Radiolytic Effects of High-Energy Leptons on Europa's Potential Organic Molecules

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This proposal investigates the radiolytic abilities of high-energy leptons on simple organic molecules, reflecting the intentions of the 2024 Europa Clipper mission. We hypothesize that, even if it were possible for Europa's subsurface ocean or ice shell to produce a redox potential through its interaction with the moon's icy surface, the radiation to which it is consistently exposed is sufficiently damaging to simple organic molecules that it results in their degradation.

WHY WE WOULD LIKE TO GO TO CERN

Dawson Technicolor is a collective of motivated students with a passion for physics. Through our engagement with high-energy physics Dawson, we have fostered a keen interest in the wide range of applications of particle physics. The opportunity to travel to CERN or DESY would further our devotion to the field, allowing us to engage others in our community. Moreover, we are excited by the prospect of realizing our experiment at CERN or DESY given that the equipment at these institutions is of exceptional quality.

INTRODUCTION

The prospect of extraterrestrial life has propelled astrophysical innovation to the forefront of research in planetary science. Of the different avenues investigating this topic, the synthesis of simple organics from inorganic molecules has been widely studied [1]. However, this is only one of several steps that must be undertaken prior to the emergence of life. Abiogenesis requires thousands of years to bear fruit, and, if these simple organic molecules—the foundation of life—are consistently subjected to high-energy radiation, it may be impossible for them to polymerize and later form protocells [2].

Jupiter's moon, Europa, has emerged as a prime candidate to investigate this query. It is hypothesized that an ocean of liquid water lies beneath its cryocrust [3]. Recent observations from the Hubble Space Telescope have provided further evidence for this subsurface ocean's existence.

This proposal investigates the prospect of life on Europa by modelling the interaction of the icy moon's cryocrust and presumed subsurface ocean with high-energy leptons that could disrupt the bonds between simple organic compounds, degrading them and inhibiting the development of life on Europa.

FRAMEWORK

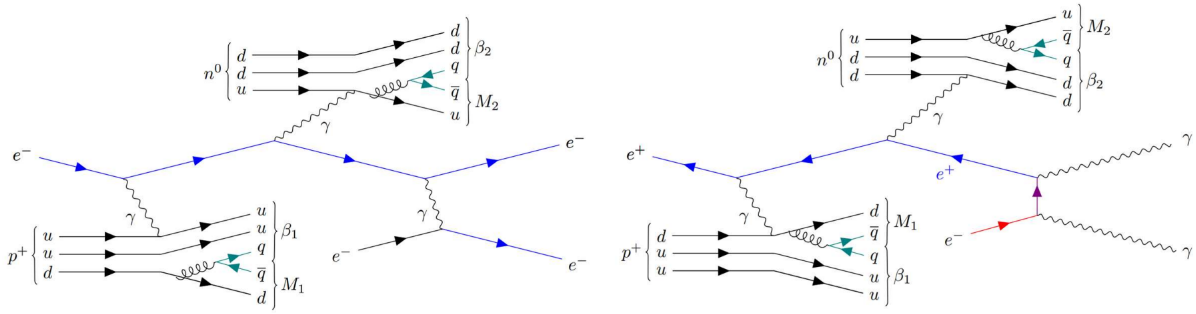

FIG. 1: Interactions of high-energy $e^{\pm}$ with protons, neutrons, and orbiting electrons. In blue are the paths taken by the respective beams as they pass between subatomic particles. In red is the annihilation of an orbiting electron. In teal are generalized quark-antiquark pairs generated via the strong nuclear force as the magnetic field of incoming leptons attracts and repels the partially-charged valence quarks of each nucleon. A baryon β and meson M result from this interaction.

An Overview of Our Model

This experiment models Europa's cryocrust using a tank of water which will be exposed to a beam of high-energy leptons.[1] Electron and positron beams will be used, as they are the principal end products of the electromagnetic cascades that occur when cosmic radiation emitted from neighbouring bodies such as Jupiter interacts with the crust [4]. While this experiment would be conducted closer to room temperature than the approximately 100 K of Europa's surface, it is suggested that, due to the energy of the beam which will irradiate our cryocrust model, the difference in the chemical interaction will be minimal [5].

It is hypothesized that with sufficient incident flux, high-energy radiation can inhibit the polymerization of simple organics by cleaving the bonds between atoms in these molecules. With the help of composite Feynman diagrams, we illustrate in Figures 1 and 2 how molecular bonds can be altered via the repulsion and annihilation of bonding electrons, as well as via modes of nuclear decay. To investigate this, it will be necessary to dissolve such molecules in our cryocrust model.

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[1] Preferably, this tank would be voluminous enough for the thorough irradiation of the aqueous solution, but also small enough such that the amount of synthetic amino acid to be dissolved within it remains reasonable. This may pose problems within the context of CERN or DESY's setup, so the dimensions of the tank will be loosely set to 30 cm x 30 cm x 30 cm and could be changed at any time to accommodate the aforementioned institutions.

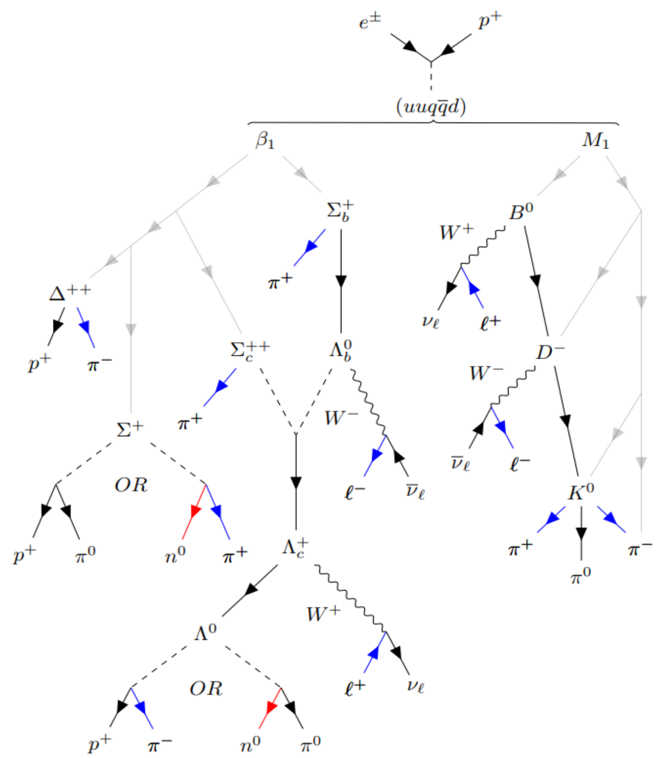


FIG. 2: Common hadron decay modes when $e^{\pm}$ interact with a proton. Each pathway initiates with β_1 and meson M_1. Highlighted in red are the pathways that result in the transformation of a nucleon via the weak nuclear force, which can result in the cleavage of bonds in an organic molecule. In blue are all pathways that will eventually decay into an electron or positron, which will in turn interact with other subatomic molecules and continue this nuclear chain reaction.

Modelling Europa's Cryocrust with Water

Europa's cryocrust is dominated by amorphous water ice, a solid state of matter in which molecules are not organized in a definite lattice pattern [6] [7]. This experiment proposes modelling this ice with water [2] As both liquid water and amorphous ice consist of the same molecular species, the fundamental electron-matter interaction is identical. Given that the high-energy beam will be travelling at relativistic speed, its interaction with liquid water should not be substantially different from its interaction with amorphous water ice, despite discrepancies between the structures and density of the these two phases.

[2] To emulate the composition of Europa's surface ice, the tank will contain aqueous Na^+, Cl^-, Mg^{2+}, Ca^{2+}, and SO_4^{2-} concentrated at approximately 0.04 kg/mol of water. In addition, the solution will be slightly basic, with a pH of approximately 8.1 [8] [9] [10]. These values are consistent with an analog study regarding Enceladus, an icy moon of Saturn; early models of Europa's subsurface water, which intrudes into the crust as plumes of vapour and cryomagma; as well as those of Earth's coastal bodies of water.

A Description of Tests and Trials

Five separate tests are proposed in this experiment, each with a different amino acid in solution. Levy *et al.* found that a simple set of amino acids, consisting of D-alanine, L-alanine, D-aspartic acid, L-aspartic acid, and glycine, can be produced under Europan conditions [11].[3] These organic molecules will be of particular interest to our study. Given that little literature exists regarding the concentration of amino acids in Europa's cryocrust and subsurface ocean, three separate trials for each amino acid in which the concentration of these molecules will vary at 25, 175, and 1315 nmol/L of water are proposed [12].[4] The amino acids will be irradiated by 3 GeV/c beams, once with electrons and once with positrons. The data will be collected using Fourier Transform Infrared (FTIR) Spectroscopy.

	D-Alanine		L-Alanine		D-Aspartic Acid		L-Aspartic Acid		Glycine	
Concentration (nmol/L)	e^-	e^+	e^-	e^+	e^-	e^+	e^-	e^+	e^-	e^+
25										
175										
1315										

FIG. 3: Sample table outlining all tests and trials. The results of the spectroscopic analysis of each irradiated sample can be an observed "Change," "No Change," or "Inconclusive." The latter case could result if the FTIR spectra cannot indicate whether the molecules are still in solution. In the case of an inconclusive test, a re-trial is suggested.

SETUP

The stream of electrons present in the DESY-II Test Beam storage ring will be exploited. It will first collide with a 7 μm carbon fibre target. The resulting Bremsstrahlung photons will collide with a copper plate, thus converting them into electron-positron pairs [13]. A 10 mm copper plate will be used in order to select 3 GeV/c lepton beams with a high rate (see Figure 4).

[3]While D and L isomers do not differ in constitution, their physical arrangement in 3D space relative to one another is distinct. As such, it is hypothesized that their radiolytic behaviours will be different, which is why a separate investigation of the enantiomers is proposed.

[4]These values were chosen based on the mean values of terrestrial oceanic amino acid concentrations that are currently known.

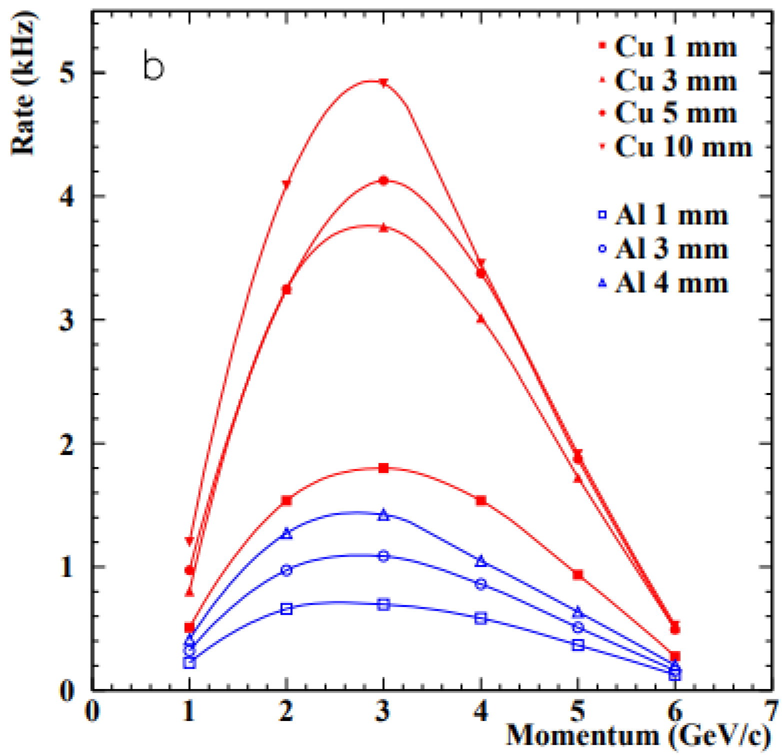


FIG. 4: DESY-II Test Beam rates for different secondary targets via Behnke *et al.* at EUDET [13]. The red curve marked by the downward pointing triangle represents the rate, in kHz, of the lepton beam emitted following the collision of Bremsstrahlung photons against a 10 mm copper plate as a function of its momentum.

Dipole magnets will be subsequently employed to separate the oppositely charged species [13]. Swiftly following this, a multi-layer, thermally insulated vacuum surrounded by multipole magnets straightens and narrows the trajectory of particles comprising the beam, thus selecting for the desired momentum of particles which then pass through a collimator to reduce its halo. A 30 cm x 30 cm x 30 cm tank containing the aqueous amino acid solution will be positioned in the path of the beam with scintillators on either side in order to verify the leptonic nature of the beam (see Figure 5).

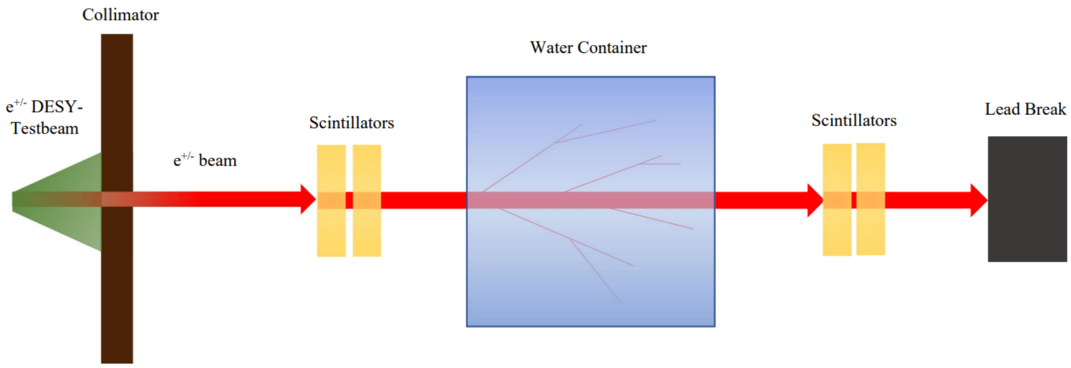


FIG. 5: Experimental Setup. After being transferred to the Test Beam 21 facility, the beam will pass through a collimater to reduce its halo. To verify the lepton beam's entry into and exit out of the solution, scintillators will be placed on either side of the tank. The second scintillators allow for the detection of any misfiring to reduce error. The 30 cm x 30 cm x 30 cm tank contains the aqueous amino acid solution. The electron or positron beam may scatter within the aqueous medium such that the main exiting beam will be much weaker than its incident counterpart. That said, a signal is still expected from the scintillators downstream before the beam is then deposited in a dense lead brick.

For a detailed analysis of the spectroscopic techniques and background reduction methods that will be used for data collection, please consult the Appendix.

WHAT WE HOPE TO TAKE AWAY FROM THIS EXPERIENCE

We hope that this experience will catalyze further growth in physics within our team and the Dawson student body as a whole. Much of our group intends to pursue further studies in the field of physics in university. Dawson's existing connections to major universities will thus be strengthened, which will provide further research opportunities for current and future members of Dawson Technicolor.

On a more personal note, we appreciate that our journey towards becoming established scientists has only just begun. We have much to learn about the rigours of science and have held this belief throughout the composition of this proposal. We hope that, if our proposal is selected, this opportunity will allow us to deepen our understanding of physics and the scientific process, furthering our growth as students.

OUTREACH ACTIVITY

We are organizing grade school presentations in the Greater Montréal Area about topics within the Standard Model of Particle Physics. Our presentations will range from teaching the basics of particle physics to qualifying quantum field theory and its implications. We also intend to present and discuss the cloud chamber we were awarded for our short-listed proposal last year, hoping to pique the curiosity of the next generation of scientists and foster in them a love for physics.

Moreover, we plan on filming a "Physicist Explains Particle Physics in 5 Levels of Difficulty" video, which will be shared on our school's social media platforms. We will arrange for the film to be shown at Dawson College's Science Fest and sent for viewing to various grade schools through our Dawson's science outreach club, *SparkMind*. To shed light on the research conducted at CERN and to spark interest in the field of particle physics, we hope to share the details of our proposal with the local scientific community in Montréal.

To this end, we have created the first level of difficulty. We invite you to view it.

ACKNOWLEDGEMENTS

We would like to thank Dawson College along with Dawson SPACE for providing the environment, support, and insight necessary to complete this research proposal. We are grateful for Prof. Manual Toharia Zapata and Prof. Joel Trudeau, without whom the realization of this project would not have been possible.

We would like to extend a special thank you to Markus Joos and Prof. Dr. Peter Watkins, who engaged with us in dialogue, fielding our questions and deepening our understanding of the physics underlying our proposal. We would also like to acknowledge that many of the students who developed this proposal were in attendance at a NASA Workshop hosted at Dawson, which revolved around the theme of ices in the solar system. We felt honoured to have had this opportunity to learn from established researchers in the field of astrophysics and owe much of our inspiration for this proposal to them.

Finally, we extend our thanks to CERN for providing the opportunity and framework to develop this proposal. We are grateful to have had the chance to engage with science and innovation in the wondrous field of particle physics.

APPENDIX

Logbook of Meetings

We invite you to follow this link to our logbook.

FTIR Analysis of Amino Acids

The prime method for analysis will be Fourier Transform Infrared (FTIR) Spectroscopy.[5] FTIR Spectroscopy will indicate whether the functional groups of the amino acids are still present before and after electron or positron radiolysis.

Prior to each test, the concentrations of D-alanine, L-alanine, D-aspartic acid, L-aspartic acid, and glycine in each sample of aqueous solution will be recorded.[6]

It is also crucial that a sample be taken prior to each test for comparative analysis with the irradiated samples collected after each test to minimize any errors that may be derived from repeatedly testing aliquots of this solution.

After each test, samples of leptonically irradiated solution will be extracted. The spectra obtained from the irradiated samples will be compared to the spectra of the amino acids (see Figure 6).

[5] This will be much more effective than UV/Vis Spectroscopy and Mass Spectroscopy, as the amino acids dissolved in solution are all of a similar mass and do not have idiosyncratic π-bonds that would facilitate in the identification of one from another.

[6] Depending on the resources available at CERN or DESY, each solution will be placed in its own tank to minimize the impact of any potential unwanted products that may appear in the water following the interactions of a high-energy lepton beam with the walls of the container. However, it is acknowledged that this may be wasteful, especially if the impact of the beams on the walls of the tank is negligible. In that case, a single tank will be emptied and refilled with the next solution between each test.

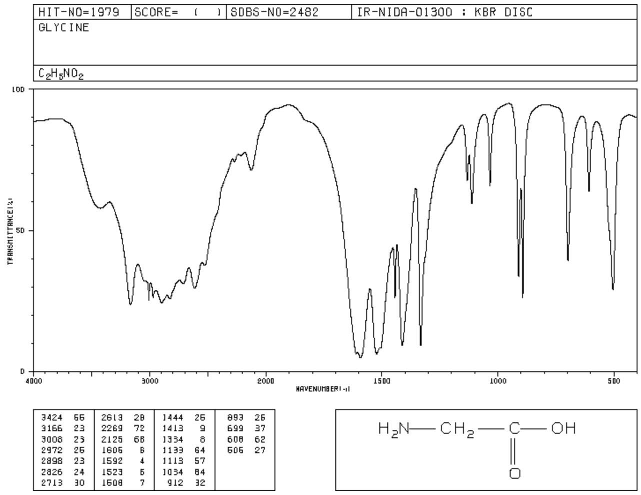


FIG. 6: FTIR Spectrum of glycine taken with a KBr disc. Note the characteristic carboxylic acid O-H, N-H, and C=O signals at wavenumbers of approximately 3300, 3500, and 1700 cm^{-1} respectively. This FTIR spectrum is provided with the purpose of explaining which prominent signals will be analyzed in this study [14]. All other spectra can be found through the AIST Spectra Database.

Lepton-Neutron Decay Modes

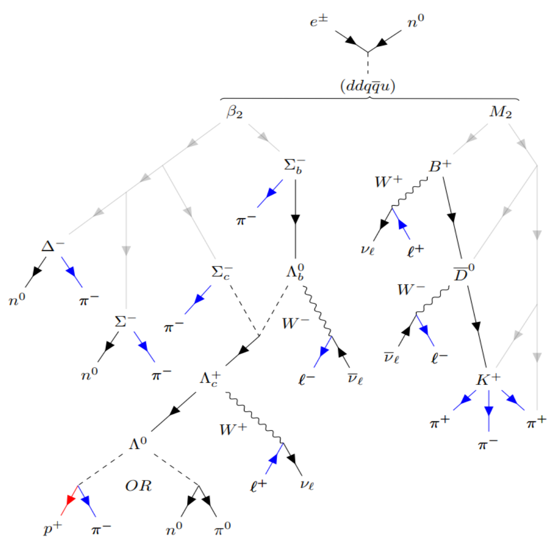
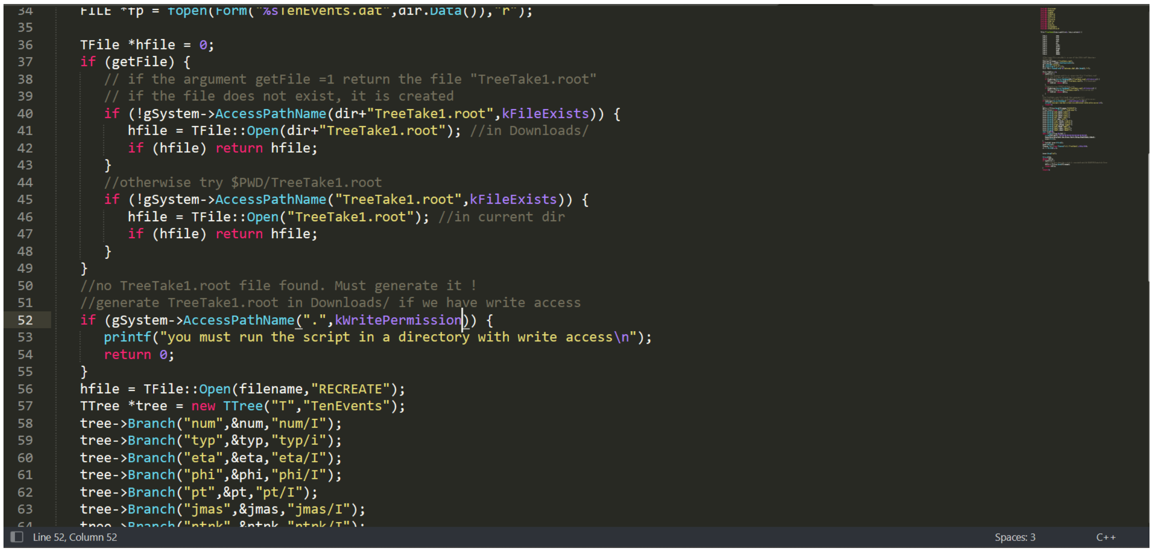


FIG. 7: Common hadron decay modes when high-energy $e^{\pm}$ interact with a neutron. Each mode initiates with a given baryon β_1 and meson M_1 that decay into a plethora of daughter molecules. Highlighted in red are the pathways that result in the transformation of a nucleon via the weak nuclear force, which can result in the cleavage of bonds in an organic molecule. In blue are all pathways that will eventually decay into an electron or positron. Note that these pathways are very similar - yet not identical - to those resulting from the interaction of such leptons with a proton.

Background Reduction



```cpp
   FILE *fp = fopen(Form("%sTenEvents.dat",dir.Data()),"r");

   TFile *hfile = 0;
   if (getFile) {
      // if the argument getFile =1 return the file "TreeTake1.root"
      // if the file does not exist, it is created
      if (!gSystem->AccessPathName(dir+"TreeTake1.root",kFileExists)) {
         hfile = TFile::Open(dir+"TreeTake1.root"); //in Downloads/
         if (hfile) return hfile;
      }
      //otherwise try $PWD/TreeTake1.root
      if (!gSystem->AccessPathName("TreeTake1.root",kFileExists)) {
         hfile = TFile::Open("TreeTake1.root"); //in current dir
         if (hfile) return hfile;
      }
   }
   //no TreeTake1.root file found. Must generate it !
   //generate TreeTake1.root in Downloads/ if we have write access
   if (gSystem->AccessPathName(".",kWritePermission)) {
      printf("you must run the script in a directory with write access\n");
      return 0;
   }
   hfile = TFile::Open(filename,"RECREATE");
   TTree *tree = new TTree("T","TenEvents");
   tree->Branch("num",&num,"num/I");
   tree->Branch("typ",&typ,"typ/i");
   tree->Branch("eta",&eta,"eta/I");
   tree->Branch("phi",&phi,"phi/I");
   tree->Branch("pt",&pt,"pt/I");
   tree->Branch("jmas",&jmas,"jmas/I");
   tree->Branch("ntrk",&ntrk,"ntrk/I");
```


FIG. 8: Screenshot of ROOT Code which generates a tree based on Monte Carlo generated data for particle collisions. This code is capable of graphing histograms based on data stored in the tree. This can then lead to further analysis of the background created during the particle reconstruction process.

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