Uniform Beam Simulation Technique for Beam Scans : NuMI, LBNF

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Motivation

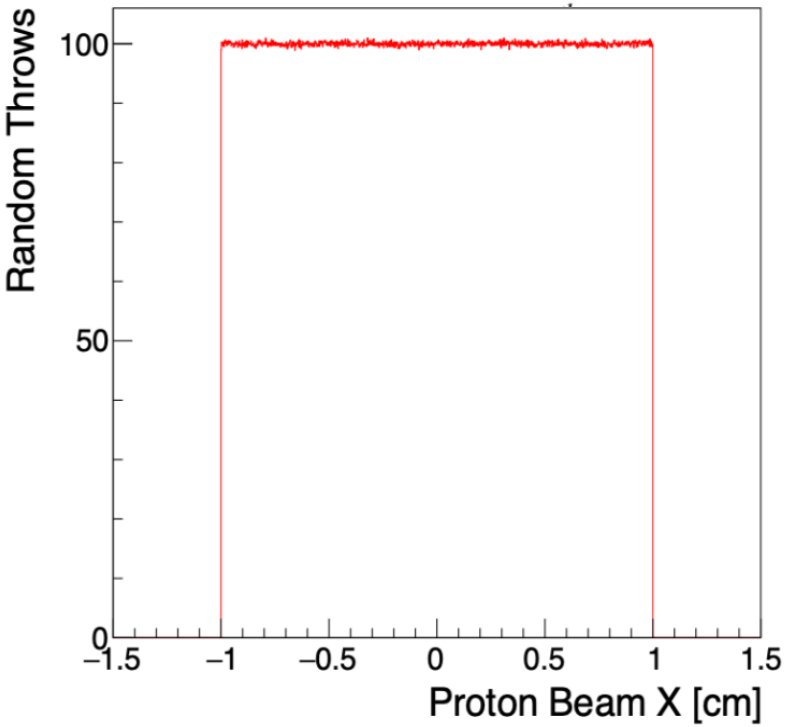
- **Aim:**
  - Create single high-statistics uniform simulation sample for each beam variable
  - Can generate as many random samples as possible from a single uniform beam sample
  - Can avoid generating multiple nominal simulation samples – reduces expensive computing resource & grid time

- Allows to do beam scan studies in simulation
- Study different beam configurations i.e., beam spot size, beam shape etc.
- ML studies, need large statistics in simulated sample to understand correlation b/w MM observation & target incidents

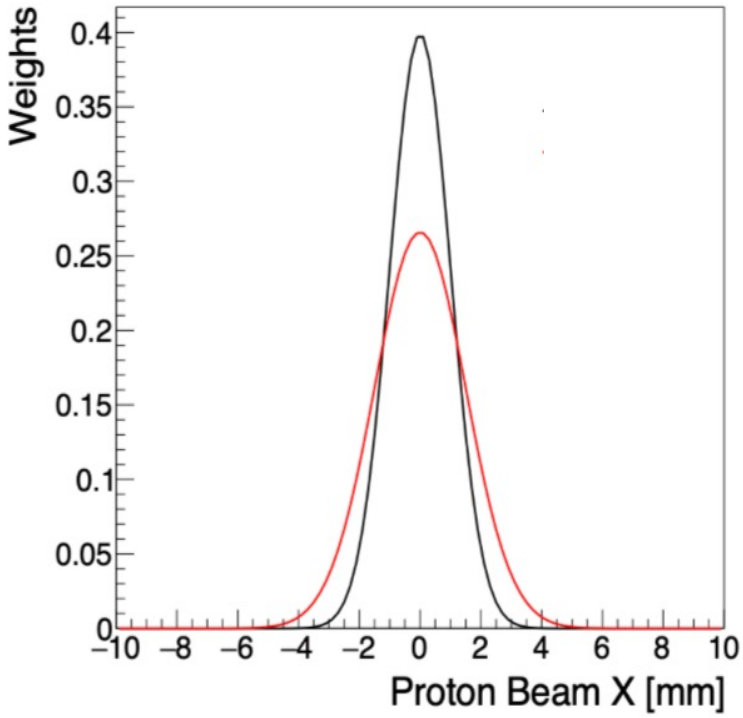
Uniform Beam Simulation for NuMI

- From uniformly distributed proton throws, weights for different proton beam settings calculated using Eqn.

$$w_i = \frac{1}{2\pi\sigma_x\sigma_y} \cdot exp\left\{-\frac{(x_i-\mu_x)^2}{2\sigma_x^2} - \frac{(y_i-\mu_y)^2}{2\sigma_y^2}\right\}$$



Random throws along horizontal beam positions to generate a uniform proton beam sample



Example of calculated weights for a selected beam setting for σ = 1.5 mm & 1.0 mm

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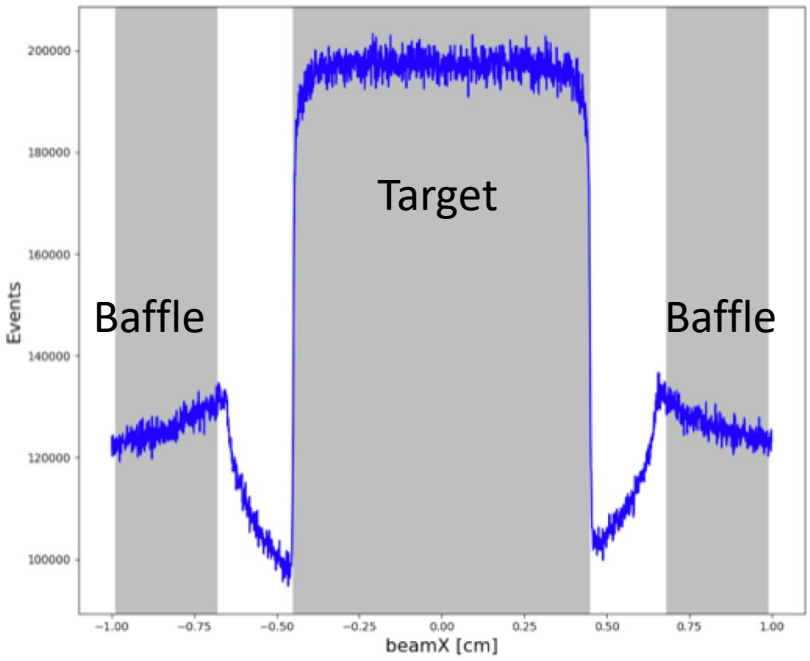
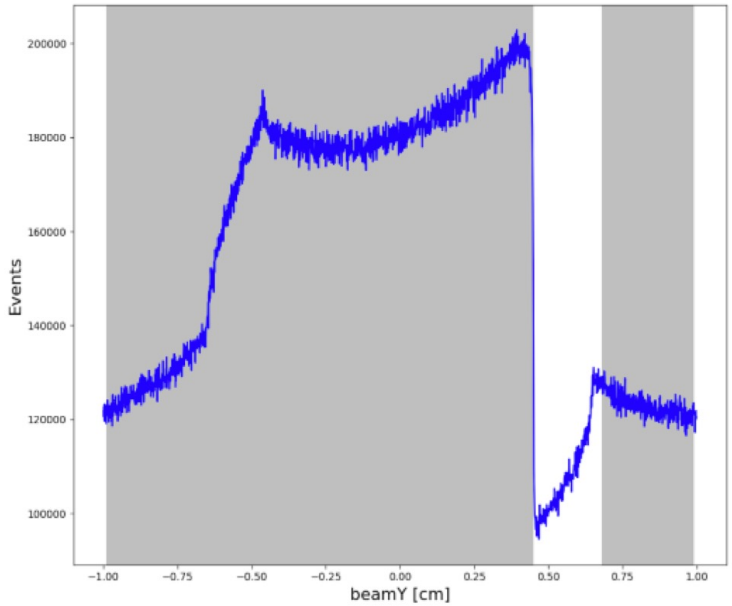
Uniform Beam Simulation for NuMI

Horizontal Proton Beam Position



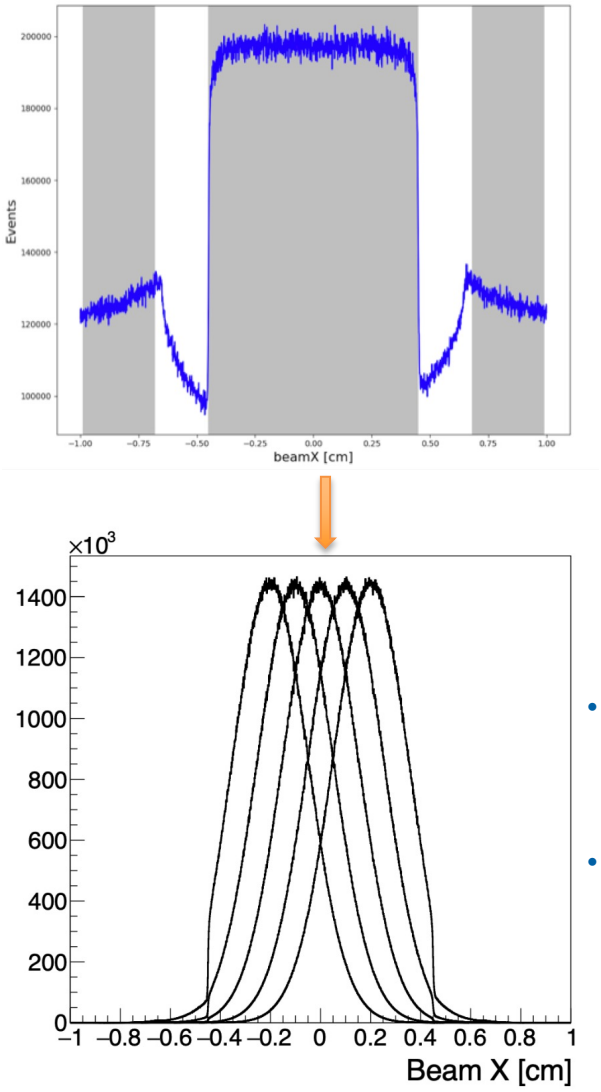
Vertical Proton Beam Position



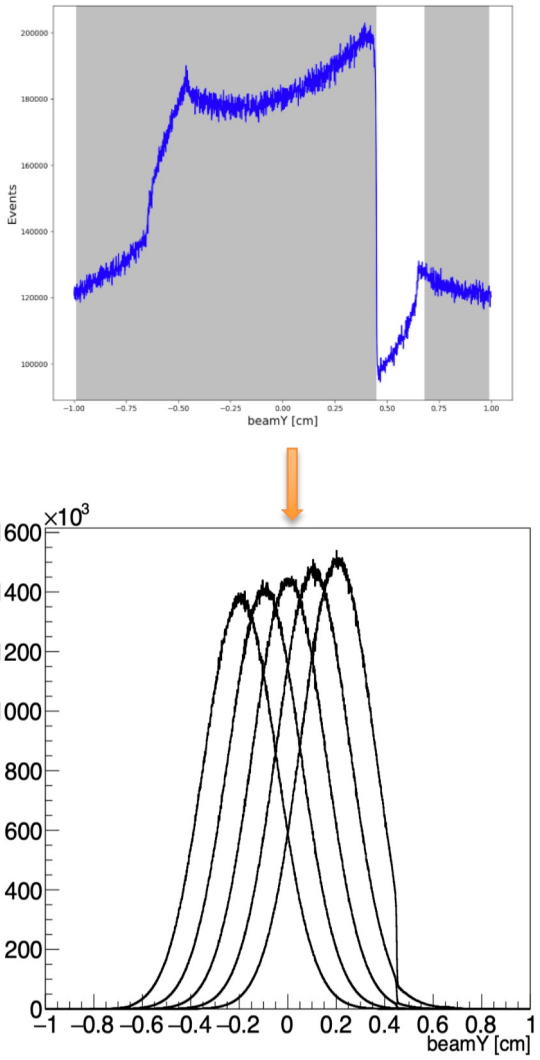
- Uniform proton beam position generated by random throws along X & Y
- Only recorded if a neutrino candidate at neutrino detector from hadron decay

Uniform Beam Simulation for NuMI

Horizontal Proton Beam Position



Vertical Proton Beam Position



- Weighted Gaussian beam profiles
- Can draw as many Gaussians as possible

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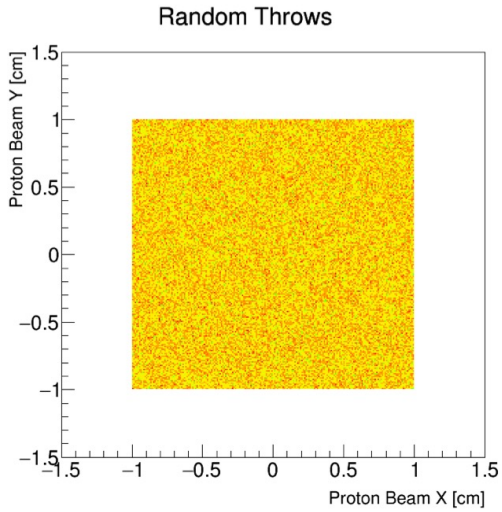
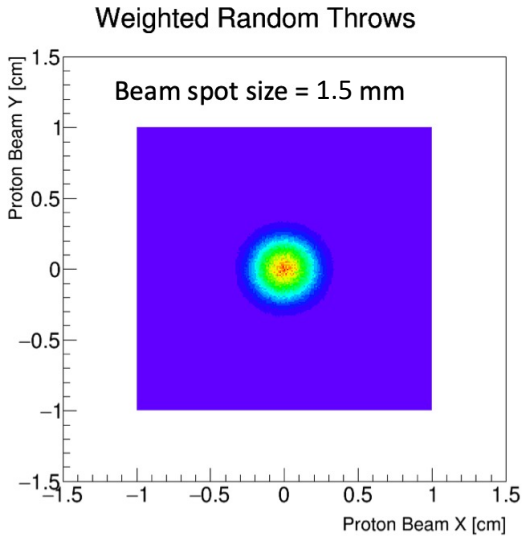
POT Estimation

1. Start with random throws



Uniform POT = 10 M

2. Generate a gaussian beam profile



POT = 2.4975 E6
= ¼ uniform POT

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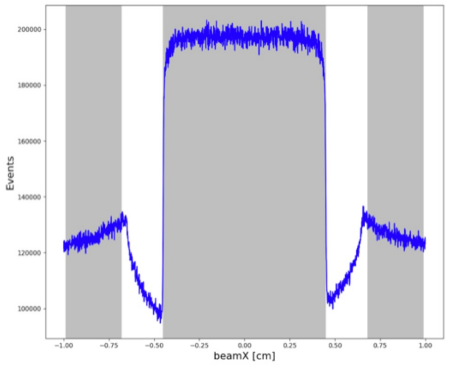
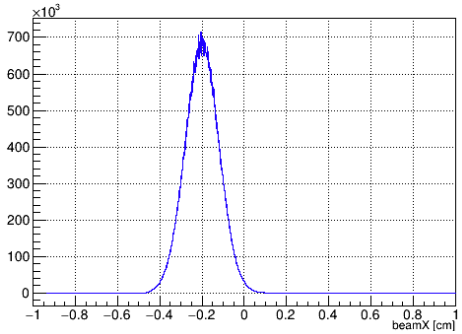
POT Comparison b/w Uniform & Nominal

1. Start with random throws



Uniform POT = 1000 M

2. Generate a gaussian beam profile

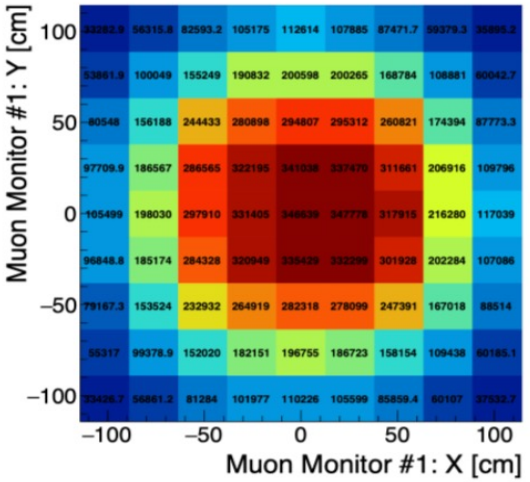


POT ~ 250 M
= ¼ uniform POT

3. Calculate tot. # of muons at MM1

1.3380E07 from uniform

1.3339E07 from nominal



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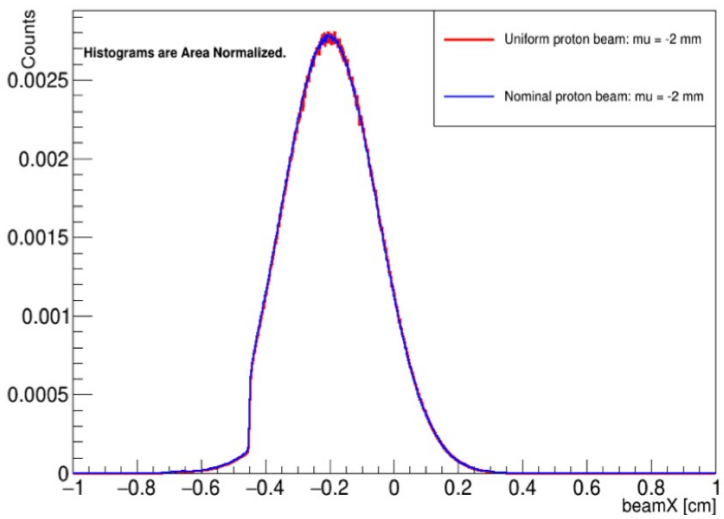
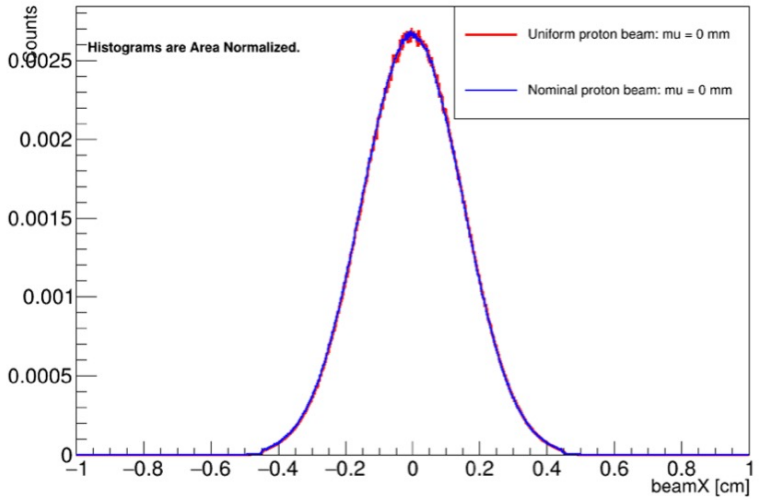
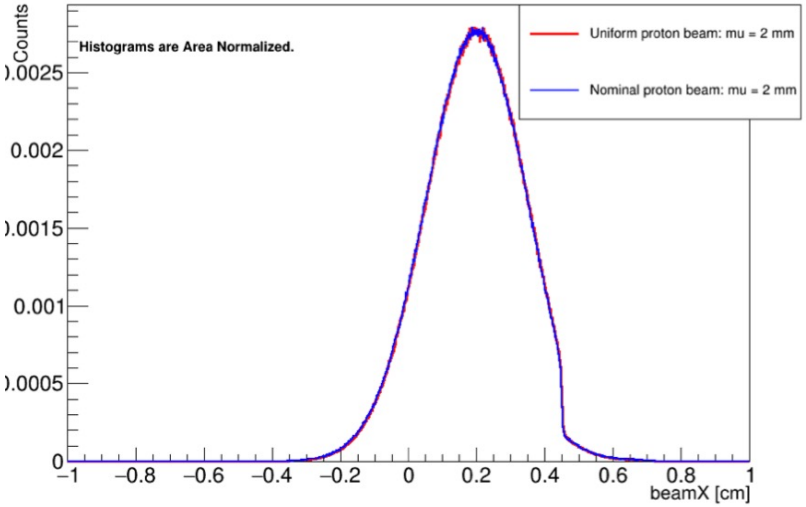
Beam Profile Comparison b/w Uniform & Nominal







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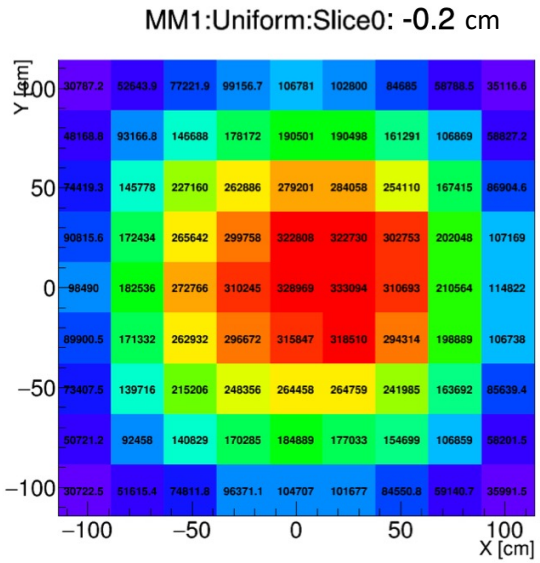
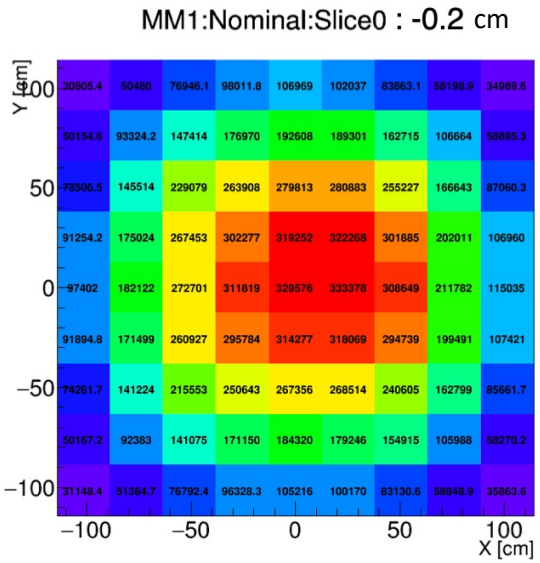
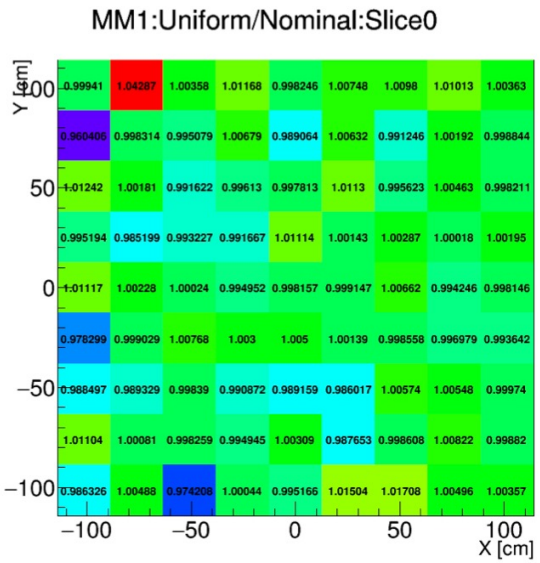
Muon Flux Profile Comparison b/w Uniform & Nominal







POT: 1000M

POT: 250M

~ 3% difference at some edge pixels – random statistical fluctuations

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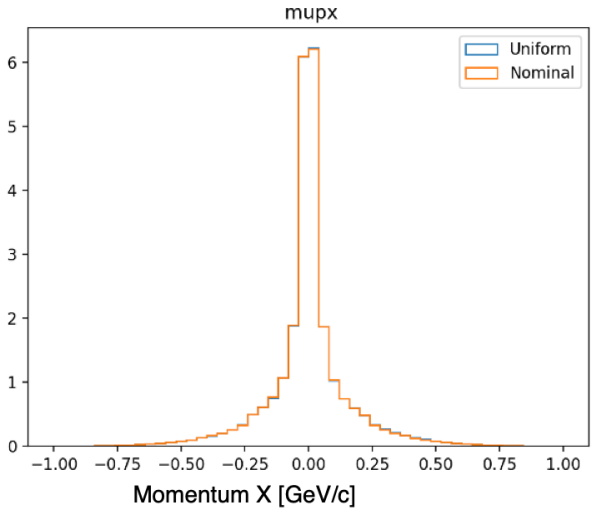
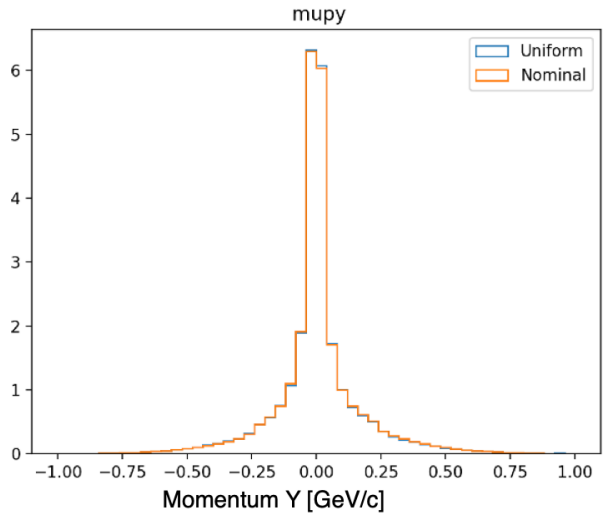
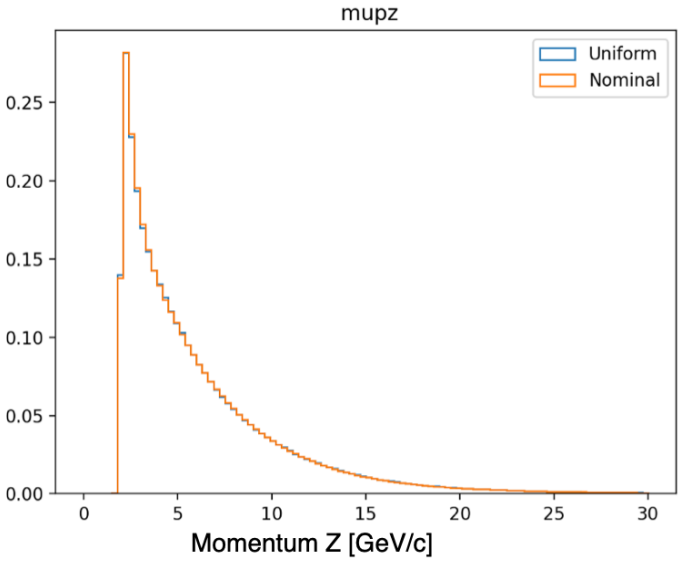
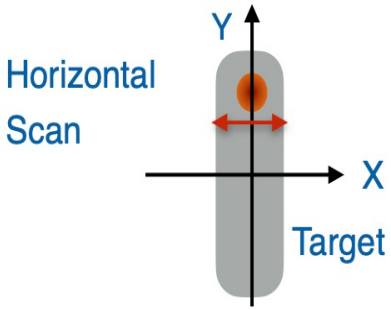
Muon Momentum Comparison b/w Uniform & Nominal

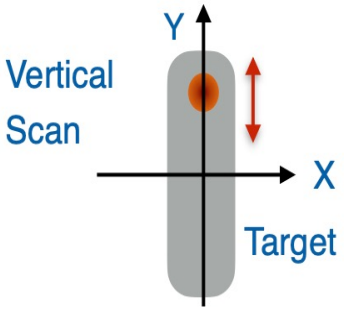


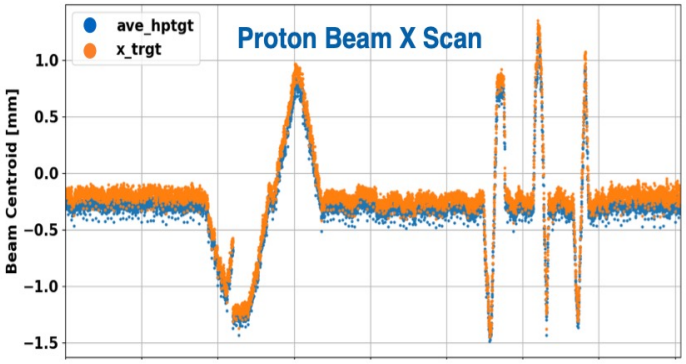


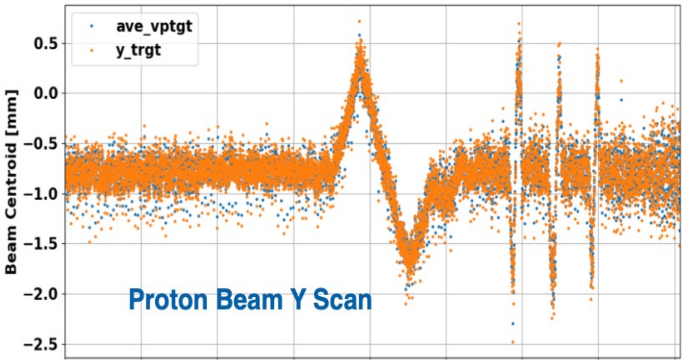


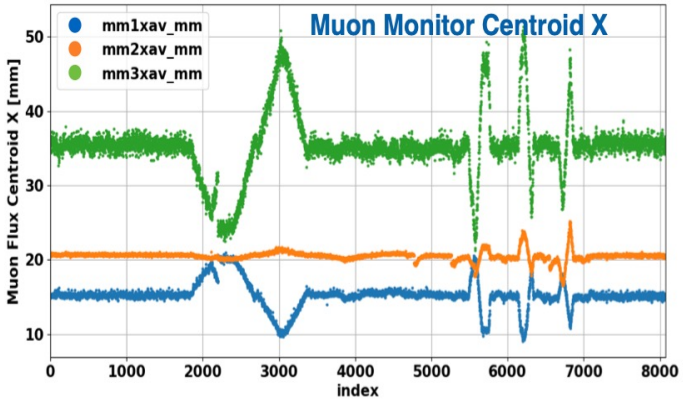
Applications

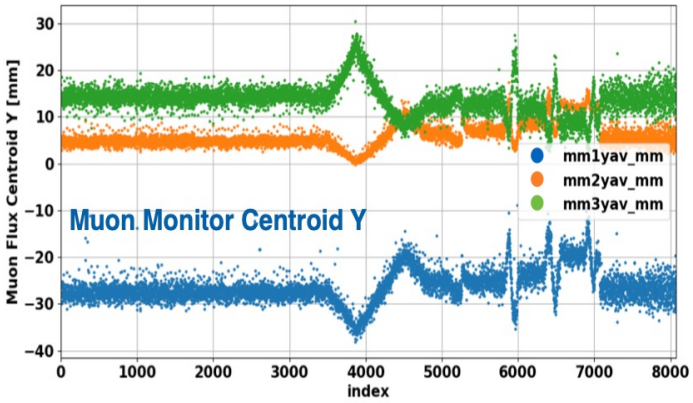












Actual beam scans with muon monitors

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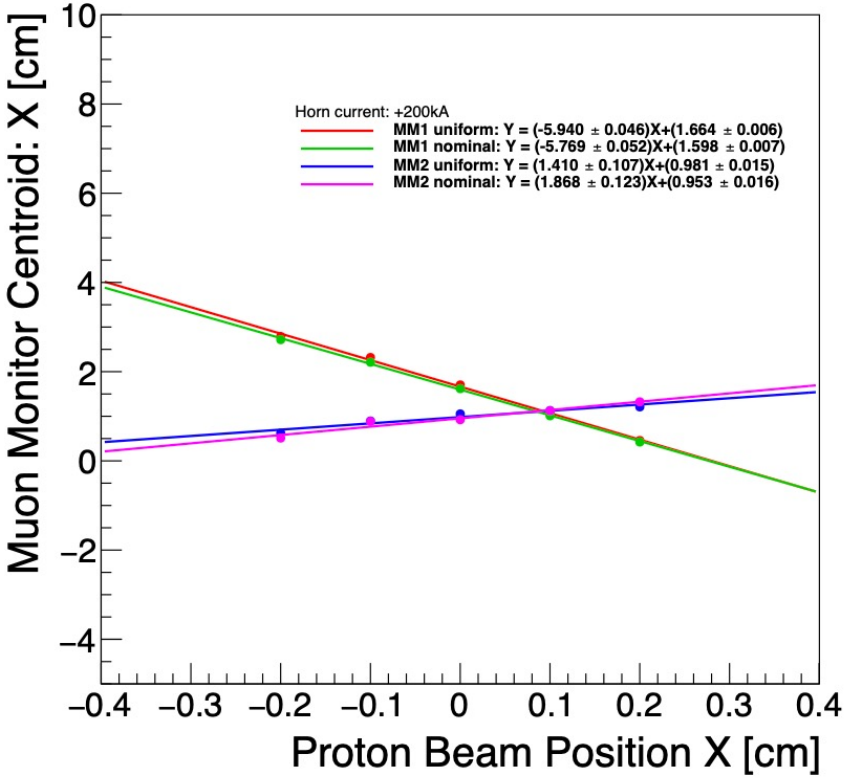
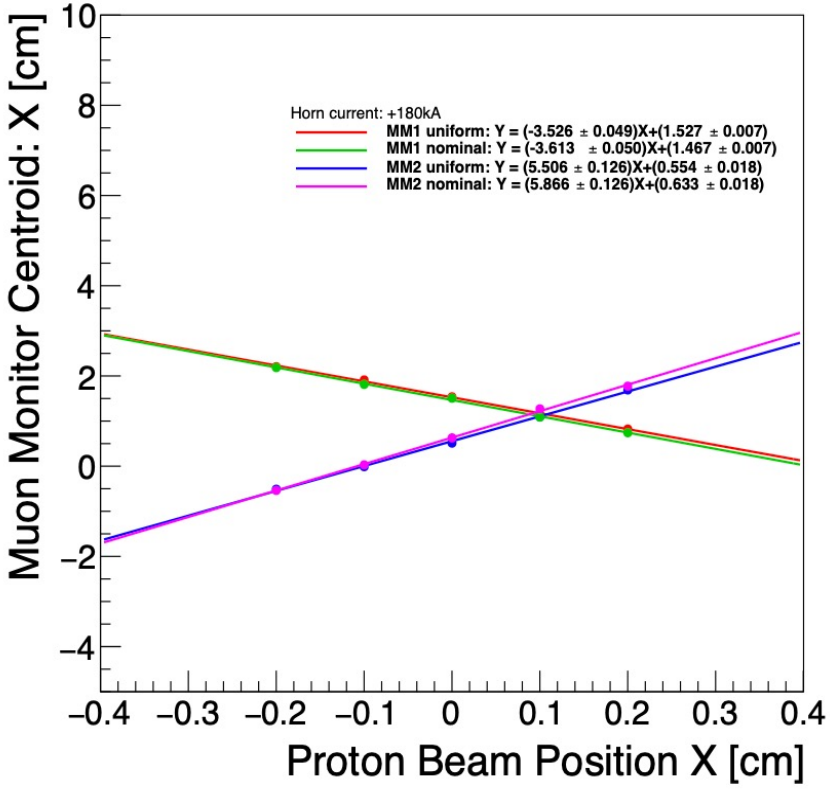
Applications

Study scans with uniform beam simulation with Muon Monitor 1 & 2

Horn current : 200 kA

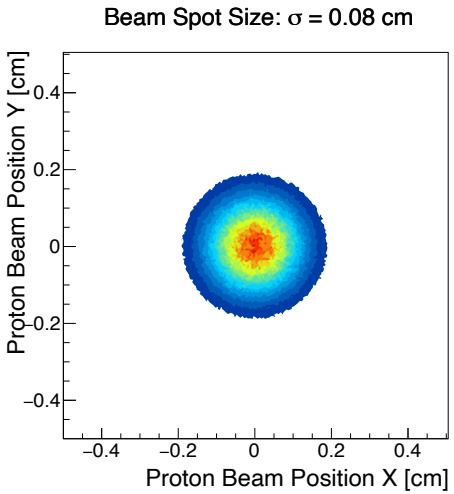


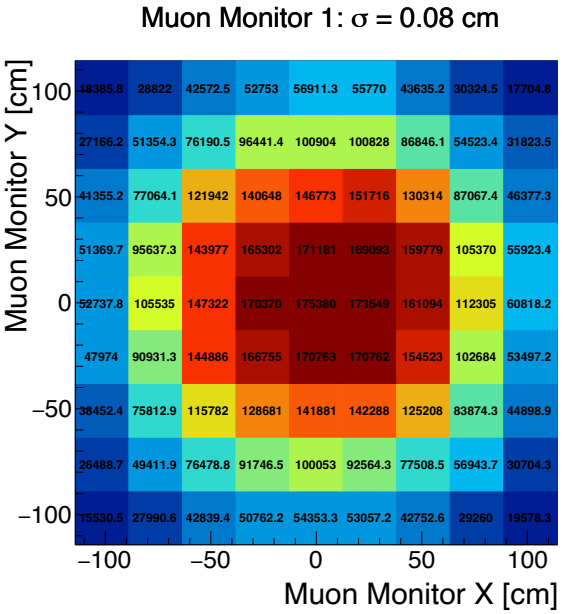
Horn current : 180 kA

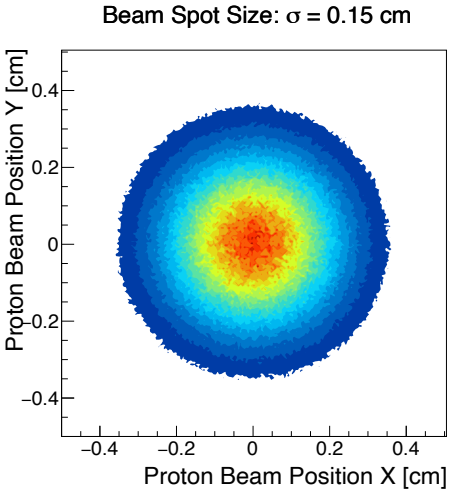


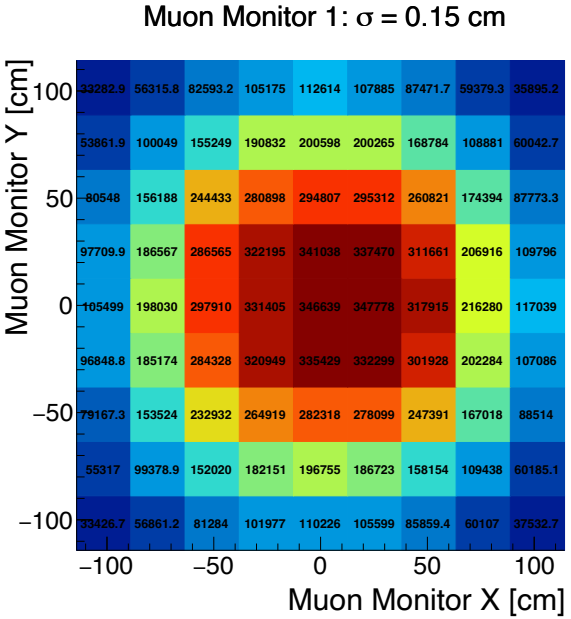
Applications

- Study beam spot size changes









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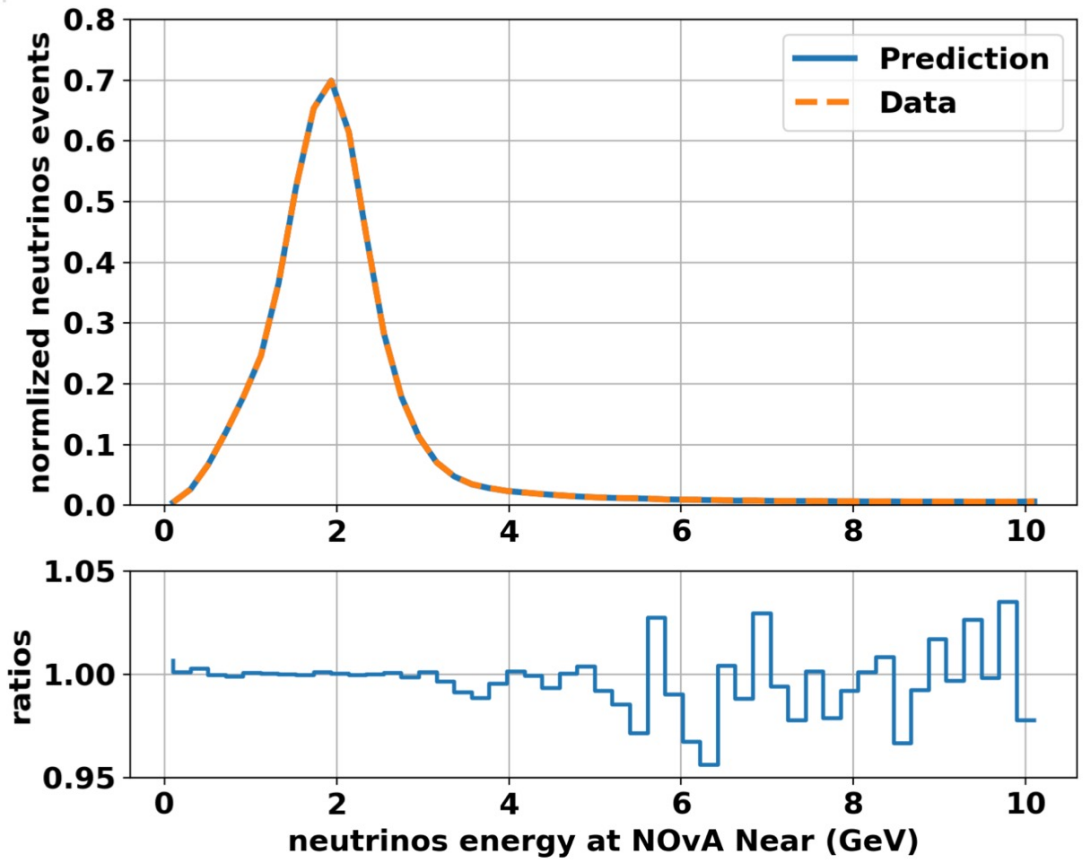
Applications

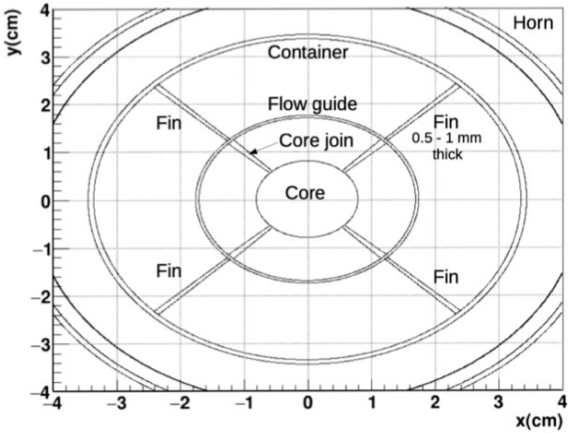
- Machine Learning studies



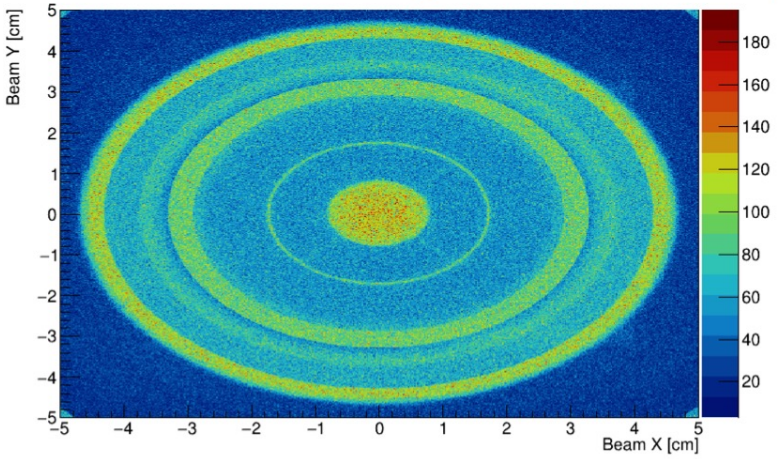
- **Uniformly distributed sample used to generate Gaussian beam profiles for different selected beam parameters**
- **Beam positions, widths etc. can be varied post-processing once one Uniform sample is generated**
- **Computational overhead greatly reduced**

LBNF Uniform Beam Simulation

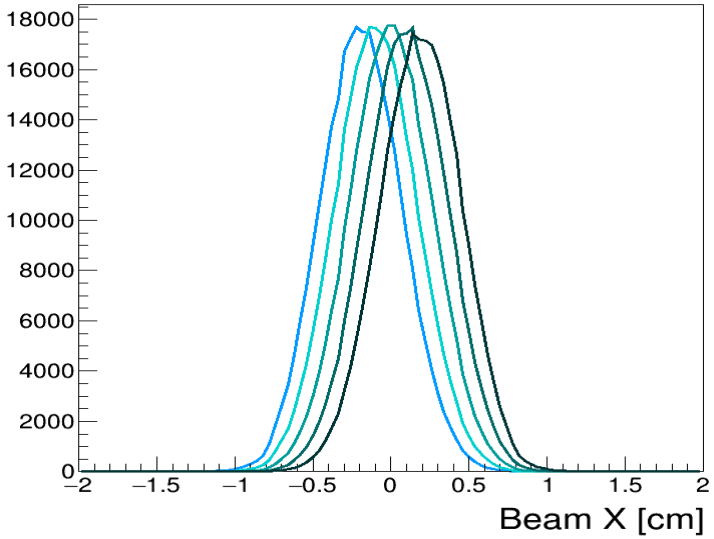
Geant 4 geometry: fins in xy plane



Interactions after throwing uniformly distributed protons



5 beam samples generated by applying Gaussian weights



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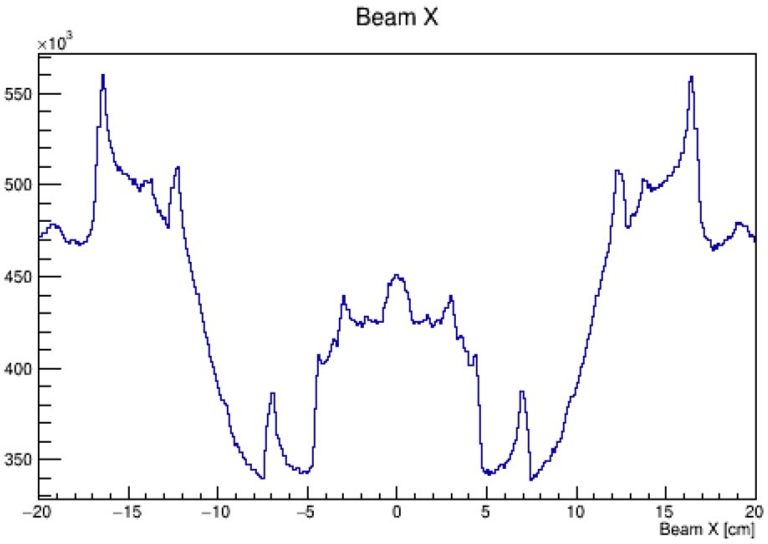
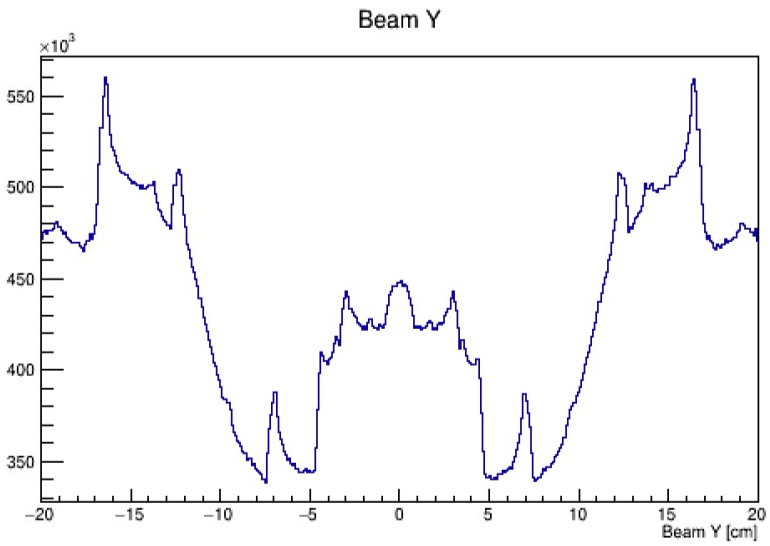
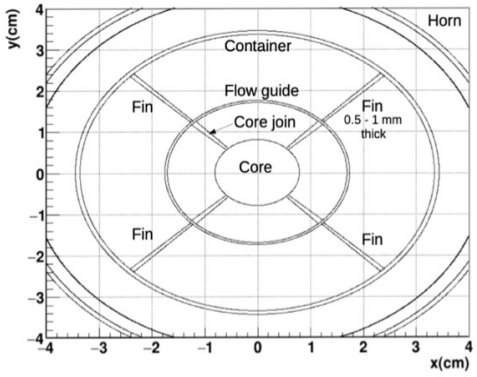
LBNF Uniform Beam Simulation

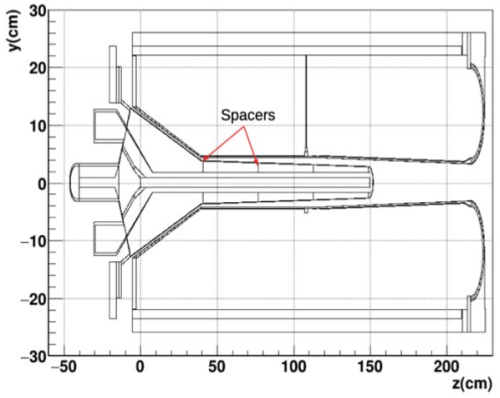




Geant 4 geometry: fins in xy plane



Geant 4 geometry: spacers



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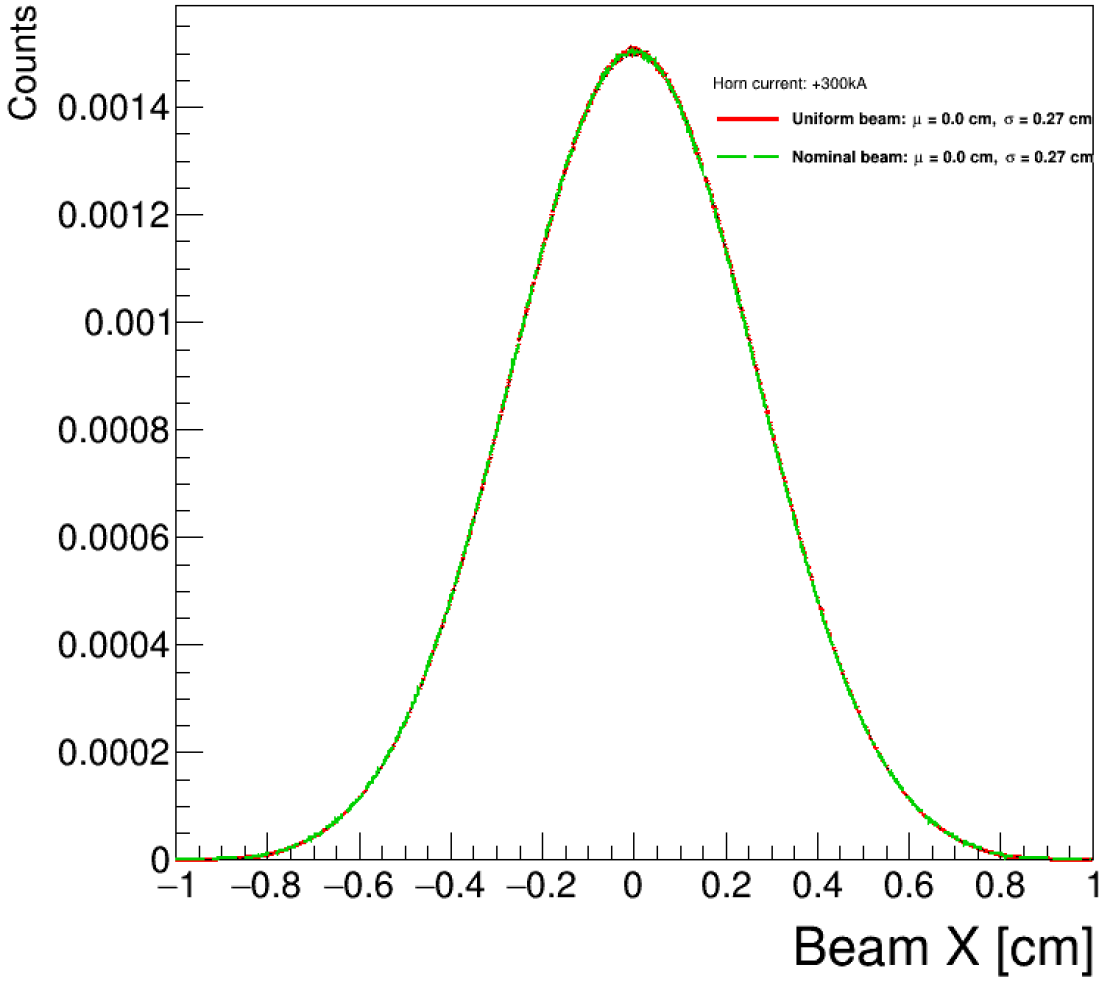
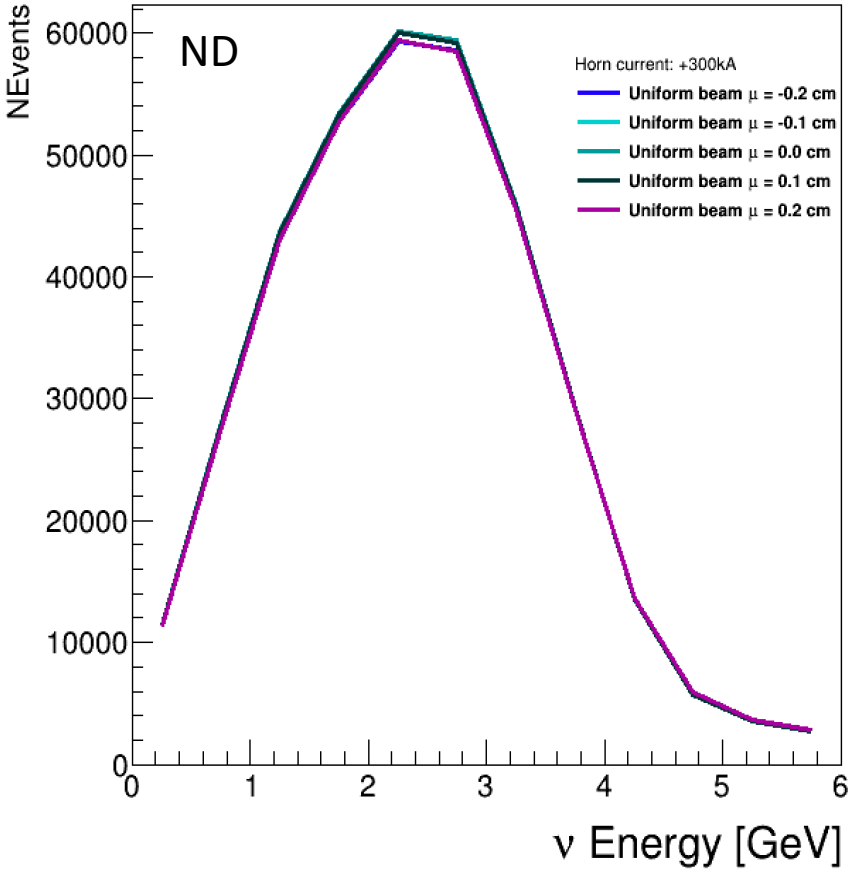
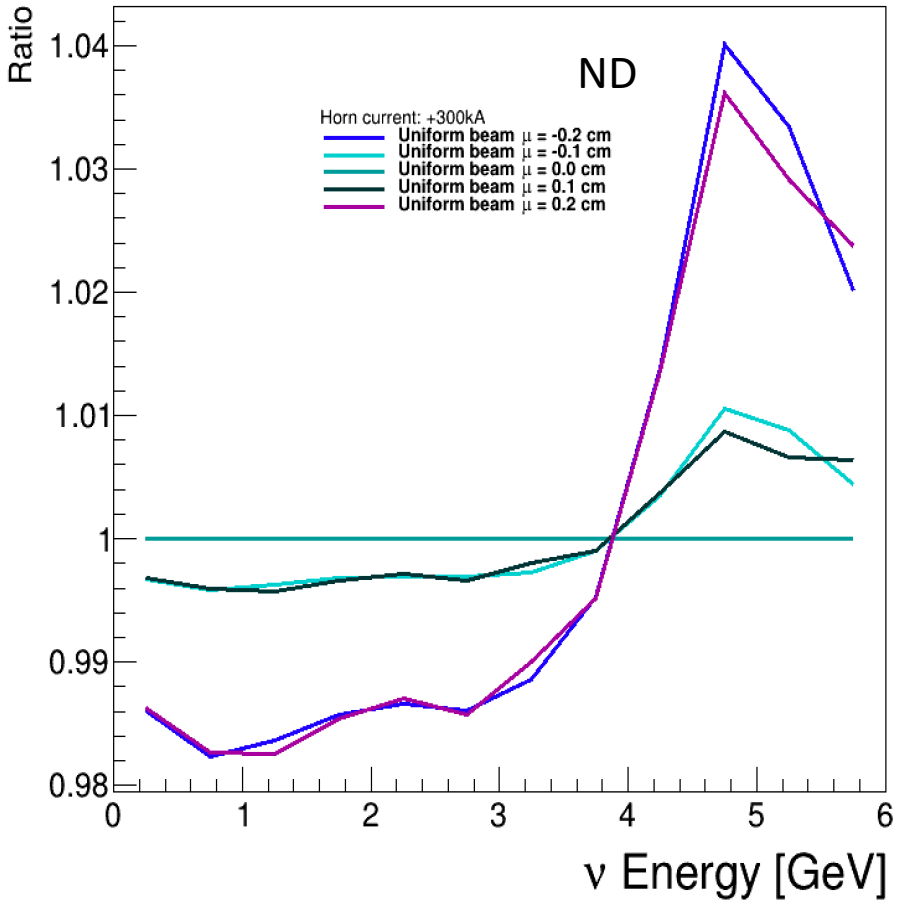
Comparing Uniform & Nominal LBNF Beam profiles



Some Examples of Application

A comparison of neutrino events by setting up different beam and horn configurations





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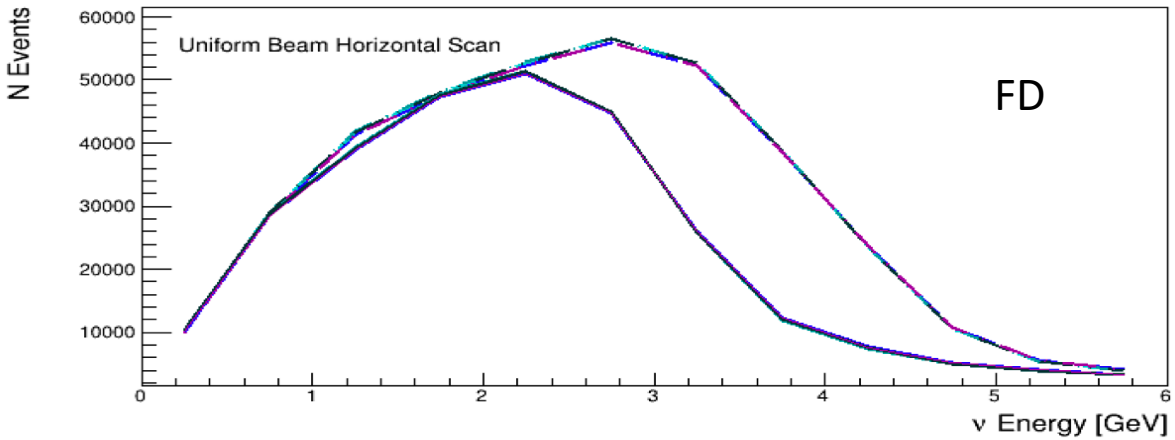

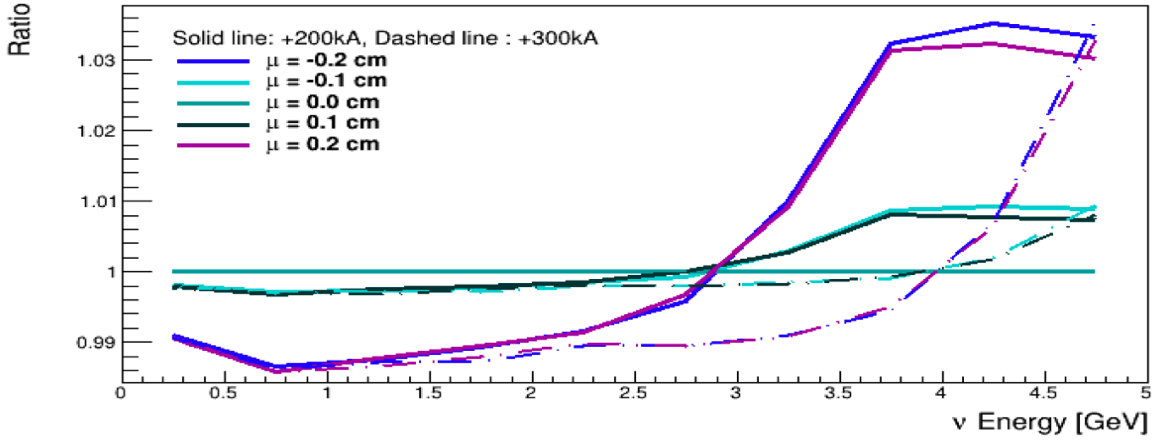

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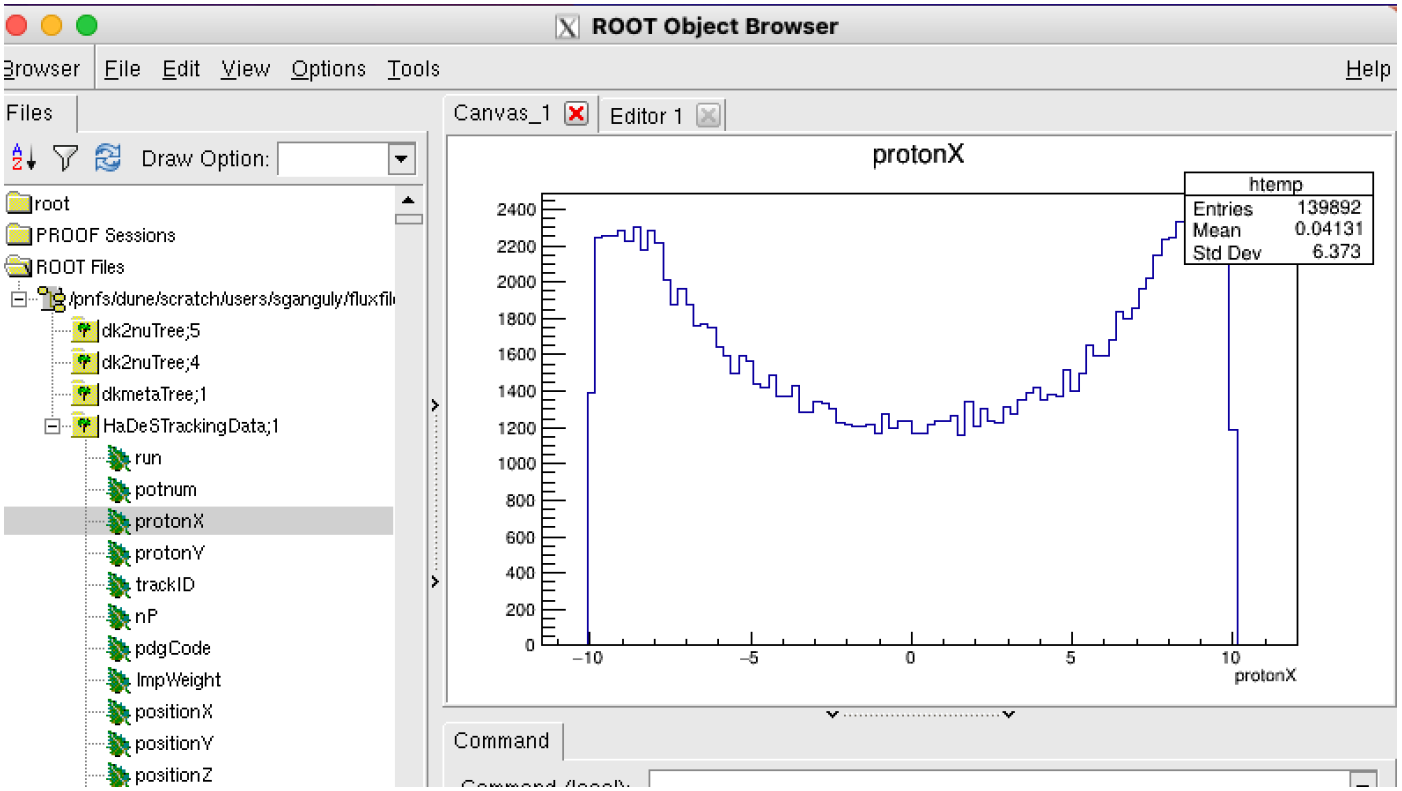
Some Examples of Application

- **Added uniform proton beam X & Y information in HaDeS simulation by placing a Tracking Plane at HaDeS location**
- **User can choose beam range, shown here b/w +/-10 mm along beam x**



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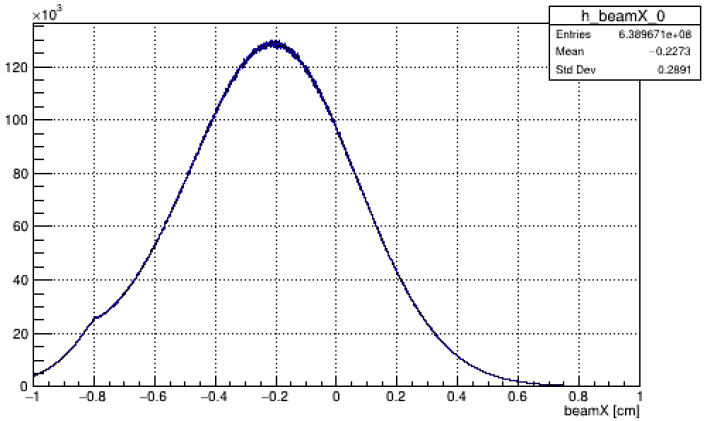
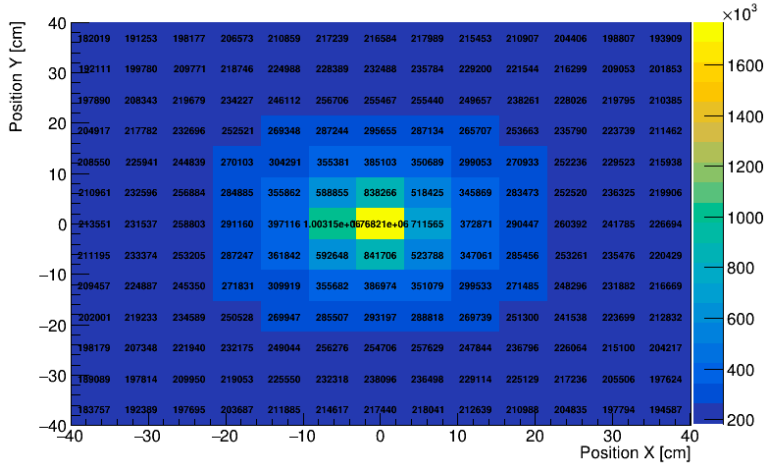
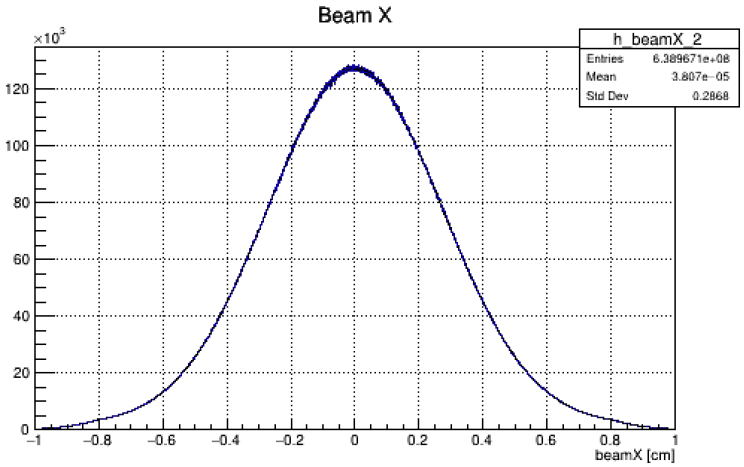
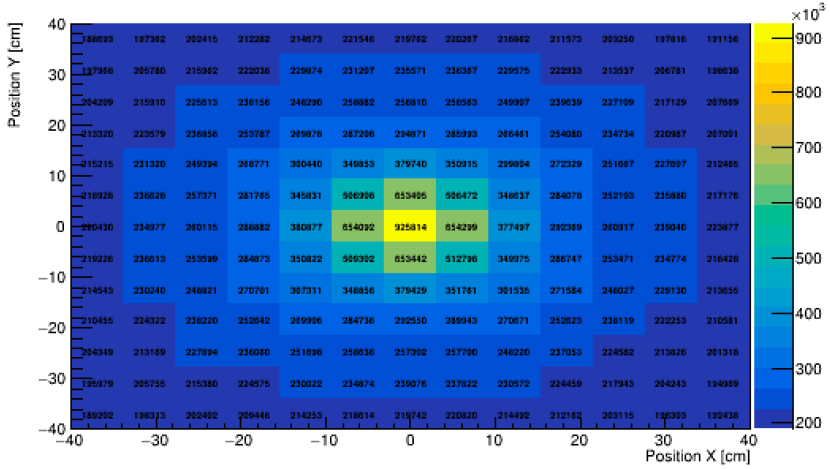
Some Examples of Application

For different gaussian slices of the proton beam look at corresponding distributions of charged particles at HaDeS









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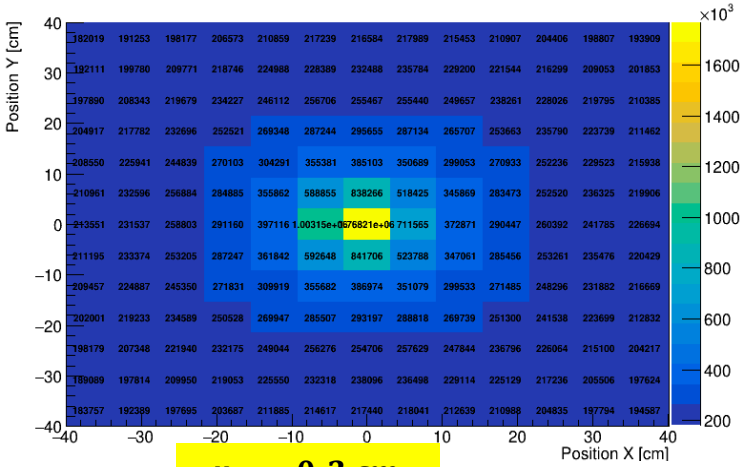
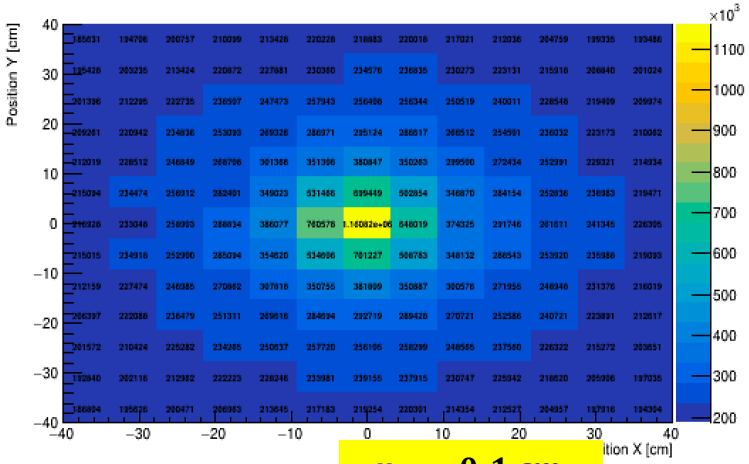
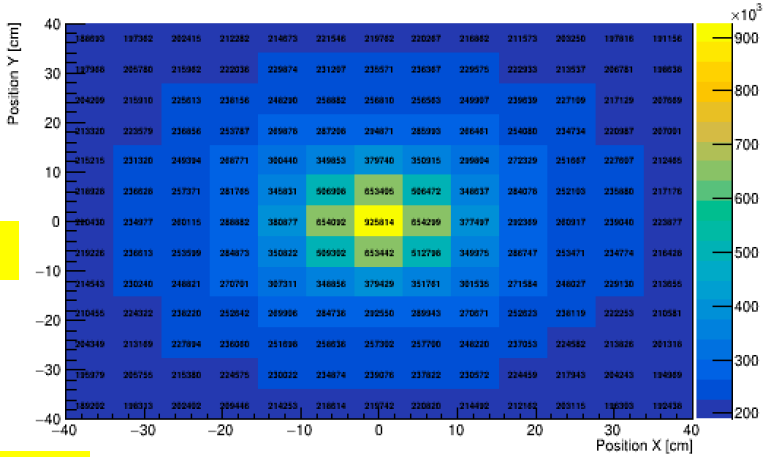


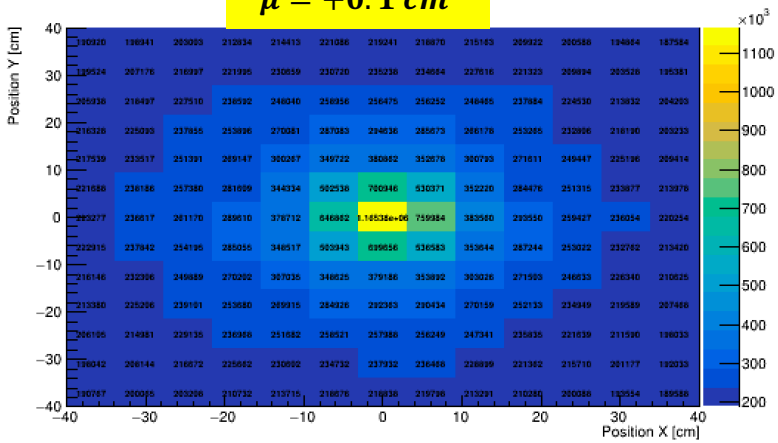
$\mu = -0.2\ cm$



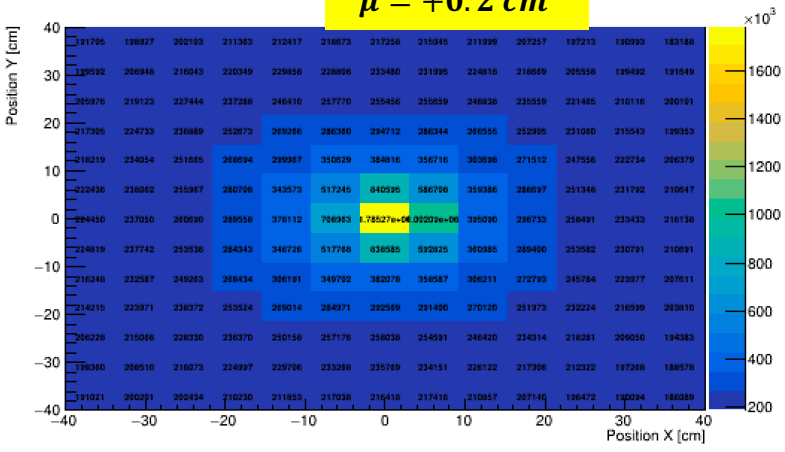
$\mu = -0.1\ cm$



$\mu = 0\ cm$



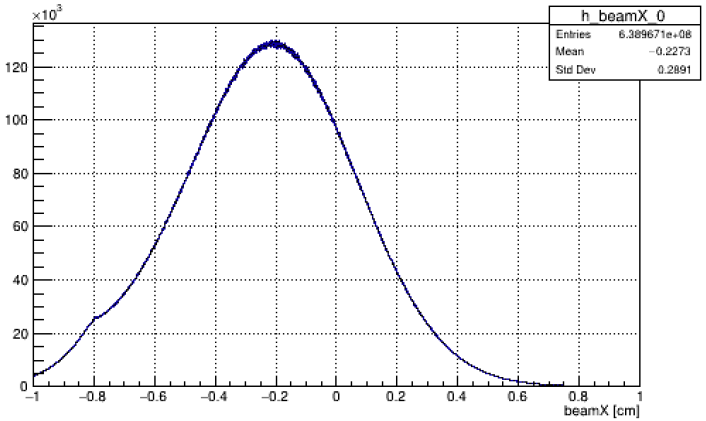
$\mu = +0.1\ cm$

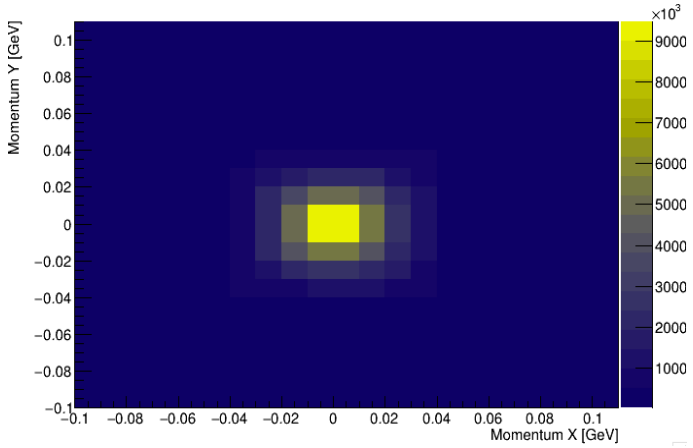


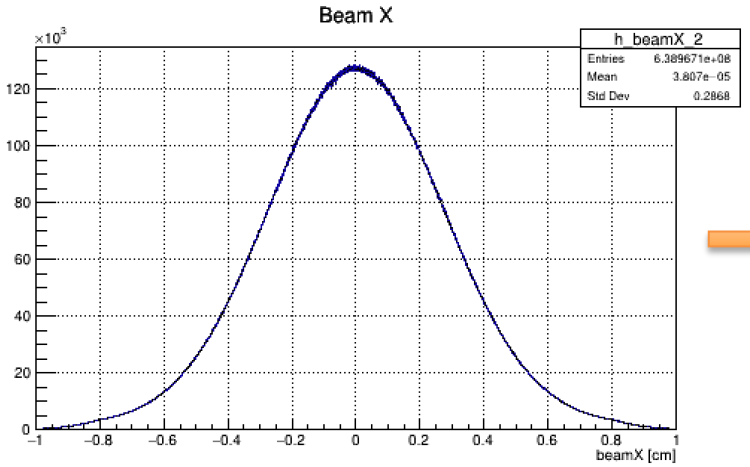
$\mu = +0.2\ cm$

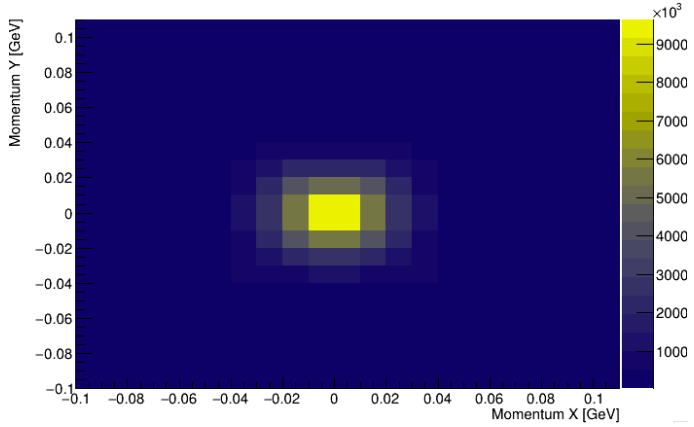
Some Examples of Application

For different Gaussian slices of the proton beam look at corresponding distributions of charged particles at HaDeS









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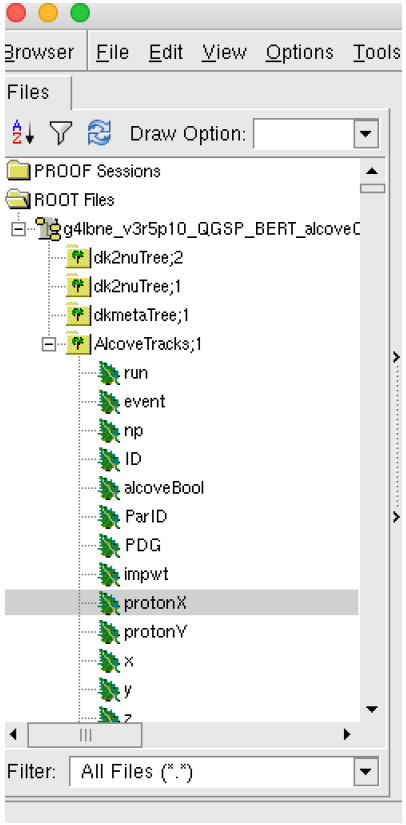
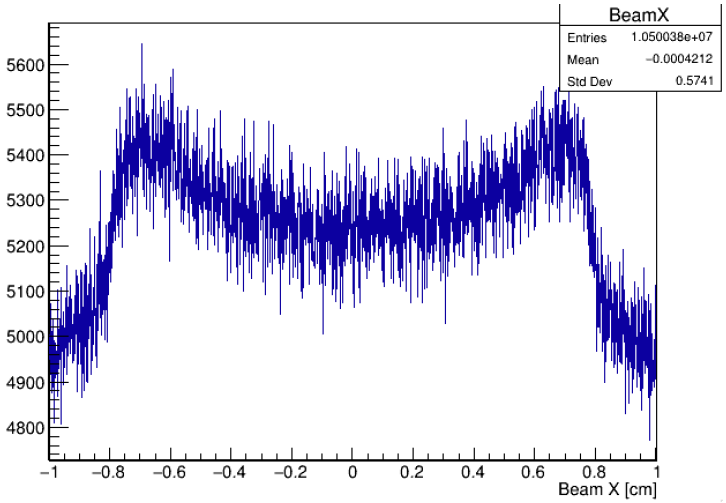
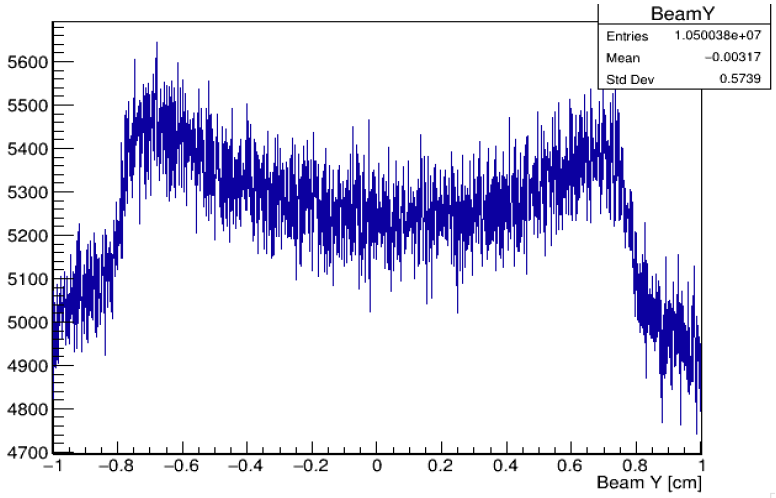
Some Examples of Application

- **Added uniform proton beam X & Y information in AlcoveTracks Tree**







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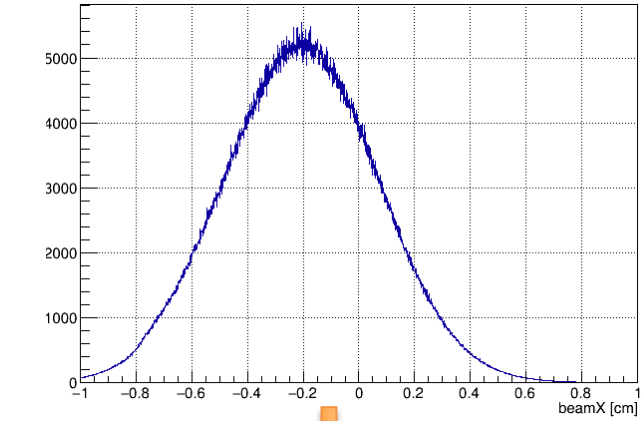
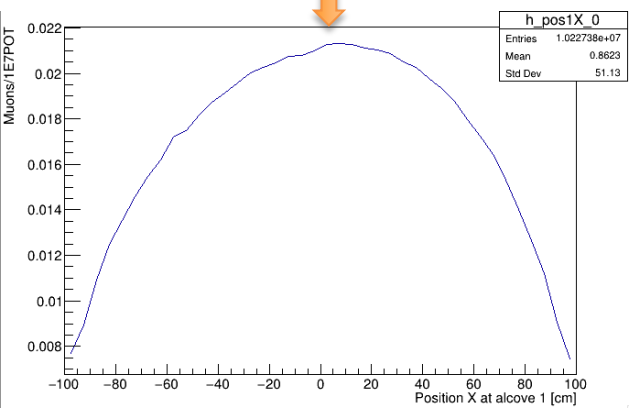
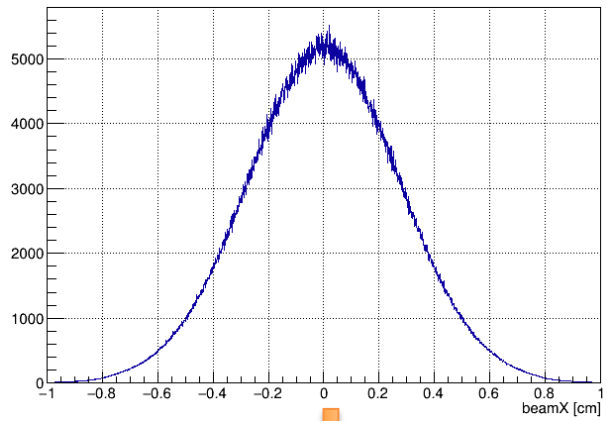
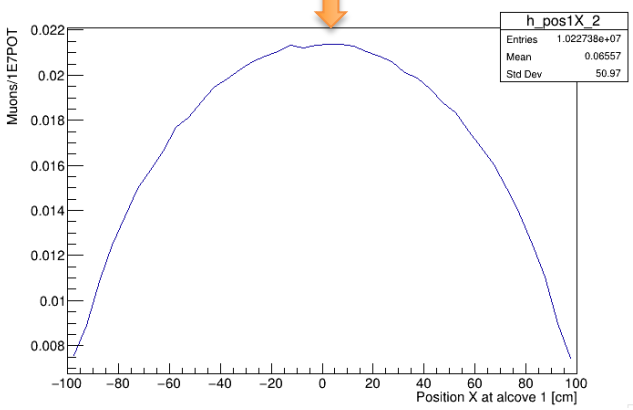
Some Examples of Application

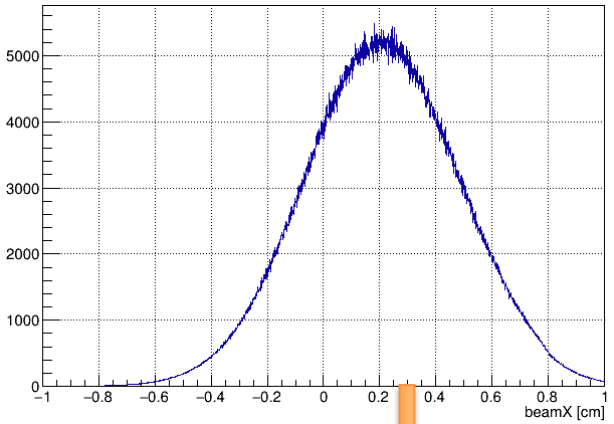
Alcove Tracking Plane 1:

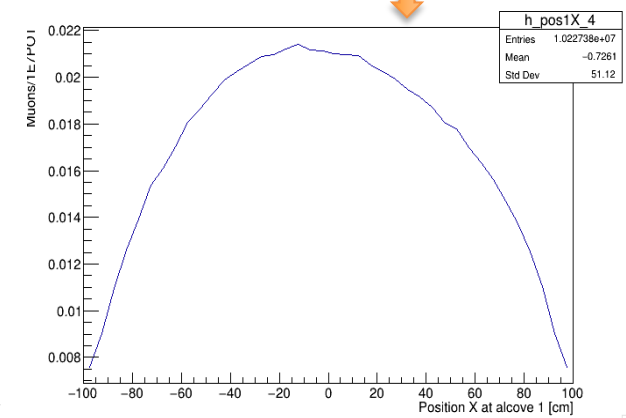












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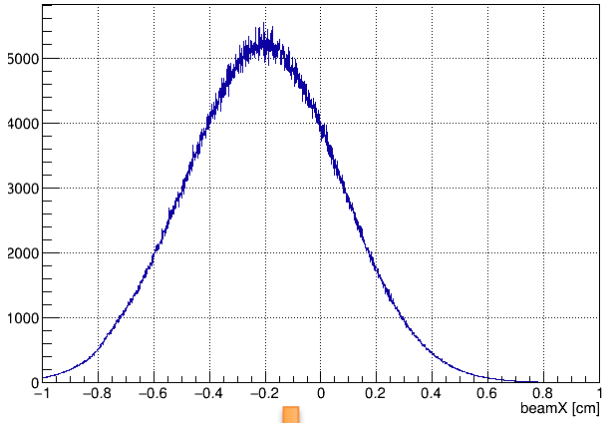
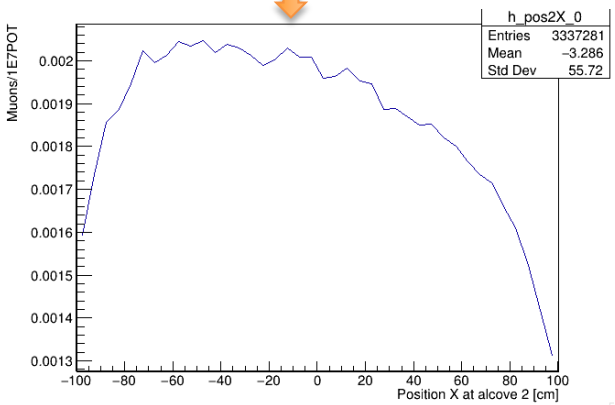
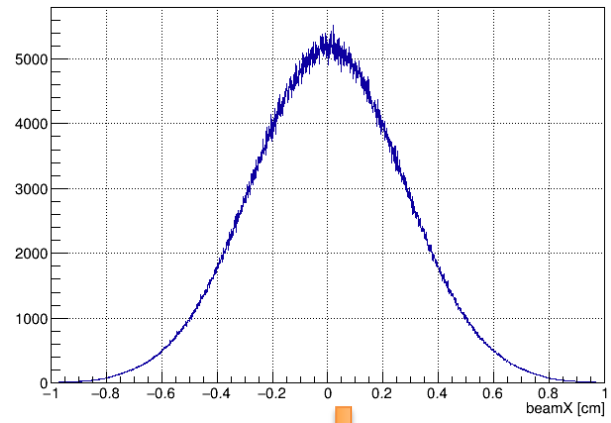
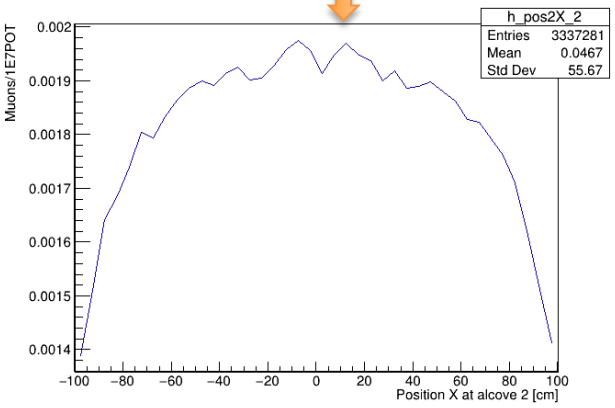
Some Examples of Application

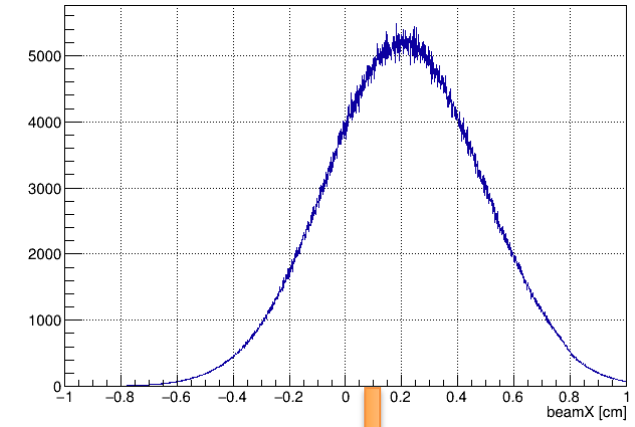
Alcove Tracking Plane 2:

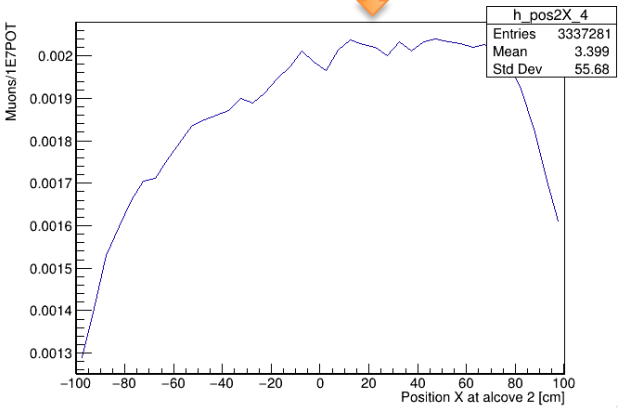












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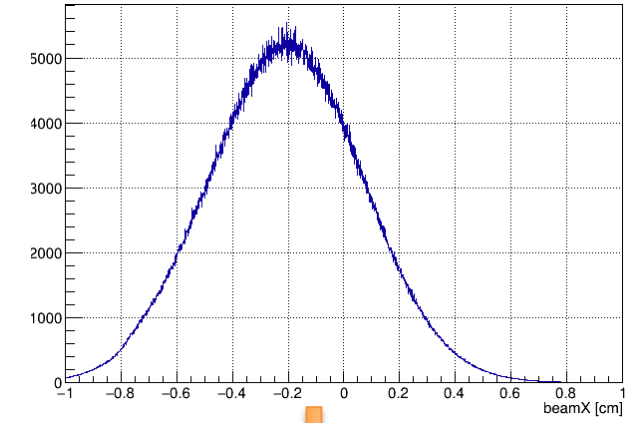
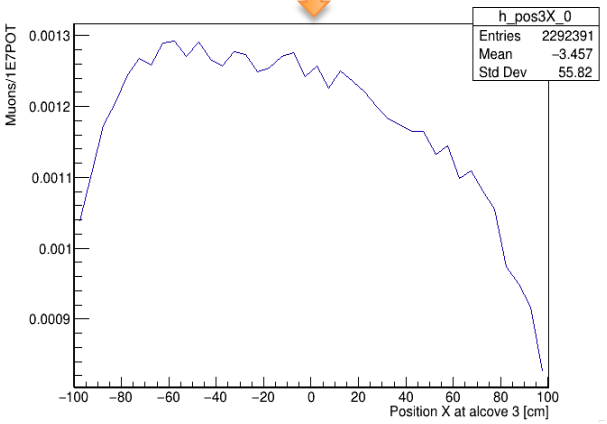
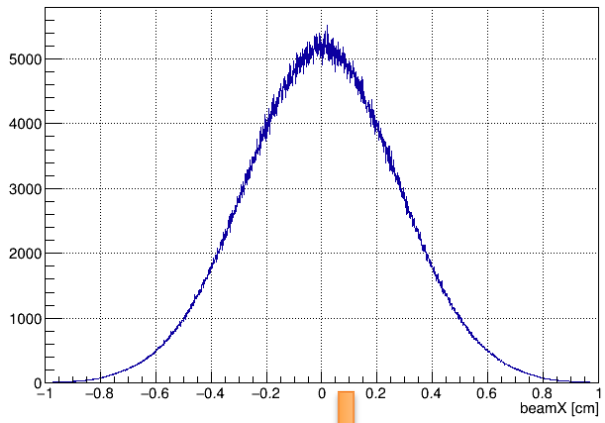
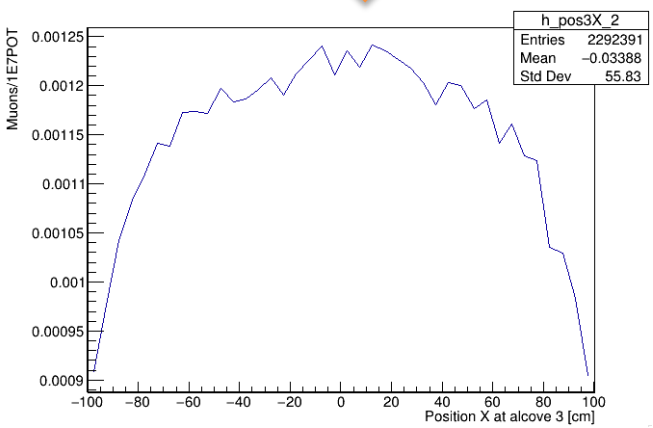
Some Examples of Application

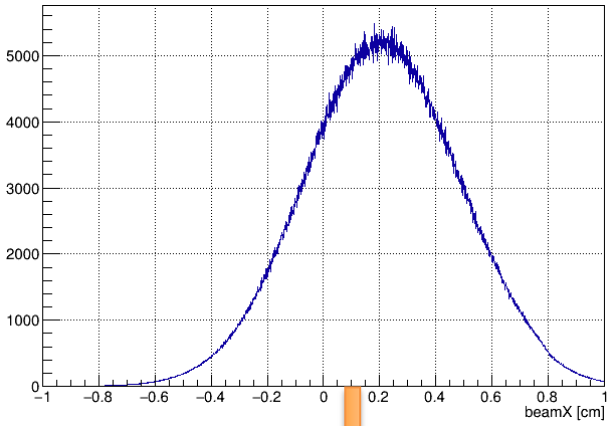
Alcove Tracking Plane 3:

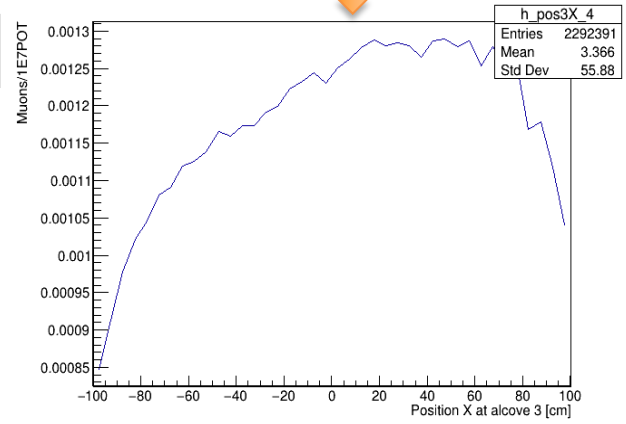












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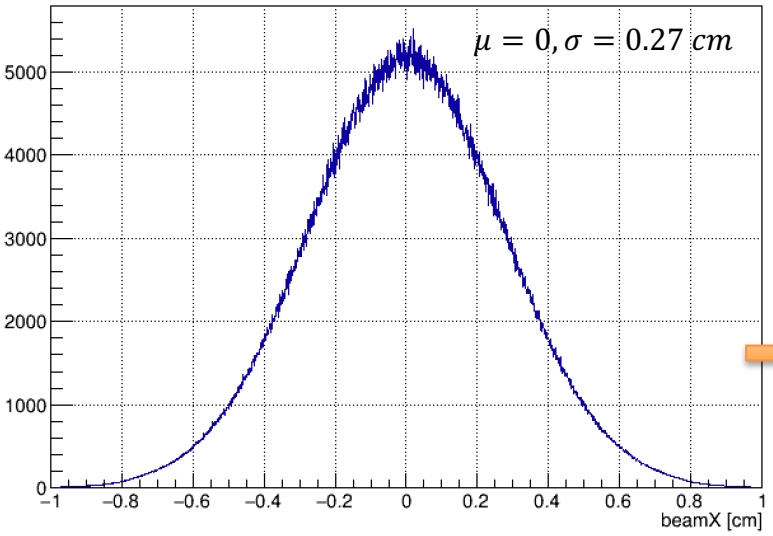
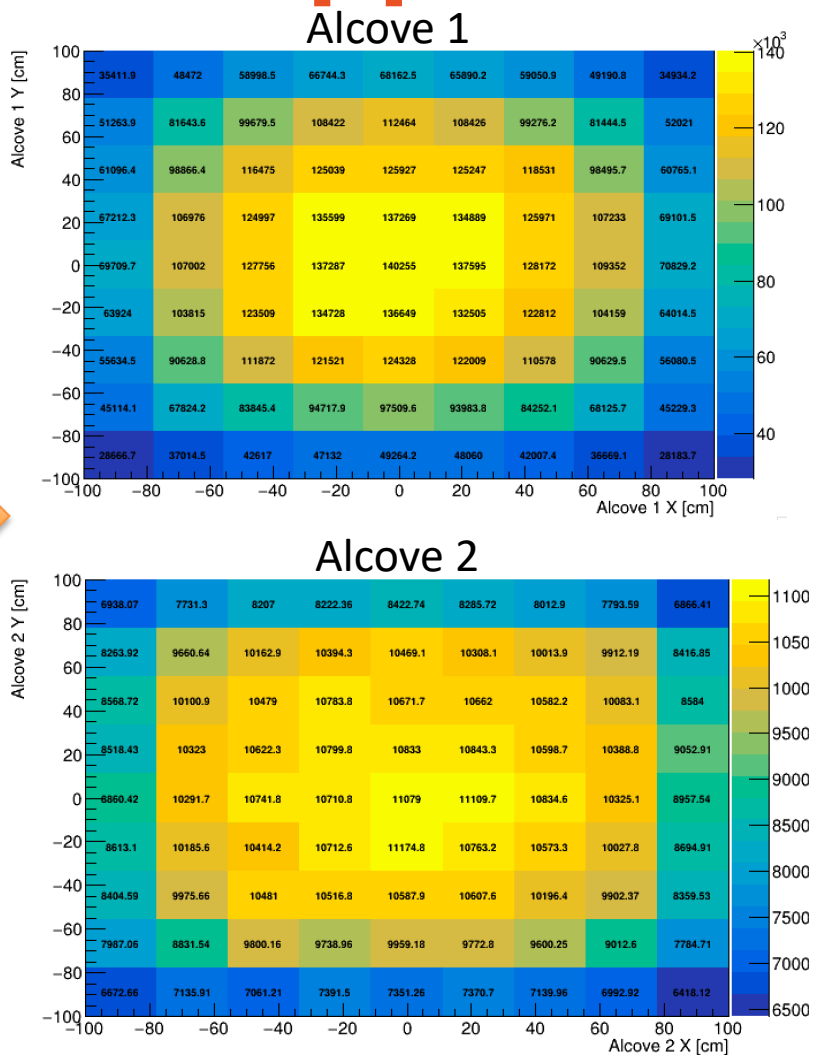
Some Examples of Application

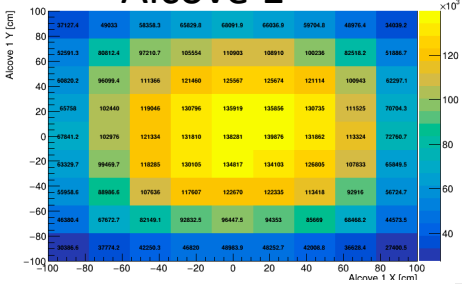


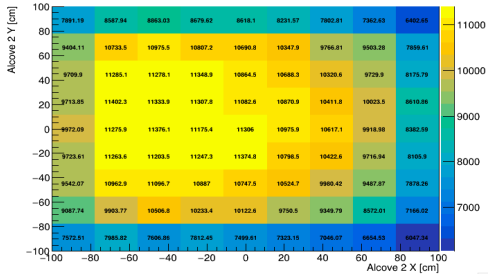


Alcove 1

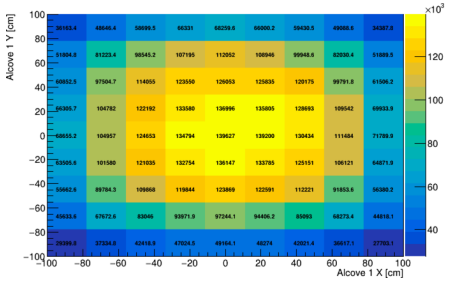
Alcove 2

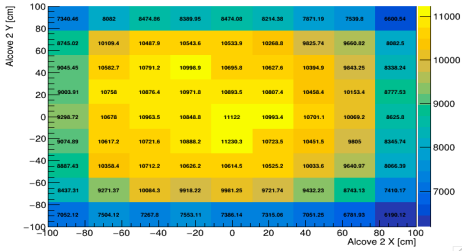
$\mu = -0.2\ cm,$
$\sigma = 0.27\ cm$





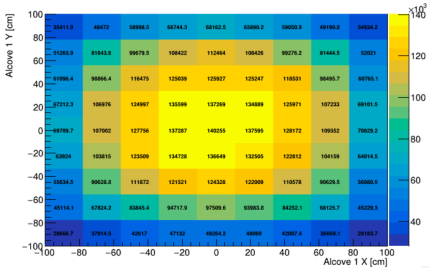
$\mu = -0.1\ cm,$
$\sigma = 0.27\ cm$

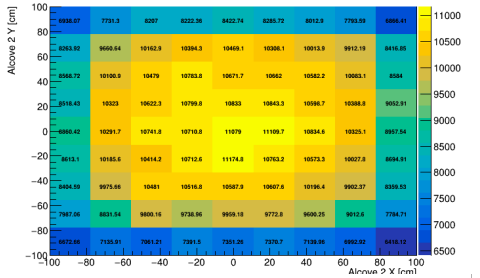




Left to right along beam X

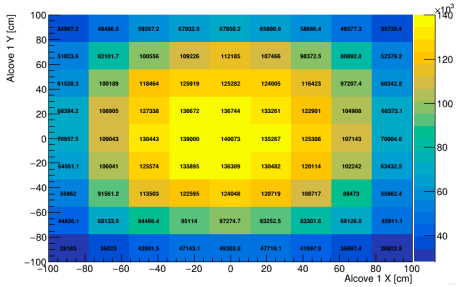
$\mu = 0.0\ cm,$
$\sigma = 0.27\ cm$

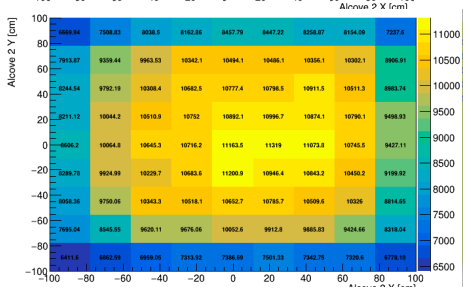




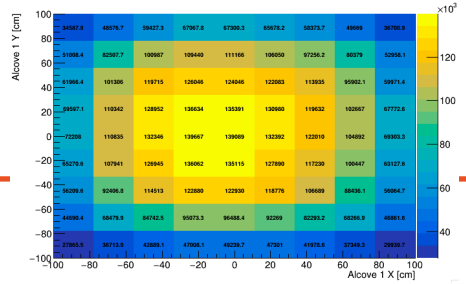
Left to right along beam X

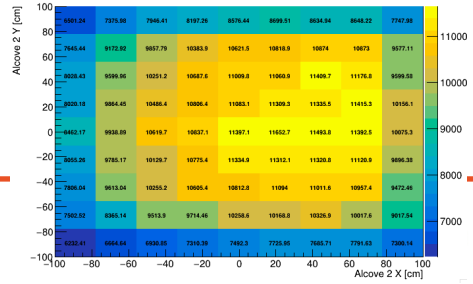
$\mu = +0.1\ cm,$
$\sigma = 0.27\ cm$



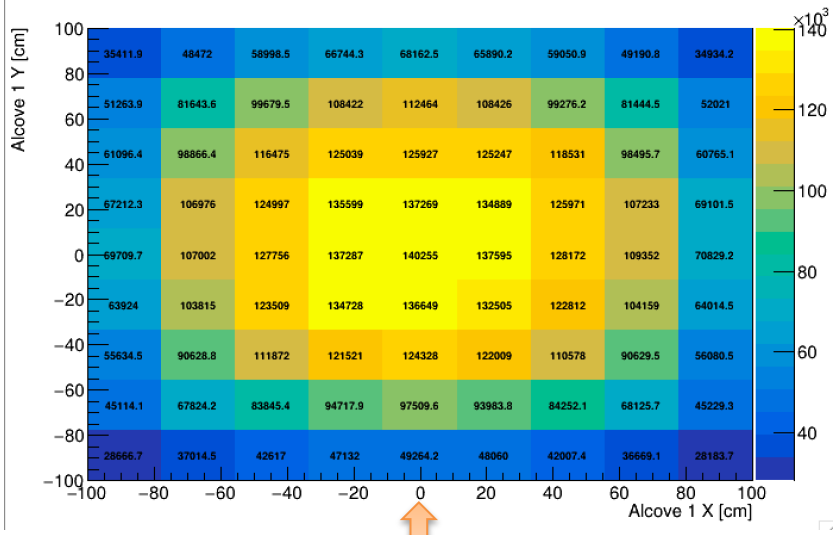


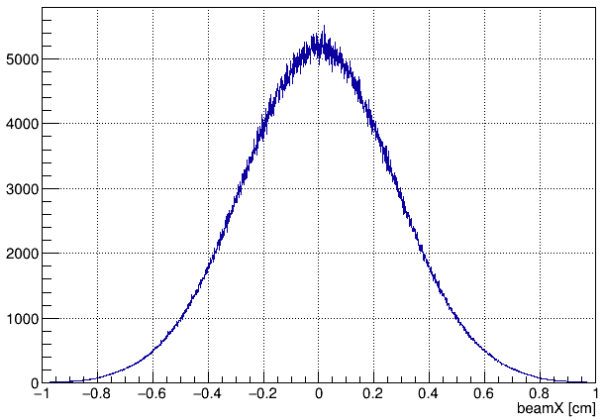
$\mu = +0.2\ cm,$
$\sigma = 0.27\ cm$



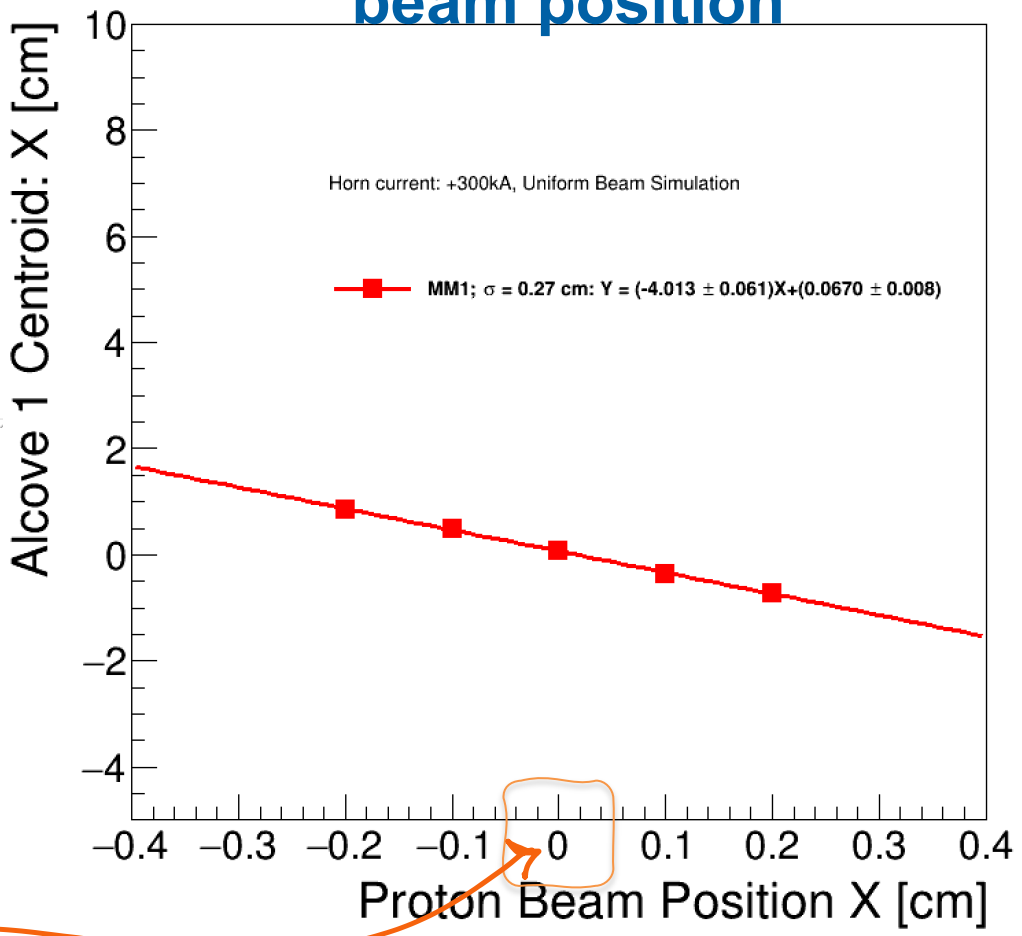


Some Examples of Application





MuMS 1 centroid vs proton beam position



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Remarks

- Effective way to generate many beam configuration possibilities without running the MC generator
- Extensive validation performed for NuMI b/w uniform beam & nominal beam simulation
- Can perform beam scans, beam spot size and horn current studies in simulation
- Can generate large statistics to split data into training and test for ML application
- Code changes have been applied to LBNF simulation
- Could be useful for beam scan studies for LBNF with simulation