Measuring the proton beam and beamline component alignment with the T2K muon monitor

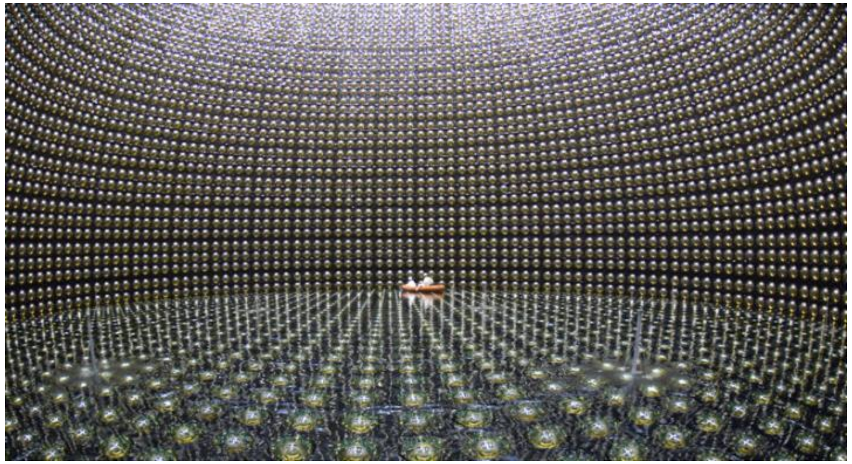
Ian Heitkamp – NBI 2024

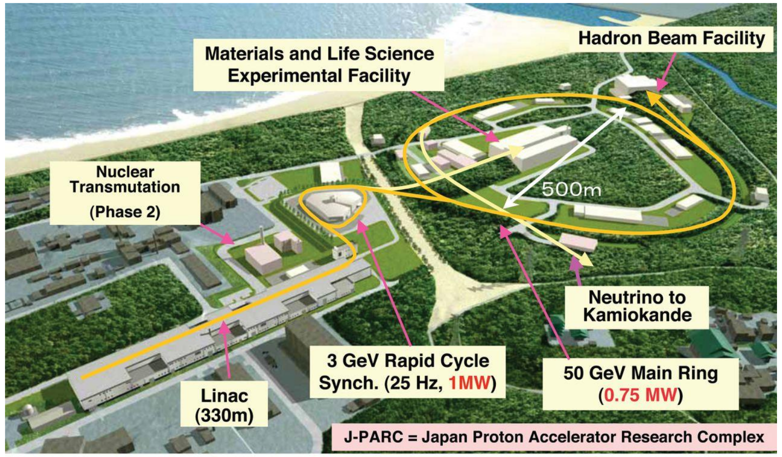
Contents

- T2K Beamline
- Muon Monitor overview and status
- EMT Development
- Proton beam position scan simulation study
- Mumon measurements of beamline alignment
- Comparison to survey results.

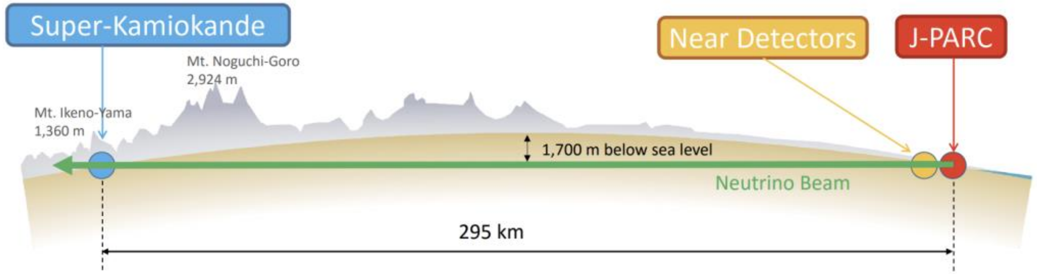
T2K Experiment – Quick Overview

- The T2K experiment is a long baseline accelerator neutrino experiment in Japan using the J-PARC accelerator complex in Tokai, Ibaraki and the Super Kamiokande detector in Hida, Gifu.



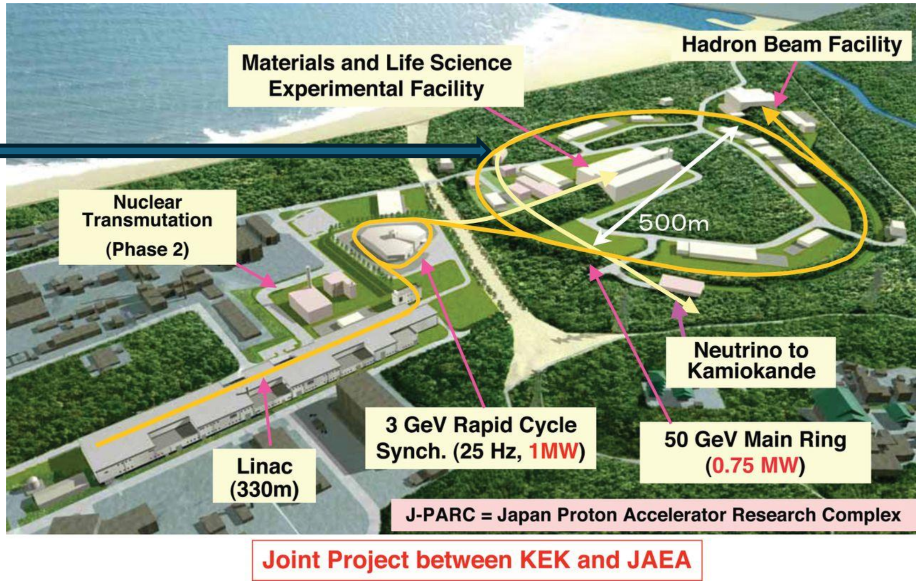


Joint Project between KEK and JAEA



T2K Experiment – Beamline

Proton beam extraction



- Proton beam extracted from main ring

➔Bent towards SK and focused onto the target

➔The baffle (a collimator) protects downstream equipment from abnormal beam

➔The beam impacts the target placed in horn 1

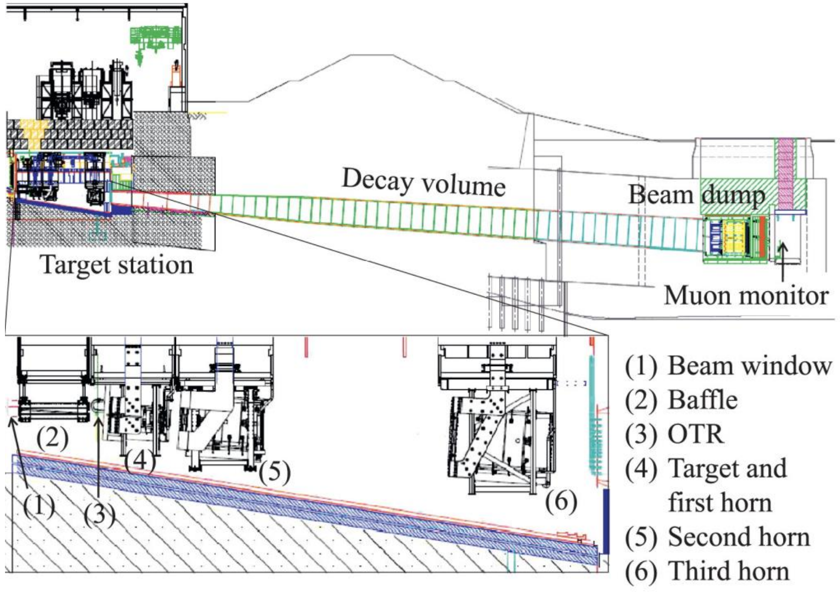
➔The proton beam is converted to mostly pions in target

➔Magnetic focusing horns focus/defocus pions depending on desired charge

➔Pions decay via the following branch to μ and ν_μ

$$\pi^\pm \to \mu^\pm + \nu_\mu \; (\bar{\nu}_\mu)$$

- There is a beam dump at the end of the decay volume to stop any remaining protons and π as well as low energy μ
- The muons are measured by the **muon monitor** to indirectly measure the neutrino beam direction.



Muon Monitor - Overview

- First detector after the target
- Conducts a spill-by-spill measurement of the muon profile.

Muon Monitor Purpose:

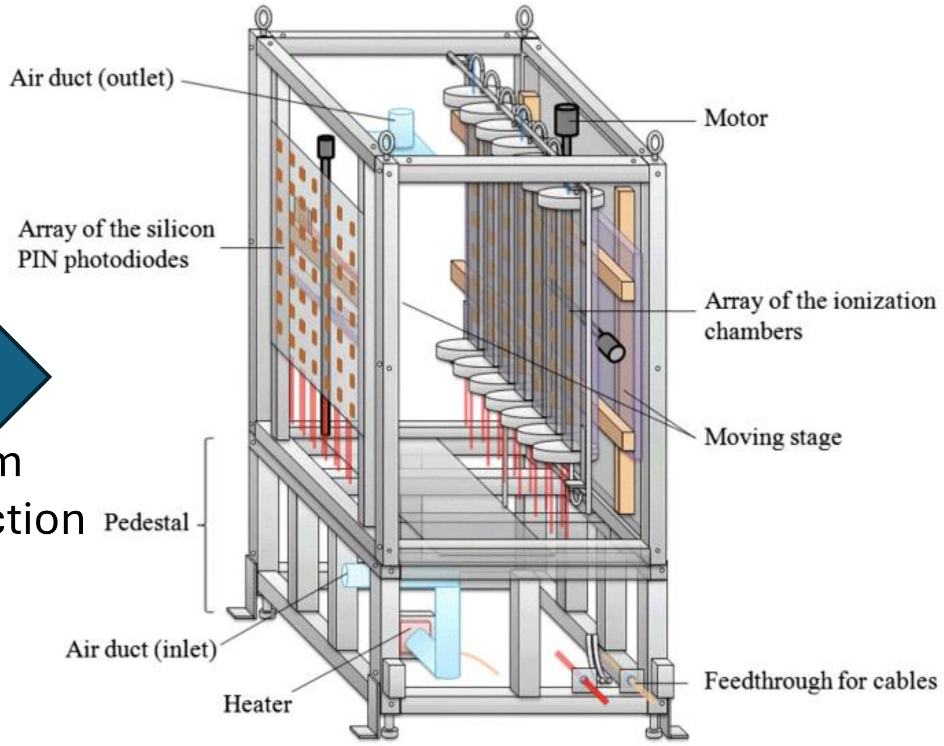
- Ensure the neutrino beam direction is accurate.
- Ensure the proton beam is properly centered on the target
- Monitor neutrino beam intensity

The Muon Monitor consists of 2 main sensor types:

- 7×7 Silicon PIN photodiode array
- 7×7 Ionization chamber array

These sensor arrays cover $150\times150\ \mathrm{cm}^2$ spaced every 25 cm

Beam direction

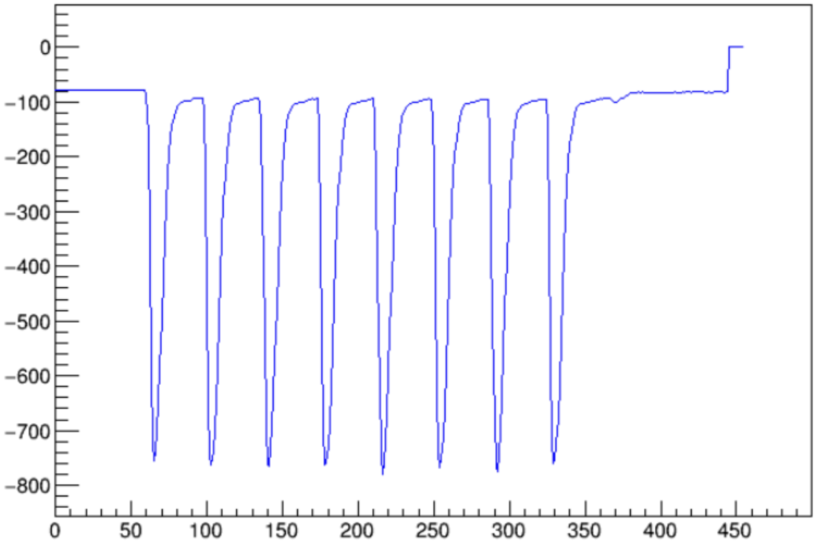


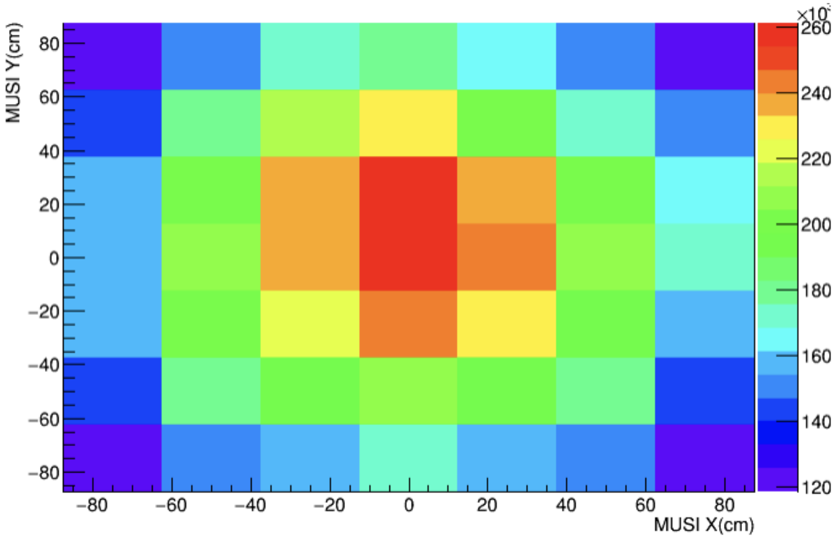
Muon Monitor – Profile Reconstruction

- Sensor waveforms are integrated to get the total charge deposited
- To reconstruct the profile, a 2D gaussian is used to fit the sensors

$$f(x,y) = C \times Exp\left(\frac{(x-x_0)^2}{2\sigma_x^2} + \frac{(y-y_0)^2}{2\sigma_y^2}\right)$$

- The muon beam center (x_0 and y_0) and muon beam width (σ_x and σ_y) are used to represent the beam.
  - Center resolution of ~3 mm.
  - Systematic uncertainty on muon beam direction of ~0.2 mrad





EMT Development - update

- Beam power is increasing, and radiation is a problem for SI sensors.

➔Mumon group is developing a new radiation tolerant sensor to replace SI sensors.

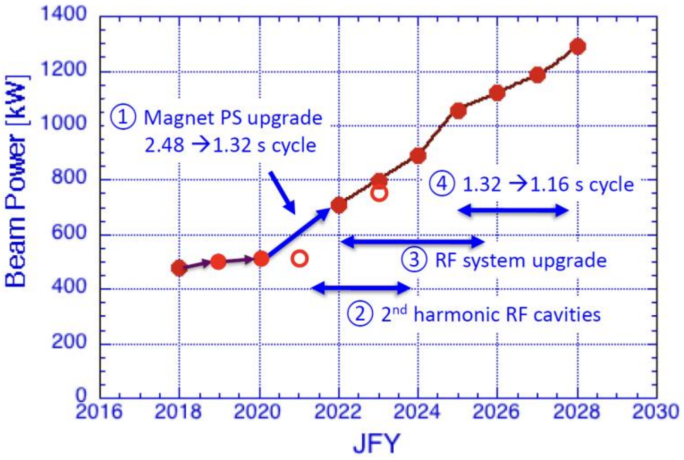
➔7 currently installed, plan to install to + shape for beamtime next month.

➔ Horizontal 1D muon profile was measured

➔Radiation tolerance was measured in situ.

  ➔To be published! (On arXiv already: https://arxiv.org/abs/2405.05877)

Upgrade plan of MR



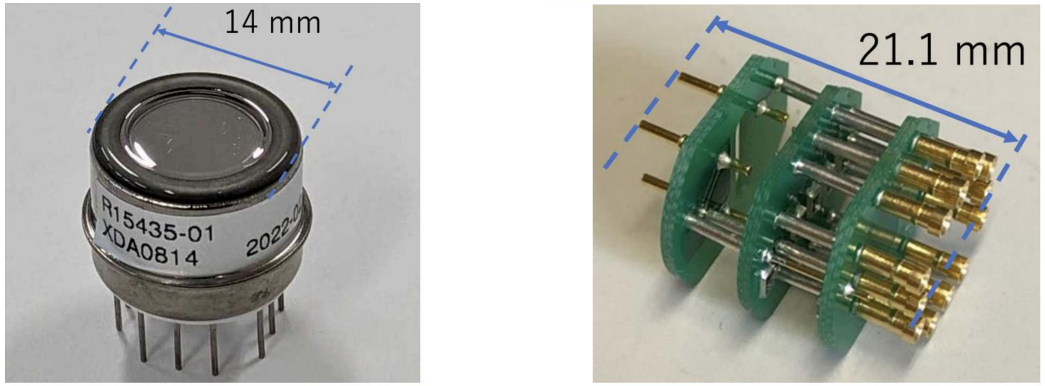
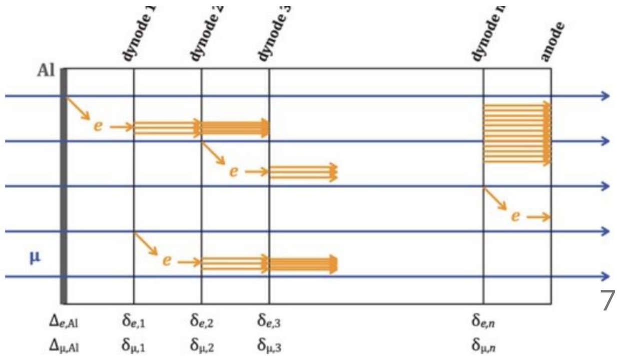


Fig. 1 Photograph of an EMT (left) and a bleeder circuit (right).



Beamline Alignment Study

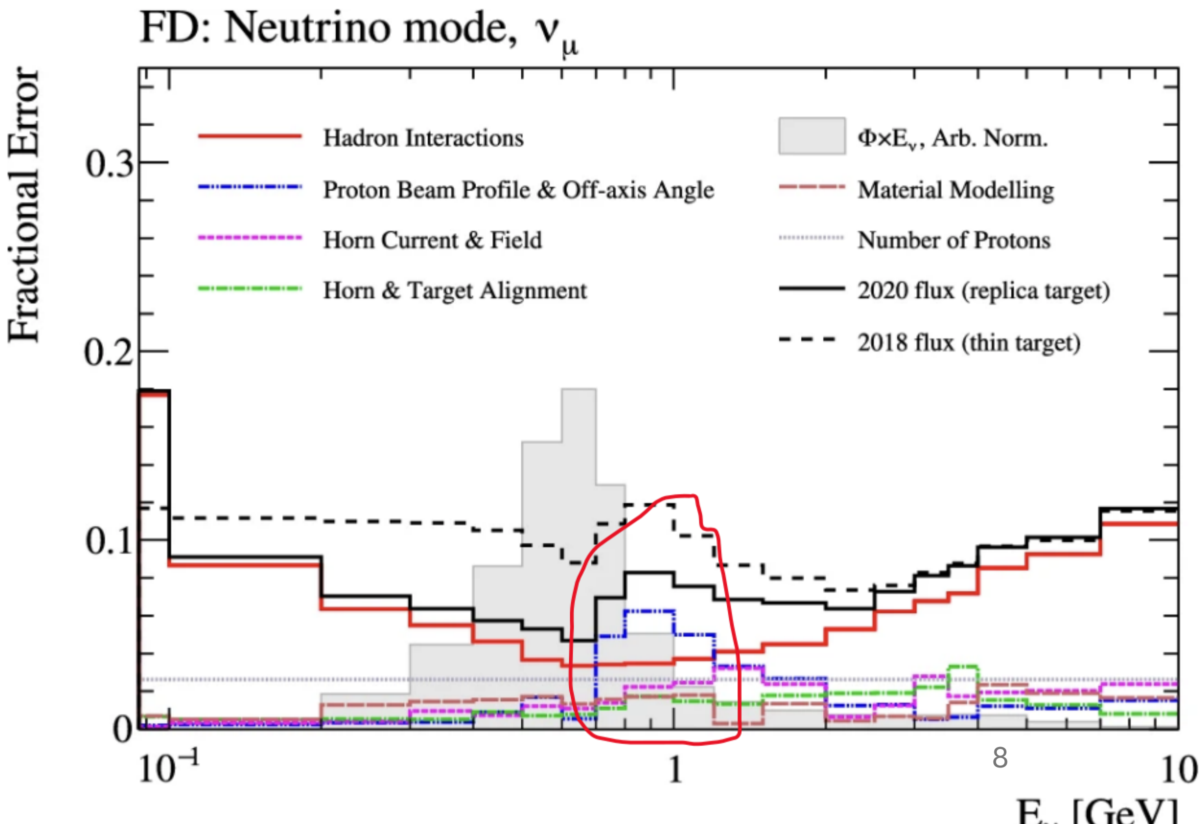
Motivation:

- Protect beamline components as energy increases
  - ➔Mumon is used for beam tuning, so need to understand mumon to tune beam well.

➔Can mumon find beamline component alignment?

- proton beam profile & off-axis angle is dominant uncertainty at high energies
  - Mumon is the first sensor after the target, so may be able to reduce
  - ➔Understanding mumon response to different beam profiles is important.

OA flux prediction systematics

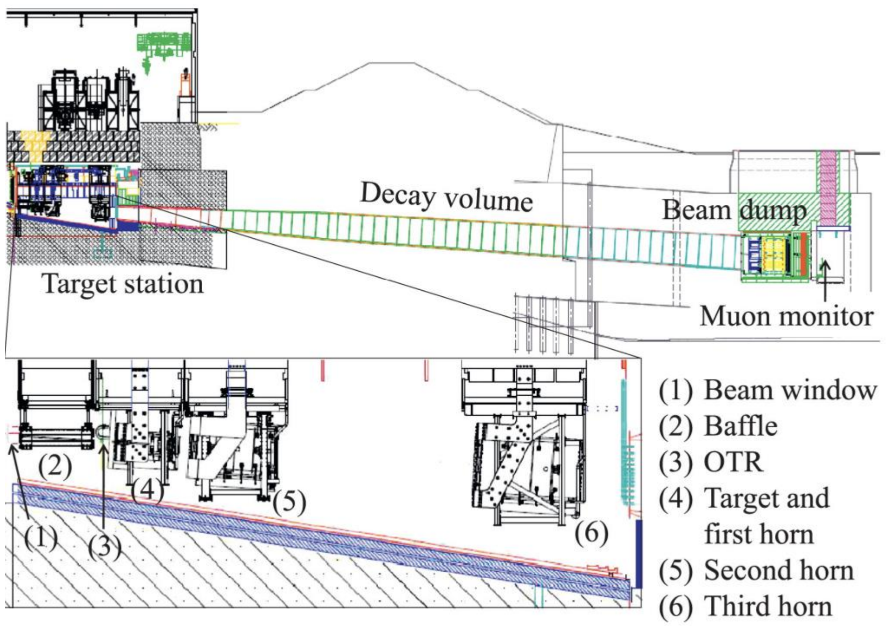


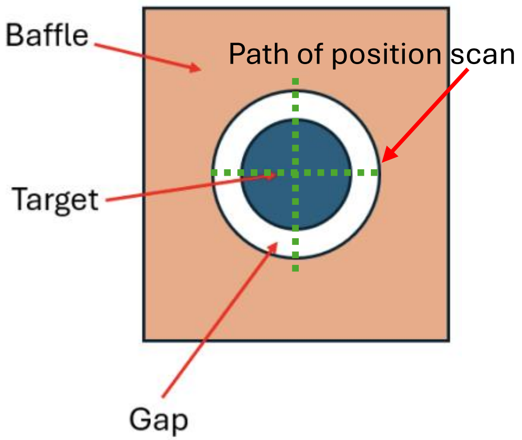
How to study Mumon Behavior?

- Beamline is complicated after target, many factors may affect mumon.

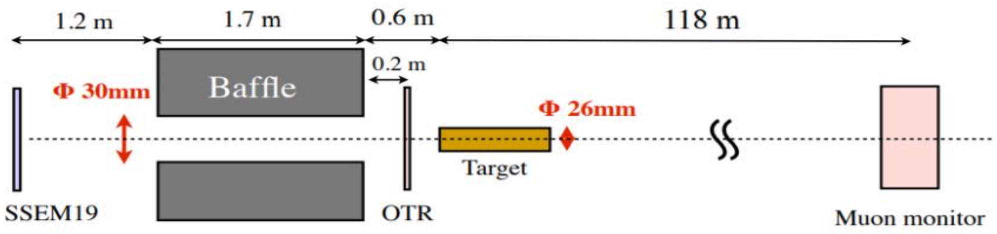
➔Can study by scanning beam over target to see correlation with beam position

➔Supplement with simulations of beamline to understand in ideal cases.

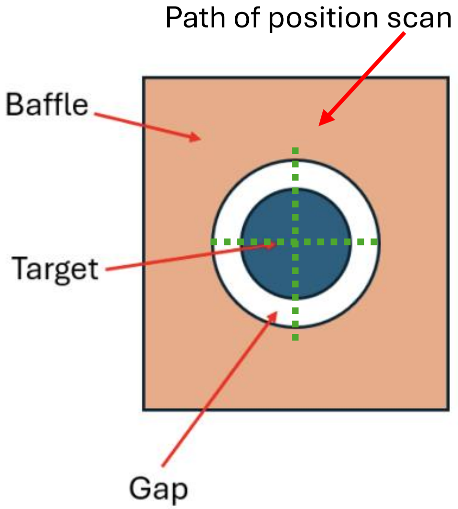




Beam Position Scan



- The proton beam is set to different positions and moved across the target, each position is 11 datapoints.
- Done with focusing horns off (0 kA), at 250 kA, and at 320 kA.

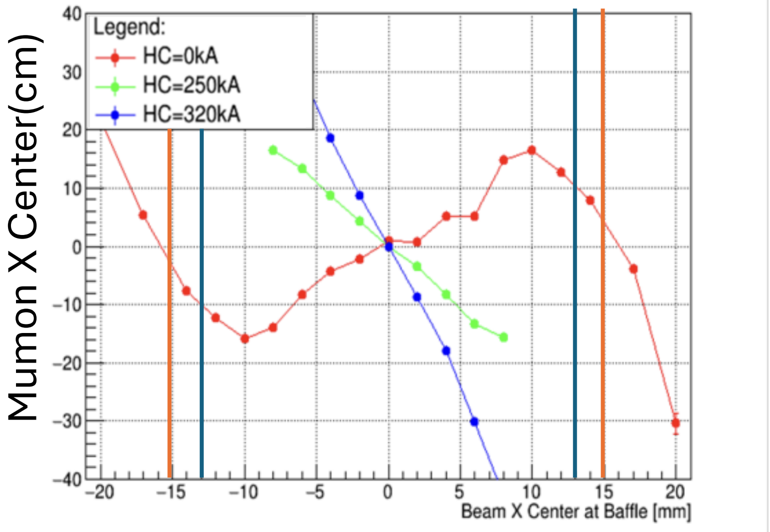


Muon monitor response: Correlate to **muon beam center** and **muon beam width**

- **Near center of target**: linear response, in ideal case, all 3 horn currents intersect at target center
- Mumon width response is quadratic near target center for horn current on case.
- 0 kA reaches a peak in mumon center as the beam reaches the edge of the target.
- Mumon width response reaches a minimum as the beam reaches the baffle, and much of it misses the target

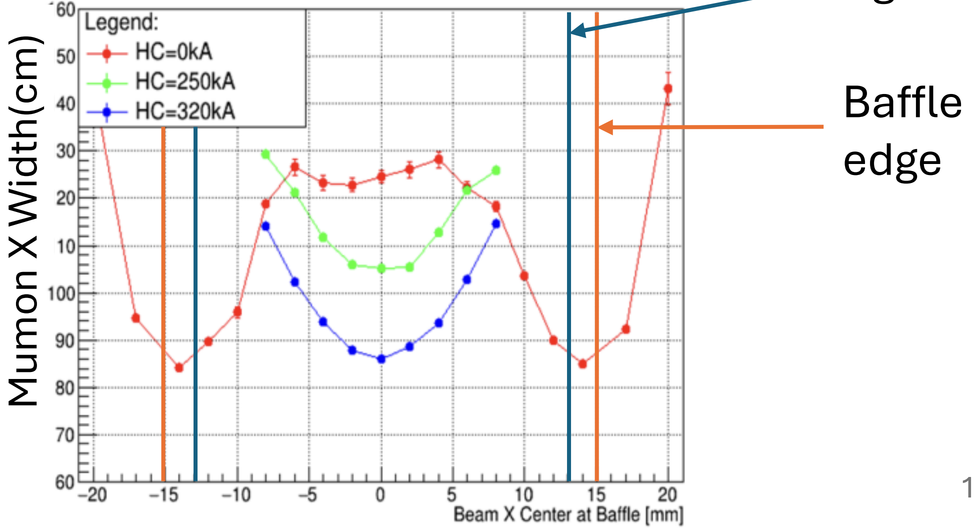
Simulation of beam position scan:

Mumon X Center v.s. Proton Beam X Position



Mumon X Width v.s. Proton Beam X Position

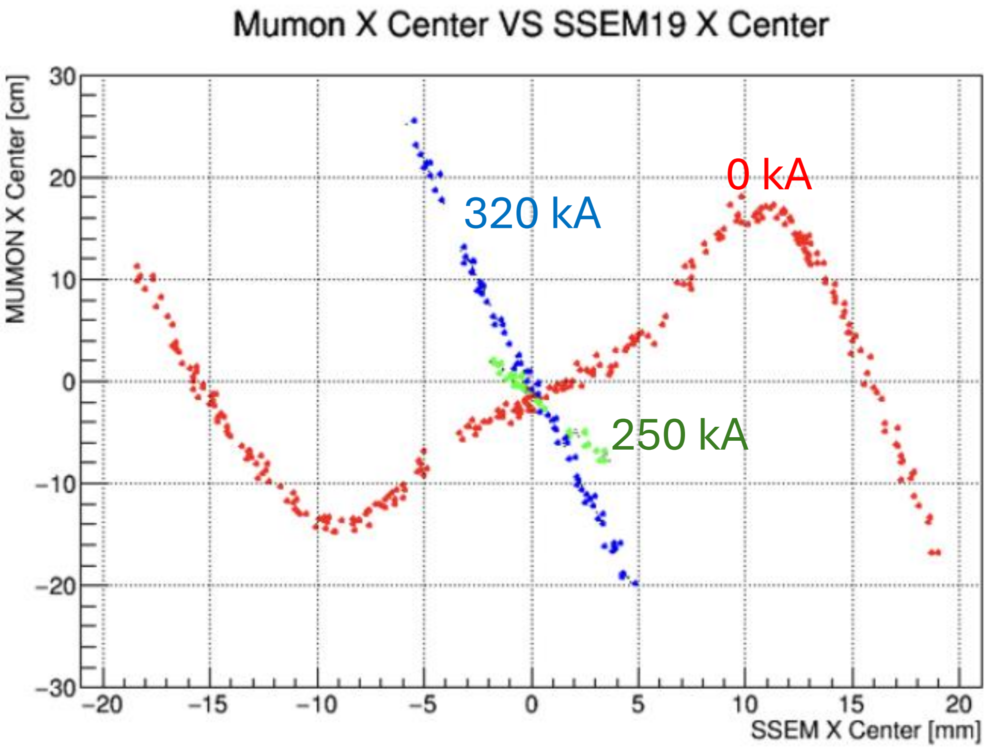
Edge of target

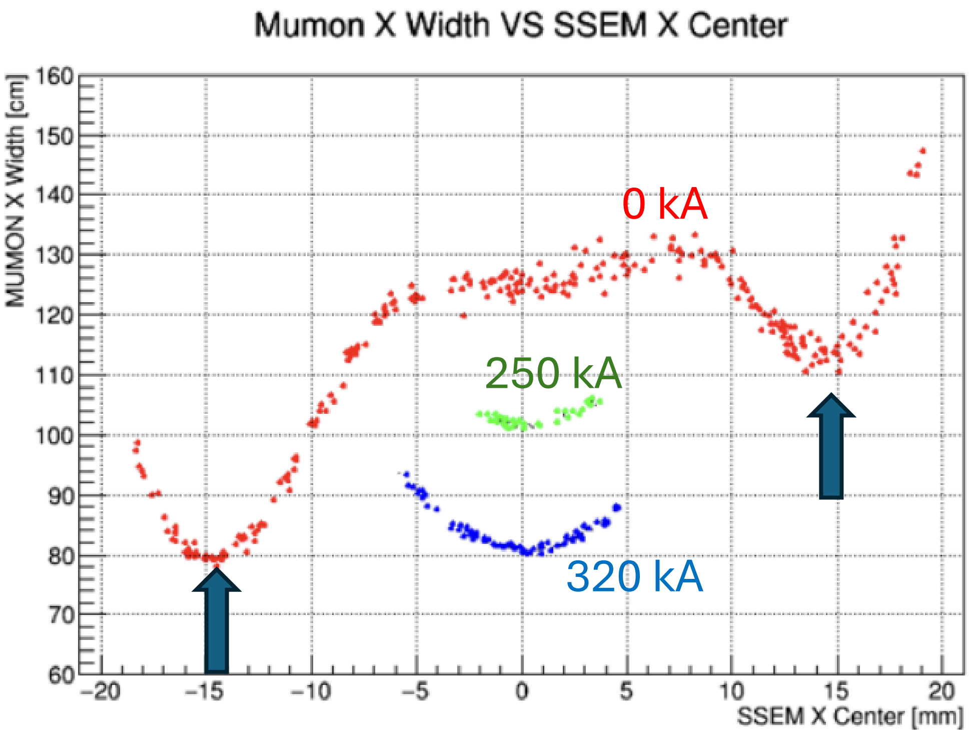


Baffle edge

Beam Position Scan – X Results

- Position scans were carried out in both T2K Run 12 (4/2023) and Run 13 (11/2023-7/2024)
- 0 kA (red), 250 kA (green) and 320 kA (blue) horn currents were used
- A significant asymmetry in the muon monitor response was observed.

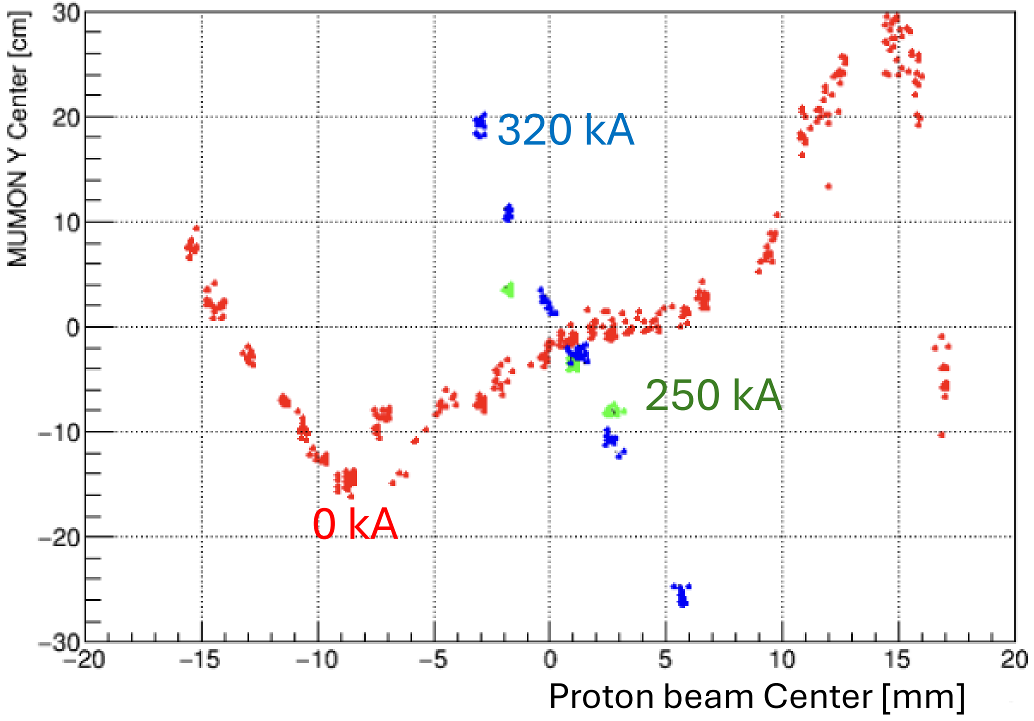




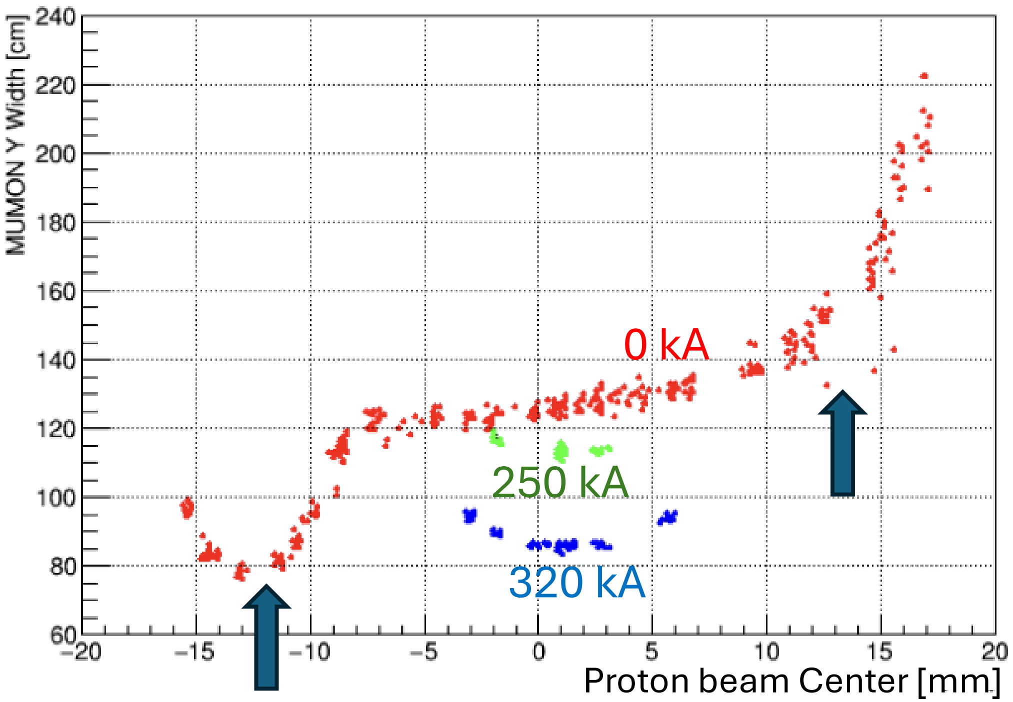
Beam Position Scan – Y Results

- A large asymmetry was observed both in muon profile center and width.

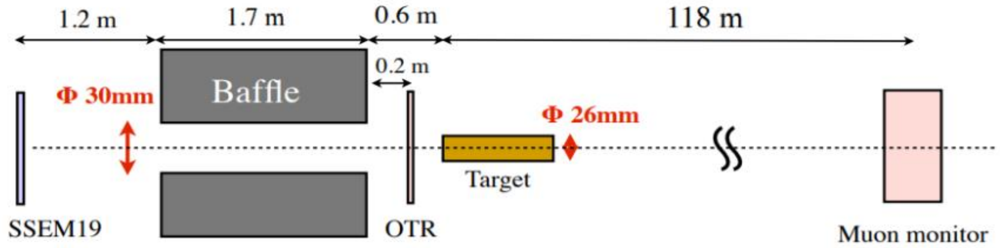
Mumon Y Center vs Proton Beam Y position



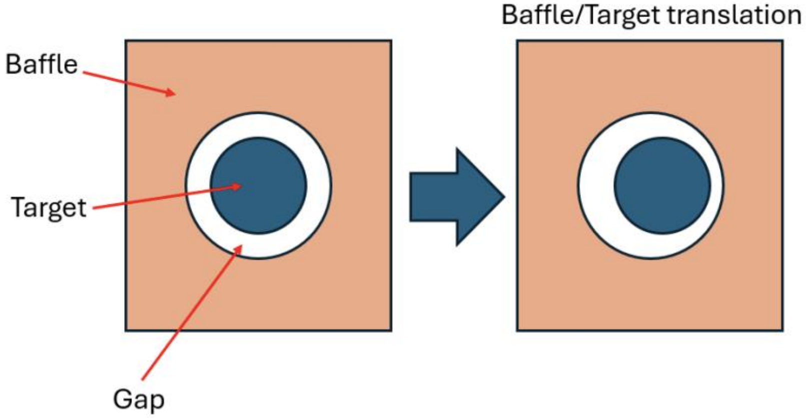
Mumon Y Width vs Proton Beam Y position



Beamline Alignment Study

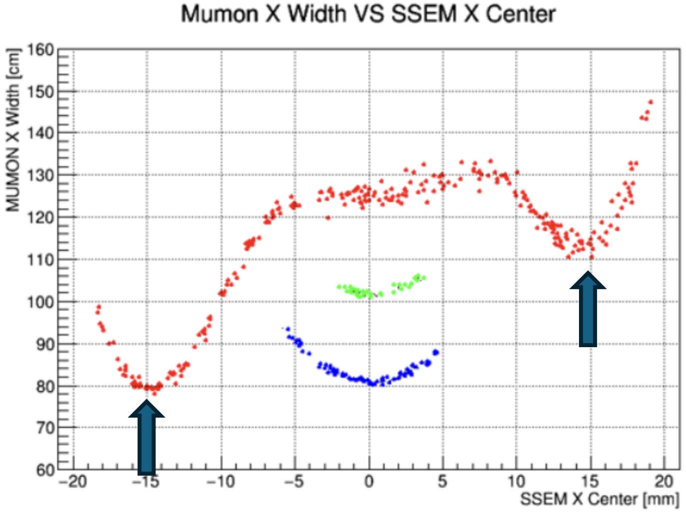


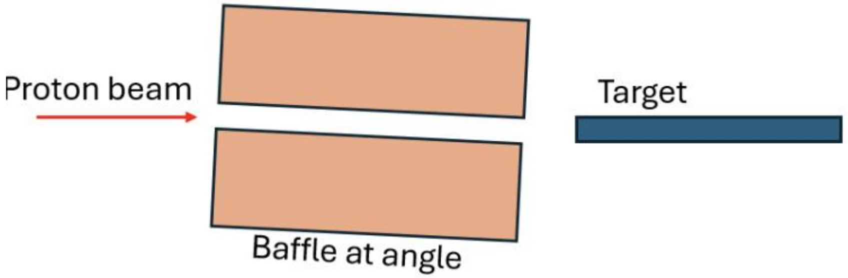
- Misalignment of baffle & target can create asymmetry seen in position scan width in 0 kA position scan



The following were tested with simulated position scans:

1. Baffle translation
2. Baffle angle
3. Target translation
4. Target angle



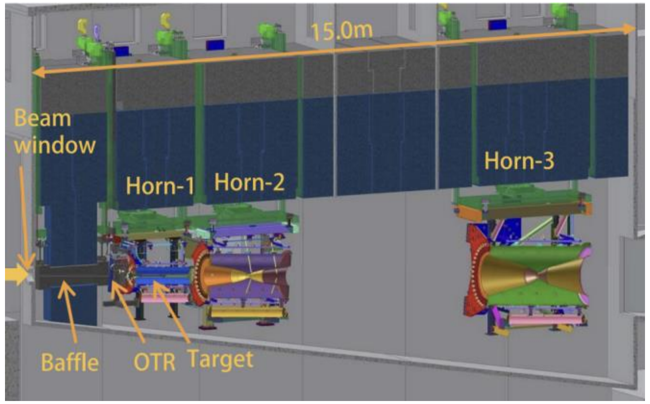


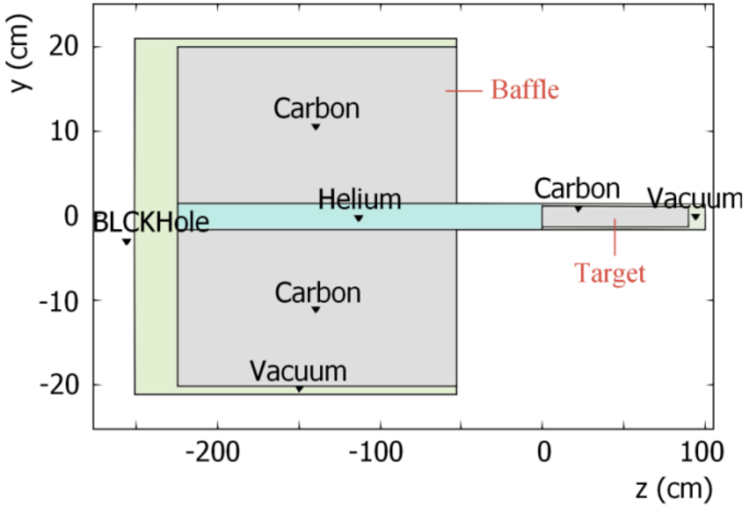
Simulation methods - Fluka & JNUBEAM

Simulation flow:

1. FLUKA simulates baffle and target
2. JNUBEAM (Geant3) imports particle information
3. JNUBEAM (Geant3) simulates remainder of beamline
4. If particle passes through muon monitor, its information is saved.

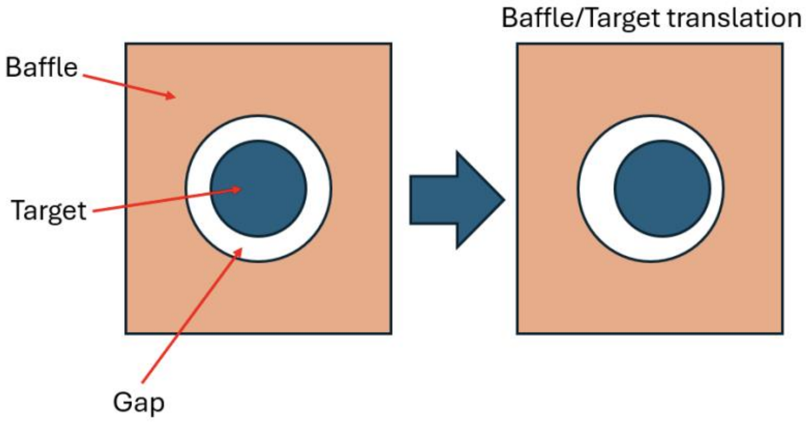
➔Fit Mumon profile to 2D gauss, plot center/width scans



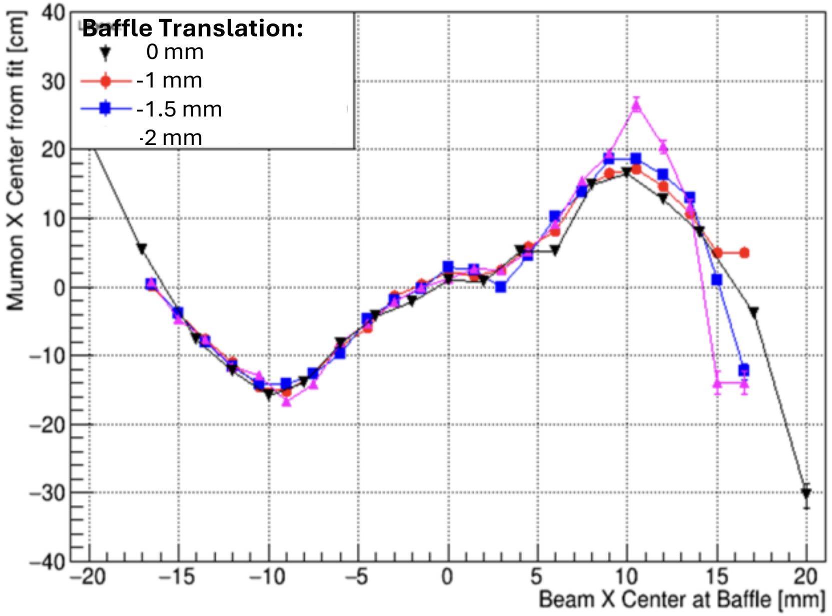


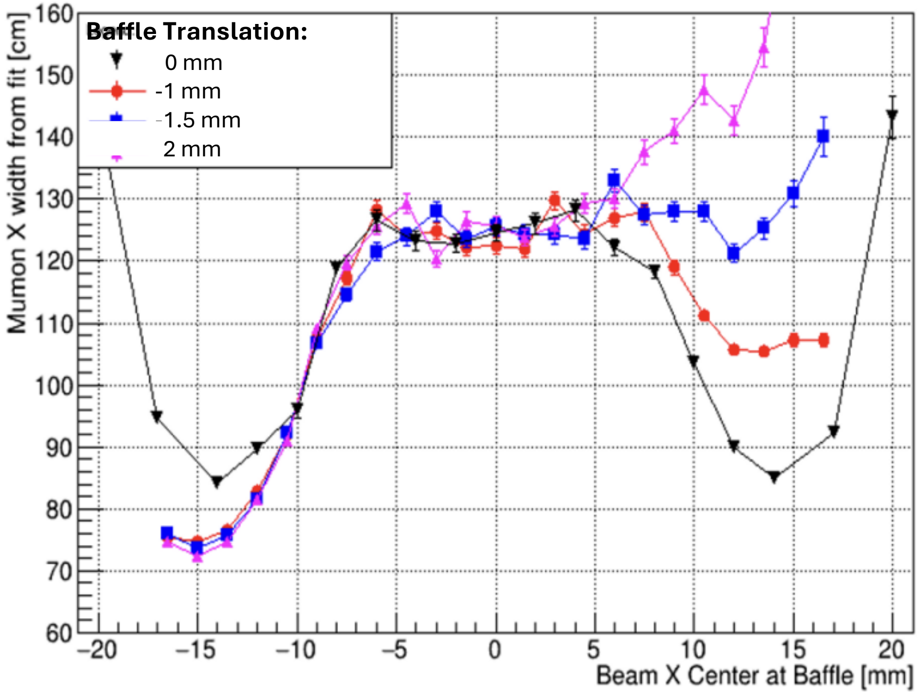
- Beam settings use a 3 mm proton beam and beam parameters from T2K run 11.

Baffle Translation

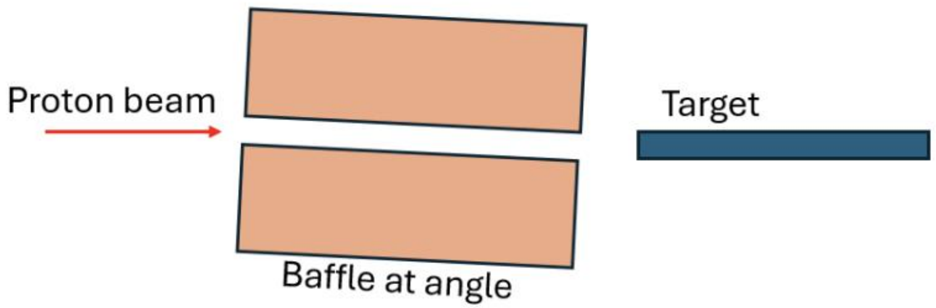


- Tested for -1 mm, -1.5 mm, -2 mm.
- To replicate width asymmetry w/ only baffle trans: between -1 mm and -1.5 mm translation



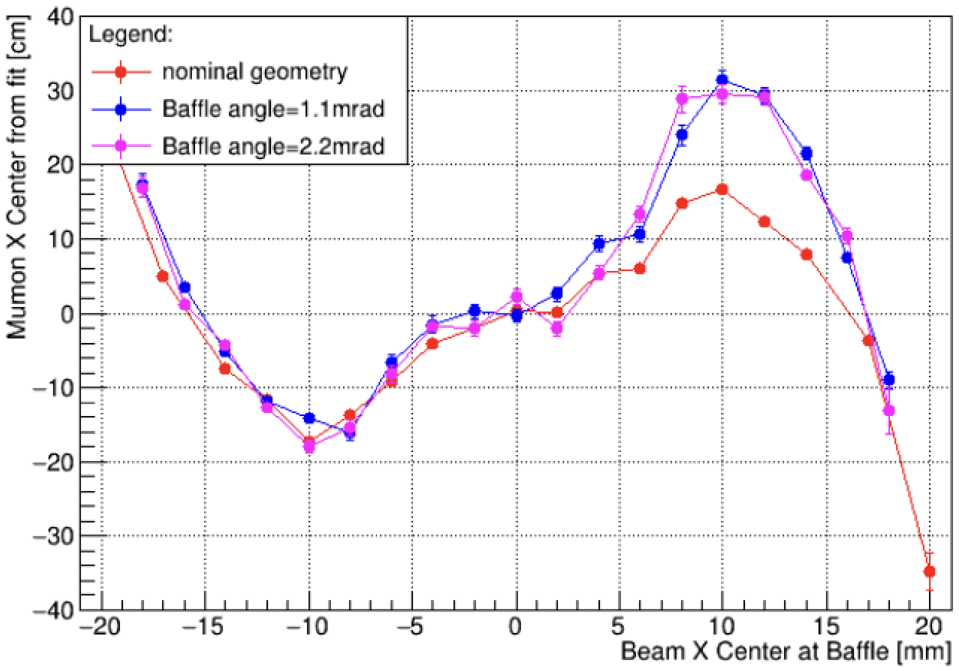


Baffle Angle

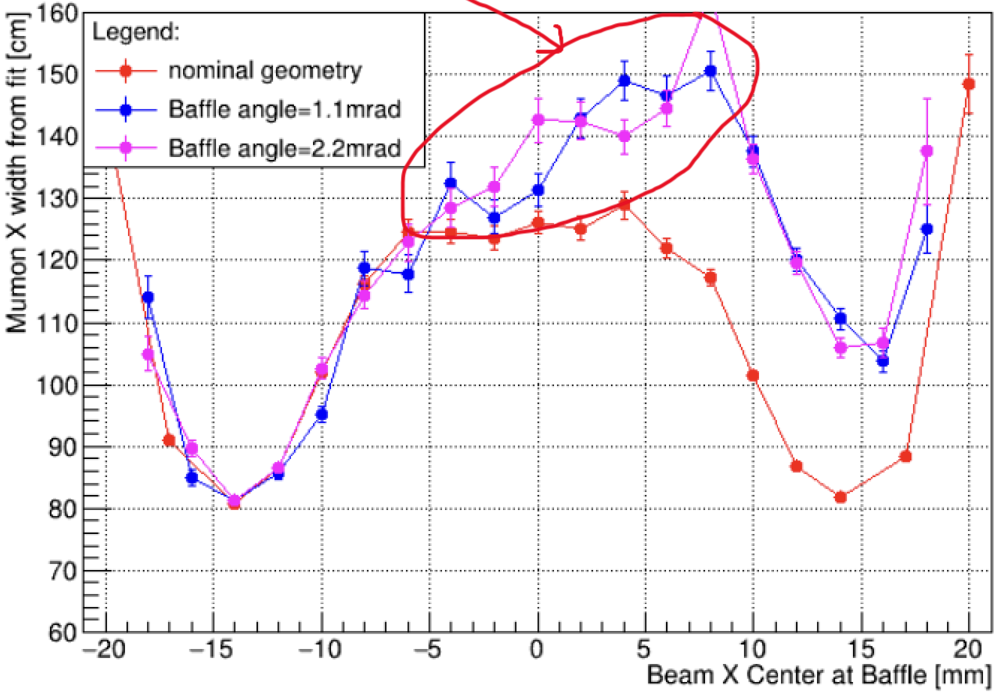


- Simulated +0.11 mrad and +0.22 mrad
- Matches observed width asymmetry at ~0.1 mrad
- Larger effect than translation (-0.1 mm near side and +0.1 mm far side is +0.11 mrad)
- A unique feature is linear response of width near center
  - This is suppressed as beam width increases (smoothing effect)

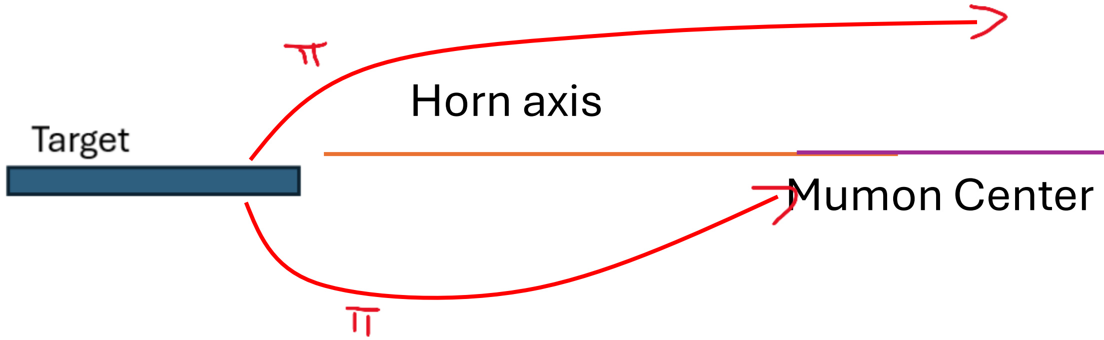
Mumon X position Baffle angle (0.11 mrad & 0.22 mrad)



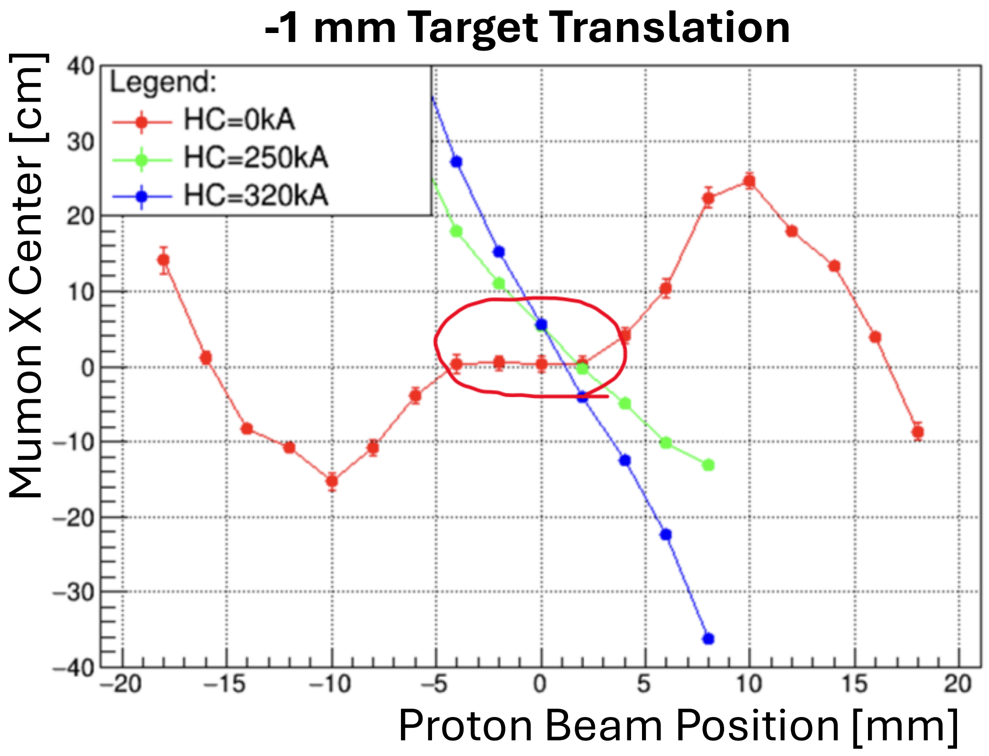
Mumon X width Baffle angle (0.11 mrad & 0.22 mrad)

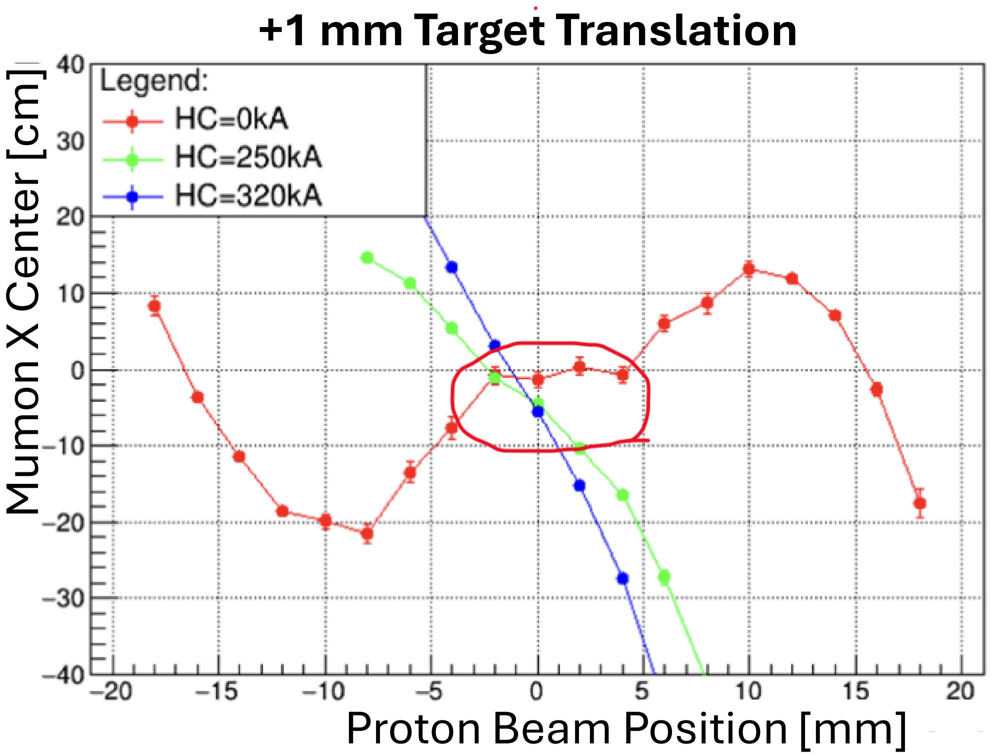


Target Translation



- Tested -1 mm and +1 mm target translation
- Horn axis offset from target axis
- HC on intersection != 0kA intersections ($\Delta \text{int} = \sim 5.8 \frac{cm}{mm}$ mumon center shift/ mm translation)
- Flat region near center of target shifts.



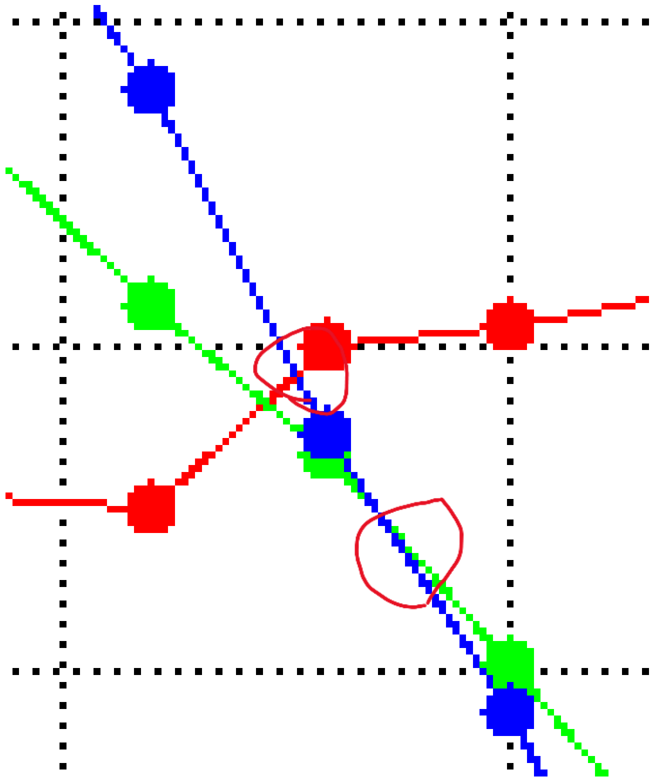


Target & Horn 1 centers

- Target is installed inside horn 1
- Simulations only translate target
  - HC-dependent offset is observed at mumon if target is offset from horn axis
    - Is this feature still here if target+horn1 are both translated?

    ➔Tested +1 mm translation, and observed similar offset to target only translation

      ➔Can treat horn1 + target as unit and focus on offset with horn 2+3

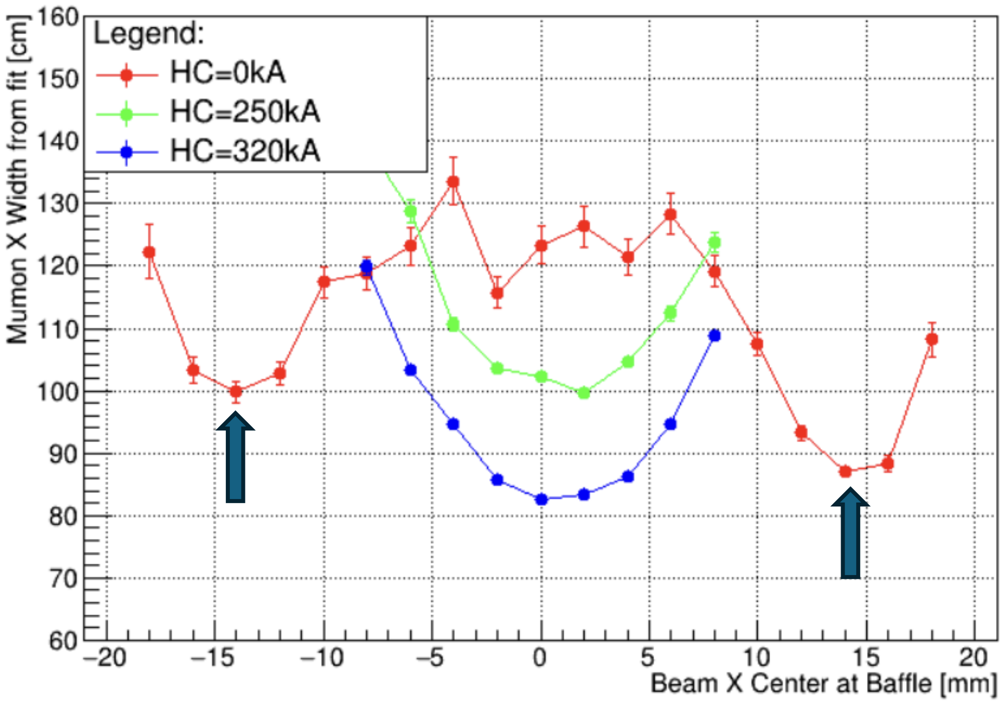


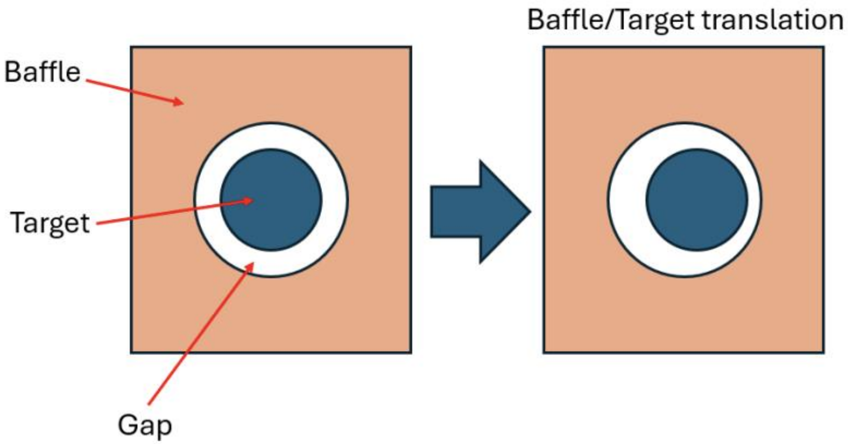
Target Translation

- Width asymmetry is based off gap between baffle/target.

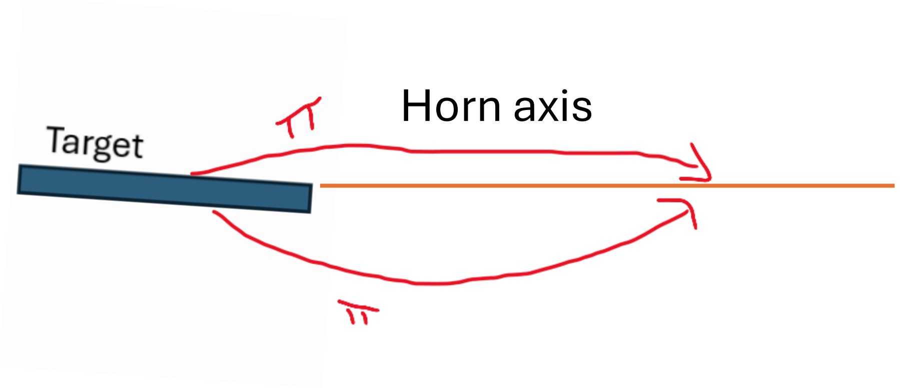
➔Opposite direction to baffle translation, but same effect

Target Translation of -1 mm in X



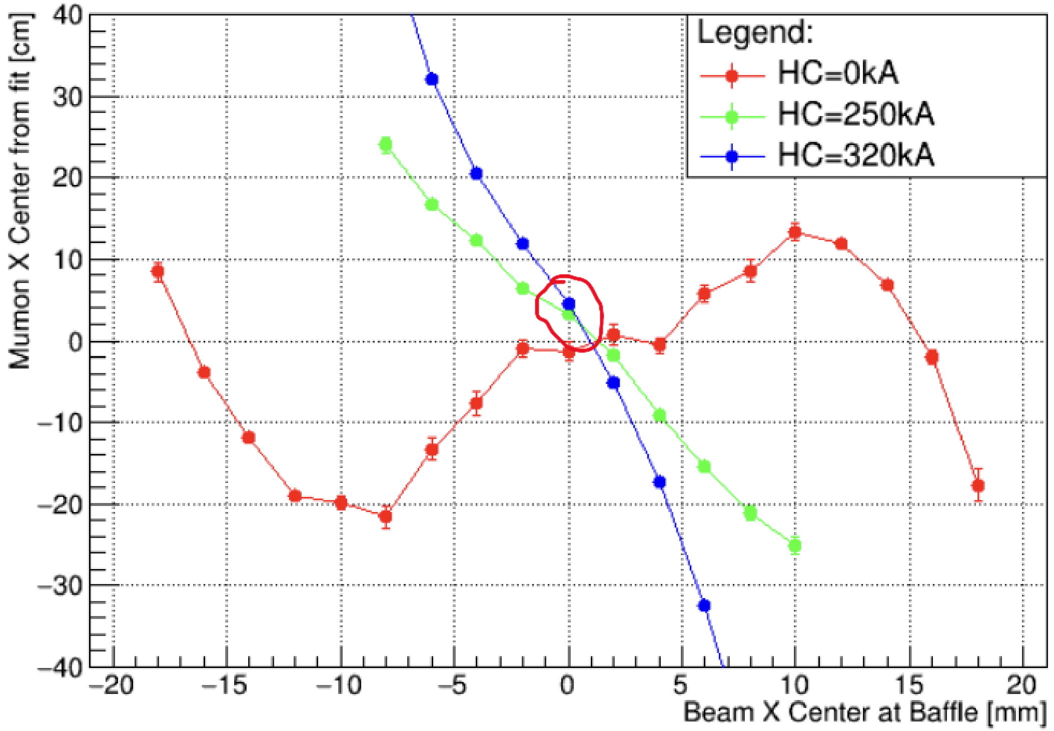


Target Angle

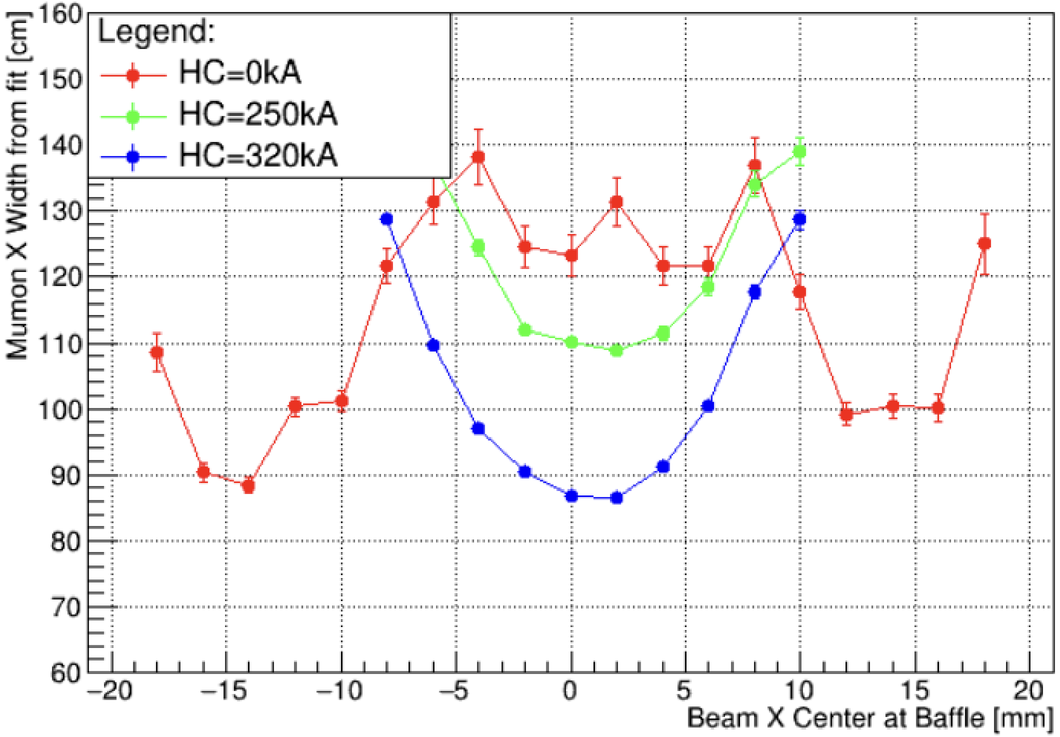


- Tested for -1 mrad and +1 mrad target angle.
- HC on intersection != 0kA intersections.
    - Smaller effect than target translation. ($\Delta\text{int} = \sim 0.74 \frac{cm}{mrad}$ mumon center shift / mrad target angle)
- Small width asymmetry created

Target X Angle of +1 mrad



Target X Angle of +1 mrad



Estimating Component Misalignment

- Can try to identify component misalignment in run 12 & 13 position scan data using features found in simulation data.

Width Asymmetry:

- Many degenerate effects, so no definitive conclusion can be found

HC on/off intersections splitting:

- Main effect was observed only with target translation
    - May have degenerate effects with horn alignment that requires further study

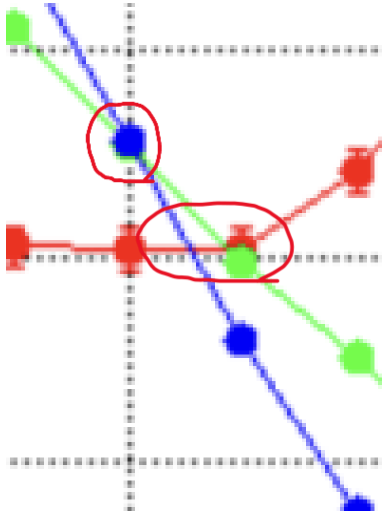
Estimating Component Alignment

- Difference between intersection of 250 kA and 320 kA lines compared to intersection of 320 kA and 0kA lines can be used to find offset between target and horn center.
- Target angle has a similar effect, so this is treated as an uncertainty on target translation (in this case, both effects are considered as independent)

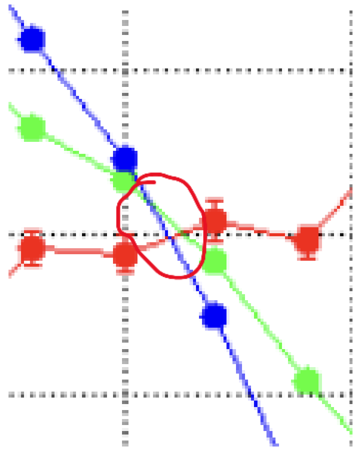
$$\Delta \text{Mumon}_{x,\text{cross,HC on}} = -\Delta_{\text{target}}(5.8\frac{\text{cm}}{\text{mm}}) + \phi_{\text{target}}(0.74\frac{\text{cm}}{\text{mrad}})$$

- Target angle is constrained from construction (2012 paper!! So may be out of date) to ±1.3 mrad for x, ± 0.2 mrad for y, which is propagated as error in the calculation

Target X Translation of -1 mm



Target X Angle of +1 mrad

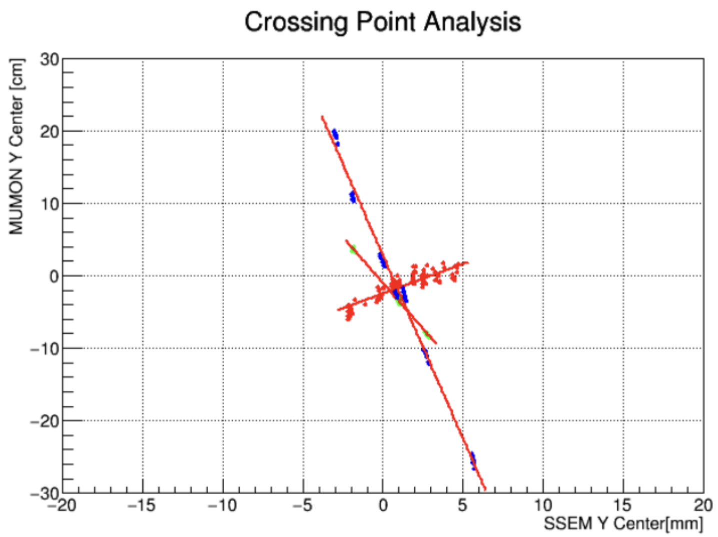


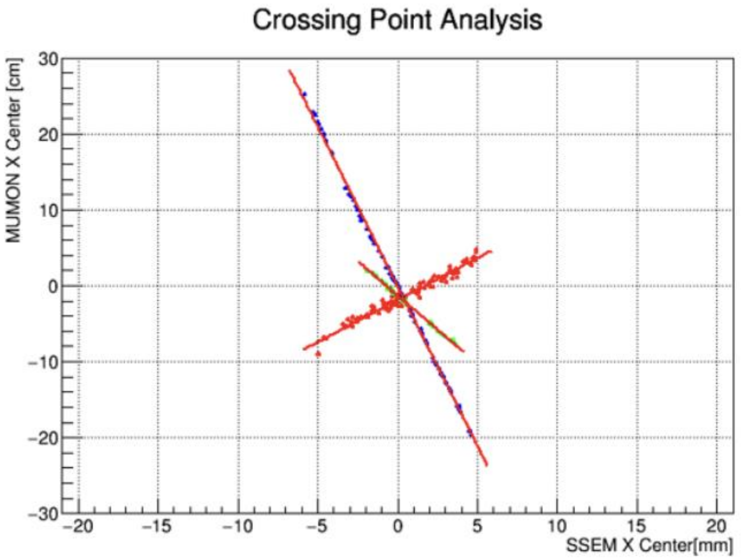
Estimating Component Misalignment

$$\Delta \text{Mumon}_{x,\text{cross,HC on}} = -\Delta_{\text{target}}(5.8\frac{\text{cm}}{\text{mm}}) + \phi_{\text{target}}(0.74\frac{\text{cm}}{\text{mrad}})$$

- Equation found from simulation results
- Target angle is assumed to be zero and error is propagated.
- No significant target translation in X,
- Y shows possible target/horn translation, but is inconsistent between Run 12 & 13

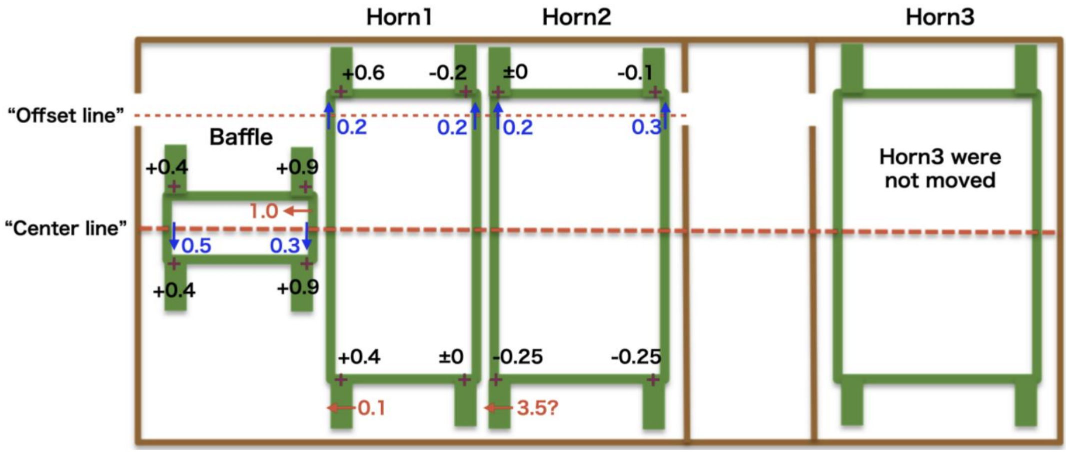
	$\Delta_{x,\text{target}}$	$\Delta_{y,\text{target}}$
Run 12:	0.11 ± 0.17 mm	0.68 ± 0.07 mm
Run 13:	0.10 ± 0.17 mm	0.48 ± 0.04 mm





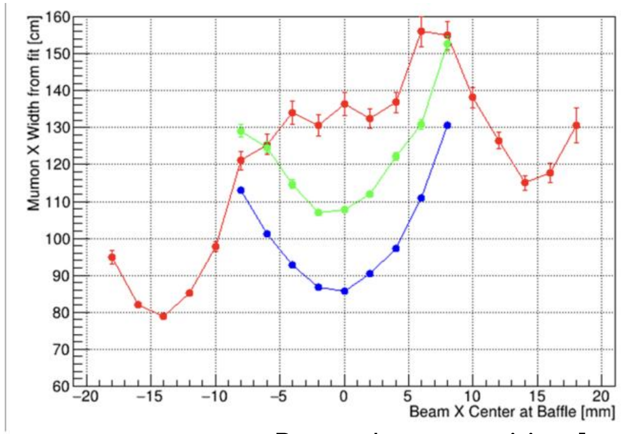
Agreement with Target Station Survey

Component misalignment	Calculated parameters	Target station survey results
X Baffle translation	N/A	-0.4 mm
X Baffle angle	Positive	+0.12 mrad
Y Baffle translation	N/A	+0.65 mm
Y Baffle angle	Positive	+0.3 mrad
X Target translation	0.1 ± 0.17 mm	+0.2 mm
Y target translation	0.58 ± 0.08 mm	+0.5 mm



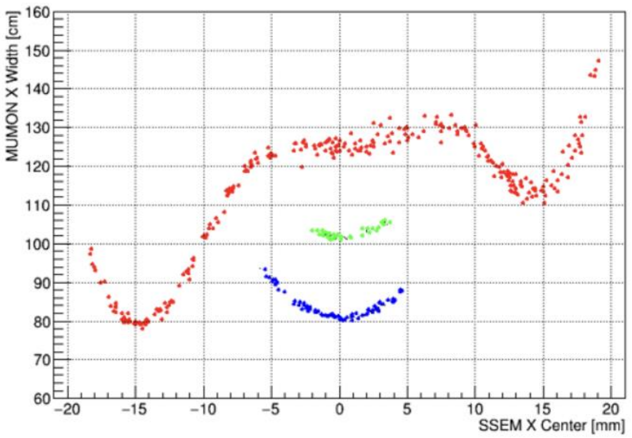
X Asymmetry reproduced with baffle parameters in simulation

Simulated Baffle Translation



Proton beam position [mm]

Observed Position Scan



Proton beam position [mm]

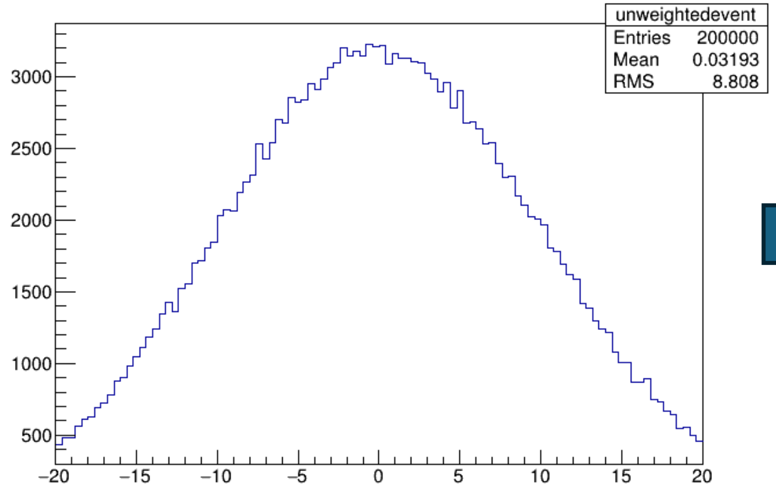
- Baffle measurements produce good agreement with asymmetry in X.
- Using only baffle measurements does not produce same asymmetry for Y
- Calculated target/horn1 translation appears to match with horn1 measurements

Future Developments

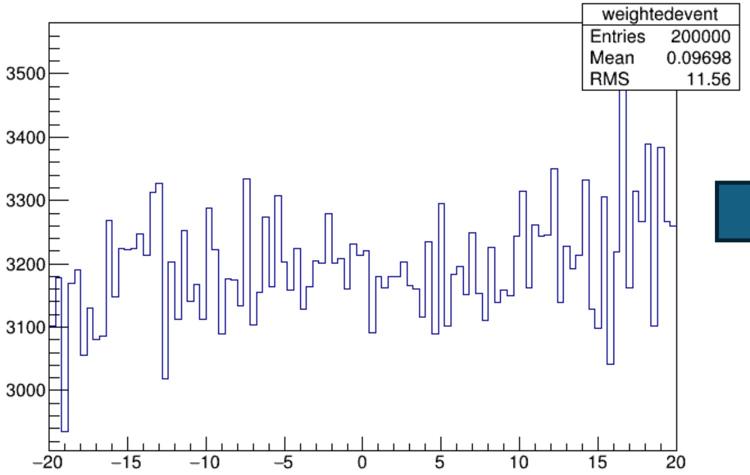
- Simulation dataset is small, but requires a lot of disk space for each run (each beam position is simulated separately)
  - ➔Instead can use large beam and reweight for each position.

Example with a test dataset w/ a random gaussian

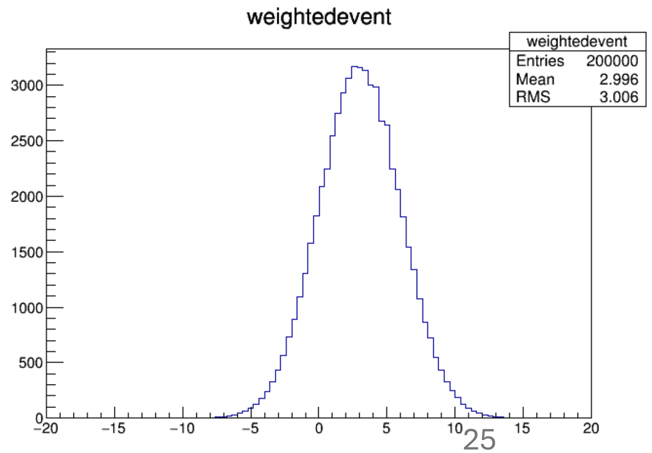
Biased events (gaussian distribution)



No biased weights (mostly flat distribution)



Reweighted weights (Gaussian with a center at x=3)



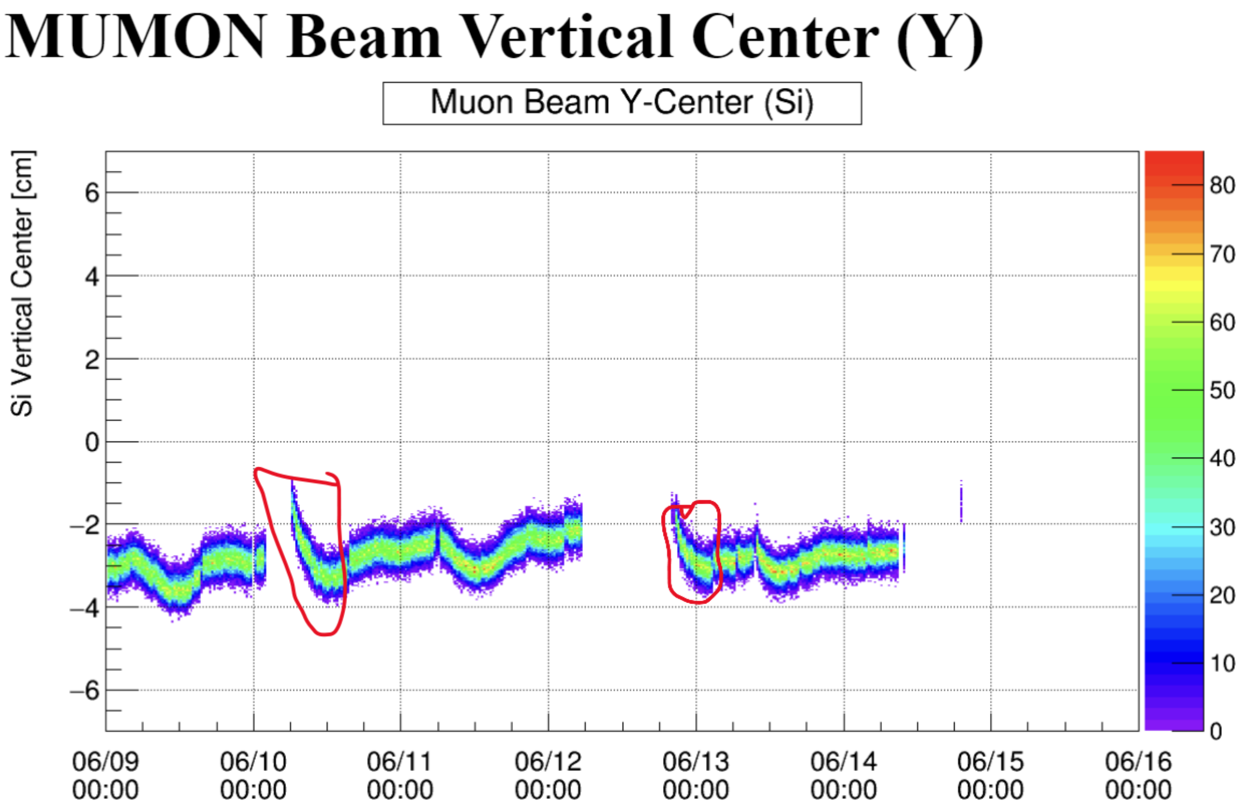
Open Questions

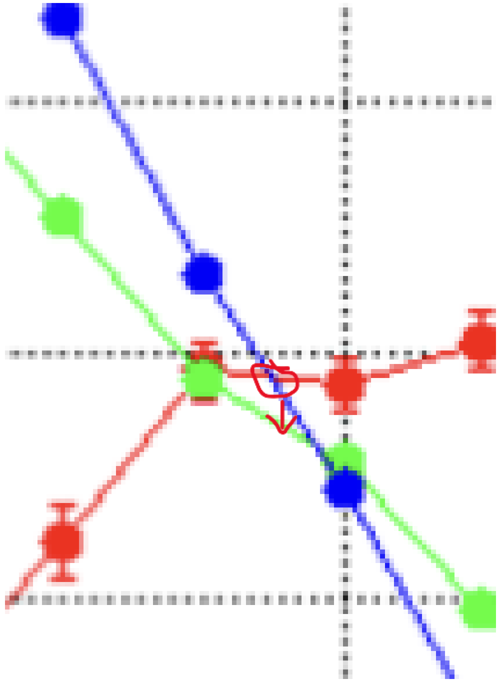
- Why does baffle angle have such a large effect?
- Horn alignment effects: Have not studied in detail.
- A more detailed analysis/fitting data
- What applications does this have for the bigger picture of T2K?

Questions or comments?

Possible explanation for initial instability seen in mumon:

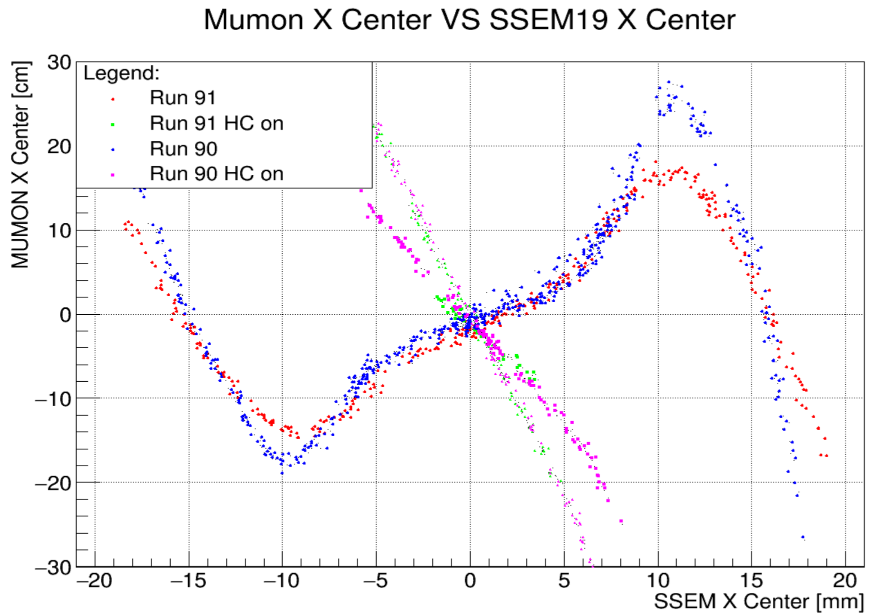
- Horn current decreases due to heating
- Since target axis/horn axis is offset, alignment found from horn on/off check is for a different horn current.

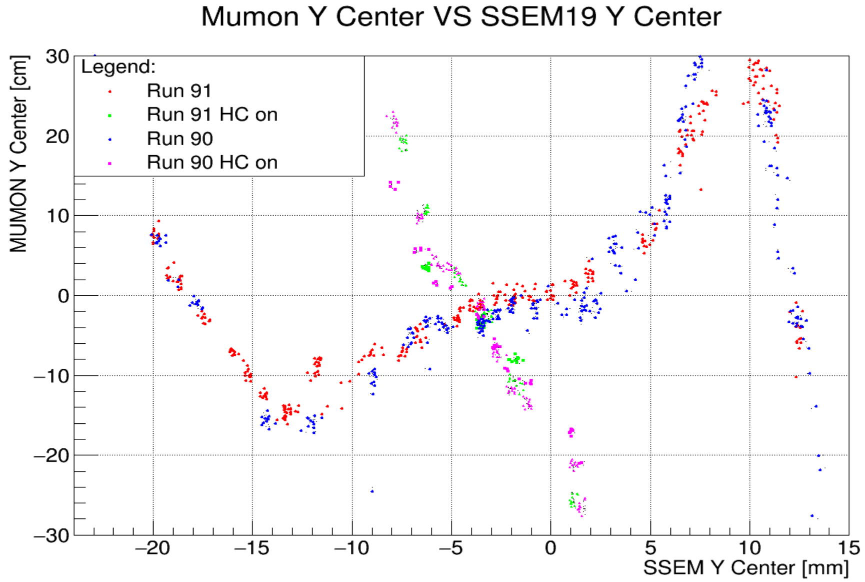


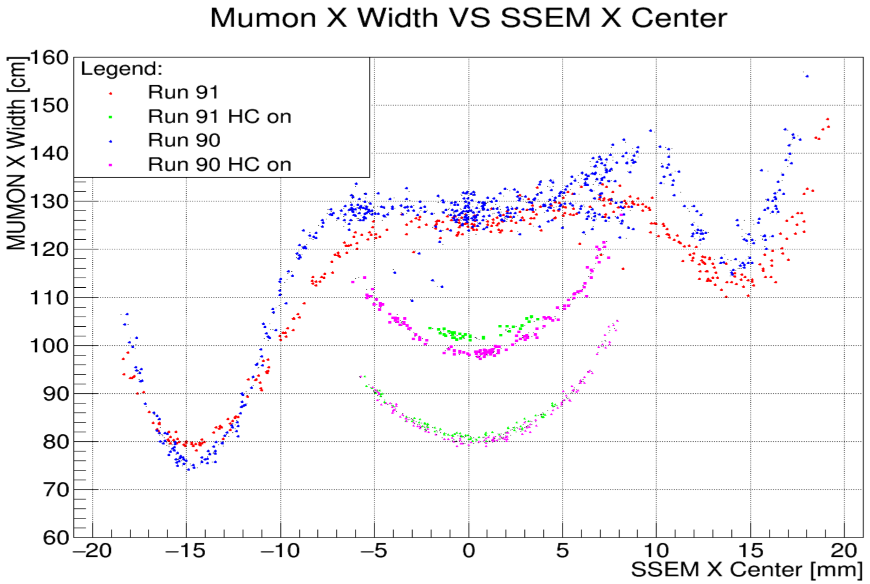


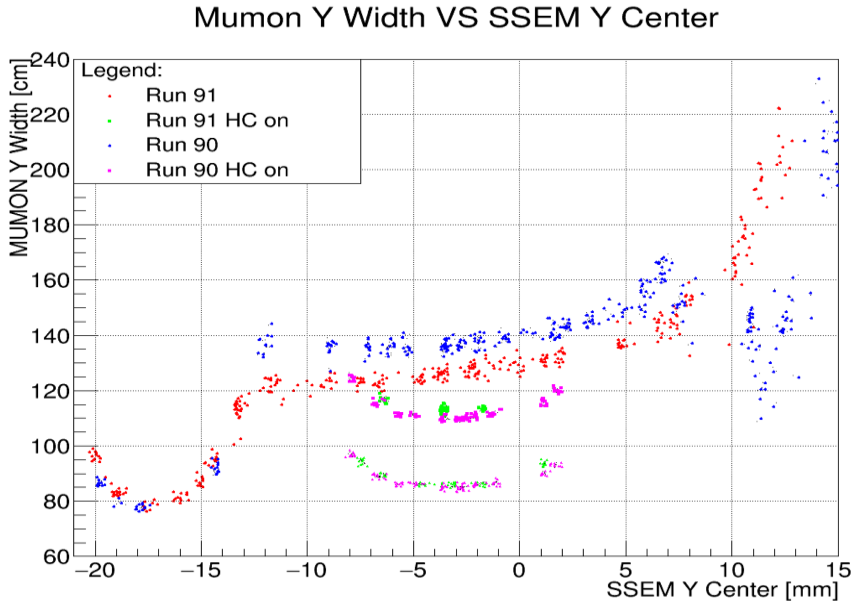
Target translation of +1 mm

Position Scan Results comparing run 12 & 13



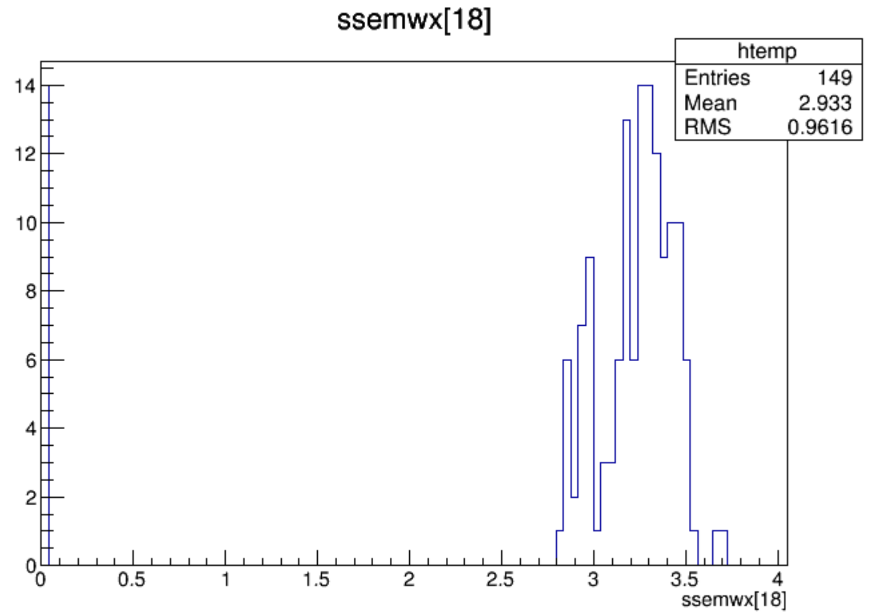


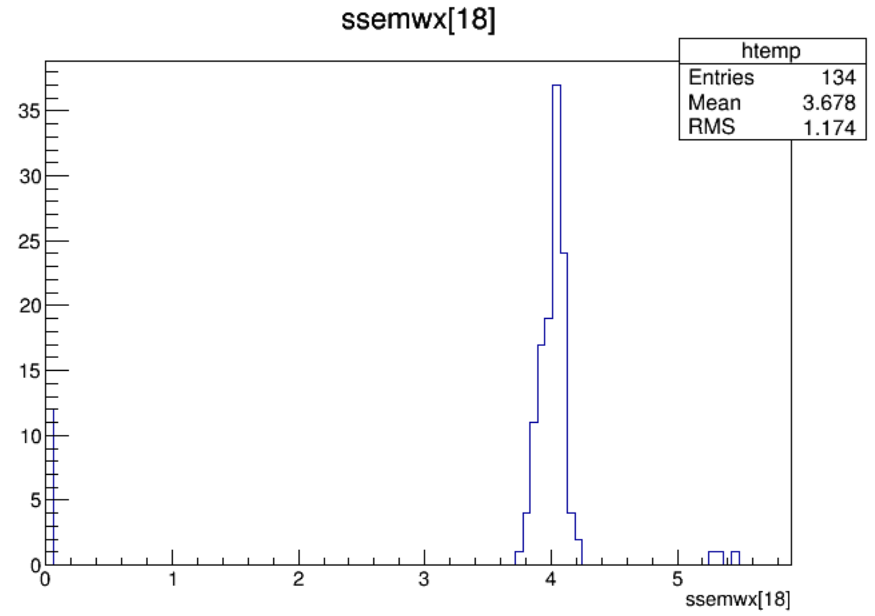




Beam width for the position scans

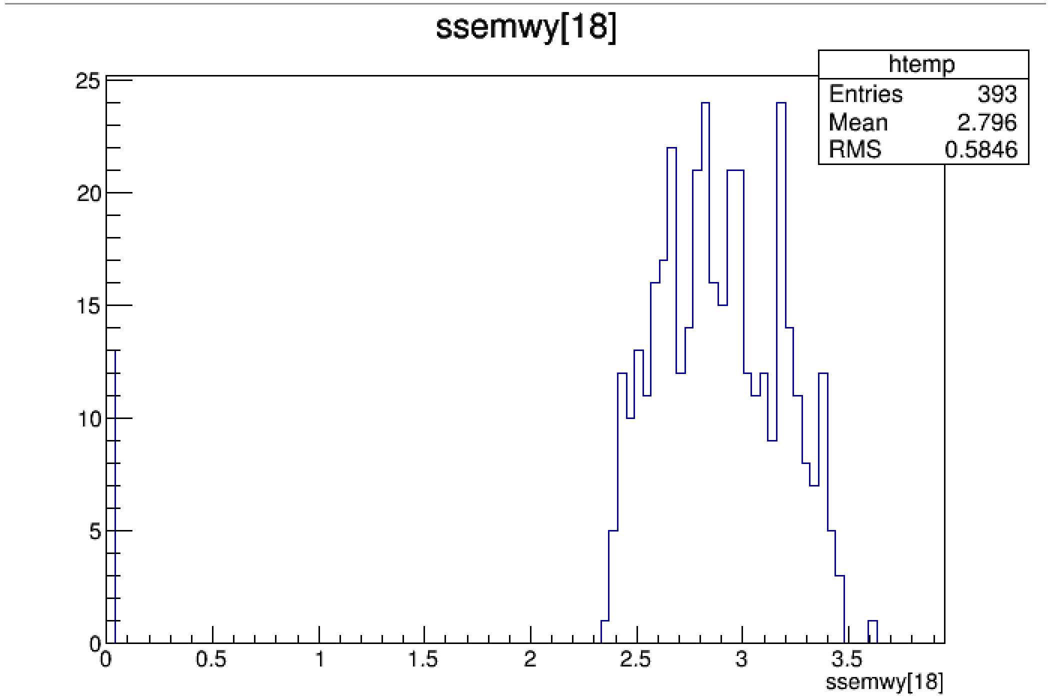
- Run 90 (left) x position scan width and Run 91 (right) position scan width at SSEM19
- This may explain the differences seen between run 90 and 91 position scans

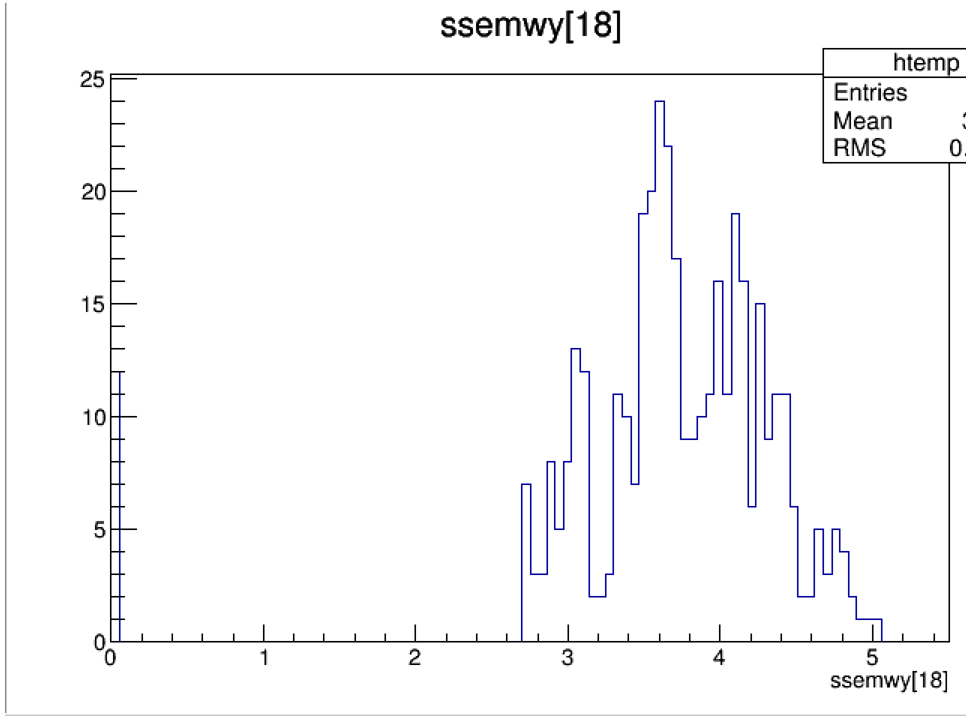




Beam width for the position scans

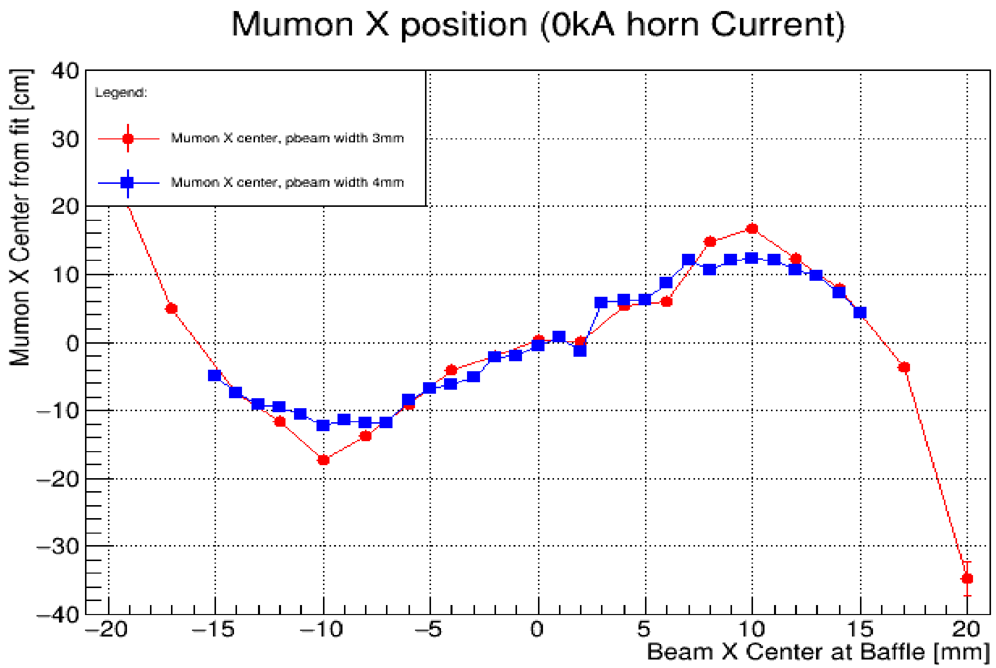
- Run 90 (left) y position scan width and Run 91 (right) position scan width at SSEM19
- Width is also higher for y position scan in run 91.

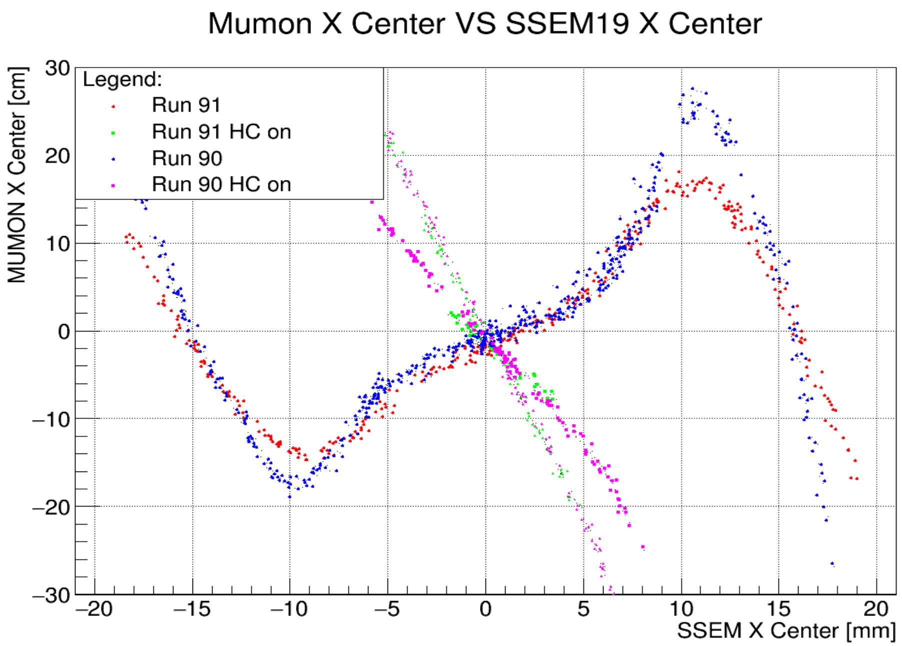




Difference between 3mm & 4mm beam width

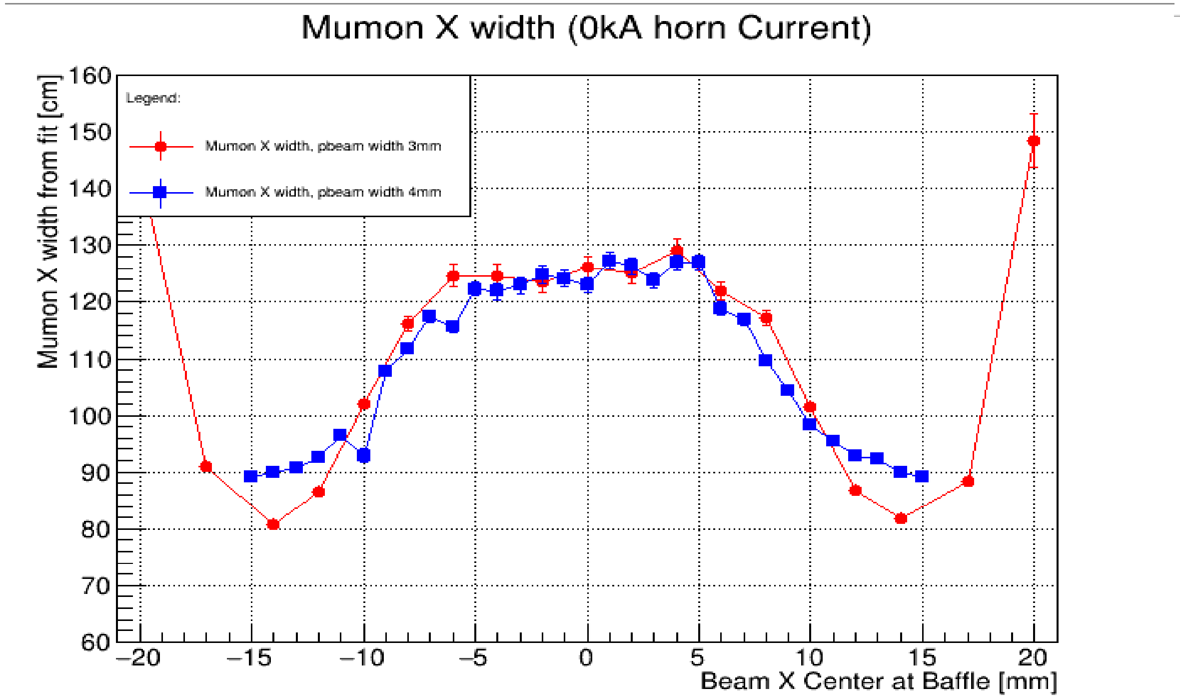
- As width gets wider, the peaks in the correlation plot get less pronounced, as seen in the difference between run 91 & 90.

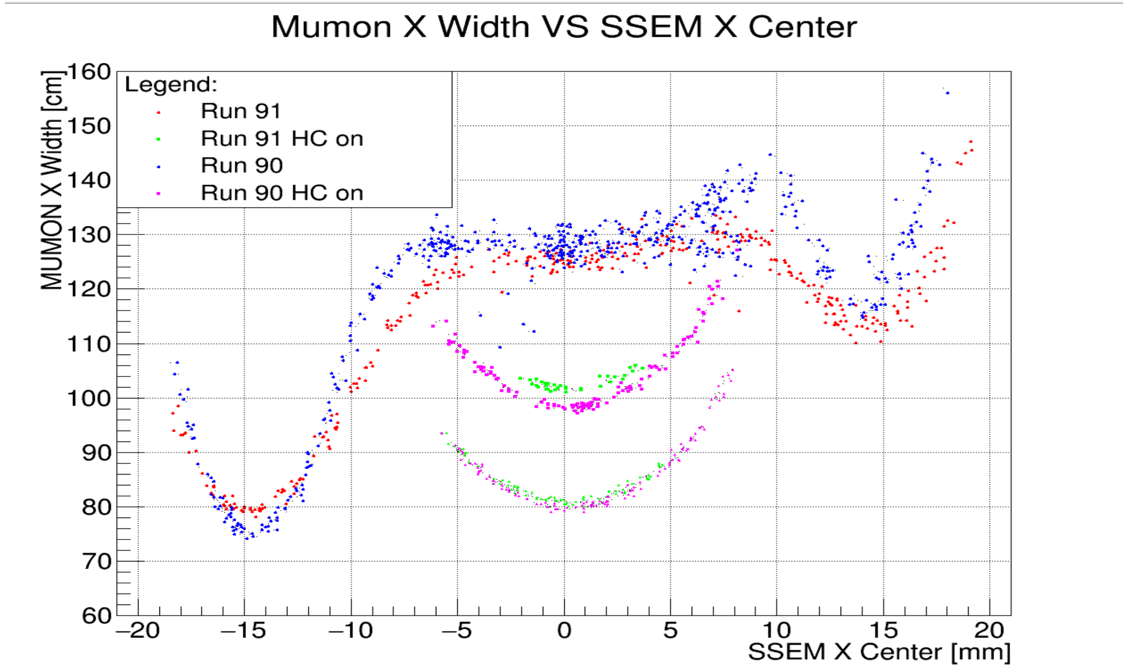




Difference between 3mm & 4mm beam width

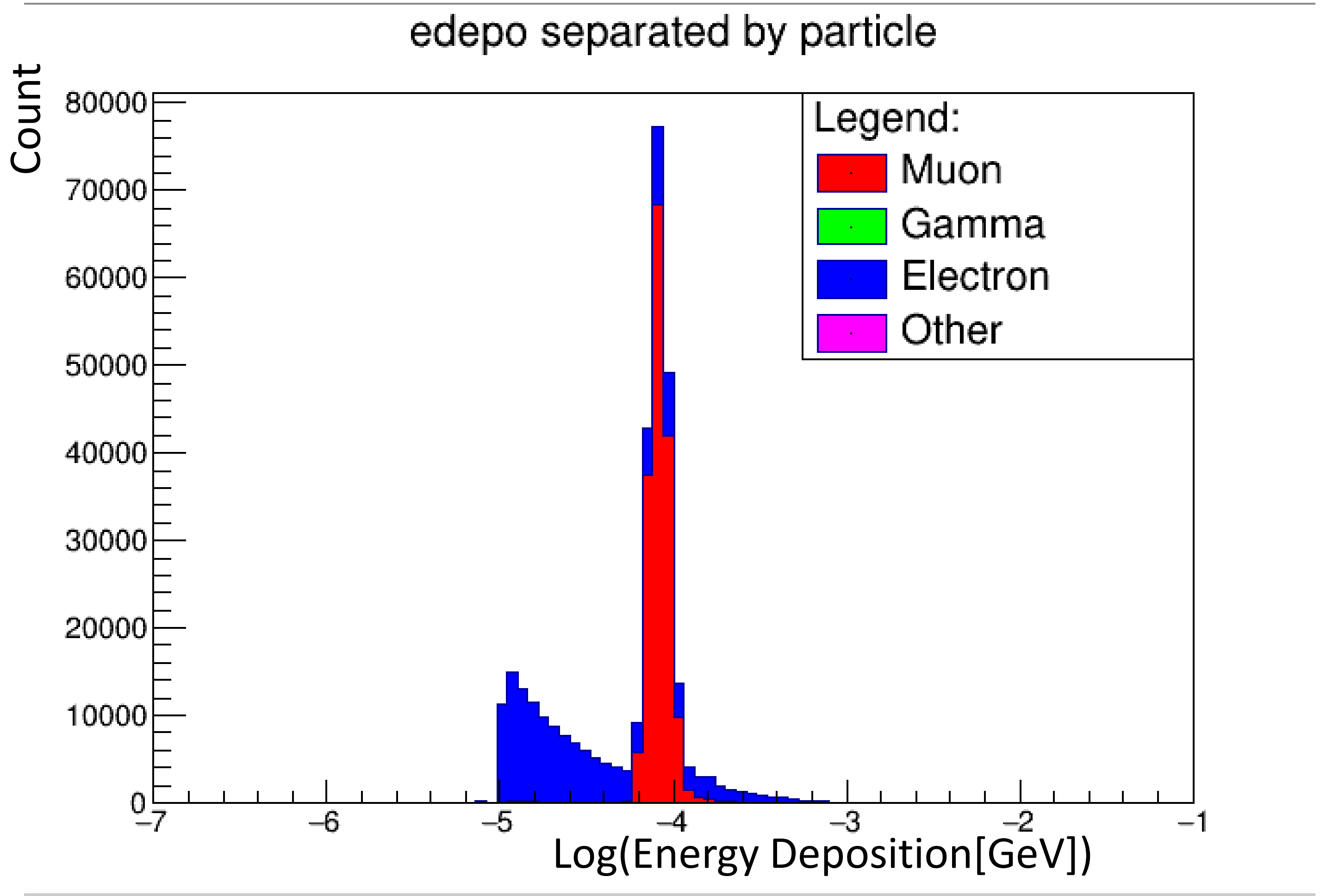
- As width gets wider, the contours of the width response get less defined, and the size of the parabolic valleys increases.





Simulation analysis – Energy Deposition by particle type

- The vast majority of energy deposition in the Mumon plane is the result of electrons and muons.
- Therefore, it is better to filter out gamma events so they do not affect the final shape of the graph as that is not reflective of actual data of Mumon SI



Update to simulation analysis

Before:

- Was weighting all particles equally for the gaussian fit

Now:

- Exclude gamma events since they do not contribute much to energy deposition in the mumon plane

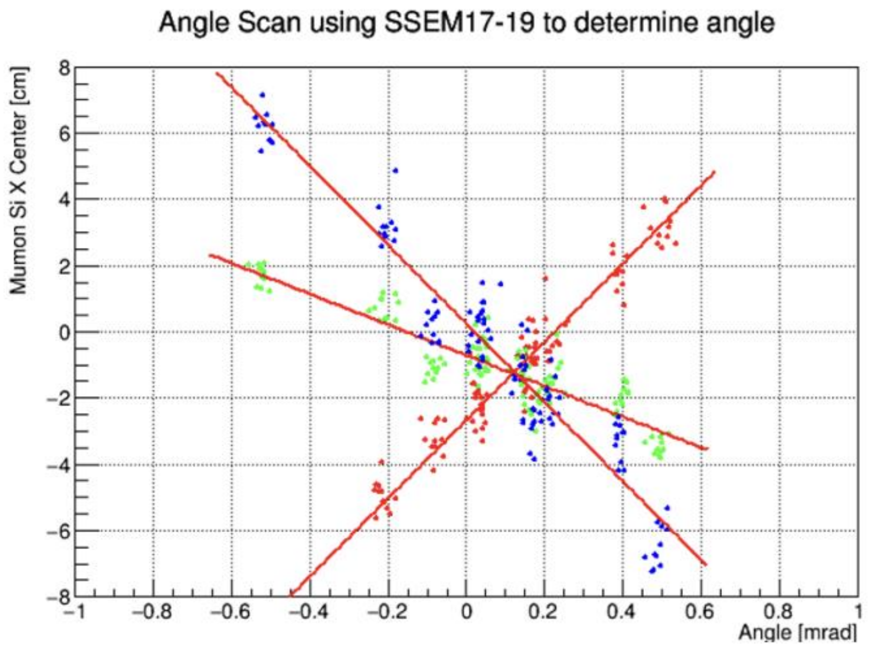
Particles from x,y=0,0 beam position, no baffle misalignment:

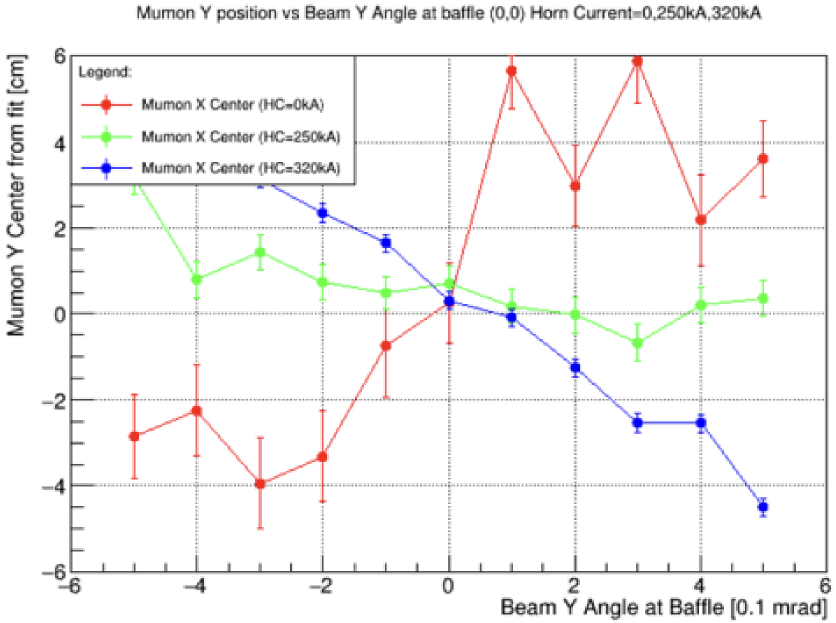
Total: 430511

- Gamma: 34%
- positron: .3%
- electron: 30.9%
- neutrino: 0
- Muon +: 21.76%
- Muon -: 12.55%
- neutron: .278%
- Other: .015%

Beam Angle Scan

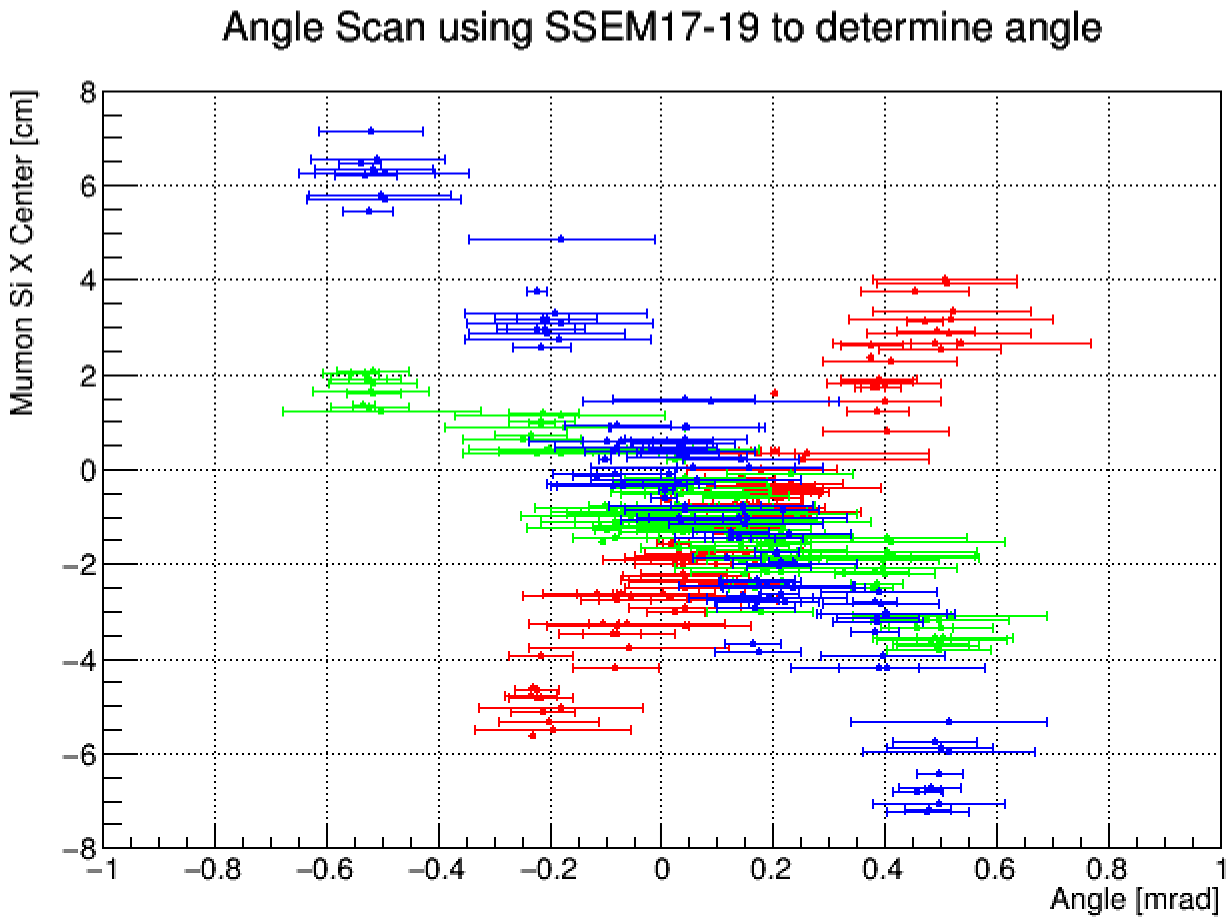
- The proton beam angle scan was carried out for X in Run 13, and for Y in Run 12.
- Similarly, the crossing point can be calculated by finding the intersection of the horn currents.





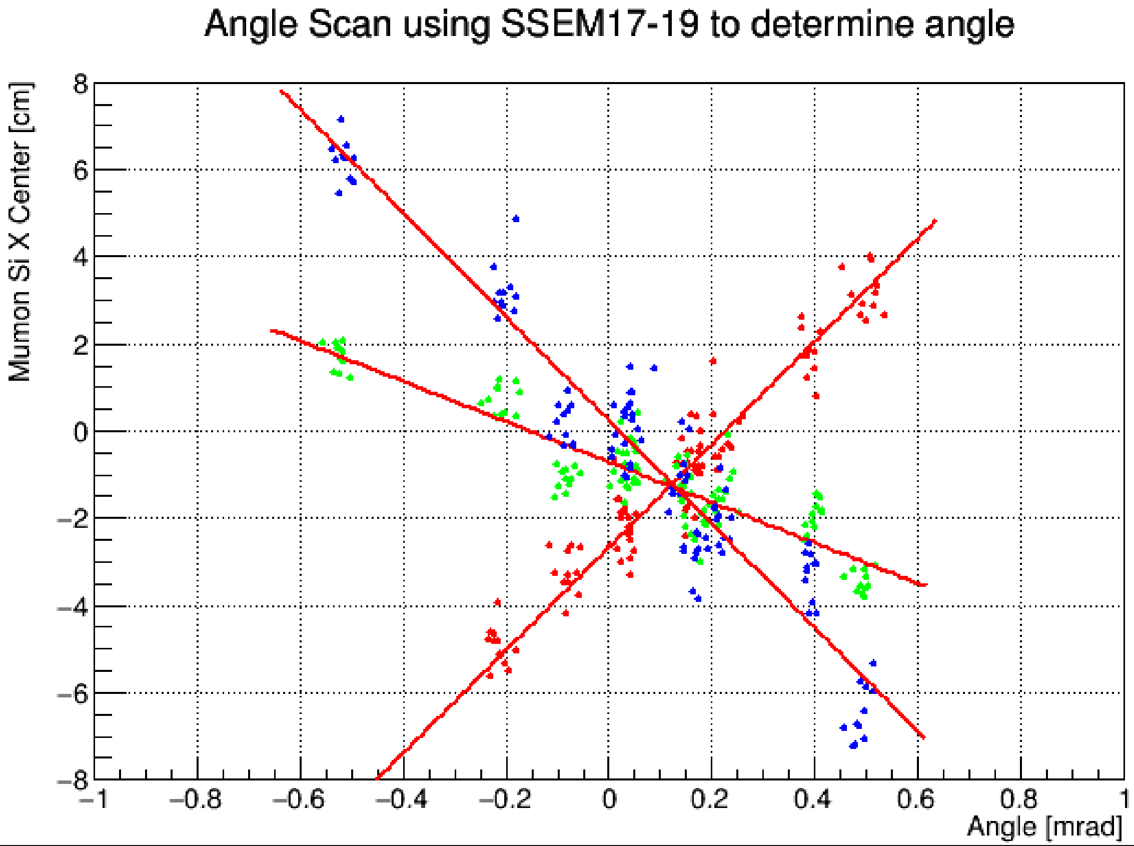
Beam Angle Scan Analysis using SSEM 17-19

- Error bars from fitting the three sensors are ~0.1-0.3 mrad

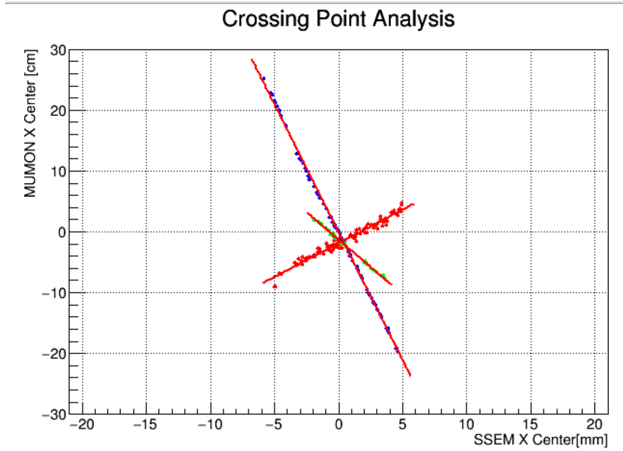


Crossing Point analysis

- Similar to position scan crossing point?
    - Could be the result of the same effect.




```
Crossing point analysis for SSEM17-19Intersection of 0kA and 320kA line w/ correction (ssem19 X,Mumon X)
0.122618+-0.0174975, -1.21237+-0.241057
Intersection of 0kA and 250kA line w/ correction (ssem19 x, mumon x)
0.118595+-0.0190919, -1.25983+-0.244437
Intersection of 250kA and 320kA line w/ correction (ssem19 x, mumon x)
0.131727+-0.0553674, -1.32068+-0.0237712
```

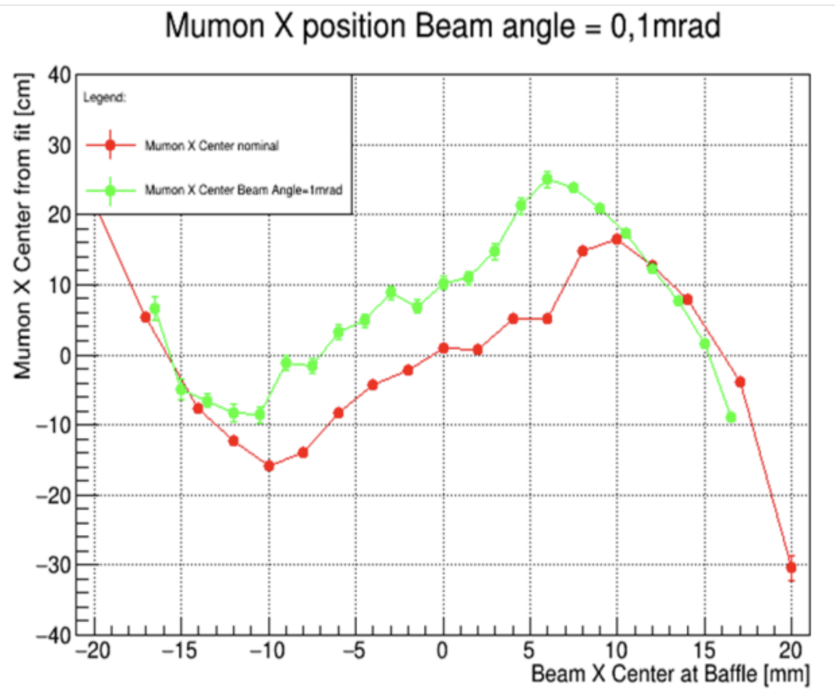


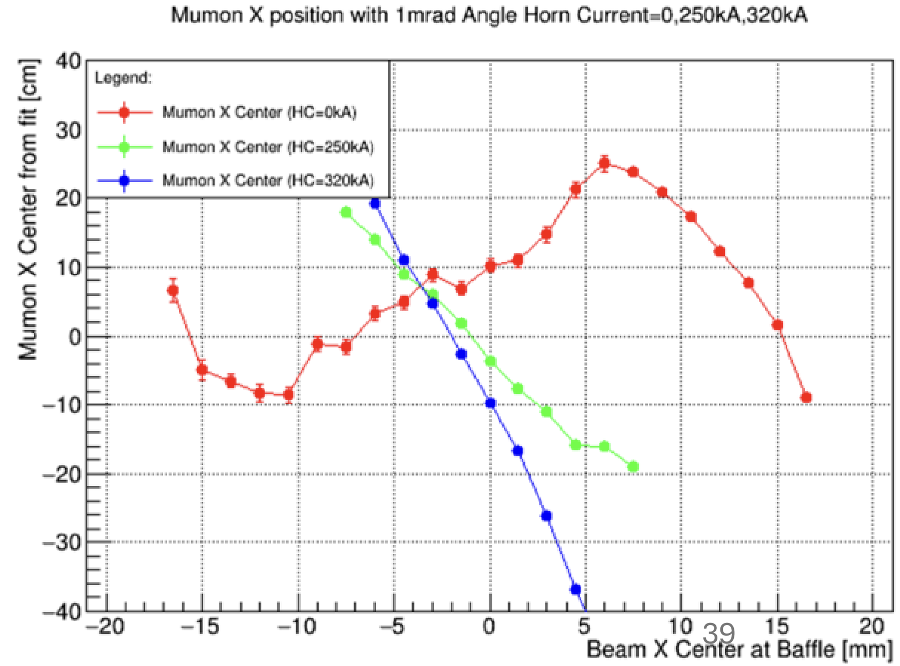

```
Intersection of 0kW and 320kW line (ssem19 X,Mumon X)
0.330851,-1.50327
Intersection of 0kW and 250kW line (ssem19 x, mumon x)
0.200739,-1.64732
Intersection of 250kW and 320kW line (ssem19 x, mumon x)
0.487755,-2.16431
```

Beam Position Scan

Beam angle systematic effects:

- Beam angle introduces a systematic effect on the beam position scan
- The beam propagates from the last measured position to the target, leading to a shift in the response.
- This also shifts the crossing point in a similar manner.
  - No crossing point splitting





Parent Particle Origin Analysis

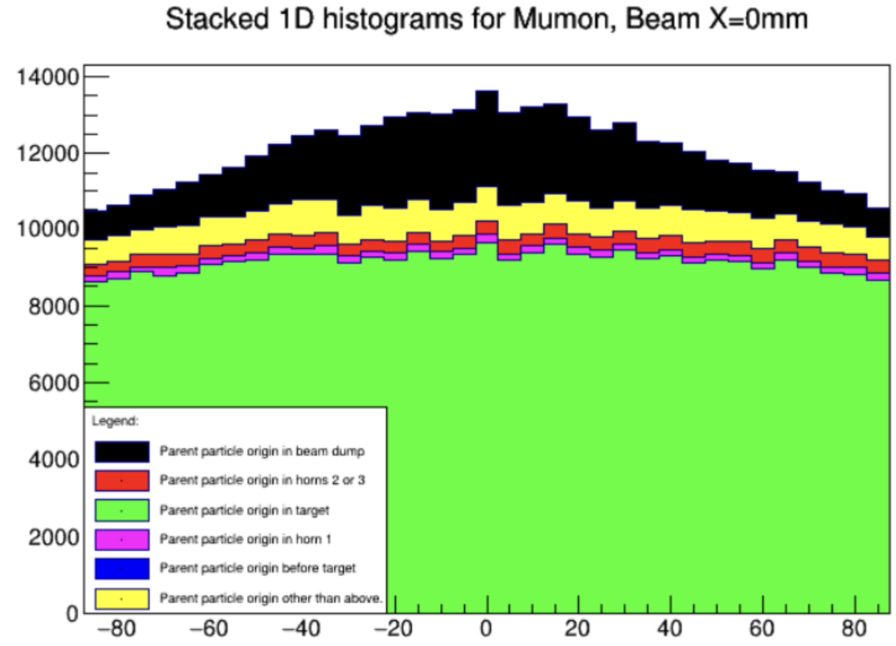
It is useful to separate the muon monitor profile based on the parent particle origin, or in other words where in the beamline the proton beam impacted

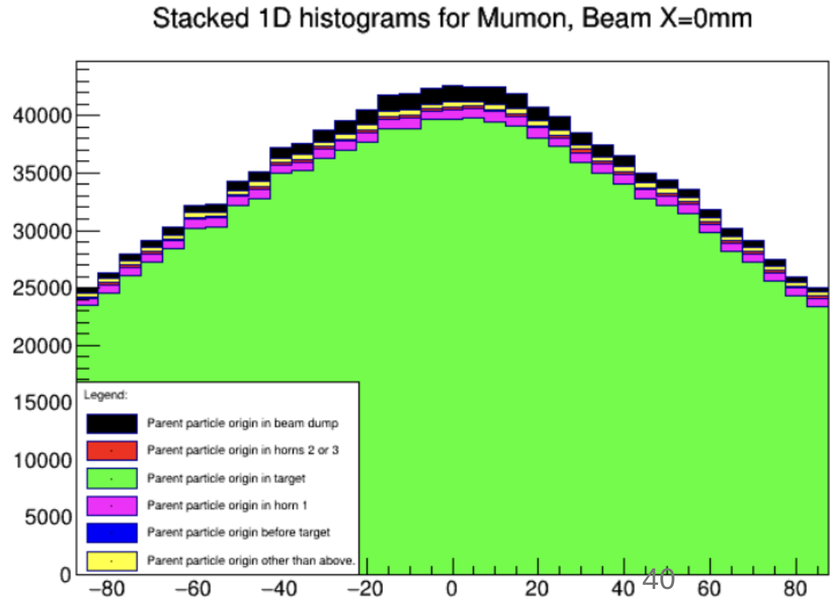
At 0 kA focusing horn current:

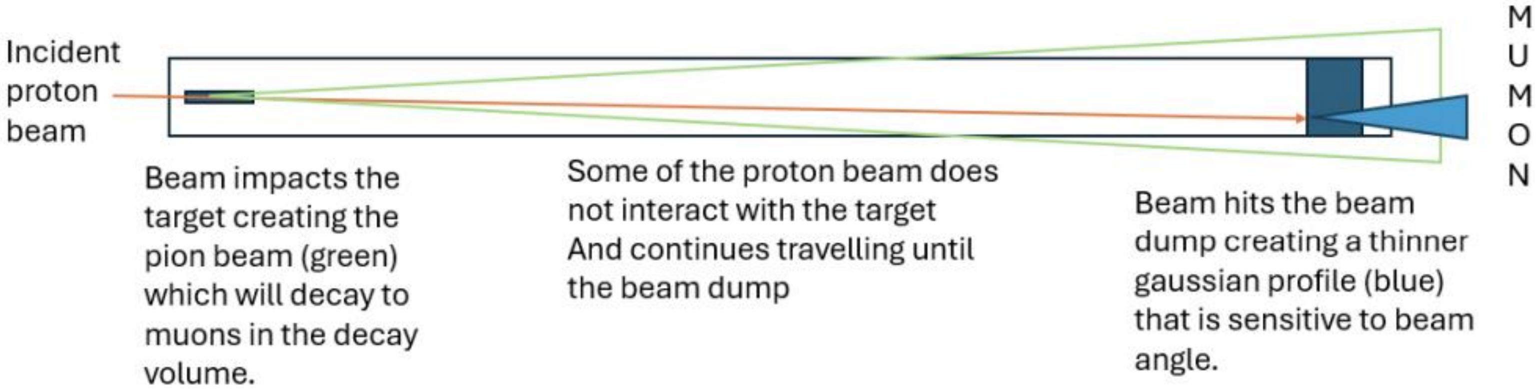
- Target origin particles form a wide gaussian
- Beam dump origin particles form a thin gaussian.

At 320 kA focusing horn current:

- Target origin particles are focused more strongly
- Beam dump origin particles are now suppressed.



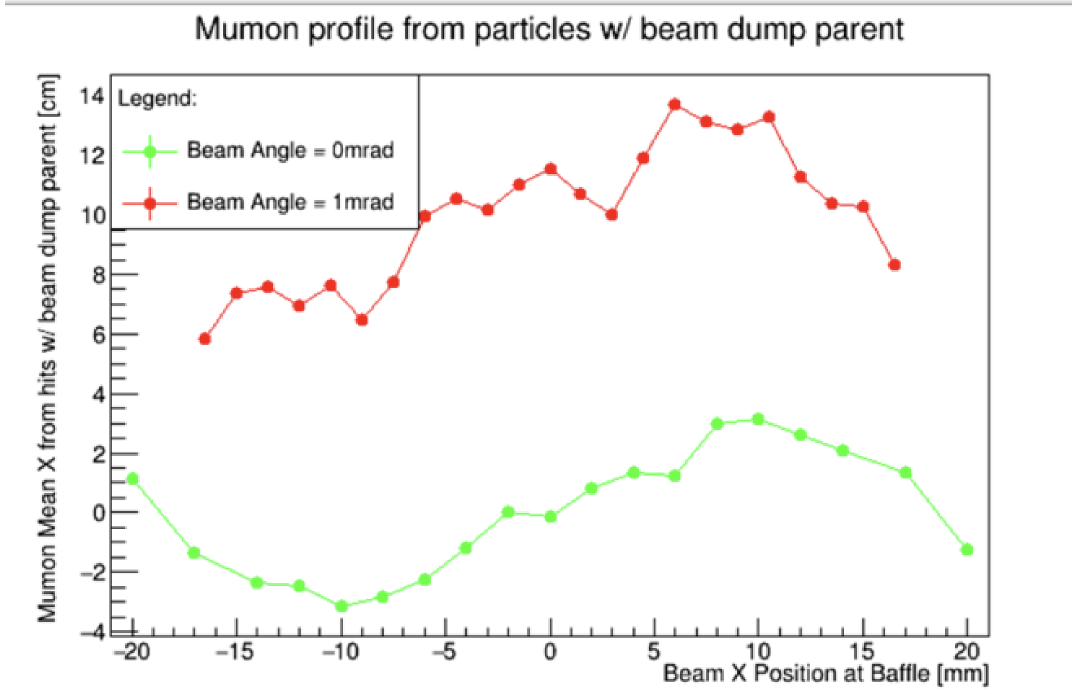




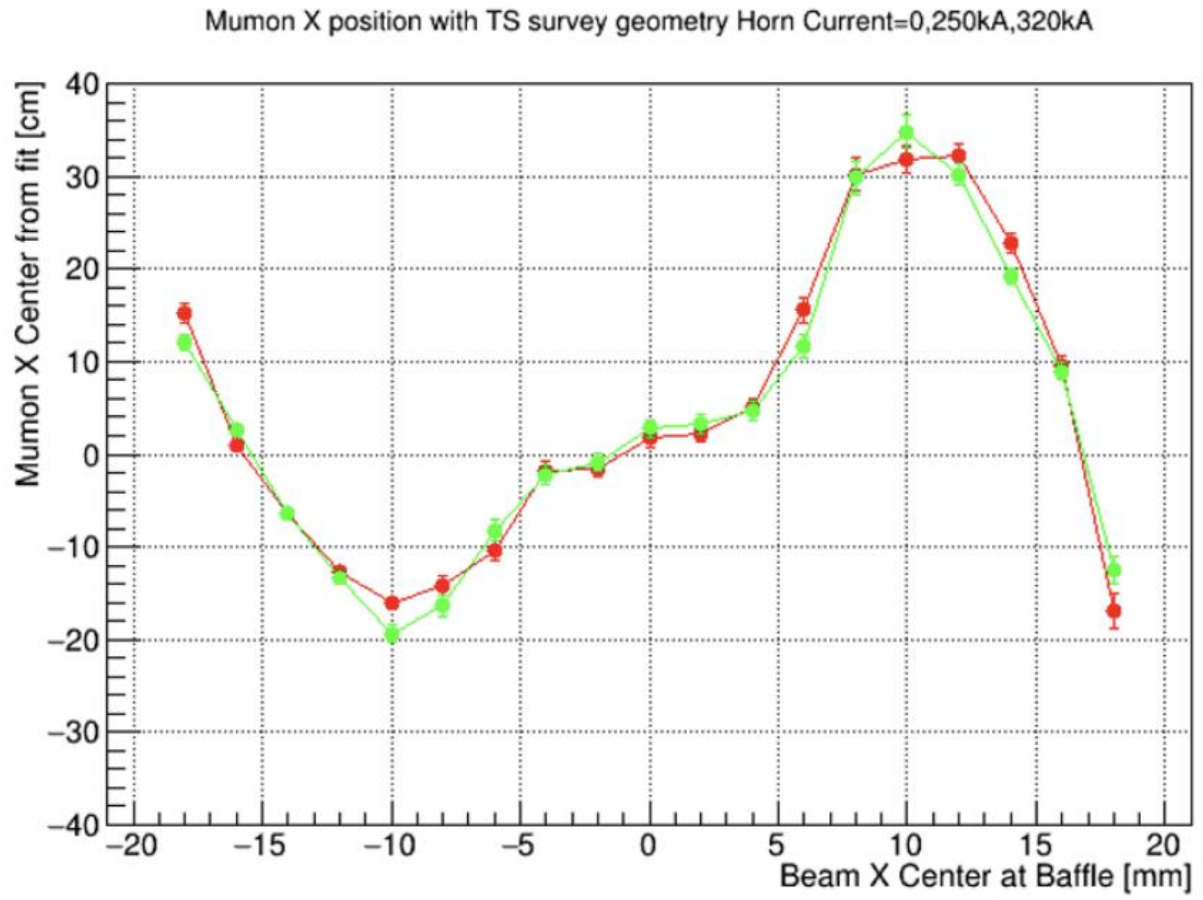
Parent Particle Origin Analysis

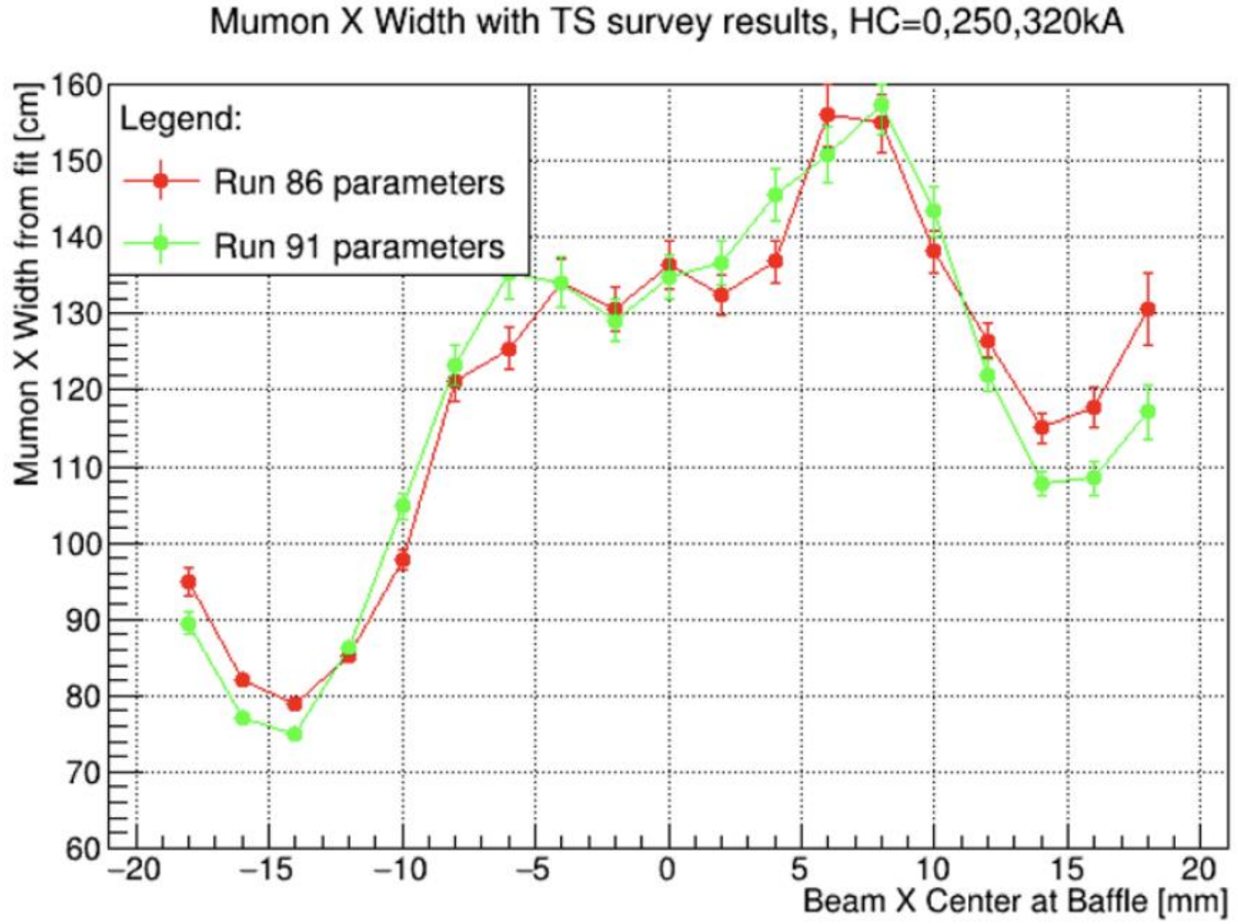
From simulations, it was found that:

- The beam dump origin gaussian is expected to have only a small dependence on proton beam position
- The target gaussian has a large dependence on proton beam position.

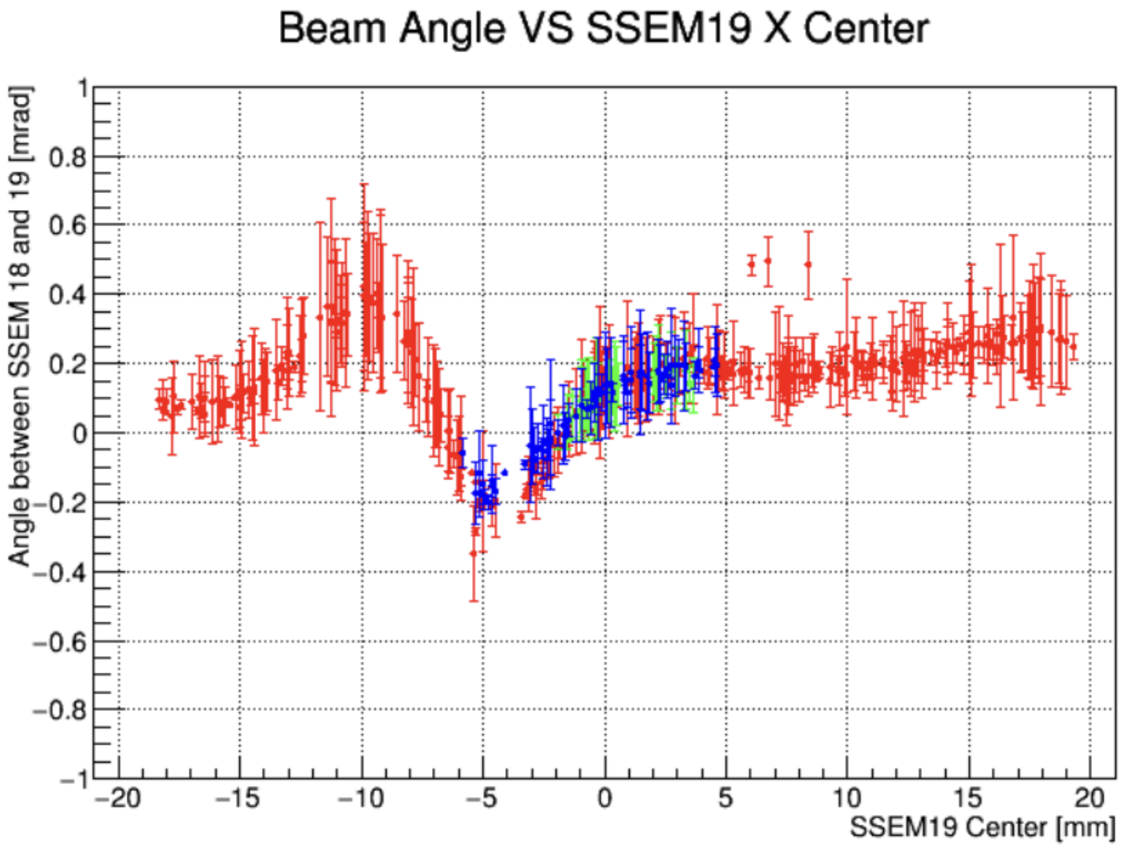


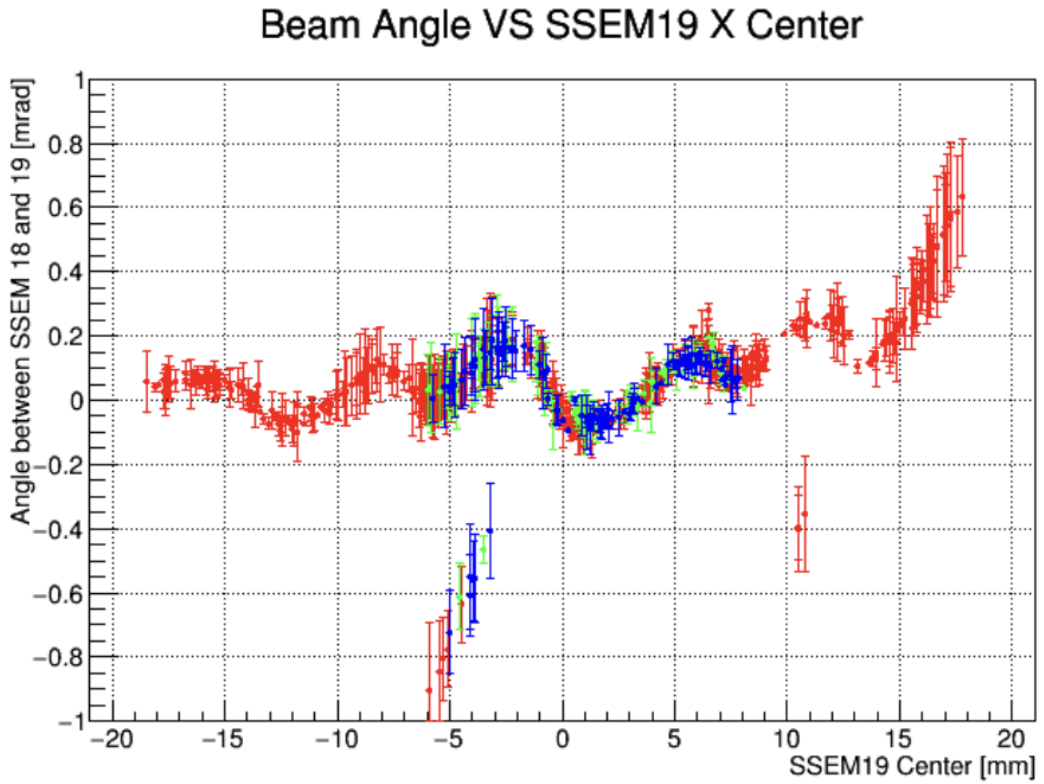
Twiss parameters



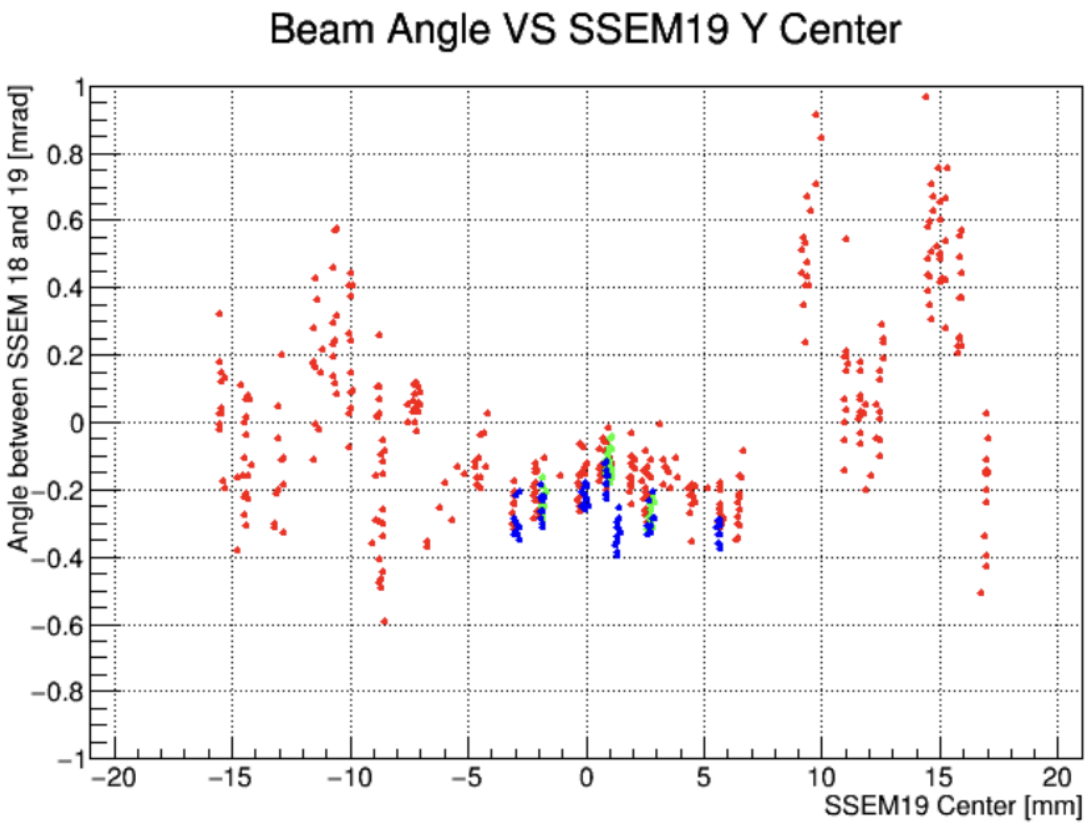


Beam Angle (X)


Beam Angle VS SSEM19 X Center
Angle between SSEM 18 and 19 [mrad]
SSEM19 Center [mm]
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−20
−15
−10
−5
0
5
10
15
20

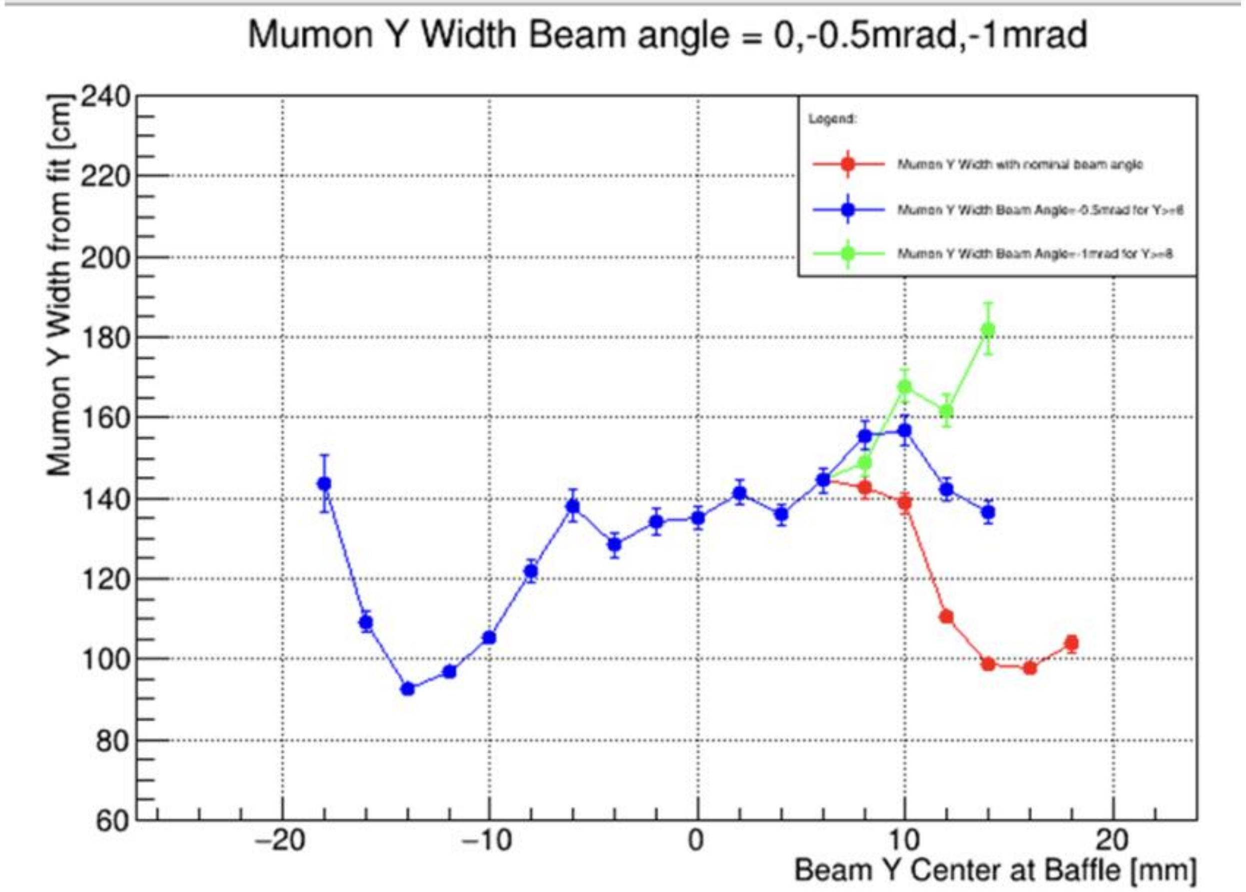

Beam Angle VS SSEM19 X Center
Angle between SSEM 18 and 19 [mrad]
SSEM19 Center [mm]
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−20
−15
−10
−5
0
5
10
15
20

Beam Angle (Y)

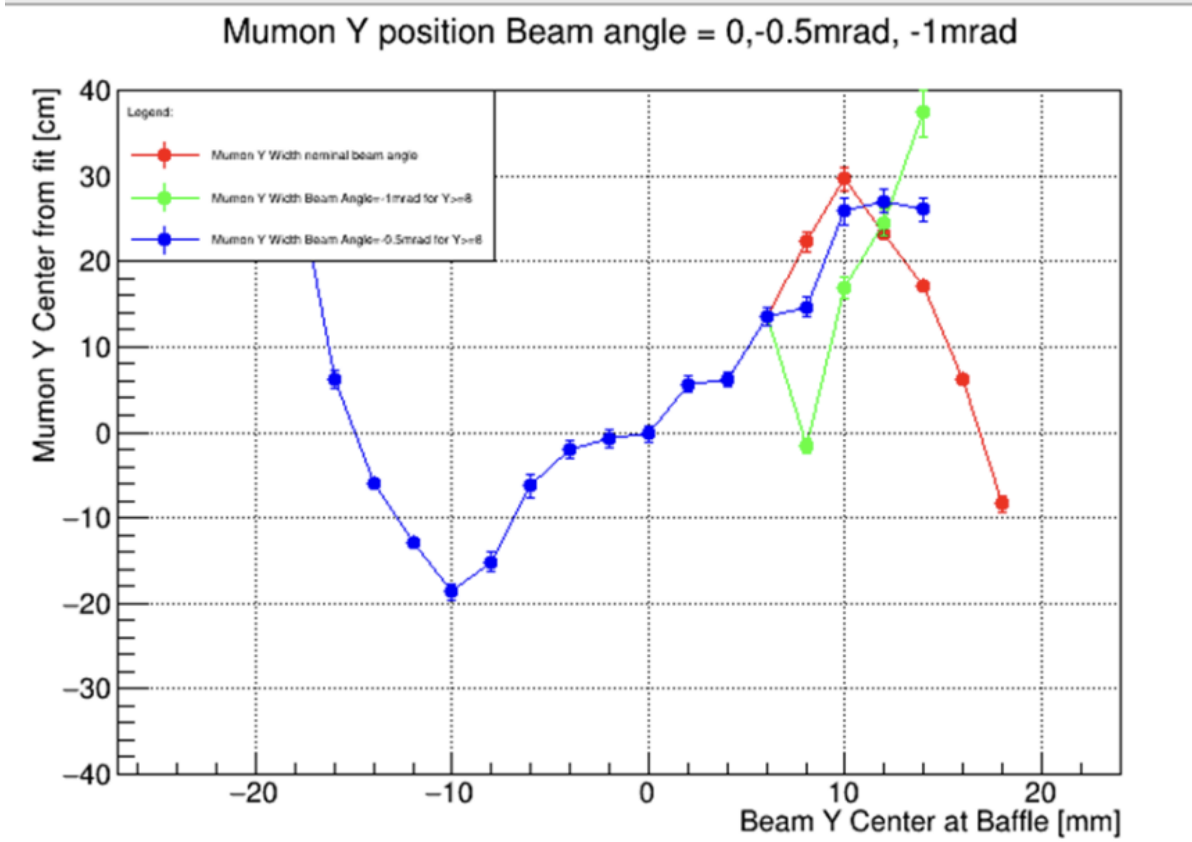


Beam Angle VS SSEM19 Y Center
Angle between SSEM 18 and 19 [mrad]
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
−20
−15
−10
−5
0
5
10
15
20
SSEM19 Center [mm]

Y Asymmetry



Mumon Y Width Beam angle = 0,-0.5mrad,-1mrad
Legend:
Mumon Y Width with nominal beam angle
Mumon Y Width Beam Angle=-0.5mrad for Y>=8
Mumon Y Width Beam Angle=-1mrad for Y>=8
Mumon Y Width from fit [cm]
240
220
200
180
160
140
120
100
80
60
−20
−10
0
10
20
Beam Y Center at Baffle [mm]



Mumon Y position Beam angle = 0,-0.5mrad, -1mrad
Legend:
Mumon Y Width nominal beam angle
Mumon Y Width Beam Angle=-1mrad for Y>=8
Mumon Y Width Beam Angle=-0.5mrad for Y>=8
Mumon Y Center from fit [cm]
40
30
20
10
0
−10
−20
−30
−40
−20
−10
0
10
20
Beam Y Center at Baffle [mm]

-1.5 mm baffle trans posscan

- No crossing point shift