Muon detection studies in ProtoDUNE-DP: light data analysis & simulation

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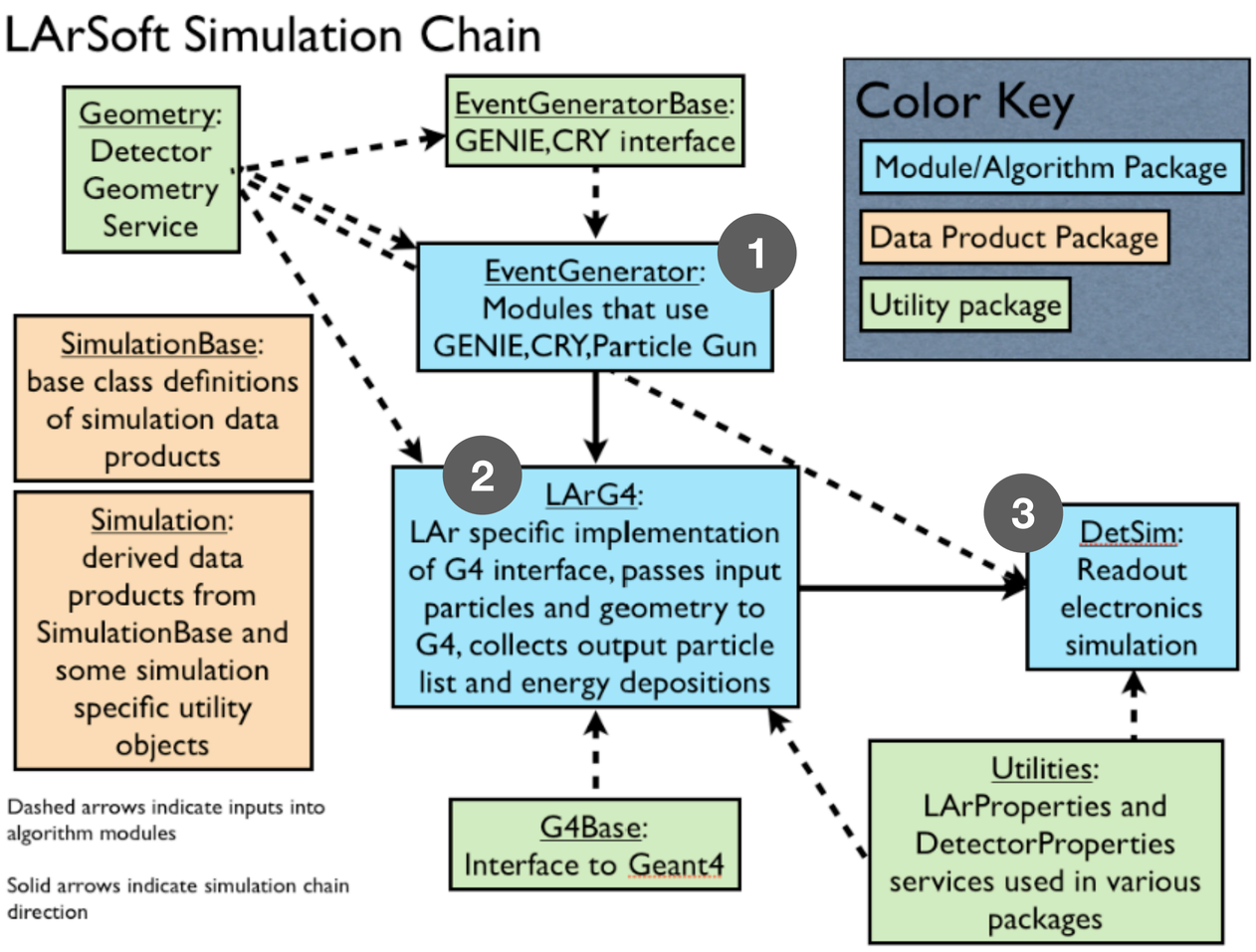
Outline

- **Light simulation chain in LArSoft**
- **New photon libraries**
- **Detection of muons crossing the detector:**
  - **Light data analysis:** S1 characterization from random trigger runs **(reminder! old results)**
  - **Light simulation:** CORSIKA **(new! ongoing)**
- **Detection of CRT-triggered muons:**
  - **Light data analysis:**
    - CRT-PMT data matching **(new! ready)**
    - S1 charge vs track-PMT distance **(new! ongoing)**
  - **Light simulation:** beam of muons crossing the CRTs **(new! ongoing)**
- **Next steps**

Light simulation chain in LArSoft

Assumptions!



Picture source: https://cdcvs.fnal.gov/redmine/projects/larsoft/wiki/Simulation

1) Event generator:

- GENIE, MARLEY, SingleGen, **CORSIKA**, **CRTgen**, etc.

2) LArG4 (geant4):

- Minimum ionizing particle (MIP): **2 MeV/cm** in LAr
- Light yield:
  - No fields: **40k photons/MeV** at null drift field
  - Fields: **24k photons/MeV** for drift field of 500 V/cm (recombination weakens). ***Plan**: include non-uniform field pattern
- Photon propagation: photon library (next slide) with **20 m** absorption length and **61 cm or 91 cm** of Rayleigh scattering length

3) Detector simulation (detsim):

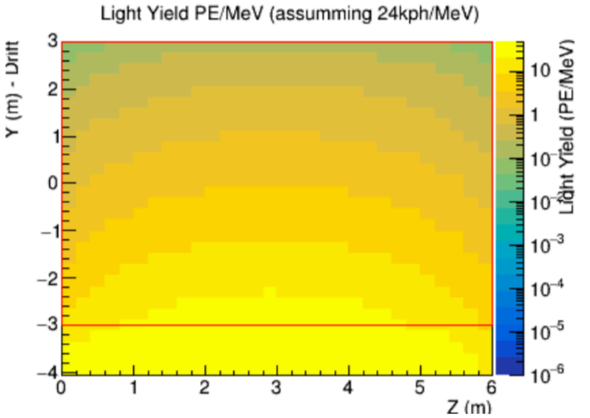
- PMTs QE (@128 nm): **0.12 for TPB**, **0.0173 for PEN** = 0.35 (PEN eff) * 0.2 (QE) * 0.247 (foil geom)
- **16 ns** sampling, **4096 ADC / 2V** dynamic range, **8 ms** readout window, **1.7 kHz** dark current at G=1e7

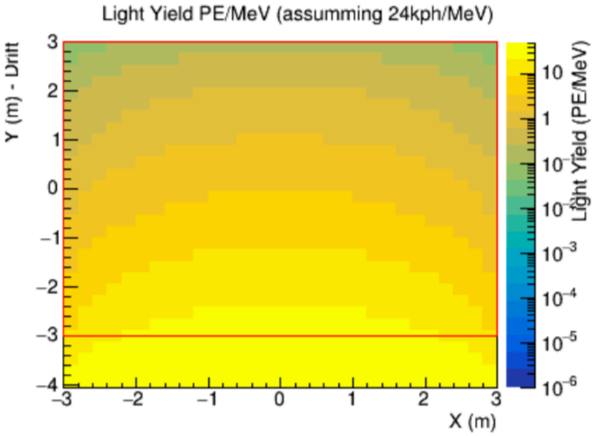
+ PMT waveform reconstruction & analysis!

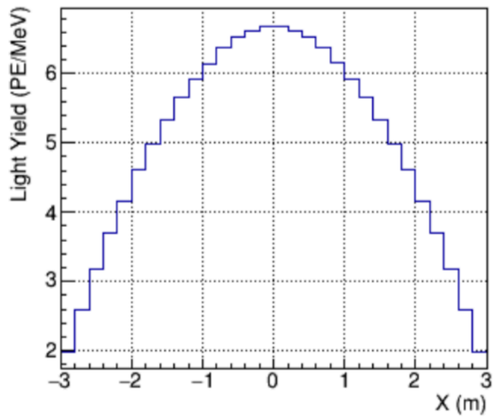
New photon libraries

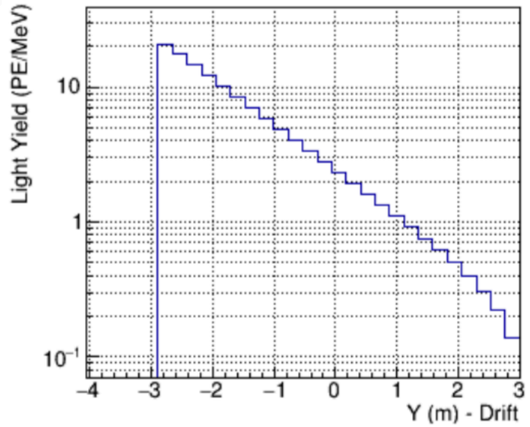
* Plots in this slide: 61 cm

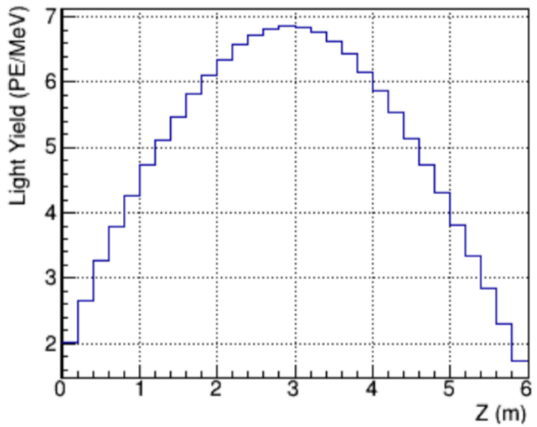
- **Only active volume (square in red) + cathode-PMT buffer**
- **Parameters (@128 nm):**
  - Absorption length: **20 m**
  - Rayleigh scattering lengths: **61 cm* and 91 cm** (two photon libraries)
- **15625 voxels** (30x30x30 voxels): ~20x24x20 cm^3, **1e8 photons per voxel**
- **Geometry: drift in y-axis**
- Another photon library with same parameters (20 m, 61 cm) but bigger voxels has been generated for background studies: light propagation outside the active volume is also simulated (full cryostat volume)

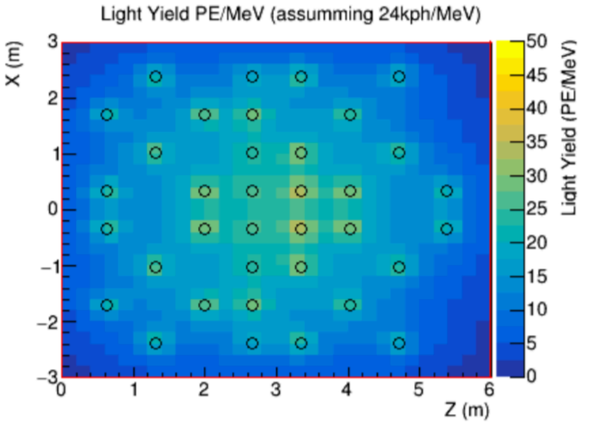








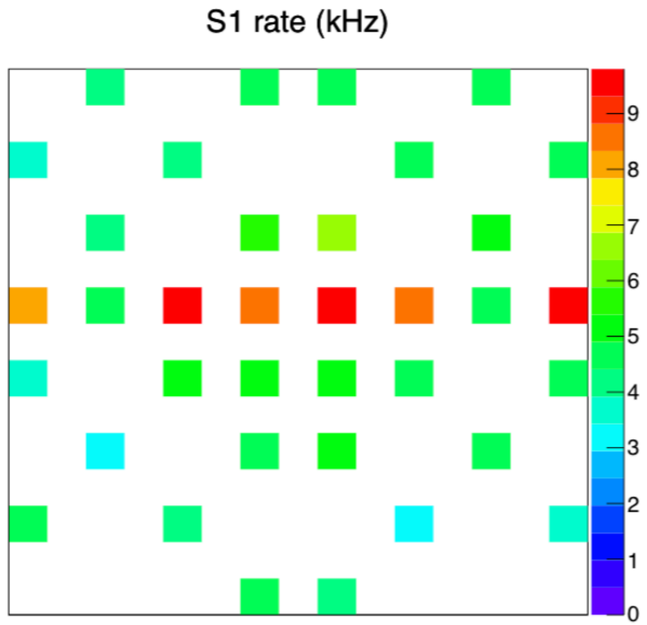


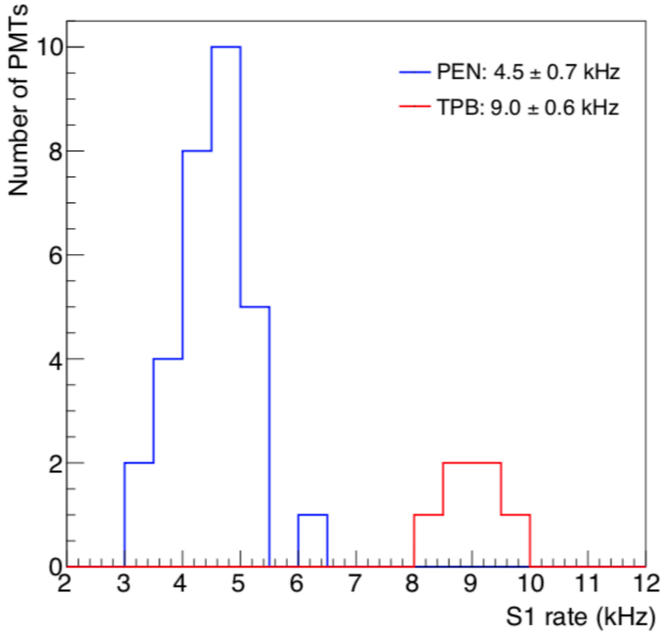


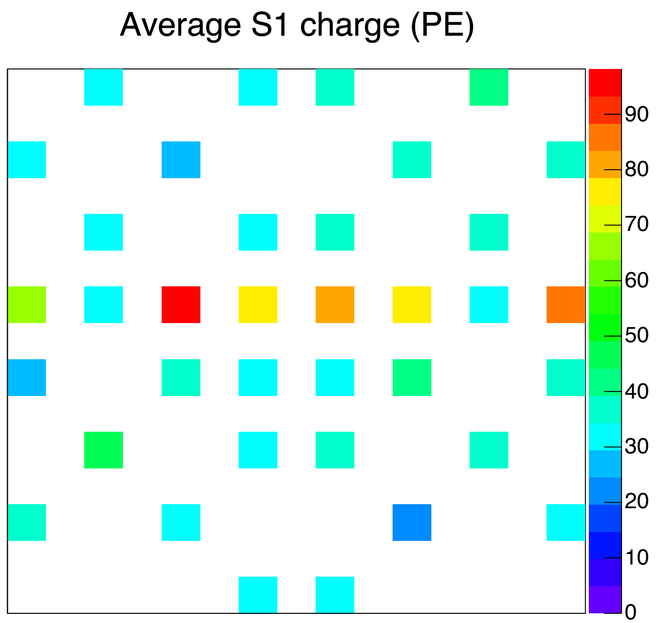
Muons crossing the detector

Light data analysis

- S1 characterization from random trigger runs **(reminder! old results)**
- See presentations in previous DPPD meetings for more details on these studies!
- **More advanced than the corresponding simulations!**







Muons crossing the detector

Light simulation

- We are using **CORSIKA** in LArSoft (simulates extensive air showers initiated by cosmic ray particles)
- Wide range of energy scales, multiple primary types (p, He, Fe, etc.), models (GHEISHA, FLUKA, etc.)…
- The module lives in **srcs/dunetpc/dune/EventGenerator/CORSIKAprotodunedp/**
- **services.Geometry: @local::protodunedphase_driftY_geo**
- **Comments:**
  - Showers are simulated externally using CORSIKA and stored in a database that is used by LarSoft
  - Certain number of showers (given by the shower flux constants) are produced within a given time window and a surface
  - A buffer is stablished to store the particles that are actually pointing to the cryostat (and save CPU time)

```
standard_CORSIKAGendp_CMC:
{
 module_type:          "CORSIKAGendp"
 SampleTime:            8.0e-3              #integration time in seconds
 TimeOffset:           -4.0e-3              #time in seconds before a spill to begin the interactions, -1.6e-3 (TPC Trig. offset) - 0.2e-3 (g4 rise time)
 ProjectToHeight:       856                 #height to which particles are projected [cm]
 ShowerInputFiles:      [
                           "/pnfs/larsoft/persistent/physics/cosmics/CERN/CORSIKA/standard/p_showers_*db",
                           "/pnfs/larsoft/persistent/physics/cosmics/CERN/CORSIKA/standard/He_showers_*db",
                           "/pnfs/larsoft/persistent/physics/cosmics/CERN/CORSIKA/standard/N_showers_*db",    seeds!
                           "/pnfs/larsoft/persistent/physics/cosmics/CERN/CORSIKA/standard/Mg_showers_*db",
                           "/pnfs/larsoft/persistent/physics/cosmics/CERN/CORSIKA/standard/Fe_showers_*db"
                        ] #list of sqlite dbs with corsika showers
 ShowerFluxConstants:  [ 1.72e4, 9.2e3, 6.2e3, 9.2e3, 6.2e3] #list of flux constants per shower file
 BufferBox:            [ -300.0, 300.0, -300.0, 300.0, -300.0, 300.0 ] #list of buffer box extensions to cryo volume in each dimension/dir (-x,+x,-y,+y,-z,+z)
 ShowerAreaExtension:  2000                #amount to extend the shower area beyond the cryo dimensions
 RandomXZShift:        1000                #amount to randomly shift shower start point in x & z [cm]
 DoRotation:           ~~true~~ false      #perform flux rotation for DP with drift in X
 UseIFDH:              false                #true for jobs at FNAL, false for jobs at CERN
}
```

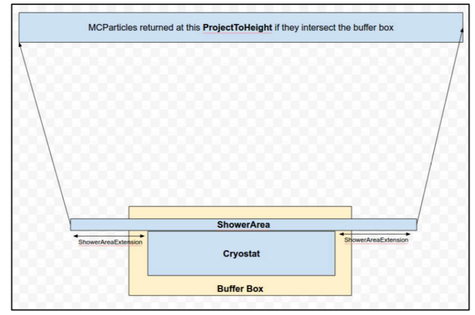
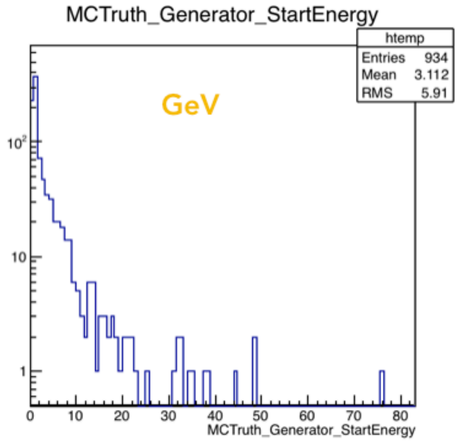


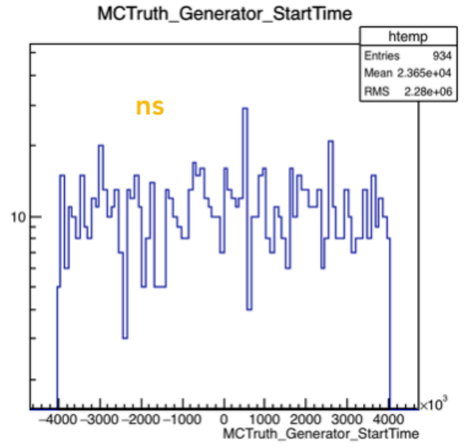
Table of parameters used in the simulation

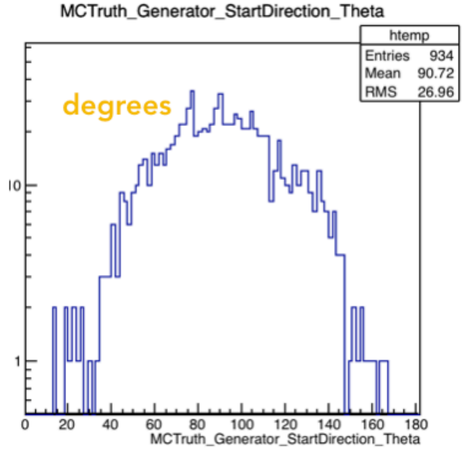
Muons crossing the detector

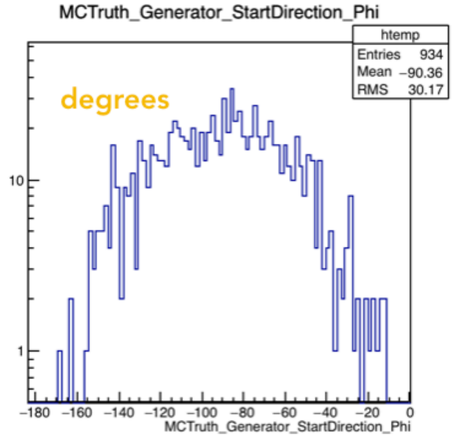
Light simulation

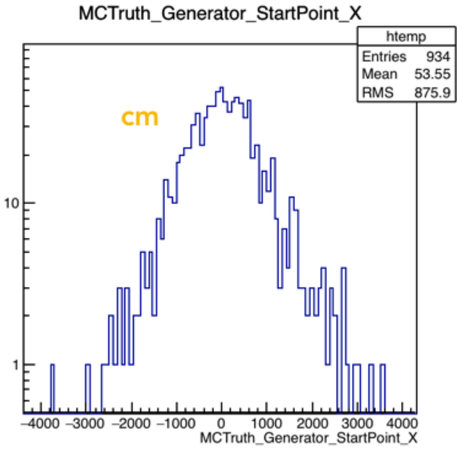
- **This example (MC):** a window of 8 ms contains 934 particles (279 μ+, 22 e+, 27 e-, 220 μ-, 103 γ, 25 p, 257 n)
- **Next step:** investigate what particles generate the light that PMTs detect

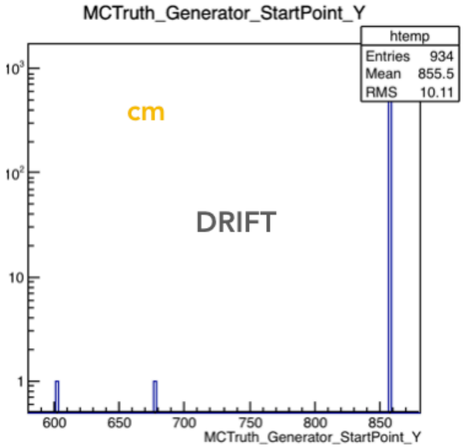


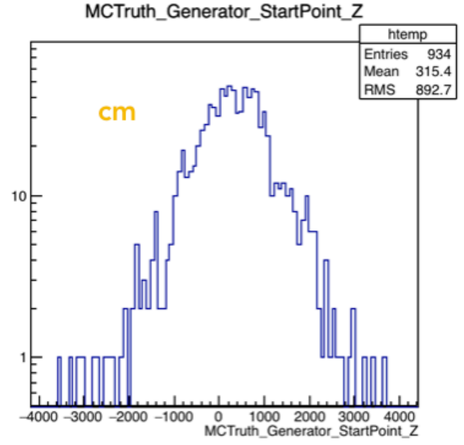












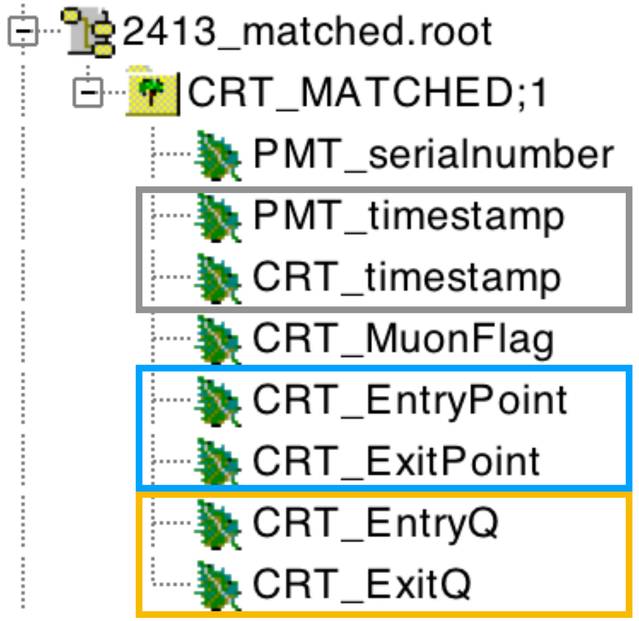
- **MC info:**
  - energy range
  - start time
  - start angles
  - start positions

CRT-triggered muons

Light data analysis

✦ **CRT-PMT data matching:**

- A program that associates (using the timestamps) every PMT event to its corresponding CRT event **is ready!**
- **Code validation**: tests with several runs + using the output for data analysis
- **38 PMT runs with CRT trigger (>300k events) taken so far (since Dec18) —> To-do**: systematic processing of all the runs when the program version is approved
- **Output** (example below): root file with CRT data that matches the PMT data (direct connection)
- MuonFlag meaning, etc. can be found in: https://indico.fnal.gov/event/23433/contribution/1/material/slides/0.pdf



—> Number of event in the run

—> PMT (from white rabbit, 1 ns precision) / CRT (1 s precision) timestamps

—> True or false (muon candidates; if false, all the other variables are empty)

—> Entry point (TOP CRT) / Exit point (BOT CRT): x,y,z in LArSoft coordinates

—> Deposited charge in TOP CRT (entry) / BOT CRT (exit)

CRT-triggered muons

Light data analysis

- **Goals:**
  - Study the S1 amplitude & charge vs the track-PMT distance for CRT data
  - Compare data with simulations for different Rayleigh scattering lengths (several photon libraries)

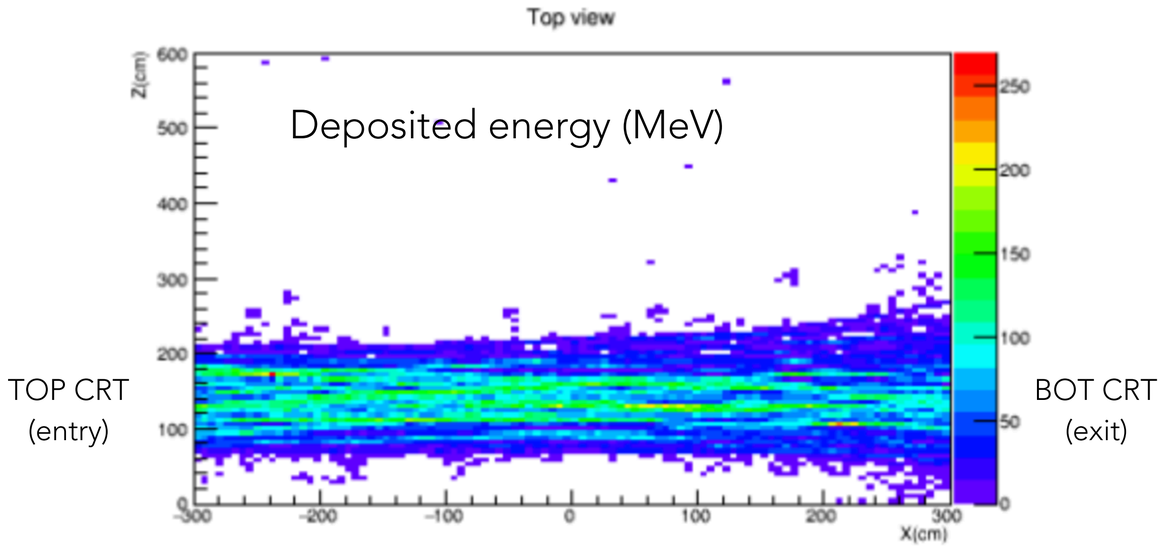
- **Minimum approach distance (track-PMT):** calculated from the CRT_entry_point, CRT_exit_point & PMT_coordinates (now available!)

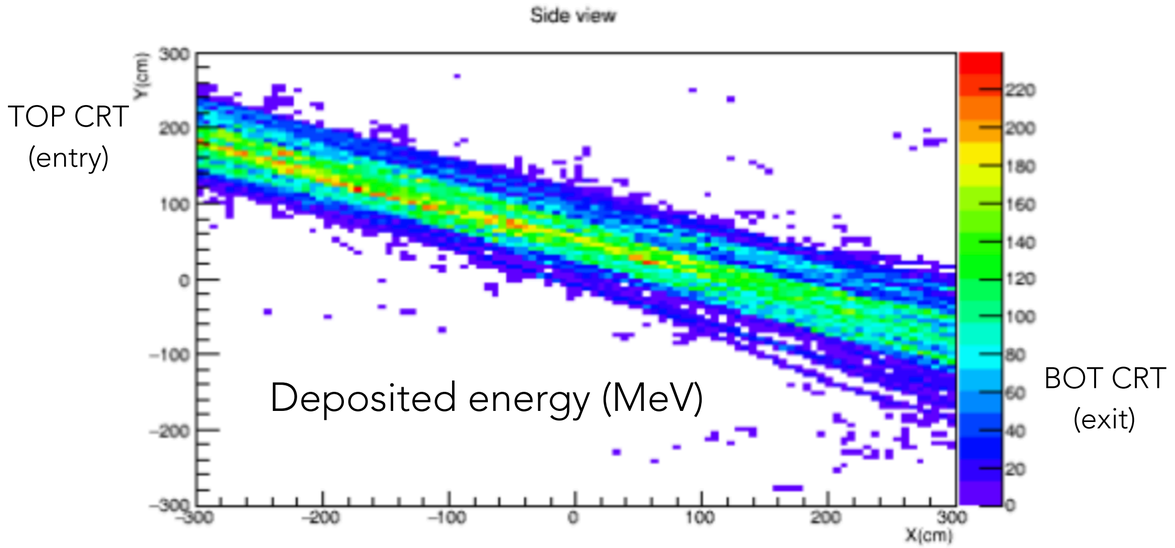
- **Event selection cuts:**
  1) Muon candidate from CRT info (top and bot fired paddles with a difference of time between 40 and 45 ns)
  2) No PMT waveform saturation
  3) Minimum S1 amplitude (~3 PE)
  4) Trigger coincidende (within 1 bin = 16 ns) among PMTs
  5) Other possible cuts: LAr active volume? Minimum track length? Angular condition?

CRT-triggered muons

Light simulation

- New module has been added in LArSoft: **CRTgen** (already available in develop!)
- It creates **single muons** following the **expected pattern given by the CRT panels.** The module…
  - gets a random point inside top CRT (entry point of the muon trajectory)
  - assigns a random energy uniformly distributed among 2-3 GeV
  - gets a random point inside bottom CRT (according to the muon momentum)
  - also supports drift in X geometry (important for the charge studies)
- **Ongoing improvements: 1)** More realistic muon energy distribution from CORSIKA, **2)** Entry/Exit point following the real muon pattern obtained from CRT data, **3)** Only muons crossing both CRTs (no beam spread)





Next steps

We want to…

- ✦ evaluate the muon-detection efficiency of the detector
- ✦ study the light propagation in LAr under different field conditions (recombination, Rayleigh scattering…)

The next tasks/steps are…

- ✦ **Common task:**
  - simulation • **Validate the reconstruction of the PMT waveforms** in the simulation

- ✦ **Muons crossing the detector:**
  - simulation • **Generate samples using CORSIKA** with conditions that are similar to the random trigger runs already analyzed for the S1 characterization and carry out the analysis+comparison

- ✦ **CRT-triggered muons:**
  - data analysis • **Apply the PMT-CRT matching systematically** for all the light runs
  - data analysis • **Continue with the analysis of the CRT trigger runs** using the new available information from the matching
  - simulation • **Improve the CRT-triggered muon simulation** (energies, entry/exit pattern from data, select *true CRT muons*)
  - simulation • **Generate samples using CRTgen** with conditions that are similar to the CRT trigger runs used for the data analysis