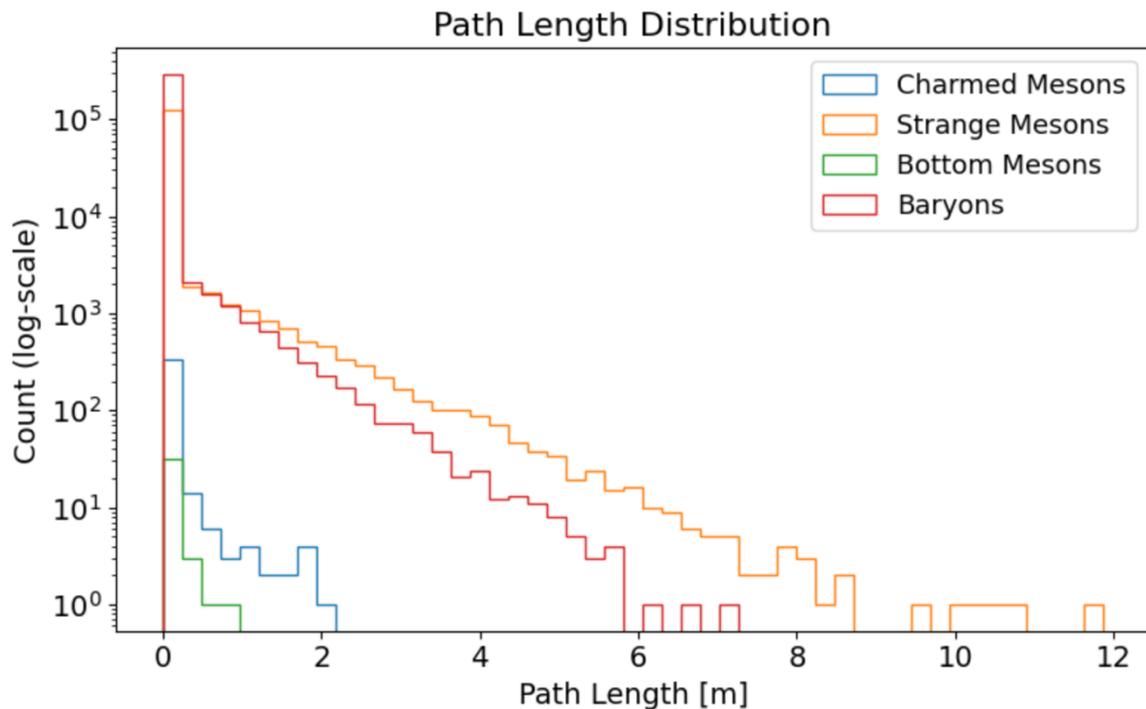
Phytia

ν_μ		100000	GeV
μ^-	91.	91709	GeV
$\rho^+(770)$		4345	GeV
π^0		3700	GeV
η		156	GeV
$K^*(892)^0$		28	GeV
$K^*(892)^-$		38	GeV
$K^*(892)^+$		5	GeV
K^-		2	GeV
$\Delta^0(1232)$		7	GeV
π^+		2	GeV

NuGen

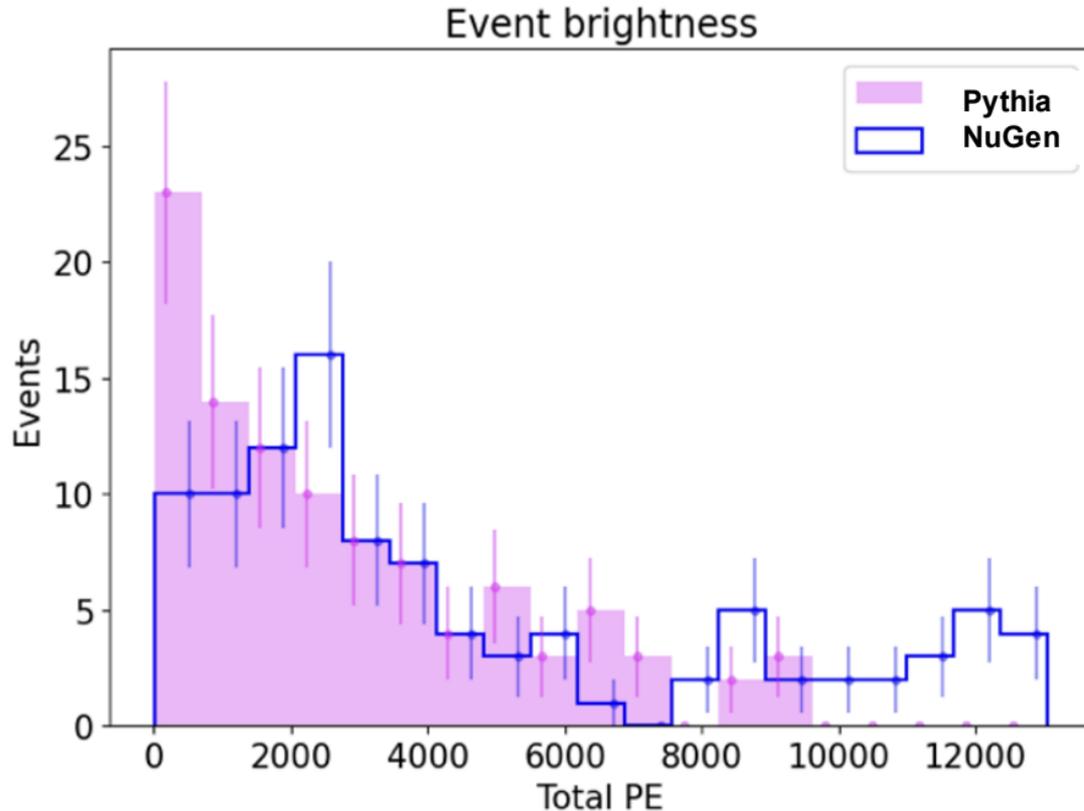
ν_μ		100000	GeV
μ^-		80773	GeV
<i>Hadrons</i>		19227	GeV

Preliminary Results



- 1000 events produced with detailed (new) simulation.
- Some hadrons travel distances similar to closest DOM distance.
- Can produce rare decays that current simulation neglects.

Preliminary Results



Comparison of light produced by 100 events.

Preliminary Conclusion

- The same events appear brighter. Brightness is what these detectors use to estimate the particle energy.
- Simplified propagation might be leading to biased energy estimation.

Needs further investigation and validation!

Next Steps

- Validation against the current baseline simulation.
- Quantify and optimize computational cost.
- Extend coverage to the full kinematic phase space.

Thanks!

Parton Distribution Functions (PDFs)

Pythia uses external **PDFs** libraries:

LHAPDF. My default set is: CTEQ, which describes:

$$f_i(x, Q^2)$$

Probability of finding parton i carrying momentum fraction x

Hadronization model: Lund String Model which produces realistic hadron multiplicities and flavor content.

Threshold Cherenkov-Energy

From relativistic kinetic energy equation and the gamma factor:

$$E_k = (\gamma - 1)mc^2$$

$$E_{Threshold} = \left(\frac{1}{\sqrt{1 - \frac{1}{n^2}}} - 1 \right) mc^2$$

Threshold energy for some particles assuming refractive index $n = 1.33$:

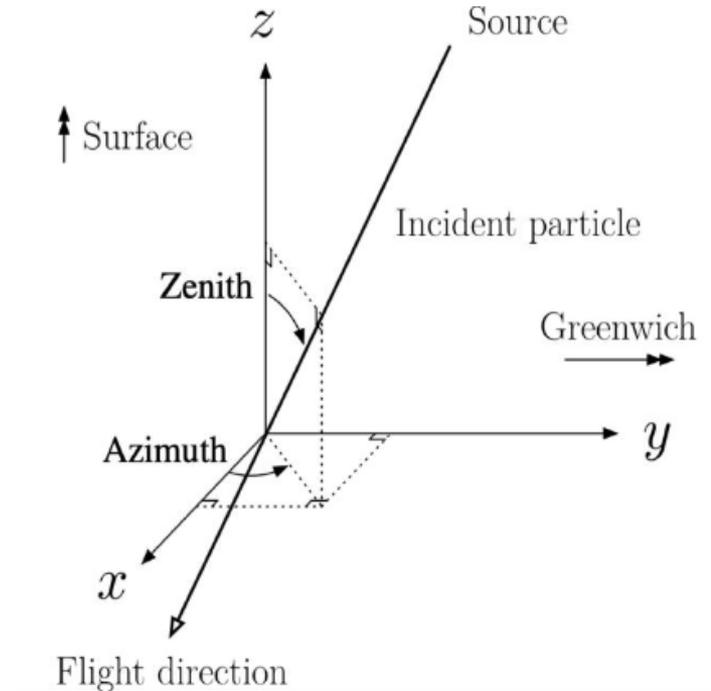
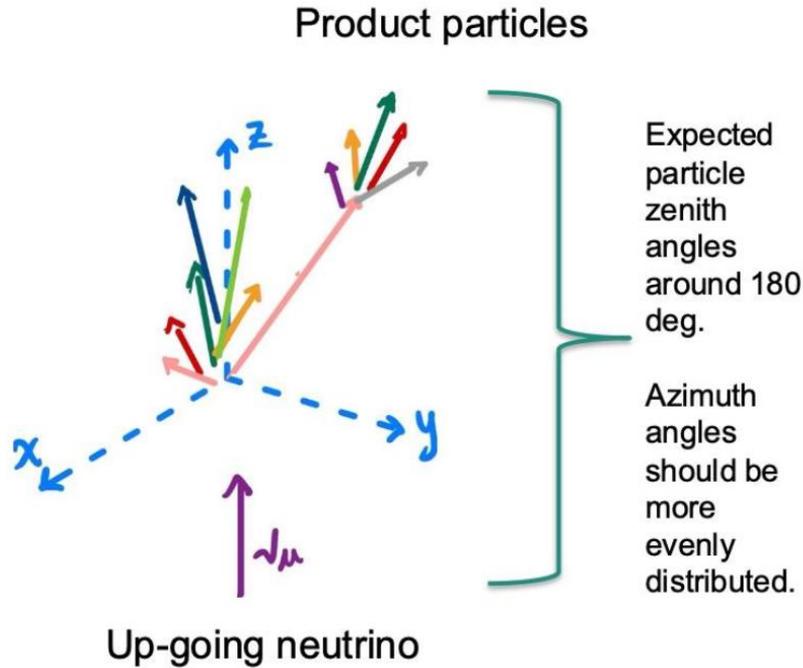
Electron $\approx 0.254 \text{ MeV}$

Proton $\approx 485 \text{ MeV}$

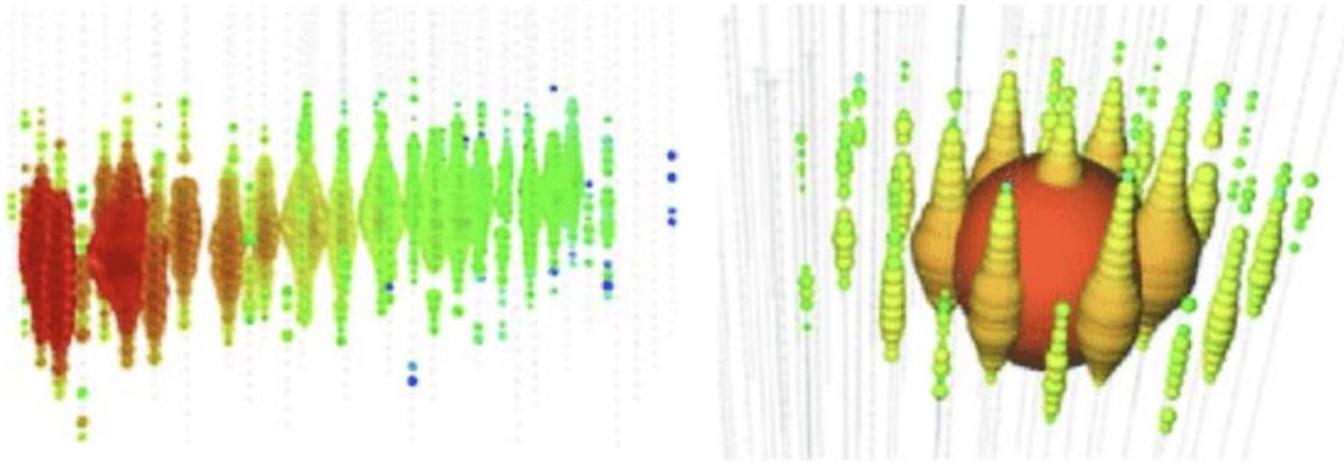
Pion^{+/-} $\approx 72 \text{ MeV}$

All the particles that don't meet the threshold are removed from the MCTree

Expected Angles for Product Particles



Track vs Cascade Topology



Taken from https://www.researchgate.net/figure/Typical-event-signatures-observed-by-IceCube-a-track-like-event-left-a-showerlike_fig1_319936518