Constructing a Muon Veto System for Mini-HALO Neutrino Detector

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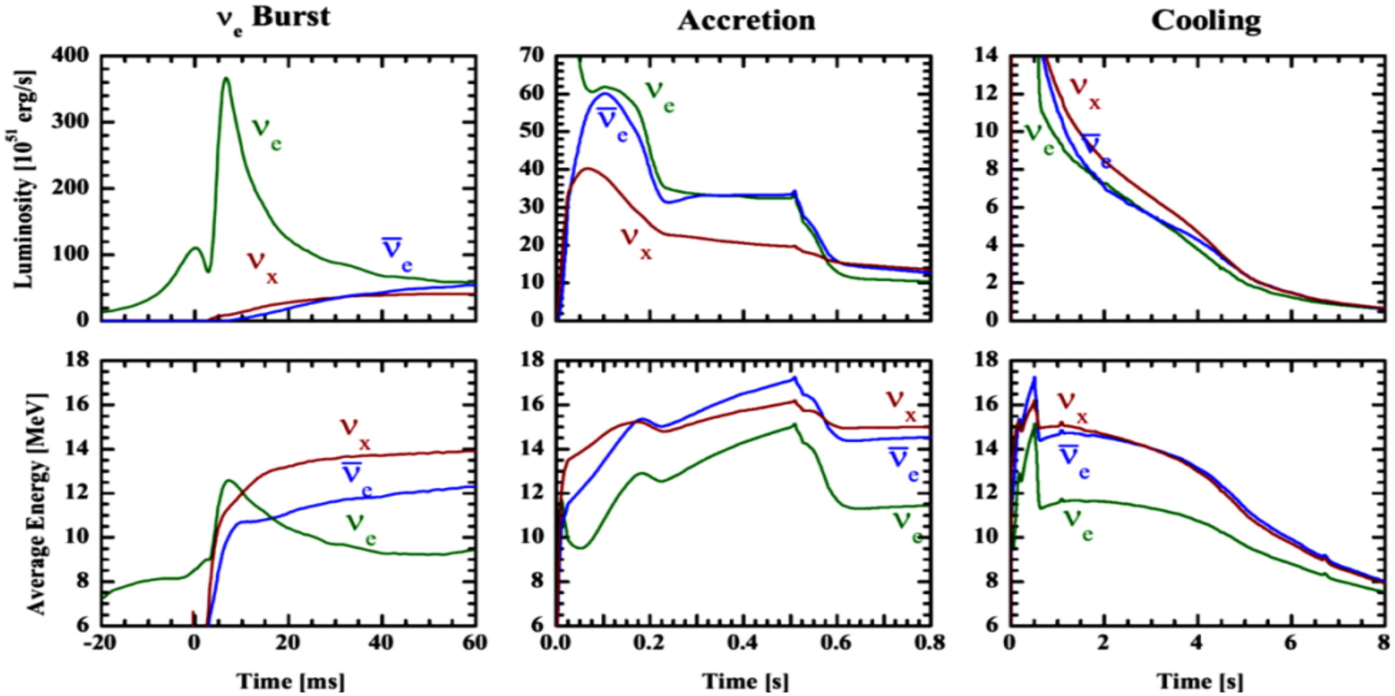
Neutrino Emission from CCSNe



Credit: Fenpeng An et al. (Feb., 2016)

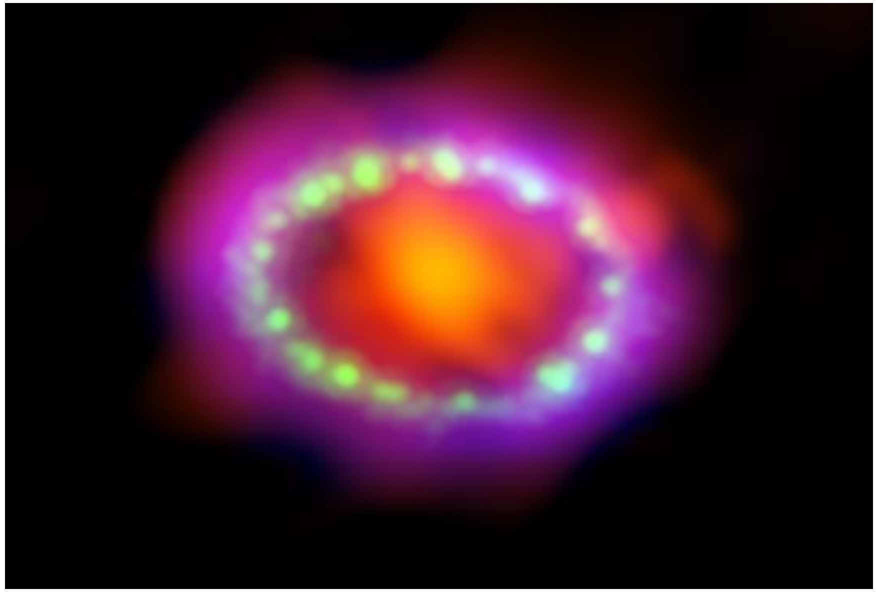


Image credit: NASA

- About 99% of the supernova explosion energy is emitted in the form of neutrinos.

- The initial electron neutrino burst happens few seconds before the final explosion and can alert astronomers on Earth before the explosion takes place (SNEWS and SNEWS 2.0).

- The complete mechanism of core-collapse supernovae explosion is not well understood and so by observing neutrinos from supernova, we can learn about several other phenomena in physics such as black hole formation, nucleosynthesis of heavy elements, etc.

- One of the ways to observe the neutrinos at supernova energy scale is through lead-based neutrino detectors such as HALO-1kT that will consist of 1000 tonnes of lead.

HALO-1kT Supernova Neutrino Detector

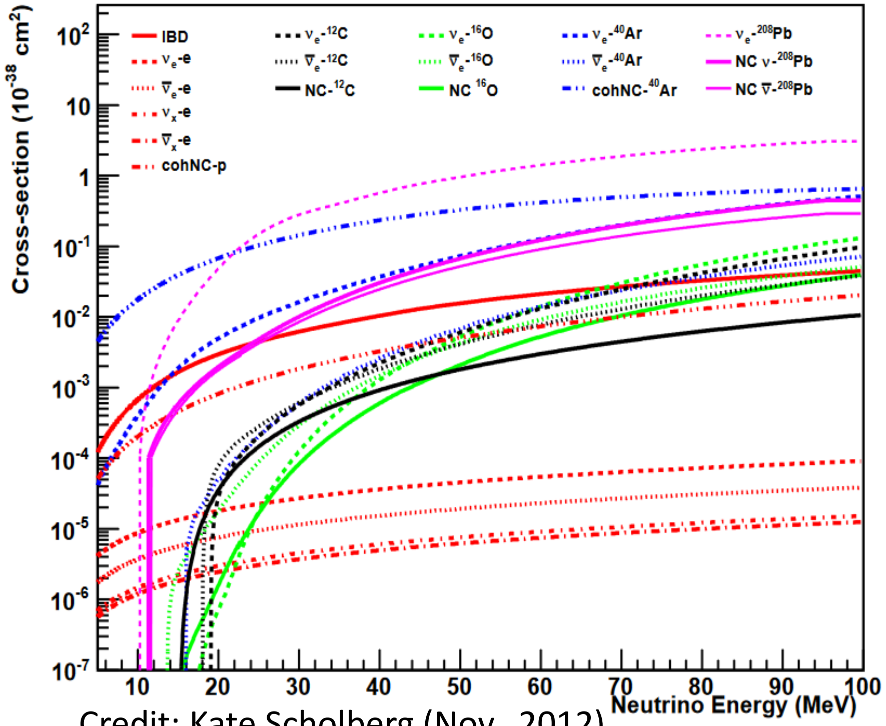
$$\mathrm{CC:}\quad \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^- - 10.3\,\mathrm{MeV}$$

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^- - 18.4\,\mathrm{MeV}$$

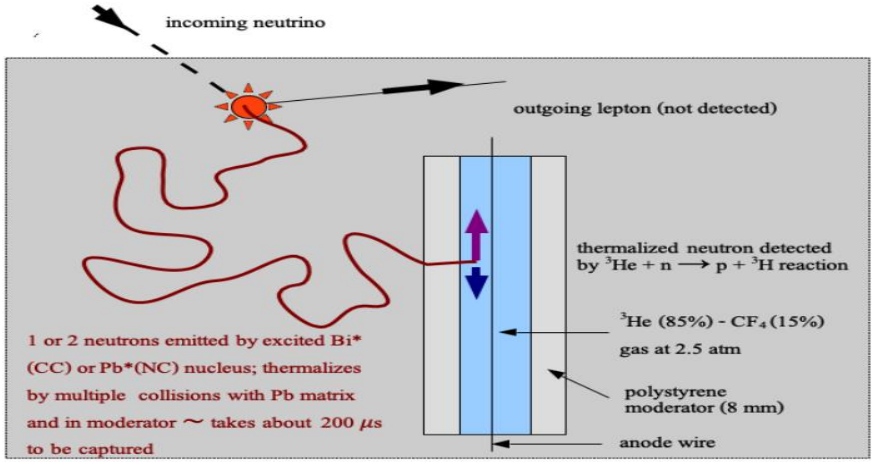
$$\mathrm{NC:}\quad \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n - 7.4\,\mathrm{MeV}$$

$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n - 14.1\,\mathrm{MeV}$$

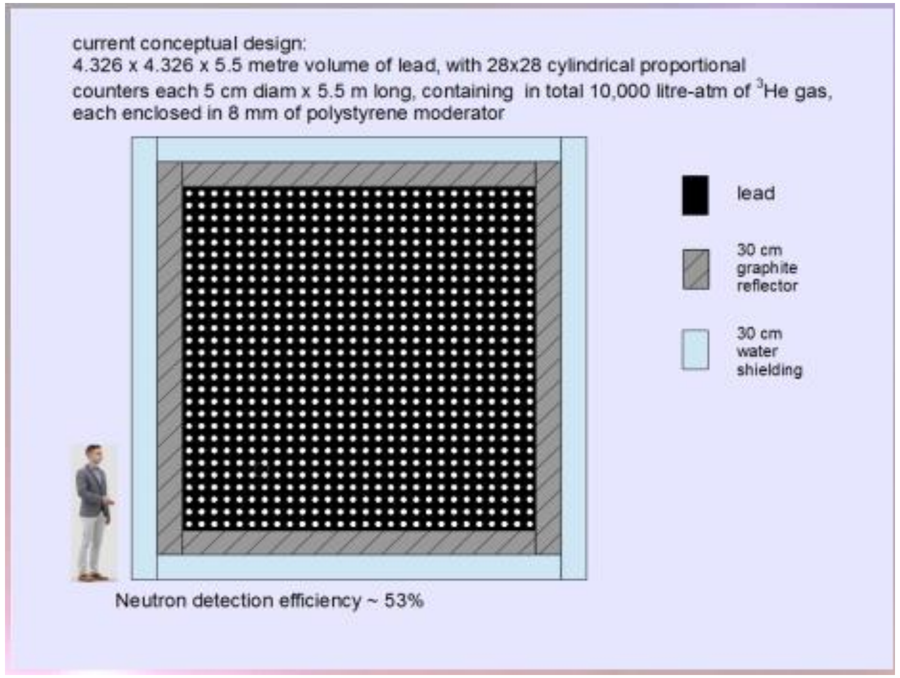
- Proposed HALO-1kT is an upgrade of the HALO supernova neutrino detector present at SNOLAB.
- Will contain approximately 1000 tonnes of lead and therefore, will have a higher neutrino interaction rate than HALO for supernovae.



Credit: Kate Scholberg (Nov., 2012)



1 or 2 neutrons emitted by excited Bi* (CC) or Pb*(NC) nucleus; thermalizes by multiple collisions with Pb matrix and in moderator ~ takes about 200 μs to be captured



current conceptual design:
4.326 x 4.326 x 5.5 metre volume of lead, with 28x28 cylindrical proportional counters each 5 cm diam x 5.5 m long, containing in total 10,000 litre-atm of ^{3}He gas, each enclosed in 8 mm of polystyrene moderator

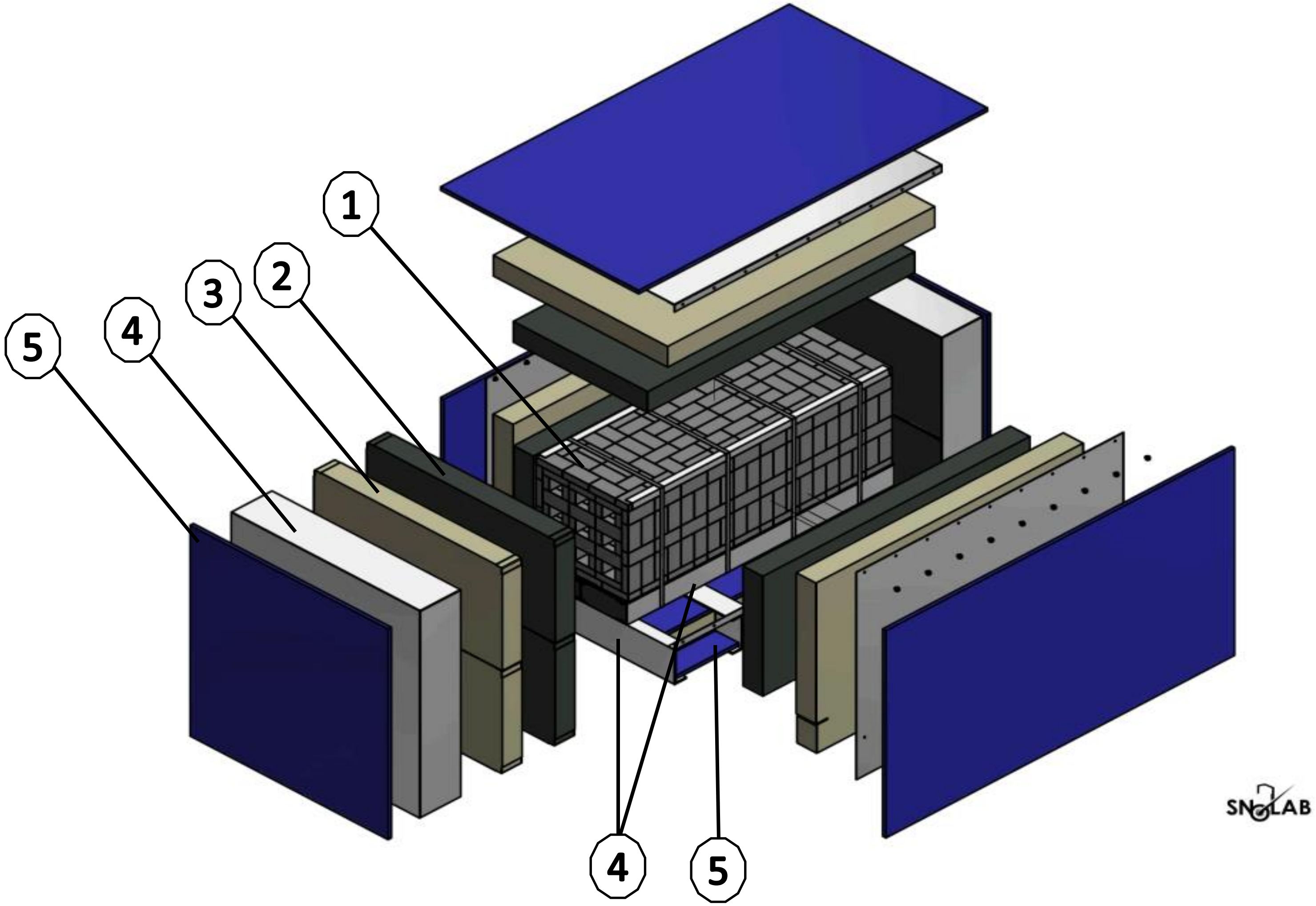
Neutron detection efficiency ~ 53%

- **The ν-Pb cross-sections, which will determine the number of neutrons produced in HALO-1kT by supernova neutrinos, have not been measured.**
- **Furthermore, for the large-scale HALO-1kT detector to be feasible we need to develop very low background He-3 counters that will be used to detect neutrons from supernova neutrinos.**
- **A small prototype detector based on the same design and principles as HALO-1kT is proposed to study the ν-Pb cross-sections and build very low background neutron counters.**

Mini-HALO Test Facility for Boosting HALO-1kT's Detection Capabilities

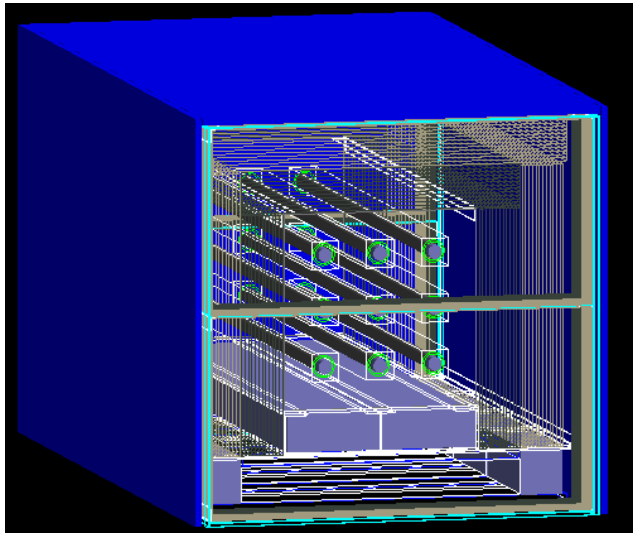
1. 800 lead bricks weighing approximately 10 tonnes that will contain nine He-3 Counters.
2. 6'' thick graphite layer to serve as a neutron reflector.
3. 6'' thick layer composed of HDPE and borated PE to shield from external neutrons.
4. Aluminum support structure to hold together all the materials in the detector.
5. 1'' thick polyvinyltoluene polymer based plastic scintillators that will serve as the muon veto system.

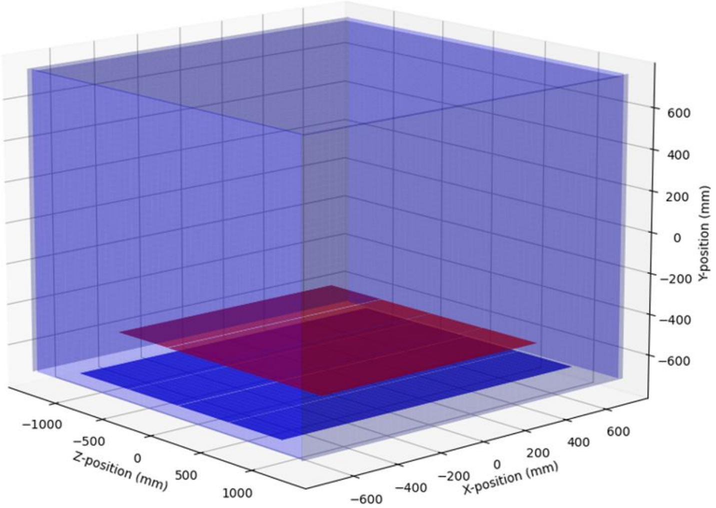
- **Main objective is to obtain highly accurate neutrino-lead cross section measurements at ORNL's SNS facility using pulsed neutrinos from muon decay at rest.**
- **All Background sources must be considered including cosmic ray muons that can mimic the signals produced by neutrinos.**

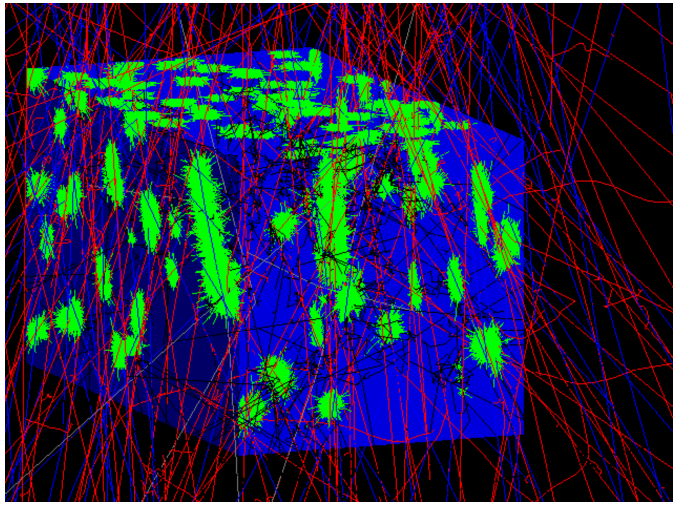


Muon Veto Simulations in Geant4

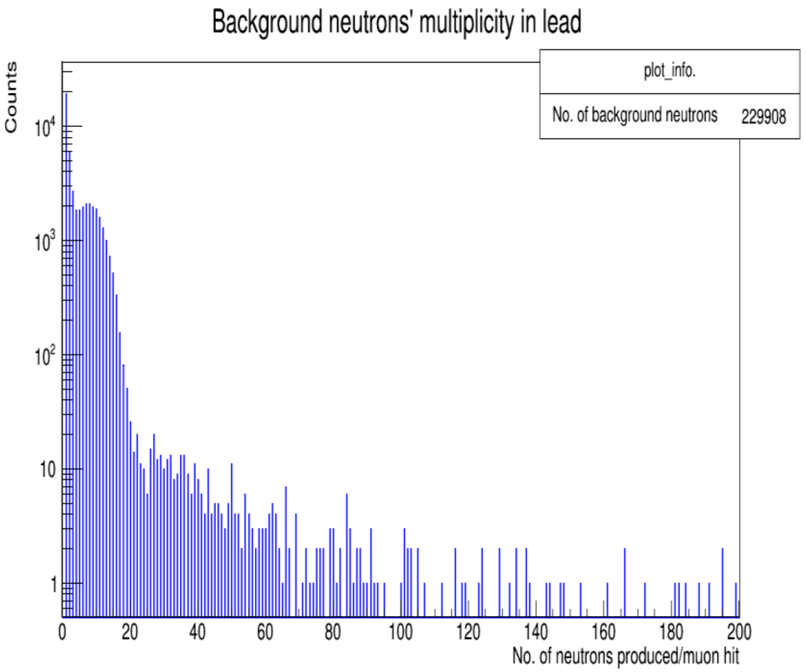
- In order to determine an optimized geometry configuration of the muon veto system, a Geant4 code for the Mini-HALO has been developed.
- Muons interacting with lead are captured by lead atoms producing neutrons and thus, can mimic the signal that we would expect from neutrinos.
- By determining the time difference between the muon hit and background triton being produced, we can veto the background events.
- Furthermore, by studying multiplicities of background neutrons and tritons, we can also differentiate between muon induced event and neutrino induced event.

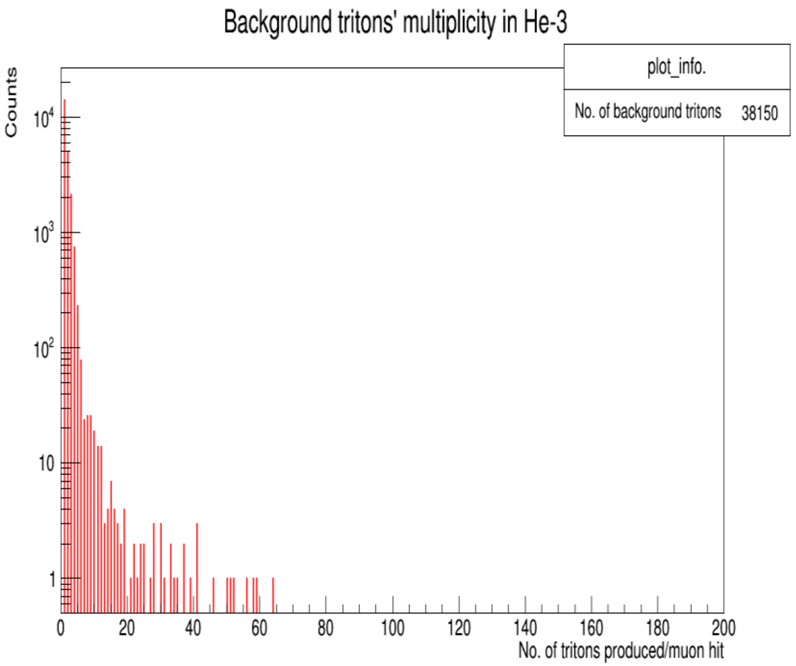


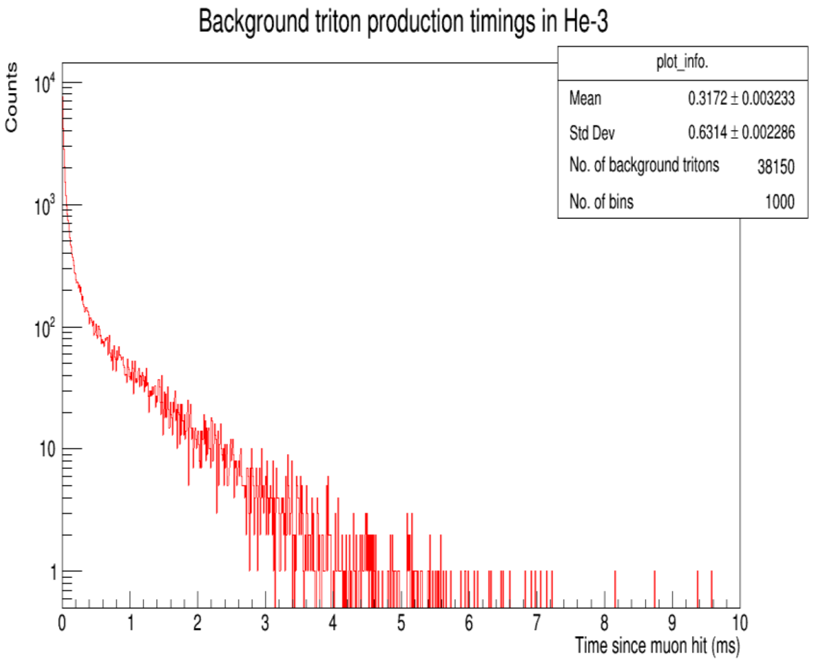




Determining Detector Dead Time and Background Multiplicities





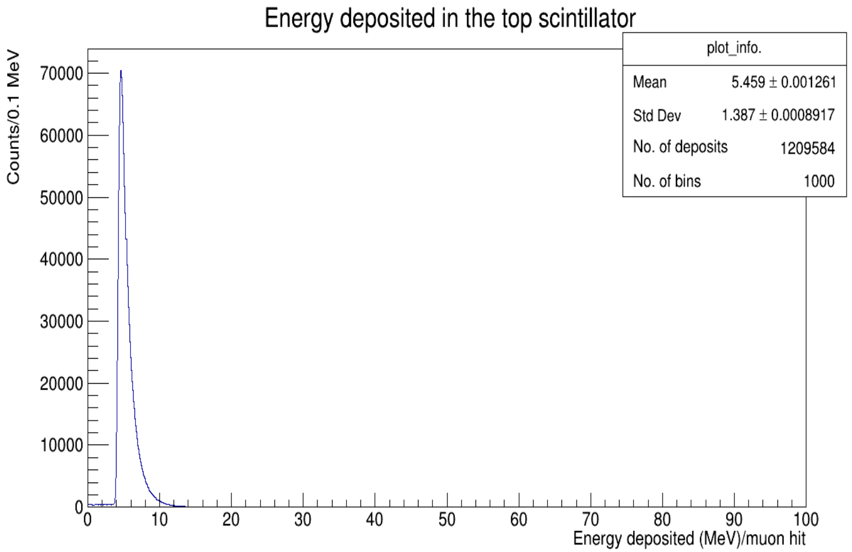


Recall that neutron multiplicity from a neutrino event can only go up to 2 neutrons per event;

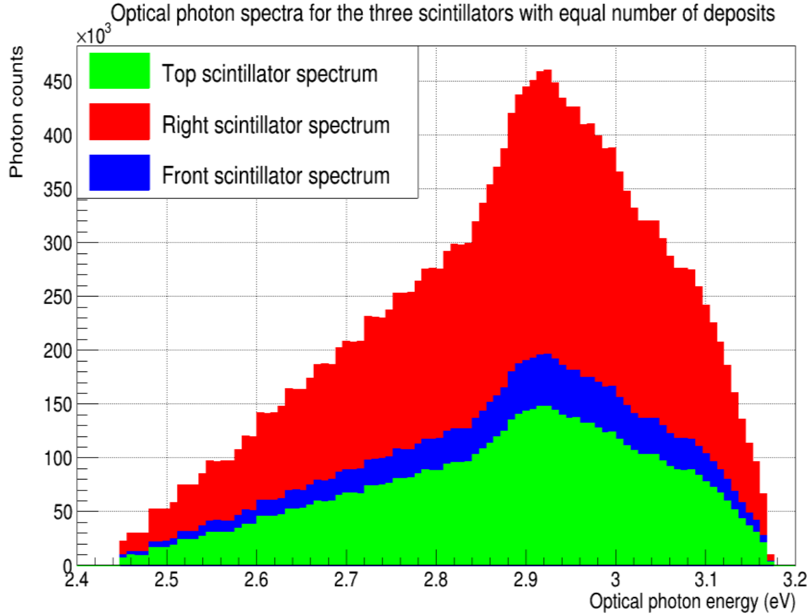
$$
\begin{aligned}
\mathrm{CC:}\quad & \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^- - 10.3\,\mathrm{MeV} \\
& \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^- - 18.4\,\mathrm{MeV} \\
\mathrm{NC:}\quad & \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n - 7.4\,\mathrm{MeV} \\
& \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n - 14.1\,\mathrm{MeV}
\end{aligned}
$$

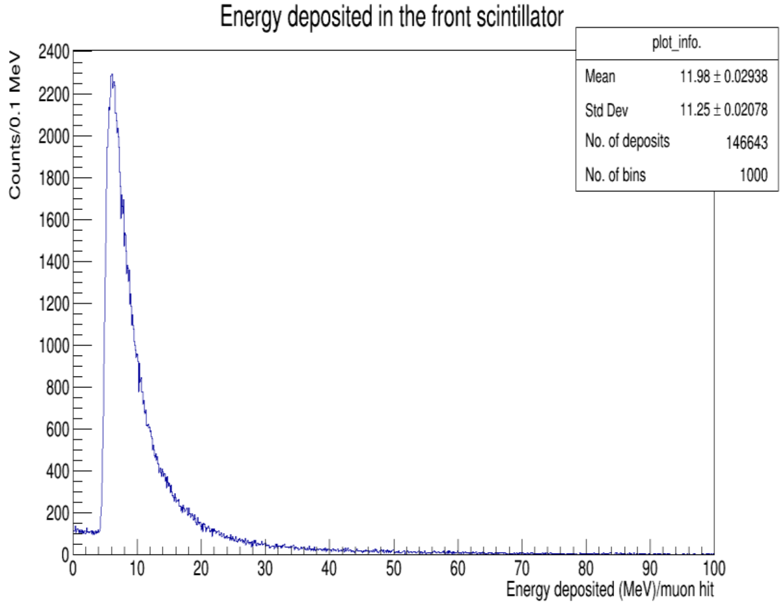
- Detector exposure to cosmic muons shows that the detector dead time is approximately 10 ms.
- Considering the cosmic muon flux at 8 m.w.e depth, we have about a 91 percent live time to detect neutrino events.

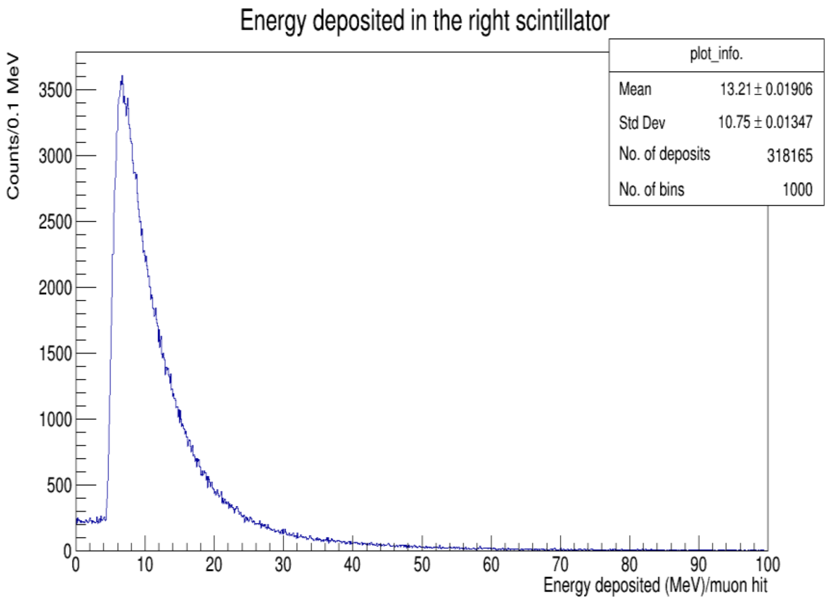
Scintillator Simulation to Determine an Optimized Geometry for the Muon Veto System



- The energy deposited by muons in scintillators on each side shows that the top scintillator has a lower average energy deposit than the scintillators on the sides.
- The muons hitting the side scintillators come at an angle and traverse more distance than the muons coming from the top.







- The number of optical photons generated shows that the highest photon yield is for the side scintillators that have higher average energy deposit.
- This optical photon spectra for the scintillators will be used along with the scintillators' surface properties and Q.E. of PMTs to determine an ideal placement for the PMTs around the scintillators to collect maximum number of photons.

Conclusions and Future Work

- The cosmic muon simulations for Mini-HALO shows that a muon takes about 0.3 ms on average to generate a background triton and the production time can go up to 10 ms.

- Based on this, we have a detector dead time of 10 ms and so from the expected muon flux hitting Mini-HALO, the estimated live time of the detector is about 91 percent.

- Furthermore, the neutron multiplicities for many background events can go higher than 2 neutrons and are thus a clear indication of muon induced events that can be vetoed.

- The average energies deposited in scintillators is about 5.5 MeV by muons that hit vertically and about 12.5 MeV by muons that hit at an angle, giving a much higher optical photon count for scintillators that are hit by muons at an angle.

- Based on this information and by including the surface properties of the scintillators and the quantum efficiency of the PMTs in the simulation, an optimal configuration for the scintillators will be determined that can collect the maximum number of photons generated by cosmic muons.

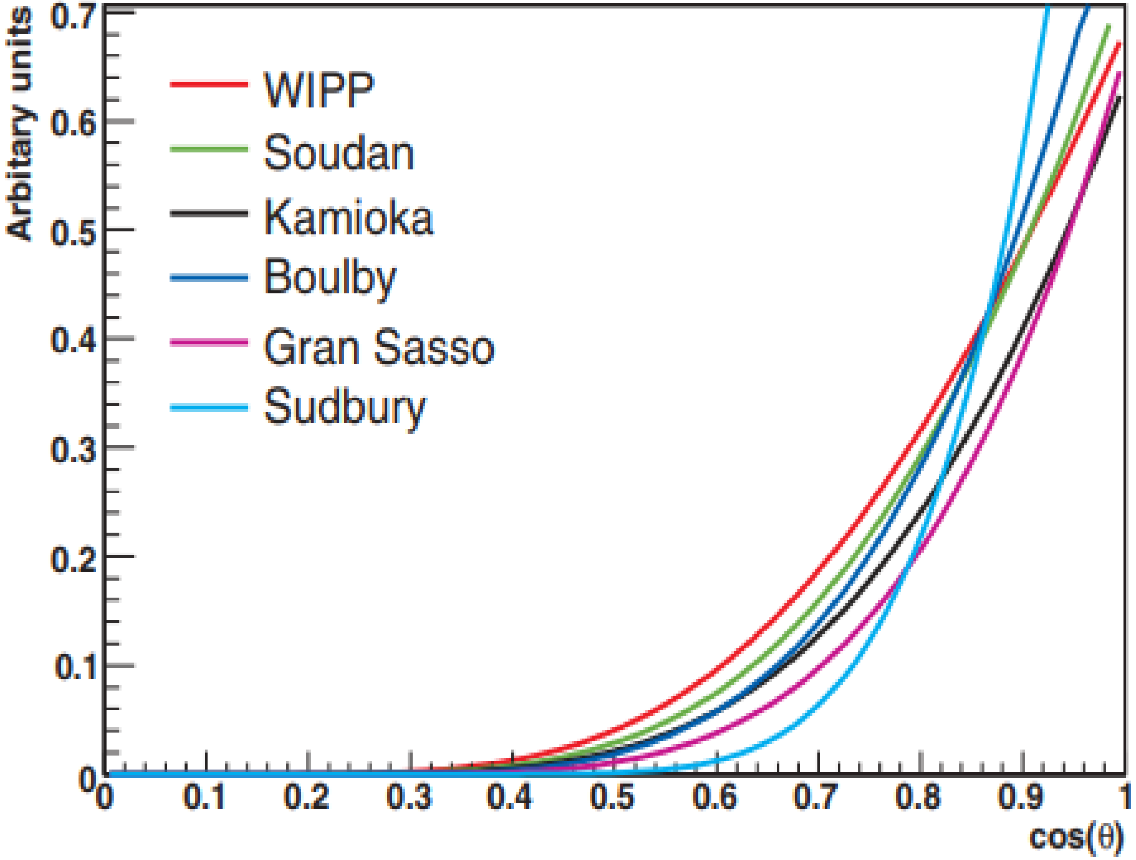
Collaborating institutions

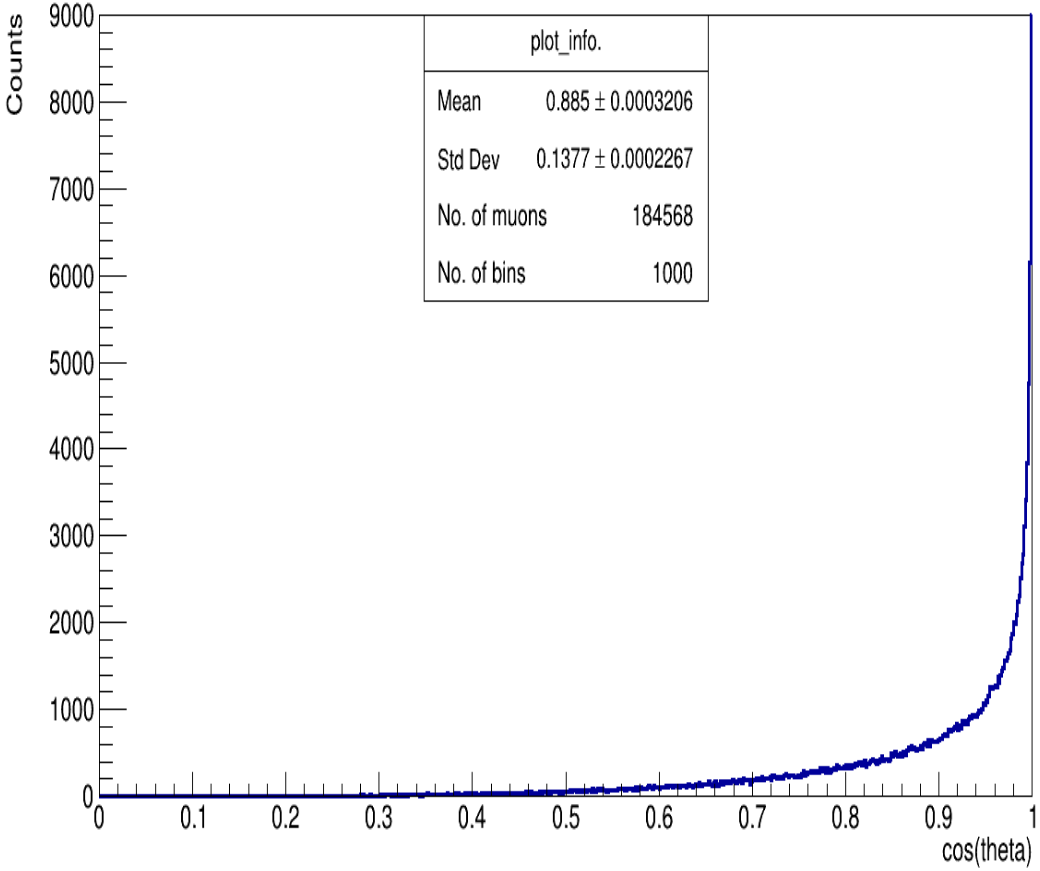
SNOLAB, Laurentian U., McDonald Institute, British Columbia Institute of Technology, U. British Columbia-Kelowna, Duke U., Fermilab, Gonzaga U., INFN-LNGS, INFN-OATA, INFN-sez Torino, Armstrong State U., U. Minnesota Duluth, McMaster U., U. Nacional Autonoma de Mexico, U. North Carolina, Oak Ridge National Laboratory, U. Regina, Simon Fraser U., TRIUMF, TORINO U., Wittenberg U., U. Washington,, Pacific Northwest National Laboratory.

Thank You!

Questions?

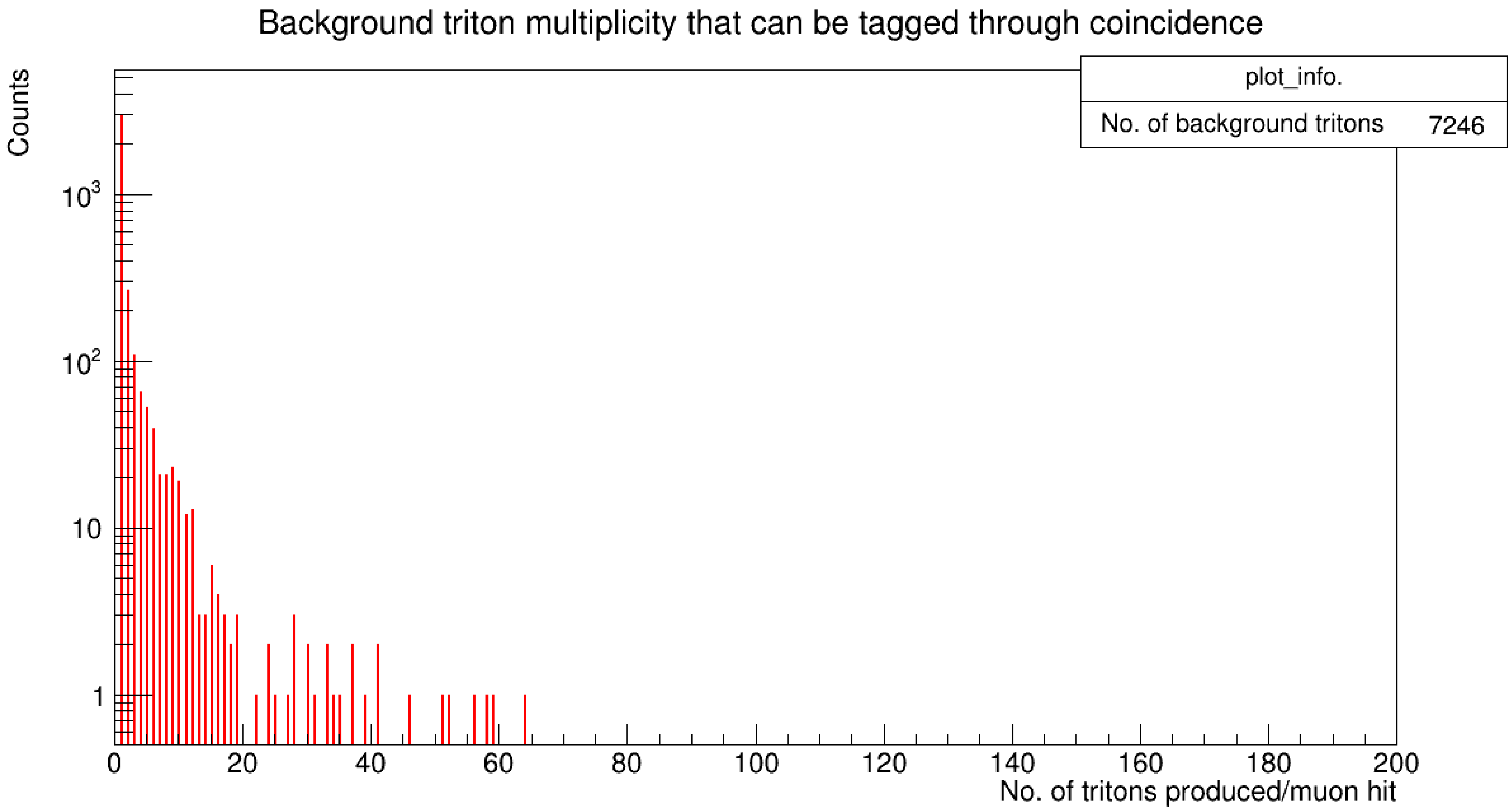
Comparing previously studied angular distribution of muons in underground laboratories with the simulation.



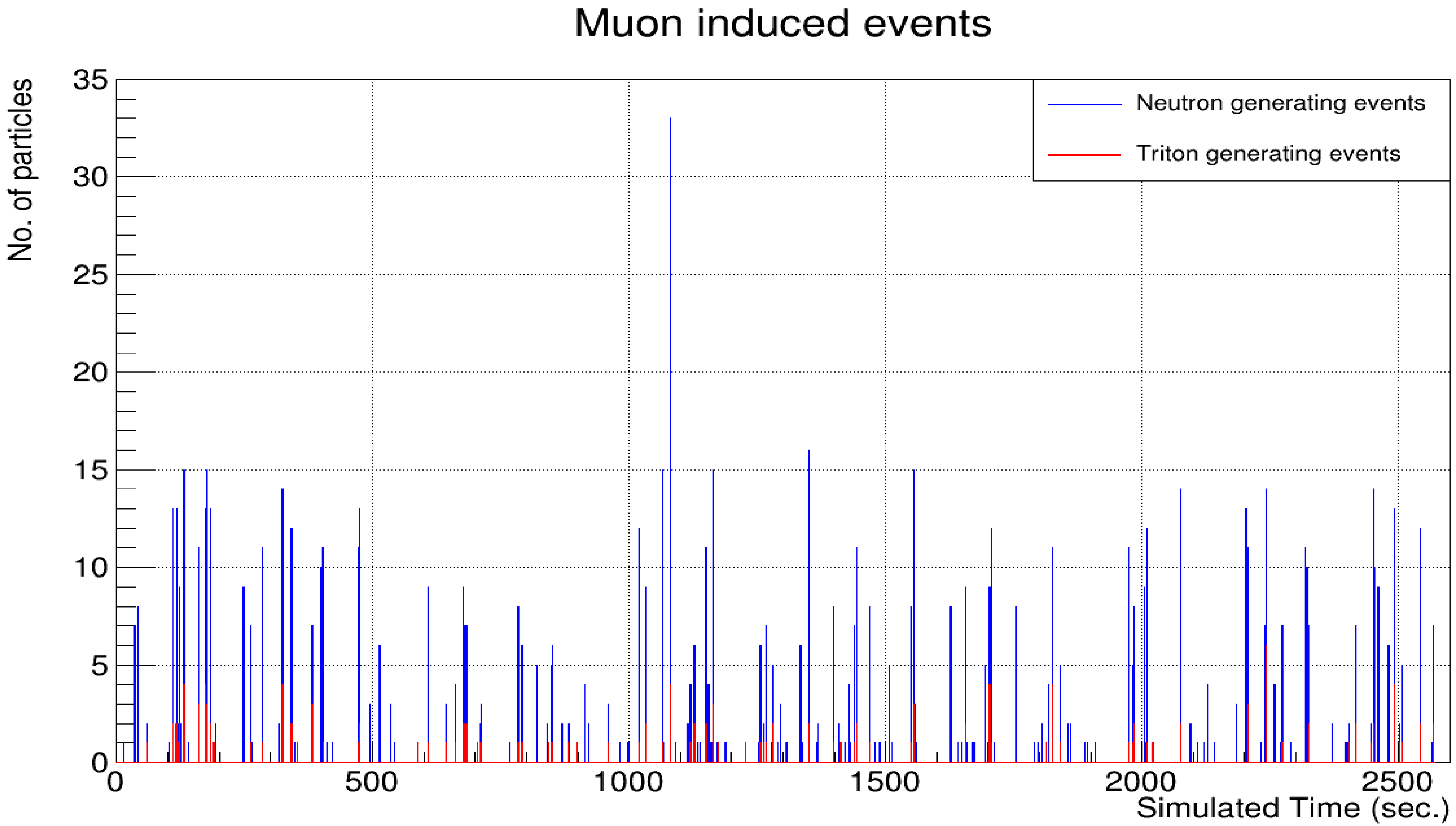


Credit: Mei and Hime (March, 2006)

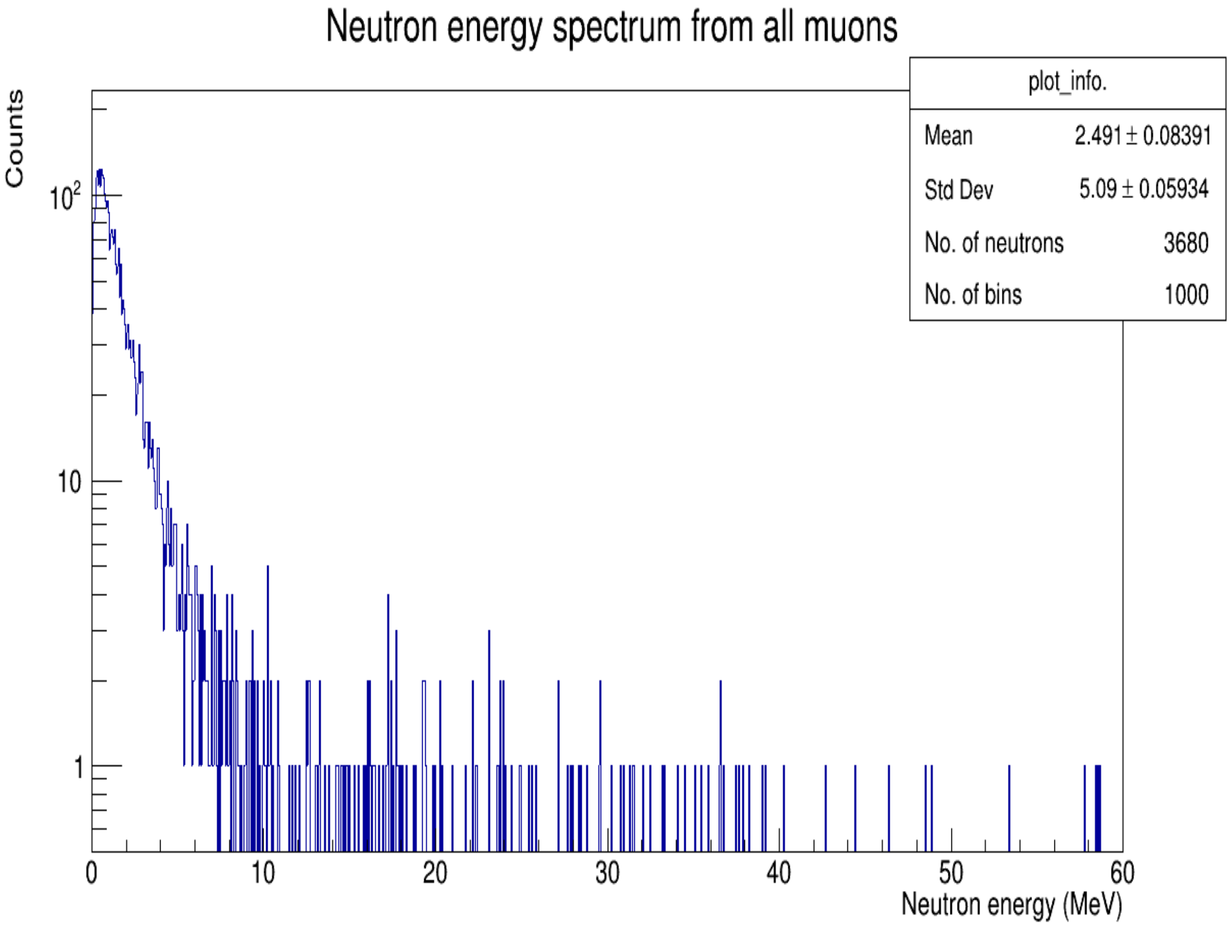
Triton multiplicity tagged from coincidence



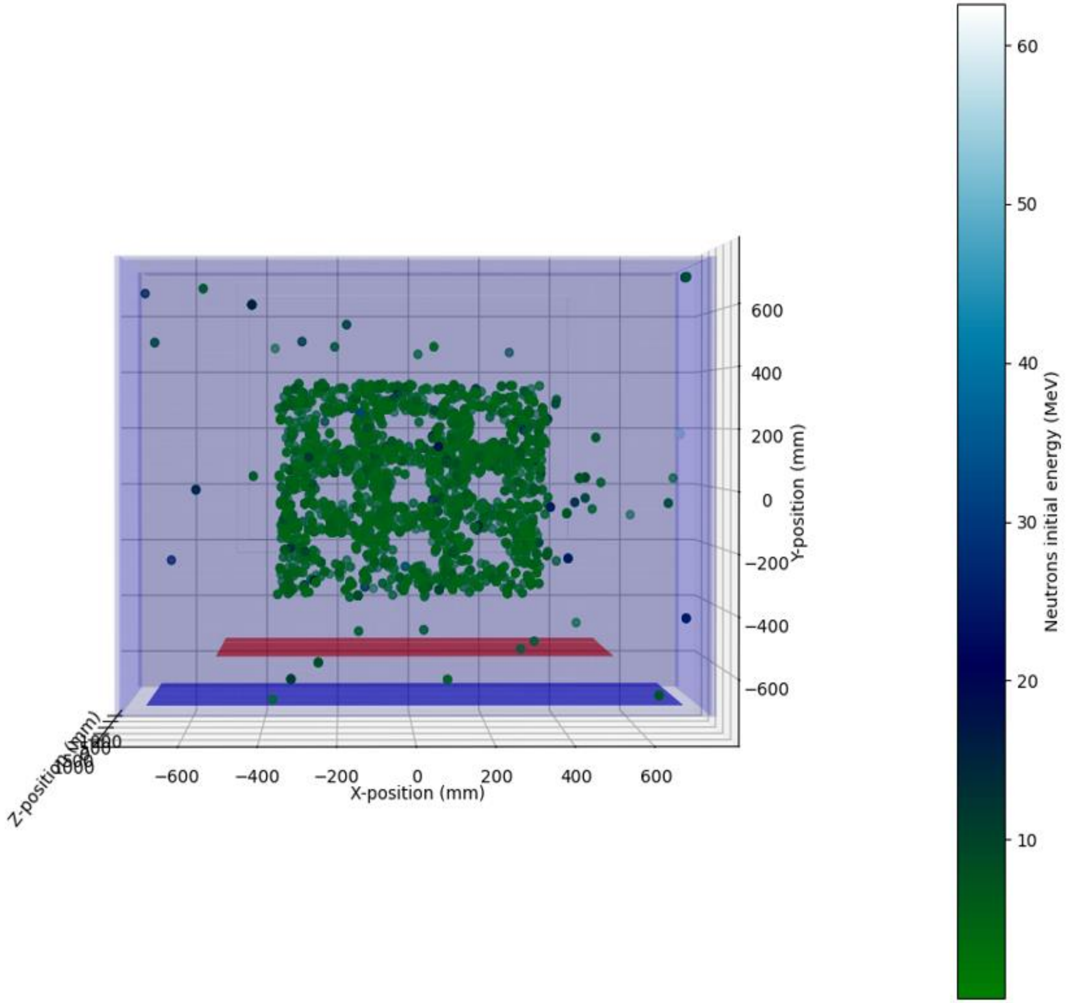
Background Events vs Exposure Time

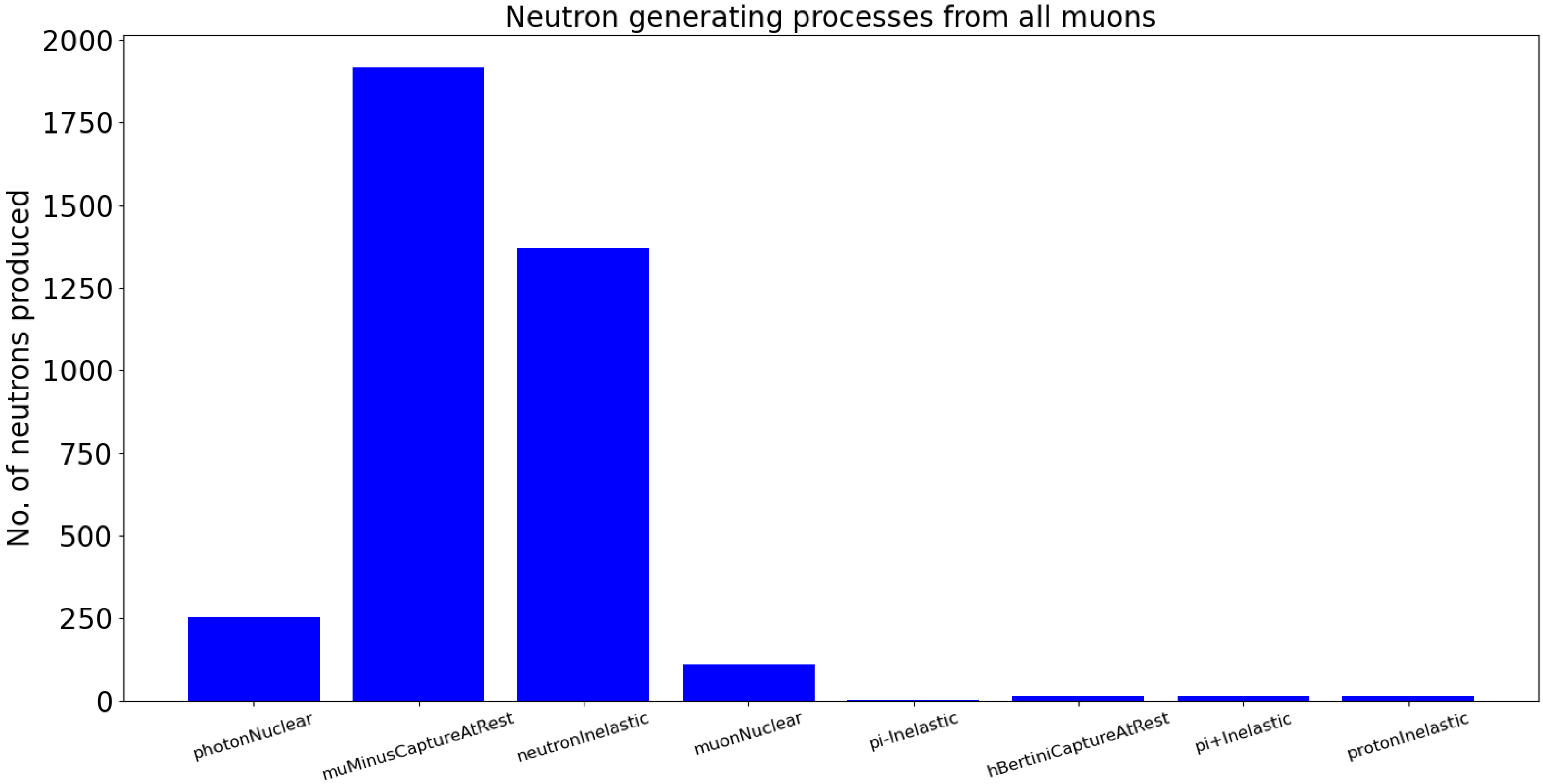


Neutrons Produced by Cosmic Muons in Mini-HALO

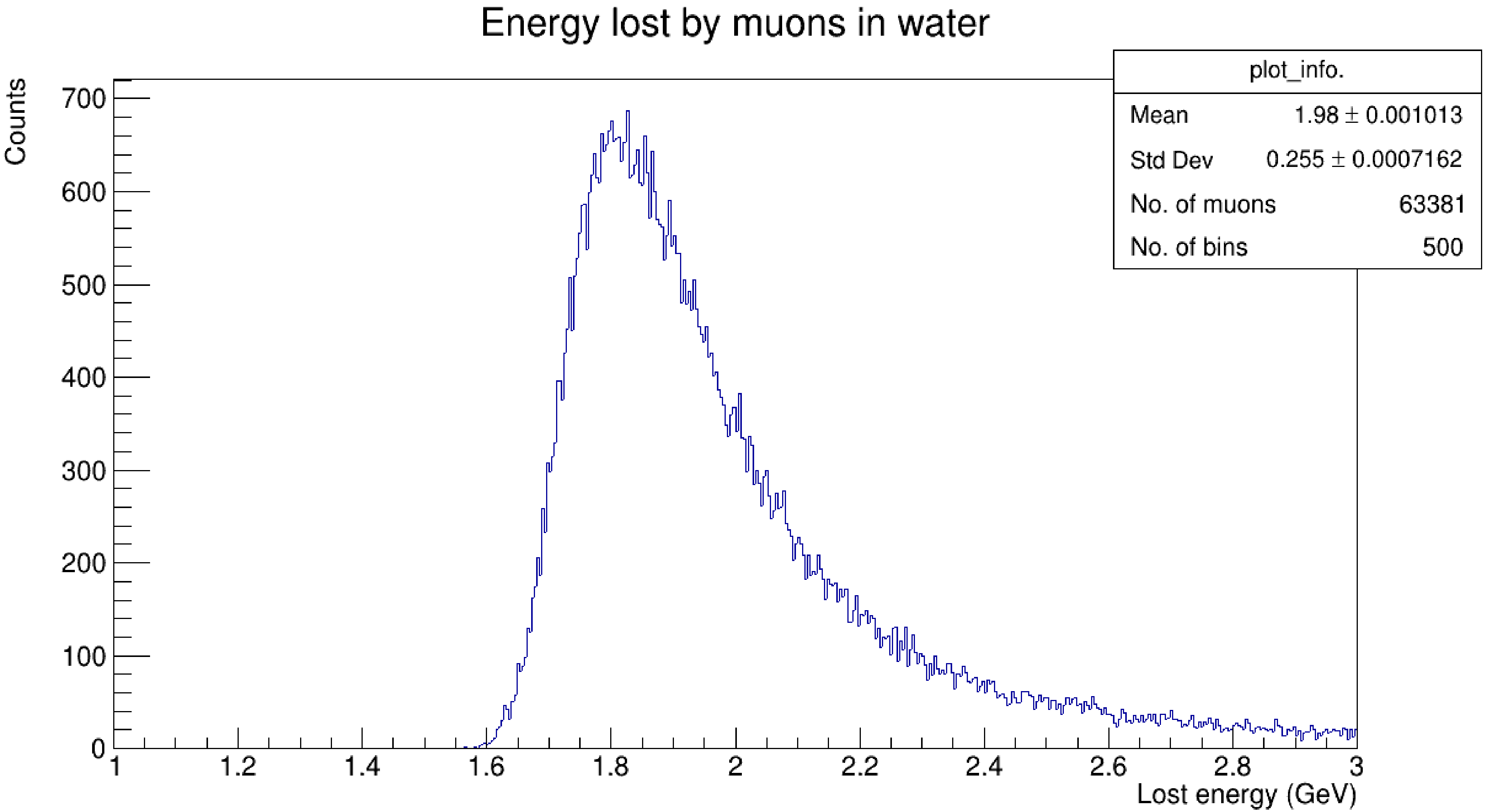


plot_info.	
Mean	2.491 ± 0.08391
Std Dev	5.09 ± 0.05934
No. of neutrons	3680
No. of bins	1000

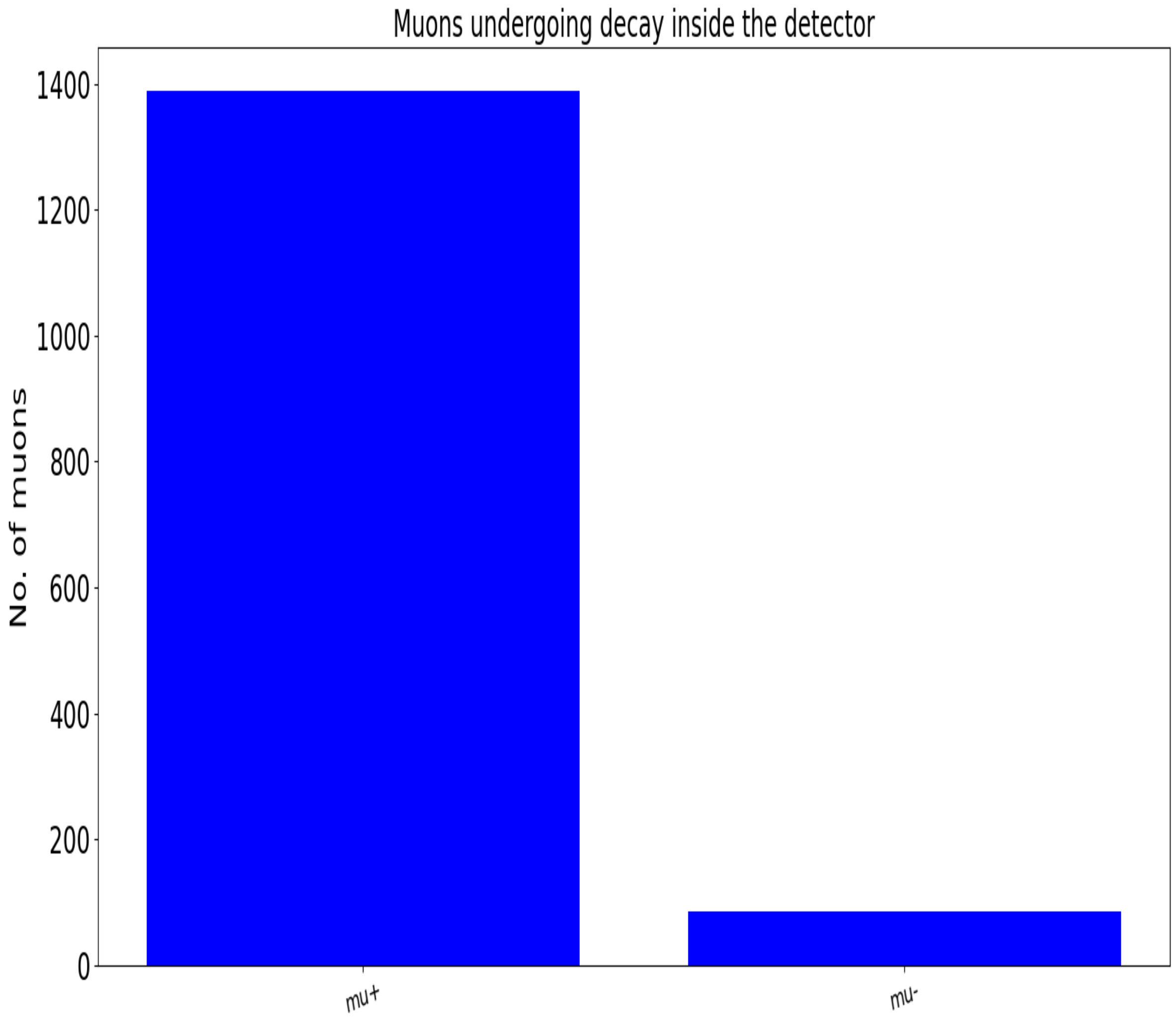


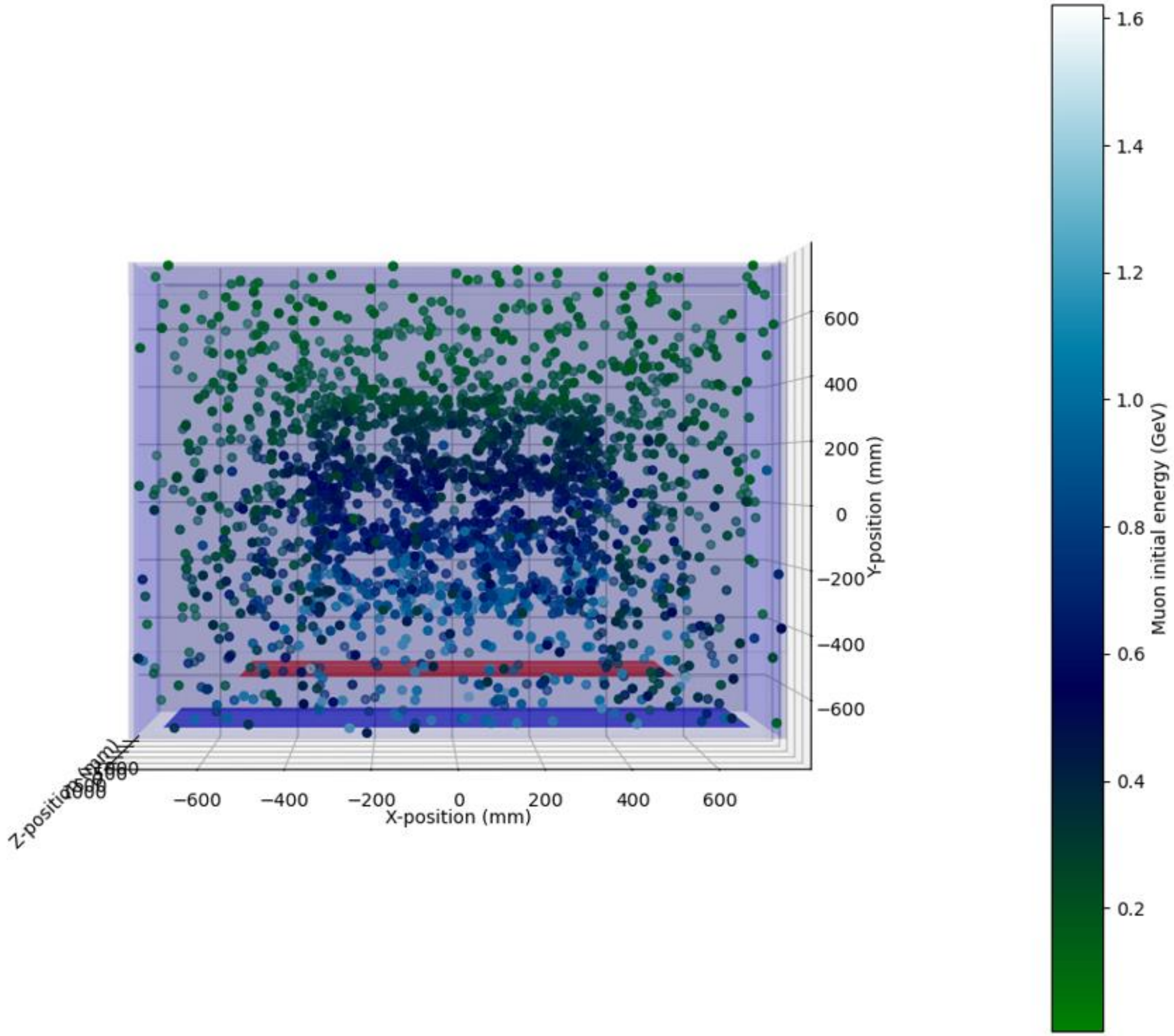

Neutron generating processes from all muons
No. of neutrons produced
2000
1750
1500
1250
1000
750
500
250
0
photonNuclear
muMinusCaptureAtRest
neutronInelastic
muonNuclear
pi-Inelastic
hBertiniCaptureAtRest
pi+Inelastic
protonInelastic

Energy Lost by Muons After Traversing 8 m.w.e



Muon Absorption in Mini-HALO





nCapture Positions in He-3 After Muon Hit