Heavy Photon Search and the Hunt for True Muonium

SLAC Lab

Harry Myers - July 2025

Harry Myers

harrymyers257@gmail.com
650.223.9647
LinkedIn

Location: Palo Alto, CA

Summary

Hi everyone, my name is Harry Myers. I moved to the U.S. from England in 2011 and am currently studying at UCLA. Outside of school, I enjoy skateboarding, scuba diving, and tennis, and I work part-time at a tennis pro shop three days a week. As part of my transfer journey to UCLA, I had the opportunity to take a gap semester, which I used to travel across Asia—visiting six countries over the span of six months.

Short Term Goals:

- Get more comfortable with web dev specifically Javascript
- Program TM visualizations using C++, python, and Root

End of Summer:

- Finish learning React
- A1 German. Ich habe drei Monate lang Deutsch gelernt

End of Year:

- Complete an AI focused resume project with a beautiful React front end.
- Deploy personal website that showcases projects I have worked on

Education

Upperclassman at UCLA Samueli school of Engineering studying Computer Science

What is Heavy Photon Search (HPS)?

An experiment designed to search for a hypothetical particle called a heavy photon

What is a heavy photon?

- Similar to a regular photon but believed to have a small amount of mass
- Thought to be a sort of dark counterpart to light and might be able to interact with dark matter
- Potentially lead to the discovery of a new fundamental force and provide insights into the nature of dark matter.
- Heavy photons are predicted to interact weakly with observable matter, making them difficult to detect directly. This weak interaction implies that they might have a relatively long lifetime and travel some distance before decaying

How does the Search Work?

- The HPS experiment uses a beam of electrons that are fired at a target containing a heavy nuclei such as tungsten
- If heavy photons exist, they could be produced in these collisions through a process called bremsstrahlung
- These heavy photons would quickly decay into an e^+e^- pair
- HPS detector is used to track the paths and energies of these electron-positron pairs, allowing scientists to reconstruct their origin and properties.

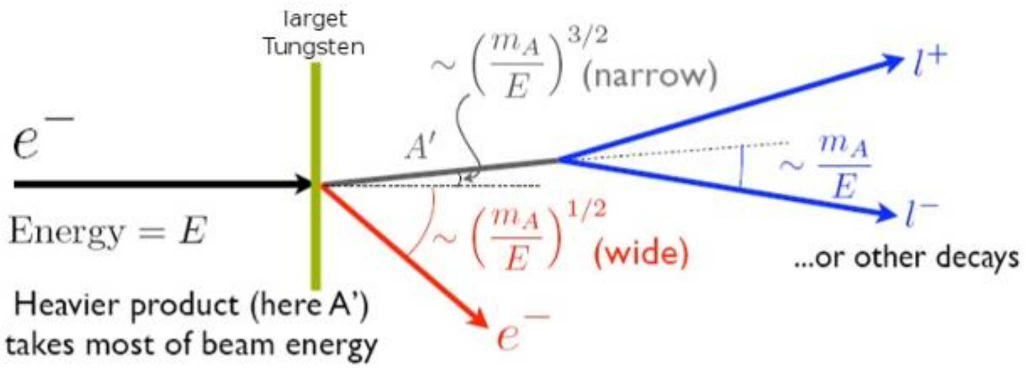


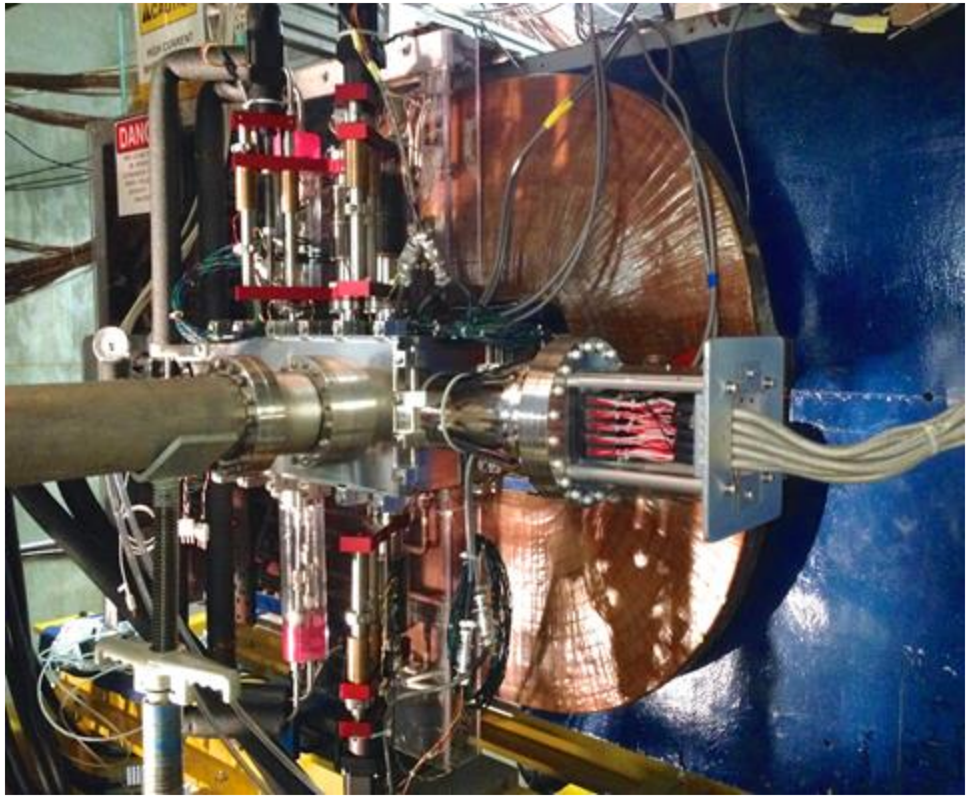
Figure 2-4: Characteristic angles for the A' and its leptonic decay products

How does HPS detect displaced vertices?

- HPS detector uses a Silicon Vertex Tracker (SVT), which consists of multiple layers of silicon microstrip sensors, to track the paths of e^+e^-

- Designed to determine their momentum and trajectory and work back along their paths to where the pair originates, known as the decay vertex.

- If the reconstructed decay vertex is found to be significantly separated from where the heavy photon would have been produced, it suggests the presence of a long-lived particle like a heavy photon.



What is True Muonium (μ+μ-)?

- Theoretically predicted exotic atom composed of a muon (μ^-) and an antimuon (μ^+)
  - Muon is like an electron but more compact and ~207× heavier

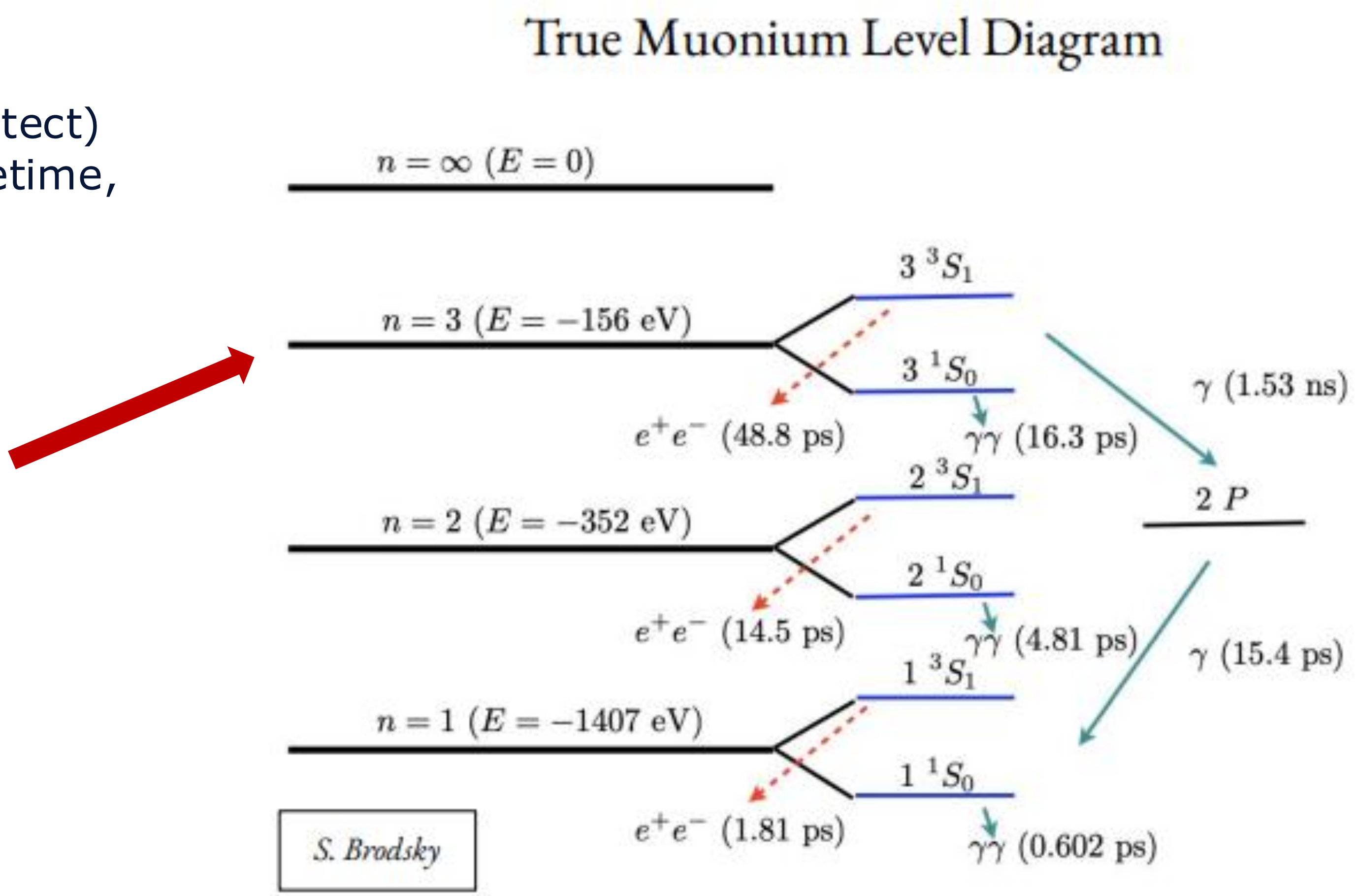
- Muonium is analogous to positronium (e^+e^-) — much more unstable
- Short-lived (~picoseconds)

- Purely QED system — no strong interaction
- Smallest QED atom
  - 512 fm Bohr radius smaller than that of hydrogen, ideal for precision tests of QED

- Can be used to verify robustness of existing HPS software

True Muonium Decay Modes

- $3^3S_1 \rightarrow e^+e^-$ (observable in HPS)
- $3^1S_0 \rightarrow \gamma\gamma$ (shorter-lived, harder to detect)
- The 3^3S_1 state decays with a 50 ps lifetime, moves 1.5 cm before decaying to e^+e^-



How might TM be detected in HPS?

- TM can be produced in the same way as heavy photons
- The triplet state of TM is decays into an e^+e^- pair identical to that of a heavy photon
- The HPS detector is specifically designed to track and measure the properties of e^+e^- pairs
- TM travels a short distance before decaying at an angle relative to the beam direction
    - We can use this information to work back to the origin of the e^+e^- pairs and check if they were once TM, much like in HPS.

Discovering True Muonium would be a significant breakthrough because it would be the first observation of this lepton-based bound state, providing a crucial test of our theory of Quantum Electrodynamics and potentially shedding light on new physics beyond the Standard Model

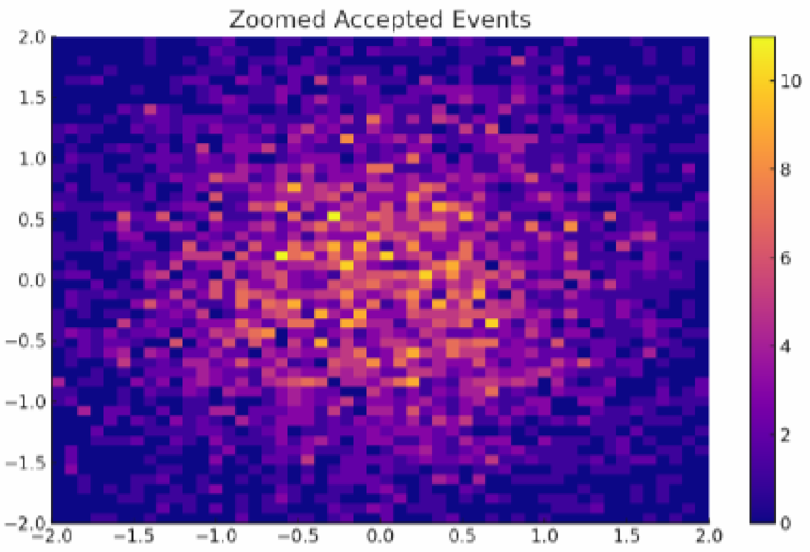
Moving Forward

Our goal is to collect data on TM that is produced at two different angles

The TM will decay into e^+e^- and we want to determine how often those e^+e^- pairs are detected

1. Calculate the **detector acceptance rate:** the fraction of how many of these pairs make it through the detector

2. Determine the acceptance rate for each of the angles we test



3 Photon Produced True Muonium Generator Studies

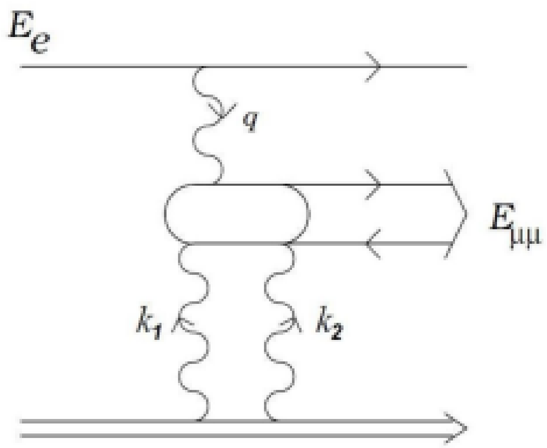
What is 3 Photon Produced TM?

When electron beam goes through the tungsten target, a rare phenomenon can happen where 3 photons to be radiated during the collision.

Rarely, these 3 photons can stick together to form orthodimuonium (triplet state of TM).

single-photon process is possible but much more rare and has increased background radiation and particle interactions making the TM more difficult to detect.

Three photon mode



Oppressed by Bethe-Heitler Background

Scattering Angle: $\theta_{3\gamma} \sim \frac{\Lambda}{x E_0}$ $\Lambda = \frac{405}{A^{1/3}}$ MeV

True Muonium Simulation Calculations

1. Initial parameters

- # of events: 1,000,000
- beam energy: 3740 MeV
- TM Mass: 211 MeV
- Lambda (angular spread) parameter: 20 MeV,
- Minimum energy fraction: $x_{min} = 211/3740 \approx 0.0564$
- True muonium lifetime: 1×10^{-12} seconds, C: 3×10^{8} m/s

2. Energy and Momentum Calculations

- Energy fraction distribution: $x = x_{min} \times \exp(U \times \ln(1/x_{min}))$ where U is uniform random [0,1]
- True muonium energy: $E_{TM} = x \times E_{beam}$ (range: 211-3740 MeV)
- True muonium momentum: $p_{TM} = \sqrt{E_{TM}^2 - M_{TM}^2}$
- Decay product momentum in rest frame: $p_{star} = M_{TM}/2 = 105.5$ MeV/c

3. Angular Calculations

- Angular spread parameter: $\theta_0 = \Lambda/(x \times E_{beam})$
- Production angles: $\theta_{prod} = |\mathrm{normal}(0, \theta_0)|$, $\varphi_{prod} = \mathrm{uniform}(0, 2\pi)$
- 3D momentum components: $p_x = p_{TM} \times \sin(\theta) \times \cos(\varphi)$, $p_y = p_{TM} \times \sin(\theta) \times \sin(\varphi)$, $p_z = p_{TM} \times \cos(\theta)$

4. Decay Process Calculations

- Decay angles in rest frame: $\theta_{decay} = \arccos(\mathrm{uniform}(-1,1))$, $\varphi_{decay} = \mathrm{uniform}(0, 2\pi)$
- Decay product momenta: $p_{decay} = p_{star} \times [\sin(\theta)\cos(\varphi), \sin(\theta)\sin(\varphi), \cos(\theta)]$
- Opposite momentum: $p_{decay\_opposite} = -p_{decay}$

Simulation Calculations cont.

1. Relativistic Boost Calculations

- Lorentz factor: $\gamma = E\_TM/M\_TM$
- Velocity parameter: $\beta = p\_TM/E\_TM$
- Boost direction: $n\_TM = TM\_mom/p\_TM$
- Boost transformation:
  i. Parallel component: $p\_parallel = (p \cdot n)$
  ii. Perpendicular component: $p\_perp = p - p\_parallel$
  iii. Boosted energy: $E' = \gamma(E + \beta p \cdot n)$
  iv. Boosted parallel momentum: p'*parallel = γ(p_parallel + βEn)*
  v. Final boosted momentum: p' = p_perp + p'*parallel*

2. Laboratory Frame Calculations

- Vertical angles: $\theta\_y = \arctan2(|p\_y|, \sqrt{p\_x^2 + p\_z^2}) \times 1000$ (in mrad)
- Opening angle: $\cos(\theta\_opening) = (p\_e^+ \cdot p\_e^-)/(|p\_e^+||p\_e^-|)$, $\theta\_opening = \arccos(\cos(\theta\_opening)) \times 1000$

3. Decay Length Calculations

- Mean decay length: $L\_mean = \beta\gamma c\tau_0$
- Decay distances: exponential distribution with mean L_mean
- Decay vertices: decay_distances × n_TM
- Decay length in mm: |decay_vertices| × 1000

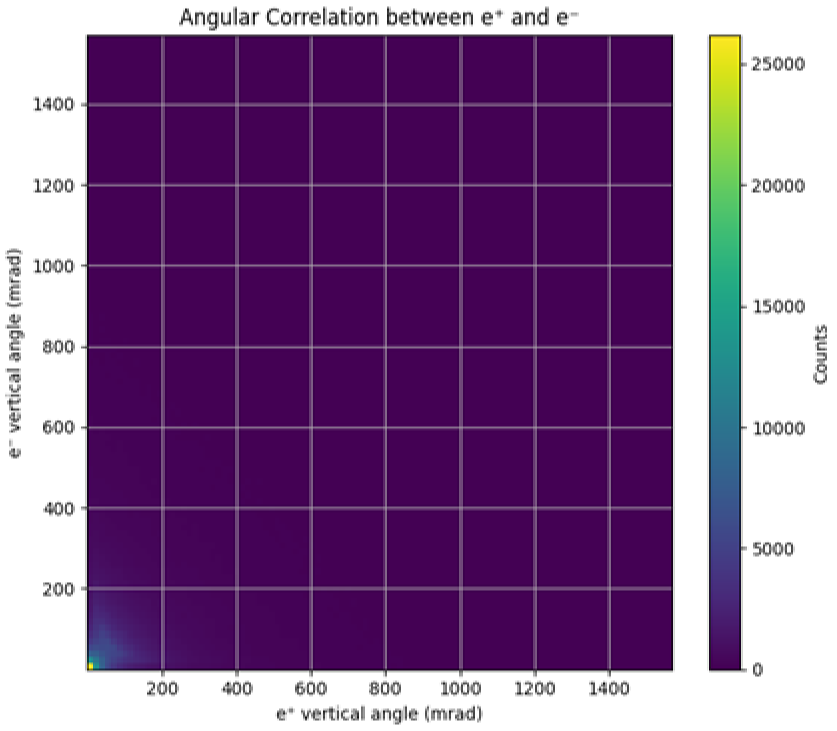
4. Detector Hit Calculations

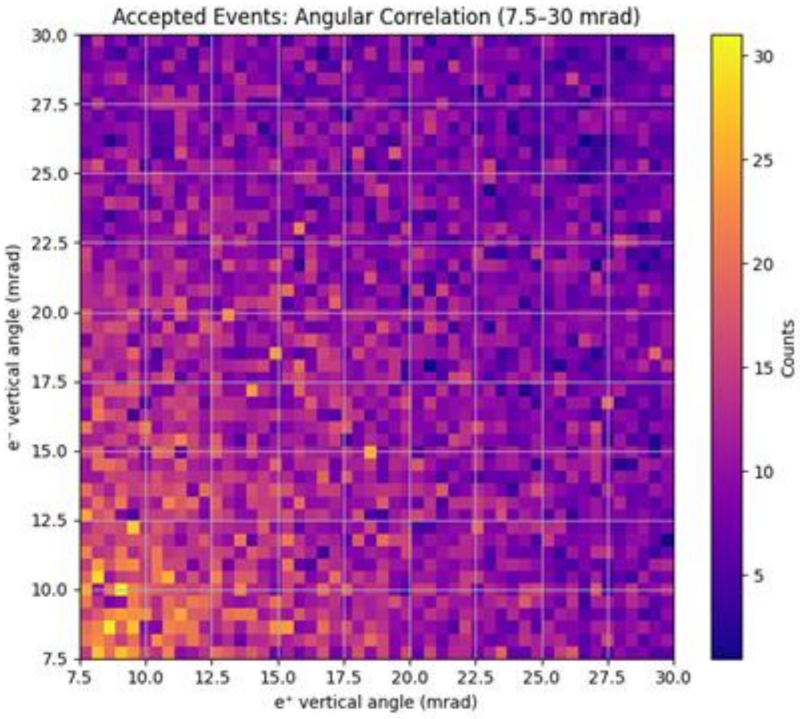
- Detector position: z_detector = 0.5 m
- Projection to detector: hit_position = decay_vertex + direction × t where t = (z_detector - z_vertex)/direction_z

Simulation results explained

Angular Correlation Plots

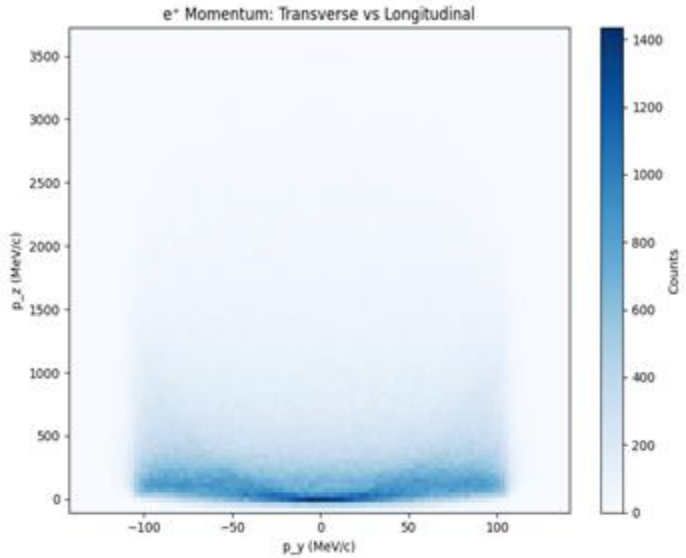
- Shows how the angles of electrons and positrons are related. The symmetrical distribution confirms that the electron and positron are emitted in opposite directions.
- Both the e+ and e− are produced at small vertical angles in the 7.5-30 mrad range.
- TM is produced with high forward momentum (boosted), so its decay products are tightly aligned with the beam direction.

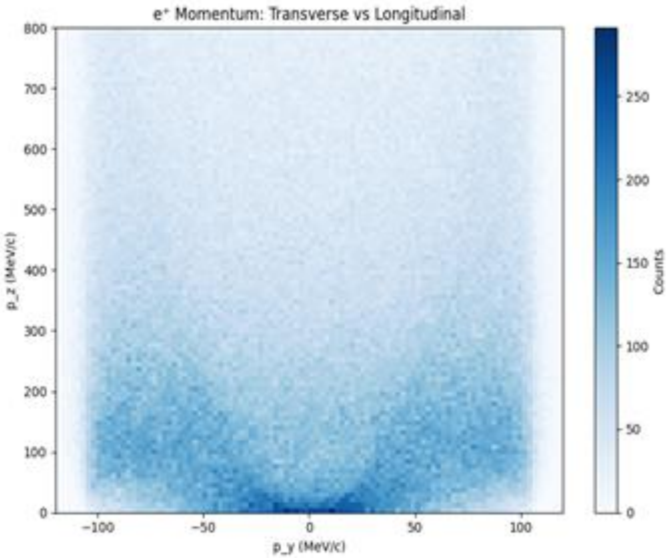




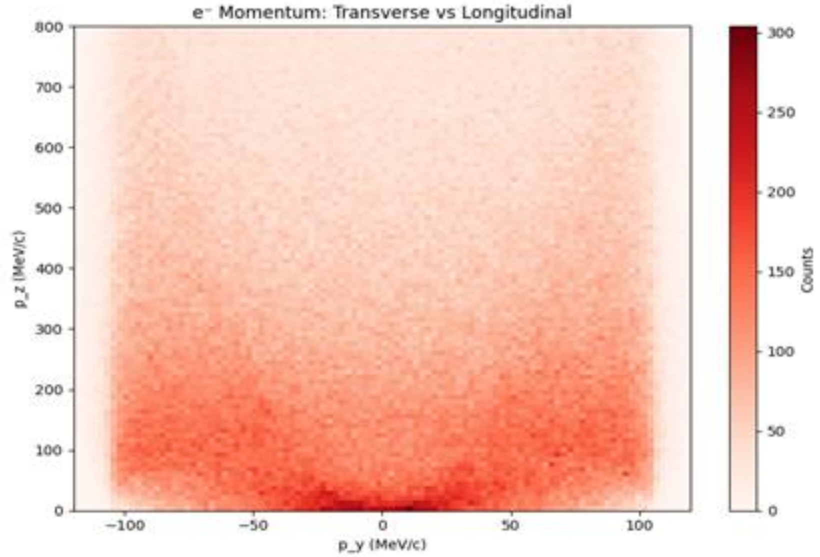
Momentum Plots

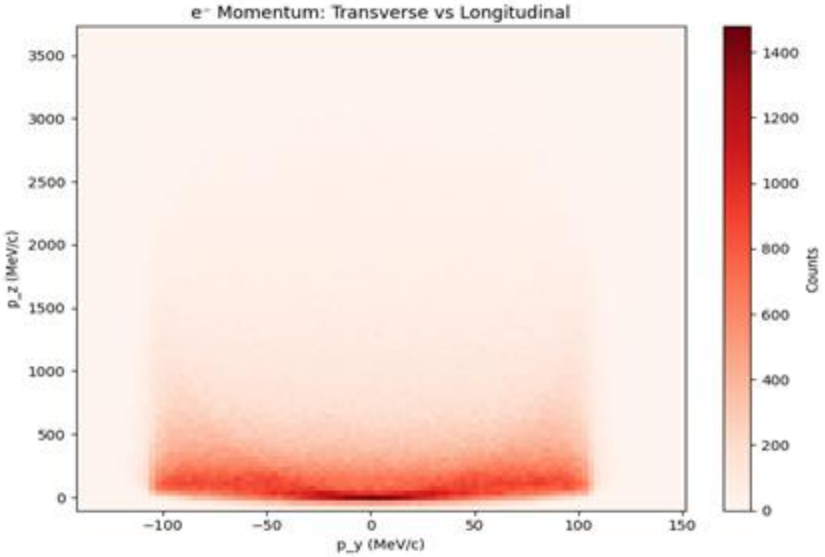
- Positrons are emitted with high longitudinal momentum and low transverse momentum
- no preferred transverse direction, symmetric about py=0
- A “V”-shaped pattern emerges with the highest event density at low pz and small py, indicating that most decays produce low-momentum positrons
- As pz increases, the distribution widens symmetrically in py, showing that higher-energy positrons can deviate a slightly greater amount
- muonium decays produce forward-emitted positrons with low transverse momentum, making them well-suited for HPS detection



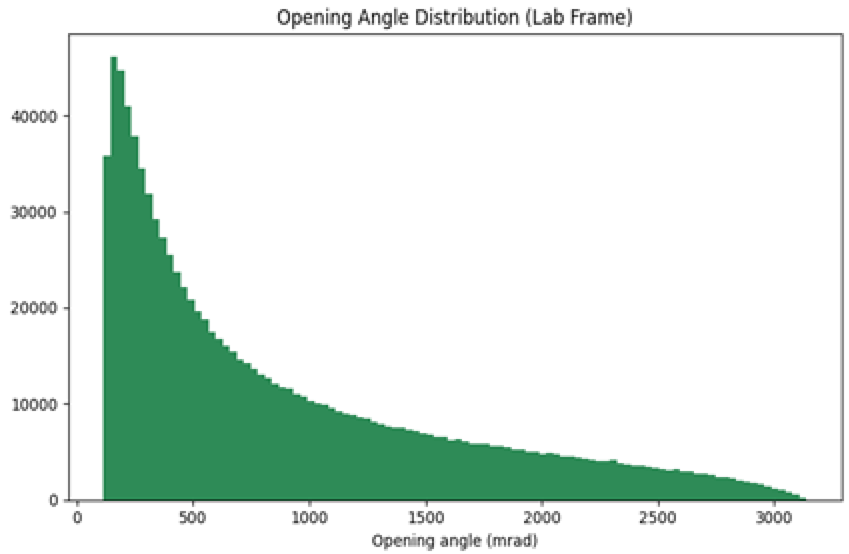


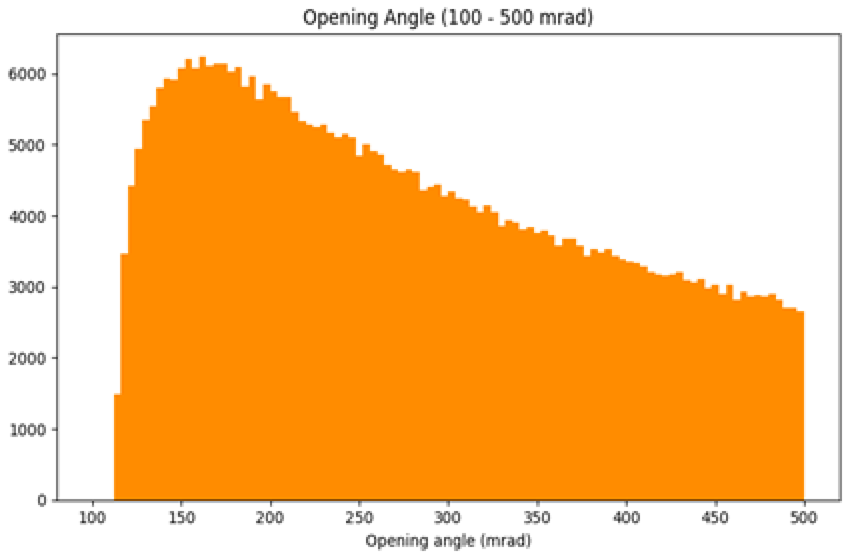
Momentum Plots



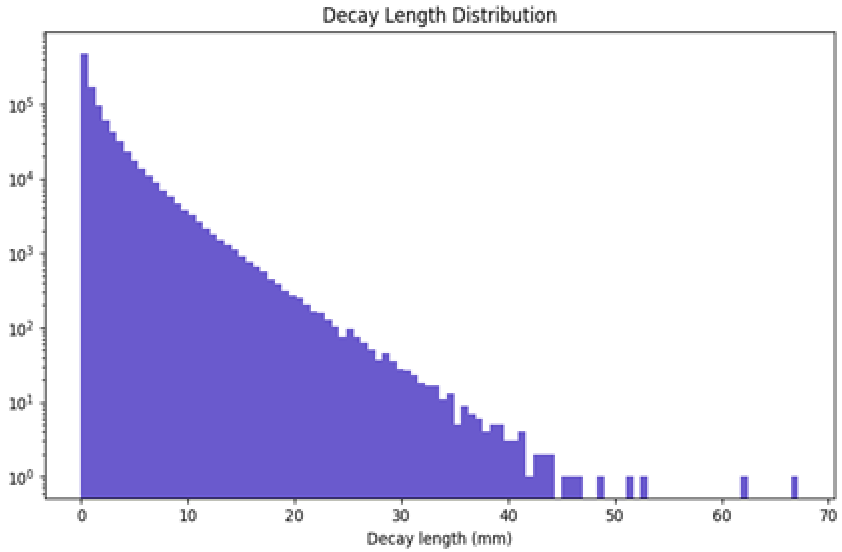


Opening Angle Plots



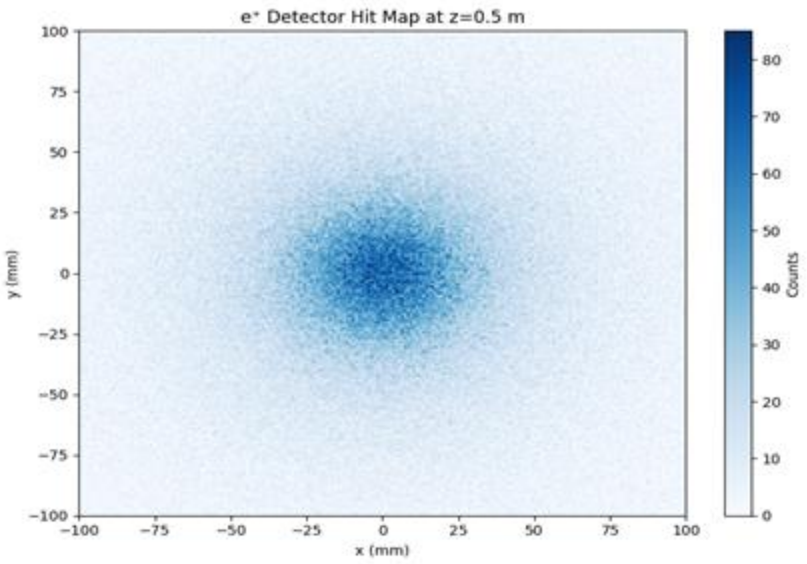


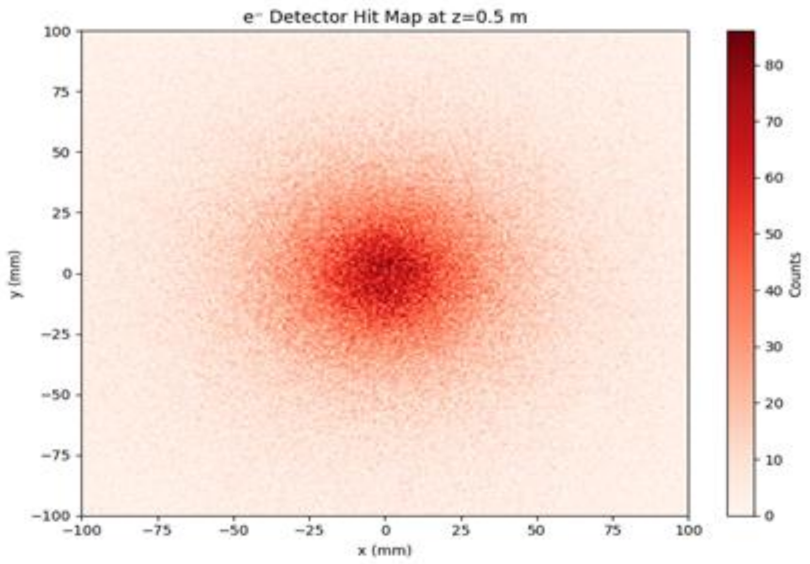
Opening Angle Plots



Detector hit maps

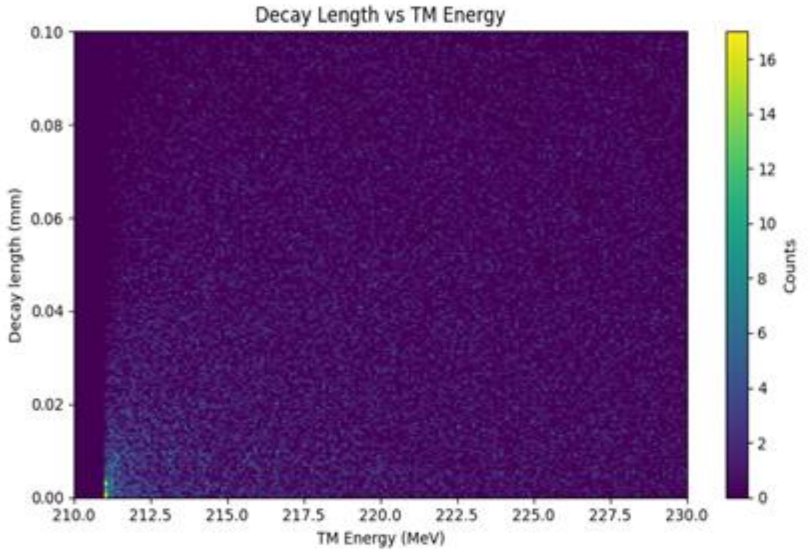
Shows where particles hit our detector

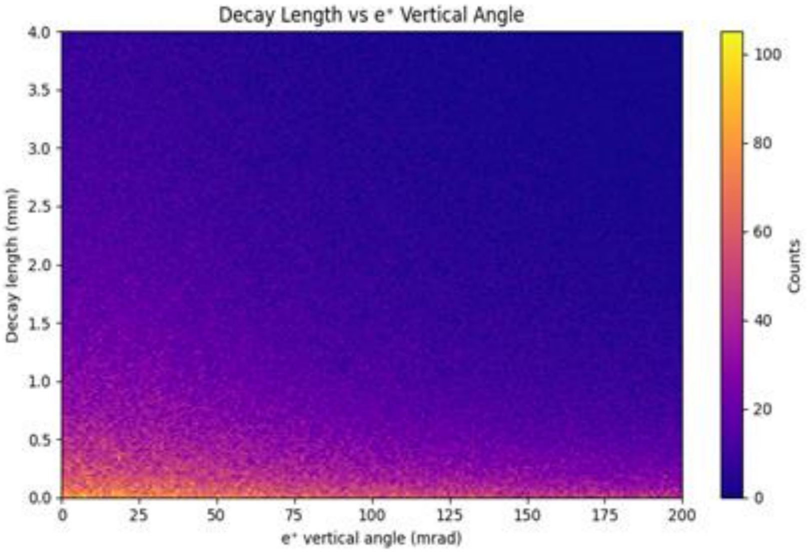




Correlation plots

Shows how different measurements are related to each other





Summary

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