Measuring Muon Induced Neutrons in the Water Phase of the SNO+ Experiment

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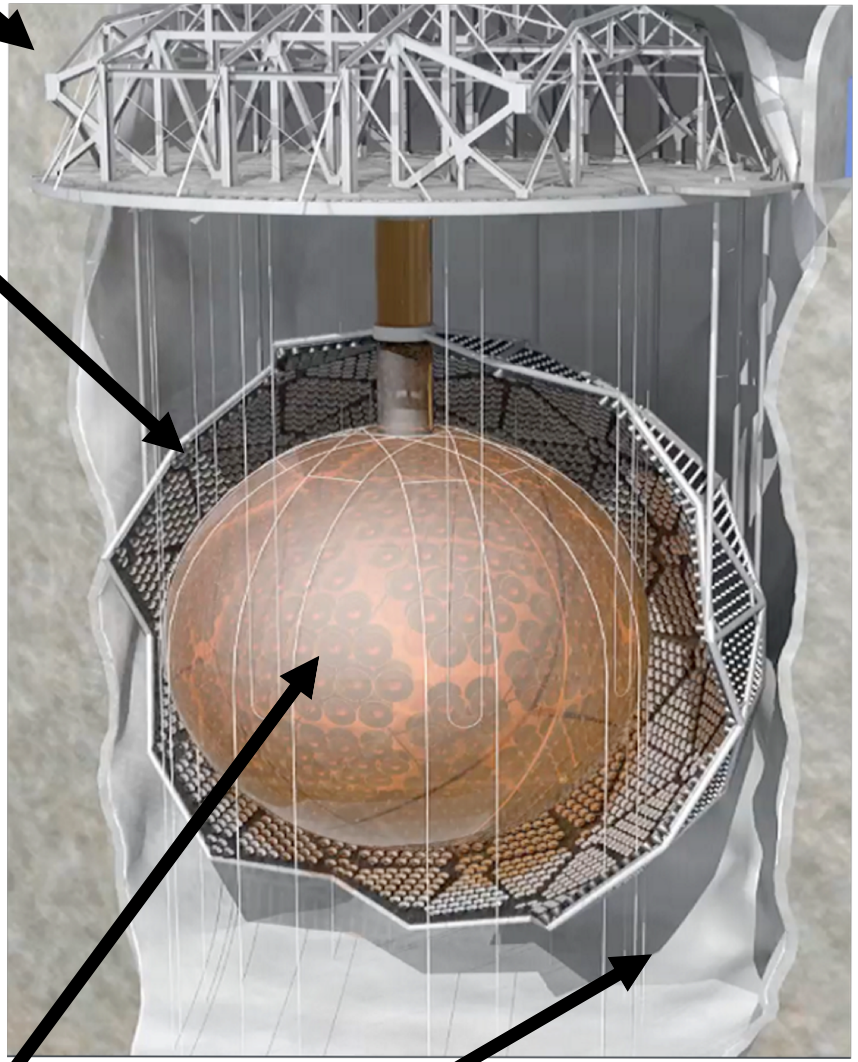
The SNO+ Detector

- General Purpose neutrino experiment.
- Main focus on the search for 0νββ.*
- Water phase currently wrapping up.**
- Scintillator filling taking place now.
  - Scintillator fill scheduled to complete in September.
  - Te loading to start in December.
  - Te loading complete May 2020.

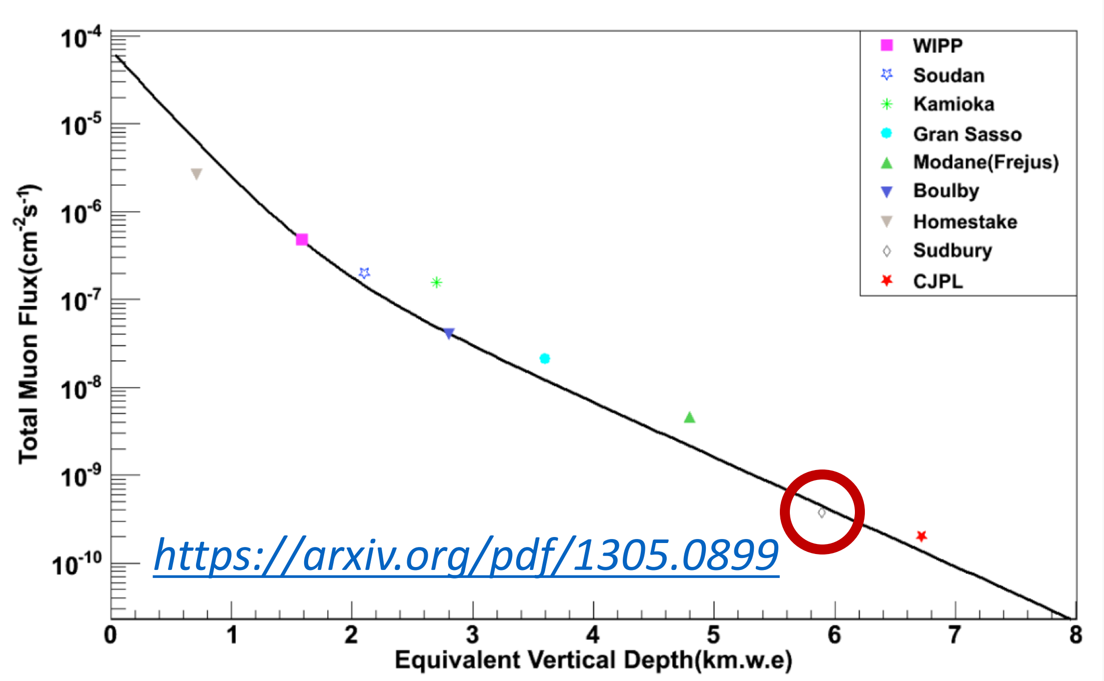


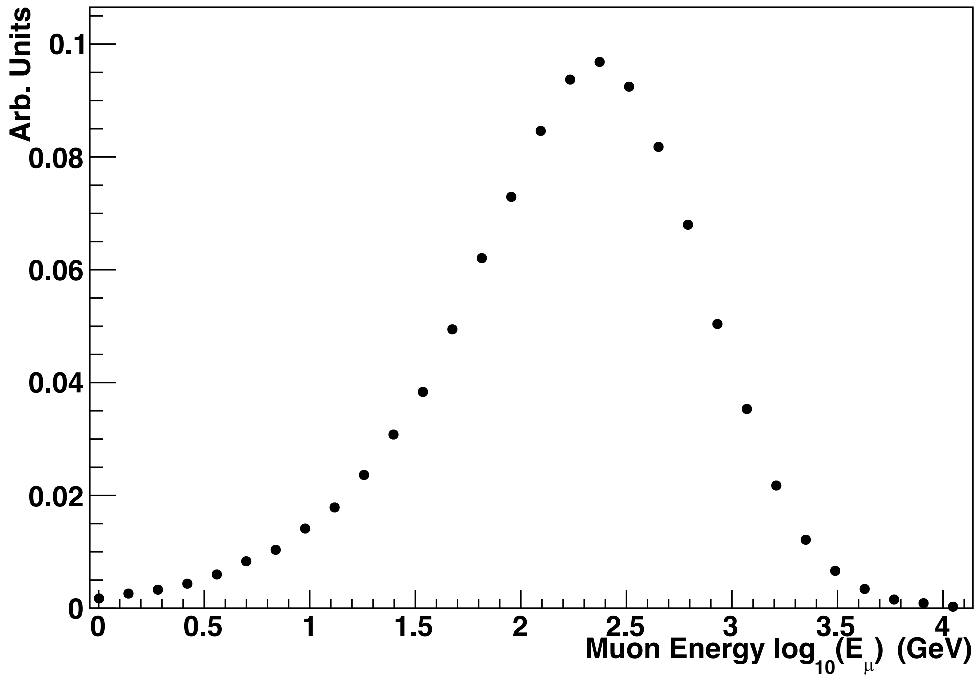
*Presentation on the sensitivity of SNO+ to 0νββ shown yesterday in parallel session 3 by Tereza Kroupova.
** Presentation on the results of the water phase shown yesterday in parallel session 3 by Martti Nirkko.

Cosmic Rays

- High energy particles collide with the atmosphere creating shower of particles.
- The majority of the particles that reach the surface are muons and neutrinos.
- 0νββ and dark matter searches are located deep underground to minimize the muon flux.
- The cosmic ray flux at SNOLAB is:

  0.27 μ/m²/day
  - Corresponds to approximately 3 muons per hour passing through SNO+ per hour.
  - Energy spectrum of muons at SNOLAB depth shown on the lower plot.

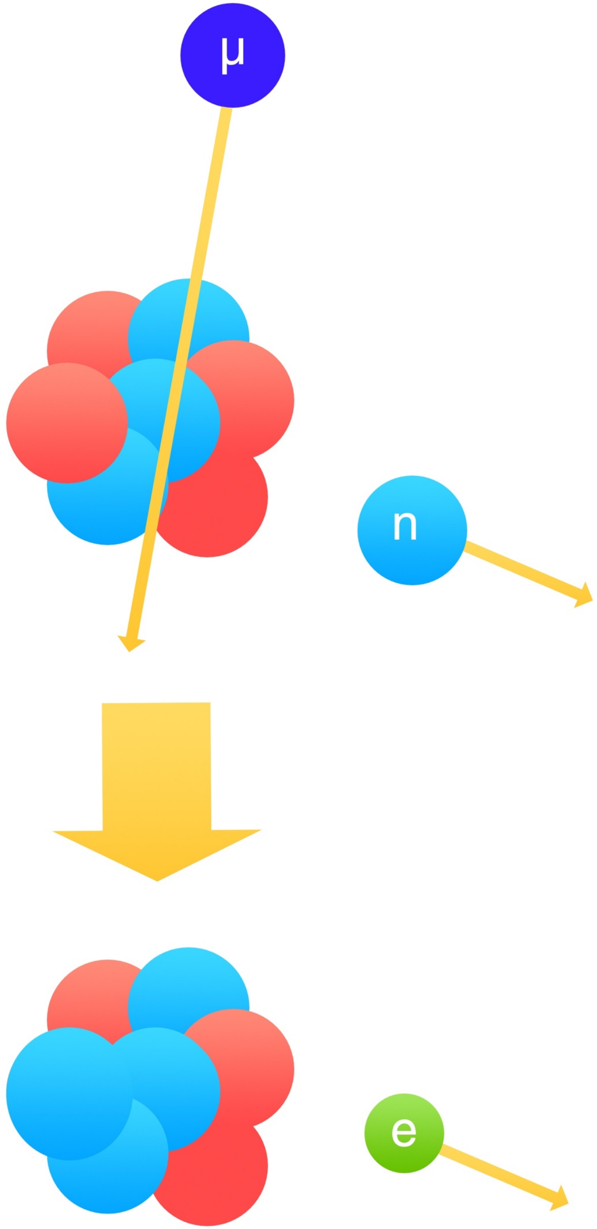




Cosmogenic Neutrons

- As the muon passes through the detector it can spallate on atoms, knocking out neutrons or protons.
- The main background to dark matter search experiments are neutrons.
- SNOLAB hosts several dark matter experiments.
- Understanding the neutron production at SNOLAB depths is crucial to improve the background estimates of these experiments.

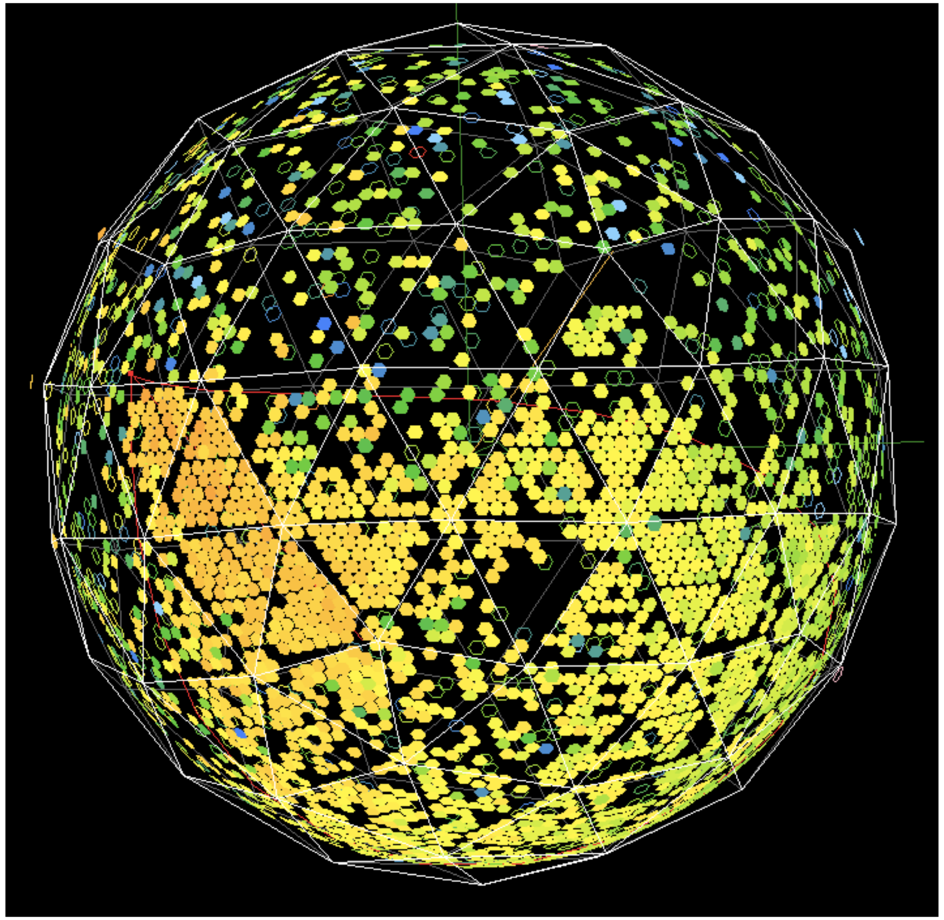
Initial spallation of a proton or neutron.



Subsequent decay of unstable radioisotope.

Analysis Method

- The entry position and exit muon direction can be determined using the topology of the PMT hits.
- Neutrons produced by the muon will thermalize before (mostly) capturing on a hydrogen.
  - Mean capture time is ~200 μs
  - Capture signal is 2.2 MeV γ
- Analysis to be performed on the water phase data of the experiment.



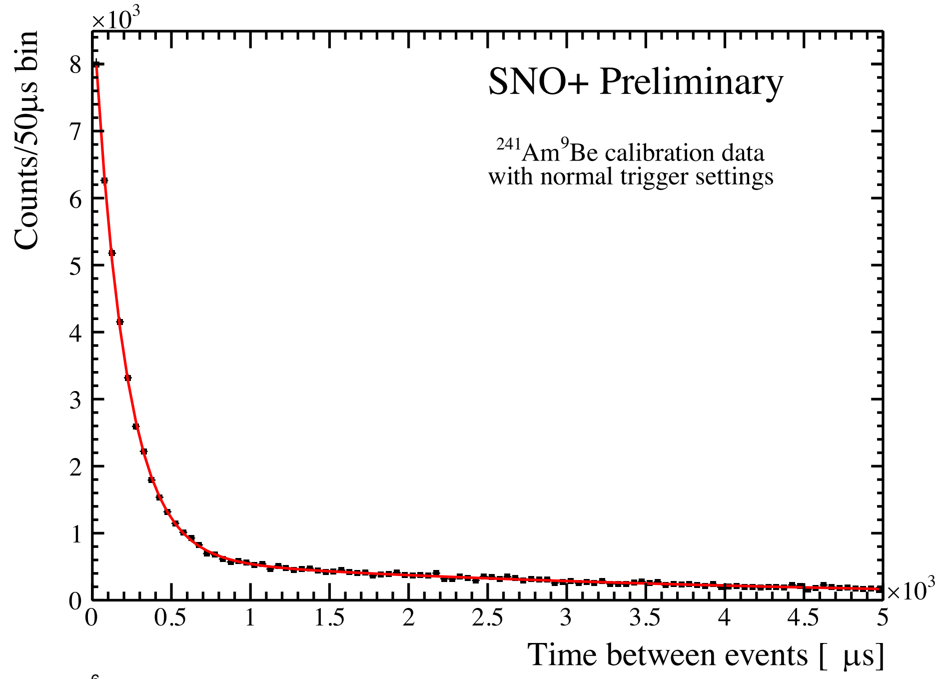
Muon event in the SNO+ event display

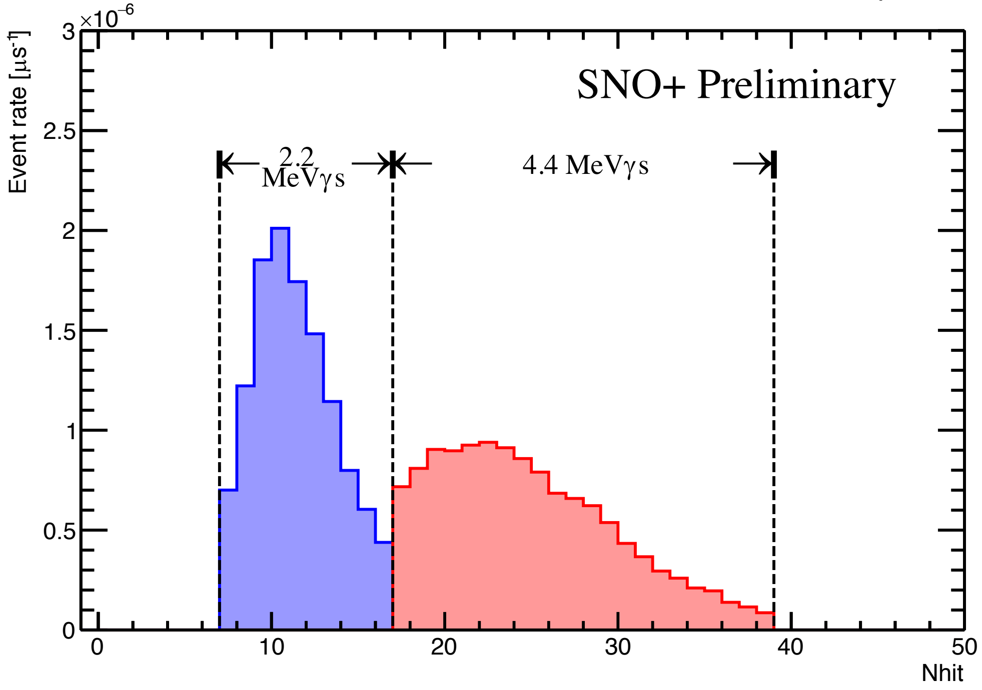
Neutron capture efficiency (In water)

- AmBe source deployed in water:
  - $\alpha + {}^{9}Be \rightarrow {}^{12}C^{*} + n$
  - ${}^{12}C^{*} \rightarrow {}^{12}C + \gamma$ (4.4 MeV prompt)
  - $n + p \rightarrow d + \gamma$ (2.2 MeV delayed)
- Measured capture time is:

  208.2 ± 2.1 μs
- Measured neutron detection efficiency

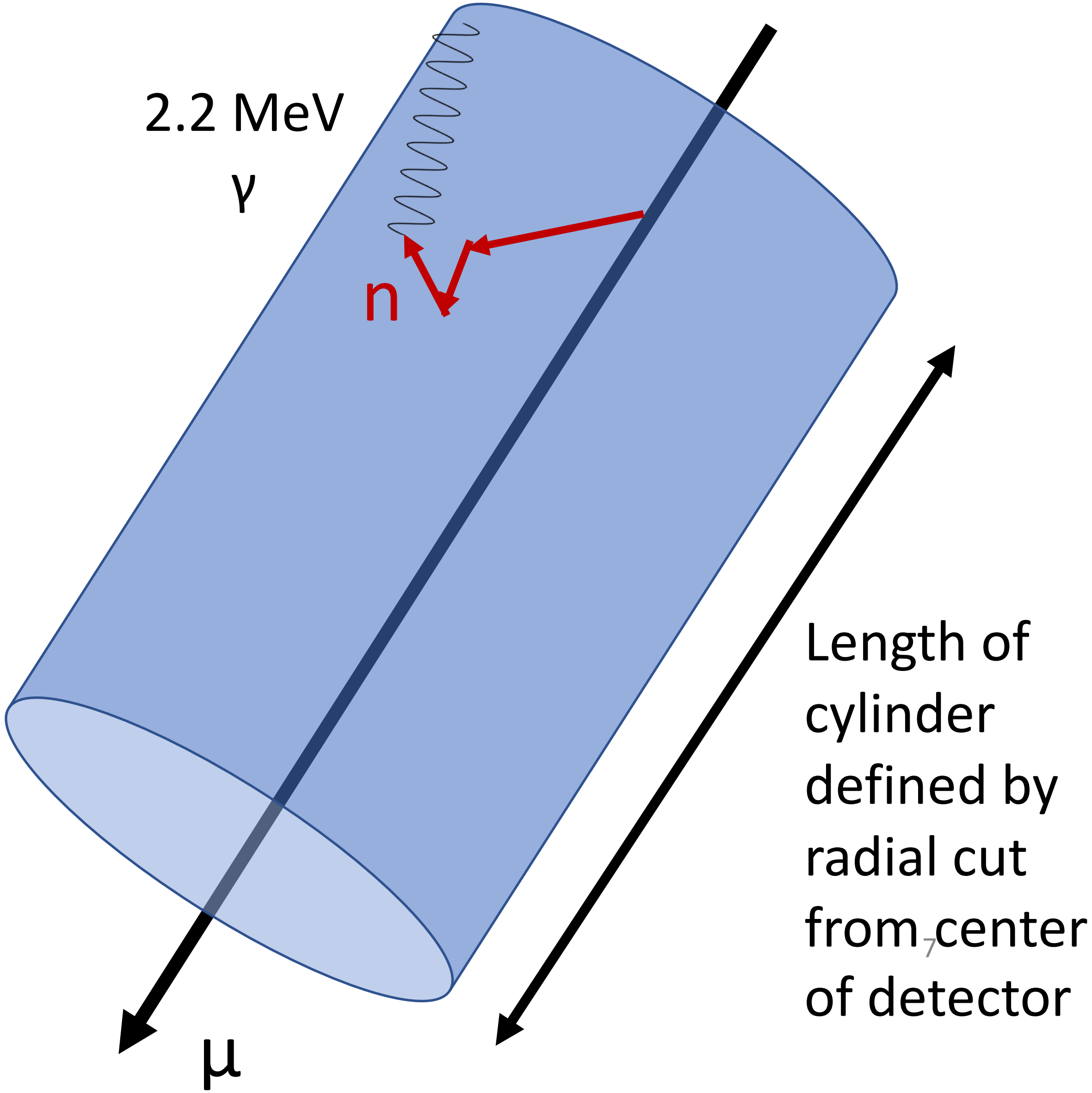
  46.5 ± 0.4 %





Analysis Method

- The track of the muon is used to define a fiducial volume surrounding the muon track.
- After the muon passes through we search for neutron captures within the fiducial volume



What we aim to measure

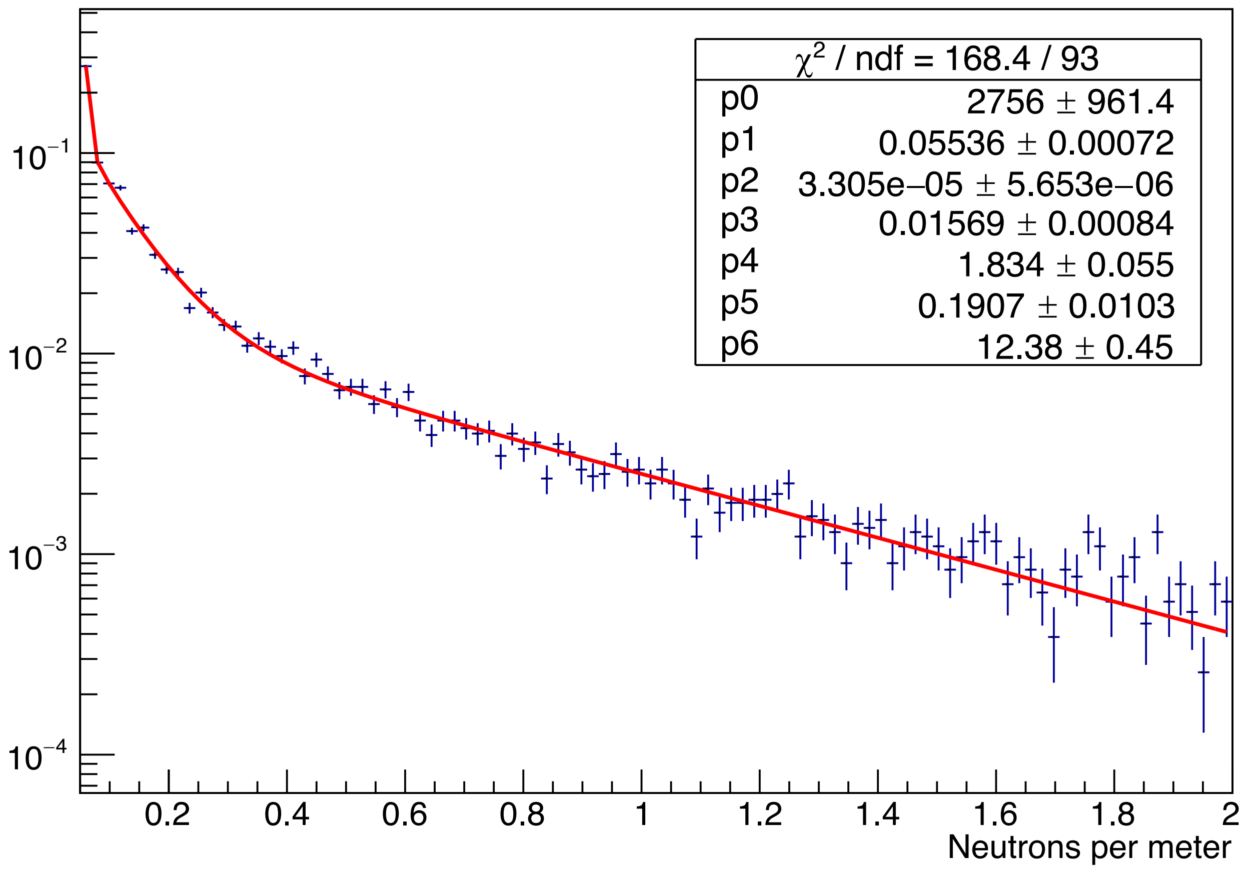
- For a given muon the number of followers will be related to this multiplicity parameter via:

$$N_{obs} = \varepsilon(\eta L - No + NI) + R_{BG} + M_{BG}$$

- Number of observed follower events to a muon → N_{obs}
- Detection efficiency for a 2.2 MeV in the fiducial volume → ε
- The number of neutrons generated per meter of track length (What we are trying to measure) → η
- The length of the muon track → L
- The number of neutrons produced by the muon which exit the fiducial volume. → No
- The number of neutrons produced by the muon external to the fiducial volume which enter it. → NI
- Random coincidences due to radioactivity → R_{BG}
- Other backgrounds due to the muon. → M_{BG}

Neutron multiplicity in GEANT

- Function represents the number of neutrons generated per meter of track length through the detector.
- Fit function is a Landau + two decaying exponentials.

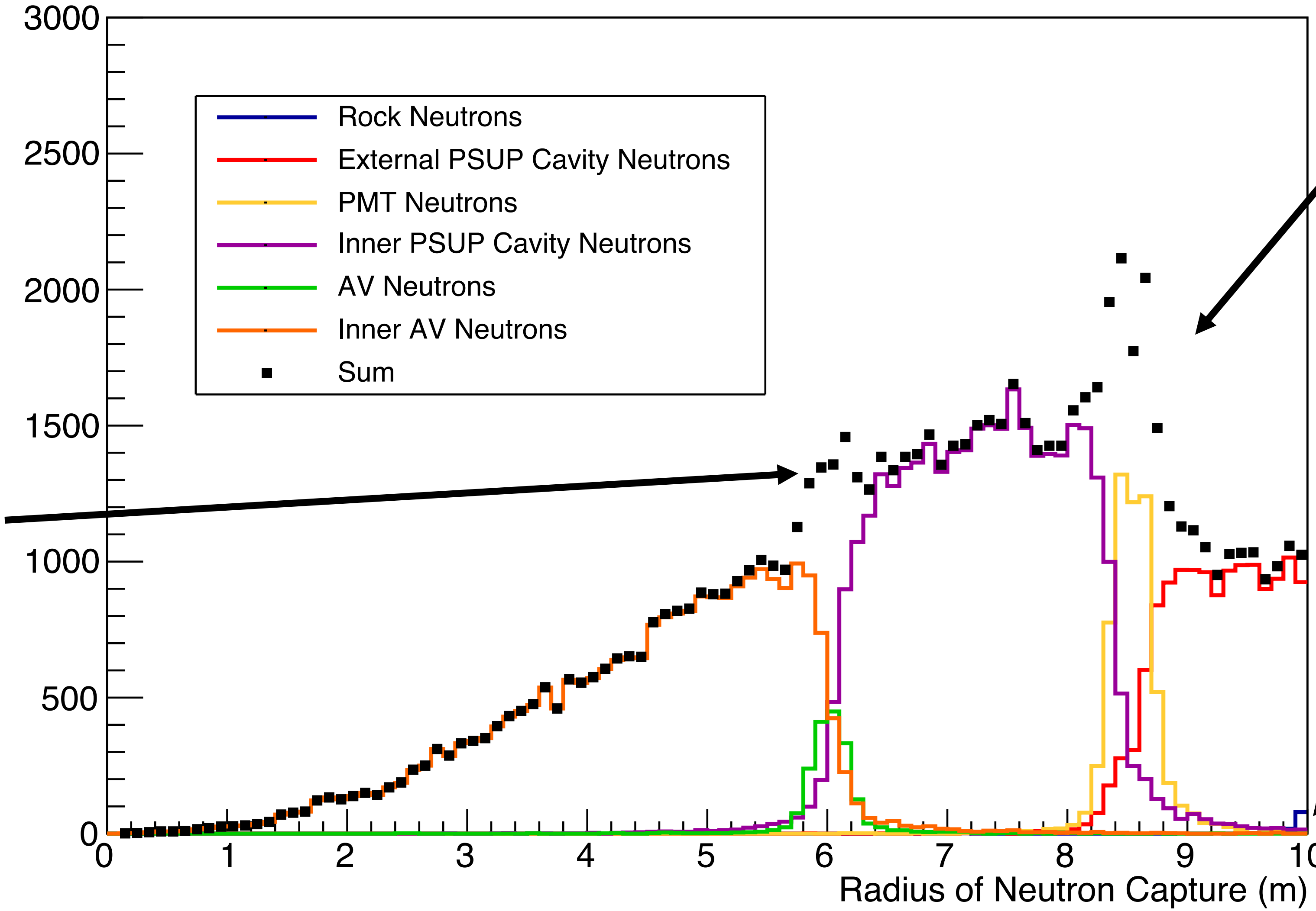


Analysis Breakdown

1. Optimize the fiducial volume
   - Simulate muons within the detector
   - Combine this with random backgrounds to produce a fake dataset
   - Optimize signal (neutron captures) over background (random and muon induced backgrounds)
2. Evaluate detector systematics on a muon by muon basis.
   - Simulate neutrons from muons using the reconstructed muon directions from data
     - Unable to simulate the muons completely due to limited computation time.
   - Use these simulations to evaluate the neutron tagging efficiency and other systematic effects.

Neutron production in the detector

Radius of neutron capture position for neutrons produced in muon simulations.



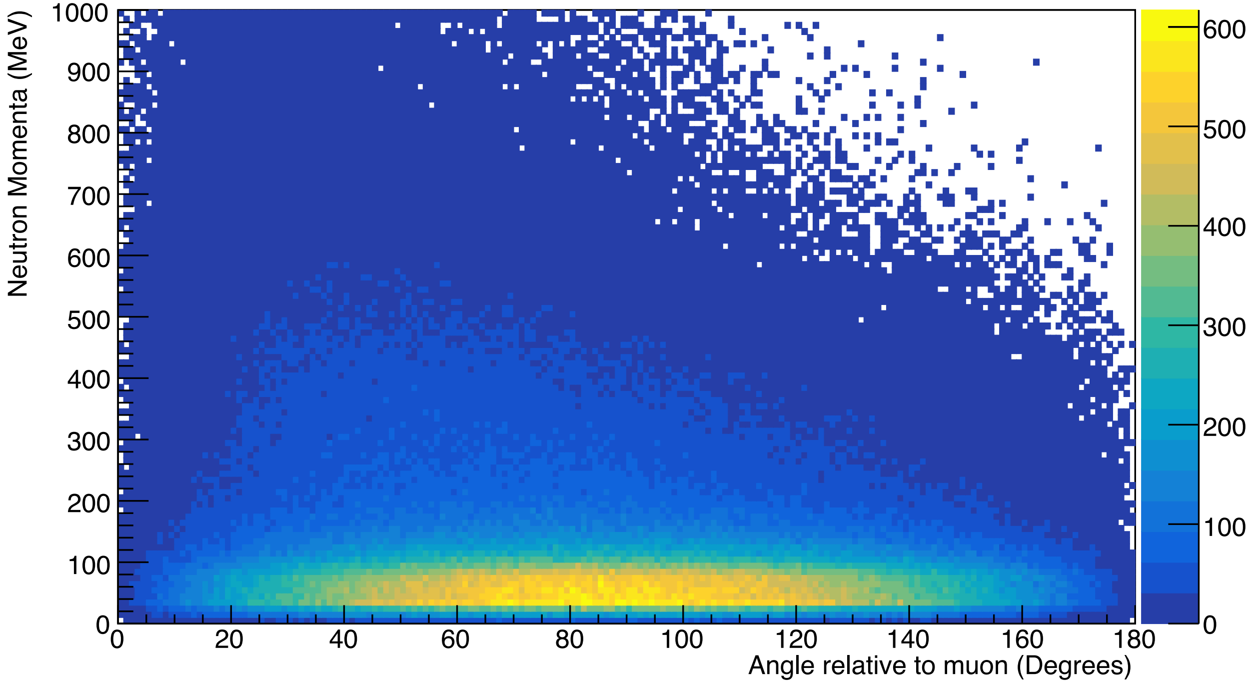
Additional peak due to spallation and captures within the AV

Peak due to spallation/captures within the PMTs

Neutrons produced by muons in the rock surrounding the cavity very rarely reach inside the PSUP

Evaluating the neutron efficiency

- Each muon simulation takes ~10 s per event to simulate.
  - Infeasible to obtain enough statistics per muon.
  - Furthermore many muons do not produce neutrons.
- Main systematic effects are thought to be due to the dynamics of the neutron.
- Solution: Extract the kinematics of the neutron from the muon simulations, then simulate neutrons with these kinematics.
  - These simulations take ~0.5 s per event

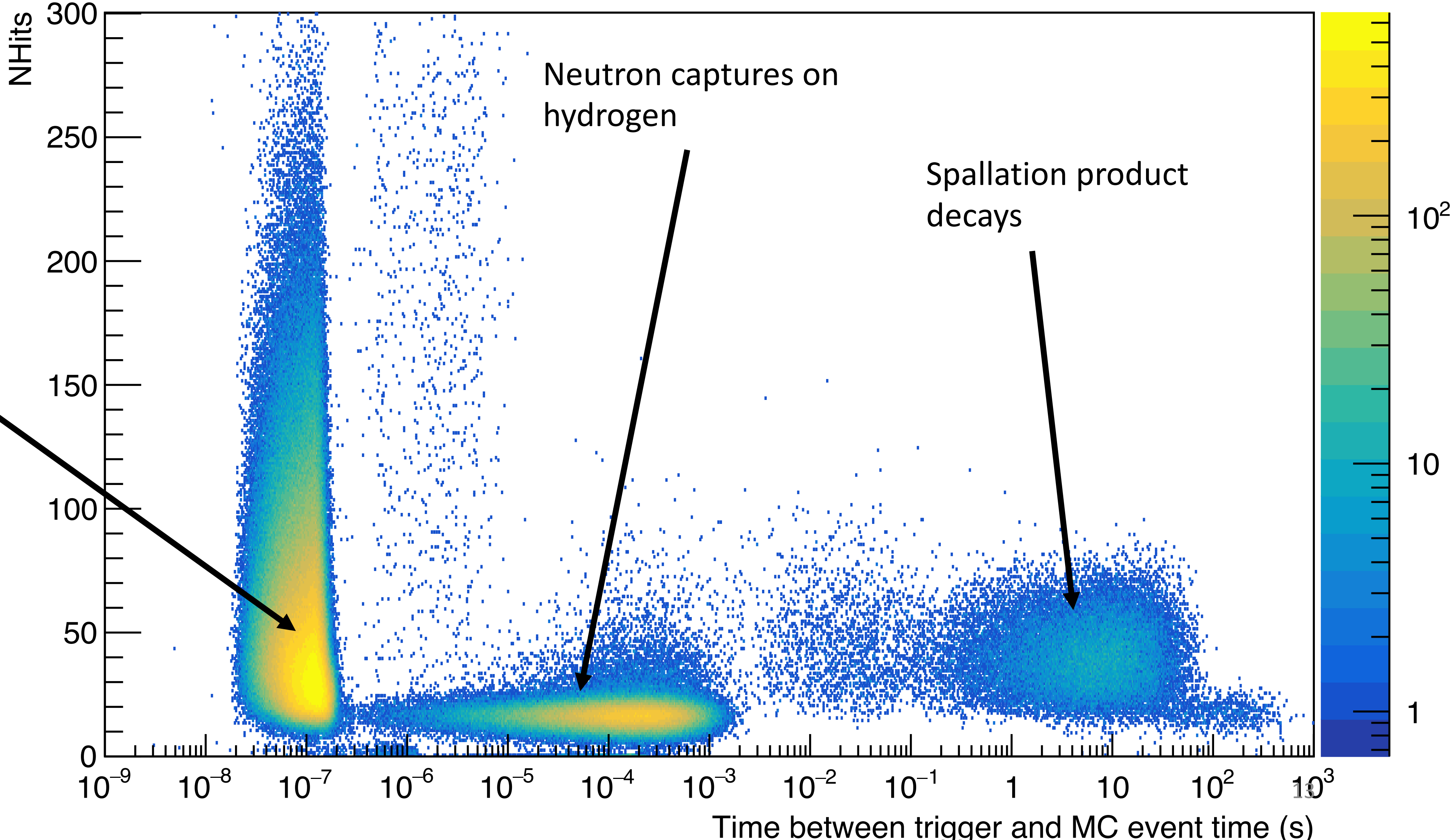


Distribution of neutron directions and energies obtained from the muon simulations.

Detector response to the neutrons

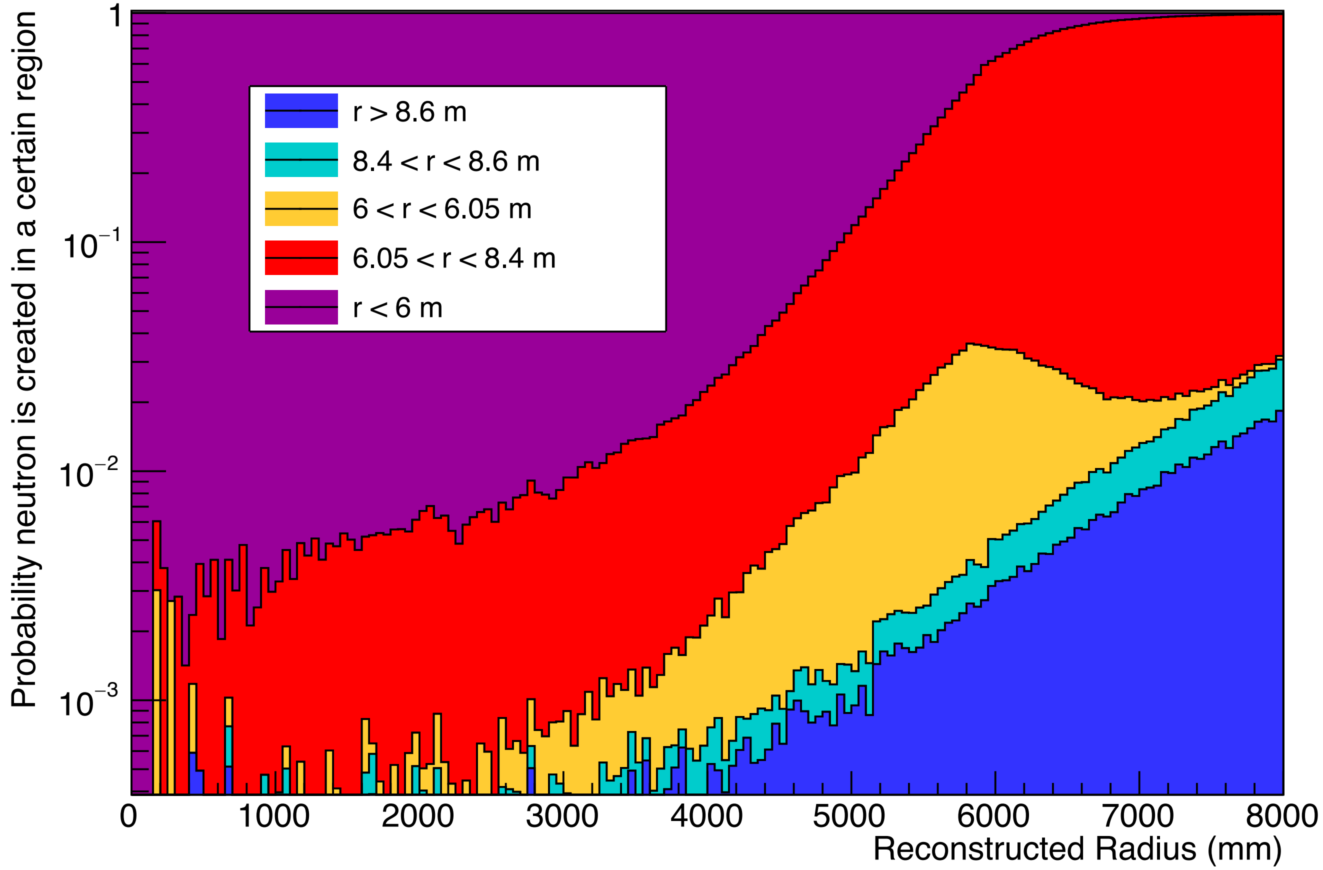
Primary scattering event (Will occur in same trigger window as muon)

Simulations were run to 1000 s after neutron generation.



Propagation of the neutrons

- Position of reconstructed capture position relative to production position subject to two effects
  - Propagation of the neutron from its creation position during thermalisation.
  - Misreconstruction of the neutron capture position.
- Approximately 3% of neutrons between PMT array and AV are due to neutrons production within the AV/PSUP external water*



*Simulations assume neutrons were generated uniformly along muon tracks, some reweighting required for additional neutrons produced in the PSUP and AV.

Conclusions

- Analysis underway to evaluate the systematics associated with the measurement of neutron multiplicity using a data driven approach.
- We are currently optimizing the selection of the neutrons, and evaluating their efficiencies on a muon by muon basis.
- Results to come soon.