A review of and HPS discovery potential for True Muonium

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Road Map

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- What is True Muonium? – Fun Facts
- Calculating Primary Production Cross Section
- Dissociation and Ideal Targets
- Total Transition Cross Sections
- Method for Calculating Yield
- HPS-MC Study (very preliminary)
  - 4.55 GeV
  - 6.6 GeV
- Next Steps

Worthwhile Resources (incomplete)

- Schuster. The Production and Discovery of True Muonium in Fixed-Target Experiments.

- Holvik E, Olsen HA. Creation of relativistic fermionium in collisions of electrons with atoms. Phys Rev D Part Fields. 1987 Apr 1;35(7):2124-2129. doi: 10.1103/physrevd.35.2124. PMID: 9957899.

- N. Arteaga-Romero, C. Carimalo, and V. G. Serbo. Production of the bound triplet $\mu^+\mu^-$system in collisions of electrons with atoms. Physical Review A, 62(3), Aug 2000.

- Stanley J. Brodsky and Richard F. Lebed. Production of the smallest qed atom: True muonium($\mu^+\mu^-$). Physical Review Letters, 102(21), May 2009.

- B. Yale. HEAVY PHOTON DISPLACED VERTEX SEARCH AT 2.3GeV WITH PROSPECTS FOR TRUE MUONIUM DISCOVERY (Chapter 8)

Production of True Muonium

$$\pi^- p \to (\mathrm{TM})n$$
$$\gamma Z \to (\mathrm{TM})Z$$
$$\boxed{e^- Z \to e^- (\mathrm{TM})Z}$$
$$Z_1 Z_2 \to Z_1 Z_2 (\mathrm{TM})$$
$$\eta \to (\mathrm{TM})\gamma$$
$$e^+ e^- \to (\mathrm{TM})$$
$$\mu^+ \mu^- \to (\mathrm{TM})$$

Quick facts:

- True muonium is the exotic "fermionium" atom consisting of a bound (μ+ μ-)
- M_{TM} ~ 2 Mμ (2 Mμ - Binding)
- Bohr Radius ~ 512 fm ⇒ very small (< hydrogen atom)
- TM Decays much sooner than μ+,μ-

Production of True Muonium

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Electro Production of Dimuonium

$$e^- Z \to e^- (\mathrm{TM}) Z$$

TABLE I: True fermionium decay times and their ratios.

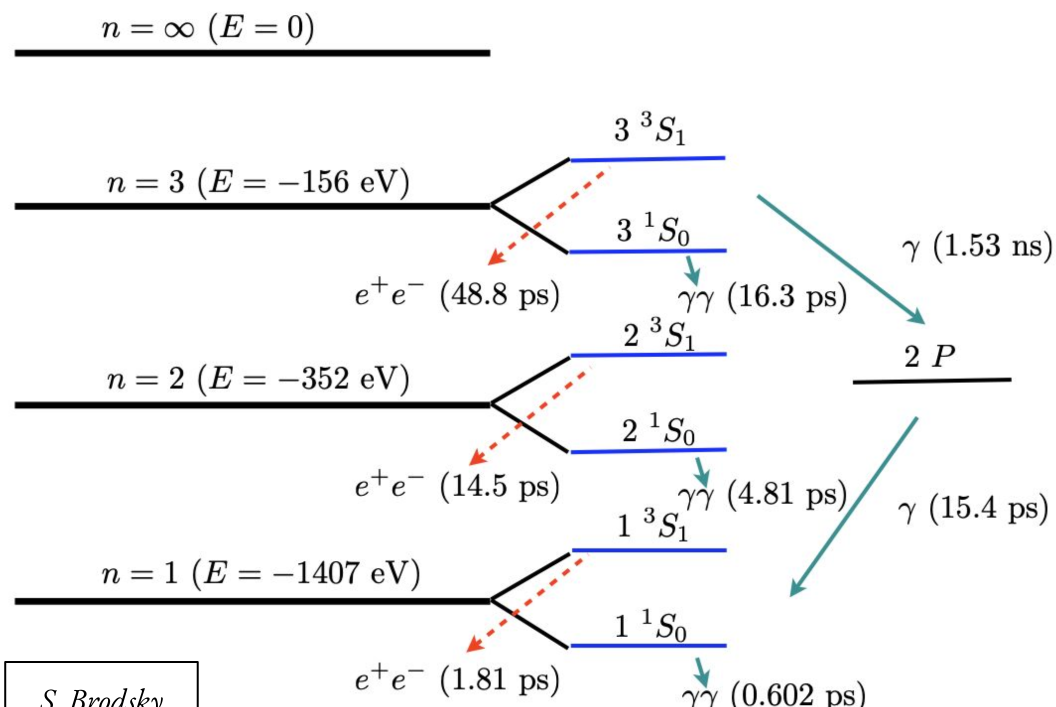
$$\tau(n^3S_1 \to e^+e^-) = \frac{6\hbar n^3}{\alpha^5 mc^2}\ ,\ \tau(n^1S_0 \to \gamma\gamma) = \frac{2\hbar n^3}{\alpha^5 mc^2}\ ,$$

$$\tau(2P \to 1S) = \left(\frac{3}{2}\right)^8 \frac{2\hbar}{\alpha^5 mc^2}\ ,\ \tau(3S \to 2P) = \left(\frac{5}{2}\right)^9 \frac{4\hbar}{3\alpha^5 mc^2}\ ,$$

$$\frac{\tau(n^3S_1 \to e^+e^-)}{\tau(n^1S_0 \to \gamma\gamma)} = 3\ ,\ \frac{\tau(2P \to 1S)}{\tau(n^1S_0 \to \gamma\gamma)} = \left(\frac{3}{2}\right)^8 \frac{1}{n^3} = \frac{25.6}{n^3}\ ,$$

$$\frac{\tau(3S \to 2P)}{\tau(2P \to 1S)} = \left(\frac{5}{3}\right)^9 = 99.2\ .$$

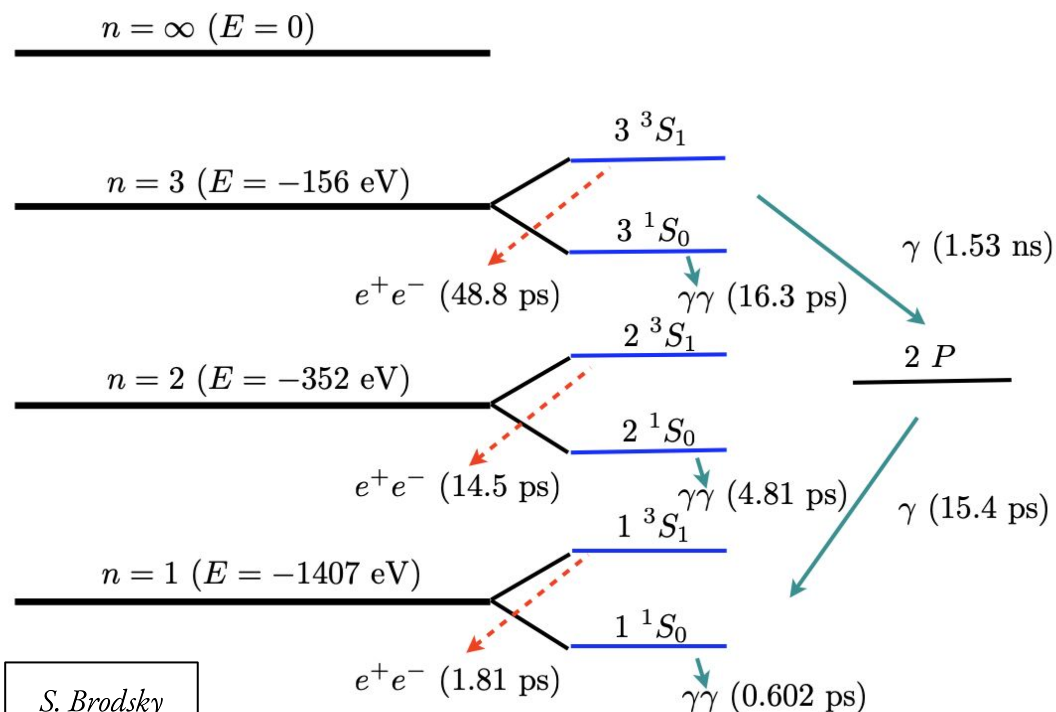
True Muonium Level Diagram



S. Brodsky

Production of True Muonium

True Muonium Level Diagram



S. Brodsky

Electro Production of Dimuonium

$$e^- Z \rightarrow e^- (\mathrm{TM}) Z$$

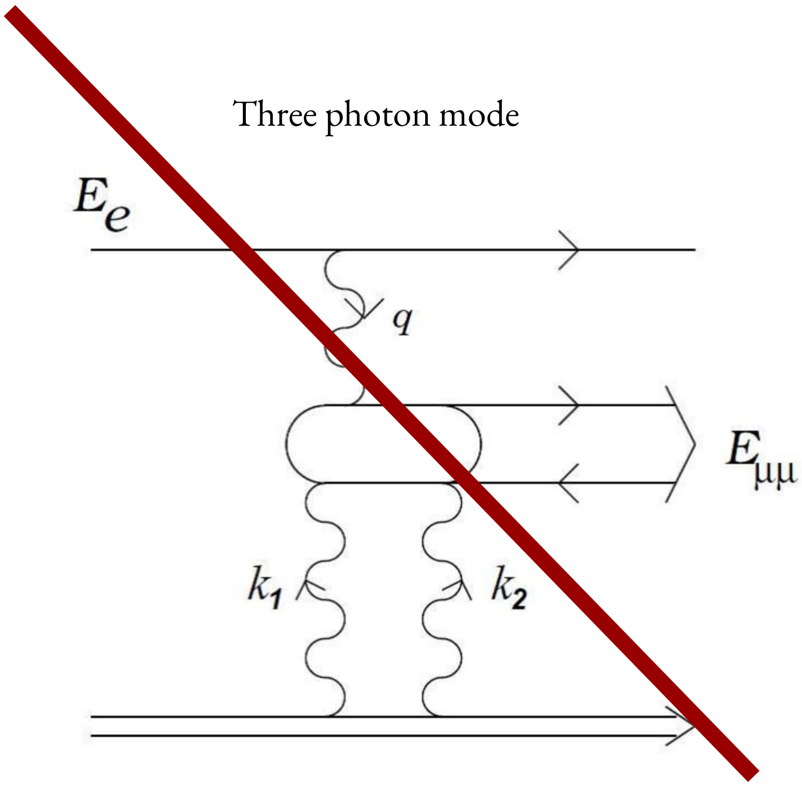
Decay Length of Interest

$$l_{dec} = \gamma\beta c\tau_{(1^3S_1)}$$
$$l_{dec}(4.55\ \mathrm{GeV}) = 1.17\ \mathrm{cm}$$
$$l_{dec}(6.60\ \mathrm{GeV}) = 1.69\ \mathrm{cm}$$

Challenge of Orthodimuonium

- Two primary production modes!

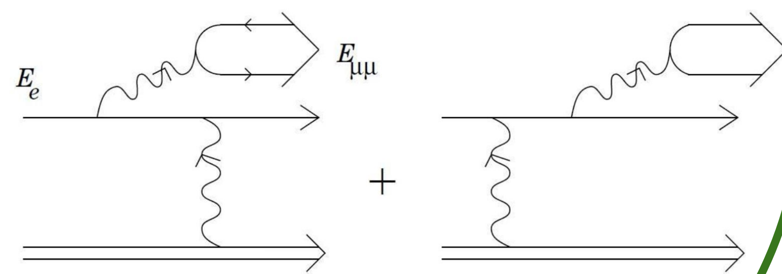
Three photon mode



Scattering Angle: $\theta_{3\gamma} \sim \frac{\Lambda}{x E_0}$

Oppressed by Bethe-Heitler Background

One photon (brem) mode

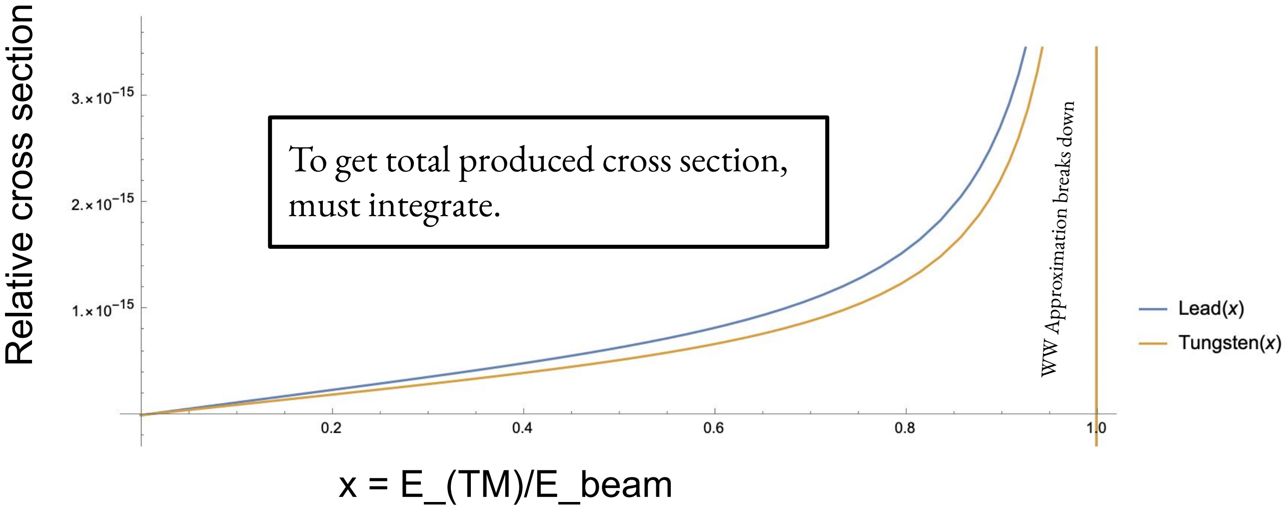


Scattering Angle: $\theta_{1\gamma} \sim \frac{m_\mu}{E_0}$

Similar Kinematics to A' !

Procedure for Calculating Primary Production Cross Section (only bremm)

$$d\sigma = \frac{1}{4n^3}\frac{Z^2\alpha^7}{m_\mu^2}\frac{x\,(1-x)\left(1-x+\frac{1}{3}x^2\right)dx}{\left[1-x+(m_e/m_{\mu\bar{\mu}})^2\right]^2}\times\left(\ln\left[\frac{(E_{beam}/m_\mu)^2\,(1-x)^2}{1-x+(m_e/m_{\mu\bar{\mu}})^2}\right]-1\right)$$



To get total produced cross section, must integrate.

Integrated Cross Sections

Pb (4.55 GeV) = 0.16 pb
Pb (6.6 GeV) = 0.33 pb
W (4.55 GeV) = 0.13 pb
W (6.6 GeV) = 0.27 pb

For more information on WW approximation: Validity of the Weizsäcker-Williams Approximation and the Analysis of Beam Dump Experiments: Production of an axion, a dark photon, or a new axial-vector boson (tldr: good for >100 MeV invariant mass, can be meh for low mass)

Total Electric Differential Cross Section and Dissociation

$$d\sigma_{\text{tot}}^{nl} = Z^2\frac{\alpha^2}{\pi}\left(1 - F^{nl0,n'l'0}(q)\right) \times \frac{1}{a^2}|\Delta(q,Z)|^2 q dq.$$

$$F^{nlm,n'l'm'}(q) = \int_0^\infty \int_0^\pi \int_0^{2\pi} x^2 \text{Sin}(\theta) e^{iqx\text{Cos}(\theta)} \times \psi^{n'l'm'}(x,\theta,\phi)^* \psi^{nlm}(x,\theta,\phi) d\phi d\theta dx$$

Thomas-Fermi-Moliere

$$\Delta(q,Z) = 4\pi \sum_{i=1}^{3} \frac{\alpha_i}{q^2 + \beta_i^2}$$

$$\beta_i = \frac{m_e b_i}{121} Z^{1/3}$$

$b_1 = 6.0, b_2 = 1.2, b_3 = 0.3$

$\alpha_1 = 0.10, \alpha_2 = 0.55, \alpha_3 = 0.35$

- Includes transition and dissociation cross sections
- Doesn't include full magnetic differential cross section (~1% difference for Pb)

Note: more complete calculation in Contribution of α2-terms to the total interaction cross sections of relativistic elementary atoms with atoms of matter

Total Electric Differential Cross Section and Dissociation

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Dissociation Length of Interest

$$l_{1S\to X} = \frac{A}{N_A \rho \sigma(1S \to X)} = \frac{1}{N\sigma(1S \to X)}$$

Note: more complete calculation in Contribution of α2-terms to the total interaction cross sections of relativistic elementary atoms with atoms of matter

Total Dissociation Length and Cross Section for Different Z

(brem 13S1)

Element	Atomic number	Atomic Density (g/cm^3)	Atomic Number Density	TM (13S1-->X) cross section (pb)	Dissociation Length (micron)
Tungsten	74	19.4	6.34E+22	5.68E+16	2.78
Gold	79	19.3	5.90E+22	6.43E+16	2.64
Lead	82	11.4	3.30E+22	6.90E+16	4.39
Bismuth	83	9.75	2.81E+22	7.06E+16	5.04

To-Do: Determine temperature at target during run operation

- This will answer viability of lead as target for special TM run
- If too hot, lead or bismuth alloys with other high z materials would help in changing melting temp

Cross Section for Specific Transitions

$$d\sigma^{nl,n'l'} = \left(1-(-1)^{l-l'}\right) Z^2 \frac{\alpha^2}{\pi}\frac{1}{a^2} q|\Delta(q,Z) \times F^{nl0,n'l'0}\left(\frac{q}{2}\right)|^2 dq$$

	from 1S	from 2S	from 2P
to 1S	0	0	3.20×10^{-20}
to 2S	0	0	3.82×10^{-19}
to 2P	3.20×10^{-20}	3.82×10^{-19}	0
to 3S	0	0	9.53×10^{-21}
to e^+e^-	2.65×10^{-20}	7.52×10^{-20}	3.34×10^{-19}
to X	6.89×10^{-20}	5.92×10^{-19}	7.61×10^{-19}

Schuster. Relative Differential cross section for different transitions.

To calculate total cross-sections for each transition must integrate total cross section and subtract relative dissociation.

- To-Do: Reproduce table with my calculations and cross sections

Calculating Yield (in progress)

Primary Contribution

$$\frac{dN_{1S}}{dz} = N_e \frac{\sigma(e^- \to 1S)}{\sigma(1S \to X)} - N_{1S}$$

z = (l_target)/(l_dissoc)

Secondary Contributions

$$\frac{dN_{2S}}{dz} = N_e \frac{\sigma(e^- \to 2S)}{\sigma(1S \to X)} - N_{2S}\frac{\sigma(2S \to X)}{\sigma(1S \to X)} + N_{2P}\frac{\sigma(2P \to 2S)}{\sigma(1S \to X)}$$

$$\frac{dN_{2P}}{dz} = N_e \frac{\sigma(e^- \to 2P)}{\sigma(1S \to X)} - N_{2P}\frac{\sigma(2P \to X)}{\sigma(1S \to X)} + N_{1S}\frac{\sigma(1S \to 2P)}{\sigma(1S \to X)} + N_{2S}\frac{\sigma(2S \to 2P)}{\sigma(1S \to X)}$$

Calculating Yield (in progress)

- Assuming 450 nA current at JLAB, 6.6 GeV beam energy, 8.75 micron tungsten target
- Total **1S**$_{(brem)}$ yield for 1 month of beam **~ 33.13**
- **To-do:** Finish yield calculations and contributions from (2S, 2P)
- Agrees mostly with Yale yield calculations
  - Note: Yale calculated only **3.94 analyzable TM events per month**, goal of hps-mc study is to determine if acceptance has improved

HPS-MC Study

- Use existing infrastructure for a scan at a single mass (Assume A' = 211 MeV) and two beam energies: **4.55 GeV, 6.6 GeV**.
- Detector used for 4.55 GeV ⟹ HPS_Nominal_I0
- Made Detector for 6.6 GeV ⟵ HPS_Nominal_6pt6GeV
  - Used field map from detector 2017-nominal-6pt6
  - Changed bfield to -1.5T

Flow using /hps-mc/python/jobs

Job script to generate A-prime events, convert to StdHep, apply transformations, and resulting simulate signal events using SLIC.

Simulate pile-up, run readout, hps-java recon, and analysis.

HPSTR reconstruction and analysis.

Dedicated TM Scripts

TM_gen_to_slic

- job.json.tmpl
- mkjobs.sh
- jars.json
- vars.json
- subArray.sh (using ap_gen_to_slic type)
- .hpsmc

run : 10666
apmass: 211.0 MeV
detector: HPS_Nominal_iter0
target_z: 0.0
ctau: 160.0 events: 10000

- output/HPS_Nominal_iter0/lhe/TM_4pt55_TMm211pt0_100.lhe.gz
- output/HPS_Nominal_iter0/slic/TM_4pt55_TMm211pt0_100.slcio

readout_recon_TM

- subArray.sh (using readout_recon type)
- **hpstr_ana**

Config files: **recon - kalSimpTuple_cfg.py, ana - anaVtxTuple_cfg.py**
Steering files:
- readout: "PhysicsRun2019TrigPulse", "PhysicsRun2019TrigMultiSingles"
- recon: /org/hps/steering/recon/PhysicsRun2019MCRecon.lcsim

- /HPS_Nominal_iter0/PhysicsRun2019TrigPulse/TM_reco_100**(.root, .slcio)**
- /HPS_Nominal_iter0/PhysicsRun2019TrigMultiSingles/TM_reco_100**(.root, .slcio)**

hpstr_ana

- subArray.sh (using hpstr type)

Added following files to hpstr:
- /analysis/selections/vertexSelection_TM_4pt55.json
- /analysis/selections/Tight_TM_4pt55.json
- /analysis/selections/Tight_pTop_TM_4pt55.json
- /analysis/selections/Tight_pBot_TM_4pt55.json
- /analysis/plotconfigs/tracking/vtxAnalysis_TM_4pt55.json

Config: anaTMTuple.py (added into hpstr/processors/config)
Run_mode: 0
Year: 2019

- /HPS_Nominal_iter0/PhysicsRun2019TrigPulse/TM_4pt55_ana_100.root
- /HPS_Nominal_iter0/PhysicsRun2019TrigMultiSingles/TM_4pt55_ana_100.root

4.55 GeV (Preliminary)

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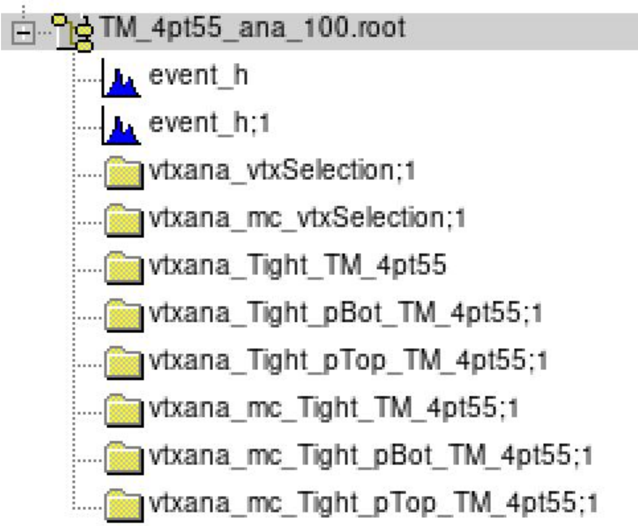
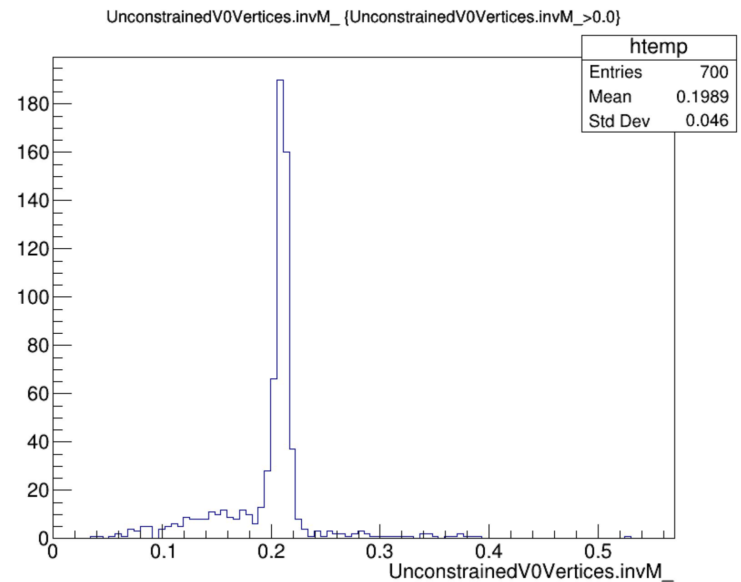
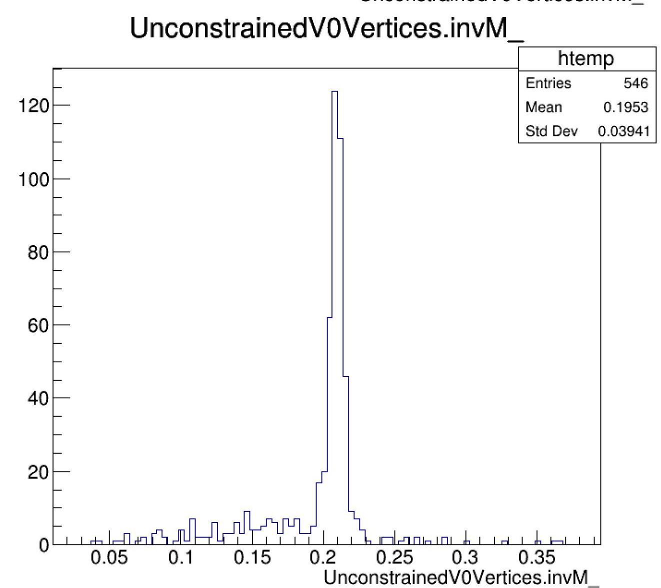






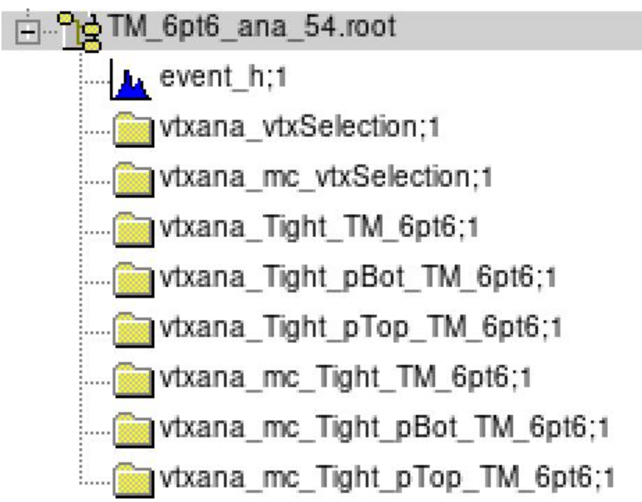
Note: Changes not made to original .json files. Will likely need to have TM specific changes and cuts (some are defined in previous Yale presentation).

Question for room: what plots would people like to see?

- Z-vertex vs mass distribution
- Momentum vs cluster energy
- TM Vertex Acceptance (for transitions too)

6.6 GeV (Preliminary)

- Tongtong made a new steering file that set DAQ configuration for a 6.6 GeV Beam **Future6pt6TrigSingles.lcsim** – thanks!
- Was able to go through the same procedure as for the 4.55 GeV
  - Tm_gen_to_slic → readout_recon → hpstr_ana
- Need to update .json files for appropriate cuts
- Noticed a print statement still set to 4.55 GeV (need to figure out where this is coming from)



Next Steps

- Finish calculation of yield to have comparison with yield
- Jupyter Notebook???
- Create weighting for z-distribution using cam's previous method
- Determine temp of target during run (dependent on E)
  - Determine appropriate alloy if need be
- Make more plots
- Calculate efficiencies and detector acceptance to compare with previous monte carlo from Yale presentation / thesis.