GRAND neutrino simulation

Overview and status

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Wednesday 17/05/2017

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Objective

> Build an end to end simulation from **tau neutrinos** (ν_τ) to **digitized data** at input of the high level trigger (**L1**).

Starting with an **U**ltra **H**igh **E**nergy (**UHE**, 100 TeV or more) ν_τ, of cosmic origin, on top of the atmosphere:

1. The ν_τ propagates through the Earth. Some of them reach the detector vicinity.
2. Close to or inside the detector area these ν_τ might be converted to an **UHE** τ which *decays in flight*.
3. Provided that the decay occurs in air, the products initiate an **air shower** whose **radio signal** might be picked up by the antennas of the GRAND radio units.
4. The self-triggering **radio units** transmit a **digitized signal** to a central unit for further processing, e.g. L1 trigger based on coincidences.

The neutrino simulation

> The present presentation concerns the simulation from the primary ν_τ to the τ decay products, i.e. (**1 & 2**). It is referred to as the **neutrino simulation**.

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Flaws of the Preliminary neutrino simulation

1. It is purely 1D. The transverse transport of ν and τ is not simulated.

   > This is OK at extreme energies. But, if one wants to precisely compute the pointing accuracy for astrophysical sources, deflections must be properly simulated.

2. There is no atmosphere. Only ν interactions in Standard Rock are taken into account, *with only isoscalar nuclei target, i.e. no electrons*.

   > Again, this is OK at extreme energies but not accurate enough below 10 PeV.

3. The τ energy loss is parametric and limited to Standard Rock.

   > Fluctuations in the energy loss are partially taken into account by the parametric model, but this is not most accurate.

> It is worth to rewrite the simulation from scratch. Let me develop why in the following.

UHE neutrino interactions

> This is a brief summary. See e.g. Gandhi *et al.* (arXiv:hep-ph/9512364) or J.A. Formaggio and G.P. Zeller (arXiv:1305.7513) for more detailed discussions.

At UHE, neutrinos interact almost exclusively by **D**eep **I**nelastic **S**cattering (**DIS**) on atomic nuclei. The two possible modes are:

- **C**harged **C**urrent (**CC**) with a $W^{\pm}$ exchange, $\nu_\tau N \rightarrow \tau X$.
- **N**eutral **C**urrent (**NC**) with a Z^0 exchange, $\nu_\tau N \rightarrow \nu_\tau X$.

In both cases the target nucleon is broken up. The good news for us is that at UHE the τ or ν_τ product carries on average **75% of the initial ν_τ energy**.

> Close to $\frac{M_W^2}{2m_e} = 6.3\ \mathrm{PeV}$ there is a narrow (Glashow) resonance for $\overline{\nu}_e$ interactions with atomic electrons, e.g. as $\overline{\nu}_e e \rightarrow \overline{\nu}_\tau \tau$ ($\mathrm{BR} = 10.9\%$).

τ decays

- More than half (**65%**) of the **τ decays are hadronic** with mostly $\pi^\pm, \pi^0$ decay products. They carry **70%** on the τ initial energy, on average.

- The remaining decay modes are leptonic, i.e. $\tau \to e\overline{\nu}_e\nu_\tau$ (18%) and $\tau \to \mu\overline{\nu}_\mu\nu_\tau$ (17%). In the later case the UHE μ escapes the atmosphere, or penetrates the ground, before decaying. So there is no air shower.

> Most of τ decays (**83%**) lead to an atmospheric shower, provided that the decay occurs in air. **All** τ decays re-generate a ν_τ. So there is a ν_τ-τ coupled transport. But, on average the daughter ν_τ carries only **30%** of the τ initial energy.

> In addition, in the case of the decay of a τ^- to an electron, a $\overline{\nu}_e$ is also generated. So, in principle it might also re-generate a $\overline{\nu}_\tau\tau$ pair by interacting with atomic electrons.

Software requirements

> We need an accurate yet efficient Monte-Carlo engine for the coupled transport of UHE ν_τ, $\overline{\nu}_e$ and τ, in an extended (~100 km) and detailed outdoor environment. Surprisingly there seem to be **none** suitable for our case?

- Many open source developments for **long baseline experiments**, e.g. GENIE, NUWRO but not geared towards UHE, e.g. limited to TeV energies and rather slow.
- Codes for **neutrino telescopes** (ANTARES, IceCube), *when open source*, seem to be rather specific, e.g. to their geometry.
- For GRAND, we plan to simulate a huge area. The Monte-Carlo needs to be highly optimized. But in a classical simulation most of the simulated ν_τ (> **99.9%**) actually don't lead to (useful) τ decays. In order to be efficient a **biasing** strategy is required.

> An elegant and efficient biasing strategy is to run the Monte-Carlo **backwards**, i.e. starting from the tau decay back to the primary cosmic neutrino. This guarantees that only **useful events** are simulated.

Software strategy

> Write a dedicated yet **modular** neutrino simulation from independent *open source* sub-packages. Subdivise the Monte-Carlo in elementary functionalities that can be run both **forward and backward**.

- **ENT** (https://niess.github.io/ent/), an **E**ngine for high energy **N**eutrinos **T**ransport. It is valid above 100 GeV and it is thread safe.
- **PUMAS** (https://niess.github.io/pumas/, arXiv:1705.05636), **S**emi **A**nalytical **MU**ons -or taus- **P**ropagation, *backwards*. An engine for the transport of relativistic μ and τ. Developed for muography. It is thread safe as well.
- **ALOUETTE** (To be pushed on GitHub), a wrapper for TAUOLA allowing also **backward decays** from a ν_τ.
- **TURTLE** (https://niess.github.io/turtle/), **T**opographic **U**tilities for **R**endering **T**he e**LE**vation. Topographic toolbox supporting world wide models and optimised for the tracking of one or more (multithreaded) Monte-Carlo particle(s). Developed for muography.

> Target the **C** language for portability, simplicity, interoperability and runtime efficiency. Keep dependencies as low as possible.

Integration status

1. **PUMAS**, fully working both forward and backward. **Extensively tested** for muography.

2. **TURTLE**, working and also **extensively tested** for muography. Some *non critical improvements* foreseen, e.g. geoid corrections for the sea level.

3. **ALOUETTE**, in principle working in both forward and backward mode. **Tests ongoing**.

4. **ENT**, working in forward mode. Backward implementation is **ongoing**. *Expected to be complete within 1 month*.

> All packages are working for a classical forward Monte-Carlo. PUMAS, ALOUETTE and ENT have been integrated in a preliminary neutrino simulation : **D**eca**A**yi**N**g **T**aus fr**O**m **N**eutrinos (**DANTON**).

Selected results : ENT

ν differential cross-sections have been implemented following Gandhi *et al.* (arXiv:hep-ph/9512364). For DIS any PDF in lhagrid1 format can be provided at the initialisation of the library.

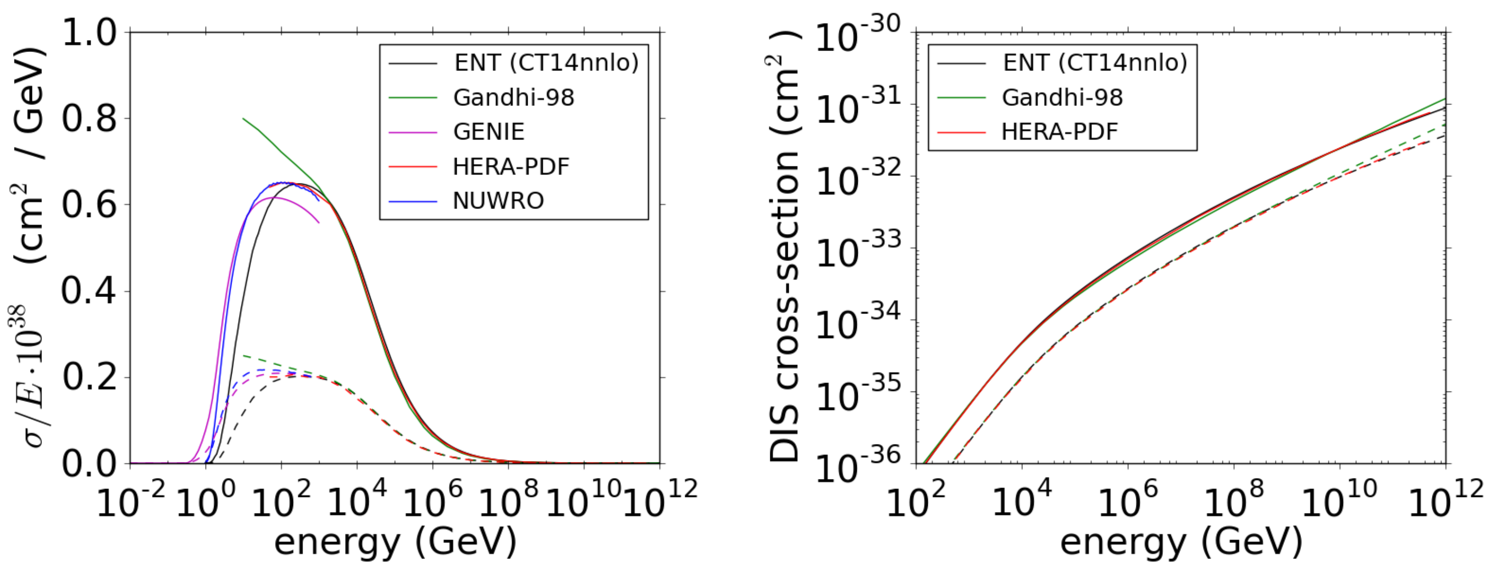

Figure 1 : Comparison of DIS cross-sections for various computations. For ENT the CT14nnlo Parton Distribution Functions have been used. Solid lines stand for CC interactions and dashed lines for NC ones.

Selected results : DANTON

> Real Physics but ideal geometry : a spherical Earth made of Standard Rock and with a core density profile given by the **P**reliminary **R**eference **E**arth **M**odel (**PREM**). The atmosphere is U.S. standard.

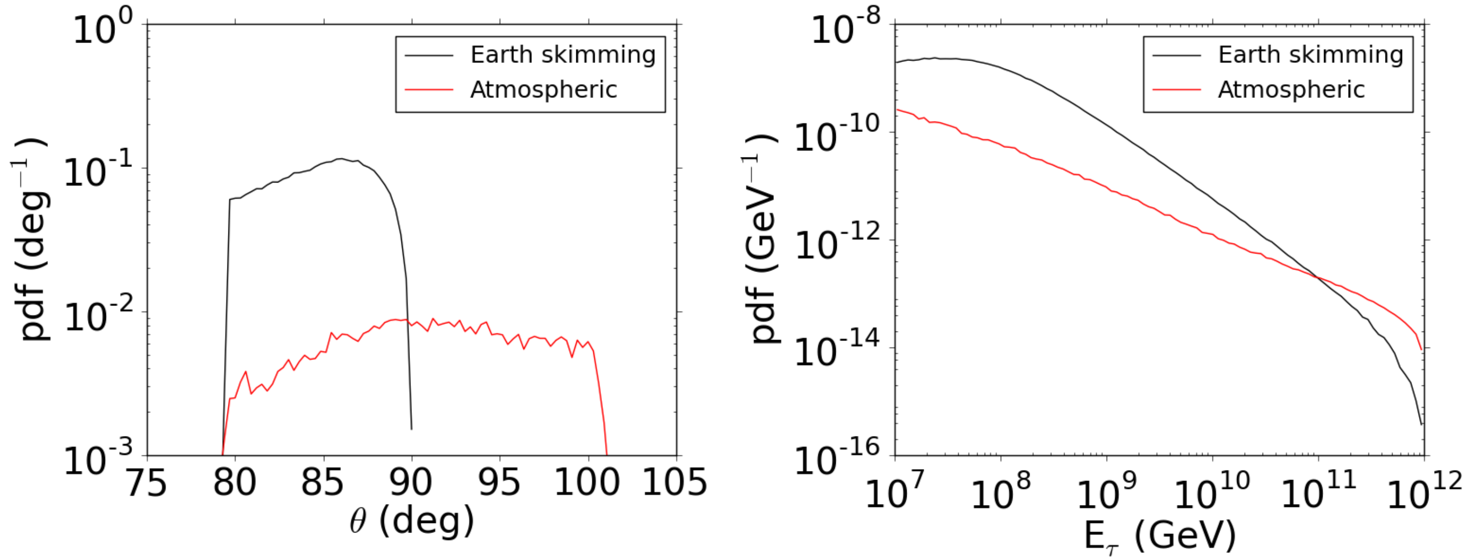

Figure 2 : Statistics of τ decaying in the atmosphere for a $1/E^2$ flux of primary ν_τ with $E \geq 10^{16}$ eV. Left: zenith angle, right: energy. Note that 87% of τ are converted in the ground and 13% have been re-generated.

Timeline

> Quite some work has already been done but still a few more months are needed in order to properly complete the neutrino simulation in backward mode.

1. Finalise the backwardisation of ENT and apply to DANTON. Validate by comparing with the forward results in the case of a spherical Earth (PREM). *1-2 months*.

2. Integrate a detailed topography with TURTLE. *1 week*.

3. Run the neutrino simulation! *Depends?*

   > Producing **1M** atmospheric tau decays in forward MC, for a spherical symmetric Earth and a threshold at 10 PeV, requires to simulate **1G** neutrinos. The corresponding CPU cost is 8.2 kHS06.h. This is 0.7% of our annual budget at CC-IN2P3 but only 1 / 100,000 of ATLAS one.

Outlook

> Using the same packages (ALOUETTE, ENT, PUMAS and TURTLE), in backward Monte-Carlo mode, other interesting Physics scenarii could be investigated. For example:

- **Radio transition radiation** from ν interaction or τ decays in rocks, close to an air boundary. *Straightforward with backward Monte-Carlo*.

- Check the sensitivity at lower energies, especially for $\overline{\nu}_e$ close to the **Glashow resonance**.