nuPyProp

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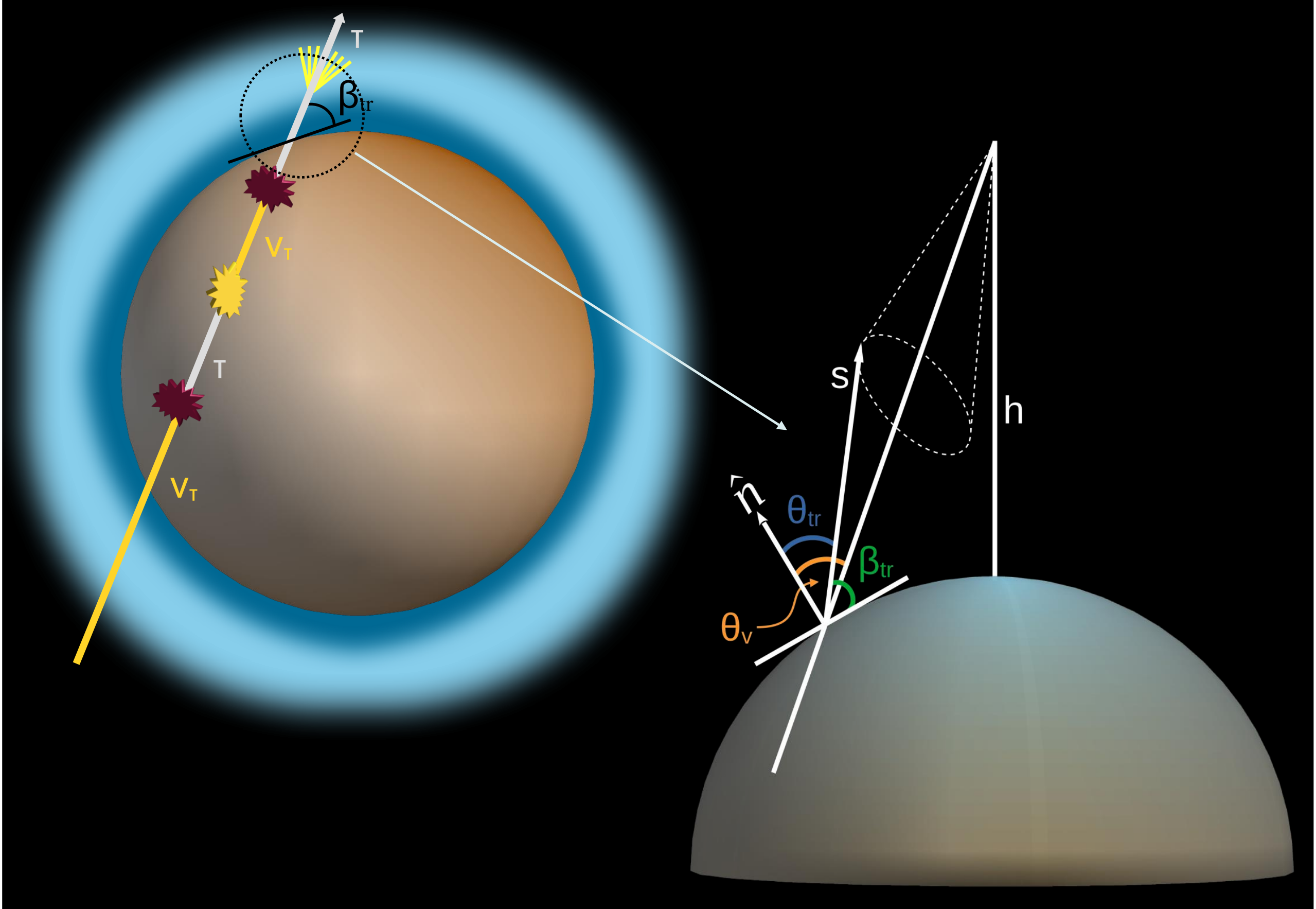
1 Overview

- Monte Carlo package that models neutrino flux attenuation & the distribution of leptons they produce in transit through the Earth.
- Essential component to determine neutrino flux sensitivities of underground, sub-orbital and space-based detectors.
- Tau neutrinos incident at modest slant depths interact in the Earth to produce τ-leptons.
- Some τ-leptons emerge from the Earth and decay in the atmosphere to produce extensive air showers.
- Future balloon-borne and satellite-based optical Cherenkov neutrino telescopes will be sensitive to upward air showers from tau neutrino induced τ-lepton decays.
- nuPyProp generates look-up tables for exit probabilities and energy distributions for **$\nu_\tau \rightarrow \tau$** and **$\nu_\mu \rightarrow \mu$**. Part of the **vSpaceSim** simulation package[12].
- Modular & flexible code runs with either stochastic or continuous electromagnetic energy losses for the lepton transit through the Earth.
- Various neutrino cross section & lepton energy loss models implemented along with templates for user defined models.
- The results are compared with other recent simulation packages for neutrino and charged lepton propagation.
- Sources of modeling uncertainties are also quantified.

2 Geometry & Shower Detection



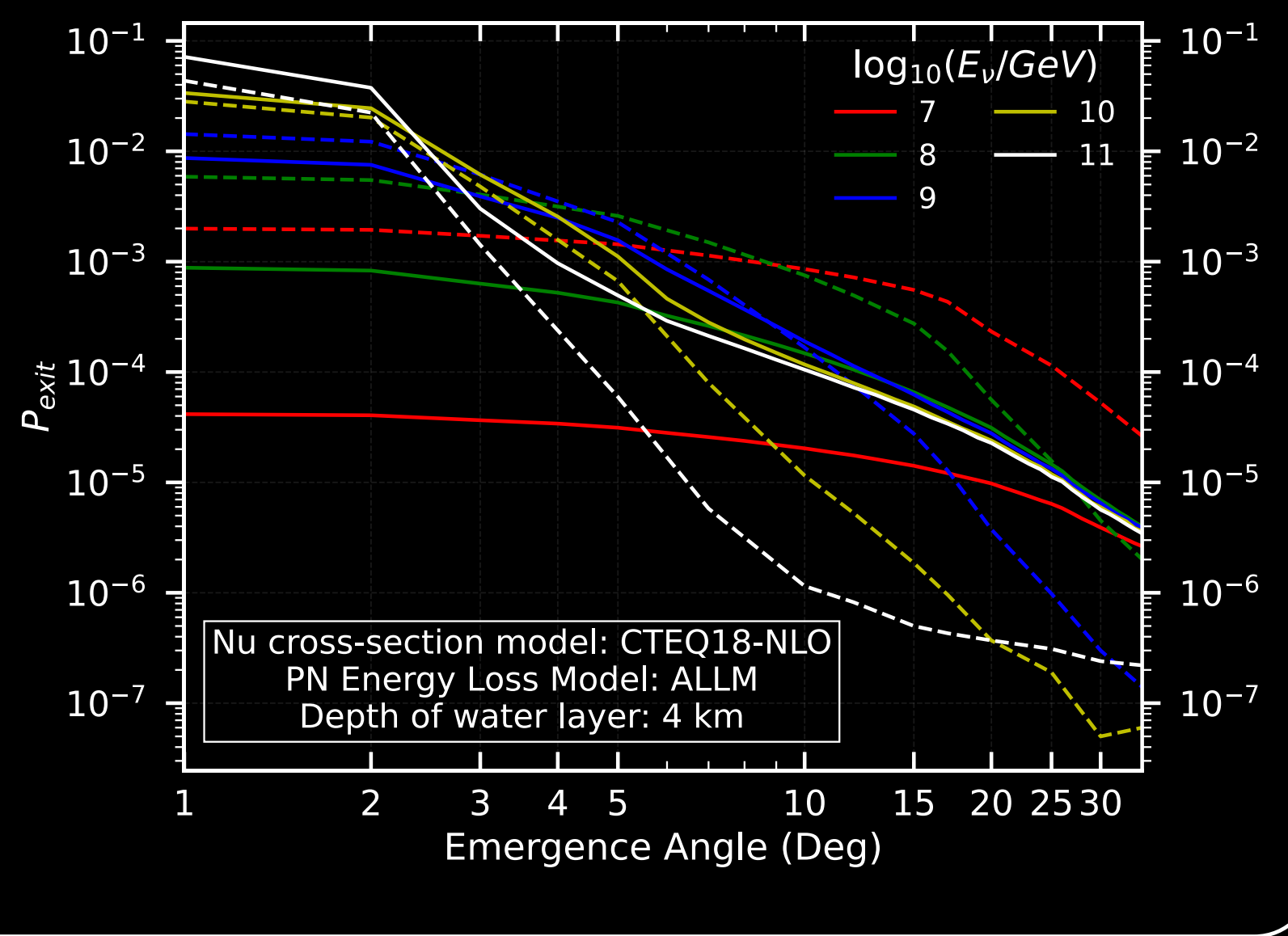
Geometry & Propagation

The observation probability can be written in terms of exit probability p_{exit}, detection probability p_{det}, and the decay probability p_{decay} for an infinitesimal path length ds[14]:

$$P_{obs} = \int \underbrace{\boxed{p_{exit}(E_\tau|E_{\nu_\tau}, \beta_{tr})}}_{\text{nuPyProp}} \times \left[\int ds'\ p_{decay}(s')\ p_{det}(E_{\nu_\tau}, \theta_\nu, \beta_{tr}, s')\right] dE_\tau$$

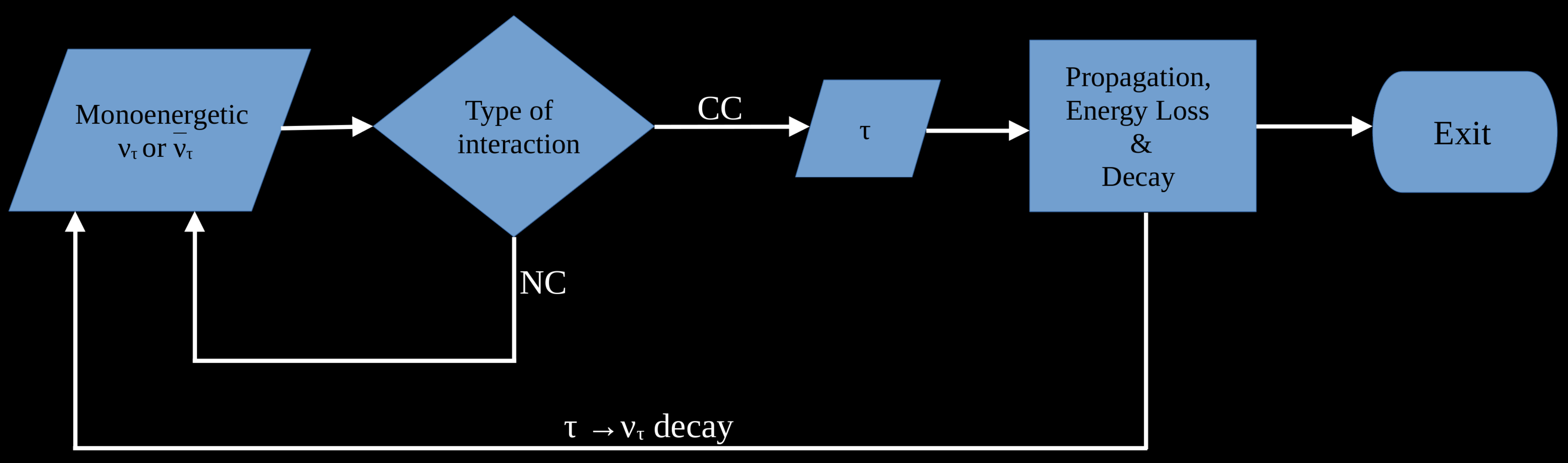
Our focus is on p_{exit} and the energy distributions of the outgoing taus, independent of the tau shower detection.

- β_{tr} denotes the Earth emergence angle.
- p_{decay} relates to the decay of the τ-lepton in the Earth's atmosphere as a function of altitude.
- p_{det} determines how much of the Cherenkov signal would be effectively observed at the detector.

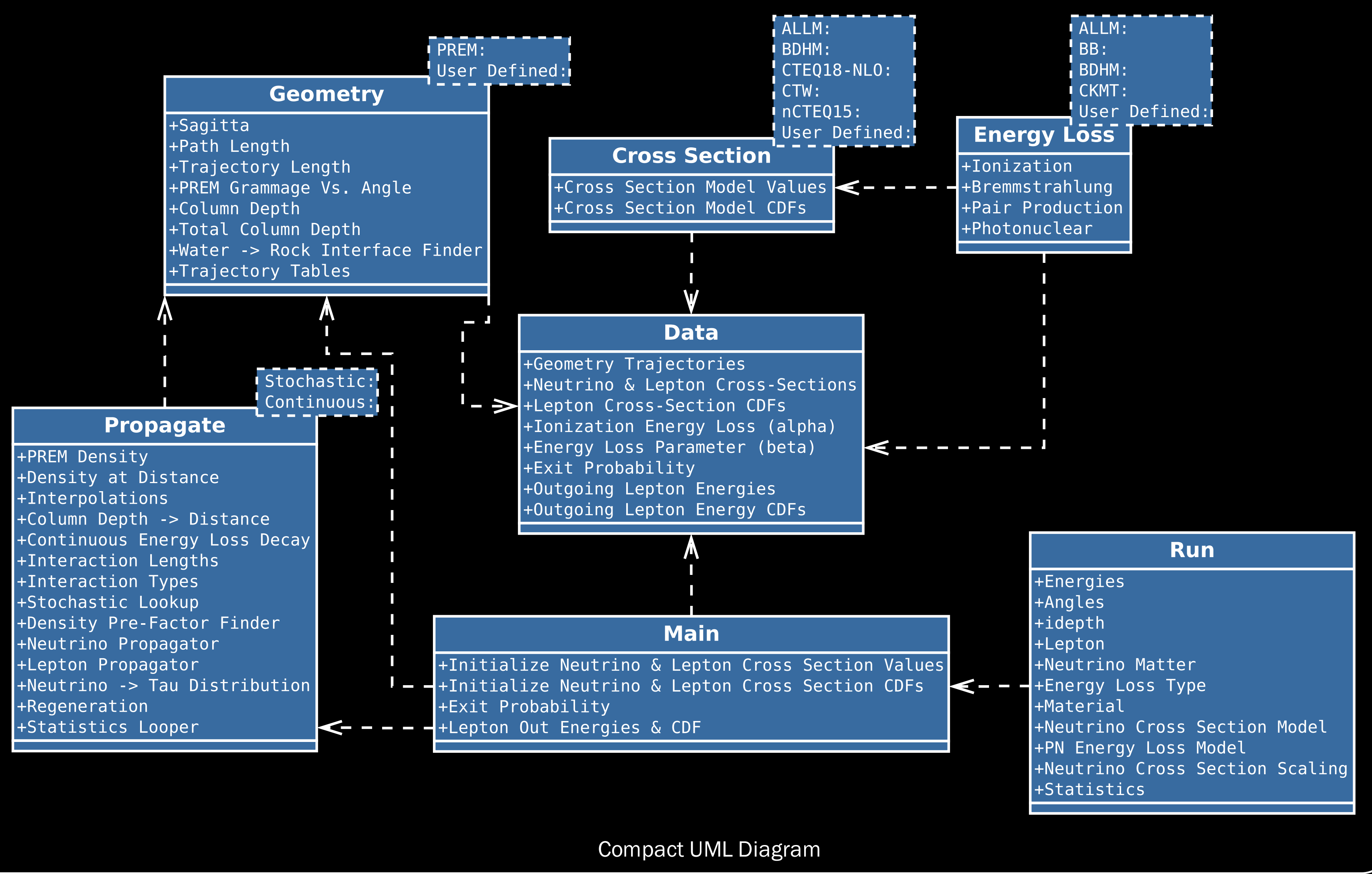


P_{exit} Vs. Earth Emergence Angles using CT18-NLO Neutrino Cross Section Model and ALLM Photonuclear Lepton Energy Loss Model for $\nu_\tau \longrightarrow \tau$ (solid) and $\nu_\mu \longrightarrow \mu$ (dashed)

3 Code Flow & Design



Propagation Flowchart



Geometry
+Sagitta
+Path Length
+Trajectory Length
+PREM Grammage Vs. Angle
+Column Depth
+Total Column Depth
+Water -> Rock Interface Finder
+Trajectory Tables

PREM:
User Defined:

Cross Section
+Cross Section Model Values
+Cross Section Model CDFs

ALLM:
BDHM:
CTEQ18-NLO:
CTW:
nCTEQ15:
User Defined:

Energy Loss
+Ionization
+Bremmstrahlung
+Pair Production
+Photonuclear

ALLM:
BB:
BDHM:
CKMT:
User Defined:

Propagate
+PREM Density
+Density at Distance
+Interpolations
+Column Depth -> Distance
+Continuous Energy Loss Decay
+Interaction Lengths
+Interaction Types
+Stochastic Lookup
+Density Pre-Factor Finder
+Neutrino Propagator
+Lepton Propagator
+Neutrino -> Tau Distribution
+Regeneration
+Statistics Looper

Stochastic:
Continuous:

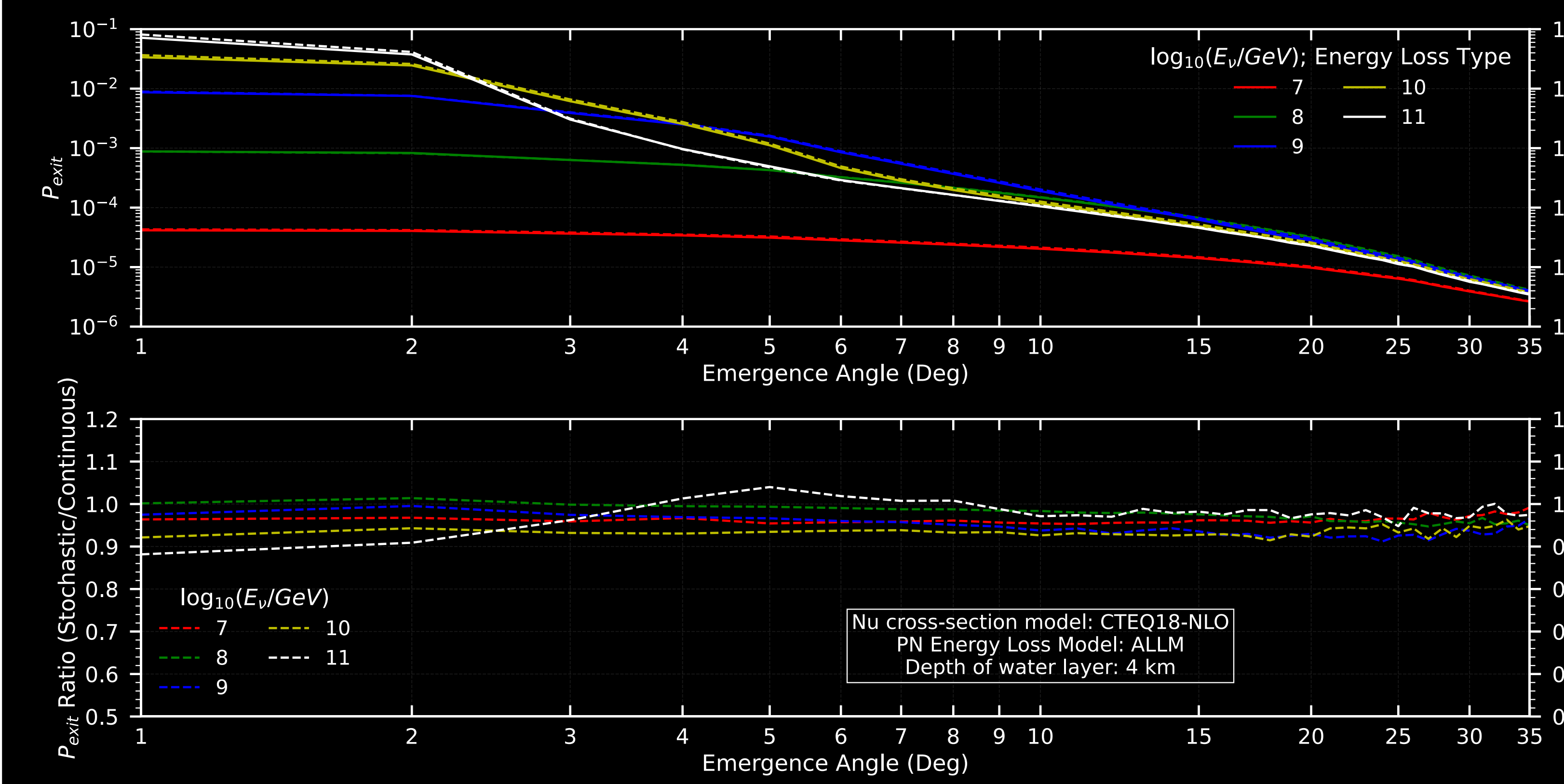
Data
+Geometry Trajectories
+Neutrino & Lepton Cross-Sections
+Lepton Cross-Section CDFs
+Ionization Energy Loss (alpha)
+Energy Loss Parameter (beta)
+Exit Probability
+Outgoing Lepton Energies
+Outgoing Lepton Energy CDFs

Main
+Initialize Neutrino & Lepton Cross Section Values
+Initialize Neutrino & Lepton Cross Section CDFs
+Exit Probability
+Lepton Out Energies & CDF

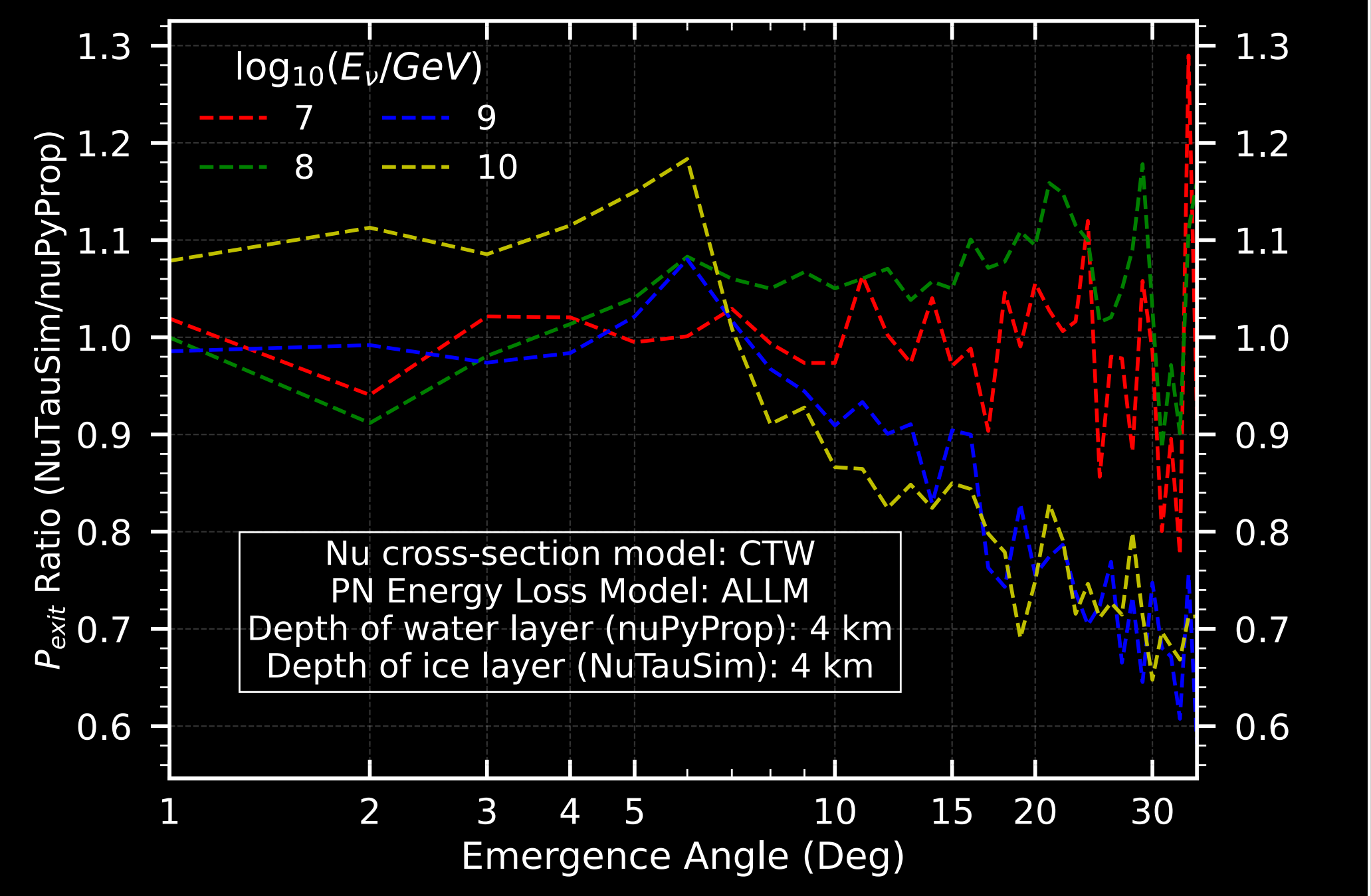
Run
+Energies
+Angles
+idepth
+Lepton
+Neutrino Matter
+Energy Loss Type
+Material
+Neutrino Cross Section Model
+PN Energy Loss Model
+Neutrino Cross Section Scaling
+Statistics

Compact UML Diagram

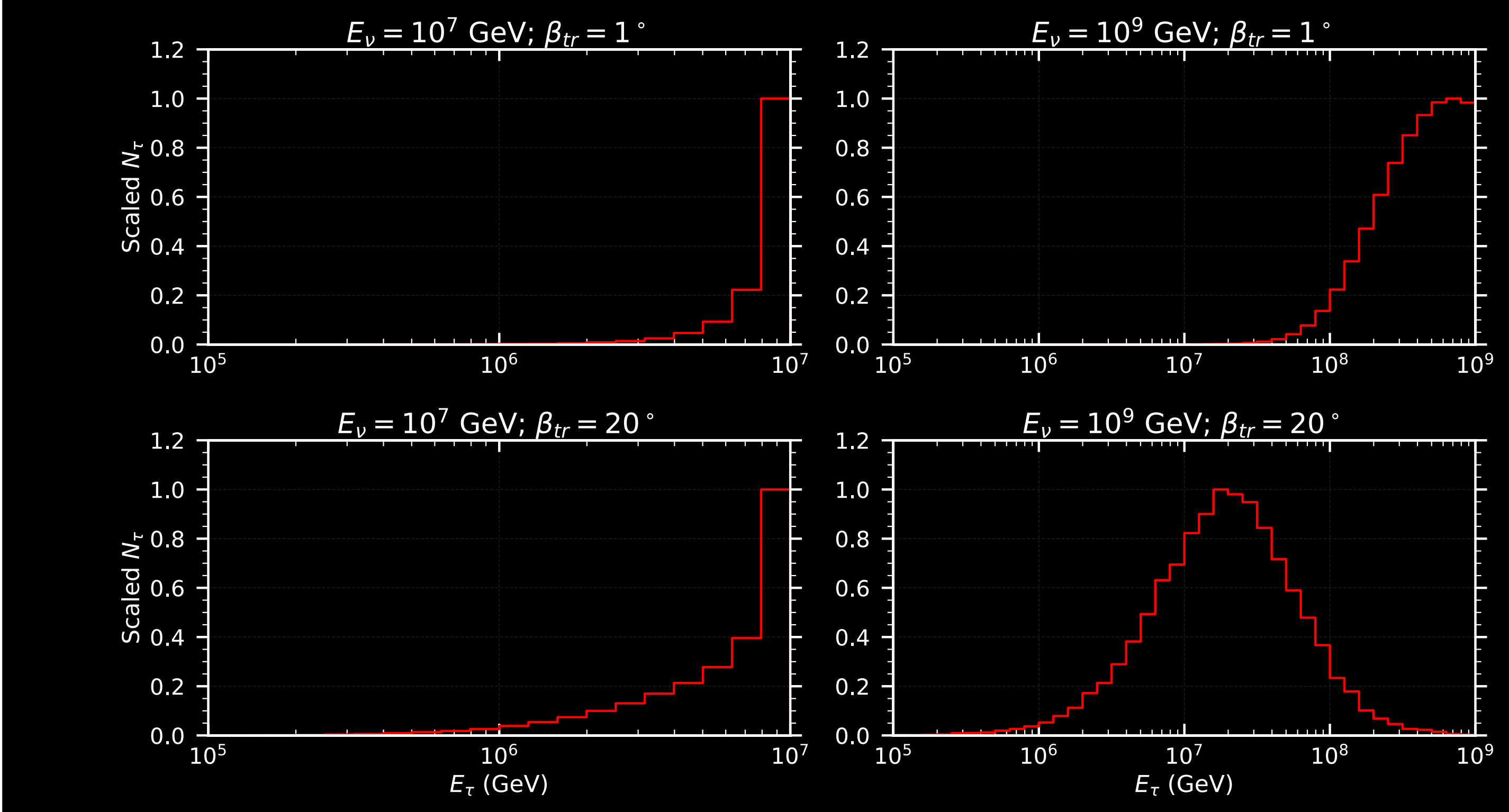
4 Results & Comparisons



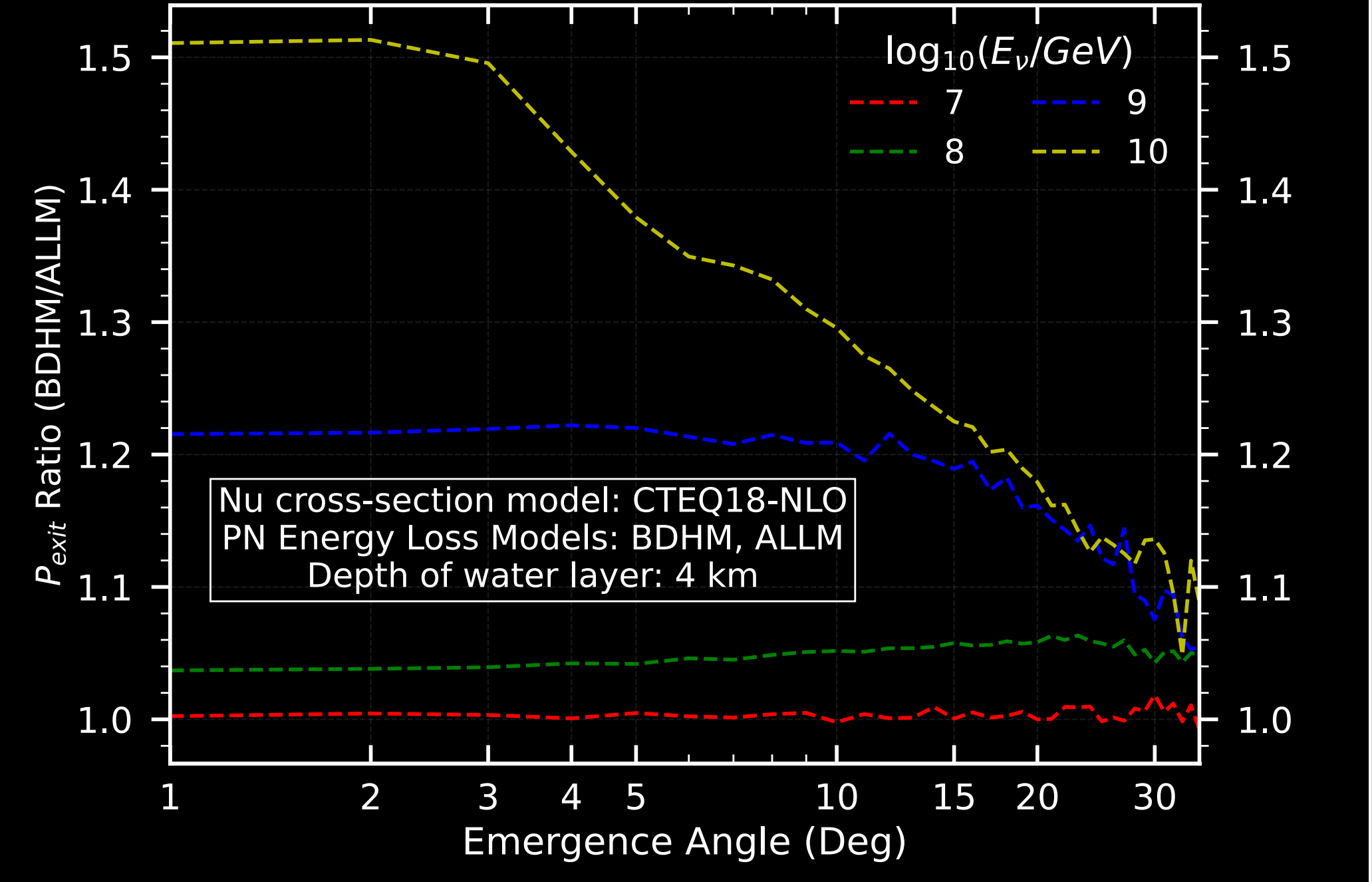
Comparison of Stochastic (solid) & Continuous (dashed) Energy Loss Mechanisms for Exit Probability Vs. Emergence Angles (β_{tr}) using nuPyProp



Comparison of Exit Probability Vs. Emergence Angles (β_{tr}) using NuTauSim[2] & nuPyProp Results, ALLM photonuclear (PN) energy loss



Outgoing Tau Energy Distributions for Select Ingoing Neutrino Energies and Earth Emergence Angles



Comparison of Exit Probability Vs. Emergence Angles (β_{tr}) using nuPyProp Results for BDHM & ALLM Photonuclear Energy (PN) Loss Models

6 Tables

$E_{\nu;\ in}$ (GeV)	Time (hrs)
10^7	0.26
10^8	1.53
10^9	5.08
10^{10}	12.43
10^{11}	12.73

Run times for nuPyProp injected with 10^8 neutrinos for Earth emergence angles from 1° to 35°, with stochastic energy loss and using University of Iowa's Argon cluster with 56 cores.

Module	Model/Type
Earth/Geometry	PREM[6], User Defined
Neutrino/Anti-Neutrino Cross Section	ALLM[1,9], BDHM[4,9], CTEQ18-NLO[7,9], CTW[5], nCTEQ15[9,11], User Defined
Ionization Energy Loss	Bethe-Bloch[8]
Bremmstrahlung Energy Loss	Petrukhin & Shestakov[8,13]
Pair Production Energy Loss	Kokoulin & Petrukhin[8]
Photonuclear Energy Loss [$F_2(x,Q^2)$, except BB]	BB[3,8], ALLM[1,8], BDHM[4], CKMT[10], User Defined
Electromagnetic Energy Loss Mechanisms	Stochastic, Continuous

Different models implemented in nuPyProp

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