# Analyzing Heavy Photon Search Simulations to Determine the Potential for True Muonium Discovery

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## Abstract

The Heavy Photon Search (HPS) is a new experiment at Jefferson Laboratory with a primary aim at searching for heavy photons. However, the experiment also has the potential to discover "true muonium", a bound state of a muon and anti-muon. The true muonium "atom" will be produced by an electron beam incident on a high Z target. The triplet state of true muonium will decay to an electron-positron pair, and reconstructing the tracks will show an invariant mass spike at approximately 211 MeV/c². Simulations of this experiment can be performed to tell us the accuracy and efficiency of our true muonium observations, and whether the experiment will be able to claim discovery.

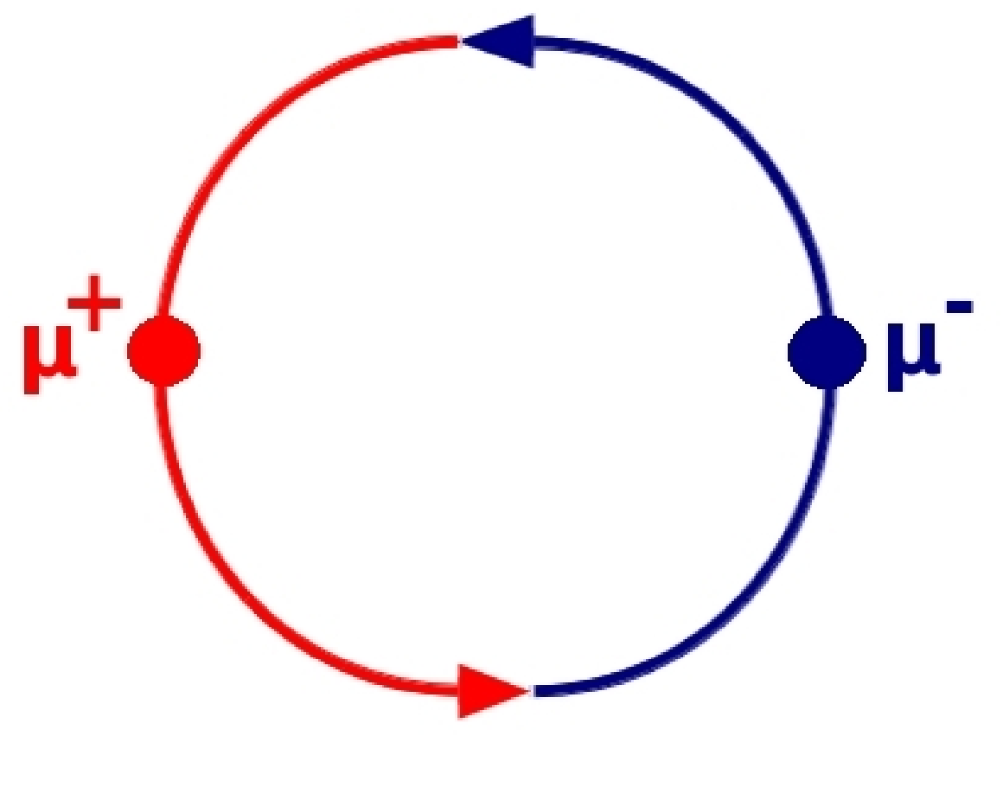
## Why Should You Care?

- True muonium has never been observed, so observing the atom would be a discovery of a new type of matter.
- True muonium is the heaviest, most compact, pure QED system and provides a test of QED theory.
- Properties of the muon itself remain a mystery, including the magnetic moment, and true muonium studies could help solve these issues.

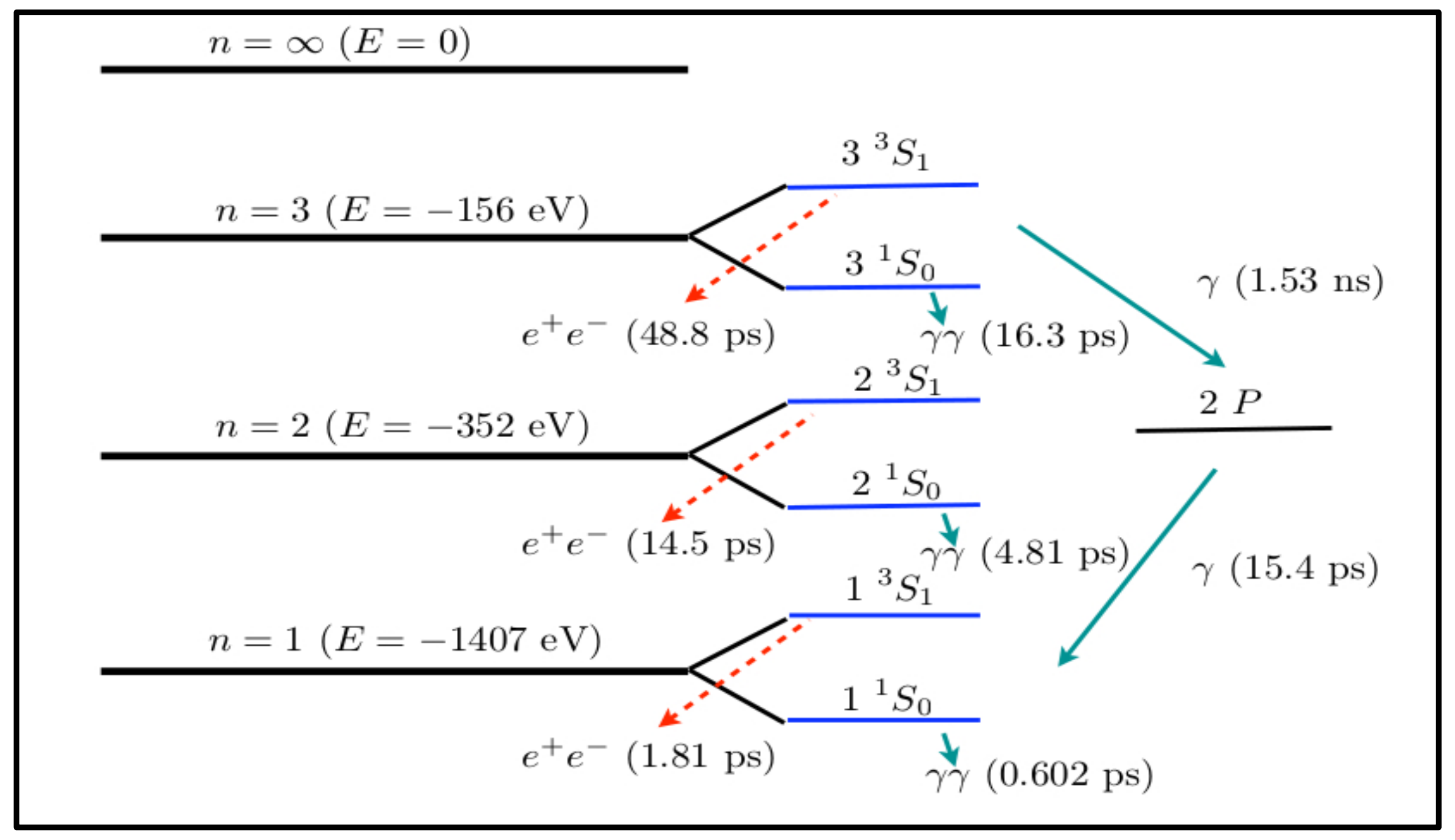
## What Is True Muonium?

True muonium is an exotic hydrogen-like atom composed of a bound state of a muon and an anti-muon. Like all atoms composed of two spin-1/2 particles, true muonium can exist in a singlet or triplet state. While the singlet state annihilates to two photons, the triplet state is of interest due to it's $e^+e^-$ annihilation which is identical to the decay of a heavy photon. It is this fact that allows the HPS experiment to be used to search for the true muonium atom.

*Representation of a true muonium atom composed of a bound state of a muon and an antimuon.*



## True Muonium Energy States



*True muonium energy levels. The HPS experiment expects to observe $1^3S$, $2^3S$, and $2^3P$ states due to their $e^+e^-$ decay. [1]*

## Production Expectations

The amount of true muonium produced depends on both the production and dissociation cross sections. For a beam energy of 6.6 GeV, and looking at the triplet state we find [2]:

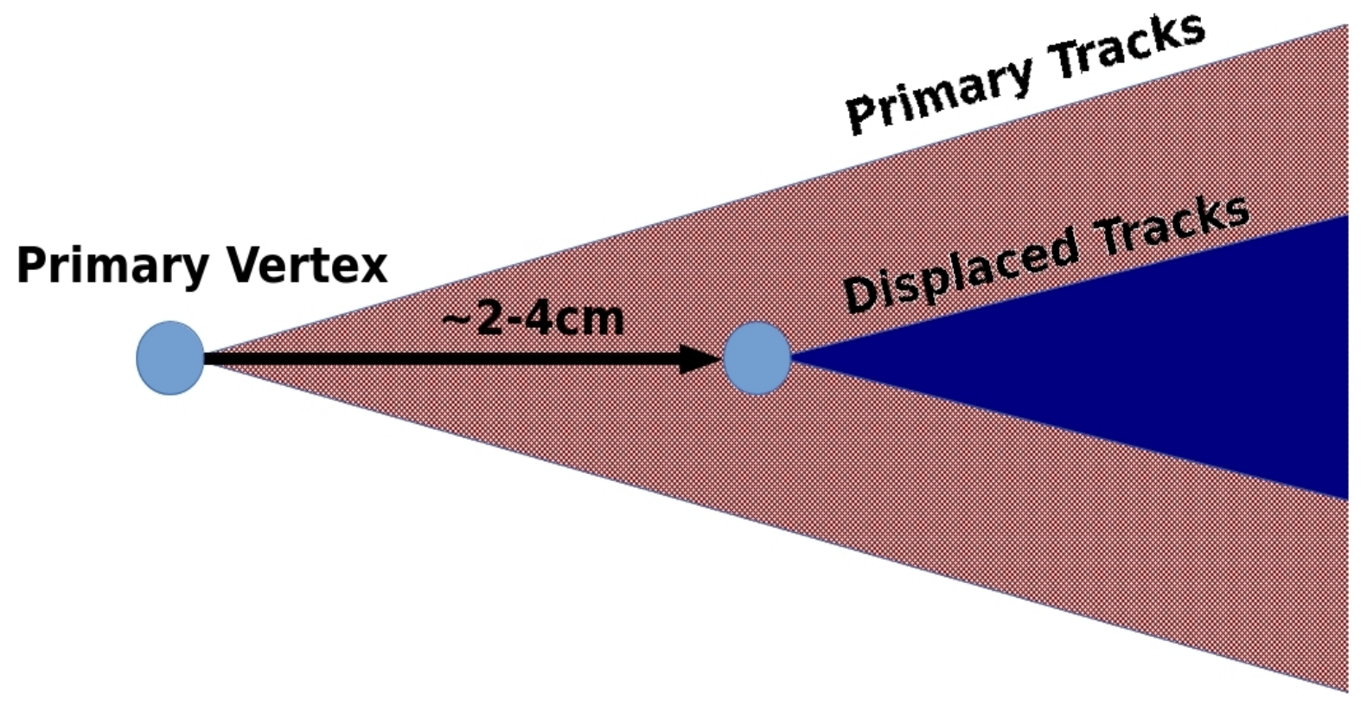
$$\sigma_{pro} \sim 6.2 Z^2 10^{-41} cm^2 \qquad \sigma_{diss} \sim 1.3 Z^2 10^{-23} cm^2$$

The large dissociation cross section implies that true muonium breaks up easily in any target. In fact, only the true muonium produced in a small fraction of the target will escape.

We will identify the true muonium event by taking a vertex cut of 1.5cm to reject QED background events, and then look for a resonance at $2m_\mu$. The number of true muonium events expected are calculated by [3]:

$$N = 200 \times \left(\frac{I}{450\,nA}\right)\left(\frac{t}{1\,month}\right)$$

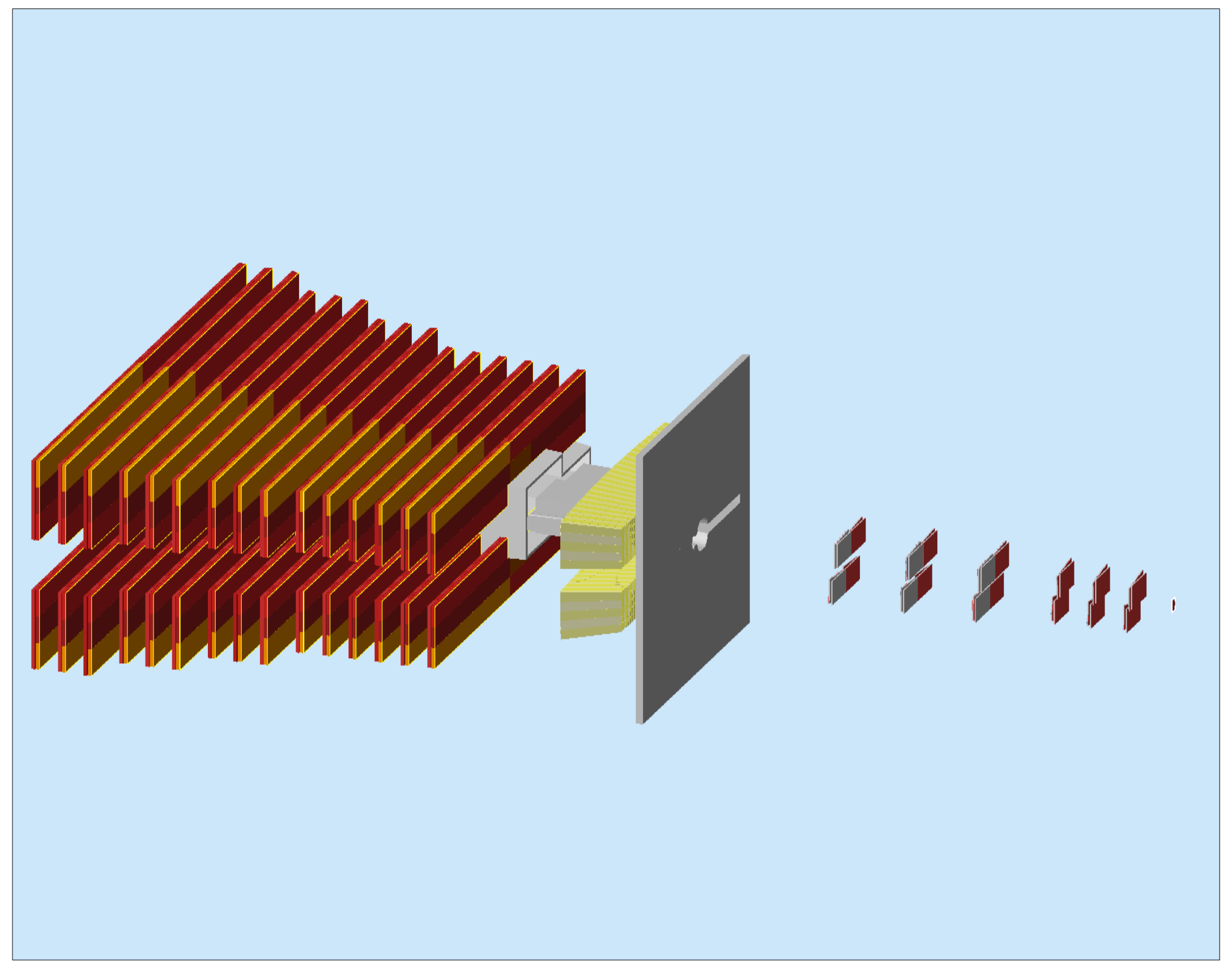
With a beam energy of 6.6 GeV, a beam current of 450 nA, 2 weeks of beam time, and a single foil target, we can expect to observe 10-20 true muonium events.



*A long decay length of the true muonium allows for a vertex cut at 1.5cm to reject background events and observe only the tracks resulting from the true muonium atom.*

## Experimental Setup

The true muonium atom will be produced by a 6.6 GeV electron beam incident on a tungsten target. The triplet state will decay into an electron-positron pair, and the energies of the decay products will be measured by an electromagnetic calorimeter downstream from the target. In between the target and the calorimeter are six silicon vertex trackers.

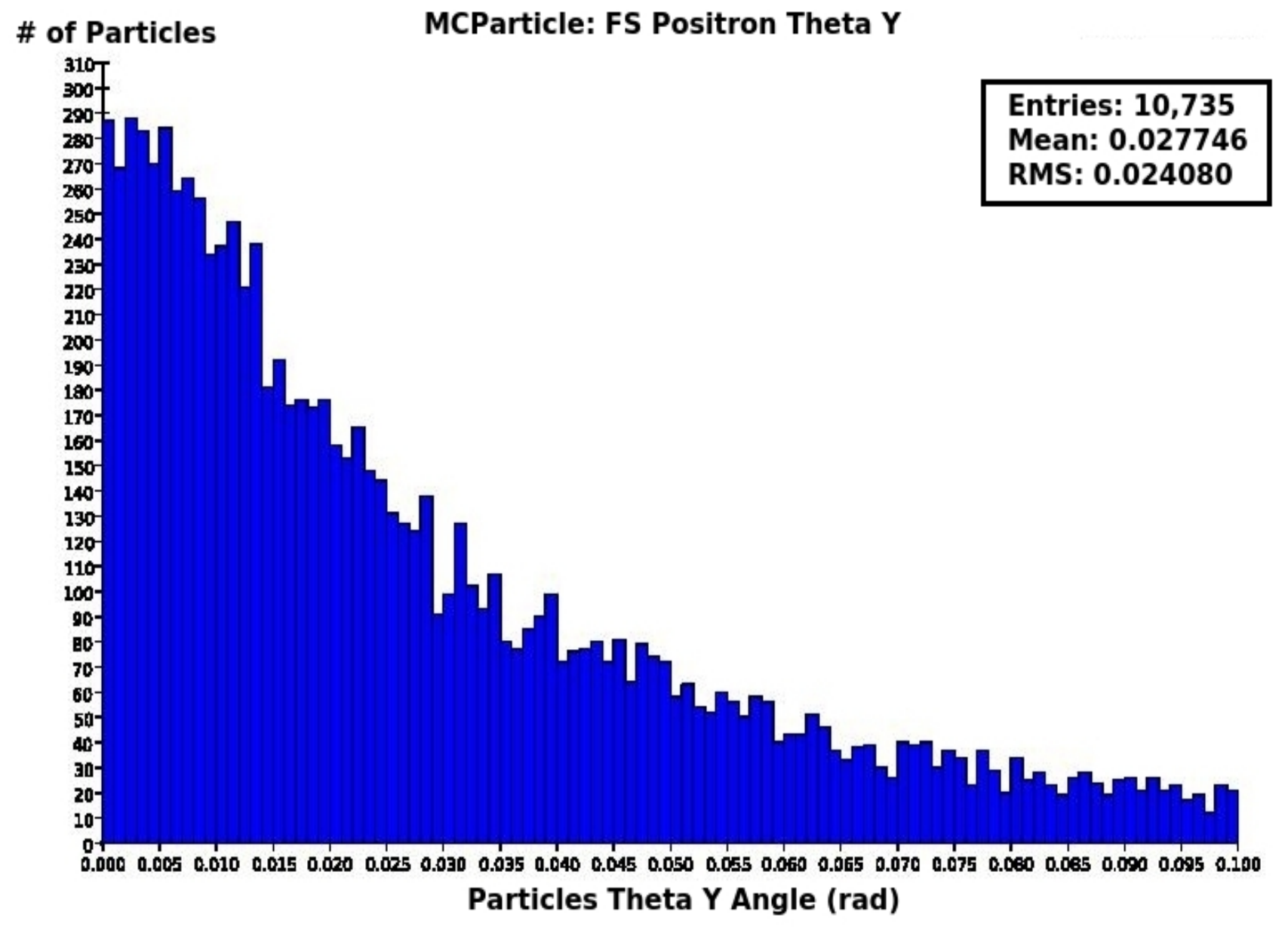


*A geometric rendering of the experimental setup. The beam will enter from the right, hit the target, and continue through the silicon vertex trackers, calorimeter, and muon detector, from right to left in the picture above.*

## Reconstruction Results

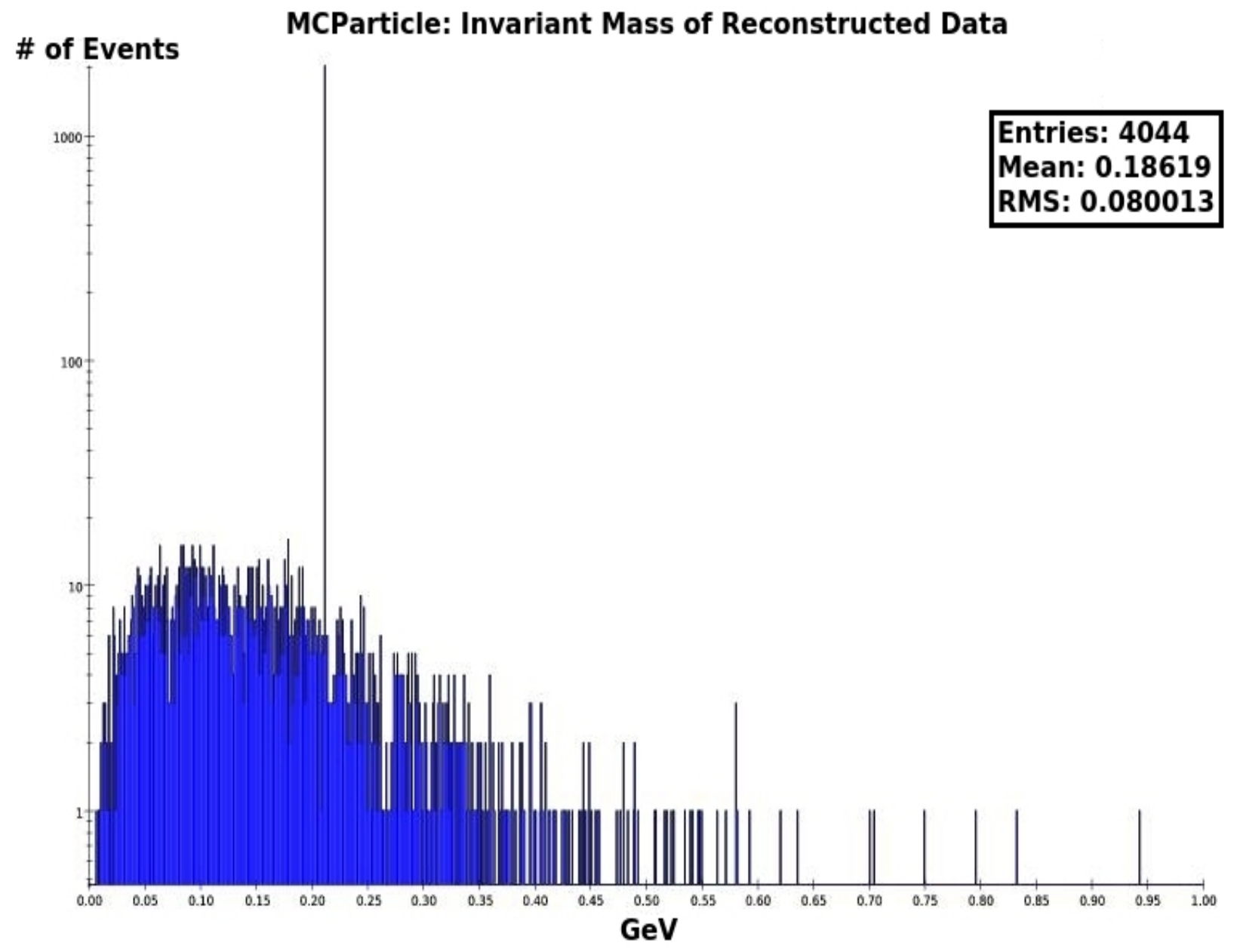
The data we see from the true muonium decay are the energies of the electron-positron pair at the calorimeter, and their two tracks that traveled through the 12 silicon vertex tracker (SVT) layers. Since we know the mass of the "atom" will be approximately 211 MeV/c², and the decay length is expected to be on the order of centimeters, a precise search window can be specified and the events reconstructed. However, due to a vertex cut to reject background events, an energy cut for triggering, and the geometry of the experimental setup, not all events are going to be observed. Comparing the reconstructed events to the total simulated events produced in the target, the reconstruction efficiency is currently found to be 16-20%.

## Data Example



*Y angular distribution of the true muonium events created in the target, prior to vertex cuts taken during reconstruction. Distribution follows a 1-cos²(x) curve as described by scattering theory.*

*Reconstructed true muonium data. The spike shown at .211 GeV is the true muonium signal, which shows 2022 events reconstructed out of the initial 10,735. This is a reconstruction efficiency of 18.84%. Elsewhere is noise caused by the beam scattering electron.*



## Future Work

In a real experiment there are more factors to consider, such as background radiation and equipment noise. These factors need to be taken into account to make sure they do not block the true muonium signal, and continuing simulation work can verify this. Furthermore, the results can possibly be improved with different target types, different energy cuts, or different vertex cuts. A thorough analysis with the simulation software can ensure that the observed true muonium is at a maximum.

## Acknowledgements and References

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[1] Stanley J. Brodsky and Richard F. Lebed. Production of the Smallest QED Atom: True Muonium (mu+ mu-). Phys.Rev.Lett., 102:213401, 2009.

[2] Egil Holvik and Haakon A. Olsen. Creation of Relativistic Fermionium in Collisions of Electrons with Atoms. Phys.Rev., D35:2124, 1987.

[3] Andrzej Banburski and Philip Schuster. The Production and Discovery of True Muonium in Fixed-Target Experiments. Phys.Rev., D86:093007, 2012.