Heavy Photon Search and the Hunt for True Muonium

SLAC Lab

Harry Myers - July 2025
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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 similar to 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.

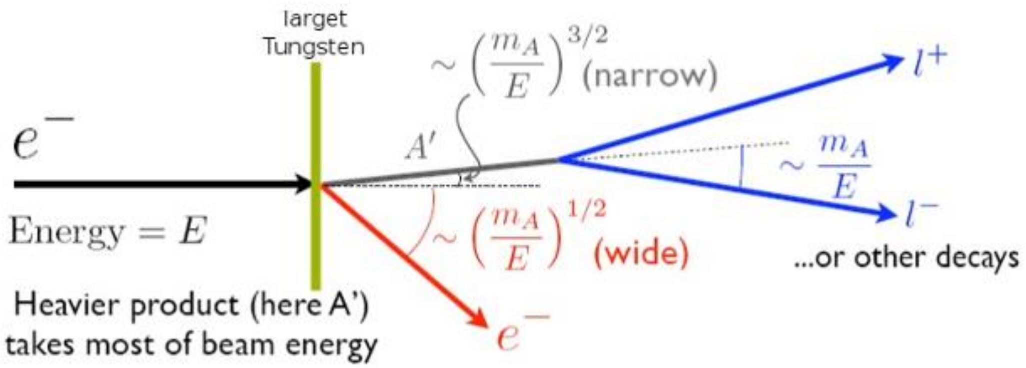
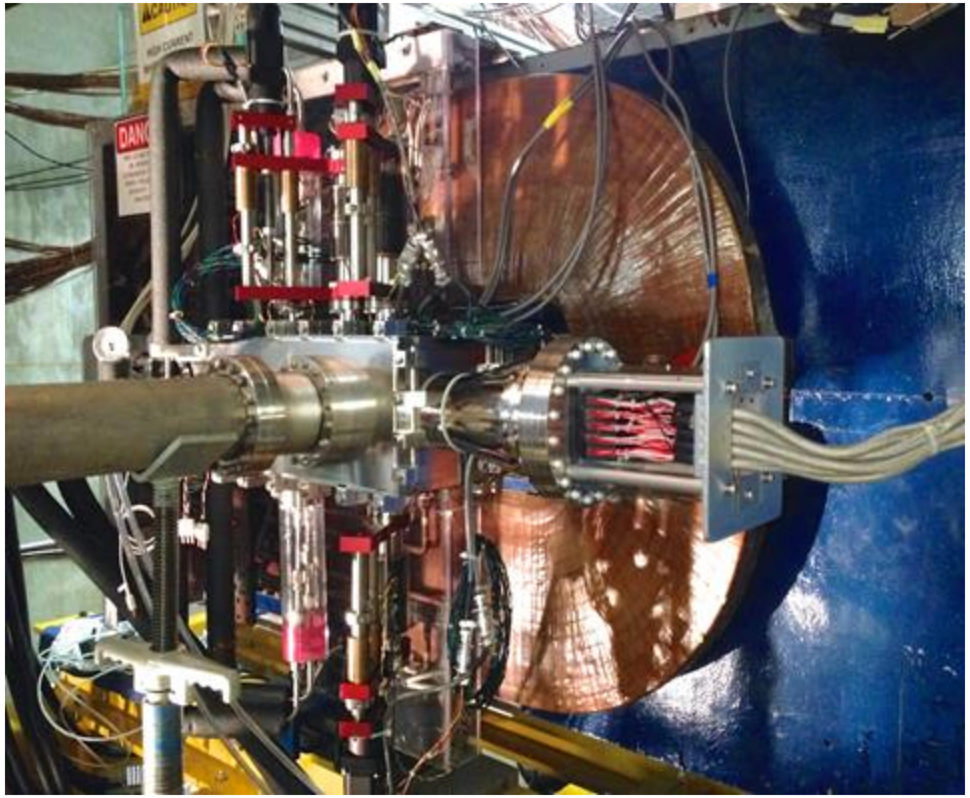


Figure 2-4: Characteristic angles for the A' and its leptonic decay products

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

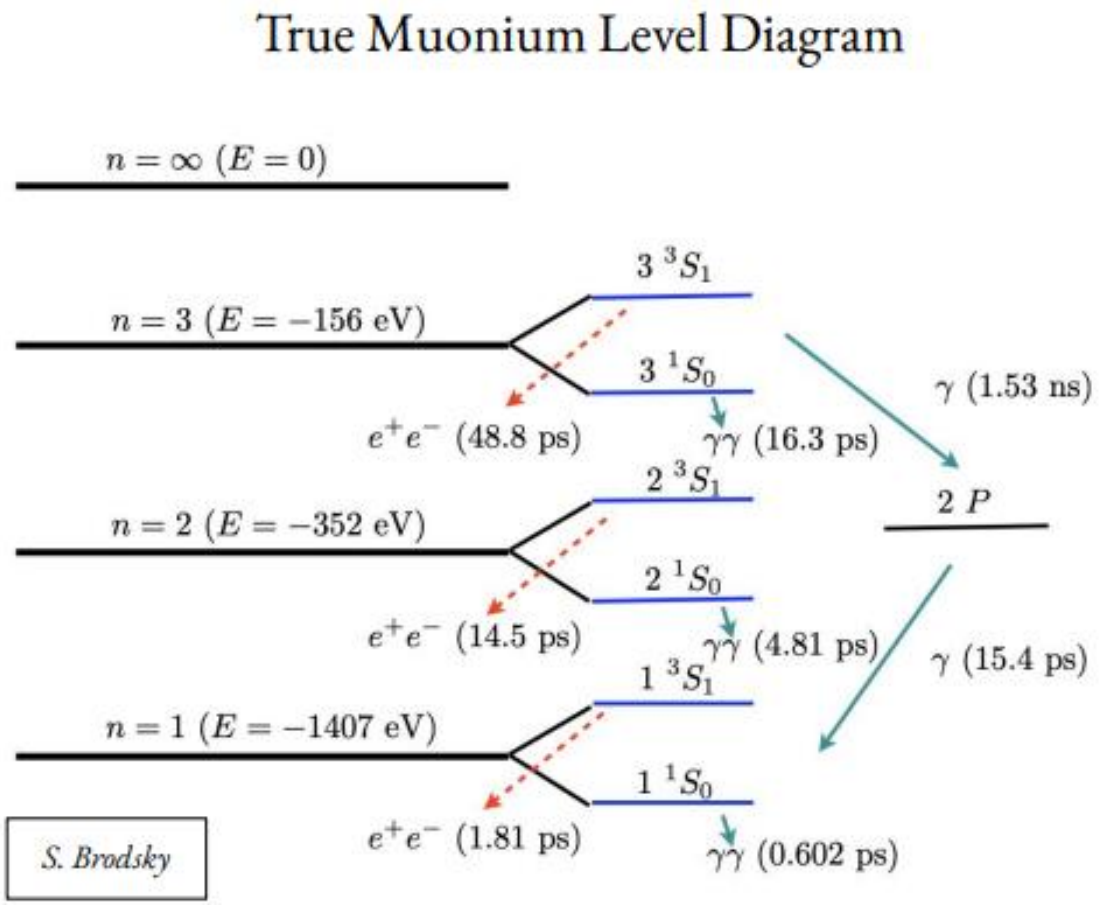
- Muonium is analogous to positronium (e^+e^-) — much more unstable
- Short-lived (~picoseconds)

- Purely QED system — no strong/weak 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

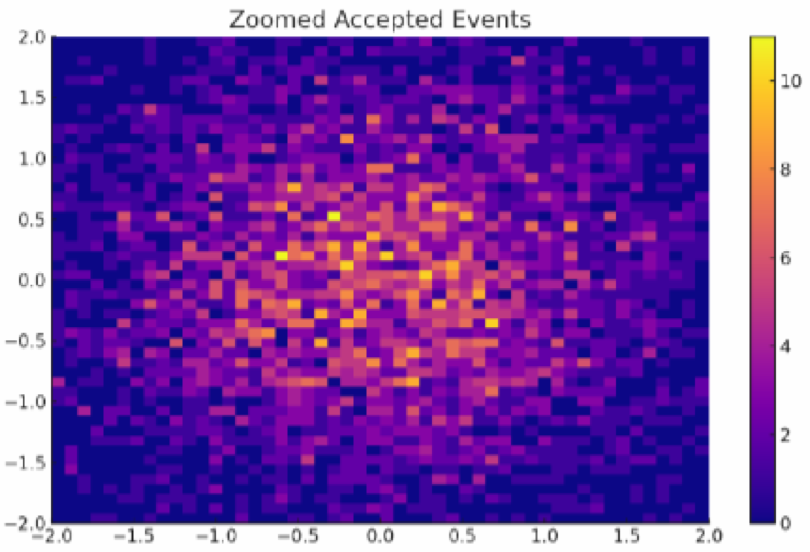
Moving Forward

Our goal is to study 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



Radiative & 3 Photon Produced True Muonium Generator Studies

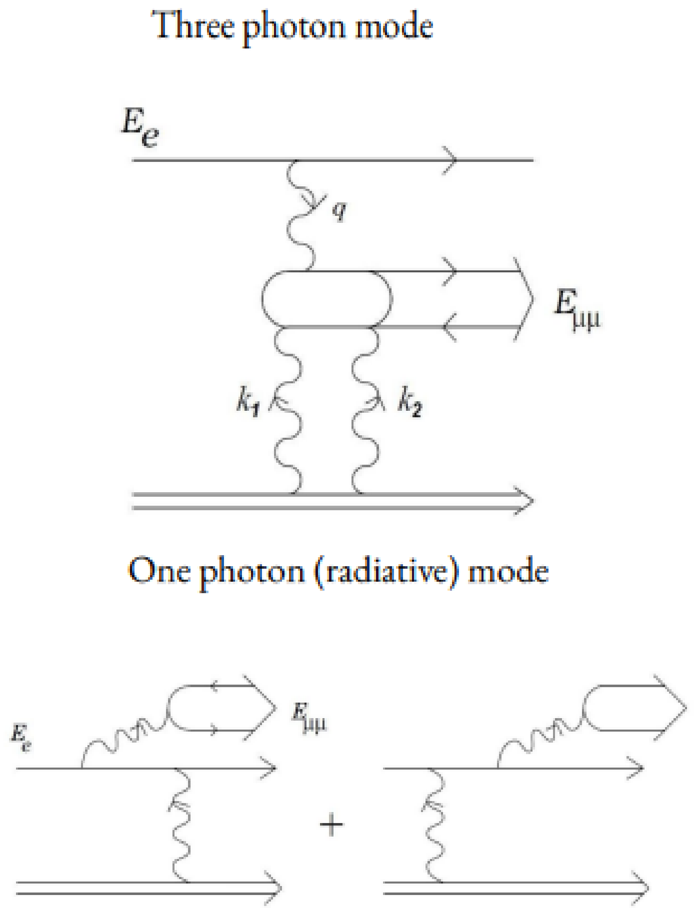
```python
def vectorized_boost(p_vec, E, beta, n, gamma):
    p_parallel = np.sum(p_vec * n, axis=1, keepdims=True) * n
    p_perp = p_vec - p_parallel
    E_boosted = gamma * (E + beta * np.sum(p_vec * n, axis=1))
    p_parallel_boosted = gamma[:, None] * (p_parallel + (beta * E)[:, None] * n)
    p_boosted = p_perp + p_parallel_boosted
    return E_boosted, p_boosted

E_eplus, p_eplus = vectorized_boost(p_decay, E_array, beta, n_TM, gamma)
E_eminus, p_eminus = vectorized_boost(p_decay_opposite, E_array, beta, n_TM, gamma)

def vertical_angle(p):
    p_x, p_y, p_z = p[:,0], p[:,1], p[:,2]
    return np.arctan2(np.abs(p_y), np.sqrt(p_x**2 + p_z**2))

theta_y_eplus_mrad = vertical_angle(p_eplus) * 1000
theta_y_eminus_mrad = vertical_angle(p_eminus) * 1000
```

What is 3 Photon & Radiative Produced TM?

When electron beam goes through the tungsten target, phenomenon can happen where photons are radiated during the collision.

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

single-photon process is possible through bremsstrahlung but more rare



True Muonium Generator Calculations

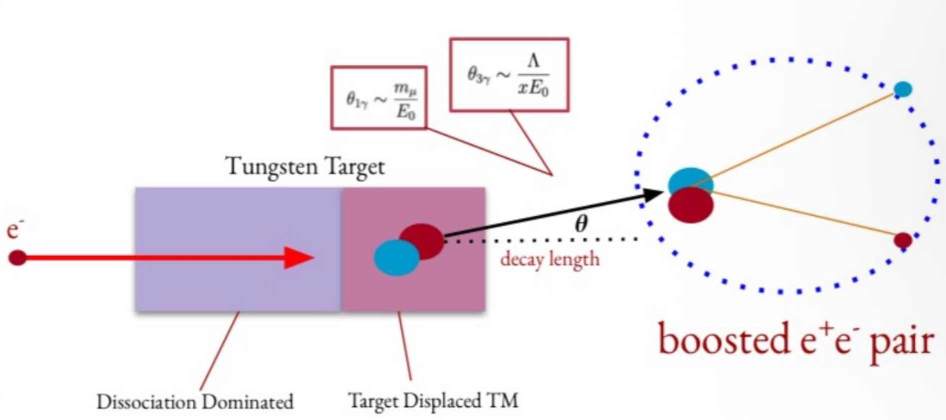
- **Initial parameters**
- # of events: 1,000,000
- beam energy: 3740 MeV
- TM Mass: 211 MeV
- Lambda (angular spread) parameter: 20 MeV,
- Minimum energy fraction: $x_{min} = 211/3740 \approx 0.0564$
- True muonium lifetime: 1×10^{-12} seconds, C: 3×10^{8} m/s

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 (difference between sim 1 & sim 2):
  - **3 photon: $\theta_0 = \Lambda / (x \times E_{beam})$**
  - **Radiative: $\theta_0 = m_\mu / E_{beam}$**
- 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: $p_{decay\_opposite} = -p_{decay}$

True Muonium Generator Calculations

1. Initial parameters

Number of Events:

$N = 1{,}000{,}000$

Beam Energy:

$E_{\text{beam}} = 3740\ \text{MeV}$

True Muonium Mass:

$m_{\text{TM}} = 211\ \text{MeV}$

Angular Spread Parameter (Λ):

$\Lambda = 20\ \text{MeV}$

Minimum Energy Fraction:

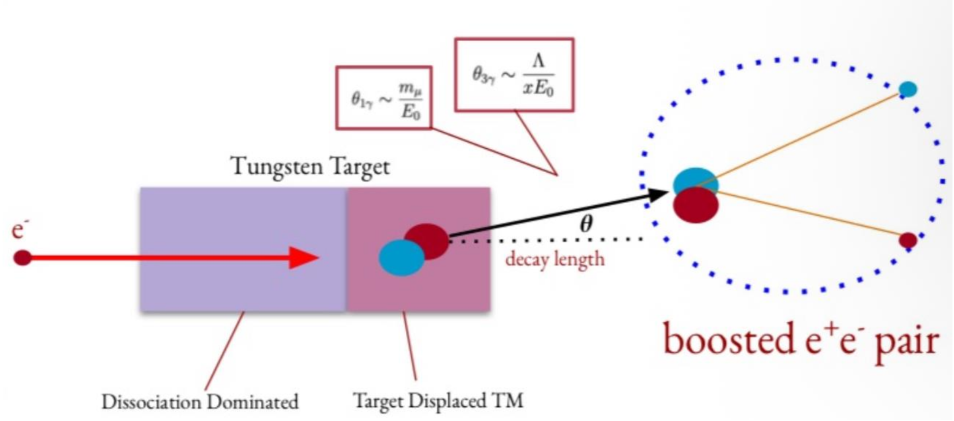
$$x_{\min} = \frac{m_{\text{TM}}}{E_{\text{beam}}} = \frac{211}{3740} \approx 0.0564$$

True Muonium Lifetime:

$\tau_{\text{TM}} = 1 \times 10^{-12}\ \text{s}$

Speed of Light:

$c = 3 \times 10^{8}\ \text{m/s}$



True Muonium Generator Calculations

2. Energy and Momentum Calculations

Energy Fraction Distribution:

$$x = x_{\min} \cdot \exp\left(U \cdot \ln\left(\frac{1}{x_{\min}}\right)\right), \quad U \sim \mathcal{U}(0,1)$$

True Muonium Energy:

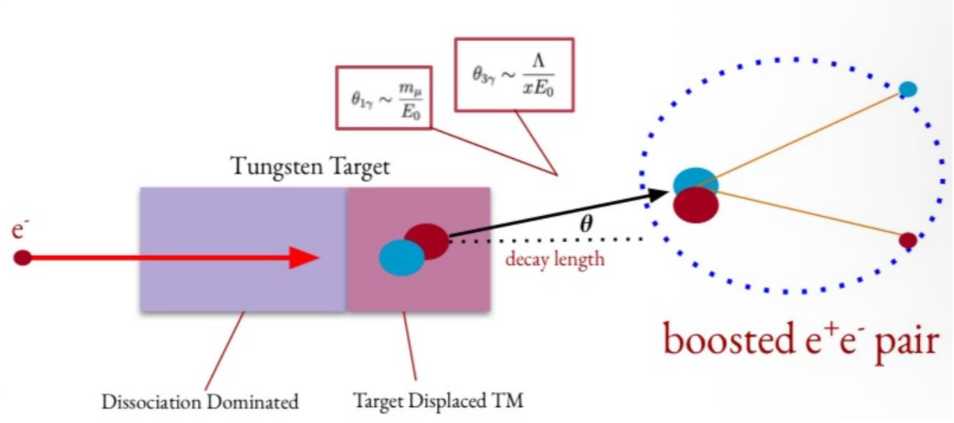
$$E_{\mathrm{TM}} = x \cdot E_{\mathrm{beam}} \quad \text{(range: 211–3740 MeV)}$$

True Muonium Momentum:

$$p_{\mathrm{TM}} = \sqrt{E_{\mathrm{TM}}^2 - m_{\mathrm{TM}}^2}$$

Decay Product Momentum in Rest Frame:

$$p^* = \frac{m_{\mathrm{TM}}}{2} = 105.5\ \mathrm{MeV}/c$$



True Muonium Generator Calculations

3. Angular Calculations

Angular Spread Parameter (θ_0)

3-Photon Production:

$$\theta_0 = \frac{\Lambda}{x \cdot E_{\text{beam}}}$$

Radiative Production:

$$\theta_0 = \frac{m_\mu}{E_{\text{beam}}}$$

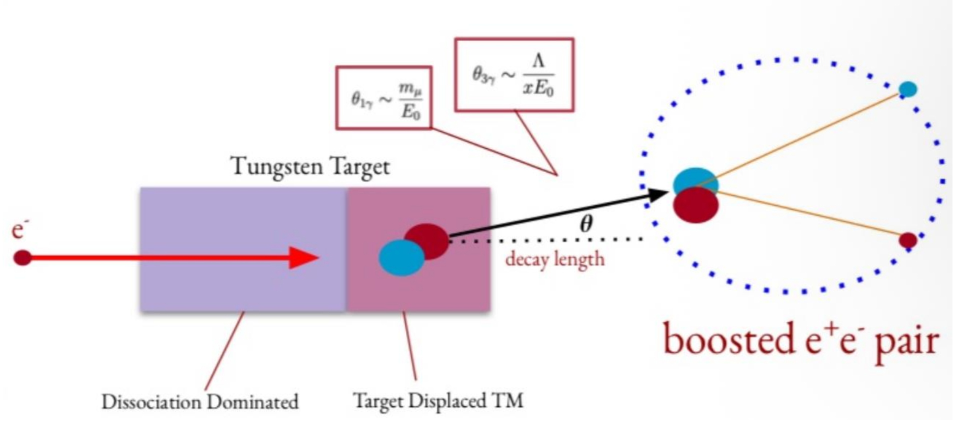
Production Angles:

$$\theta_{\text{prod}} \sim |\mathcal{N}(0, \theta_0)|, \quad \phi_{\text{prod}} \sim \mathcal{U}(0, 2\pi)$$

3D Momentum Components:

Given p_{TM} and angles $\theta = \theta_{\text{prod}}$, $\phi = \phi_{\text{prod}}$:

$$p_x = p_{\text{TM}} \cdot \sin(\theta) \cdot \cos(\phi)$$
$$p_y = p_{\text{TM}} \cdot \sin(\theta) \cdot \sin(\phi)$$
$$p_z = p_{\text{TM}} \cdot \cos(\theta)$$



True Muonium Generator Calculations

4. Decay Process Calculations

Decay angles in rest frame:

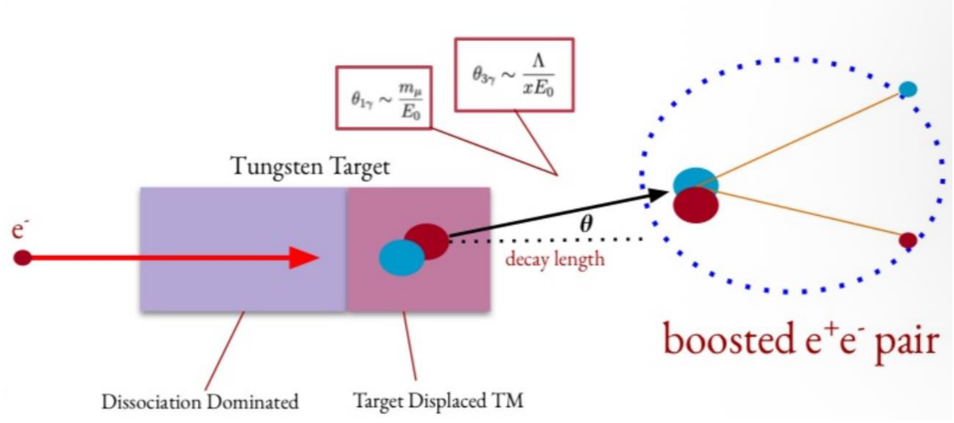
$$\theta_{\text{decay}} = \arccos(\text{uniform}(-1,1)), \quad \phi_{\text{decay}} = \text{uniform}(0,2\pi)$$

Decay product momentum vector:

$$\vec{p}_{\text{decay}} = p^* \begin{bmatrix} \sin(\theta)\cos(\phi) \\ \sin(\theta)\sin(\phi) \\ \cos(\theta) \end{bmatrix}$$

Opposite momentum vector:

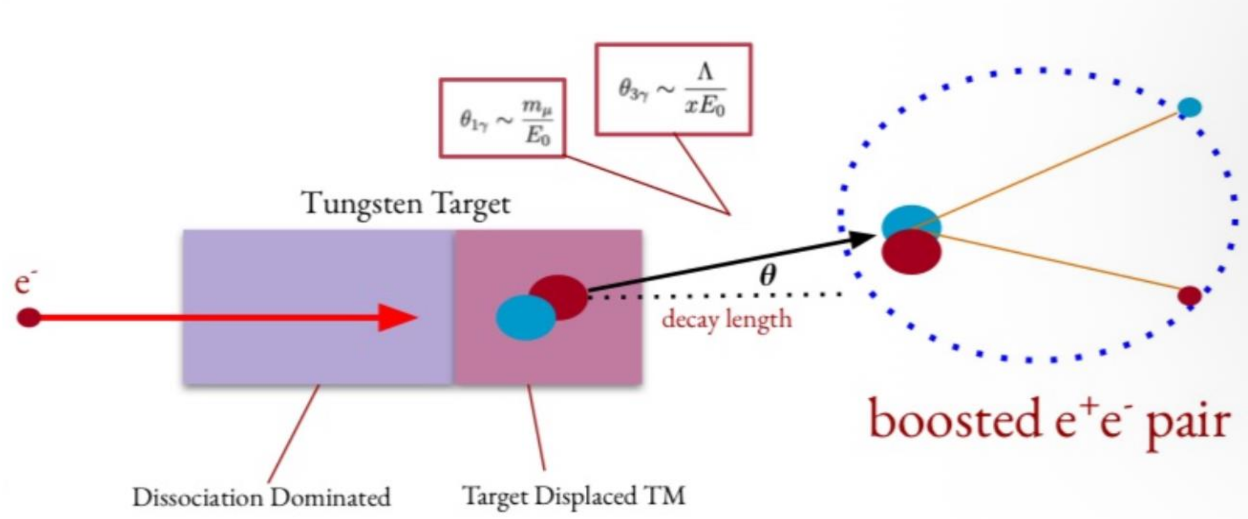
$$\vec{p}_{\text{decay, opposite}} = -\vec{p}_{\text{decay}}$$



Generator Calculations cont.

5. 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: $p'_{parallel} = \gamma(p_{parallel} + \beta E n)$
    - v. Final boosted momentum: $p' = p_{perp} + p'_{parallel}$



6. Laboratory Frame Calculations

- Vertical angles: $\theta_y = \arctan2(|p_y|, \sqrt{p_x^2 + p_z^2}) \times 1000$ (in mrad)
- Opening angle: $\cos(\theta_{opening}) = (p_{e^+} \cdot p_{e^-})/(|p_{e^+}||p_{e^-}|)$, $\theta_{opening} = \arccos(\cos(\theta_{opening})) \times 1000$

7. 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

8. 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

True Muonium Generator Calculations

5. Relativistic Boost Calculations

Lorentz Boost Quantities

Lorentz Factor:

$$\gamma = \frac{E_{\mathrm{TM}}}{m_{\mathrm{TM}}}$$

Velocity Parameter:

$$\beta = \frac{p_{\mathrm{TM}}}{E_{\mathrm{TM}}}$$

Boost Direction (unit vector):

$$\vec{n}_{\mathrm{TM}} = \frac{\vec{p}_{\mathrm{TM}}}{|\vec{p}_{\mathrm{TM}}|} = \frac{\vec{p}_{\mathrm{TM}}}{p_{\mathrm{TM}}}$$

Boost Transformation Decomposition

Parallel Component of Momentum:

$$\vec{p}_{\parallel} = (\vec{p} \cdot \vec{n})\vec{n}$$

Perpendicular Component of Momentum:

$$\vec{p}_{\perp} = \vec{p} - \vec{p}_{\parallel}$$

Boosted Quantities

Boosted Energy:

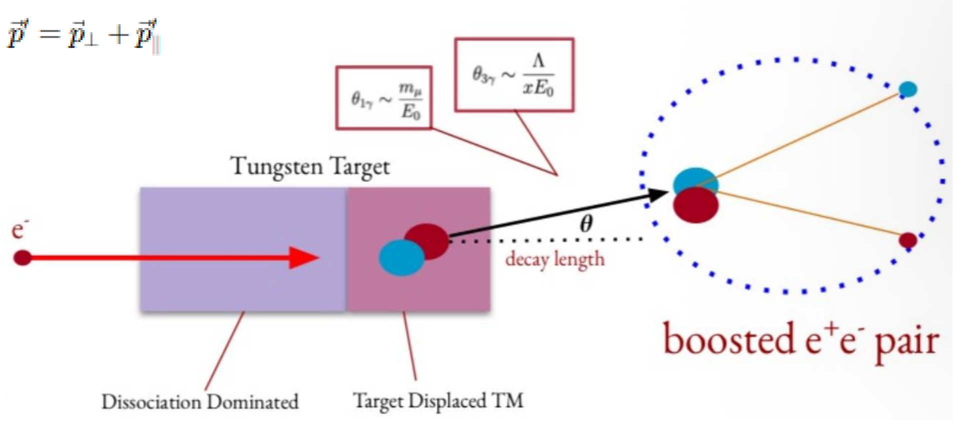
$$E' = \gamma\,(E + \beta(\vec{p} \cdot \vec{n}))$$

Boosted Parallel Momentum:

$$\vec{p}_{\parallel}' = \gamma\,(\vec{p}_{\parallel} + \beta E \vec{n})$$

Final Boosted Momentum:

$$\vec{p}' = \vec{p}_{\perp} + \vec{p}_{\parallel}'$$



True Muonium Generator Calculations

6. Laboratory Frame Calculations

Vertical Angle (in milliradians):

$$\theta_y = \arctan 2\left(|\vec{p}_y|,\ \sqrt{p_x^2 + p_z^2}\right) \times 1000\ \text{mrad}$$

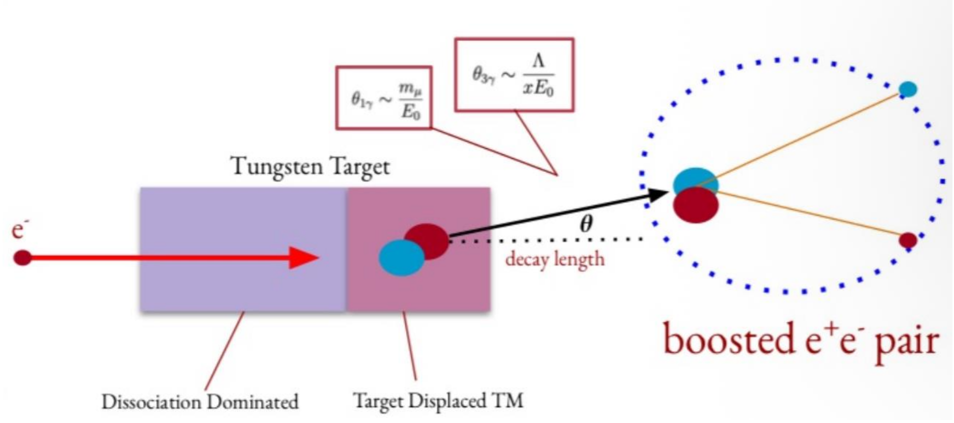
Opening Angle Between e^+ and e^-:

Cosine of Opening Angle:

$$\cos(\theta_{\text{opening}}) = \frac{\vec{p}_{e^+} \cdot \vec{p}_{e^-}}{|\vec{p}_{e^+}|\,|\vec{p}_{e^-}|}$$

Opening Angle (in milliradians):

$$\theta_{\text{opening}} = \arccos\left(\cos(\theta_{\text{opening}})\right) \times 1000\ \text{mrad}$$



True Muonium Generator Calculations

7. Decay Length Calculations

Mean Decay Length:

$$L_{\text{mean}} = \beta\gamma c\tau_0$$

Where:

- $\beta = \frac{p_{\text{TM}}}{E_{\text{TM}}}$
- $\gamma = \frac{E_{\text{TM}}}{m_{\text{TM}}}$
- $c = 3 \times 10^8 \text{ m/s}$
- $\tau_0 = 1 \times 10^{-12} \text{ s}$

Decay Distances:

$$L \sim \text{Exponential}(L_{\text{mean}})$$

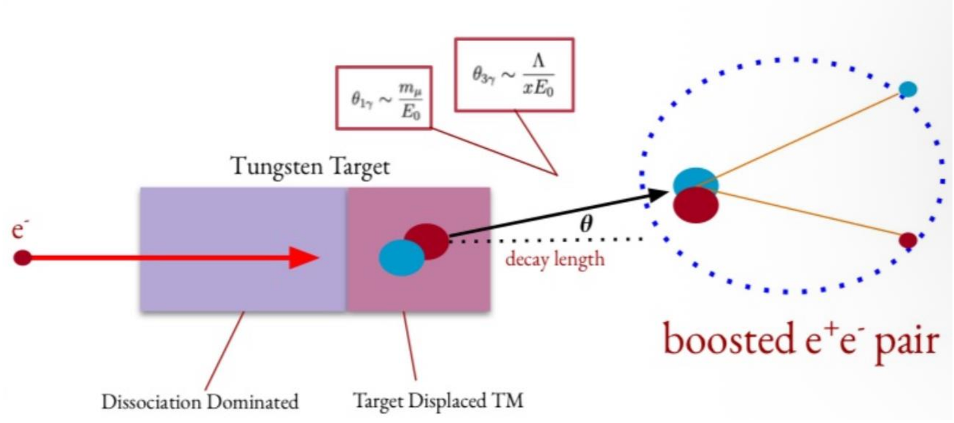
Decay Vertices (in space):

$$\vec{v}_{\text{decay}} = L \cdot \vec{n}_{\text{TM}}$$

Where $\vec{n}_{\text{TM}}$ is the boost direction unit vector.

Decay Length in Millimeters:

$$|\vec{v}_{\text{decay}}| \times 1000 \text{ mm}$$



True Muonium Generator Calculations

8. Detector Hit Calculations

Detector Position:

$$z_{\text{detector}} = 0.5\ \text{m}$$

Projection to Detector Plane:

We project the decay product's trajectory to the detector plane at $z = z_{\text{detector}}$.

Let:

- $\vec{v}_{\text{decay}} = (x_0, y_0, z_0)$ be the decay vertex
- $\vec{d} = (d_x, d_y, d_z)$ be the unit direction vector of the decay product
- t be the scalar distance along the direction vector needed to reach the detector plane

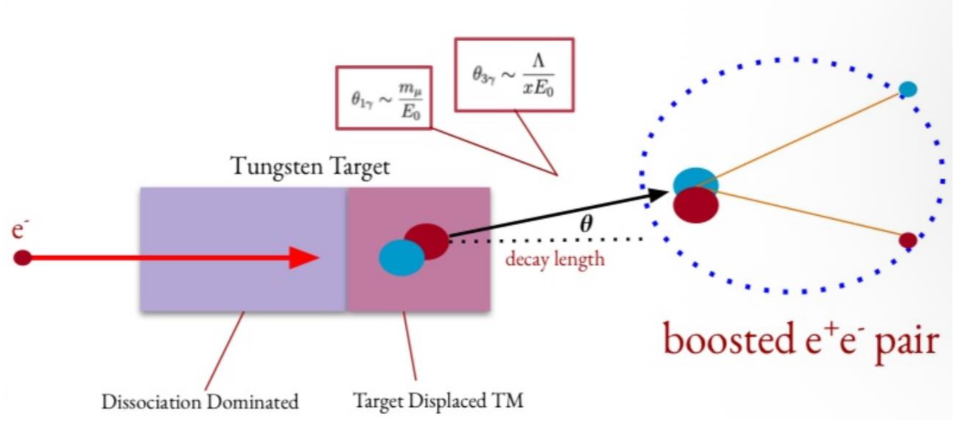
Then:

$$t = \frac{z_{\text{detector}} - z_0}{d_z}$$

$$\vec{r}_{\text{hit}} = \vec{v}_{\text{decay}} + t \cdot \vec{d}$$

Or explicitly:

$$\vec{r}_{\text{hit}} = \begin{pmatrix} x_{\text{hit}} \\ y_{\text{hit}} \\ z_{\text{hit}} \end{pmatrix} = \begin{pmatrix} x_0 + td_x \\ y_0 + td_y \\ z_0 + td_z \end{pmatrix} \quad (\text{with } z_{\text{hit}} = z_{\text{detector}})$$



Simulation results explained

Angular correlation Plots

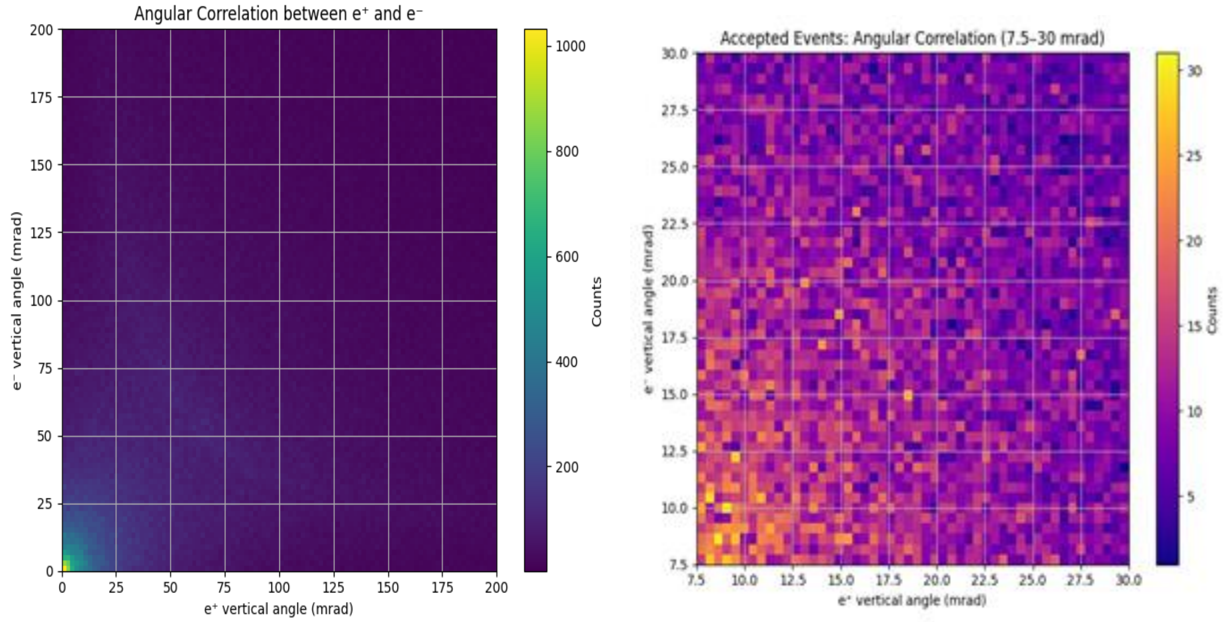
3 photon:

- Both e^+ and e^- are produced at small vertical angles in the 7.5-30 mrad range, very close to the origin.
- TM is produced with high forward momentum (boosted), so its decay products are tightly aligned with the beamdirection.
- Angular speed varies with particle energy (theta0 = Lambda/(xE_beam))

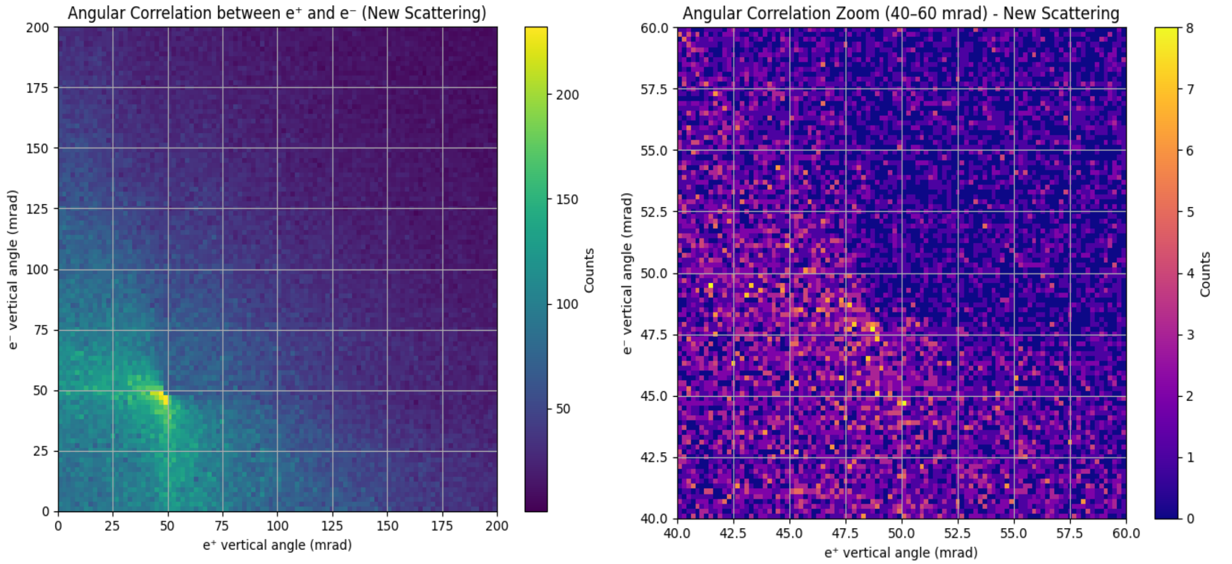
Radiative (1 photon):

- Concentration centered around ~48 mrad for both the e^+ and e^-
- more symmetric distribution because the angular spread is constant for all events (theta0 =mass_muon/E_beam)

3 Photon Production



Radiative Production



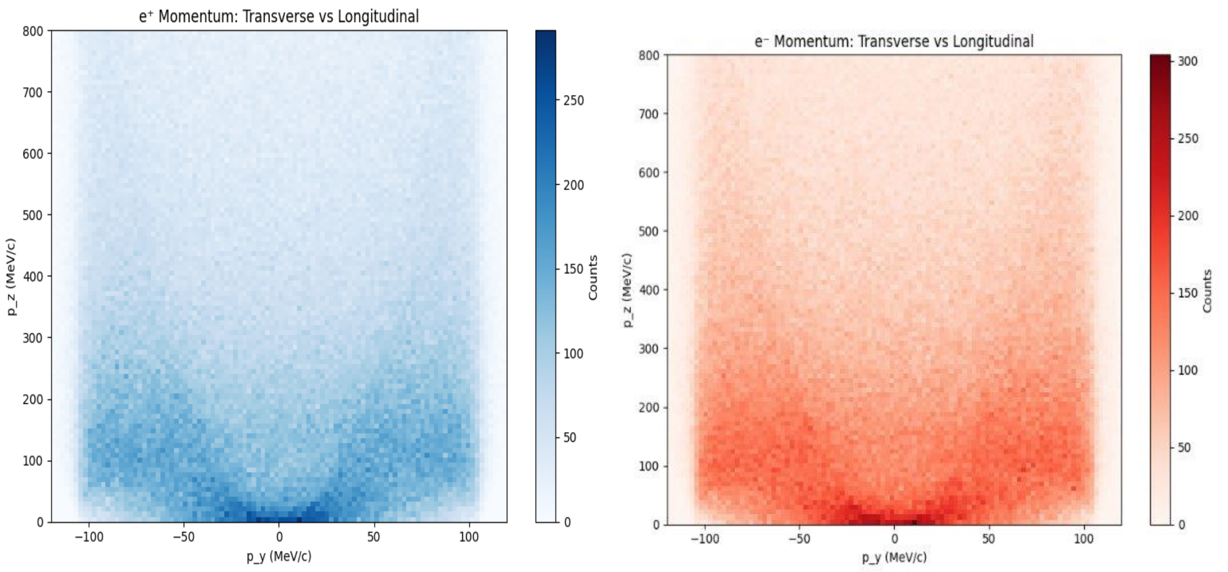
Momentum Plots Positron (blue) & Electron (red)

- No preferred transverse direction, symmetric about py=0
- Highest event density at low pz and small py, indicating that most decays produce low-momentum positrons
- “U”-shaped pattern emerges; as pz increases, thedistribution widens symmetrically in py , showing thathigher-energy positrons can deviate a slightly greateramount
- muonium decays produce forward-emitted positrons with low transverse momentum, making them well-suited for HPS detection
- Radiative forms a cone-like distribution on the sides

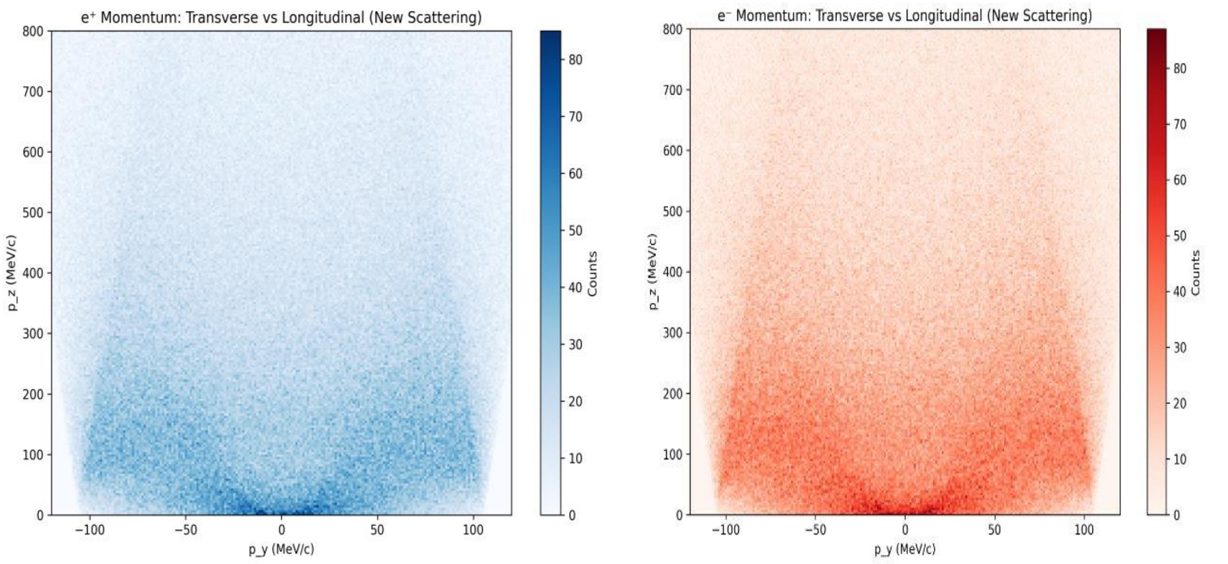
Main observation:

- 3 photon production has a wider transverse momentum density range

3 Photon Production



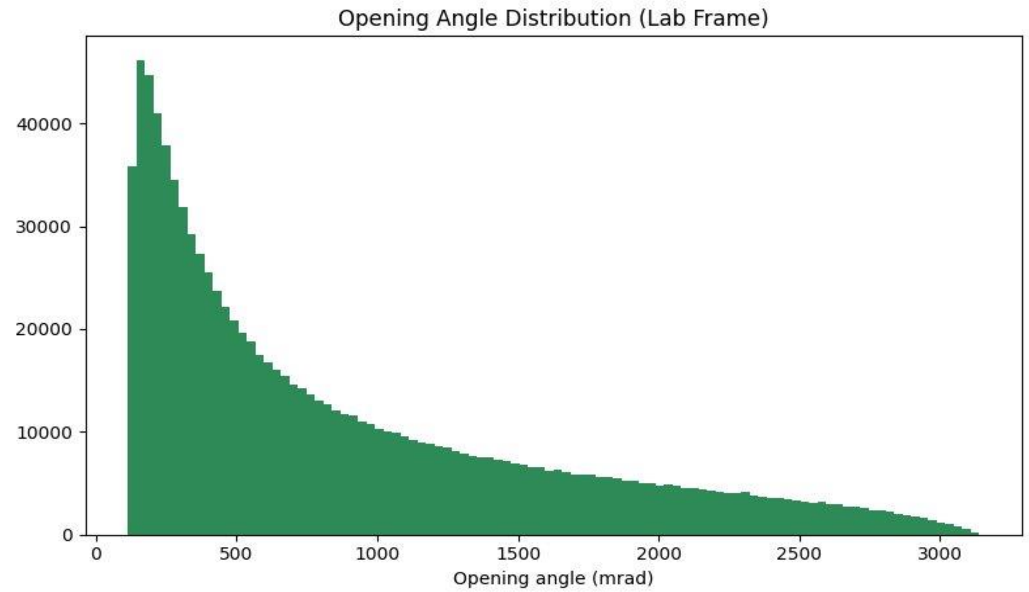
Radiative Production



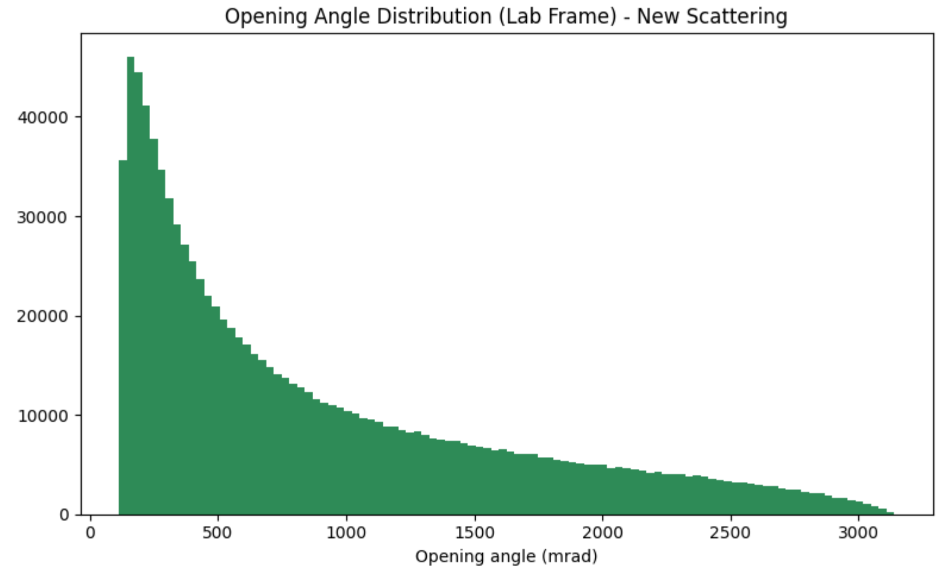
Opening Angle Distributions

- Sharp peak at very small angles (~200 mrad)
- Very steep drop off about half as many events for each time doubling opening angle
- Plots yeild similar results

3 Photon Production

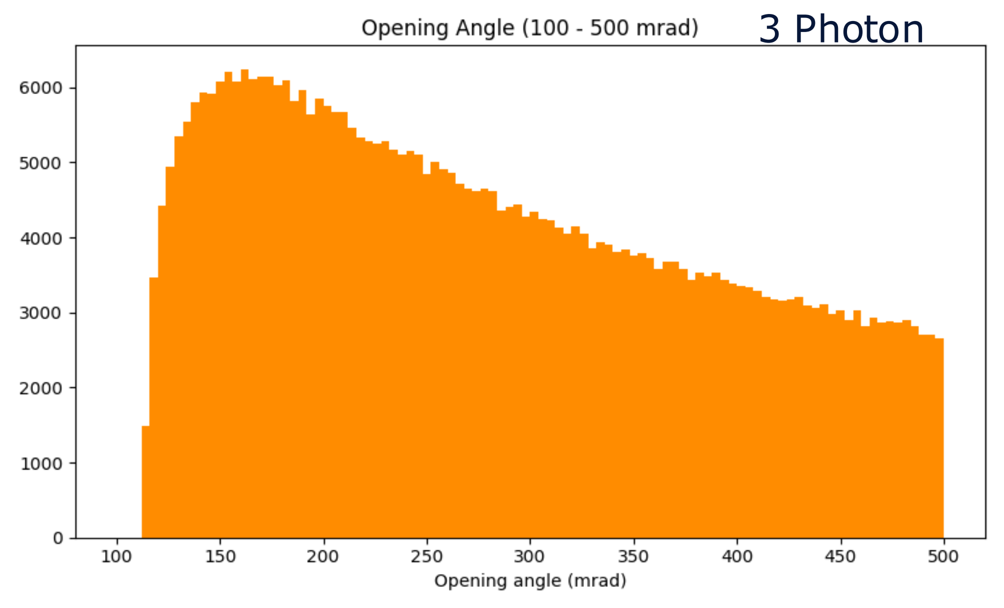


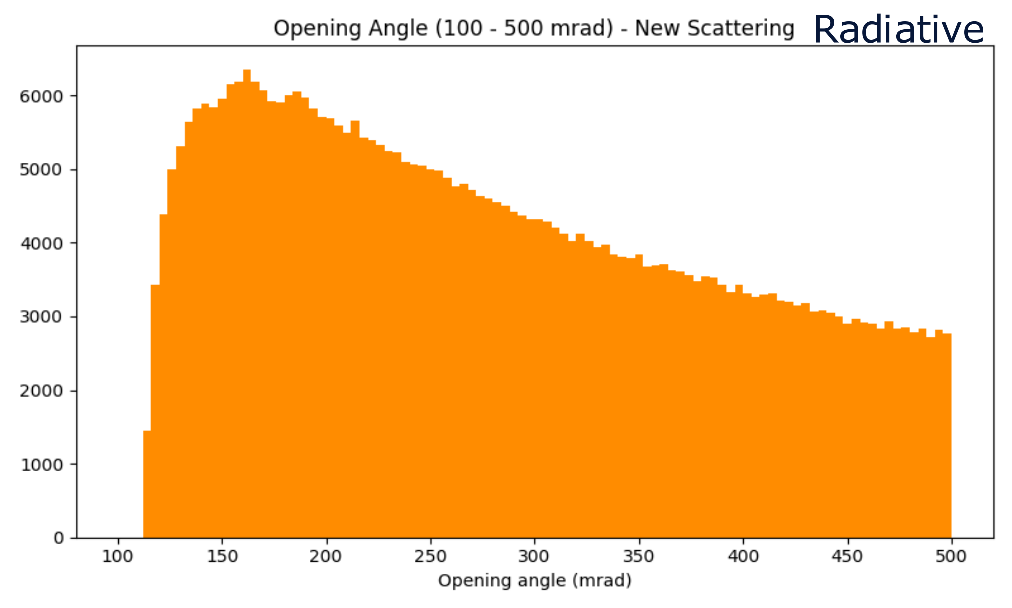
Radiative Production



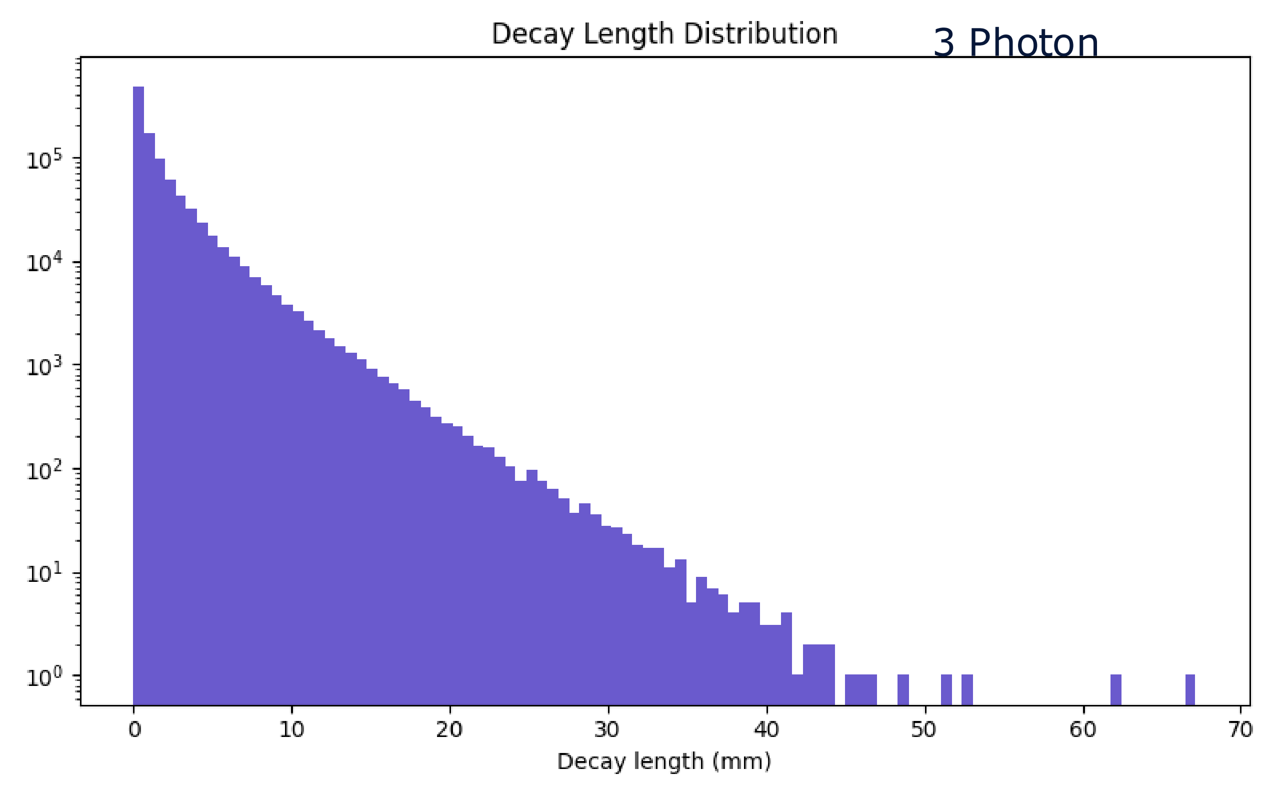
Opening Angle Distrbutions Cont.

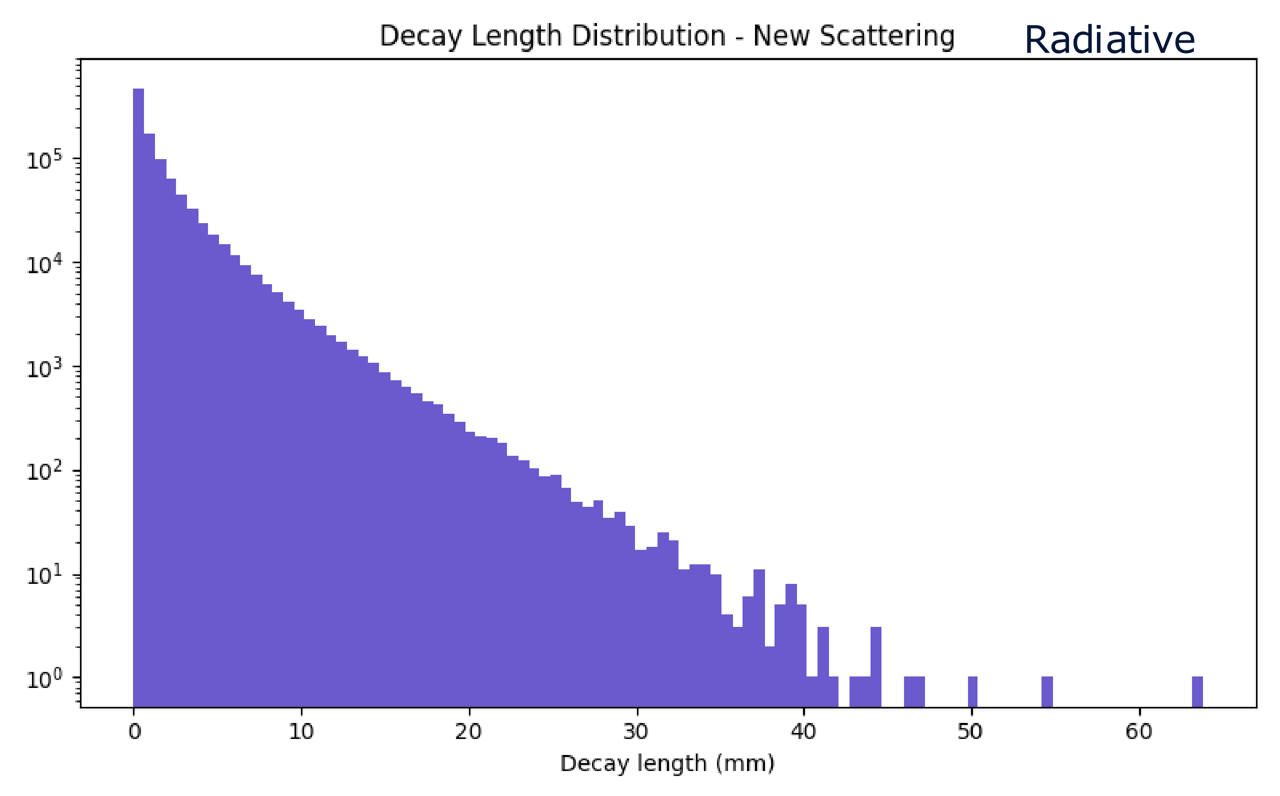
- Zoomed in the x axis to go up to 500mrad from 2500mrad
- Added more bins





Decay Length Distributions

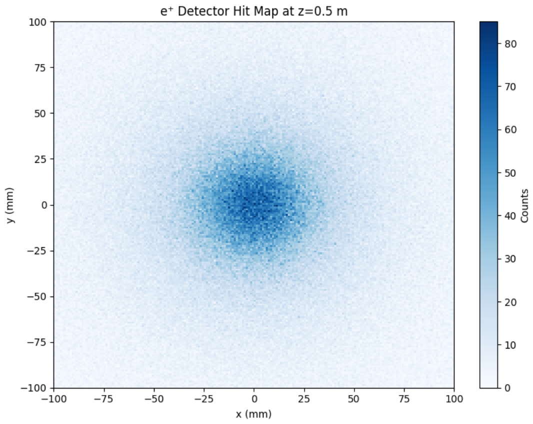


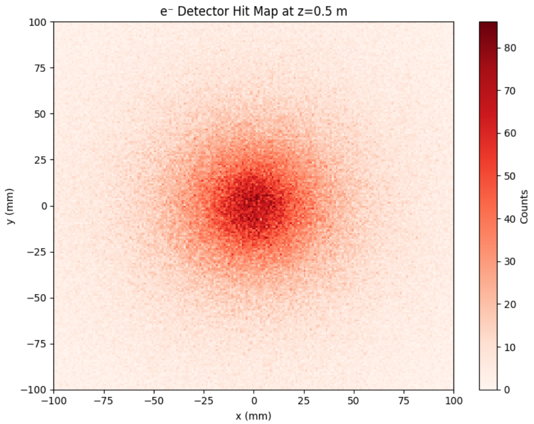


Detector Hit Maps

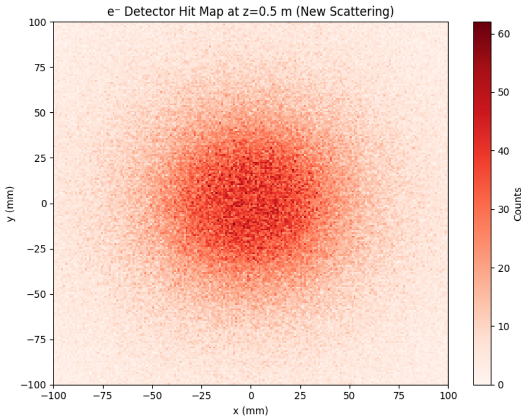
- Detector is .5 meters away from target (z axis)
- All four hit maps circular cluster centered around (0, 0) with a radius of ~25 mm.
- Indicates that decay products are highly forward-directed with minimal transverse spread.
- No significant geometric offset between three-photon and radiative modes, suggesting that **both channels produce TM with similar boost directions and decay geometry**.

3 Photon Production

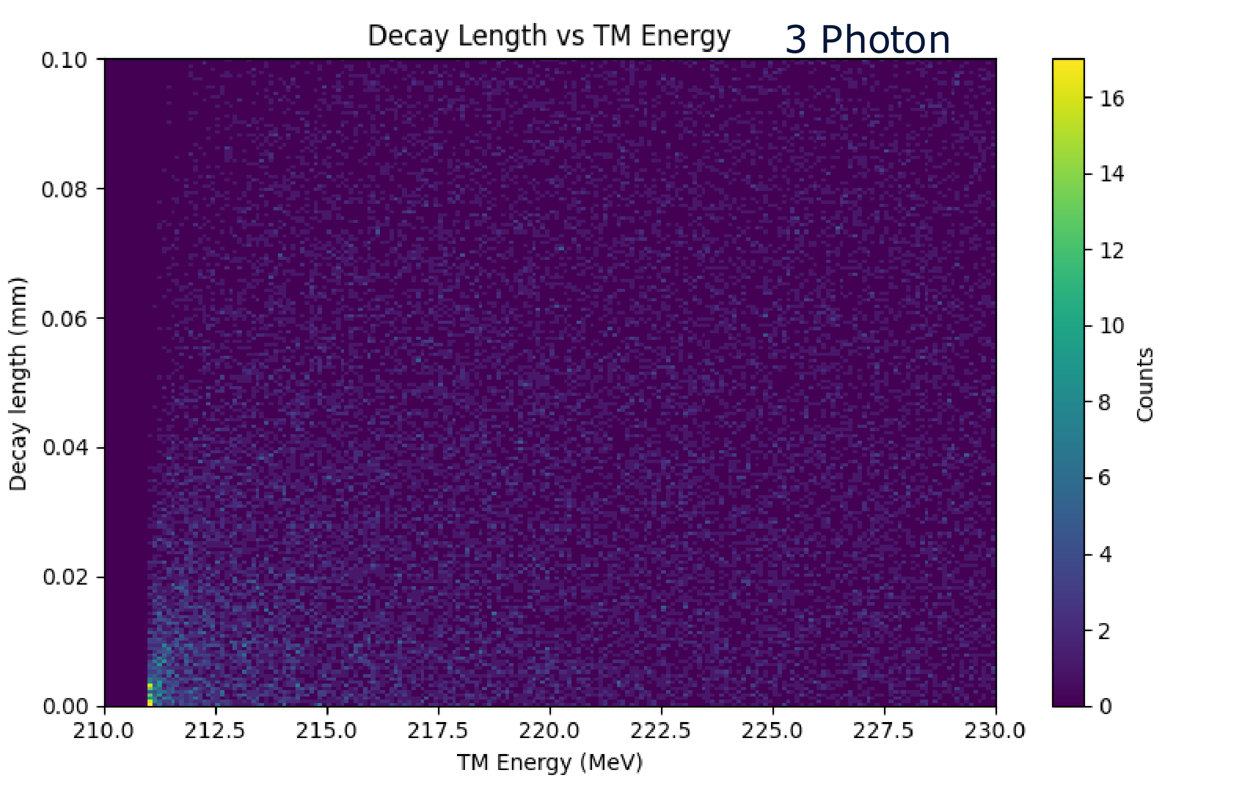


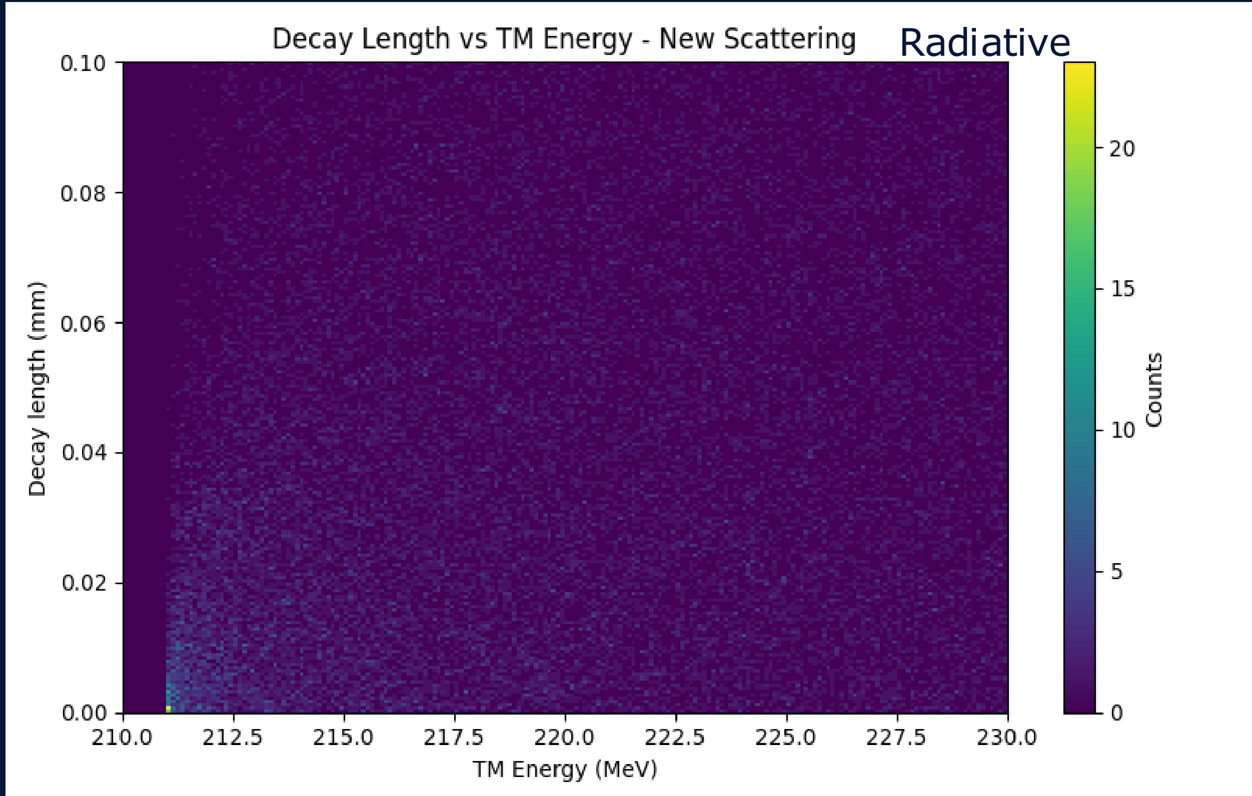


Radiative Production

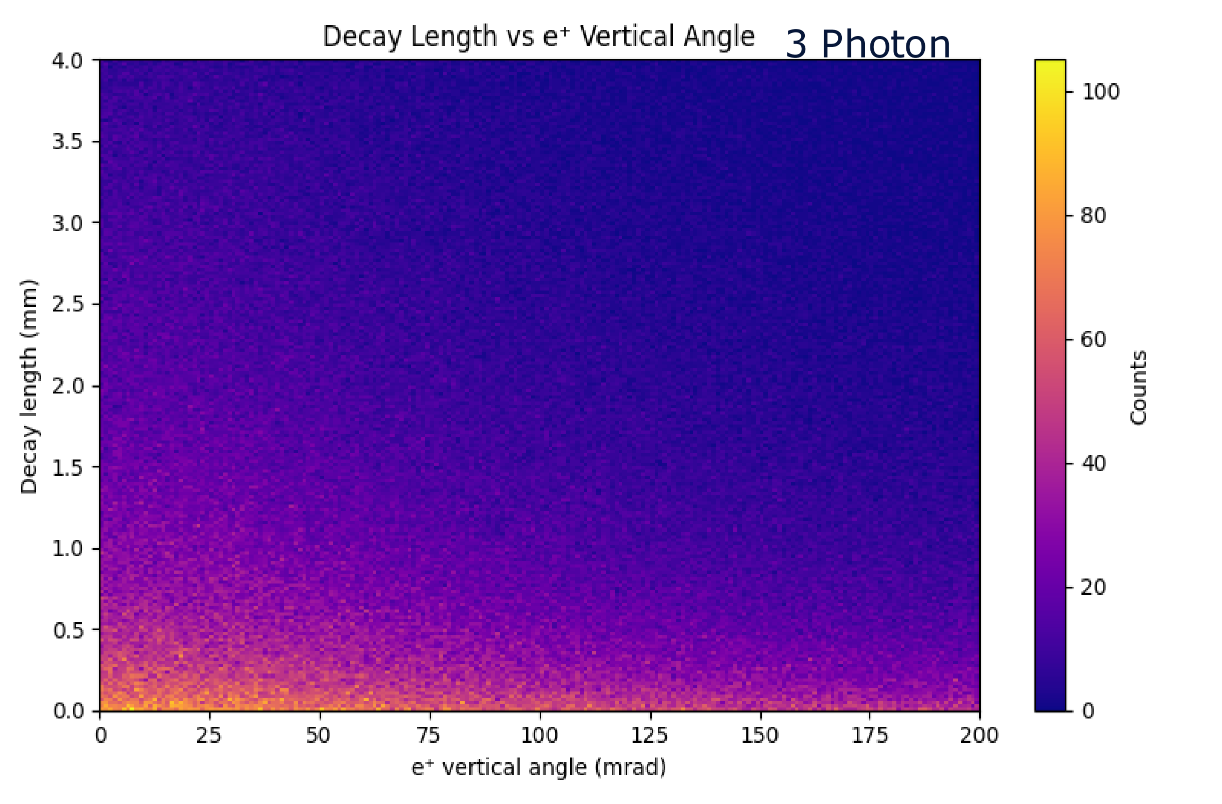


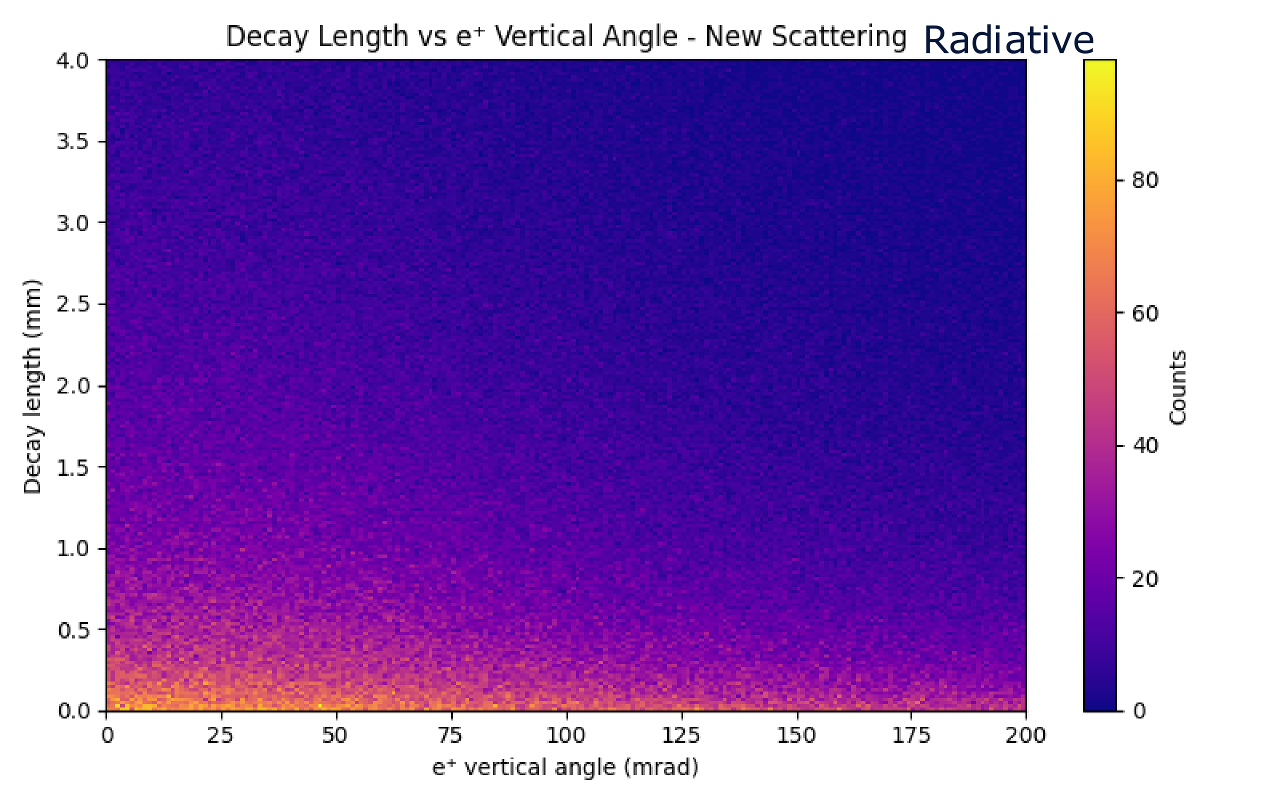
Correlation Plots Decay Length vs TM Energy





Correlation Plots Cont. Decay Length vs Vertical Angle





Summary

TM production via both processes results in tightly focused, symmetric decay signatures that are highly forward-peaked, making them ideal for detection in precision forward spectrometers like HPS.

To Do:
Explaination for slides previous 2 slides
Angular implications slides 22

Next steps

- Code base writes to LHE file. Learn how to send LHE to SLIC file which is a file format that can be read by our detector