WCTE run plan, prospects and first analyses

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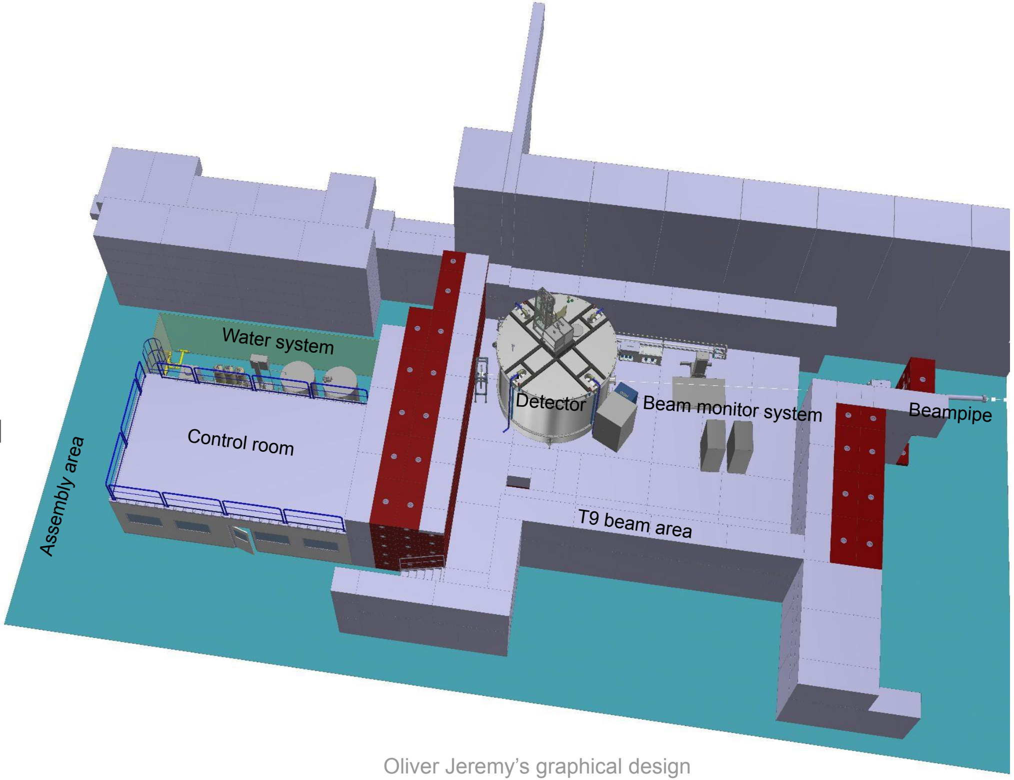
Contents

Introduction

The Water Cherenkov Test Experiment (WCTE) is a prototype water Cherenkov detector placed in the T9 East Hall facility at CERN, operated with secondary beam of low momentum (200-1200 MeV/c) flux of charged particles.



Oliver Jeremy's graphical design

Main goals:

- prove the new technologies that are being developed for next-generation water Cherenkov detectors,
- calibration/ detector response,
- study physics of particle propagation, Cherenkov production, secondary interactions, neutrons…

Design overview

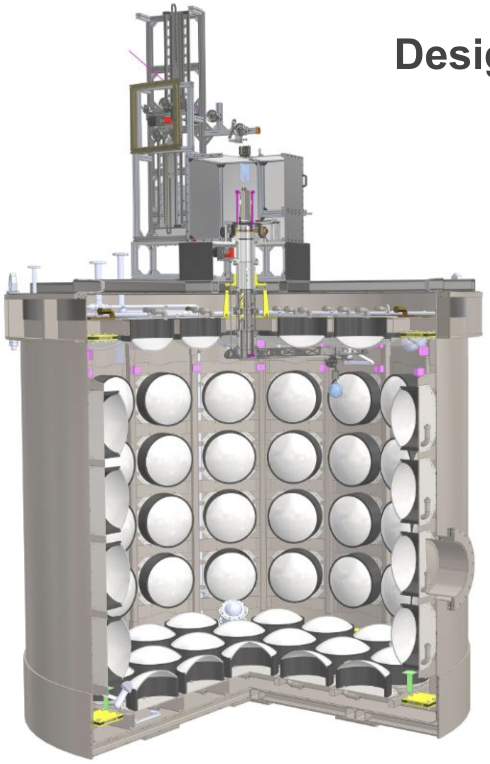
It consists of a tank of 3.50 m height and 3.80 m diameter, where the stainless steel support structure is going to be fitted.

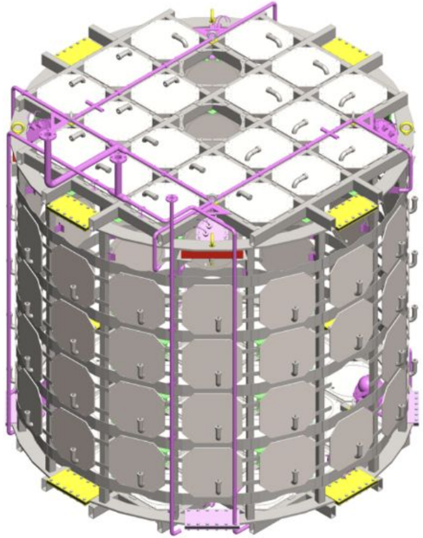
On it, 93 multi-photomultipliers -mPMTs- modules, each of them consisting in 19 3”PMTs, are mounted.

The ~4 m diameter of the tank was chosen to have particle containment (including reasonable containment of neutrons, i.e. 90% of neutrons contained!) and that is relevant for the IWCD.

41 ton of ultra-pure water will fill the tank.

Tank lid accommodates deployment of calibration sources, cabling and water circulation system.

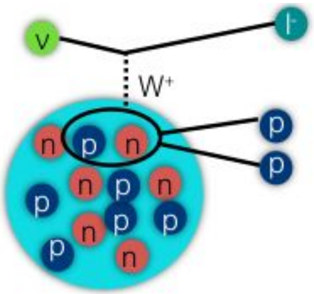




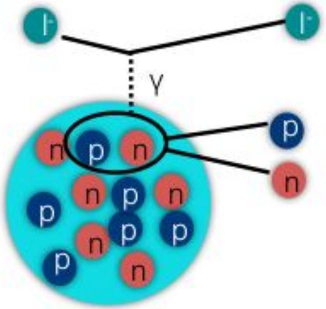
Oliver Jeremy’s graphical design

Physics: particle interactions in WCTE

Lepton scattering (e-, μ-)

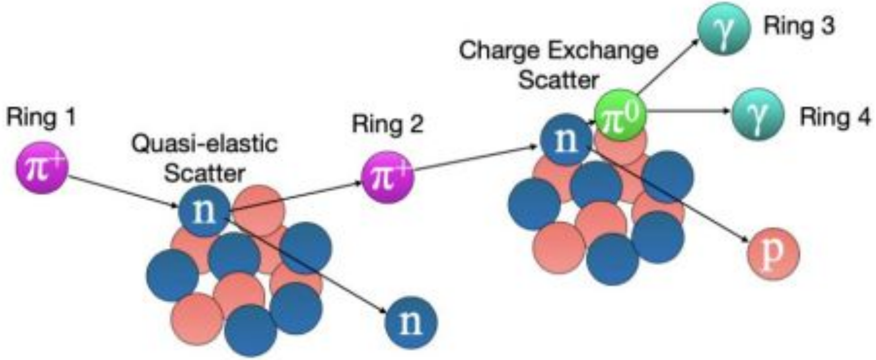


ν-nucleus scattering

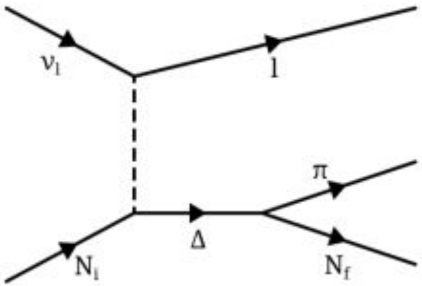


e-/μ--nucleus scattering

Pion scattering (π+)



π scattering in water



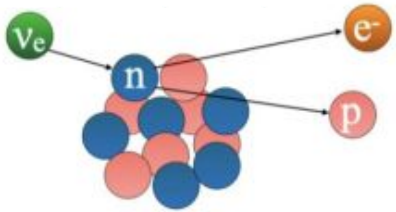
Feynman diagram for ν resonant π production

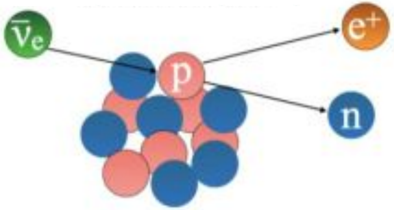
π of 500 MeV/c or less are produced in these interactions; we can study them in WCTE

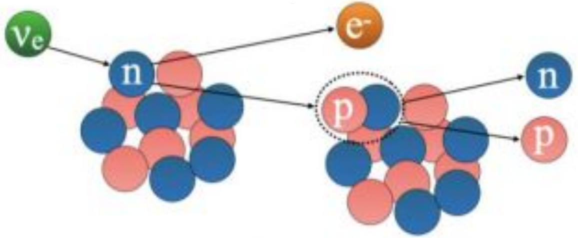
Neutron production and scattering in water

Antineutrino CCQE

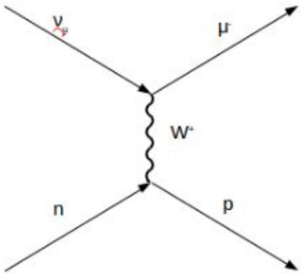
Secondary interaction



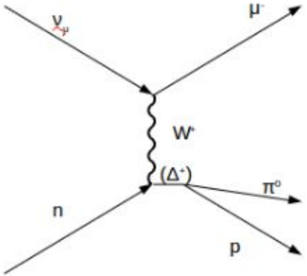




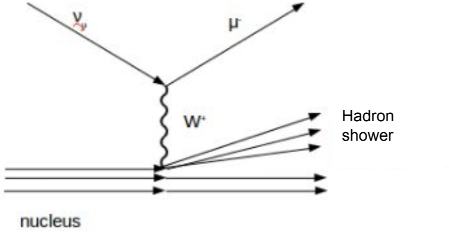
Neutrino CCQE



Feynman diagram for a CCQE interaction with muon ν



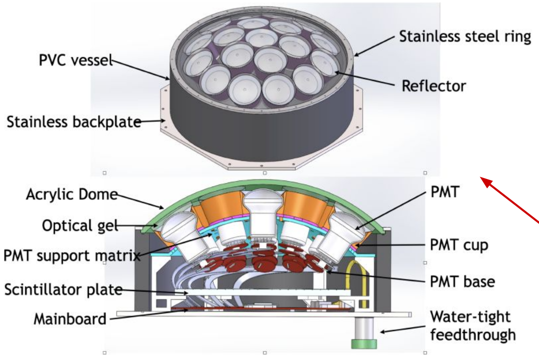
Feynman diagram for a ν resonant π production with Δ



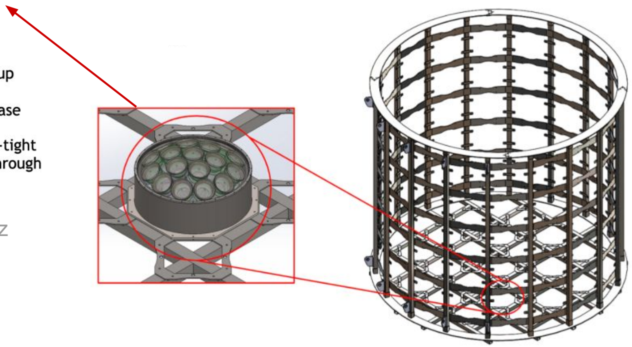
Feynman diagram for a ν DIS interaction

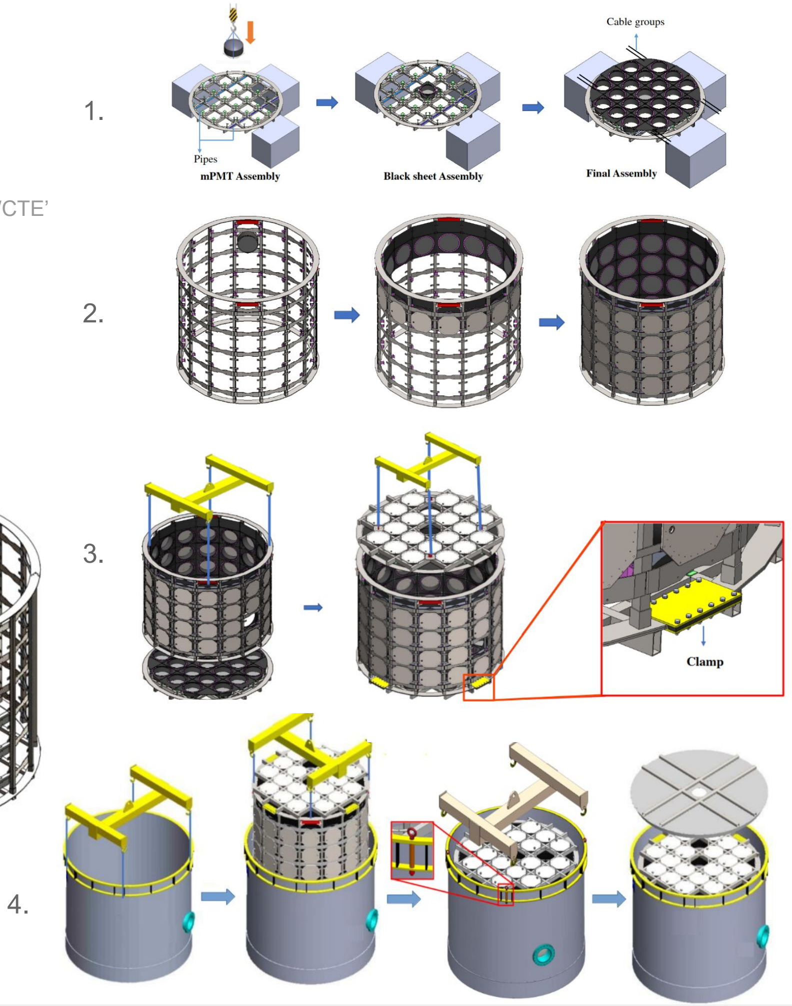
WCTE assembly and data taking

See slides from J.Pelegrin, 'Design and installation of WCTE'



'Technical introduction for the WCTE', Mark Hartz





Calendar

The assembly is about to be completed during these days:

- from October 9th, 1 week to install everything at T9 beam area.
- commissioning starting October 16th.

First data taking period:

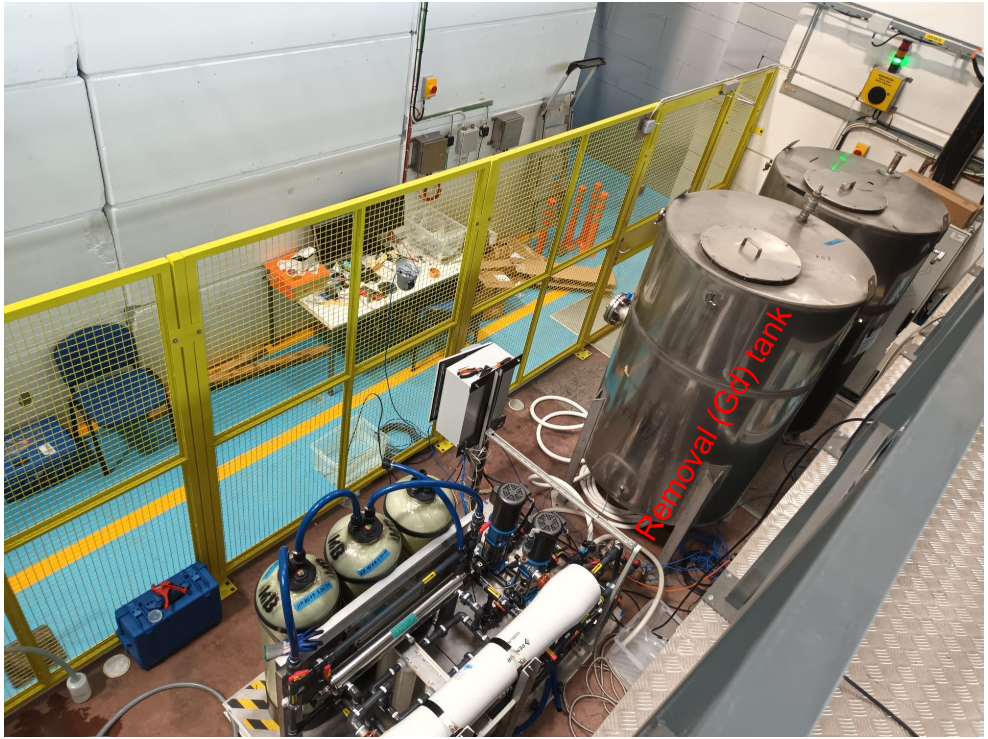
- October 16th - November 27th, 2024.
- from November 27th, 2 weeks for calibration.

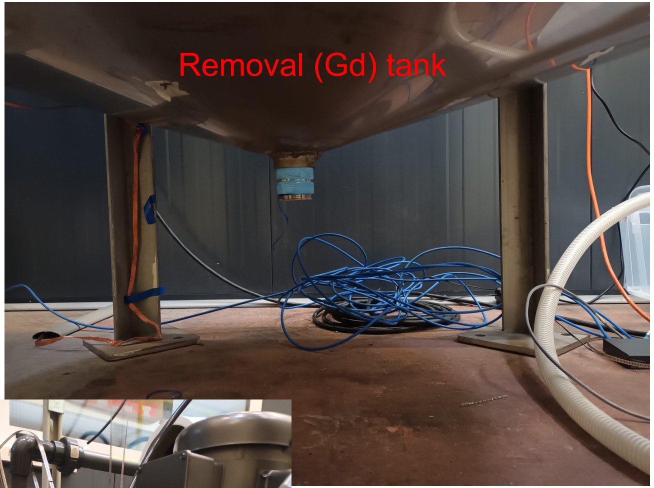
Second run is planned for spring 2025, ultra-pure water with Gd loaded to enhance neutron tagging.

T9 area @ CERN
(my experience)

2 Sept. 2024

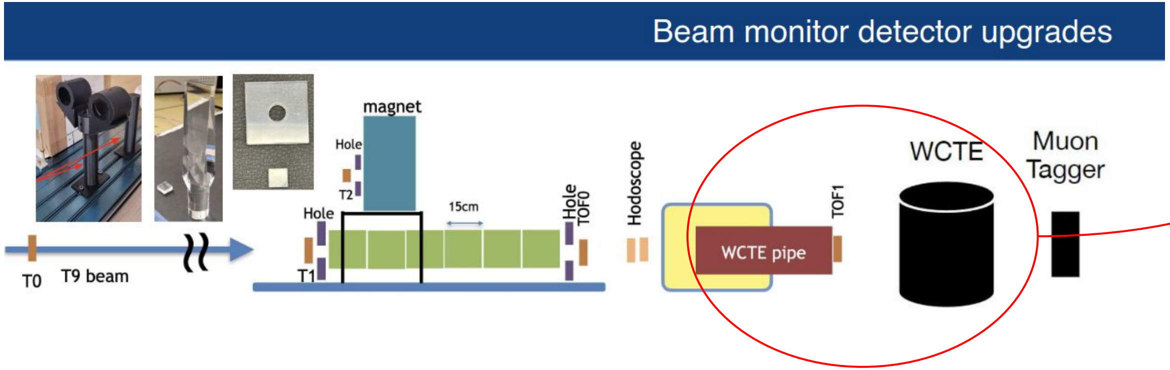
Water system (purification and Gd mixing)





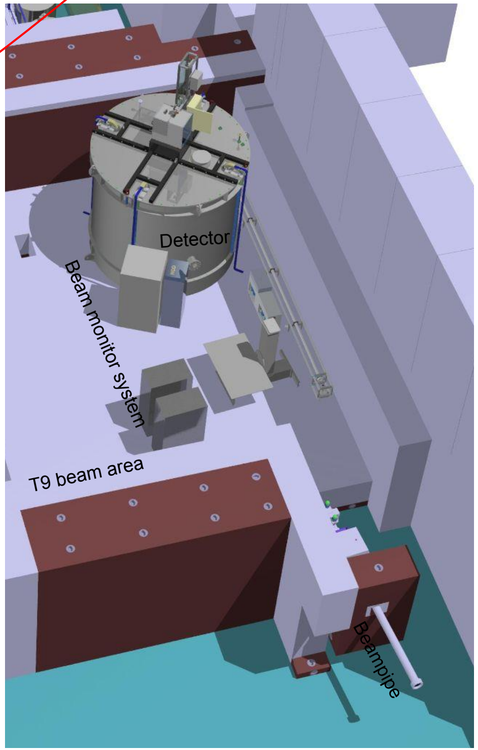
6 & 9 Sept. 2024

This is the charged particle setup!
WCTE will also study γ (Tagged Gamma Configuration).



'Beam Status', Akira Konaka for the WCTE general meeting, Sept. 6, 2024

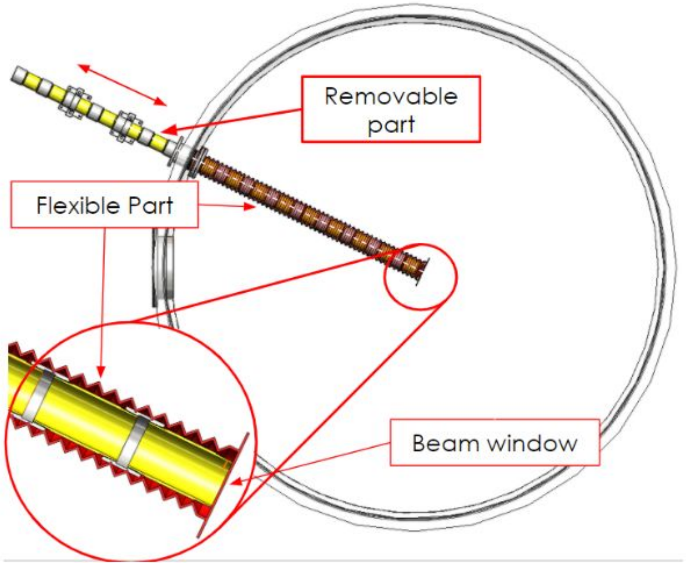
Oliver Jeremy's graphical design

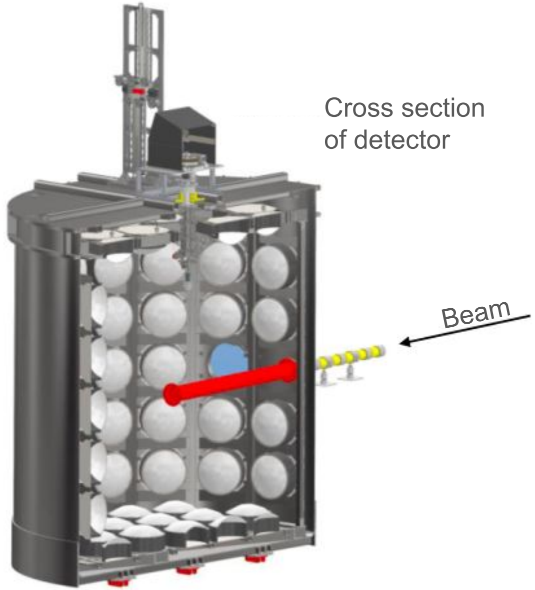


This is the beam monitor schematic view. All these components will be outside WCTE tank and will identify the beam particles and its characteristics.

Then we will be able to study one-to-one each event, from the beam and also its behaviour inside the tank.

We will only care about the pipe and the tank, as the purpose of this analysis is to optimize the beam pipe length.



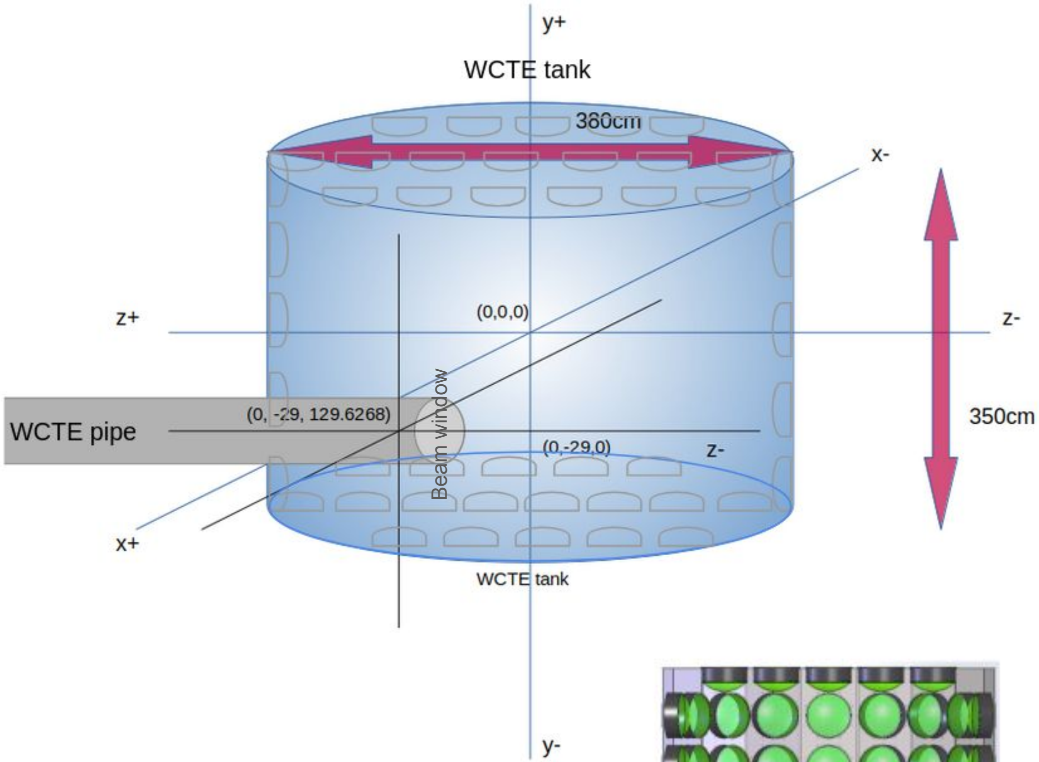


'Technical introduction for the WCTE', Mark Hartz

Simulations & analyses

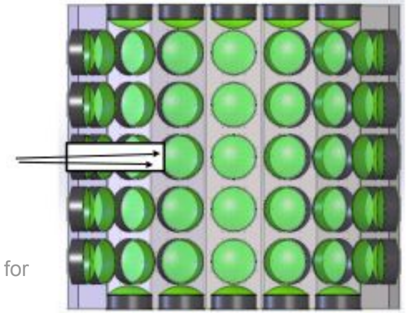
We use WCSim, which is a GEANT4 based program for developing and simulating water Cherenkov detectors: https://github.com/WCTE/WCSim

Macros produced with MC_Production: https://github.com/WCTE/MC_Production




```
/gps/direction 0 0 -1
```

Geometry considered in this analysis



'Introduction to Hyper-K, the IWCD and the WCTE', Mark Hartz for the WCTE Meeting at CERN, July 18, 2018

We assume 129.6268 cm to be the 'wall' (already considering the distance between the wall and the blacksheet + PMTs' domes), and 0 cm the center of WCTE tank.

```
/run/verbose 1
/tracking/verbose 0
/hits/verbose 0


/WCSim/WCgeom nuPRISMBeamTest_16cShort_mPMT
/WCSim/Geometry/RotateBarrelHalfTower true

/WCSim/PMT/ReplicaPlacement false
/WCSim/PMT/PositionFile /scratch/elena/elena_wcsim/install/data/mPMT_Position_WCTE.txt


/WCSim/Construct

/WCSim/PMTQEMethod SensitiveDetector_Only
/WCSim/PMTCollEff on

/WCSim/SavePi0 false

/DAQ/Digitizer SKI
/DAQ/Trigger NoTrigger

/control/execute /scratch/elena/elena_wcsim/install/macros/daq.mac

/WCSim/random/seed 291413421

/DarkRate/SetDarkMode 1
/DarkRate/SetDarkHigh 100000
/DarkRate/SetDarkLow 0
/DarkRate/SetDarkWindow 4000

/mygen/generator gps
/gps/particle e-
/gps/energy 200 MeV
/gps/direction 0 0 -1
/gps/position 0 -29 77.25233535353536 cm

/Tracking/fractionOpticalPhotonsToDraw 0.0

/WCSimIO/RootFile wcsim_e-_Beam_200MeV_30cm_0040.root

/run/beamOn 1000
```

Only `particle`, `energy` and z coordinate of the `position`* are variables in this study.

For each particle (e-, mu-, pi+), we have generated 100 files with fixed energy (200, 300, 400, 500, 600, 700, 800, 900, 1000 MeV), where only the z position is varying, ranging from 129.6268 cm to 0 cm, 1000 events each

*where the particle is appearing inside the tank at the end of the WCTE pipe, i.e. where the particles are ejected into WCTE tank.

We transform the `.root` file - macro output - into `.npz` file, the one that we use to develop our analysis and our plots.

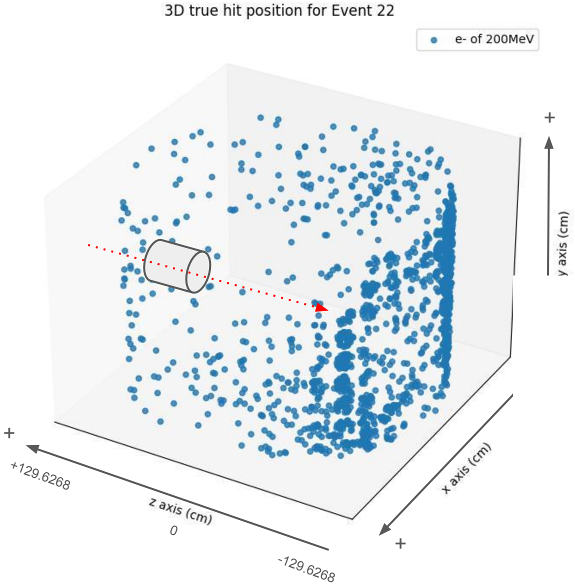
```
all_variables = ['event_id', 'root_file', 'pid', 'position', 'direction', 'energy', 'digi_hit_pmt', 'digi_hit_charge', 'digi_hit_time', 'digi_hit_trigger', 'true_hit_pmt', 'true_hit_time', 'true_hit_pos', 'true_hit_start_time', 'true_hit_start_pos', 'true_hit_parent', 'track_id', 'track_pid', 'track_start_time', 'track_energy', 'track_start_position', 'track_stop_position', 'track_parent', 'track_flag', 'trigger_time', 'trigger_type']
```

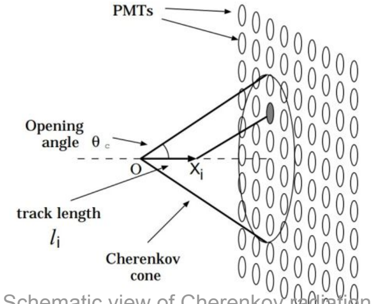
These are all the variables currently available, from which we used `true_hit_pos` for the number of PMT hits (`n_hits`) and `digi_hit_charge` (`total_charge(Q) = sum(digi_hit_charge)`), among others*.

*`position`, `direction`, `energy`, `digi_hit_pmt` were also used in a first detailed analysis with a single generated file.

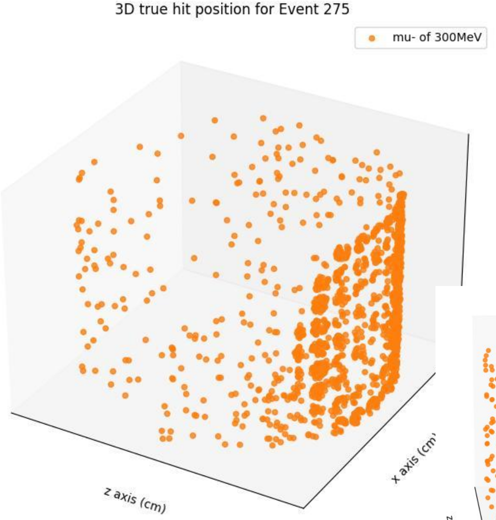
Preliminary

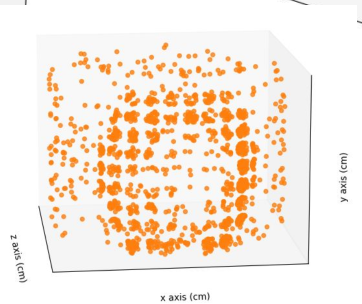
Charged particles (e-, mu-, pi+)

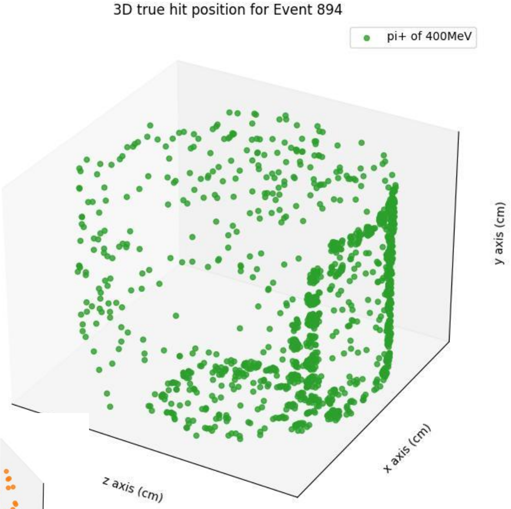




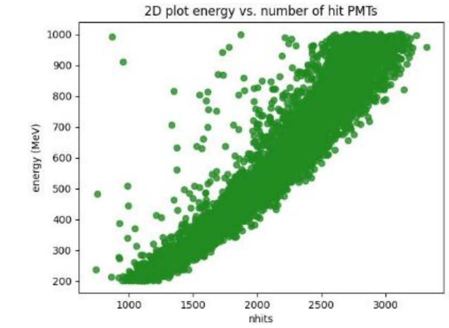
Schematic view of Cherenkov radiation, where *O* is the vertex, *li* is the track length of the charged particle from it, and the photons that hit the *ith* PMT, were emitted at *Xi*.

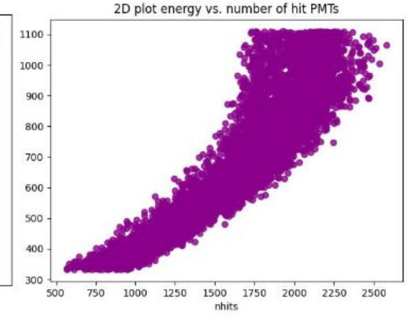


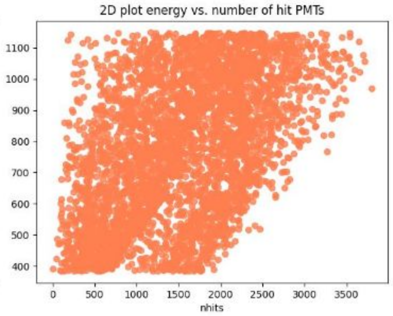


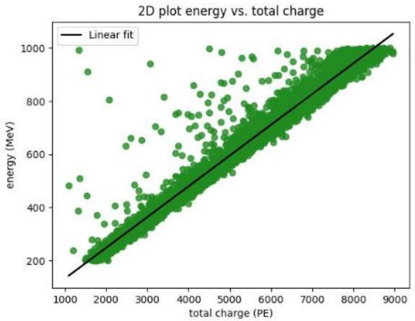


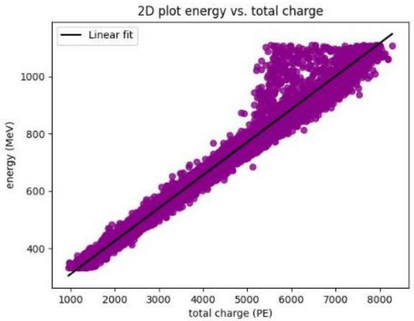
Preliminary

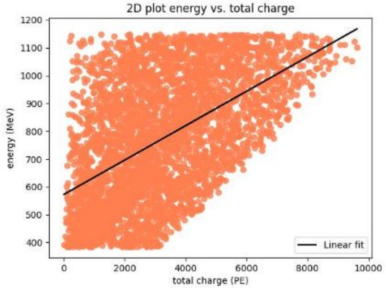












5000 events in the file of e-

5000 events in the file of mu-

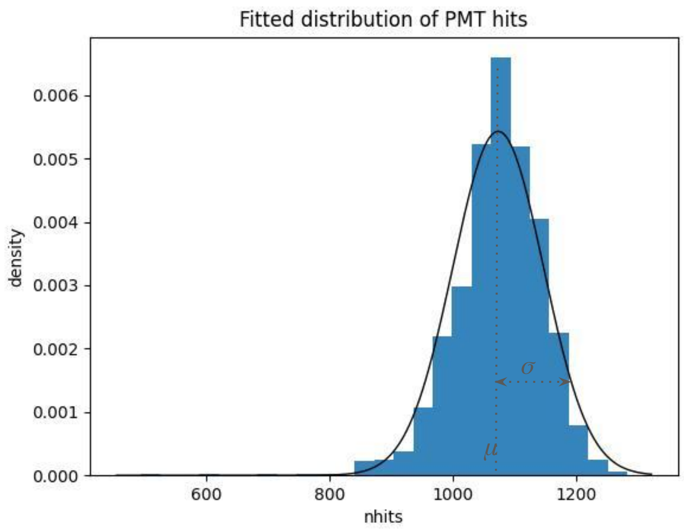
3947 events in the file of pi-

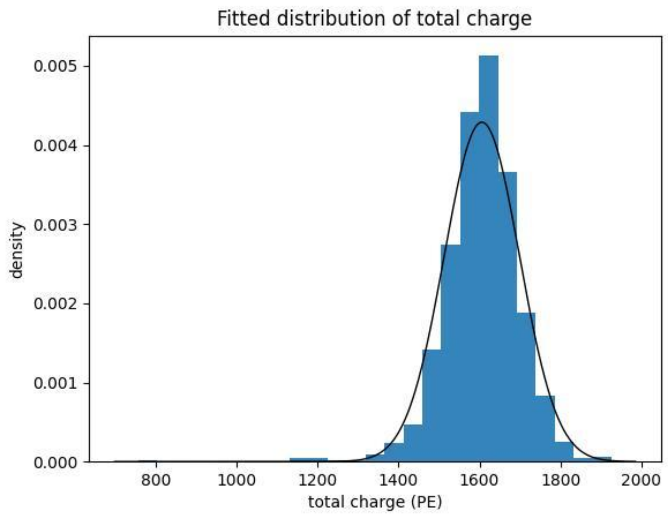
Negative pions interact not only through electromagnetic force, but also the strong one, leading to a higher absorption of these particles because of the oxygen nuclei.

This is the reason why energy vs. nhits for π- do not follow such a linear relationship.

Therefore, we will not consider π- in this analysis.

We have developed a **Gaussian fit** over the distribution of the number of PMT hits (`digi_hit_pmt` variable), using a generated file of 1000 events of e^- with a fixed momentum of 200 MeV/c.





Same for the distribution of the total charge

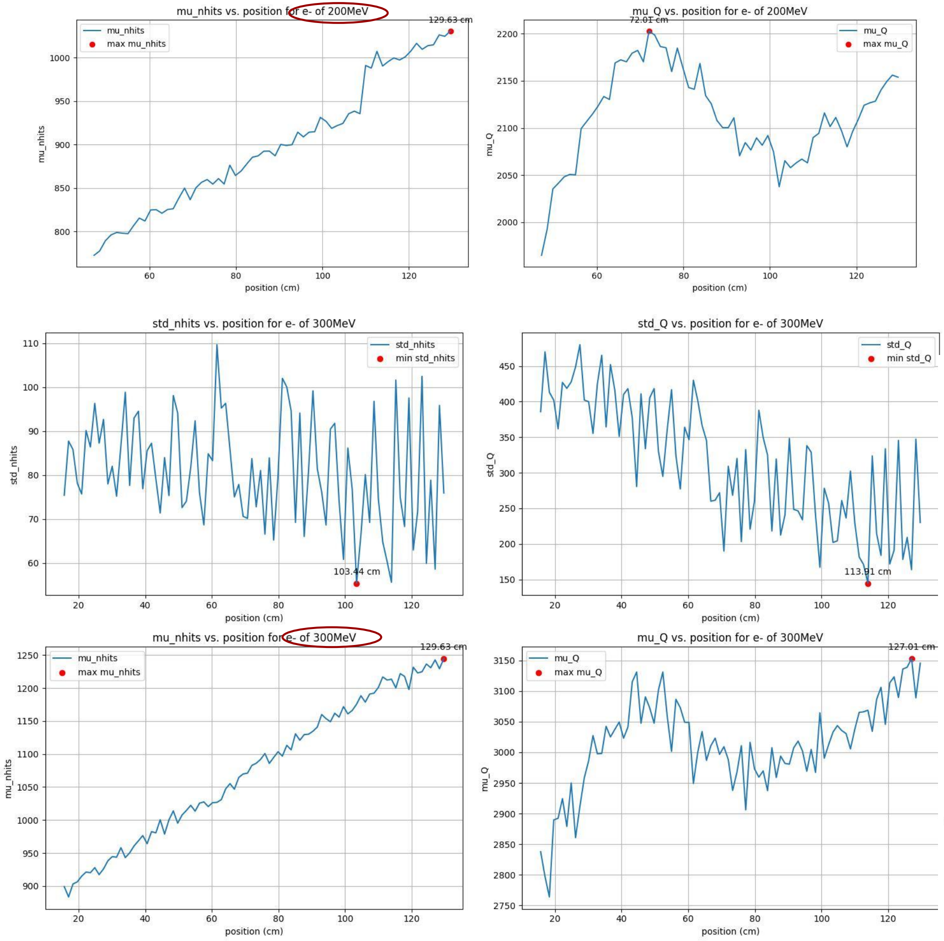
(`Q = sum(digi_hit_charge)`)

σ: standard deviation

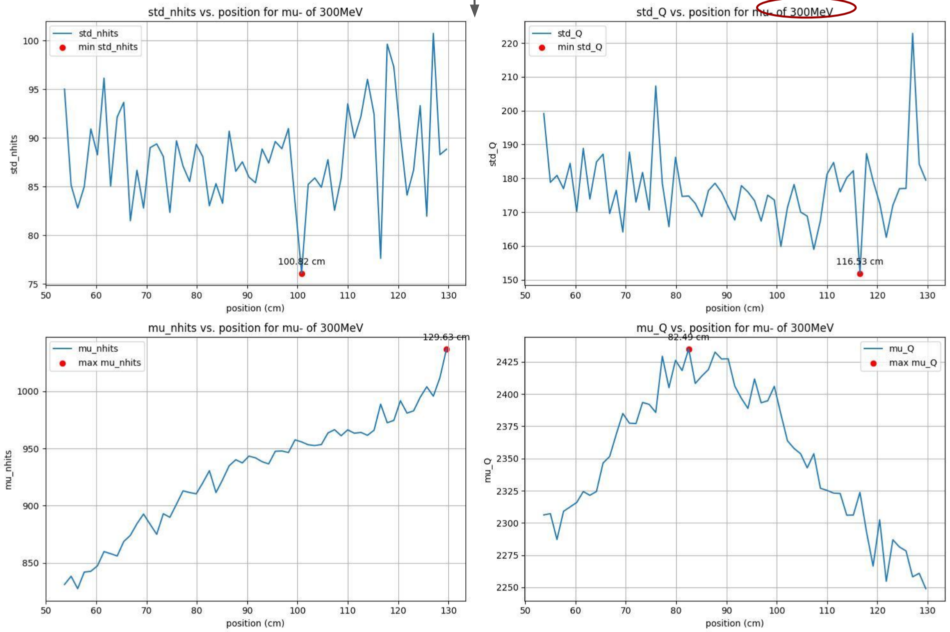
μ: mean

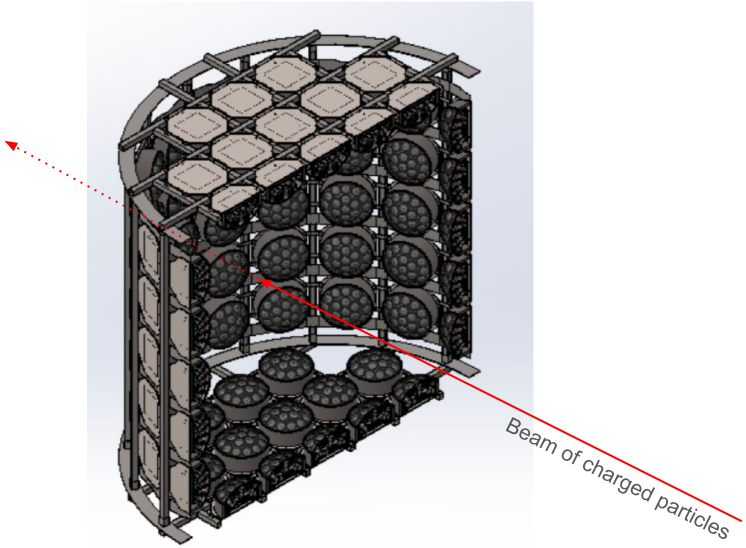
We can discard σ plots, and focus only on those of the μ.

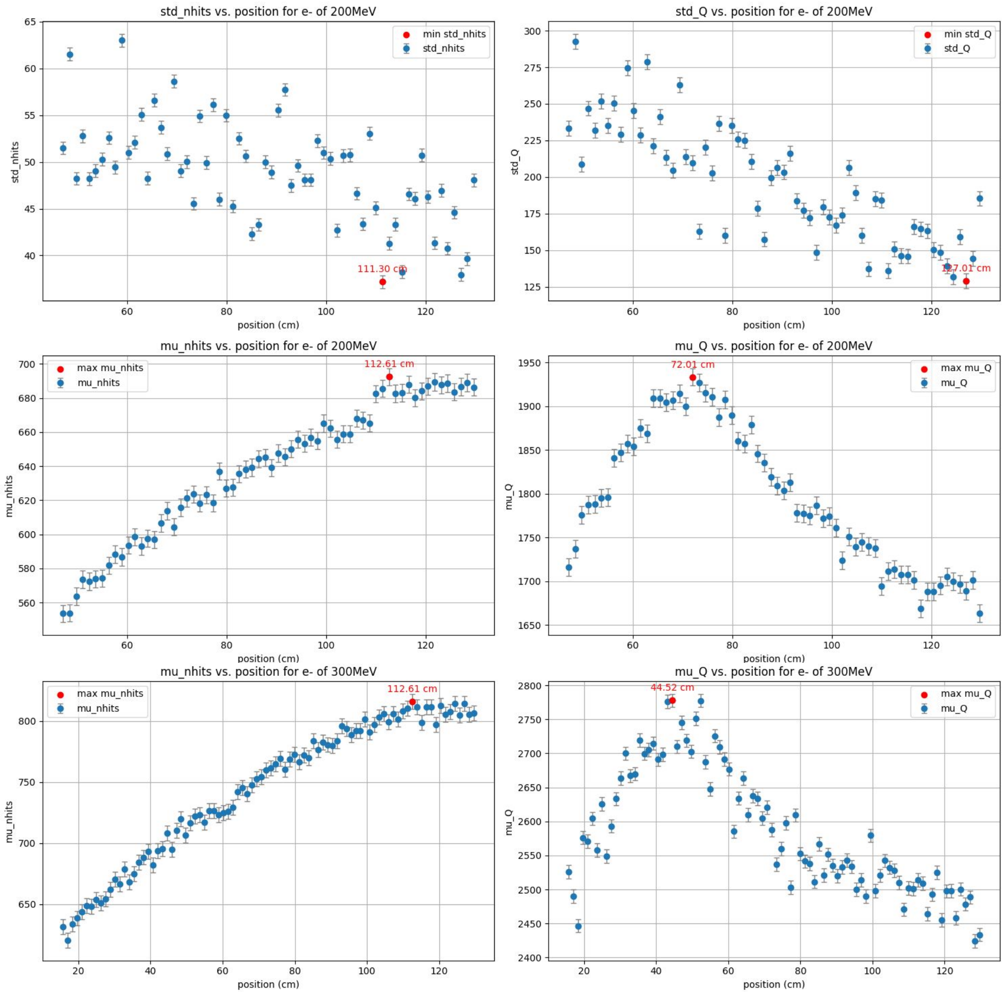
electrons



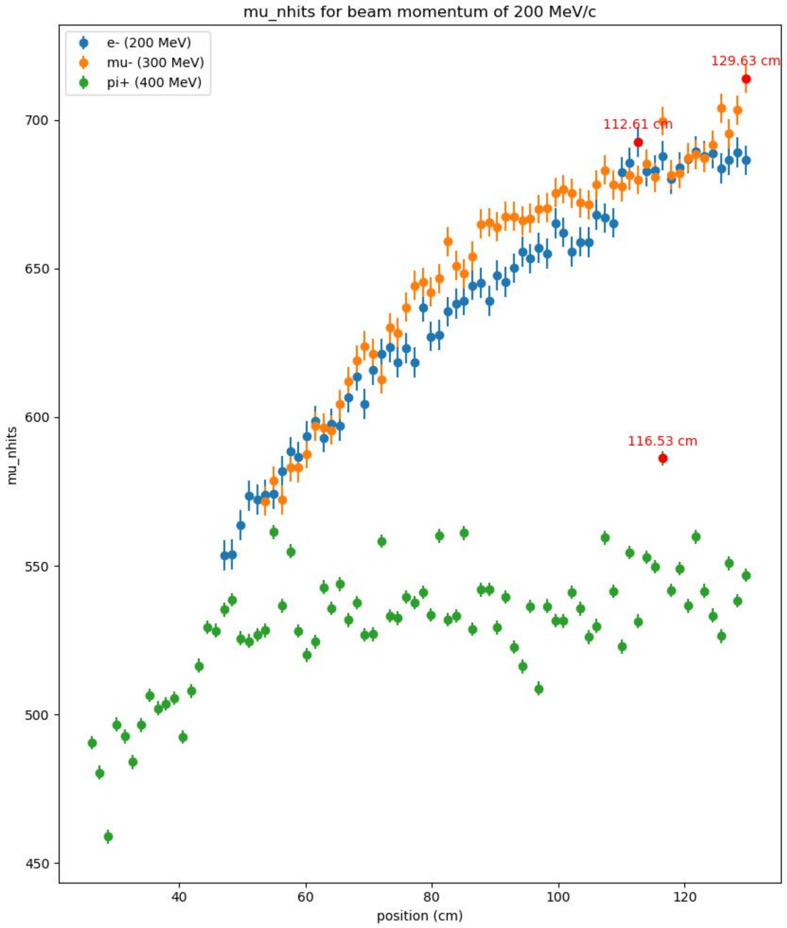
muons

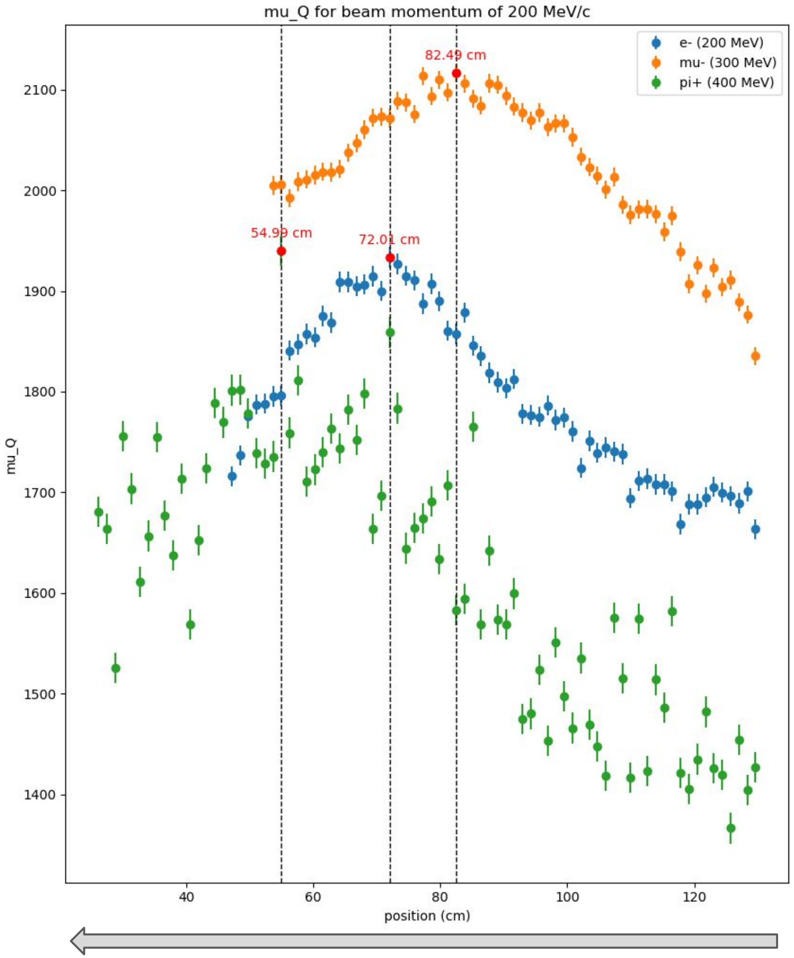






We developed a cut ⟶ considering only forward mPMTs for the next step of the analysis





It is clear that `total_charge` `(Q)` is a better parameter for this study.

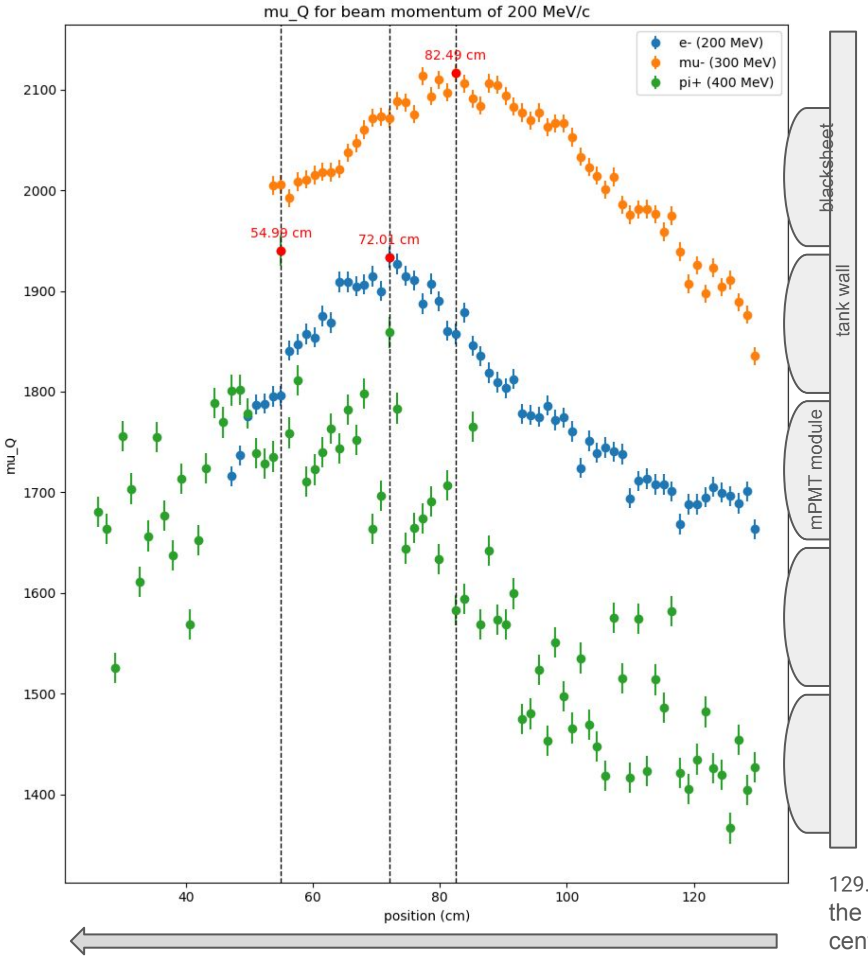
129.6268 cm end of the dome, 0 cm the center of WCTE tank.

- We will based our conclusions in the results for this low beam momentum value, for which charged particles will have the most sensible behavior when interacting.

- Emphasized lepton interactions over π.

- In particular *e*- which interact quickly in water, while μ- are very penetrating, thus they suffer less absorption.

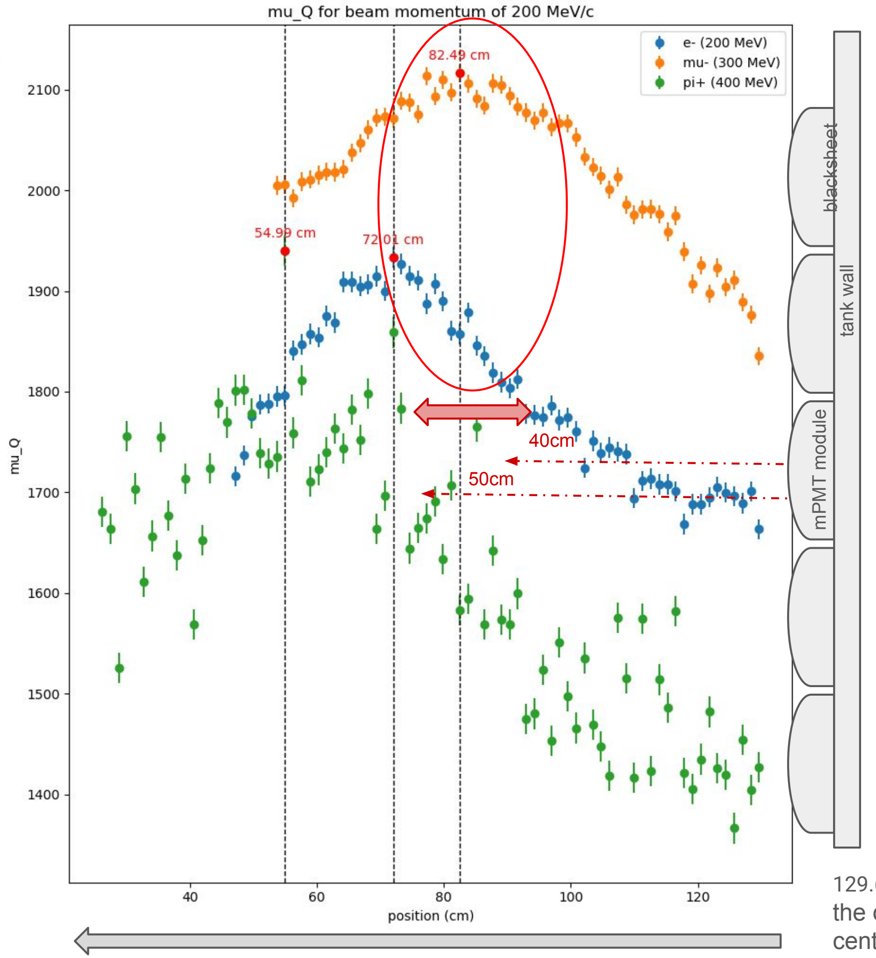
- As we move away from the peak, particles escape the detector before emitting all their energy; the result should be as close as possible to it.



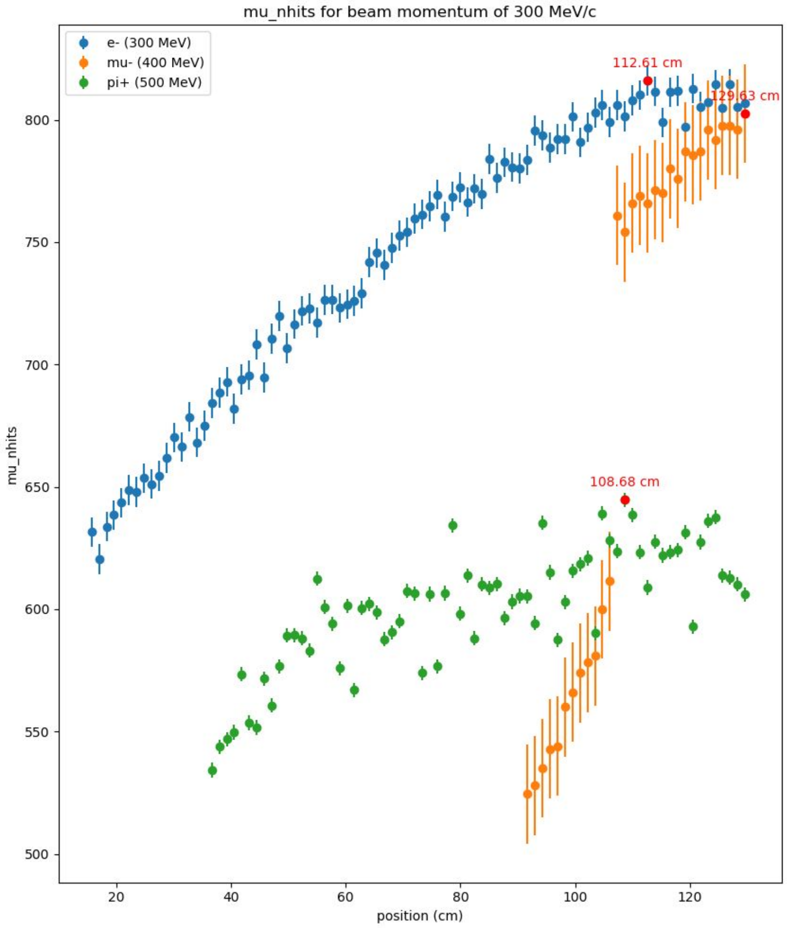
129.6268 cm end of the dome, 0 cm the center of WCTE tank.

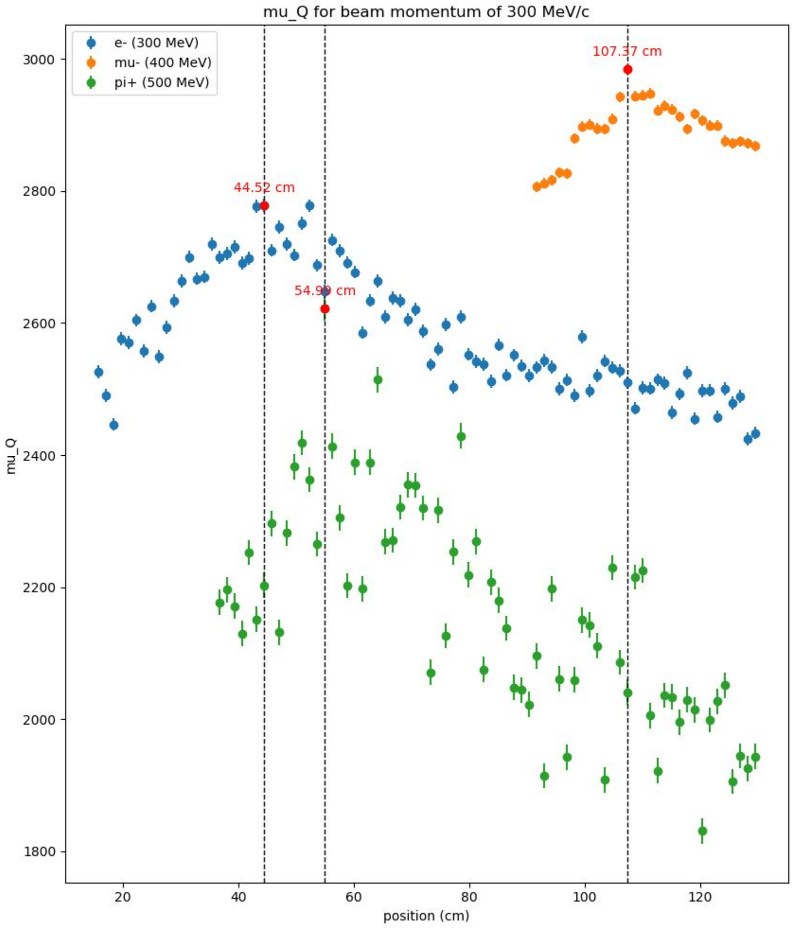
beam momentum(MeV/c)	particle	max mu_Q(PE)	position(cm)
200	e-	1933.3414306640625	72.01488888888889
200	mu-	2116.433837890625	82.48978181818183
200	pi+	1940.01513671875	54.99318787878788

By establishing the beam window in the region between 40 and 50 cm from the end of the mPMT dome, we expect to have the best detection efficiency of WCTE for charged particles at low momentum!

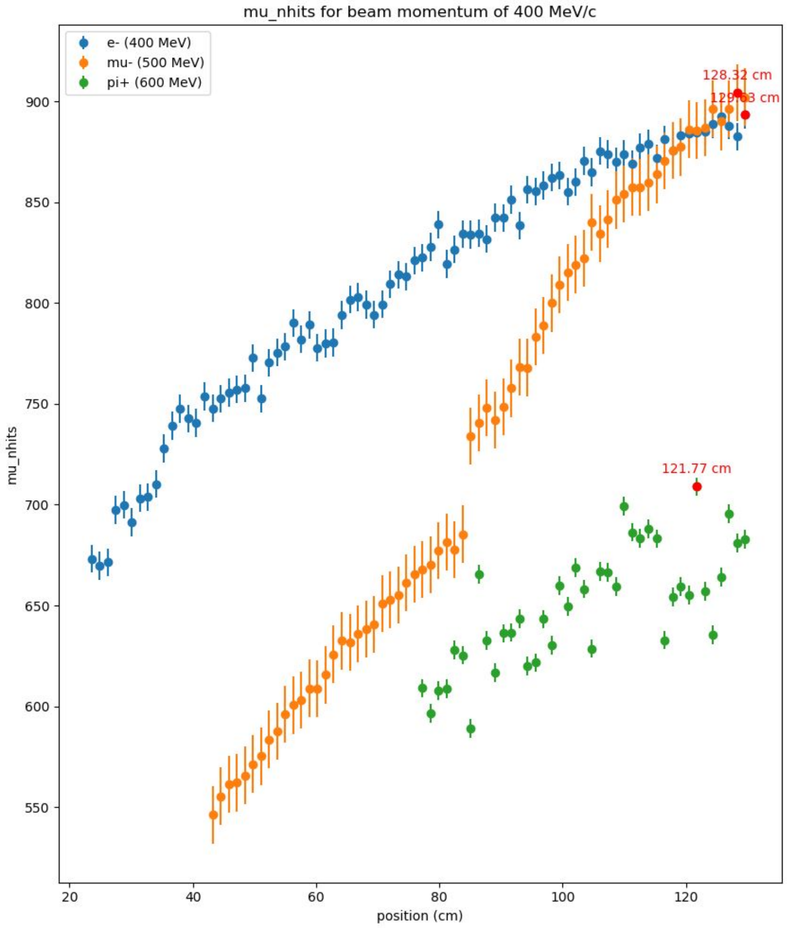


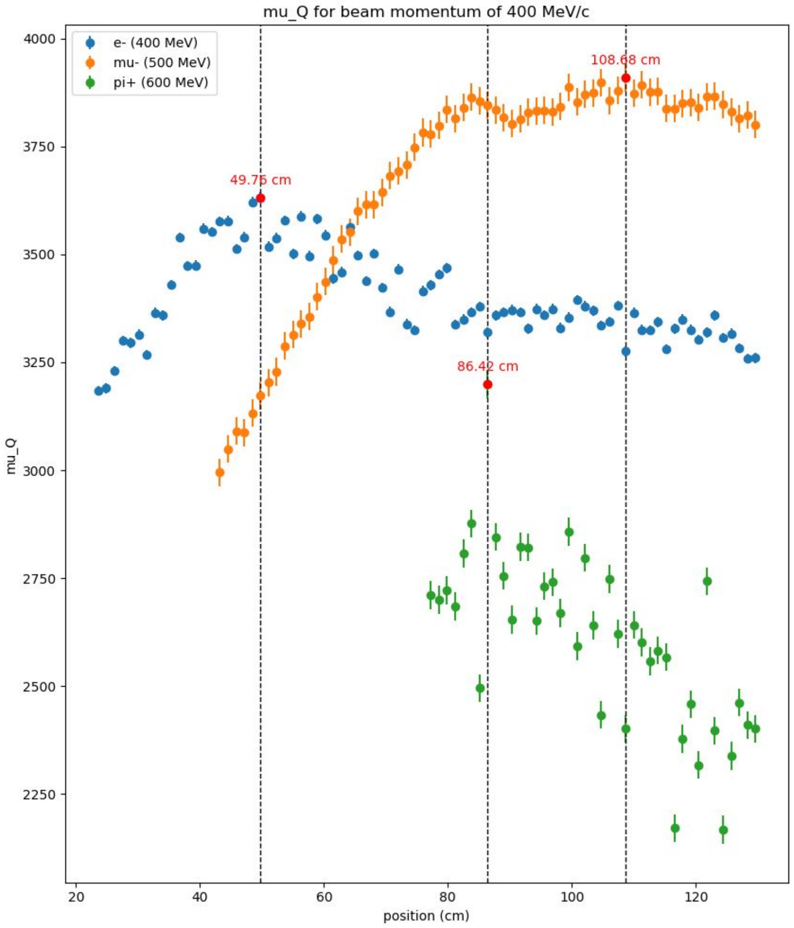
129.6268 cm end of the dome, 0 cm the center of WCTE tank.





Something strange is happening with muons, need to check this!

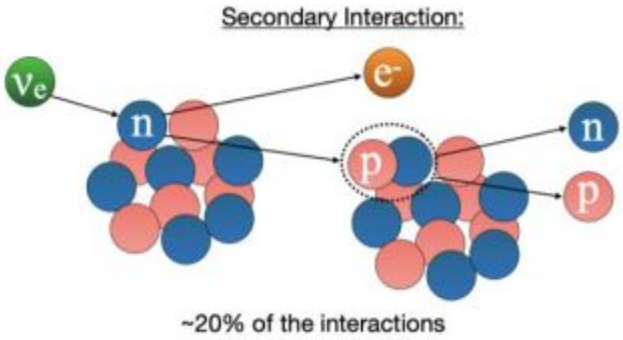

mu_nhits for beam momentum of 400 MeV/c
e- (400 MeV)
mu- (500 MeV)
pi+ (600 MeV)
128.32 cm
129.63 cm
121.77 cm
mu_nhits
position (cm)

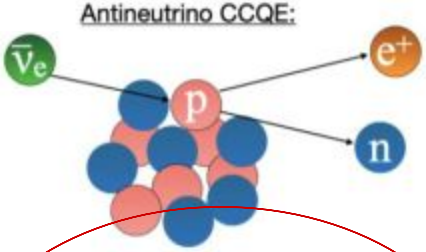

mu_Q for beam momentum of 400 MeV/c
e- (400 MeV)
mu- (500 MeV)
pi+ (600 MeV)
108.68 cm
49.76 cm
86.42 cm
mu_Q
position (cm)

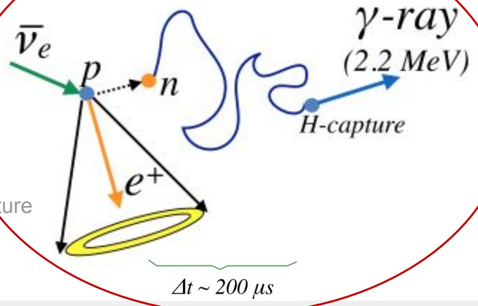
Neutrons

Tagging and detailed study of these particles in WCTE

- Neutrons are secondary particles produced once a ν interacts with ultra-pure water.
- These secondary interactions makes it hard to understand relative rate of *n* from ν and anti-ν.
- They can be detected through the outgoing 2.2 MeV gamma ray.
- For HyperK, it will be very interesting to improve our knowledge about *n* secondary production.

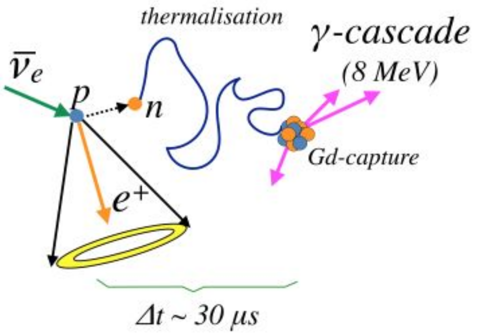






Schematic diagram of IBD with H-neutron capture

Schematic diagram of IBD with Gd-neutron tagging



To be continue….

- By loading Gd in this ultra-pure water, we increase considerably the detection efficiency (8 MeV gamma cascade).

Future analysis with Gd

Data taking in spring 2025

Summary

- WCTE to **prove new technologies** developed for next-generation water Cherenkov test experiment (e.g. mPMTs for the IWCD, HK experiment).
- Study **detection response** (as we did in this analysis).
- **Assembly is about to be finished during this week**, and from October 9th, 1 week to install in T9 beam area.
- First data taking period: **October 16 - November 27, 2024**. Second run **with Gd: spring 2025**.
- By developing a detailed study about the **optimization of the beampipe length**, we have found that **the best region is from 40 to 50 cm inside the tank from the dome of the mPMTs**, for charged particles (based on the results obtained for low momentum).
- For **neutrons**, a **similar study is going on**, but we do not expect to rely heavily on a specific value due to neutrons' nature. Future analysis of neutrons with Gd loaded.

References

1. M. Barbi et al., *Proposal for a Water Cherenkov Test Beam Test Experiment for Hyper-Kamiokande and Future-large Water-based Detectors,* tech. rep., CERN, Geneva, March 2020 https://cds.cern.ch/record/002712416

2. The WCTE Collaboration, *Water Cherenkov Test Experiment (WCTE) Annual Report*, tech. Rep., CERN, Geneva, April 2023 https://cds.cern.ch/record/2857041

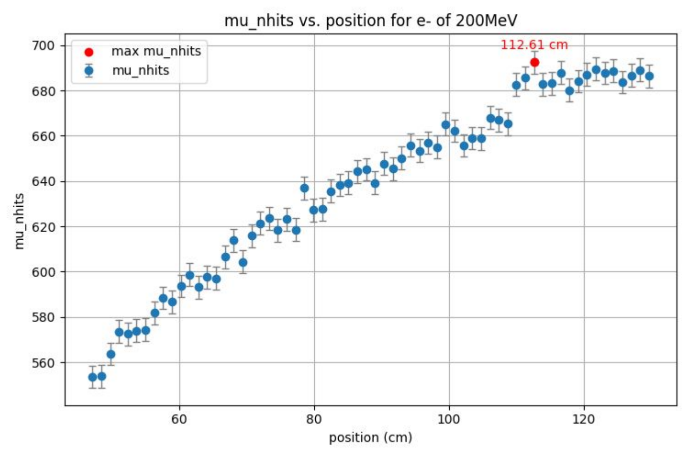
3. E. Ramos, *Water Cherenkov Test Experiment (WCTE) and beam test of July 2023,* poster at the 22nd International Workshop on Next Generation Nucleon Decay and Neutrino Detectors, Procida, Italy, Oct. 2023 https://wcte.hyperk.ca/documents/drafts/poster_nnn23.pdf/view

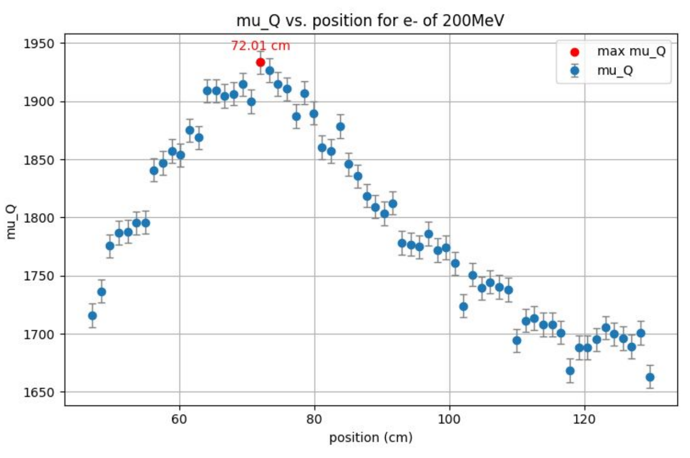
4. B. Bourguille, *Study and modelization of a neutrino-nucleus CCQE interaction model*, Doctor Thesis, IFAE, Barcelona, Spain, April 2020 https://www.tdx.cat/bitstream/handle/10803/670411/brbo1de1.pdf?sequence=1&isAllowed=y

5. J. Kumeda, *Detailed Studies of Neutrinos Oscillations with Atmospheric Neutrinos of Wide Energy range from 100 MeV to 1000 GeV in Super-Kamiokande*, Doctor Thesis, University of Tokyo,, Sept 2002 https://www-sk.icrr.u-tokyo.ac.jp/sk/_pdf/articles/kameda_d.pdf

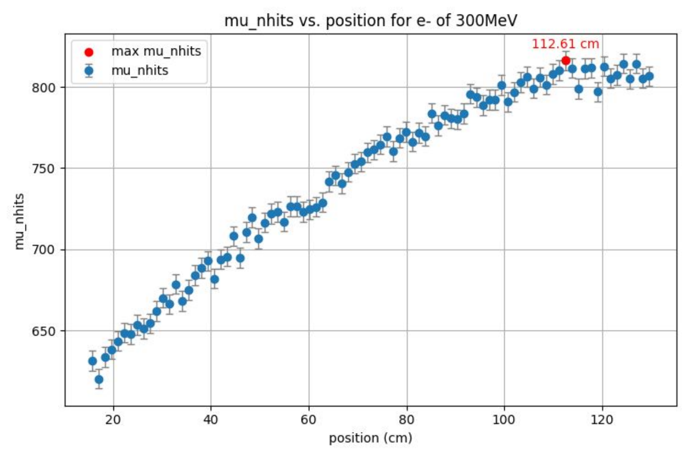
Thank you!

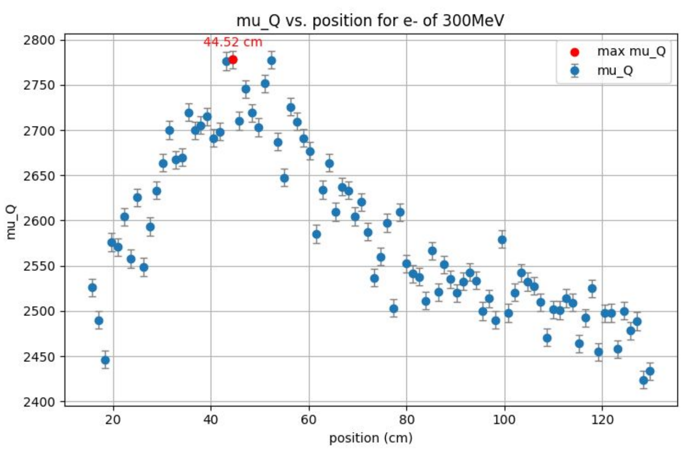
Backup slides

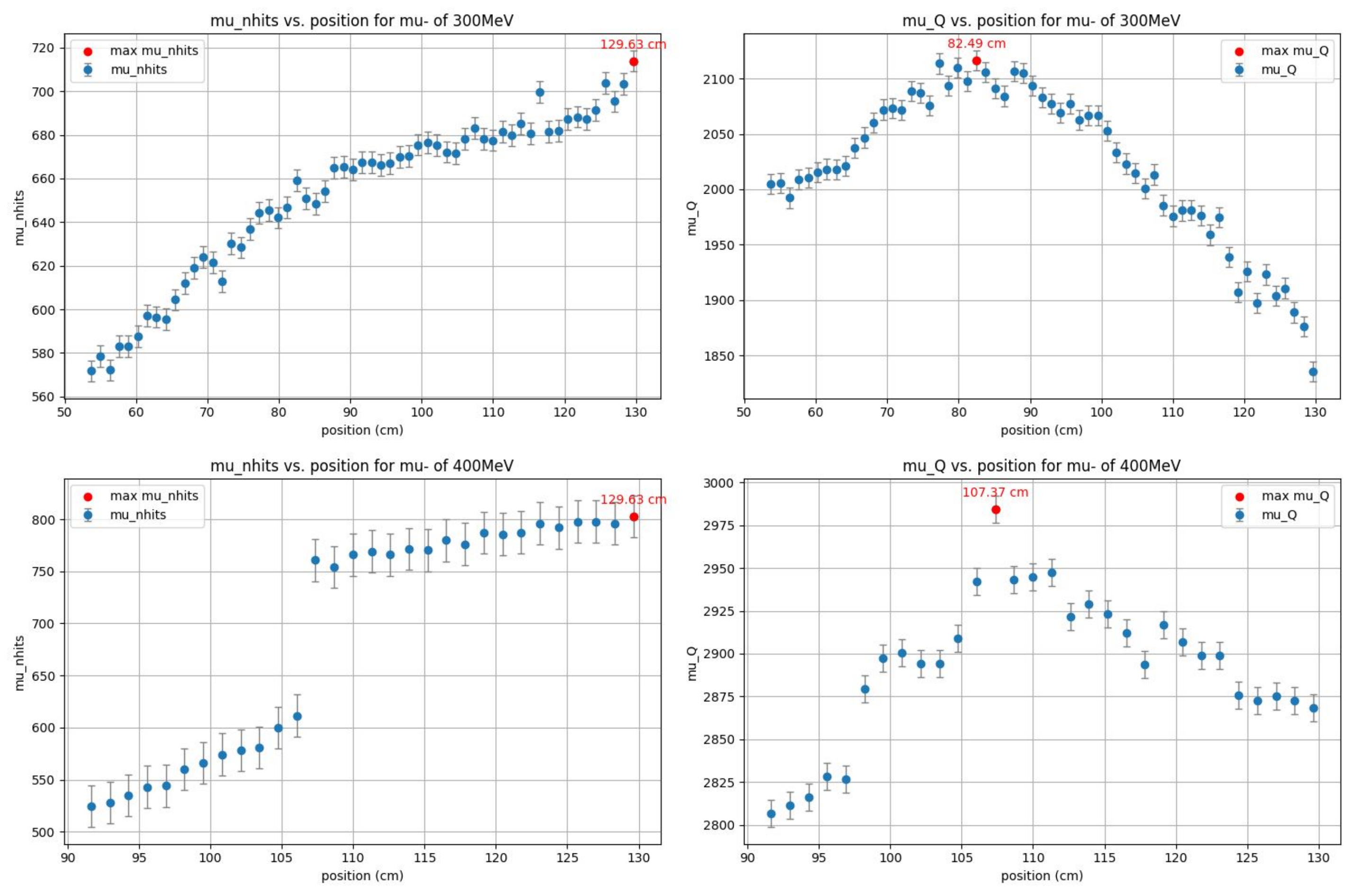

mu_nhits vs. position for e- of 200MeV
max mu_nhits
mu_nhits
112.61 cm
mu_nhits
position (cm)


mu_Q vs. position for e- of 200MeV
max mu_Q
mu_Q
72.01 cm
mu_Q
position (cm)

electrons

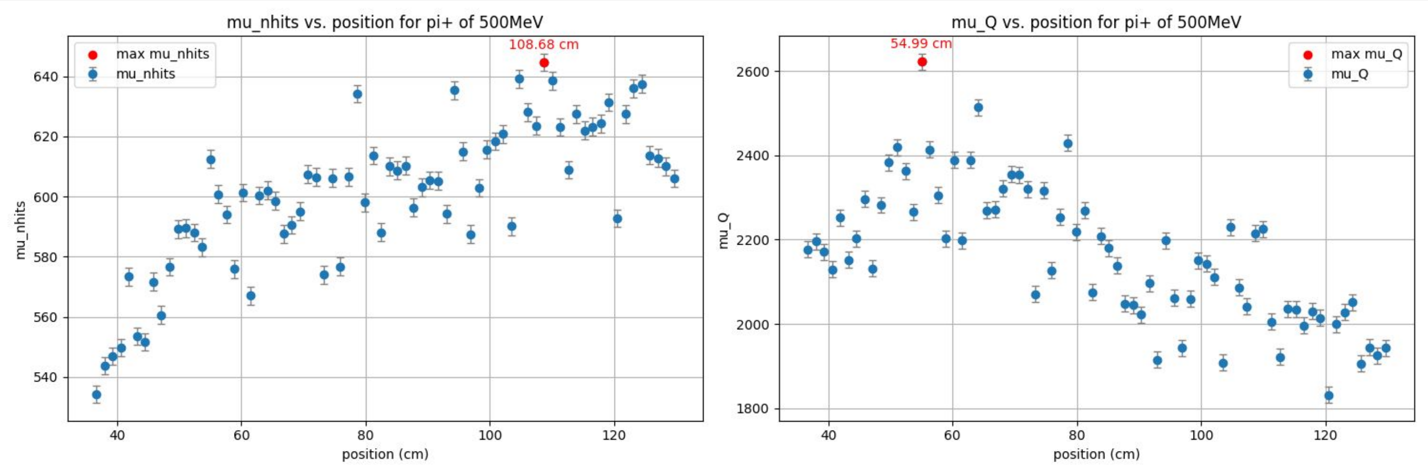

mu_nhits vs. position for e- of 300MeV
max mu_nhits
mu_nhits
112.61 cm
mu_nhits
position (cm)


mu_Q vs. position for e- of 300MeV
max mu_Q
mu_Q
44.52 cm
mu_Q
position (cm)

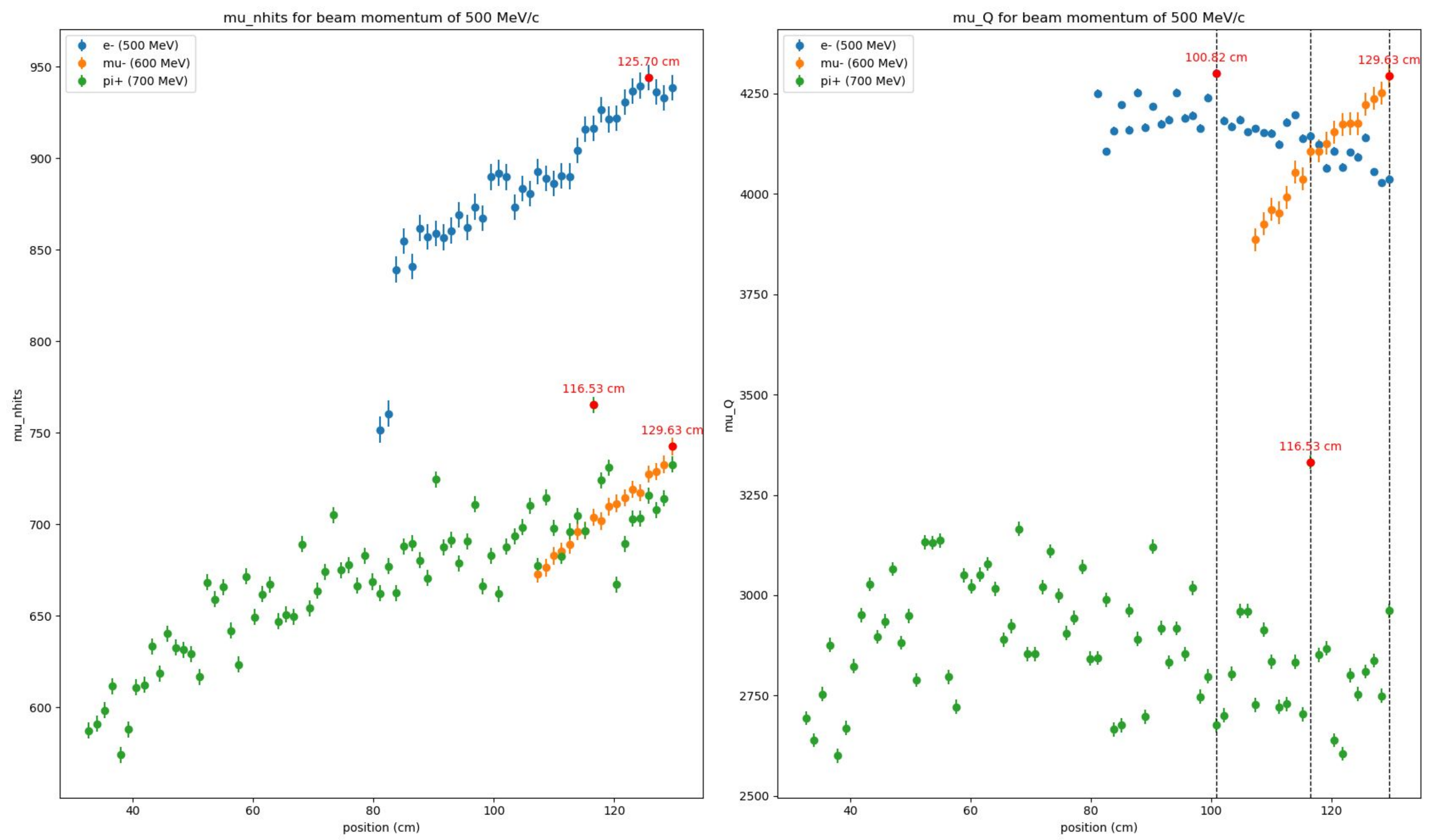


muons

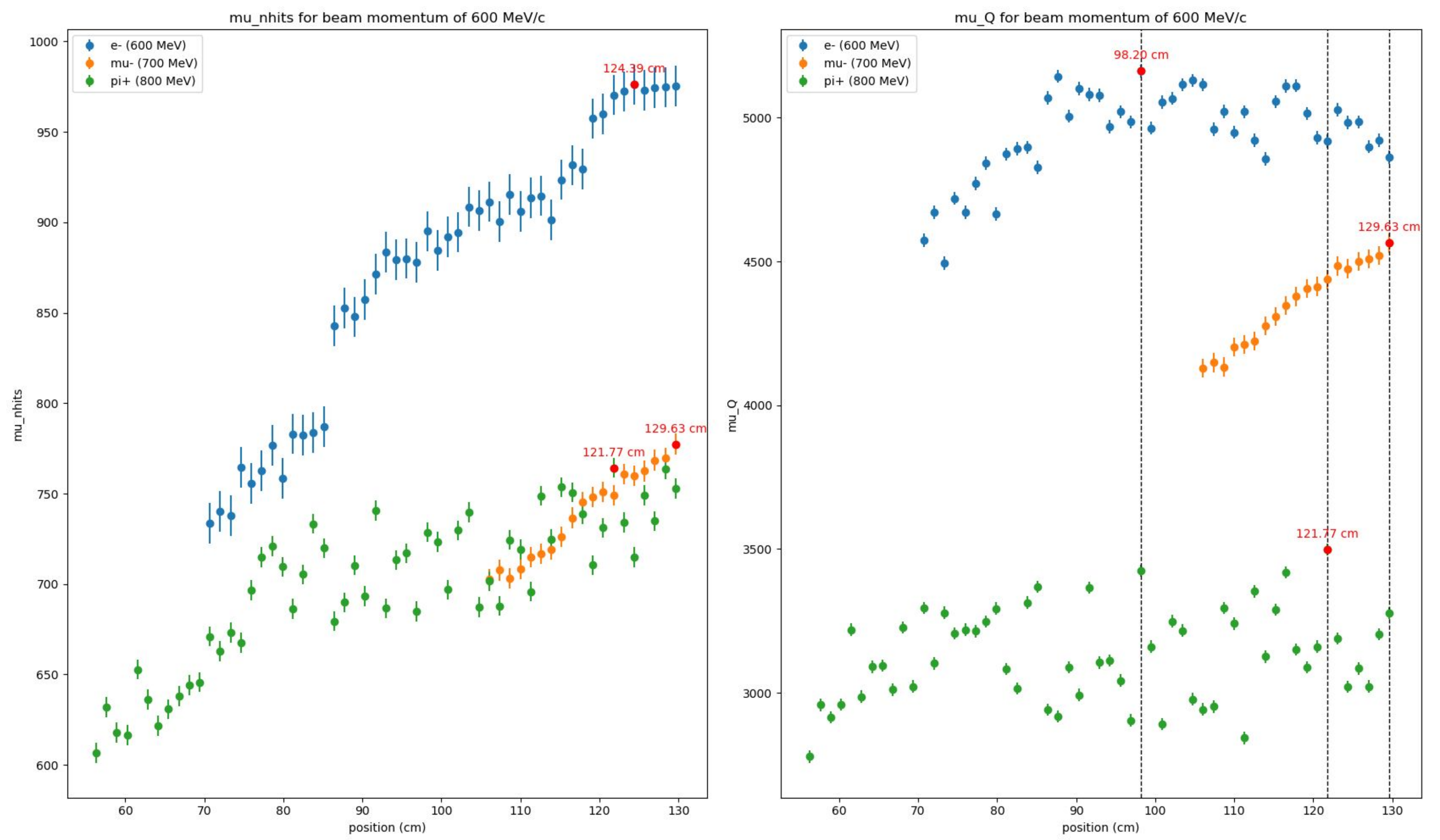
Something strange is happening with muons, need to check this!

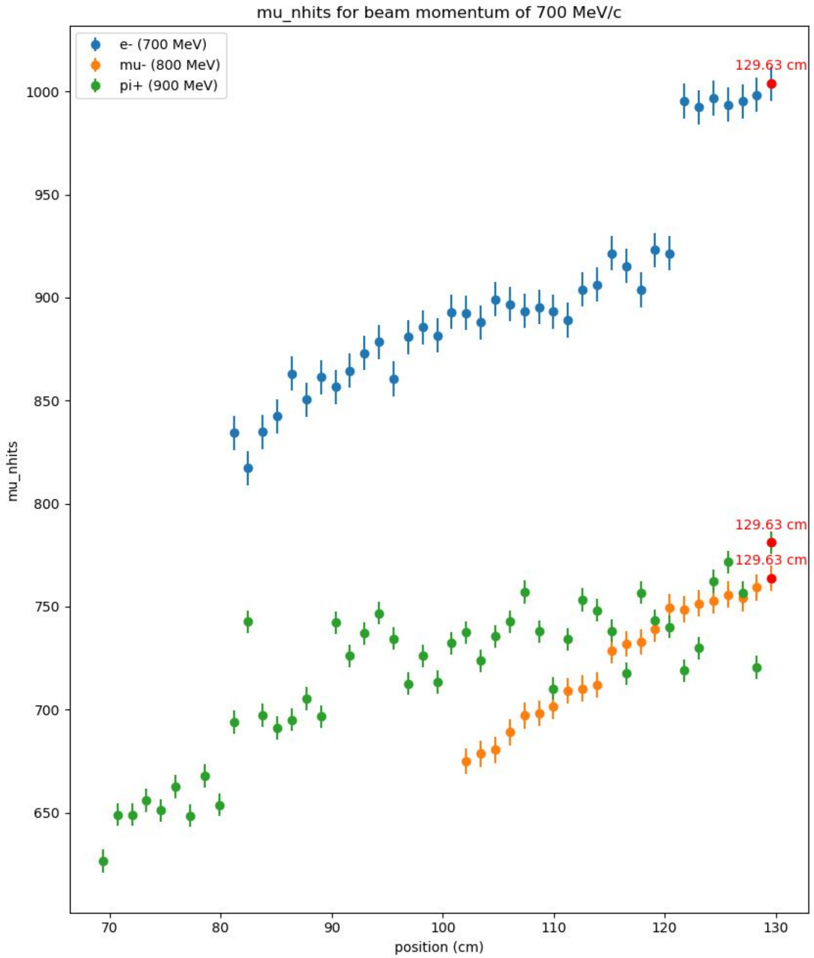

mu_nhits vs. position for pi+ of 500MeV
max mu_nhits
mu_nhits
108.68 cm
mu_nhits
position (cm)
mu_Q vs. position for pi+ of 500MeV
max mu_Q
mu_Q
54.99 cm
mu_Q
position (cm)

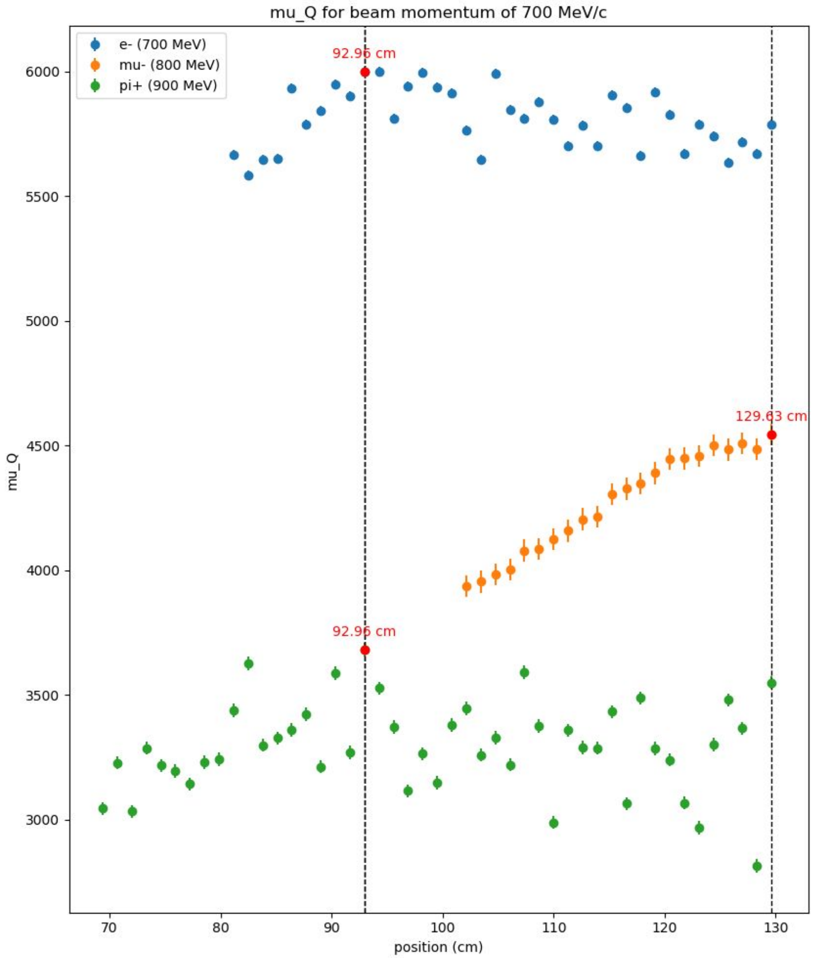
pions



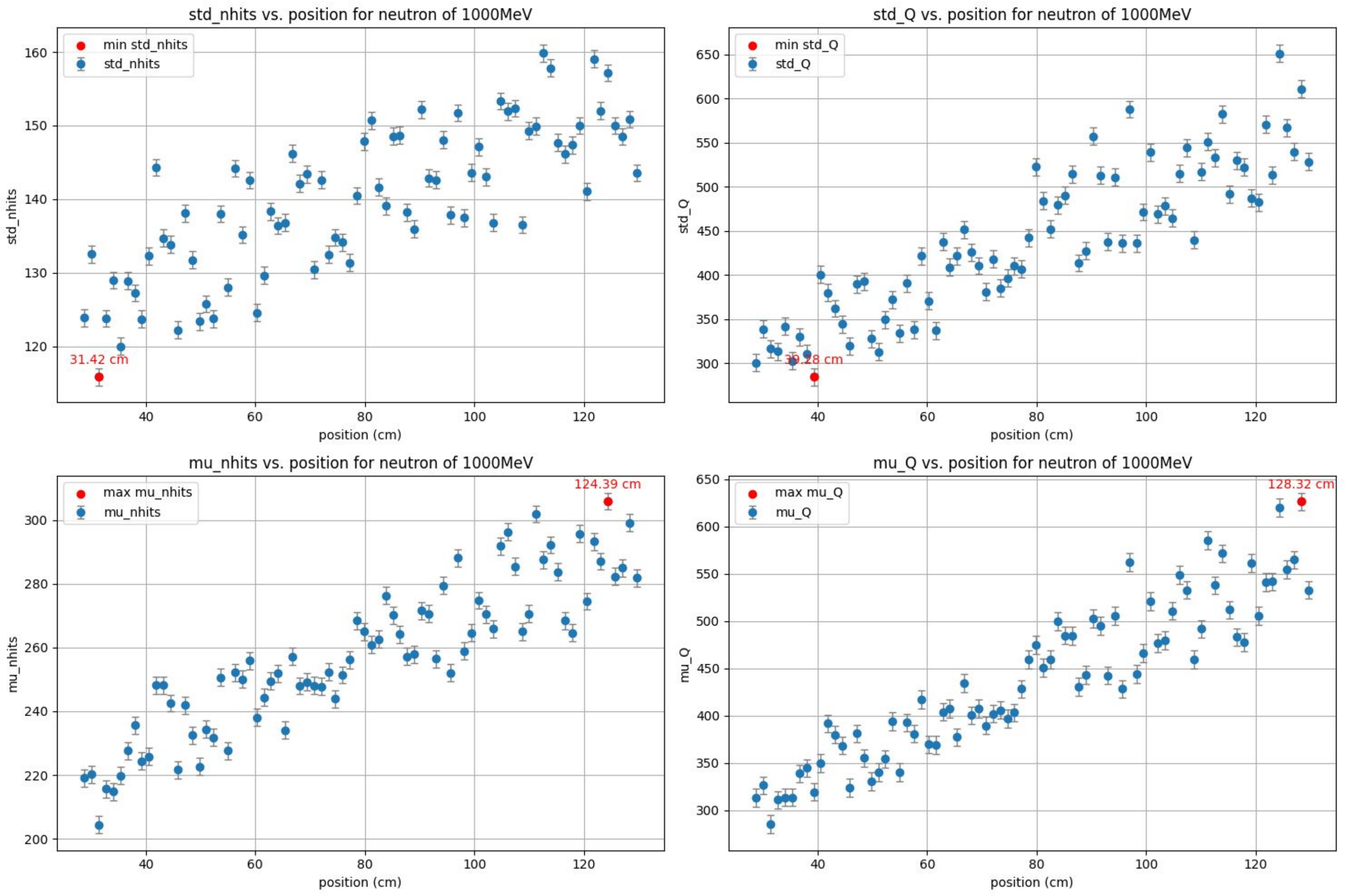
mu_nhits for beam momentum of 500 MeV/c
e- (500 MeV)
mu- (600 MeV)
pi+ (700 MeV)
125.70 cm
116.53 cm
129.63 cm
mu_nhits
position (cm)
mu_Q for beam momentum of 500 MeV/c
100.82 cm
129.63 cm
116.53 cm
mu_Q
position (cm)


mu_nhits for beam momentum of 600 MeV/c
e- (600 MeV)
mu- (700 MeV)
pi+ (800 MeV)
124.39 cm
129.63 cm
121.77 cm
mu_nhits
position (cm)
mu_Q for beam momentum of 600 MeV/c
98.20 cm
129.63 cm
121.77 cm
mu_Q
position (cm)

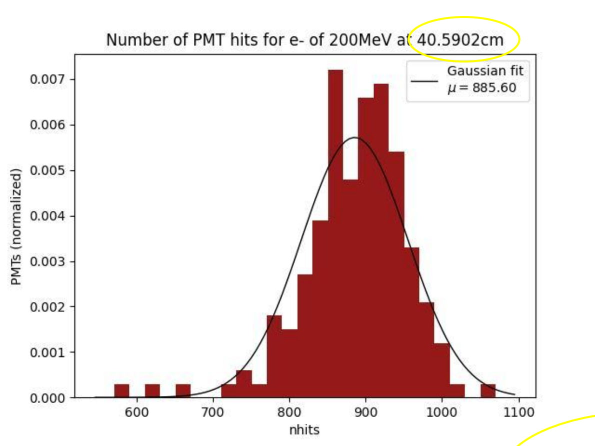

mu_nhits for beam momentum of 700 MeV/c
e- (700 MeV)
mu- (800 MeV)
pi+ (900 MeV)
129.63 cm
129.63 cm
129.63 cm
mu_nhits
position (cm)
650
700
750
800
850
900
950
1000
70
80
90
100
110
120
130

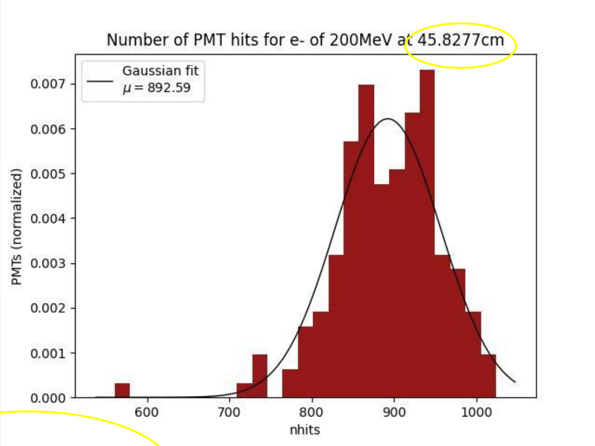

mu_Q for beam momentum of 700 MeV/c
e- (700 MeV)
mu- (800 MeV)
pi+ (900 MeV)
92.96 cm
129.63 cm
92.96 cm
mu_Q
position (cm)
3000
3500
4000
4500
5000
5500
6000
70
80
90
100
110
120
130

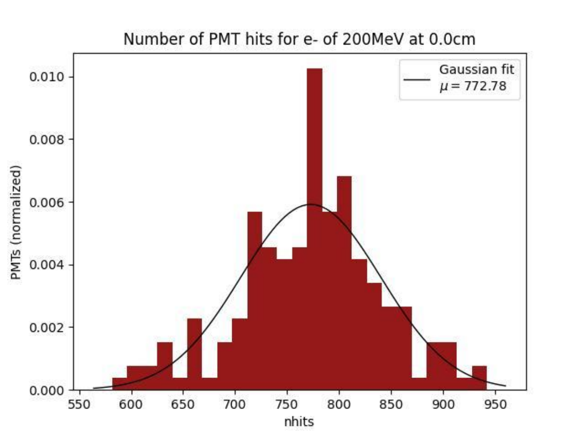
Preliminary



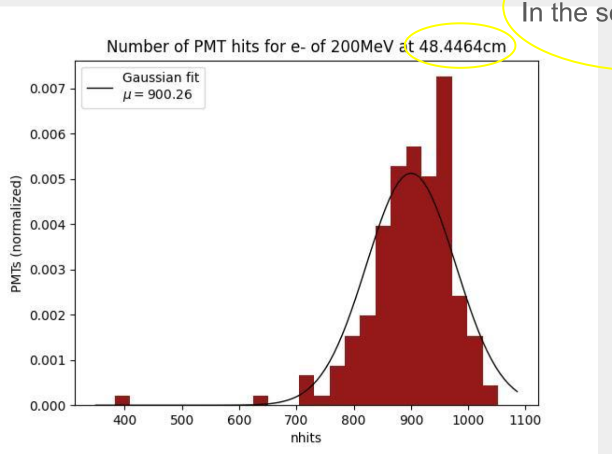
neutrons

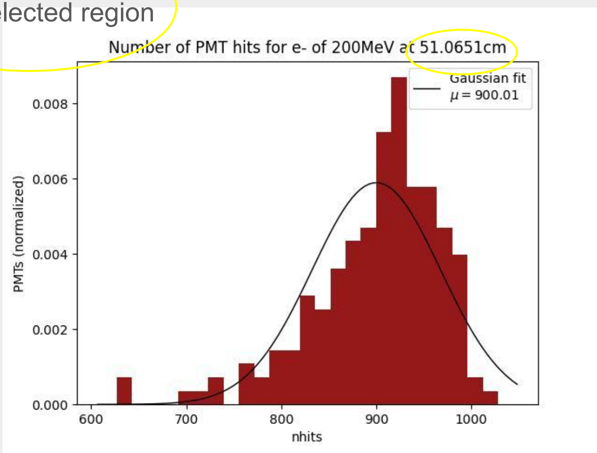


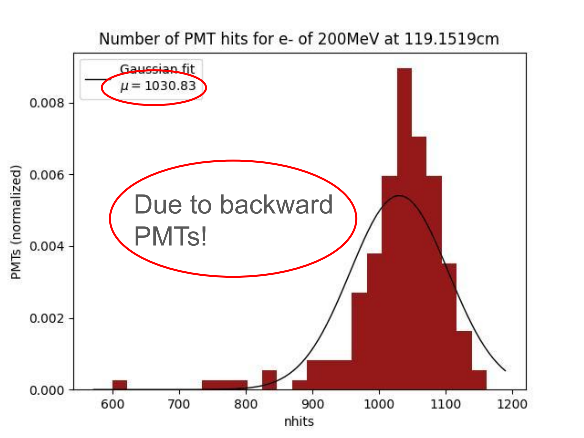


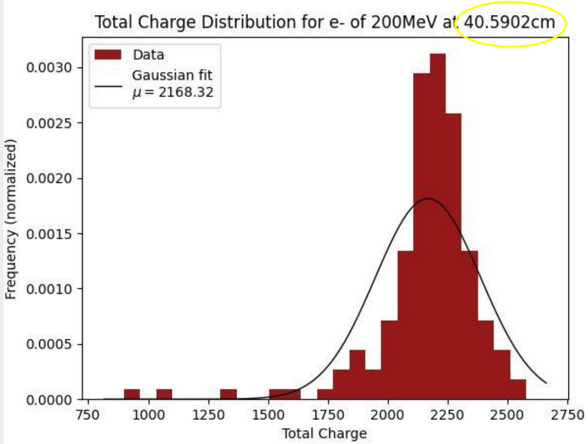


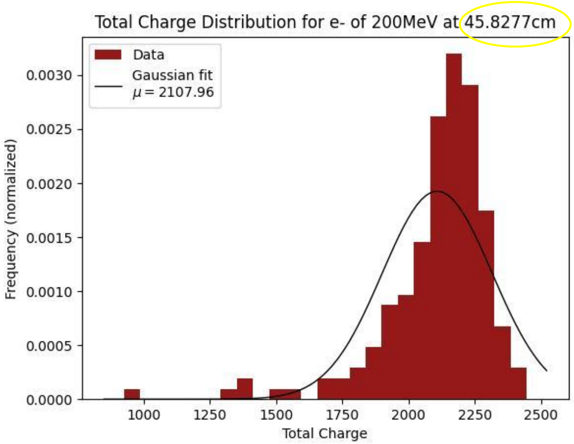
In the selected region

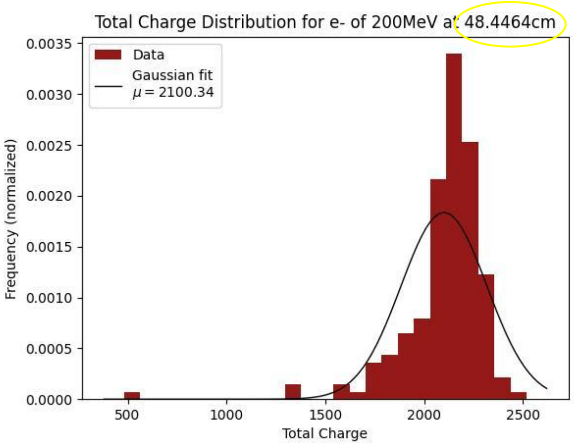


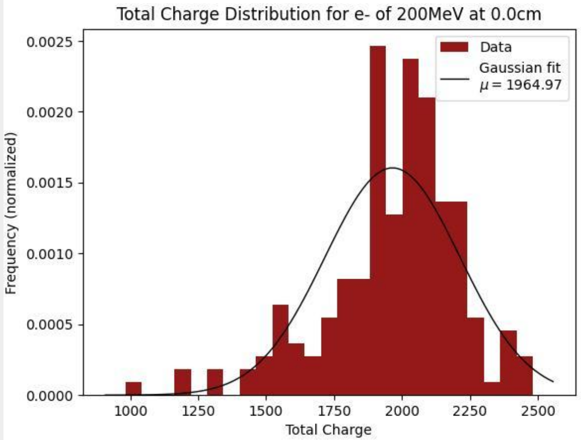


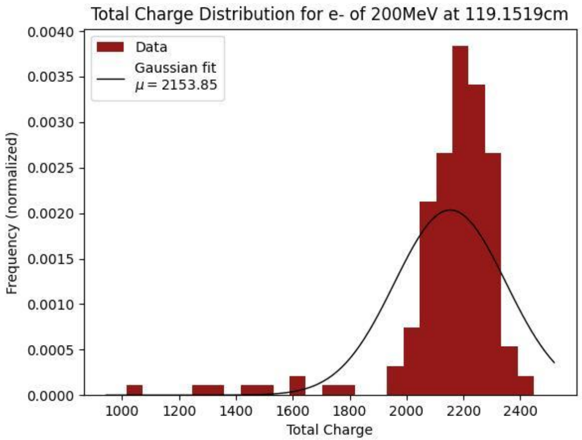



Total Charge Distribution for e- of 200MeV at 40.5902cm
Data
Gaussian fit
$\mu = 2168.32$
Frequency (normalized)
Total Charge


Total Charge Distribution for e- of 200MeV at 45.8277cm
Data
Gaussian fit
$\mu = 2107.96$
Frequency (normalized)
Total Charge


Total Charge Distribution for e- of 200MeV at 48.4464cm
Data
Gaussian fit
$\mu = 2100.34$
Frequency (normalized)
Total Charge


Total Charge Distribution for e- of 200MeV at 0.0cm
Data
Gaussian fit
$\mu = 1964.97$
Frequency (normalized)
Total Charge


Total Charge Distribution for e- of 200MeV at 119.1519cm
Data
Gaussian fit
$\mu = 2153.85$
Frequency (normalized)
Total Charge