X PARTICLE GENERATOR - SIGNAL IMPACT

PRAD COLLABORATION MEETING FALL 2025

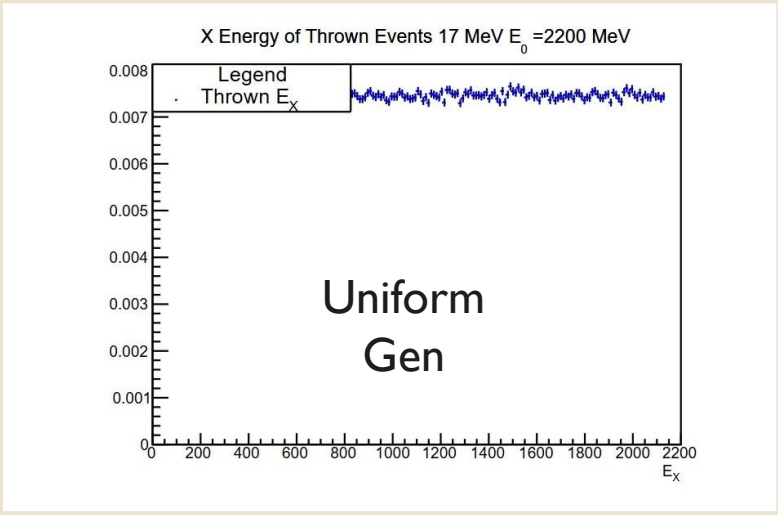
Jefferson Lab
Thomas Jefferson National Accelerator Facility

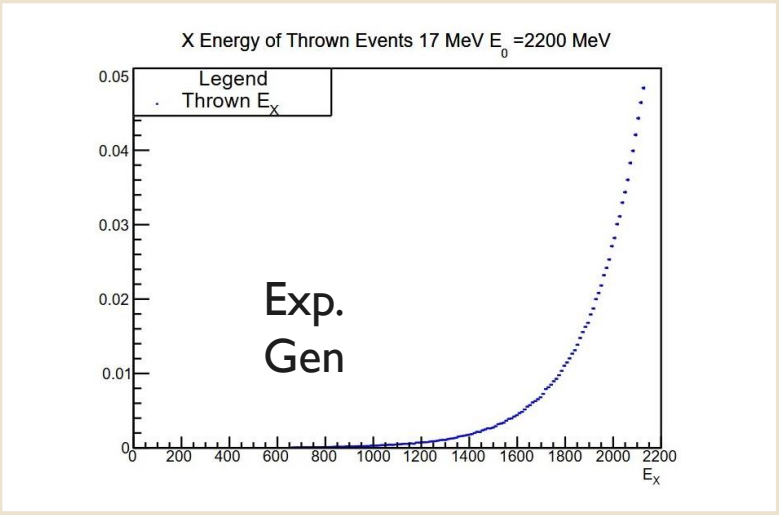
MISSISSIPPI STATE UNIVERSITY
DEPARTMENT OF PHYSICS
AND ASTRONOMY

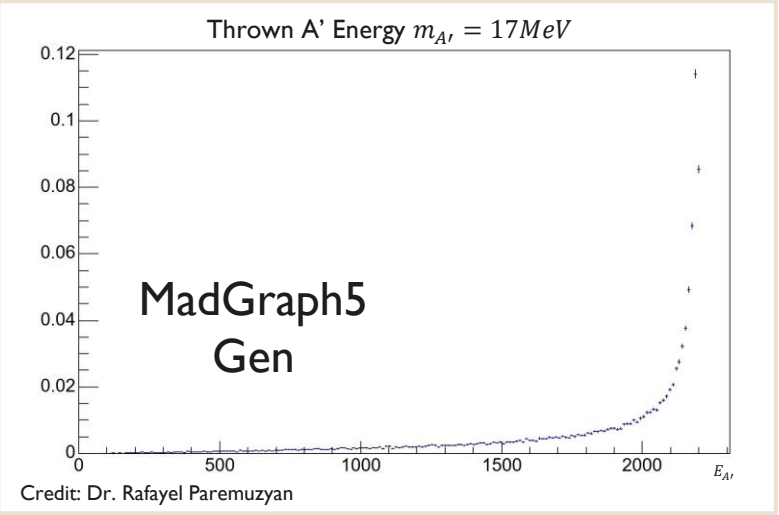

Mount Rainier Photo Credits: Mateo Maughlin

OUTLINE

- How the generator works
- Main Questions
- Geometric Acceptance
- XY Distribution Decay Particles
- Figure of Merit Study
- Invariant Mass Reconstruction







HOW THE GENERATOR WORKS:

- Generates e' in somewhere in HyCal with energy from $E' = (0.03 - 0.7)E_{beam}$.
- Emits X in the direction of the q vector with the remaining energy that the scattered beam electron does not carry.
- Immediately decays the X into e+e- back-to-back pair at a random angle in the X rest frame which is then boosted to the lab frame.
- Project the decay particles $7.5m$ to the face of HyCal and an event is accepted if all three particles are captured.
- Threw $1M$ events per mass.

MAIN QUESTIONS

1. **What is the impact of beam energy on the signal?**
2. **What is the impact of the different absorbers on the signal?**
3. **What is the impact of the target thickness on the invariant mass reconstruction?**

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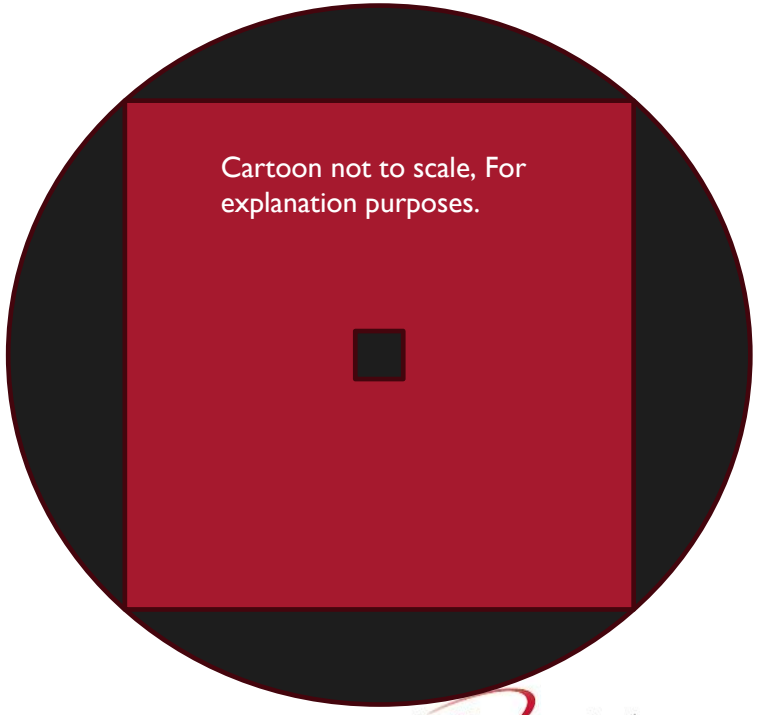
ACCEPTANCE

ADDRESSING QUESTIONS #1,AND 2

APPROXIMATING LOSSES OF e'

- Events are only accepted when the scattered beam electron and the decay e+e- pair all reach the crystal section of HyCal.
- In order to approximate at least some of the losses of the e', I let the angle vary from the minimum to maximum of HyCal's crystal section at 7.5m but included phi variance and rejected those which fell out of the acceptance.



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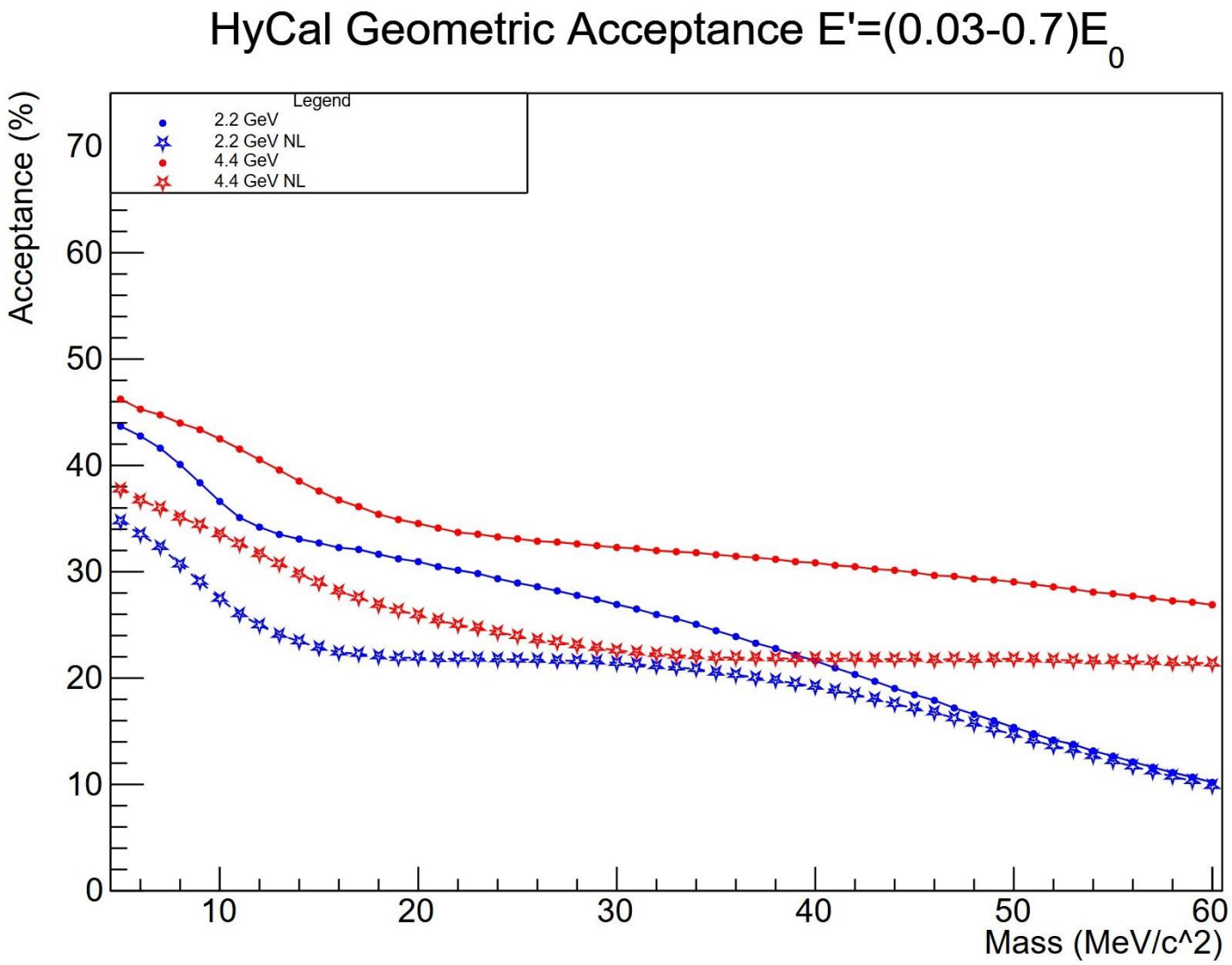
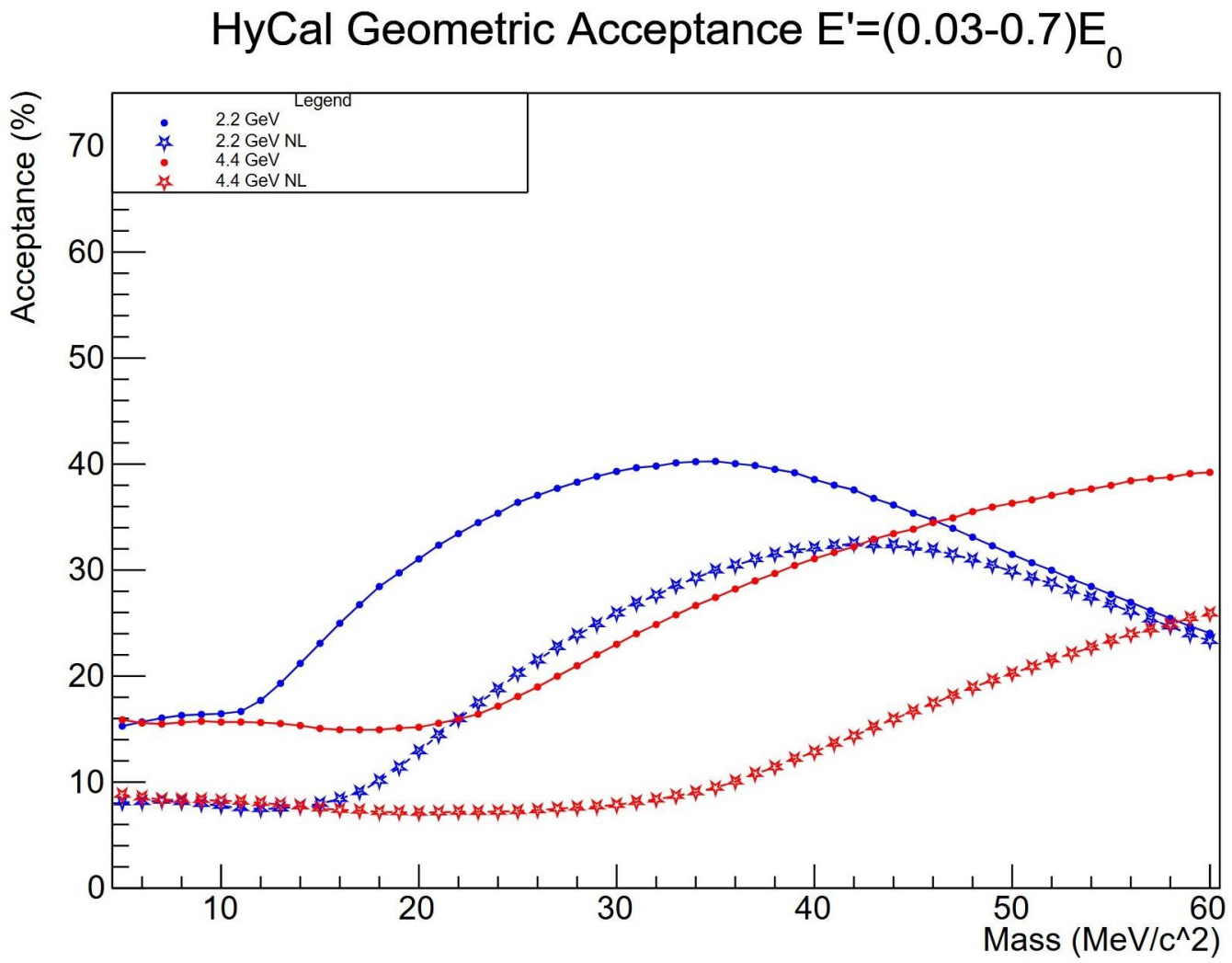
GEOMETRIC ACCEPTANCE (UNIFORM ENERGY)

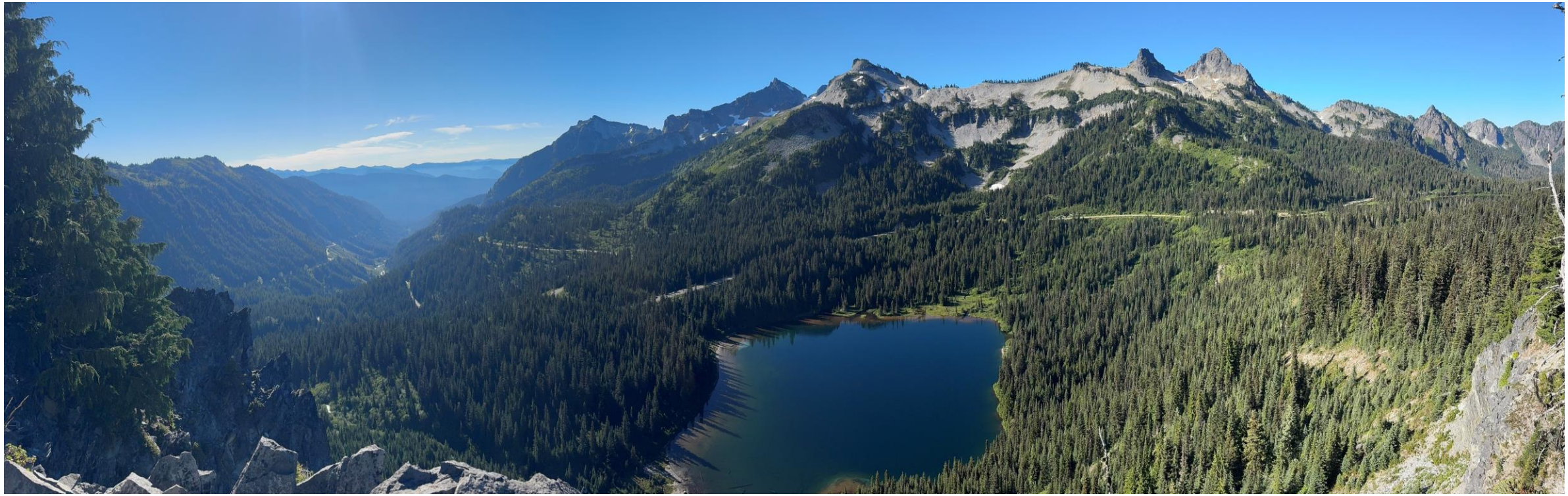
- Red – 4.4 GeV beam
- Blue – 2.2 GeV beam
- Dots – Small Absorber
- Stars – Large Absorber
- For 17MeV 2.2GeV beam
  - ~22% with Large Absorber
  - ~35% with Small Absorber
  - ~1.6x improvement in acceptance



GEOMETRIC ACCEPTANCE (EXP ENERGY)

- I used an exponential distribution of energy to mimic the A' model loosely.
- For 17MeV 2.2GeV beam
  - ~10% with Large Absorber
  - ~26% with Small Absorber
  - ~2.6x improvement in acceptance
- In terms of beam energy, the flat model shows better acceptance at 4.4 GeV, but the 2.2 GeV values are still adequate.
- The A' model suffers at 4.4 GeV, but the enhancement for 2.2 GeV means that will be good enough for either model.





XY DISTRIBUTION OF DECAY PARTICLES

ADDRESSING QUESTION #2

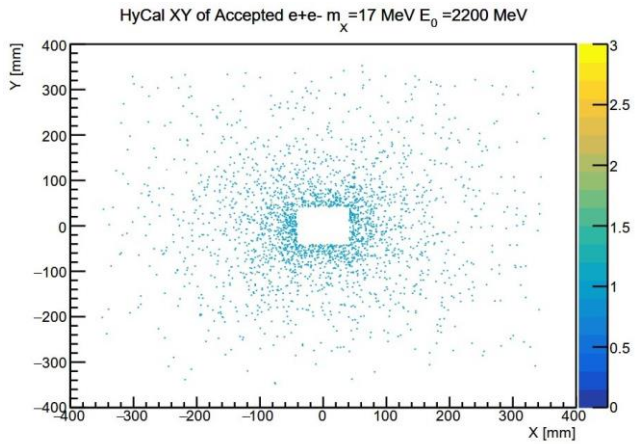
17 MeV – 2.2 GeV Beam (Uniform Gen.)

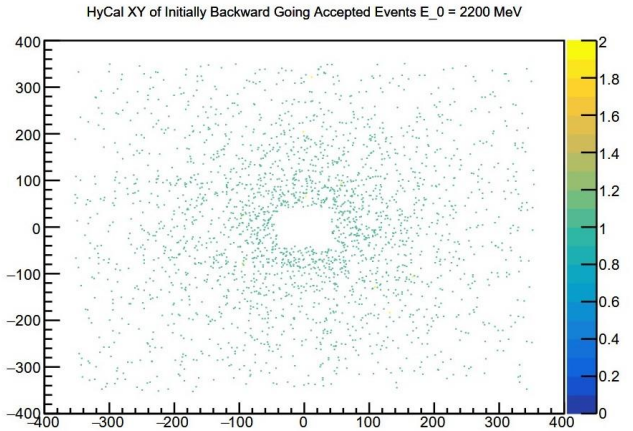
- My generator does not differentiate between e+ and e-
- It only knows which one was initially backwards going and which was initially forwards going in the X rest frame.
- Each plot shows the first 2500 accepted particles.

Initially Forward Going

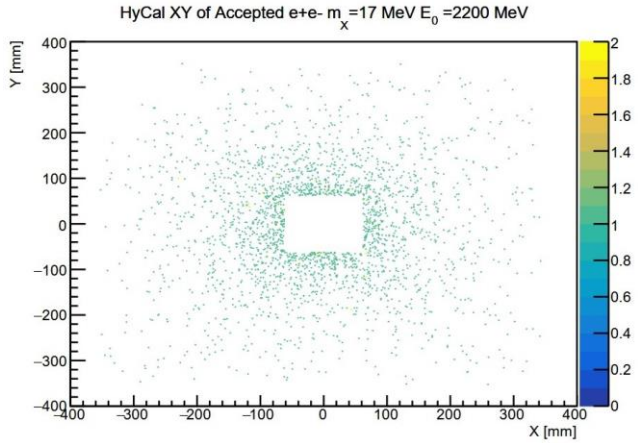
Initially Backward Going

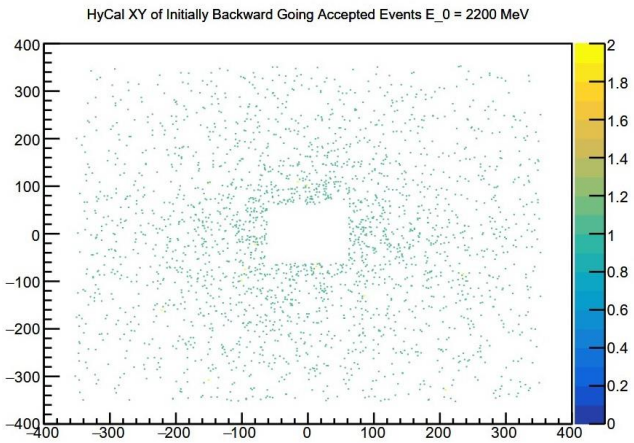
Small Absorber:





Large Absorber:

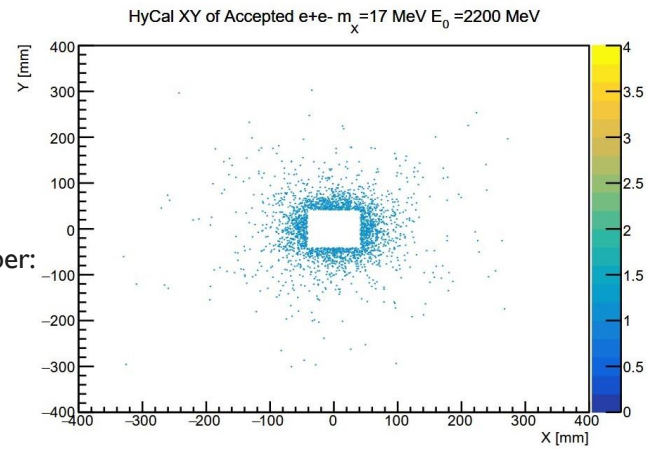


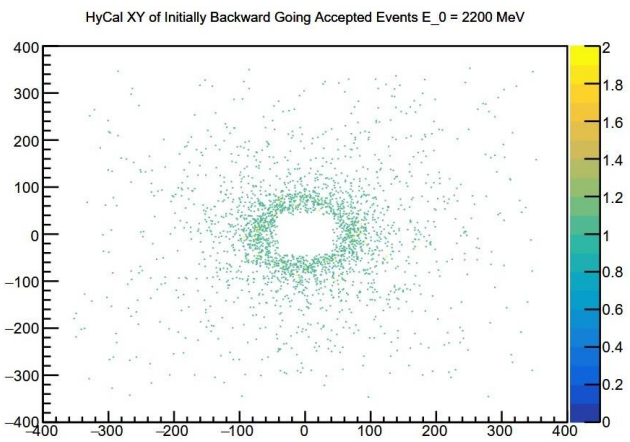


Initially Forward Going

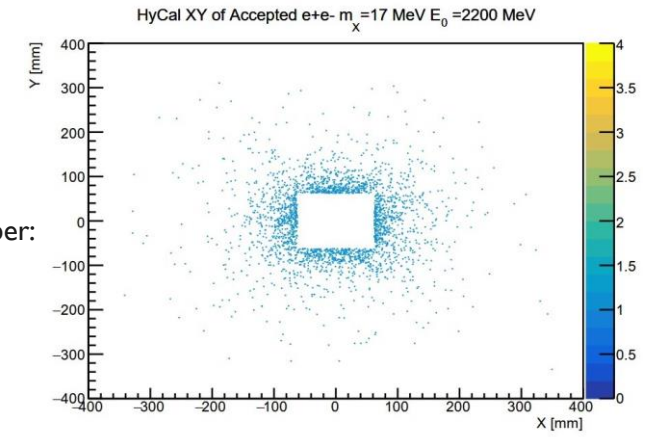
Initially Backward Going

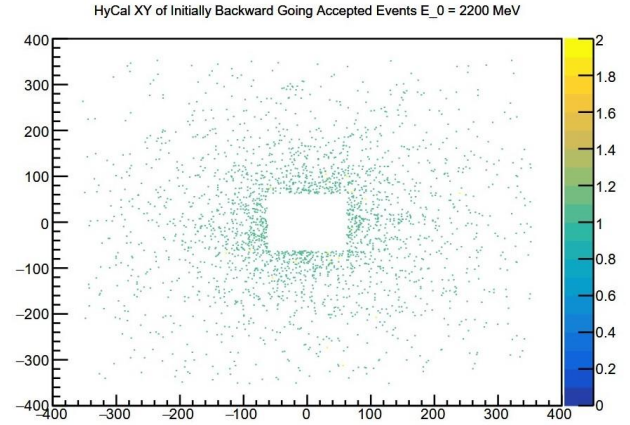
Small Absorber:





Large Absorber:





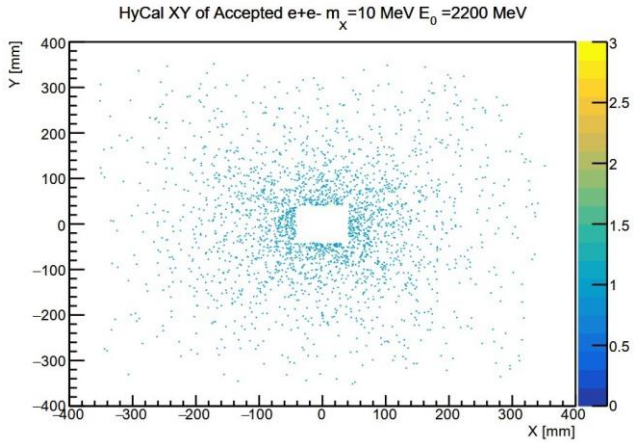
17 MEV – 2.2 GEV BEAM (EXP. GEN.)

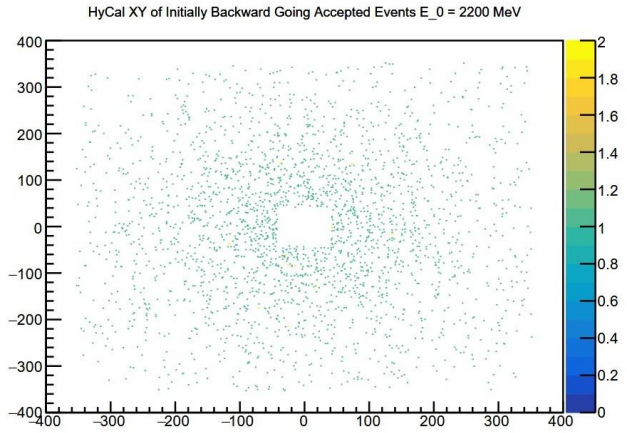
10 MEV – 2.2 GEV BEAM UNIFORM GEN.

Initially Forward Going

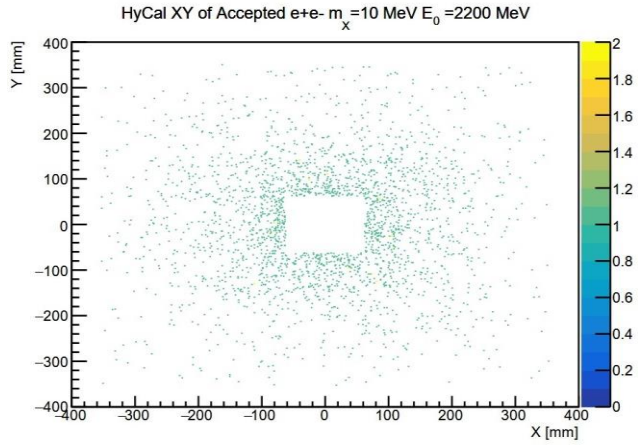
Initially Backward Going

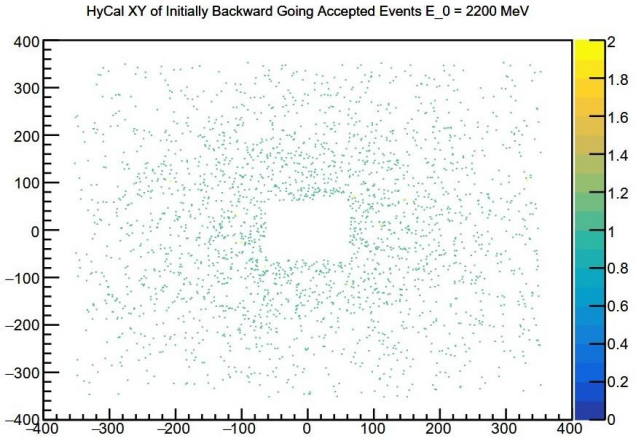
Small Absorber:



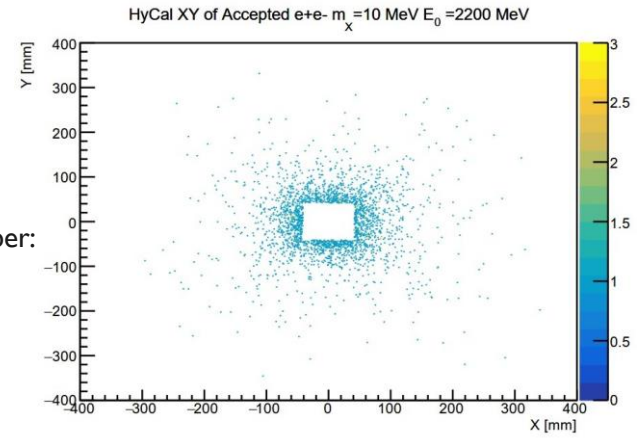
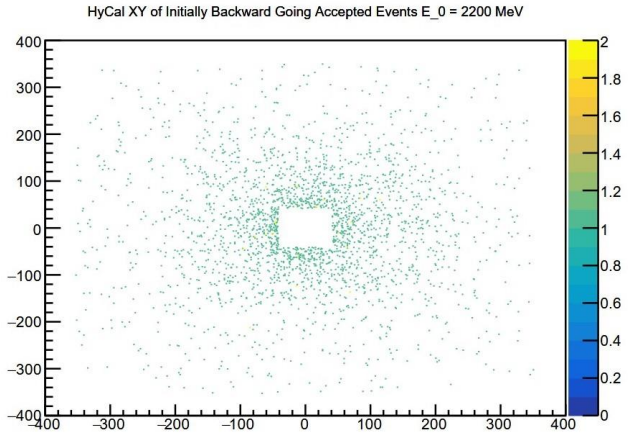
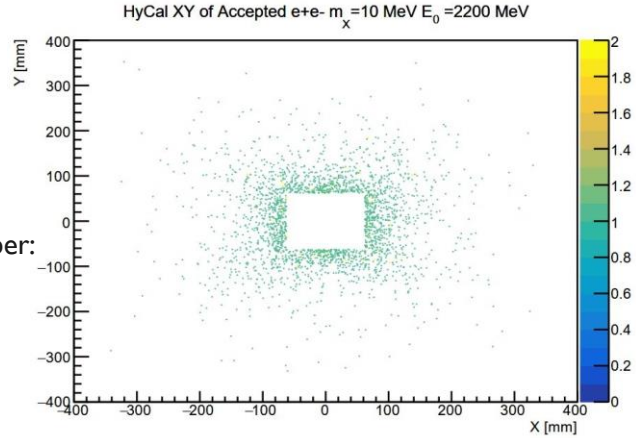
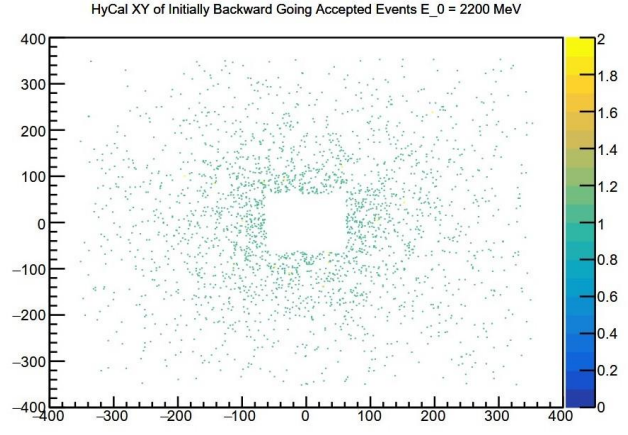


Large Absorber:





10 MEV – 2.2 GEV BEAM (EXP. GEN.)

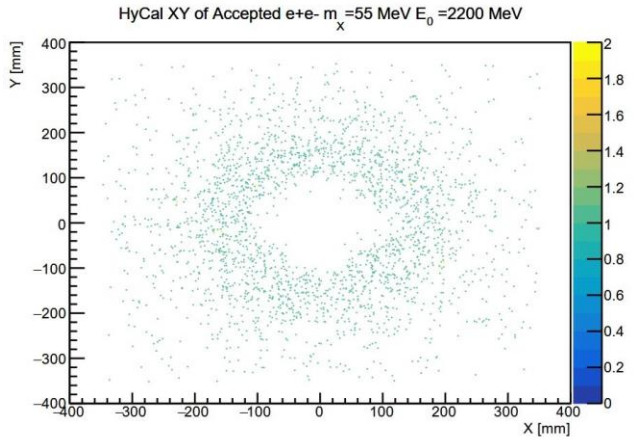
	Initially Forward Going	Initially Backward Going
Small Absorber:		
Large Absorber:		

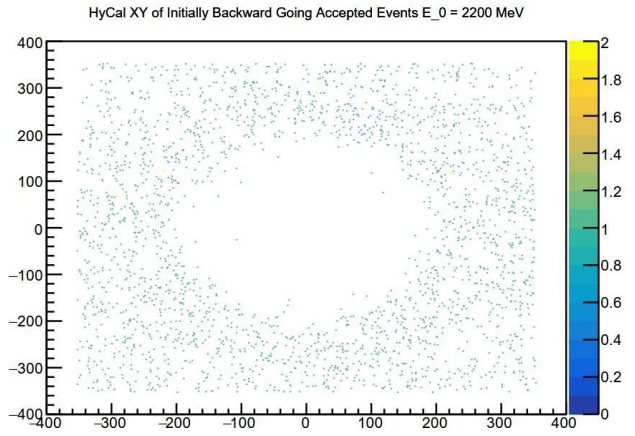
55 MEV – 2.2GEV BEAM UNIFORM GEN.

Initially Forward Going

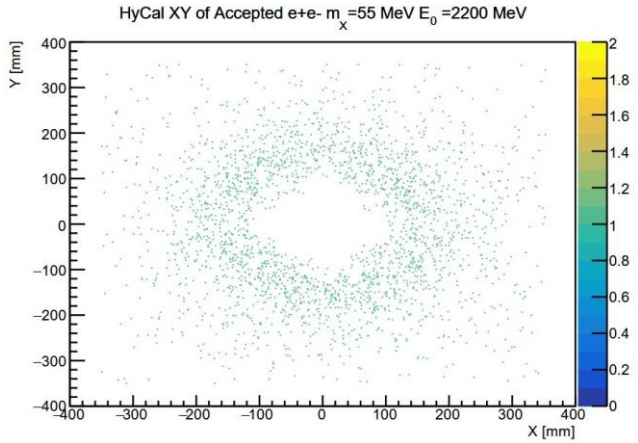
Initially Backward Going

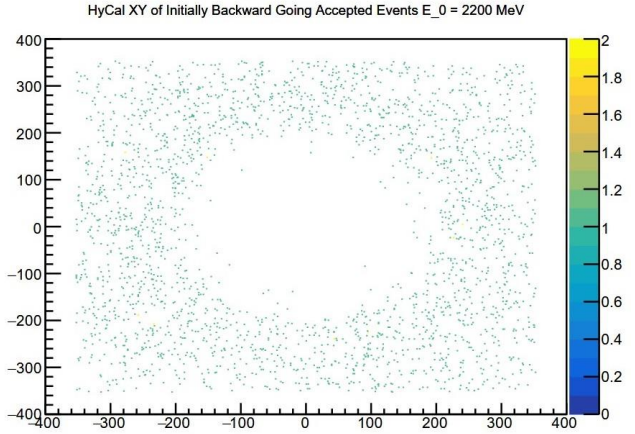
Small Absorber:





Large Absorber:

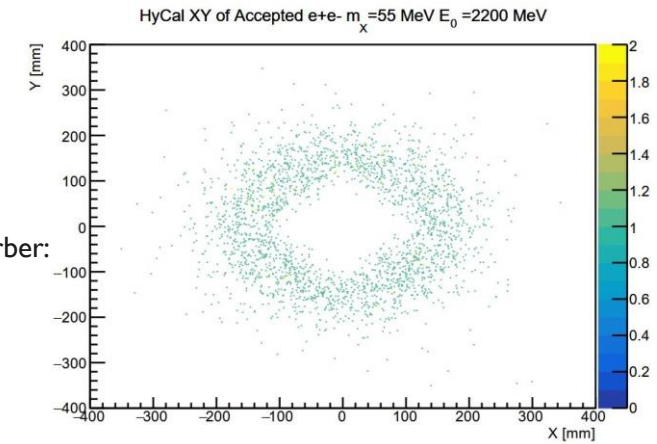


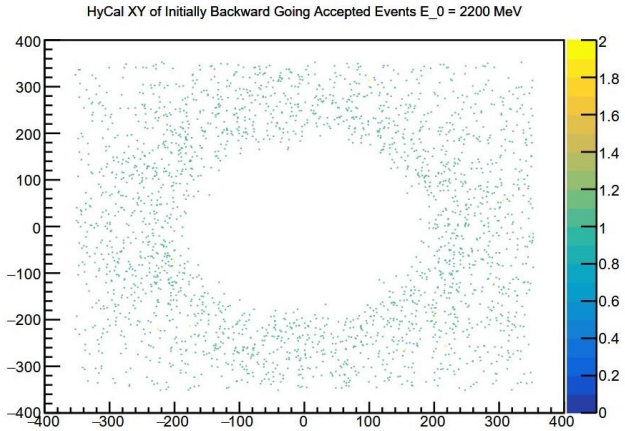


Initially Forward Going

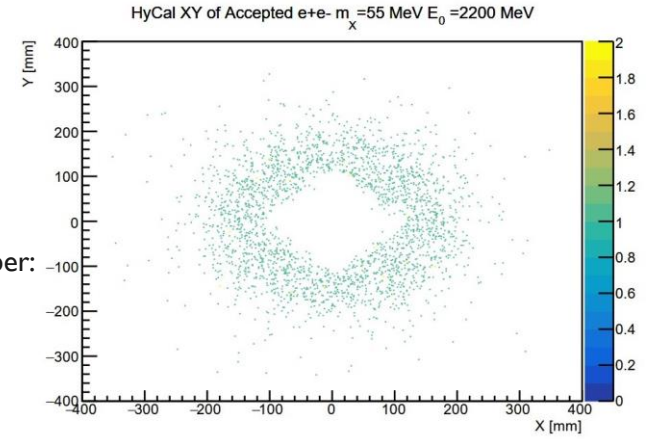
Initially Backward Going

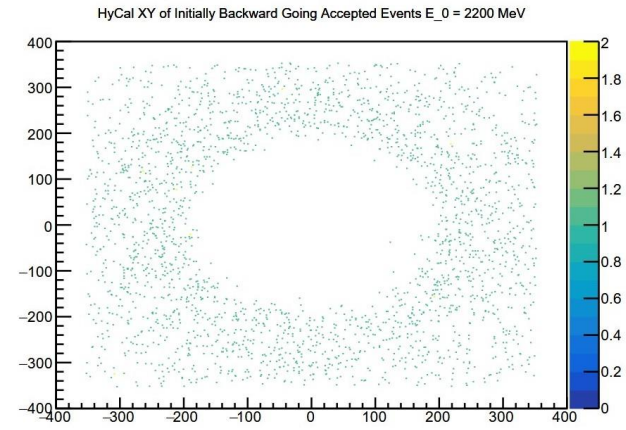
Small Absorber:





Large Absorber:





55 MEV – 2.2 GEV BEAM EXP. GEN.

- In addressing the absorber, keeping the smaller absorber opens more of the detector, allows for more of the acceptance to be away from the edges, and boosts the generally expected yields.
- This is more extreme for the A' model, but still applicable for the flat model.

FIGURE OF MERIT

ADDRESSING QUESTIONS #1, AND 2 WHILE TRYING TO INCLUDE IMPACT OF RADIATION DOSE AND ENERGY RESOLUTION

HOW THE FIGURE OF MERIT VALUES ARE CALCULATED

- Weight each accepted hit by 1/energy resolution relative to the maximum energy resolution and bin it into bins the size of each crystal. Then divide the value in each bin by the radiation dose in that crystal divided by 15 (setting to 1 is the value less than 1 meaning the resolution is assumed to be unaffected by the radiation dose).

$$\frac{1}{\frac{\left(\frac{\sigma_E}{E}\right)_i}{\left(\frac{\sigma_E}{E}\right)_{max}} * \frac{R_n}{15} * N_{thrown}}$$

- $\left(\frac{\sigma_E}{E}\right)_i = \left(\frac{2.6\%}{\sqrt{E_i}}\right)$ indicates the energy resolution of each hit in HyCal (3 per accepted event)
- R_n indicates the radiation dose in each crystal for the given setting
- N_{thrown} is the number of events thrown (1 million in this case)

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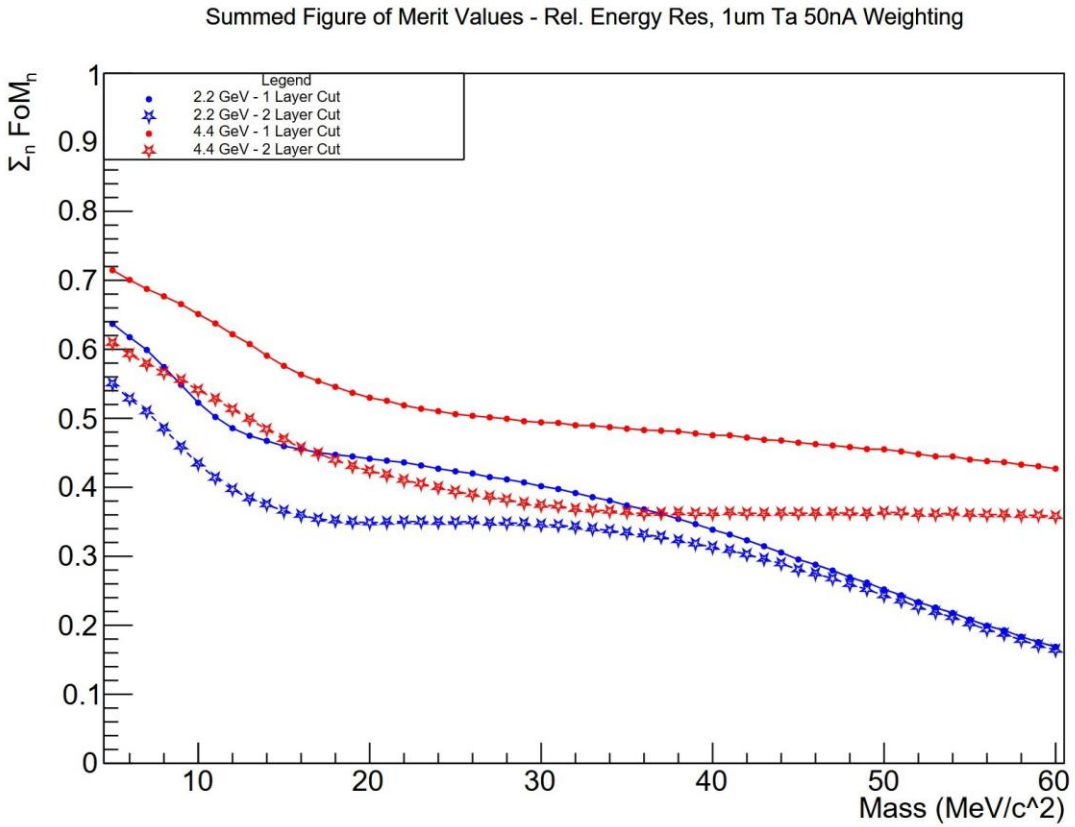
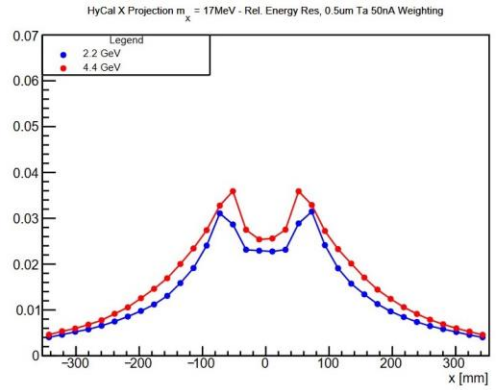
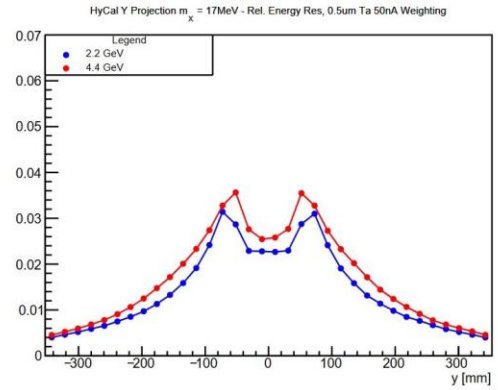
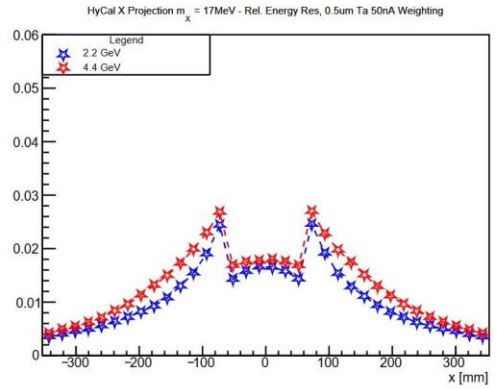
$1\mu m$ Ta 50nA Beam – Uniform Gen.

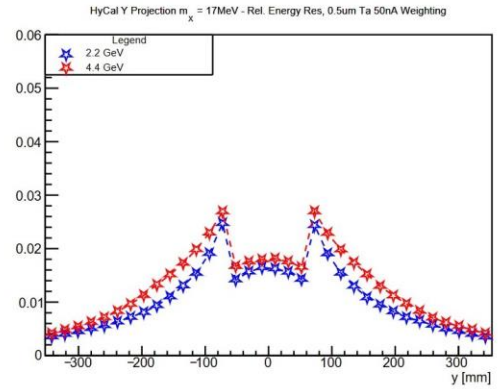


$m_X = 17\,{}^{MeV}/_{c^2}$



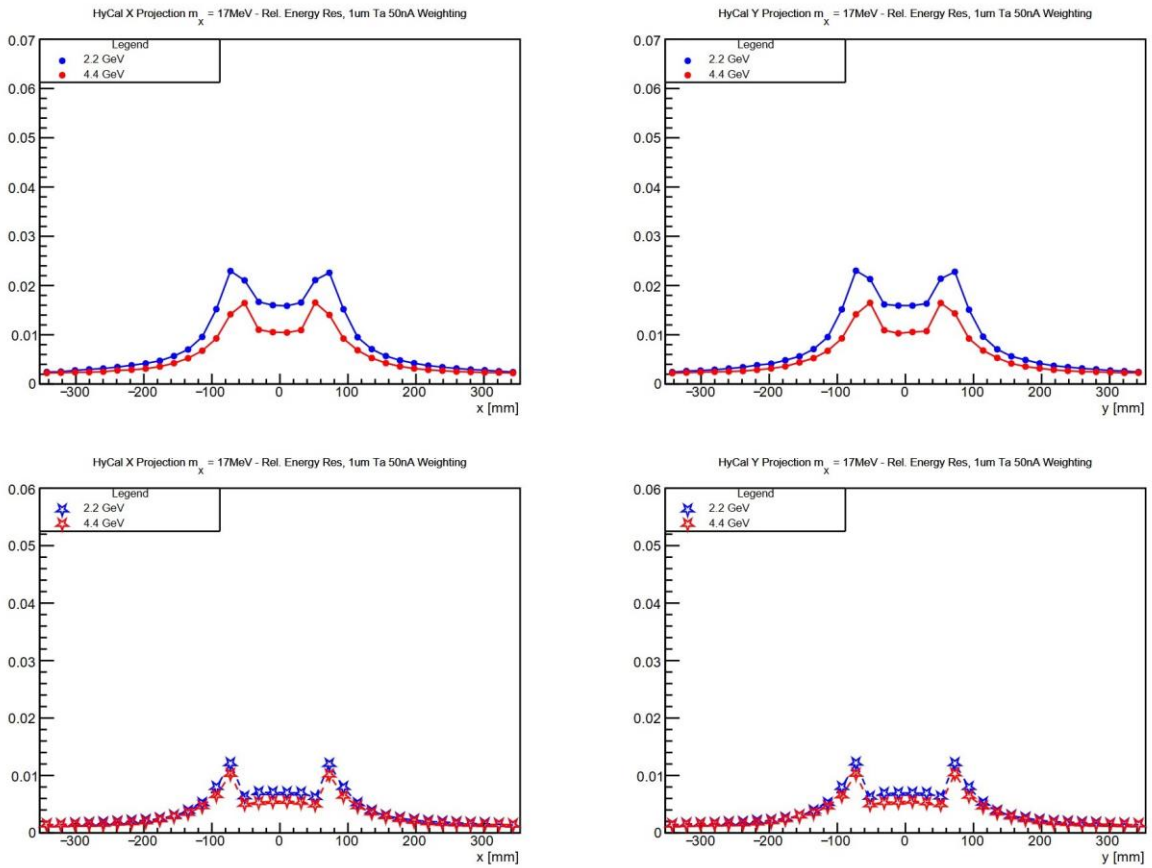


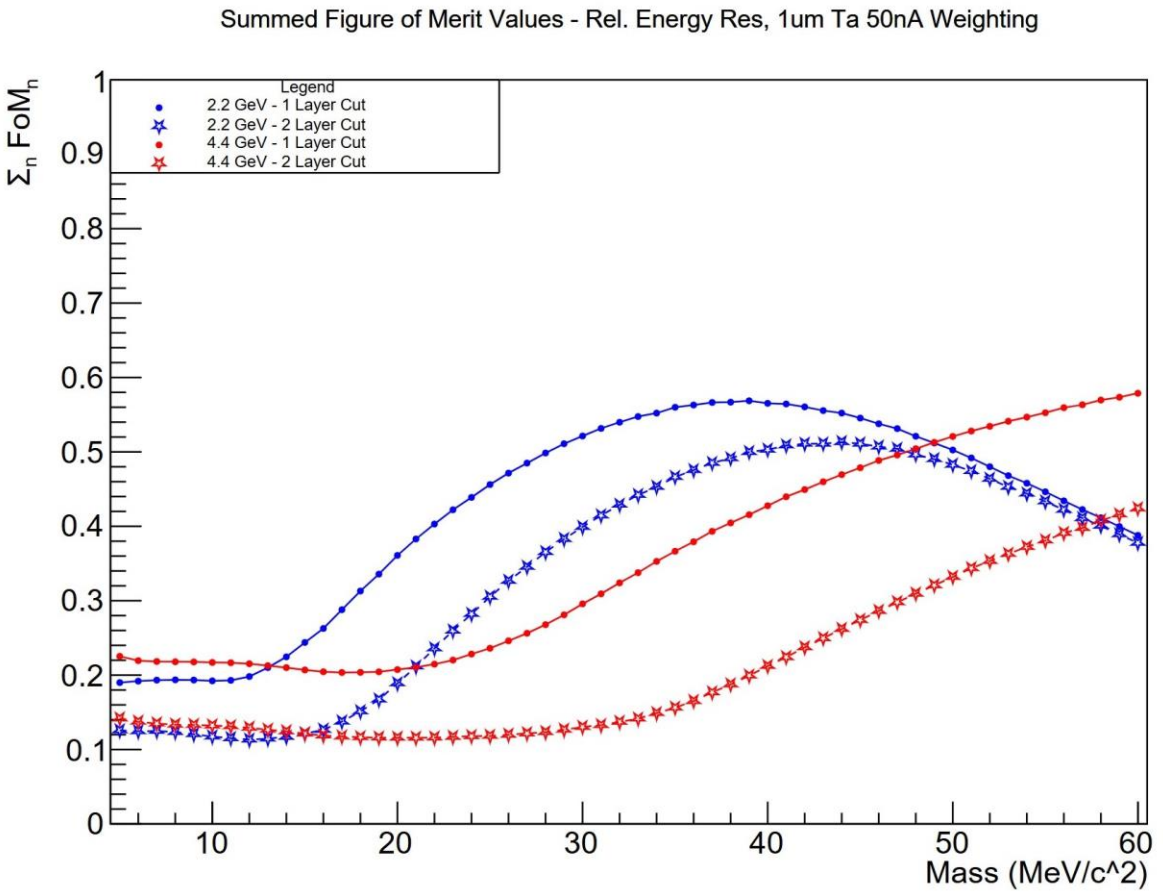




$m_X = 17\,^{MeV}/_{c^2}$

$1\mu m$ Ta 50nA Beam – Exp. Gen.





INVARIANT MASS RESOLUTION

INVARIANT MASS RECONSTRUCTION RESOLUTION - σ_{m_X}

- Included sources of error:
  - Energy:
    - HyCal – Assumed $\frac{\sigma_E}{E} = \frac{2.6\%}{\sqrt{E}}$ for each particle in HyCal
    - Energy Loss to Multiple Scattering in Target – Modeled with randomly sampled Landau Distribution with the most probable value defined by the energy loss to Bremsstrahlung (which is close enough in our energy scales) with scale defined as described in PDG Section 34.
  - Position:
    - $\Delta\theta$ – from multiple scattering in the target PDG Section 34
  - I assumed that most that would be affected by downstream effects (the Vacuum Chamber window) could be rejected with the GEMs.

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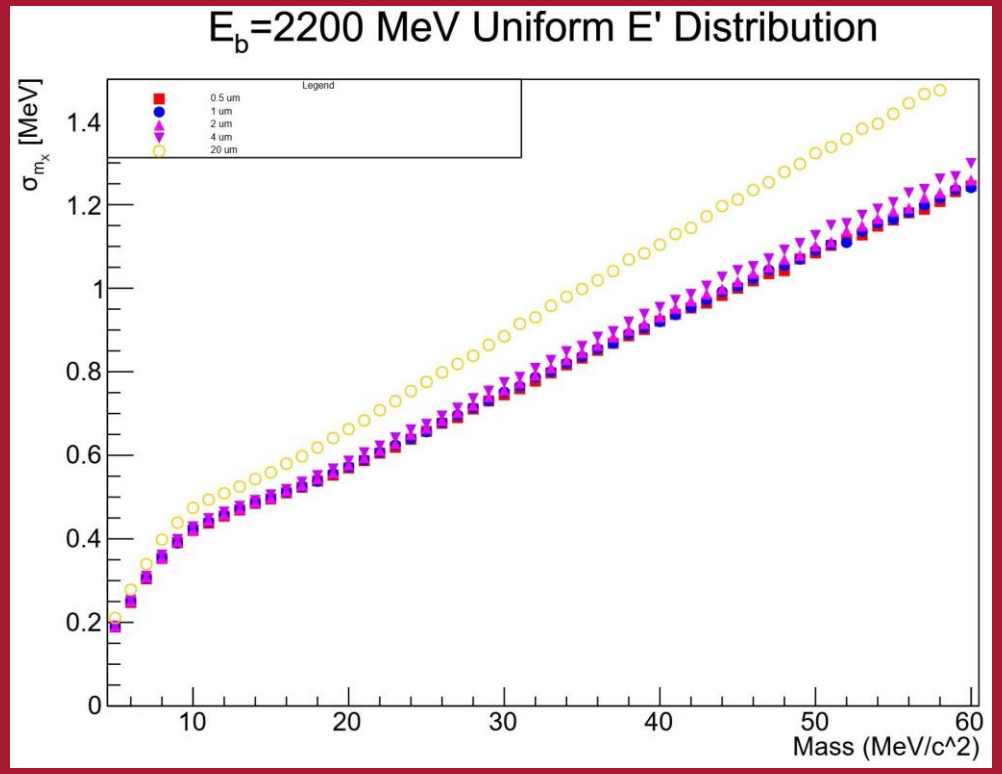
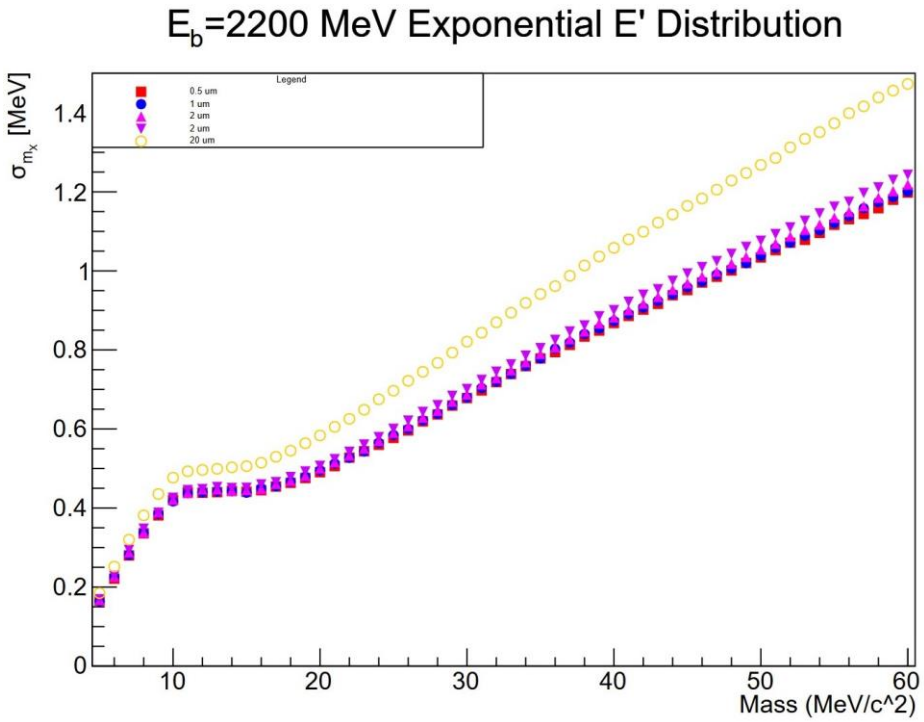
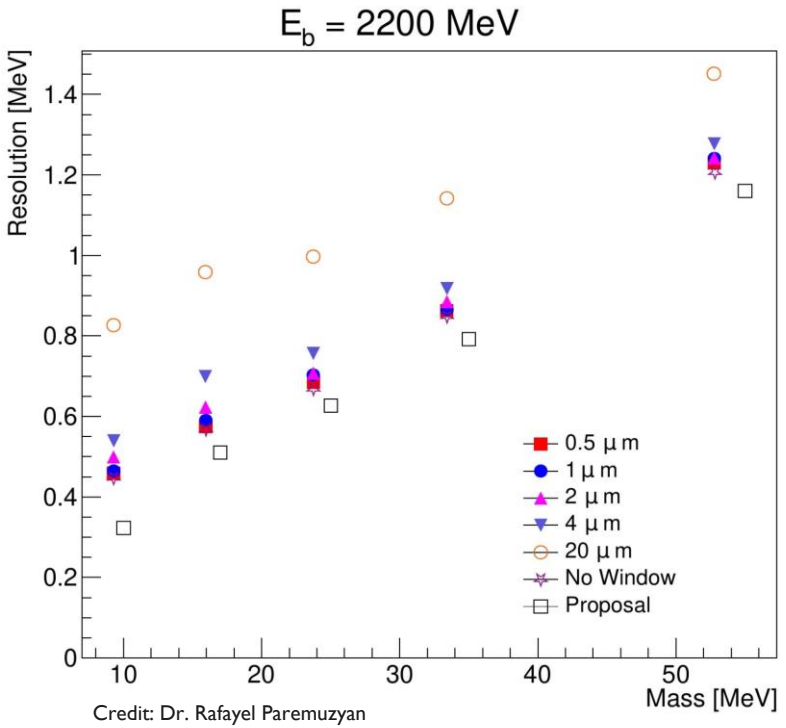


DIFFERENCES WITH TARGET THICKNESS

- Target Thickness does not seem to have much effect on the resolution of the mass reconstruction until you get to be very thick.
- This agrees with Rafo's findings.
- There is some underestimation for thicker targets for lower masses, which makes sense given the approximation that I used for the energy loss in the target.





Credit: Dr. Rafayel Paremuzyan

MASS RESOLUTION WITH EXP. GENERATION

- When using the exponential generation method, the resolution is in better agreement with the results that Rafo got, suggesting that this accounts for the major sources of resolution loss.

CONCLUSION

- From these results, we can say that the acceptance benefits when we are able to use the smaller absorber, and 2.2 GeV beam, energy allows for an optimal acceptance for the A' model without sacrificing the acceptance of another expectation.
- The signal XY distribution shows that opening the innermost crystal layer by using the smaller absorber allows for more of the peak acceptance region to be more away from the edges of the detector.
- In terms of invariant mass reconstruction resolution, we can tolerate increases in thickness (within reason) due to the dominating component being HyCal's energy resolution.

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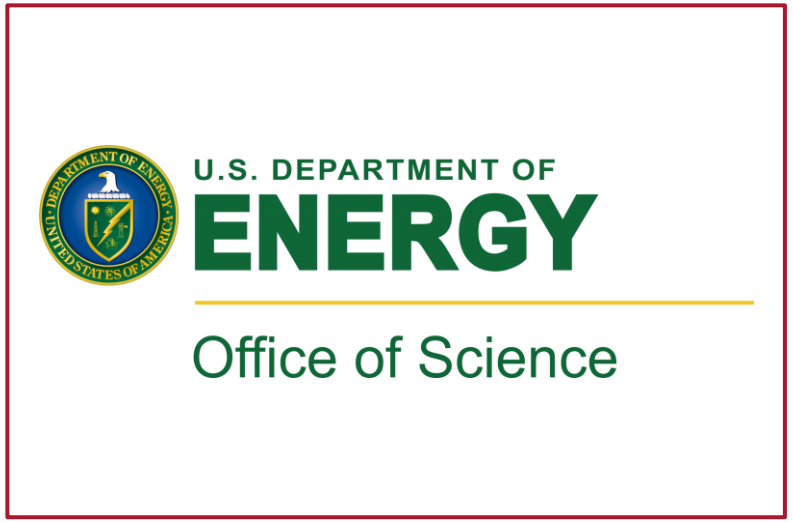


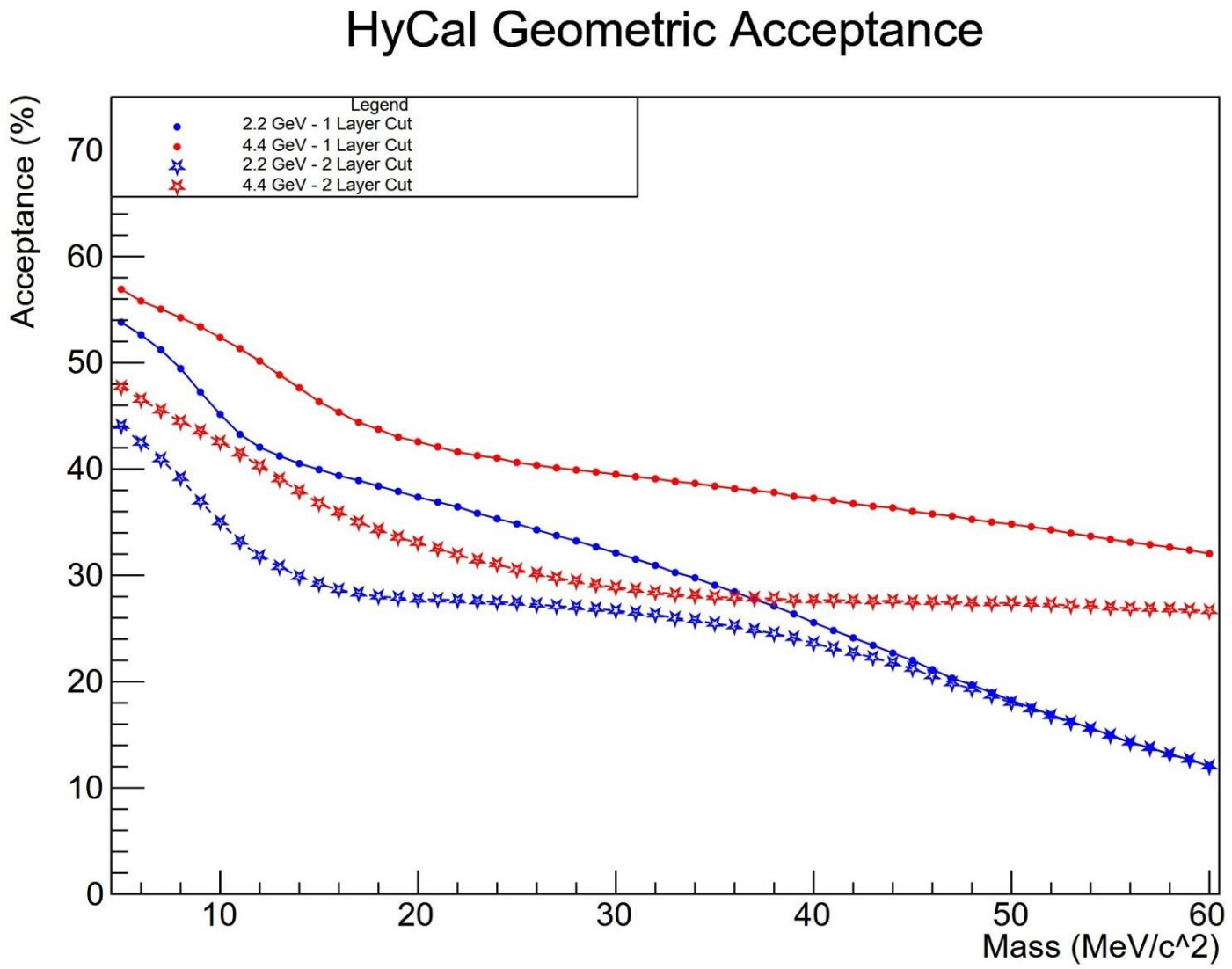
ACKNOWLEDGEMENTS

- US Dept. Of Energy under contract #DE-FG02-07ER41528
- JSA/JLab Graduate Student Fellowship
- My Advisor: Dr. Dipangkar Dutta, Mississippi State
- Dr. Rafayel Paremuzyan
- Dr. Ashot Gasparian
- Dr. Tyler Hague
- PRad Collaborators

BACKUP SLIDES

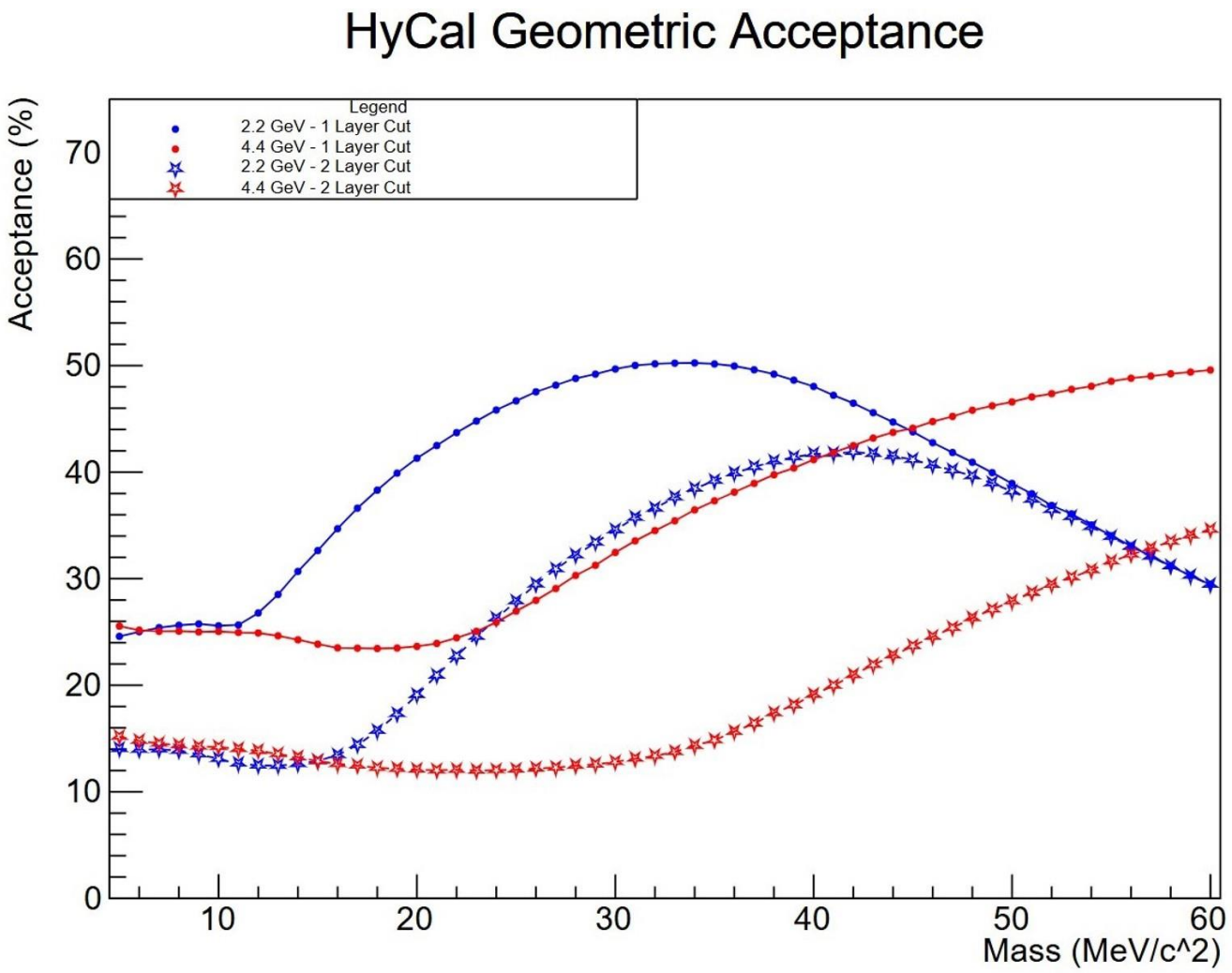
GEOMETRIC ACCEPTANCE (UNIFORM ENERGY)

- When all e' are accepted I reproduced the results as seen in the proposal.
- For 17MeV 2.2GeV beam
  - ~28% with Large Absorber
  - ~40% with Small Absorber
  - ~1.43x improvement in acceptance



GEOMETRIC ACCEPTANCE (EXP. ENERGY)

- I also generated with an exponential energy distribution where the E_X is peaked at the beam energy to mimic some of what is seen in the A' model.
- For 17MeV 2.2GeV beam
  - ~15% with Large Absorber
  - ~38% with Small Absorber
  - ~2.5x improvement in acceptance

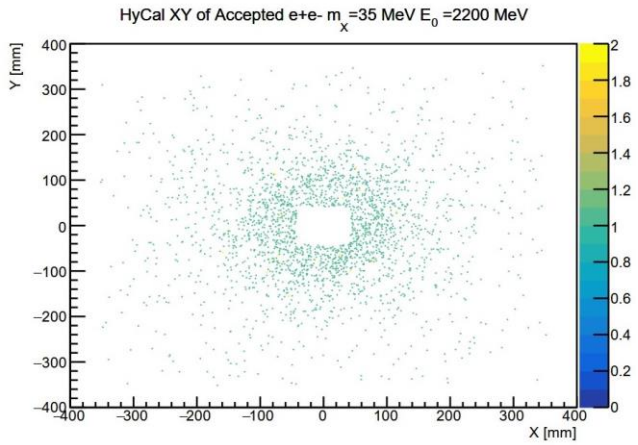


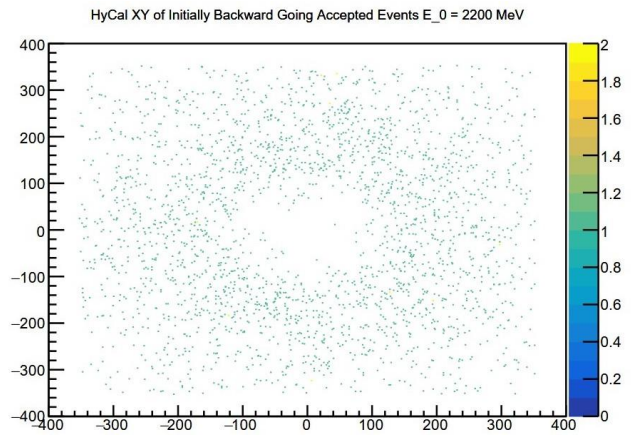
35 MEV – 2.2GEV BEAM UNIFORM GEN.

Initially Forward Going

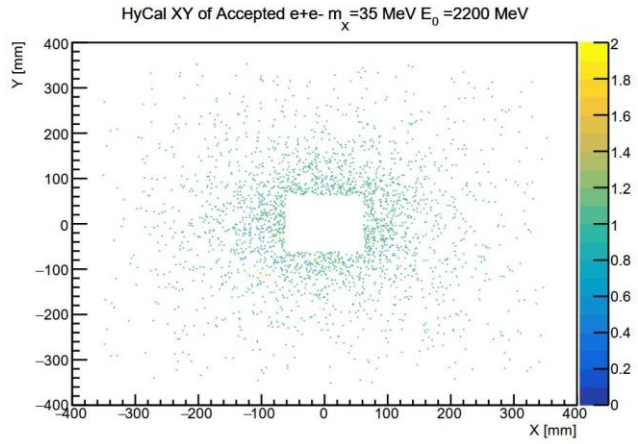
Initially Backward Going

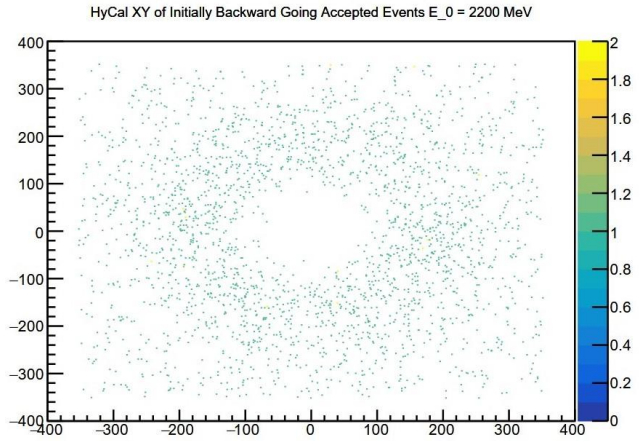
Small Absorber:





Large Absorber:



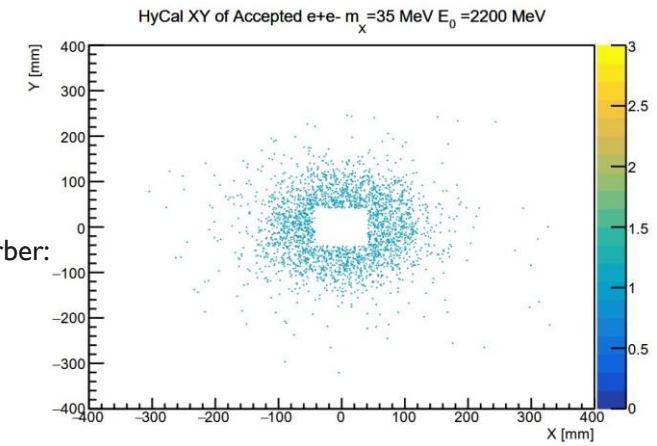


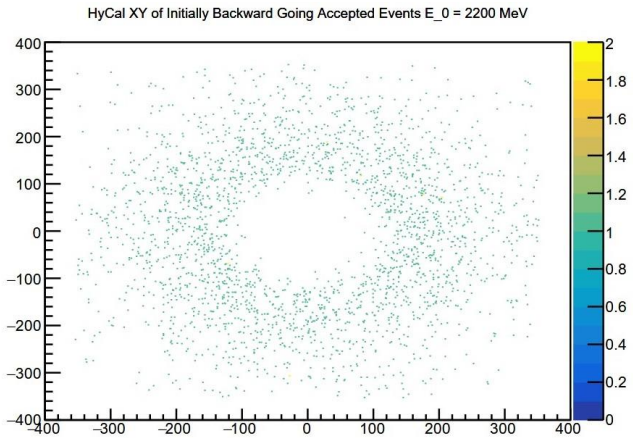
Initially Forward Going

Initially Backward Going

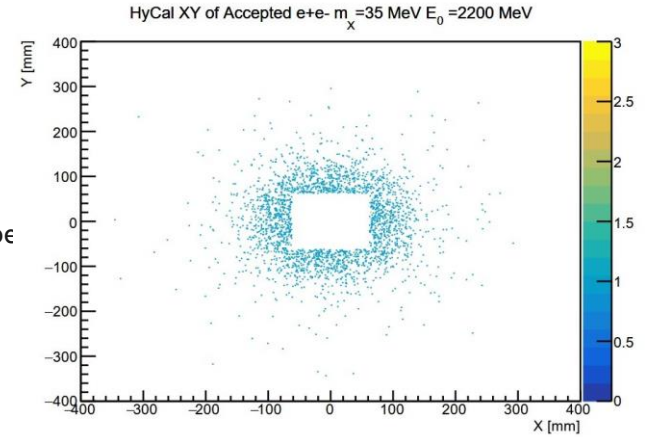
35 MEV – 2.2 GEV BEAM EXP. GEN.

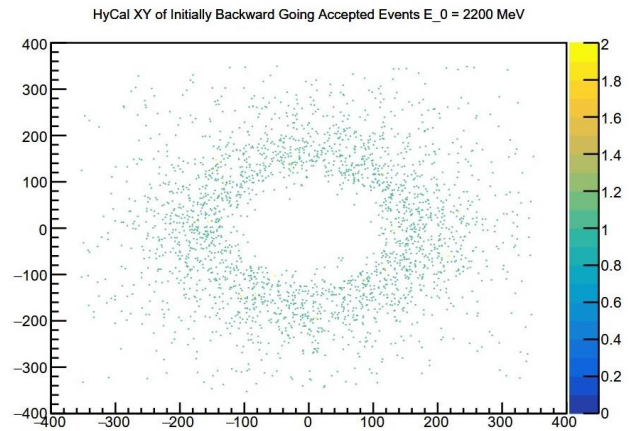
Small Absorber:



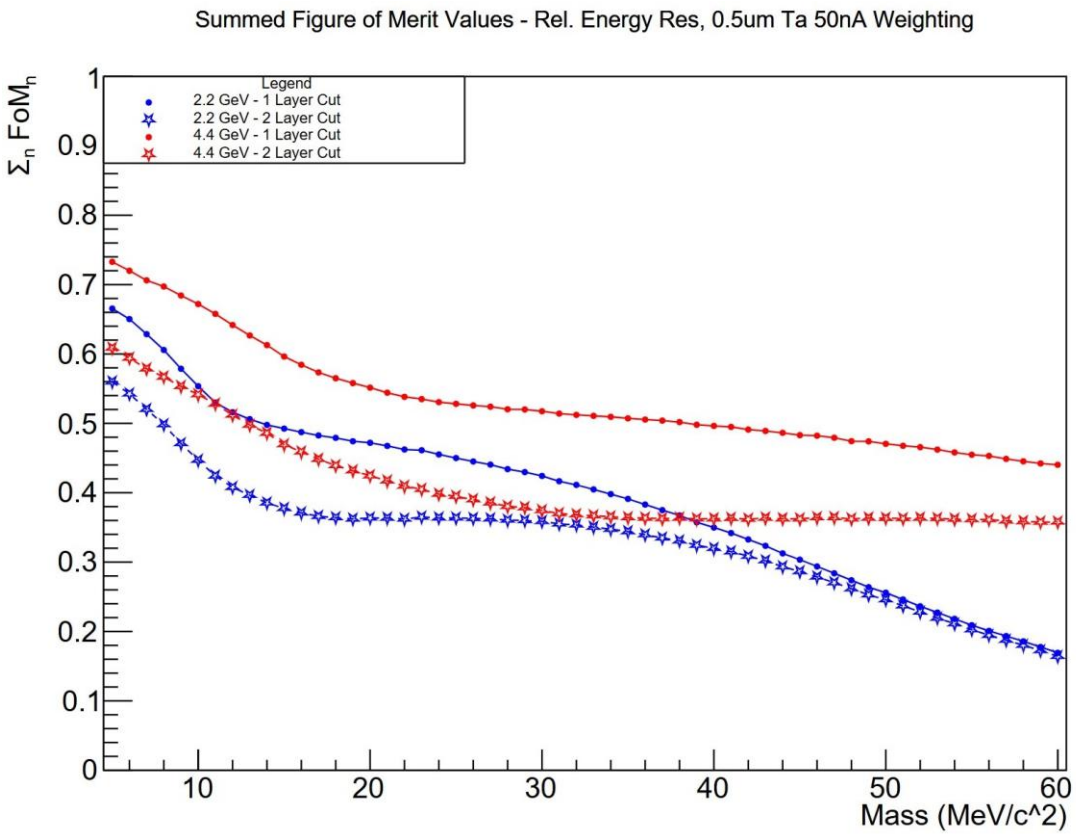


Large Absorbe

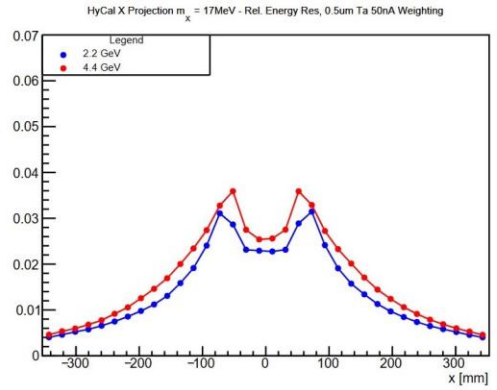


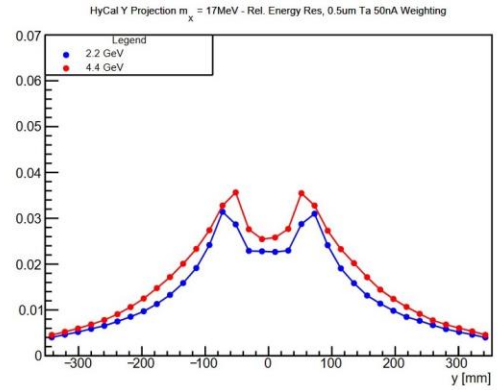


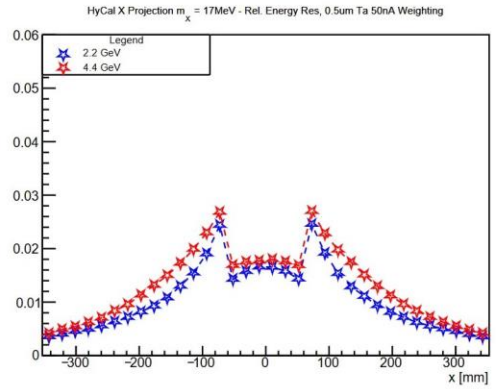
$0.5\mu m$ Ta 50nA Beam – Uniform Gen.

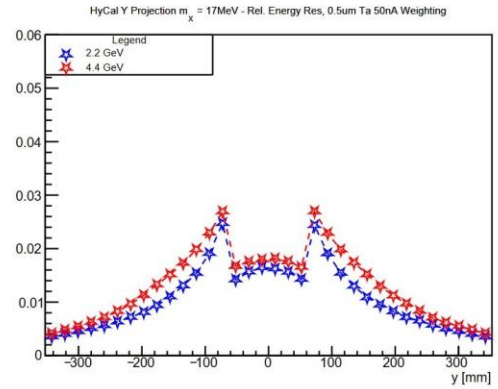


$m_X = 17\,^{MeV}/_{c^2}$



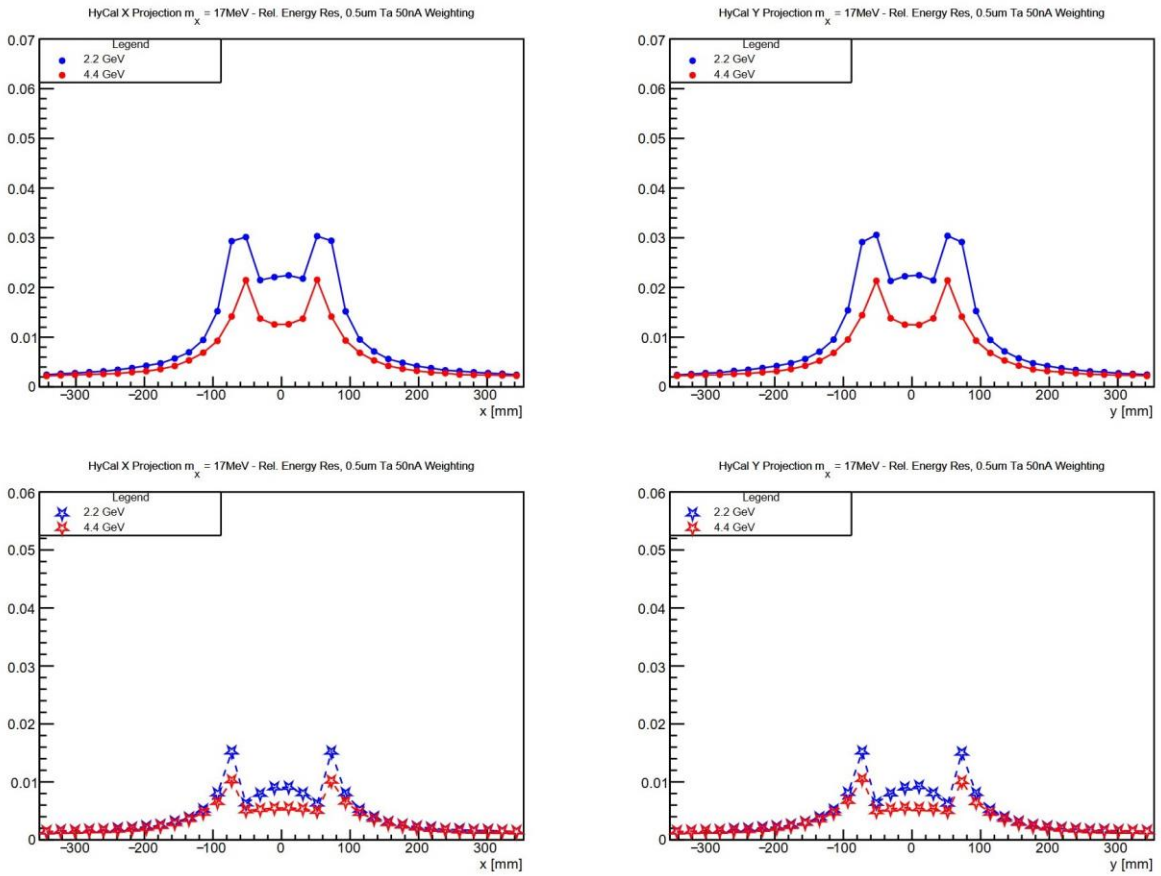


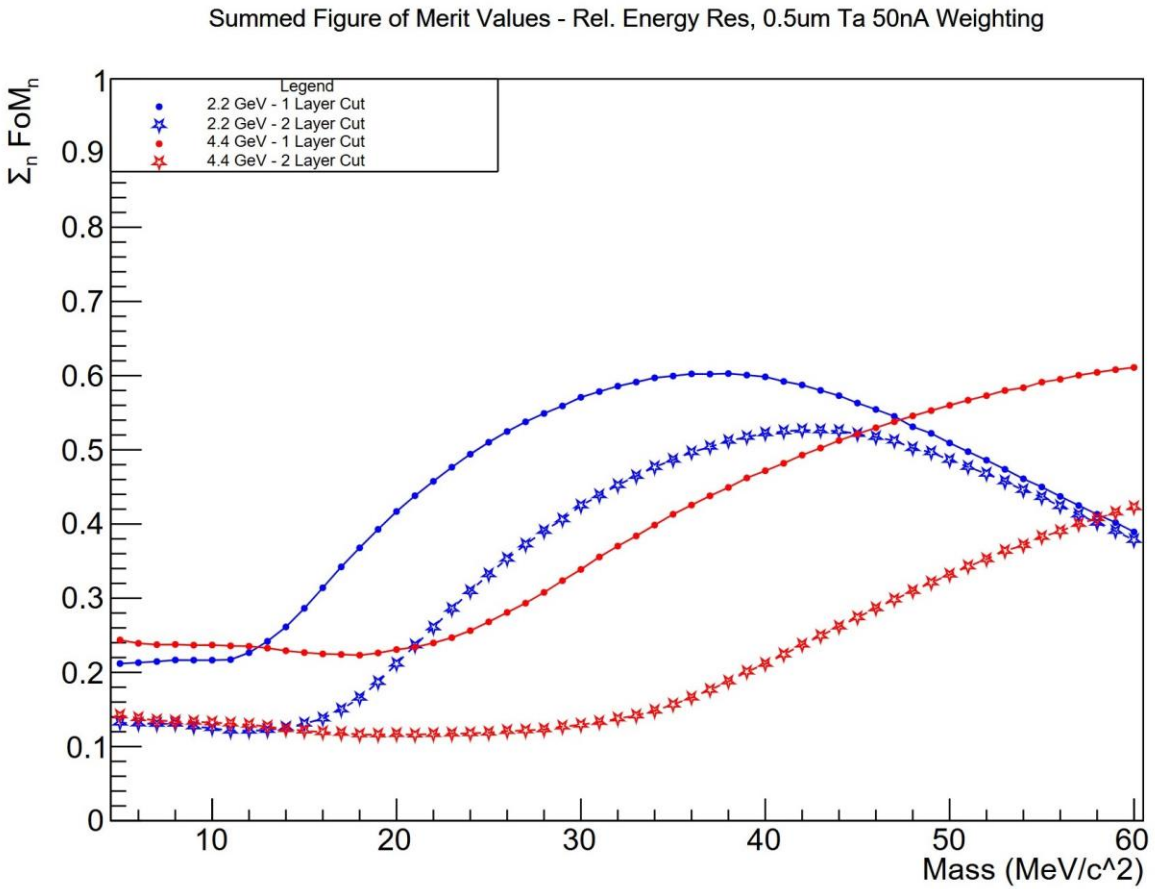




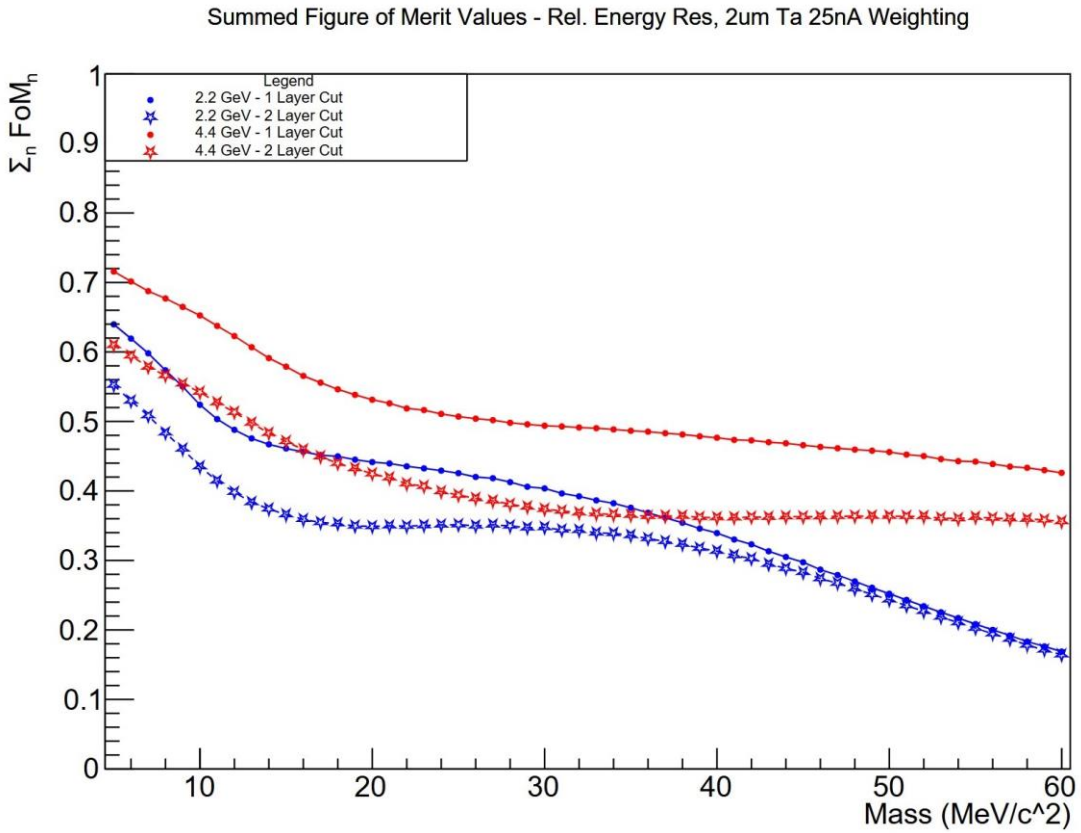
$m_X = 17\,^{MeV}/_{c^2}$

$0.5\mu m$ Ta 50nA Beam – Exp. Gen.

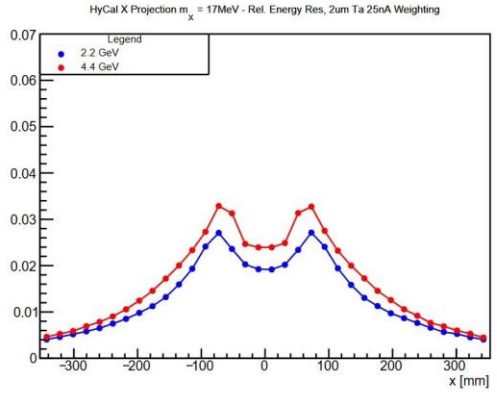


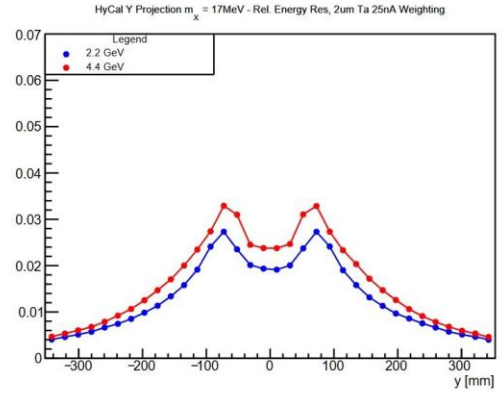


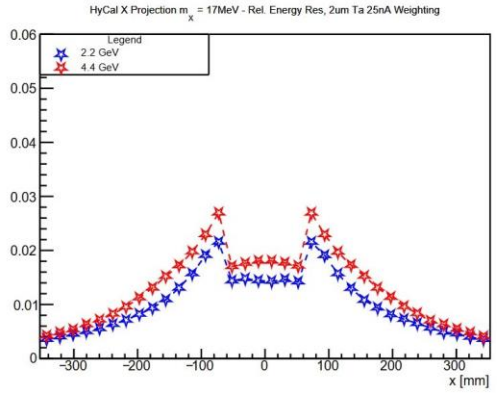
$2\mu m$ Ta 25nA Beam – Uniform Gen.

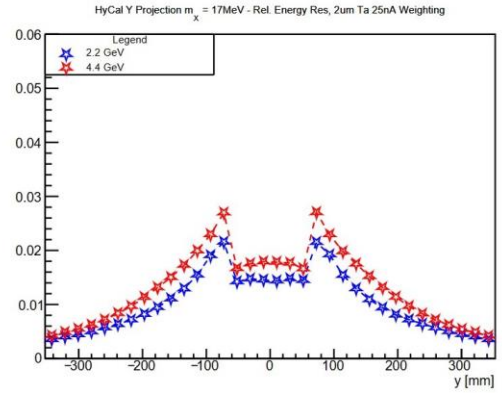


$m_X = 17\,^{MeV}/_{c^2}$



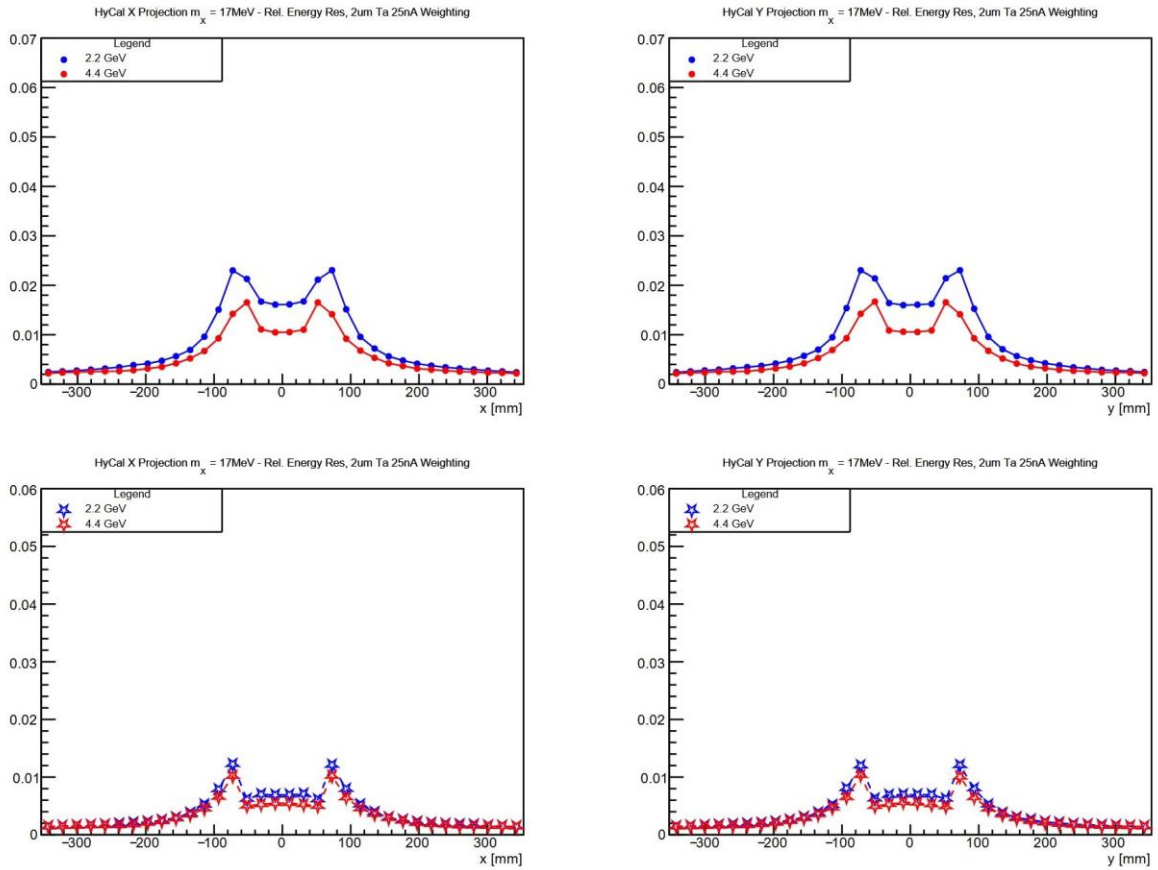


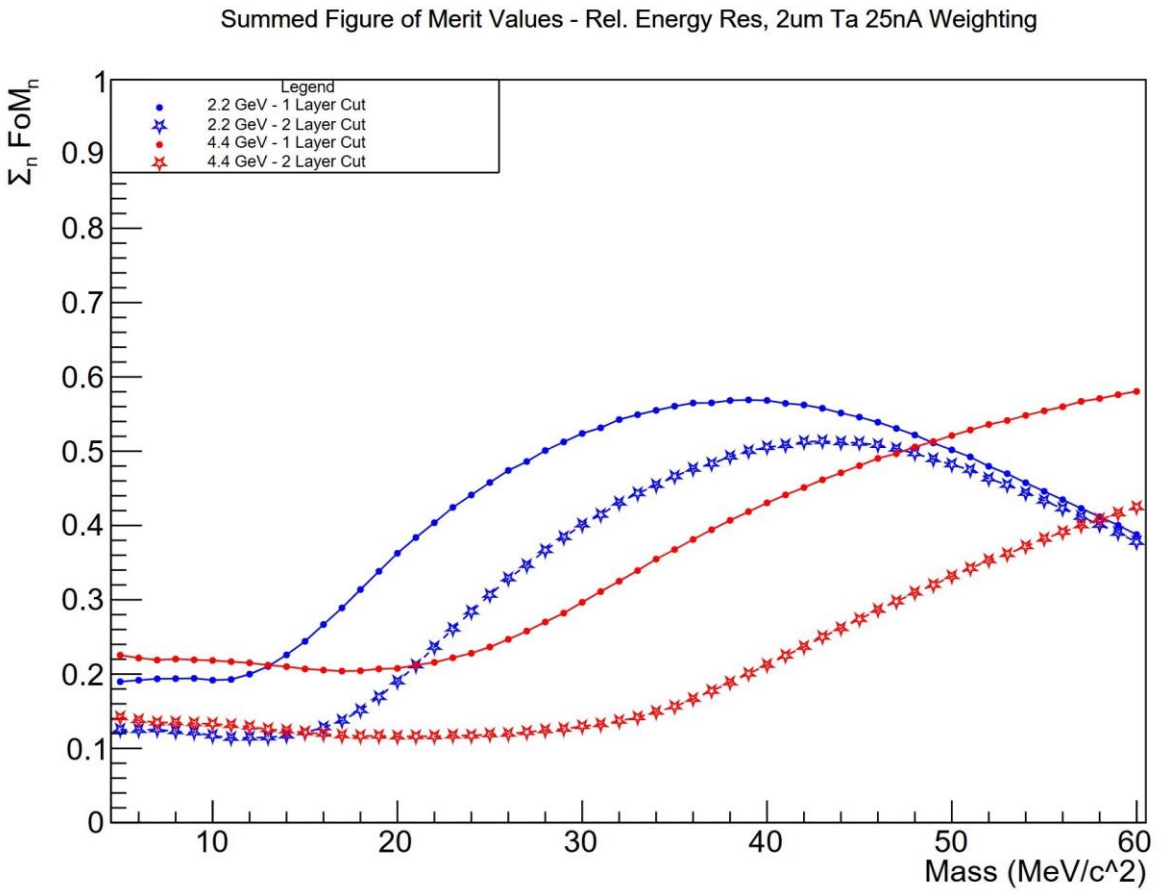




$m_X = 17\,^{MeV}/_{c^2}$

$2\mu m$ Ta 25nA Beam – Exp. Gen.





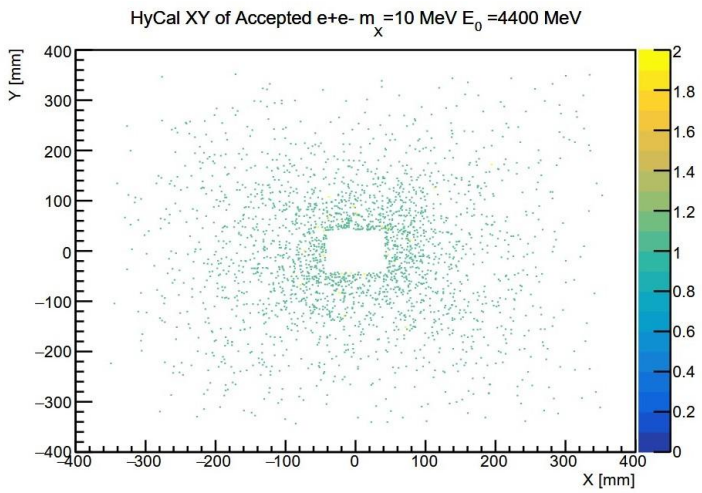
4.4 GEV XY DISTRIBUTION

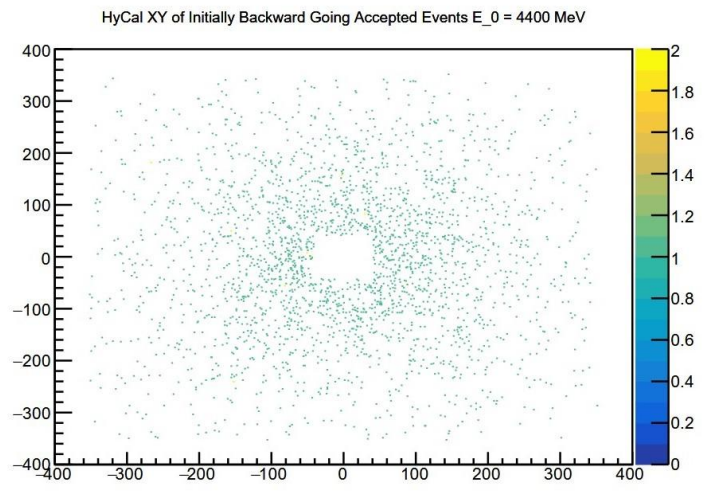
Initially Forward Going

Initially Backward Going

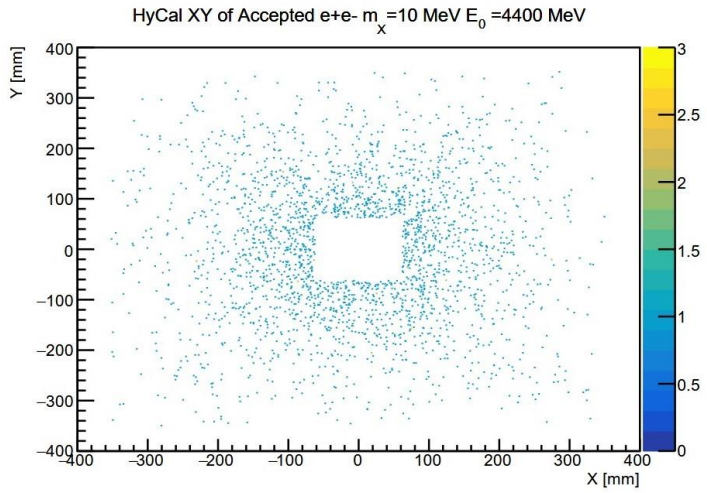
10 MEV – 4.4 GEV BEAM; UNIFORM GEN.

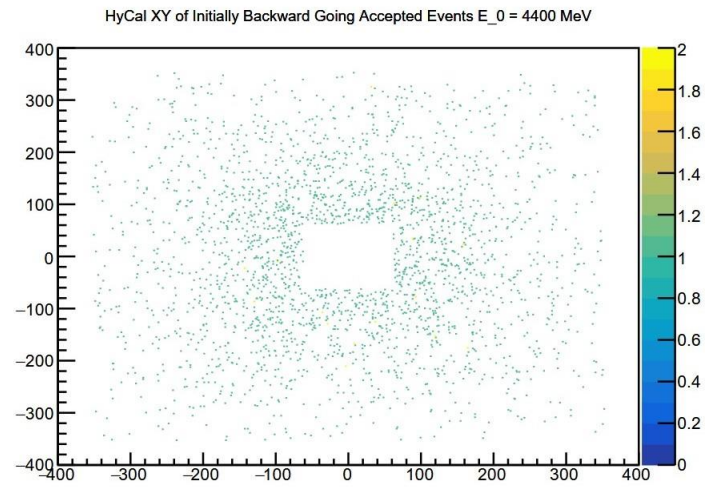
Small Absorber:





Large Absorber:

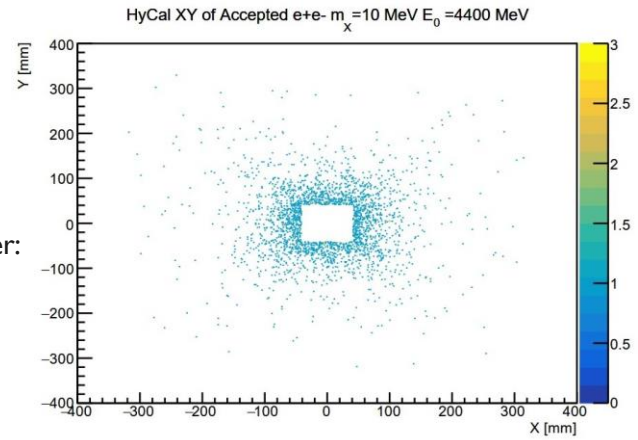


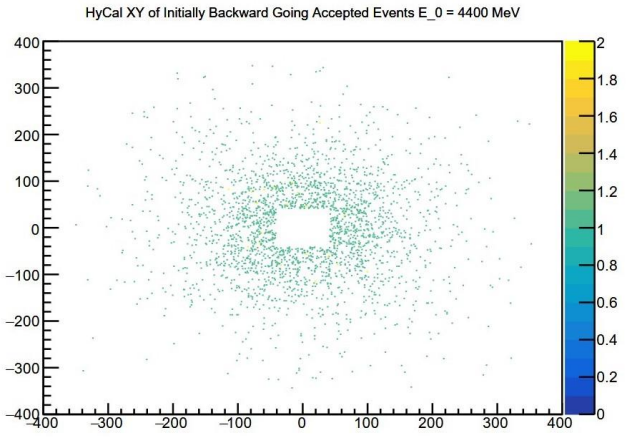


Initially Forward Going

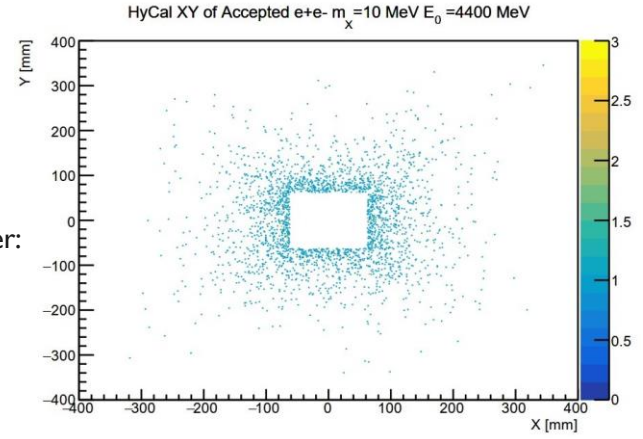
Initially Backward Going

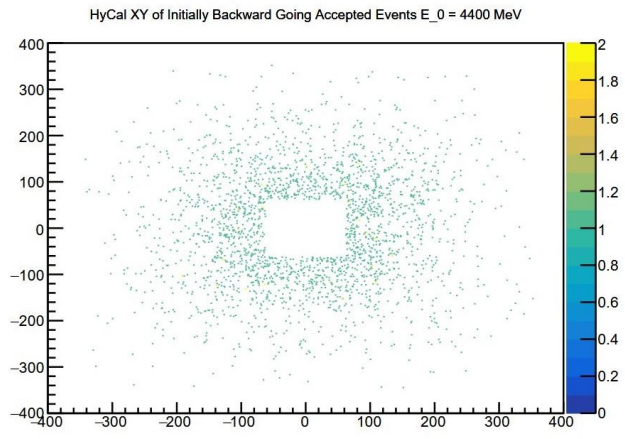
Small Absorber:





Large Absorber:





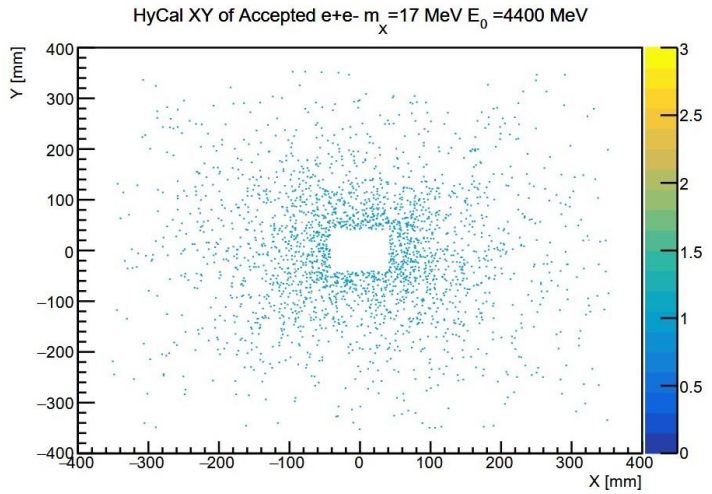
10 MEV – 4.4 GEV BEAM; EXP. GEN.

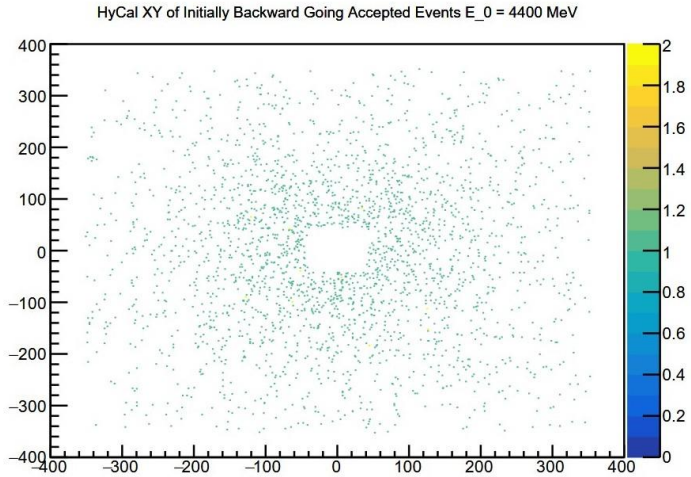
Initially Forward Going

Initially Backward Going

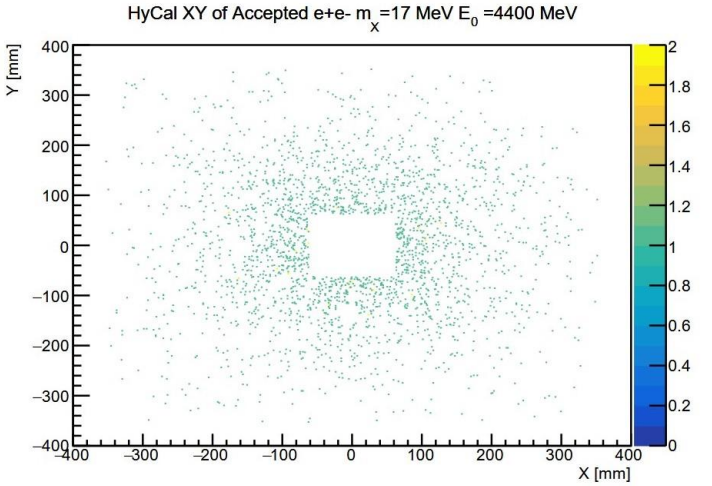
17 MEV – 4.4 GEV BEAM; UNIFORM GEN.

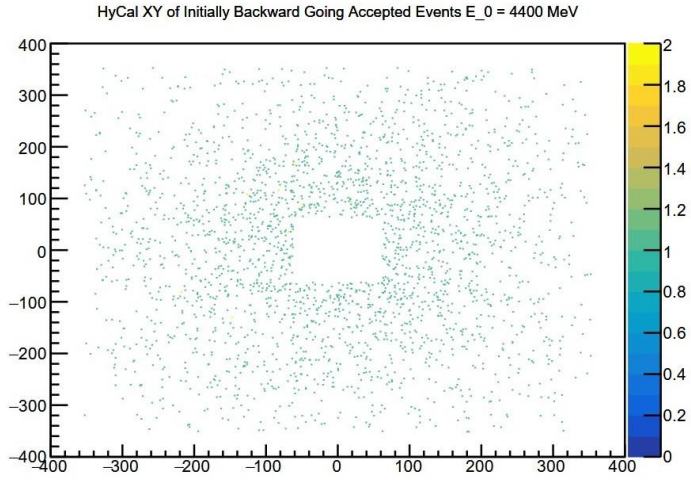
Small Absorber:





Large Absorber:

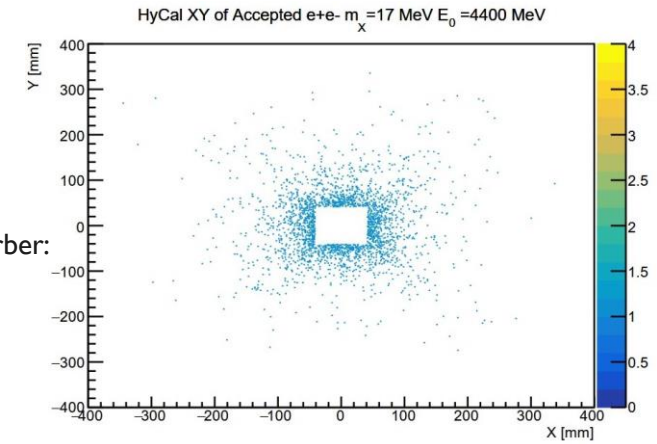


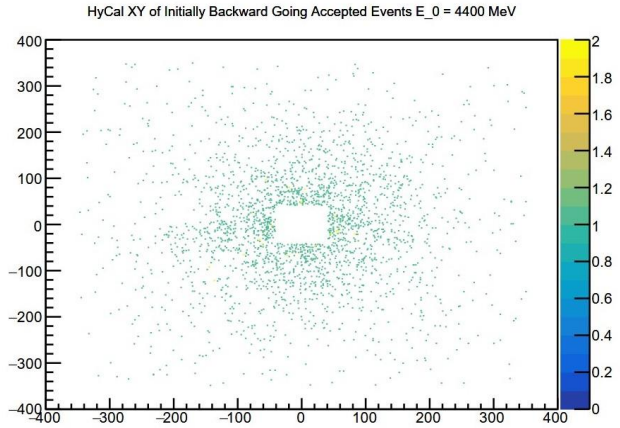


Initially Forward Going

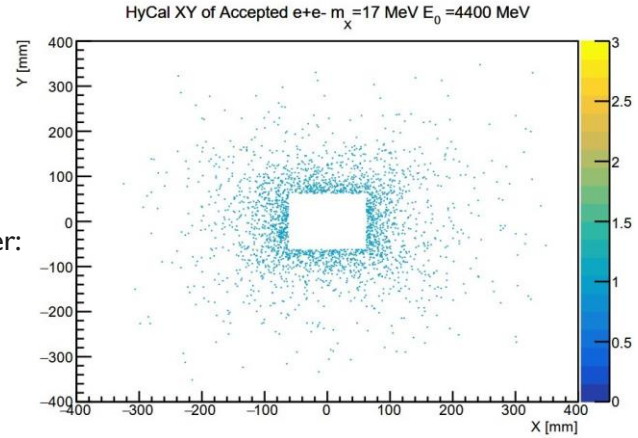
Initially Backward Going

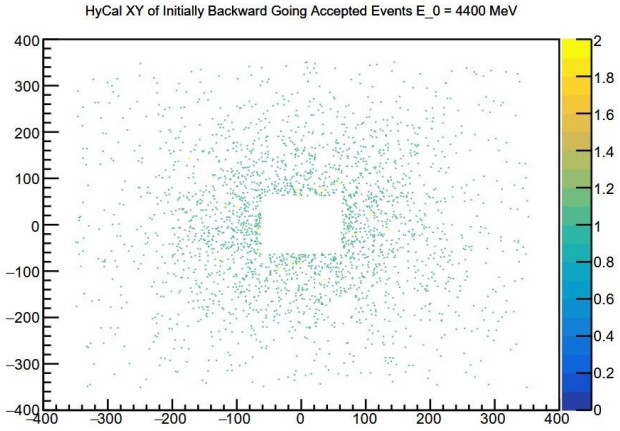
Small Absorber:





Large Absorber:





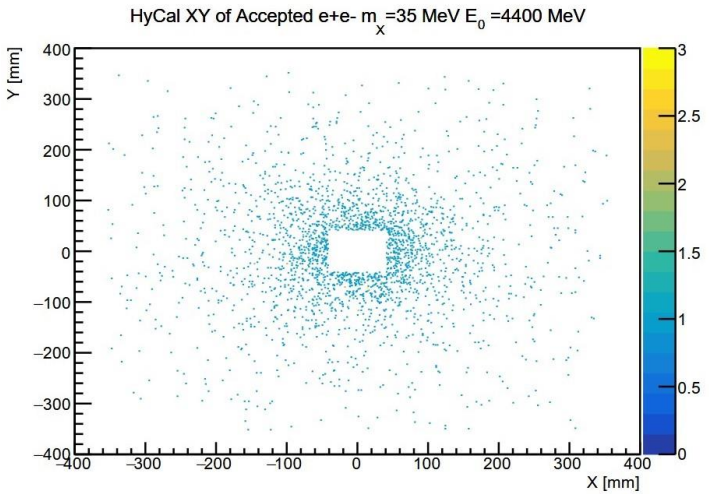
17 MEV – 4.4 GEV BEAM; EXP. GEN.

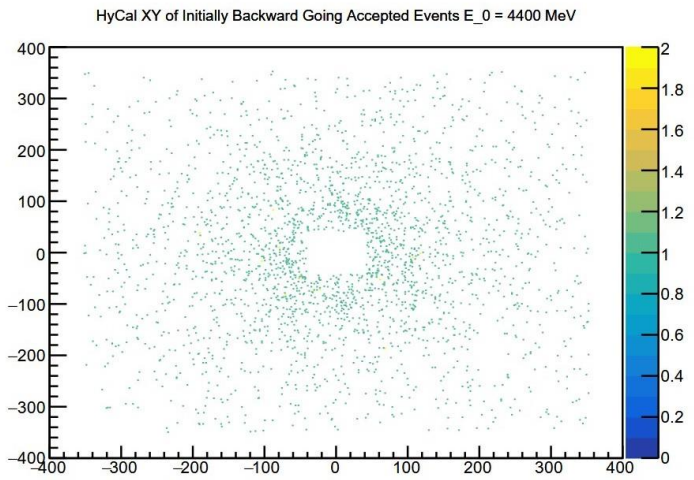
Initially Forward Going

Initially Backward Going

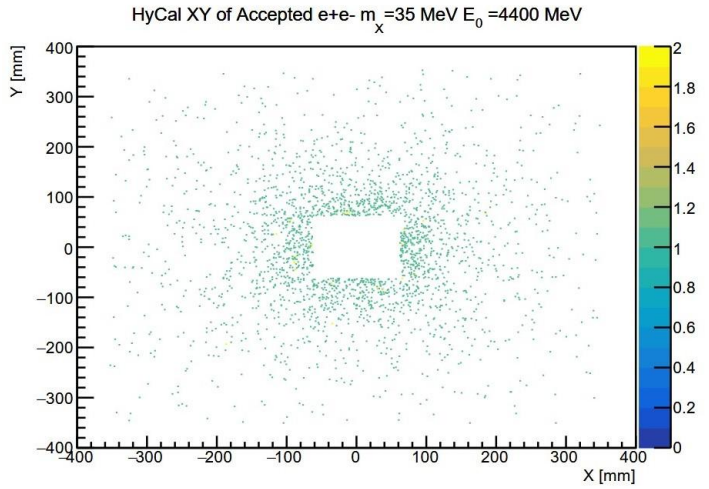
35 MEV – 4.4 GEV BEAM; UNIFORM GEN.

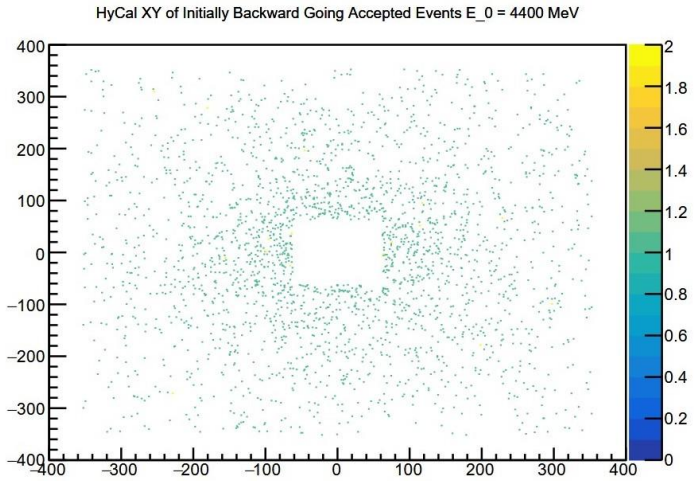
Small Absorber:





Large Absorber:

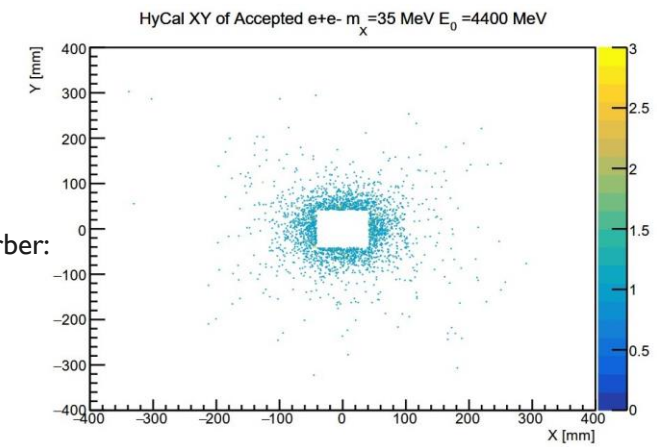


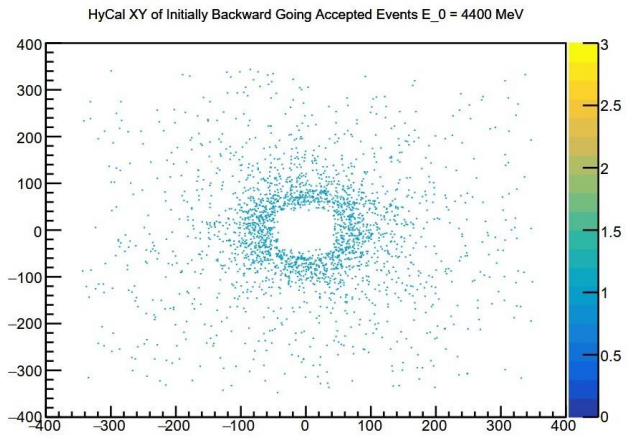


Initially Forward Going

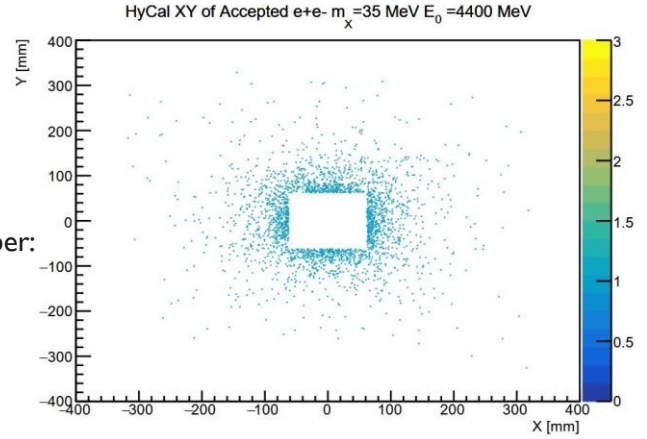
Initially Backward Going

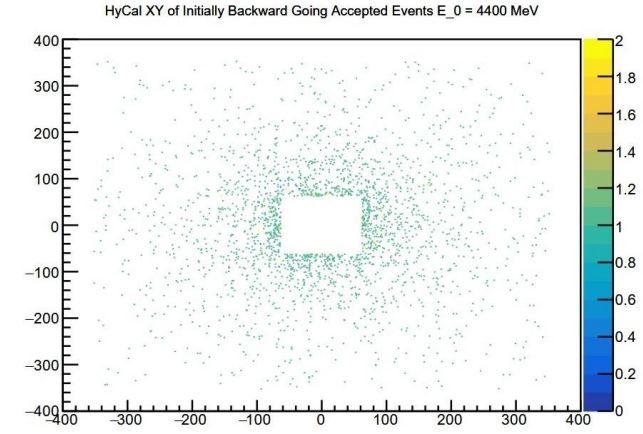
Small Absorber:





Large Absorber:





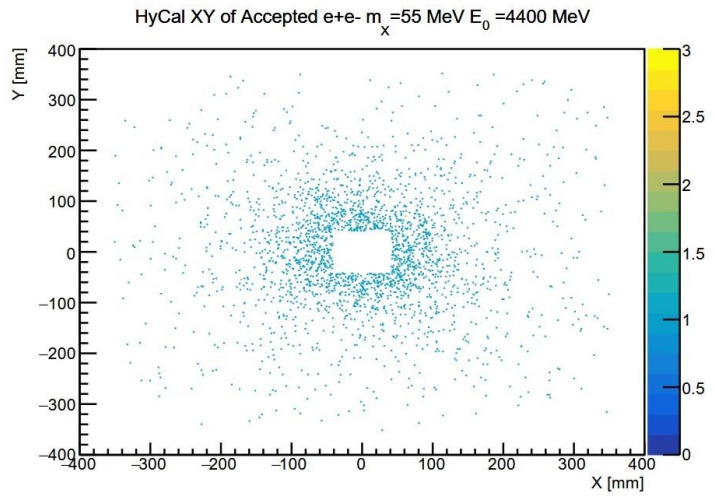
35 MEV – 4.4 GEV BEAM; EXP. GEN.

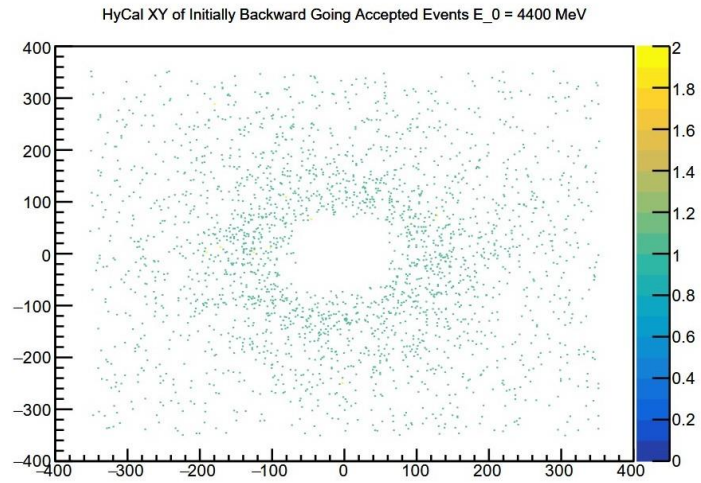
Initially Forward Going

Initially Backward Going

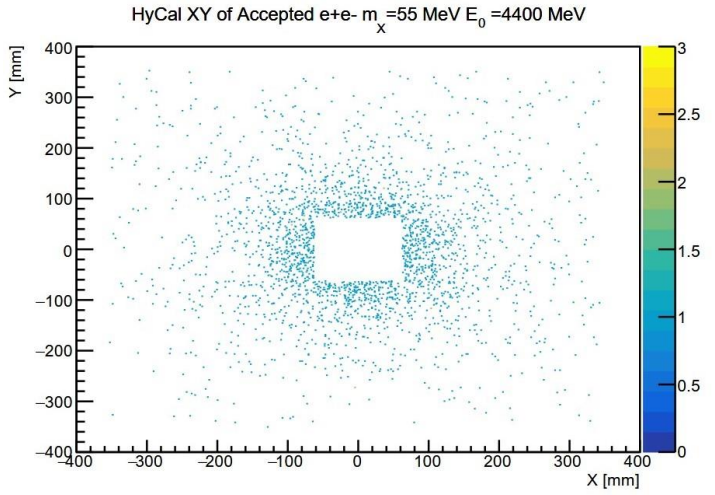
55 MEV – 4.4 GEV BEAM; UNIFORM GEN.

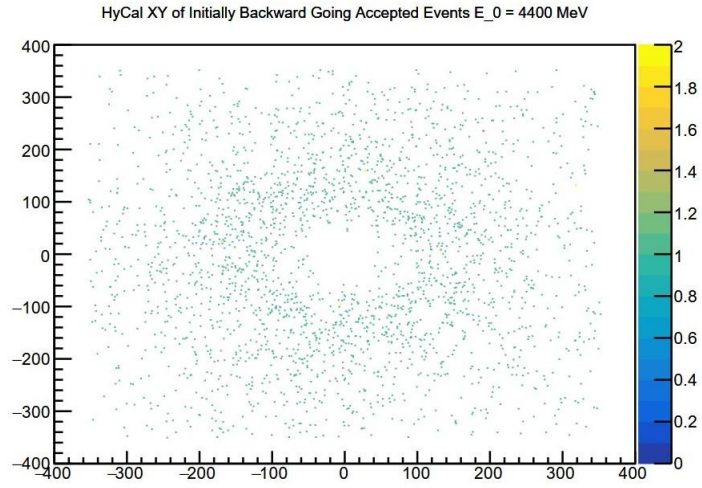
Small Absorber:





Large Absorber:

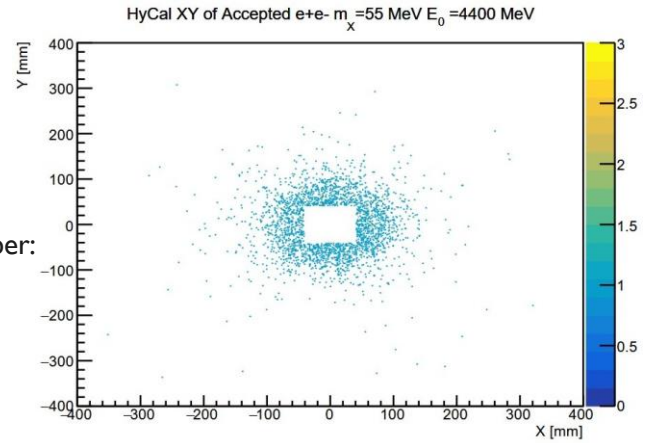


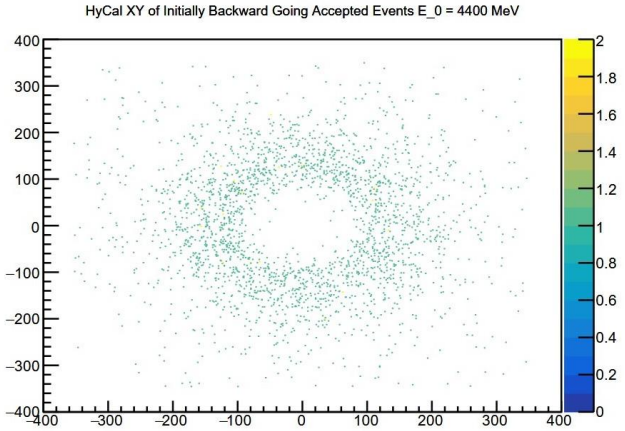


Initially Forward Going

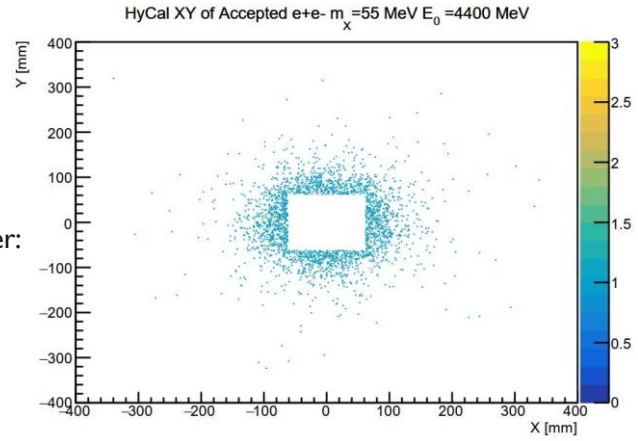
Initially Backward Going

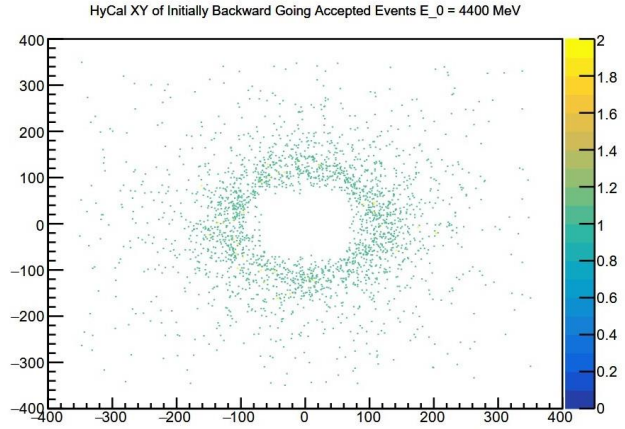
Small Absorber:





Large Absorber:





55 MEV – 4.4 GEV BEAM; EXP. GEN.