Introduction

- Gamma Ray Bursts (GRBs) together with Active Galactic Nuclei (AGN) are the most energetic phenomena in the Universe and they are among the leading candidates for the sources of ultra-high energy cosmic rays.
- Hadronic accelerations in these objects would imply jet fluxes.
- Neutrinos can travel straight through the Universe without deflection by magnetic fields (unlike cosmic rays) nor absorption by dust (unlike photons).
- Currently, neutrino telescopes have the sensitivity to observe such astrophysical neutrinos.
- Due to the low event rate, robust statistical methods are needed to achieve the necessary significance for signal discovery.
- Neutrinos are expected during three phases: precursor (before the γ emission), prompt (during the γ emission) and afterglow.
- Long (≥2 s) and Short (<2 s) GRBs are believed to originate from different progenitors. LGRBs could be related to the explosion of very massive stars whereas SGRBs could originate from mergers of binary compact objects.
- A separate LGRB/SGRB analysis allows the use of specific statistical methods in order to increase the sensitivity of the analysis.

Long GRBs

- Several statistical methods were compared using a toy-model simulation.
- Use of 491 LGRBs detected by satellites (time, position, angular uncertainty, redshift).
- Generate 3 mHz of atmospheric neutrino background events uniformly distributed over the Northern Hemisphere and in time.
- Angle between events and GRBs simulated as Gaussian taking into account the GRB position uncertainty and the angular resolution of the track reconstruction.
- Prompt signal events follow a flat distribution during T90 with Gaussian tails.
- Precursor events are generated 2 minutes before the GRB trigger time at the source (the redshift effect is taken into account).
- Auto-Correlation:
  - The method generates a distribution with the time differences of all event pairs.
  - The distribution is binned and the probability of a certain number of entries per bin is computed and compared between data and background.
- Likelihood:
  - Defines a test statistic as
  \[ T = \sum_{i=1}^{N} \left( n_i - E_i \right) \left( \ln \left( \frac{n_i}{E_i} \right) + \frac{E_i}{n_i} - 1 \right) \]
  with S and B the signal and background PDFs and \( n_i \) the expected number of signal (background) neutrinos.
- PLT:
  - This method considers the signal as a perturbation of the background.
  - As in the Likelihood case it uses signal and background PDFs but the maximisation is performed as a function of the perturbation location.
  - A hybrid method using Likelihood and the Auto-Correlation was also considered and it gives promising results.

Short GRBs

- First dedicated search for neutrinos from Short GRBs.
- Two statistical methods were compared.
- In both cases, events are selected in an angular window around the GRB which takes into account the uncertainty of the GRB position and the event reconstruction.
- Cut and Count:
  - Select events on a 4 s time window around the GRB trigger time.
  - Use Poisson statistics to assess the significance.
- Erlang distribution:
  - The Erlang distribution gives the probability of having a time \( \Delta t \) to contain \( n \) events (in this analysis \( n = 2 \)).
  - From the time differences between observed consecutive events, the \( \Delta t \) distribution to contain 2 consecutive events in the interval is constructed.
  - This distribution is compared to the expected Erlang distribution using a \( \chi^2 \) test-statistic.
  - The Cut and Count method has a better sensitivity for prompt neutrinos but it is not sensitive to the other phases.
  - In order to be sensitive to the three neutrinos phases, the use of the Erlang distribution is preferred.
  - The event selection involves a Boosted Decision Tree (BDT) algorithm that allows an efficient background and signal separation.
- The sensitivity is presented as a function of the BDT score in order to define the optimal cut value.

Results for a time window of 1h and an angular window of 15° (3° for A-C).

We expect that the optimisation of the statistical methods both for long and short GRBs combined with a more efficient event selection can result in a neutrino detection in relation with a GRB or in stringent upper-limits on the neutrino flux.

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