Preliminary

A review of and HPS discovery potential for True Muonium

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Road Map

- What is True Muonium?
- Calculating Primary Production Cross Section
  - Radiative
    - Dissociation and Ideal Targets
    - Calculating Yield
  - Three Photon Production Mechanism
- HPS-MC Study
  - 4.55 GeV Acceptance Result
  - 6.6 GeV Roadblock
- Next Steps

True Muonium

- True muonium is the exotic “fermionium” atom consisting of a bound (μ+ μ-)
- M_{TM}~ 2 Mμ (2 Mμ - Binding)
- Has yet to be experimentally verified
- True muonium decays sooner than constituent muons
- Offers unique precision test of QED
- 512 fm Bohr radius smaller than that of hydrogen
- Can be used to verify robustness of existing HPS software

Production of True Muonium

$$\pi^- p \to (\mathrm{TM})n$$

$$\gamma Z \to (\mathrm{TM})Z$$

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

$$Z_1 Z_2 \to Z_1 Z_2 (\mathrm{TM})$$

$$\boxed{\eta \to (\mathrm{TM})\gamma}$$

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

$$\mu^+ \mu^- \to (\mathrm{TM})$$

Production mechanism we care about

Mechanism Considered for LHCb run 3 search: Discovering True Muonium at LHCb

Production of True Muonium

Electro Production of Dimuonium

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

TABLE I: True fermionium decay times and their ratios.

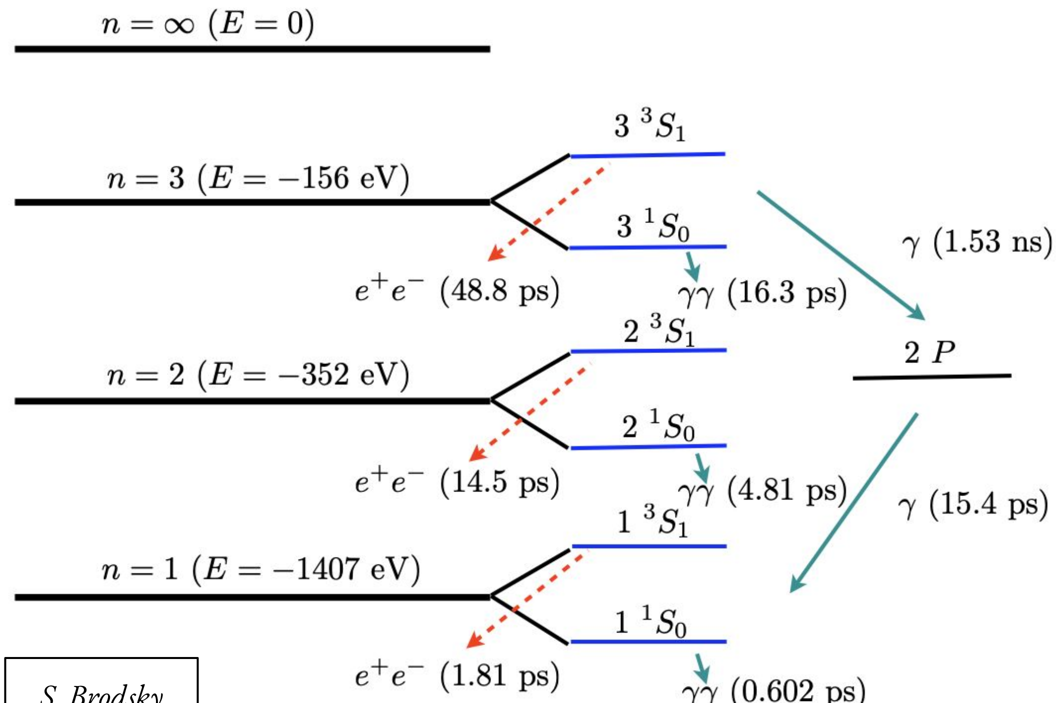
$$\tau(n^3S_1 \to e^+e^-) = \frac{6\hbar n^3}{\alpha^5 mc^2}\ ,\ \tau(n^1S_0 \to \gamma\gamma) = \frac{2\hbar n^3}{\alpha^5 mc^2}\ ,$$

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

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

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

True Muonium Level Diagram



S. Brodsky

Production of True Muonium

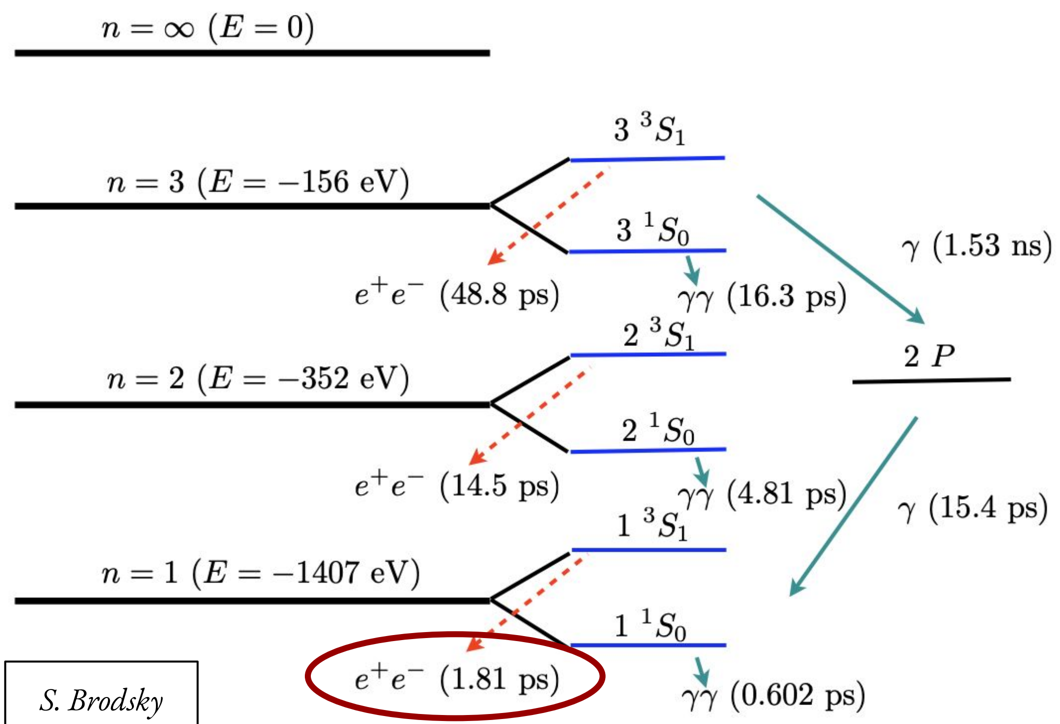
Electro Production of Dimuonium

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

Decay Length of Interest

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

True Muonium Level Diagram



S. Brodsky

Primary Production Modes of Orthodimuonium

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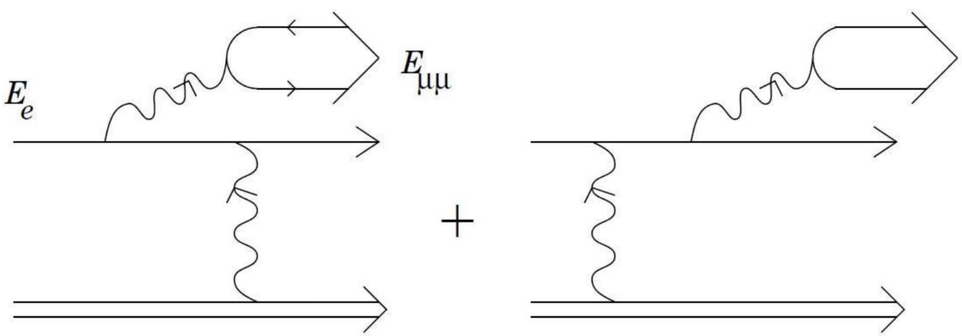
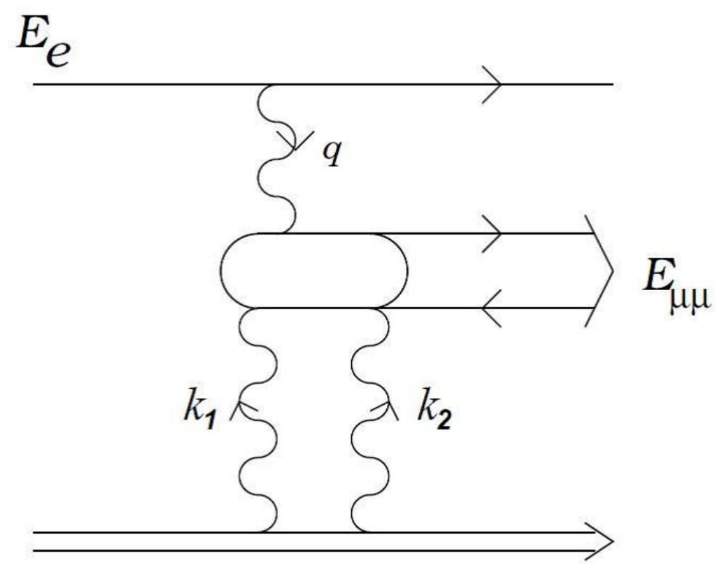
One photon (radiative) mode



Similar Kinematics to A' !

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

Three photon mode

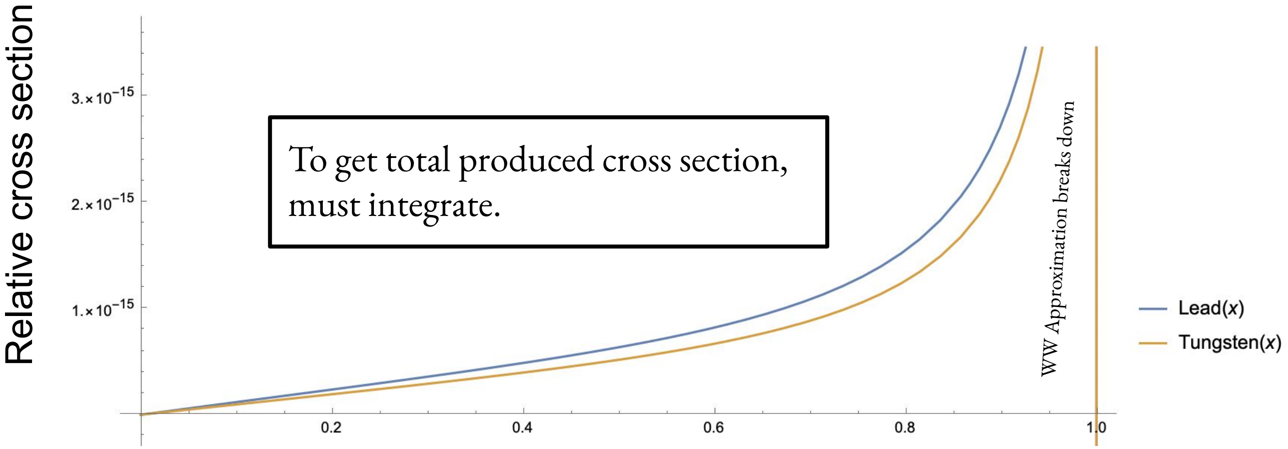


Oppressed by Bethe-Heitler Background

Scattering Angle: $\theta_{3\gamma} \sim \frac{\Lambda}{xE_0}$ $\Lambda = \frac{405}{A^{1/3}}$ MeV

Calculating Radiative Production Cross Section

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



$$x = \frac{E_{\mathrm{TM}}}{E_{\mathrm{beam}}}$$

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

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

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

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

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

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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)

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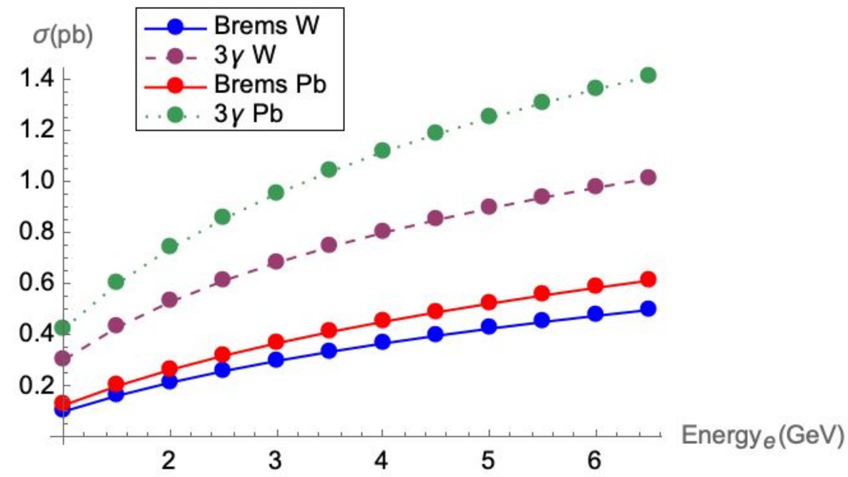
Element	Atomic number	Atomic Density (g/cm^3)	Atomic Number Density	TM (13S1-->X) cross section (pb)	Dissociation Length (micron)
Tungsten	74	19.4	6.34E+22	5.68E+16	2.78
Gold	79	19.3	5.90E+22	6.43E+16	2.64
Lead	82	11.4	3.30E+22	6.90E+16	4.39
Bismuth	83	9.75	2.81E+22	7.06E+16	5.04

- Changing the target would lead to an increased yield by changing the dissociation length and increasing overall integrated cross section.
- Still need to calculate temperature at target.



B. Yale. Integrated cross section for Lead and Tungsten compared at different beam energies.

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.

Calculating Yield (in progress)

Primary Contribution

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

$$z = \frac{l}{l_{1S \to X}}$$

Secondary Contributions

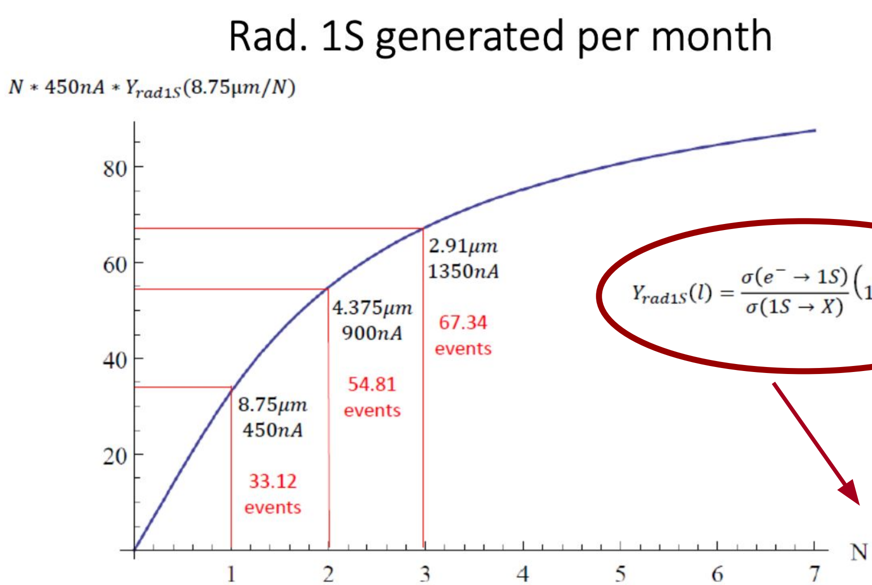
$$\frac{dN_{2S}}{dz} = N_e \frac{\sigma(e^- \to 2S)}{\sigma(1S \to X)} - N_{2S} \frac{\sigma(2S \to X)}{\sigma(1S \to X)} + N_{2P} \frac{\sigma(2P \to 2S)}{\sigma(1S \to X)}$$

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

Calculating Yield (in progress)

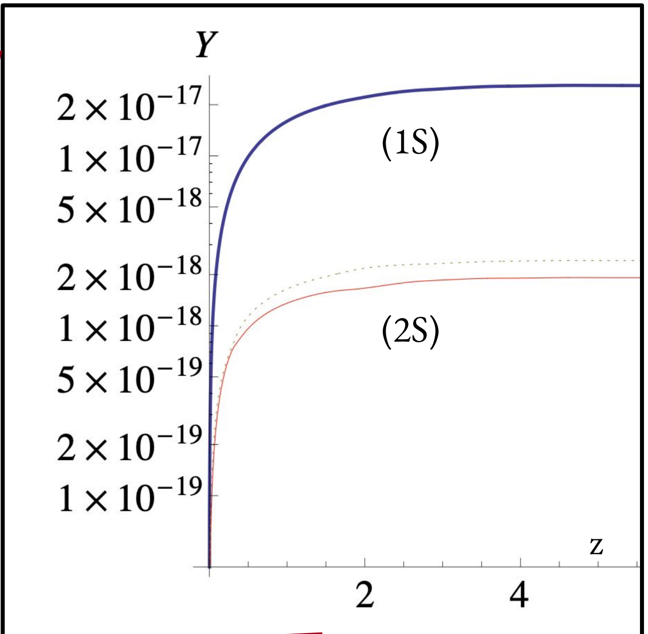
Primary Contribution

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



$$Y_{rad1S}(l) = \frac{\sigma(e^- \to 1S)}{\sigma(1S \to X)}\left(1 - e^{-\frac{l}{l_{1S \to X}}}\right)$$

Relative Yield



B. Yale. Optimizing events by maximizing luminosity for a tungsten target

P. Schuster. Relative abundance of TM as a function of distance traversed through target measured in units of dissociation length.

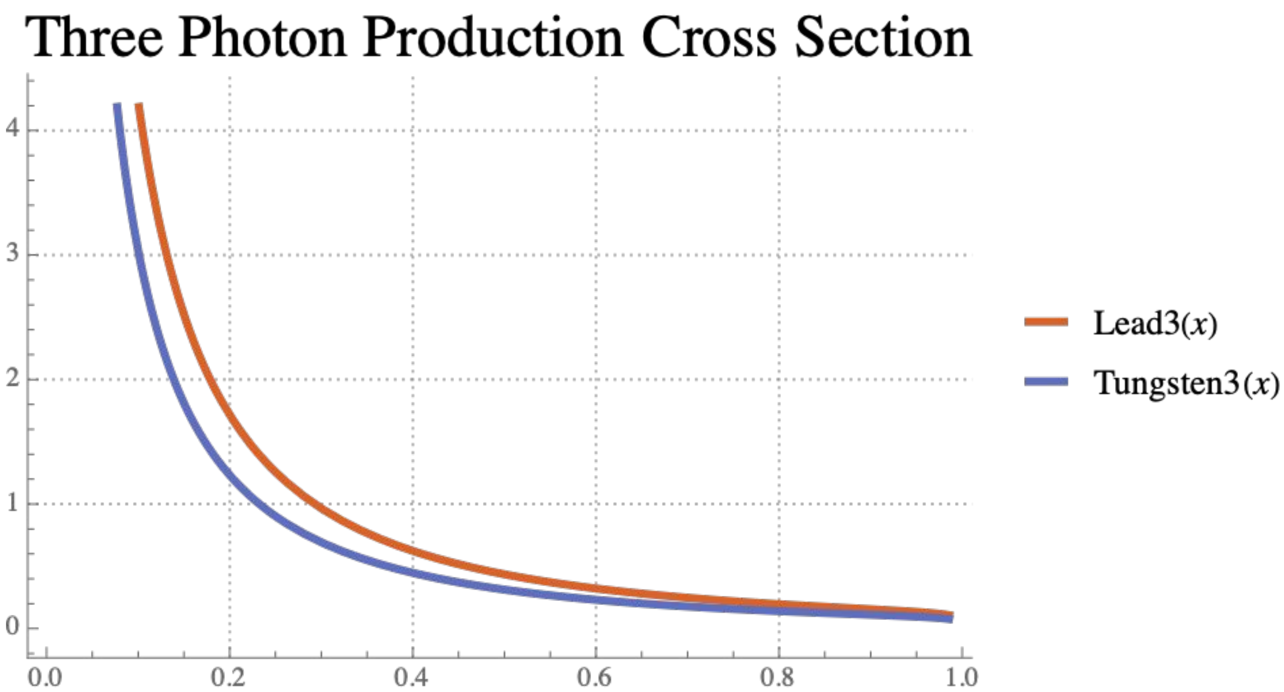
Calculating Yield (in progress)

- 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
  - Yale calculated **3.94 analyzable TM events per month**
  - With detector acceptance discussed later we expect **(2.58 - 3.15)** analyzable events per month

Calculating 3 Photon Production Cross Section

Taking into account atomic screening

$$\frac{d\sigma}{dx} = \frac{1}{4n^3} Z^2 \frac{\alpha^7}{m_\mu^2} \left(\frac{Z\alpha\Lambda}{m_\mu}\right)^2 \frac{4B}{x} \times \left(\left(1 - x + \frac{x^2}{2}\right) \mathrm{Log}\left[\frac{(1-x)\,(m_\mu)^2}{x^2\,(m_e)^2}\right] - 1 + x\right)$$



- More dependent on energy fraction than beam energy
- Calculating Total yield is equivalent process to radiative

Three photon mechanism is derived fully here: [Production of the bound triplet μ+ μ- system in collisions of electrons with atoms]

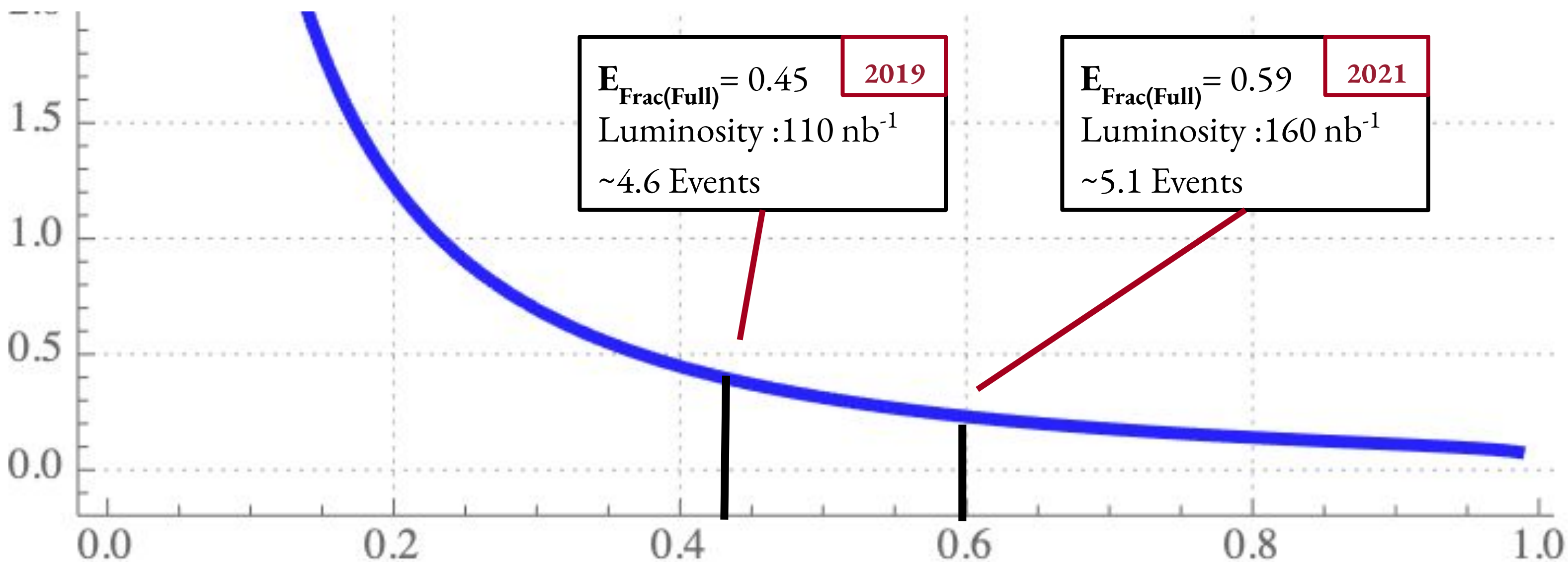
Prospects of 3 Photon Events in Previous Data (Without Acceptance Cuts)

Triggers used during runs limit number of potential events.

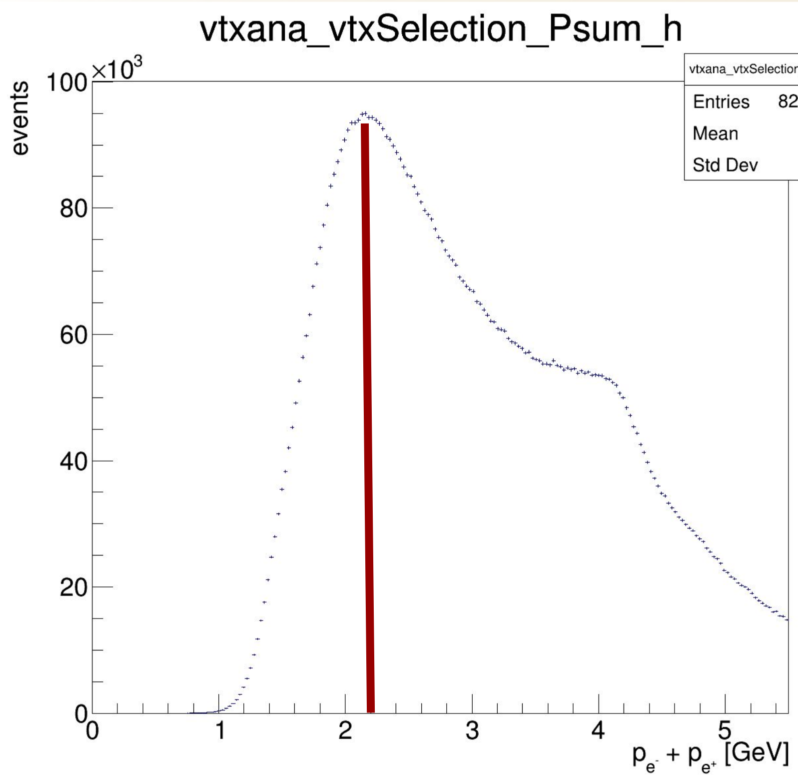
- 2019 and 2021 trigger reach full sensitivity at ~2.2 GeV,
- we are sensitive to ~½ events from 1 GeV - 2.2 GeV

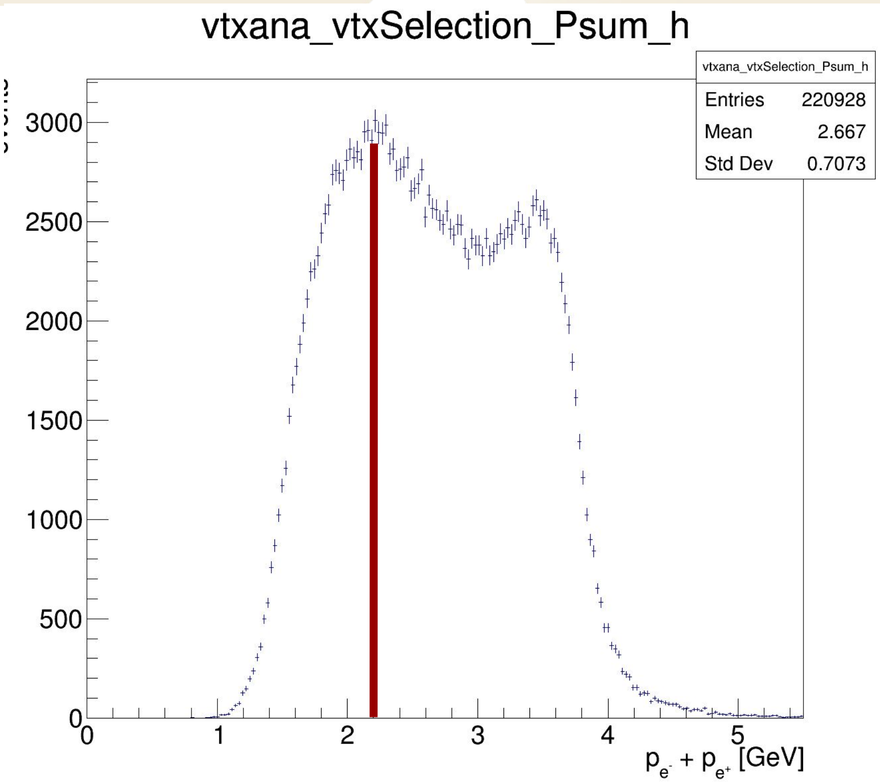
Year	$E_{Frac(partial)}$	$E_{Frac(Full)}$
2019	0.22	0.46
2021	0.27	0.59

Run Year	Total Number of Electrons	Int Cross section at Efrac (full) [pb]	Int Cross section at Efrac (partial) [pb]	Full Sensitivity Yield	Half Sensitivity Yield
2019	1.56E+18	0.099	0.147	2.72	1.93
2021	2.27E+18	0.059	0.141	2.35	2.81



Psum Plots illustrating optimal Efrac and detector sensitivity for 2019/2021





Full detector efficiency: 2019

Full detector efficiency: 2021

Note: previously mentioned partial sensitivity to events before reaching full efficiency. Total number slightly overestimated as more events are produced at lower $\mathbf{E_{Frac}}$

Plots: C. Bravo.

Summarizing Three Photon Production

- Total Events from 2019/2021 ~ 9.7
  - Motivating toy monte carlo study to more concretely determine kinematics and determine detector efficiency for these events.
- If these particles are traveling through detector, would then need to determine if a lower PSum trigger would help for future runs

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

ap_gen_to_slic → **readout_recon** → **hpstr_job**

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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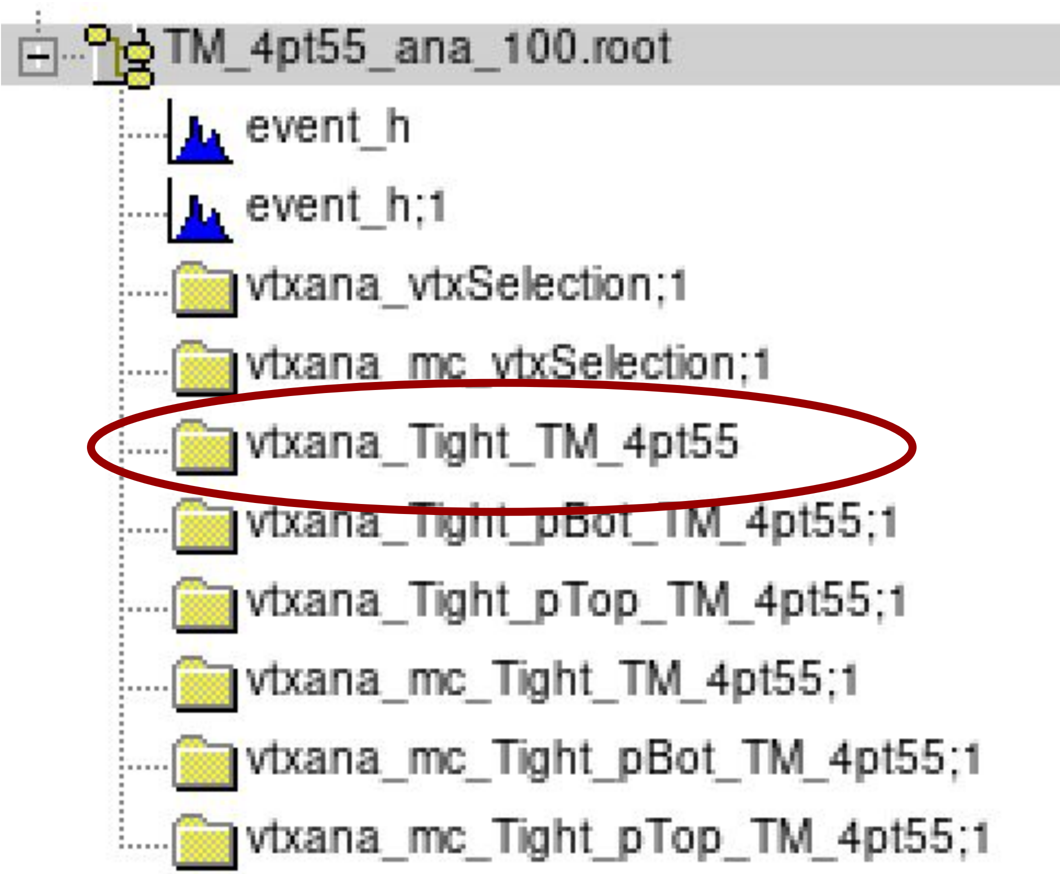
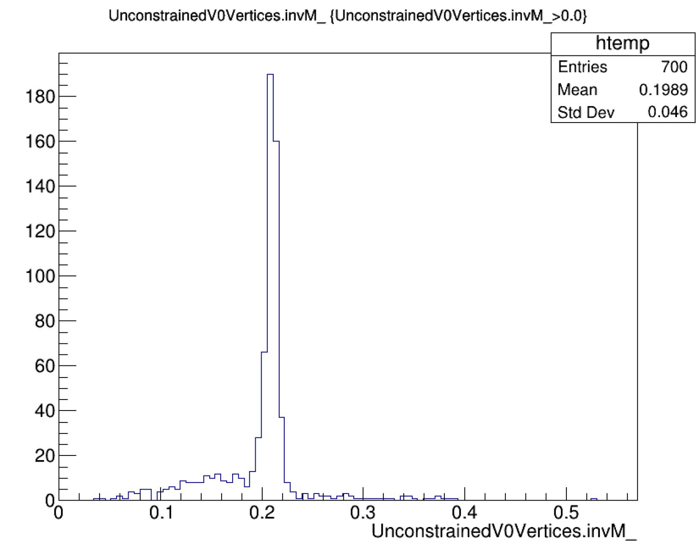
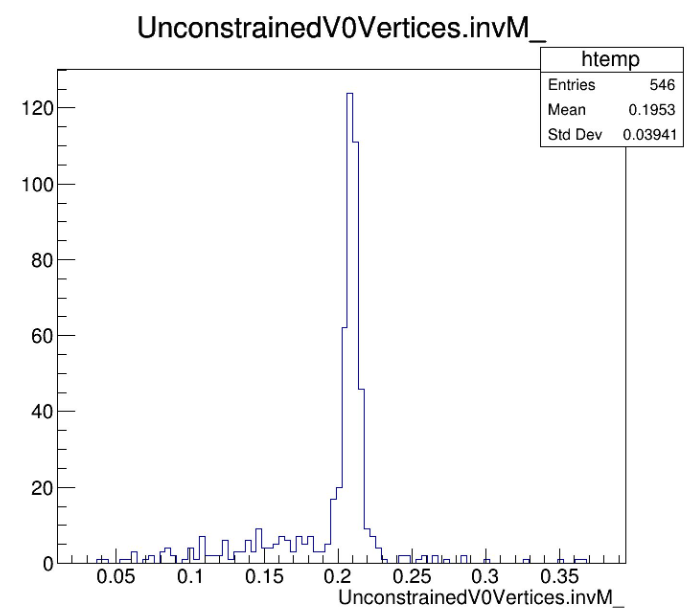
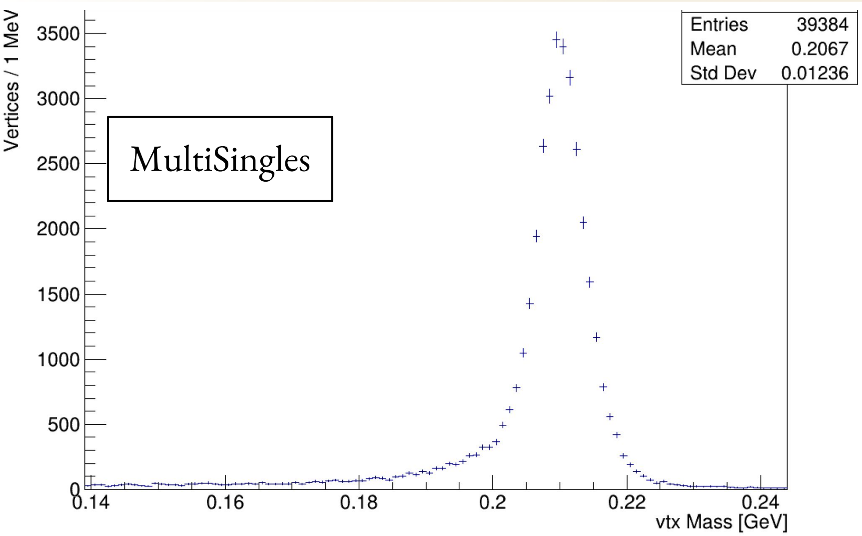
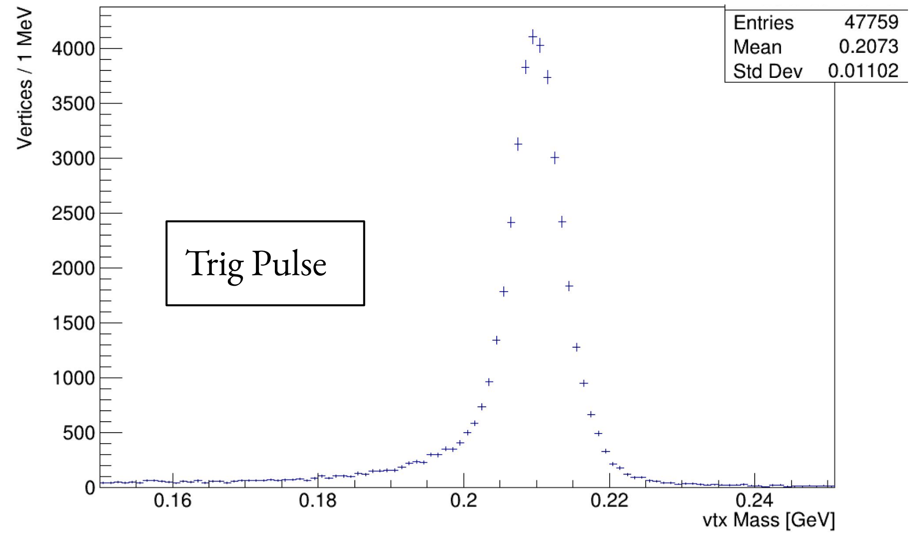


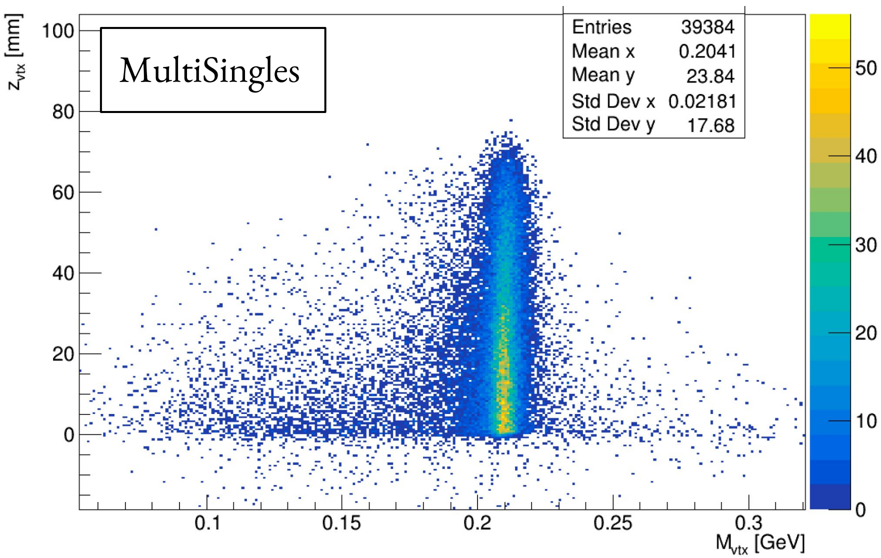


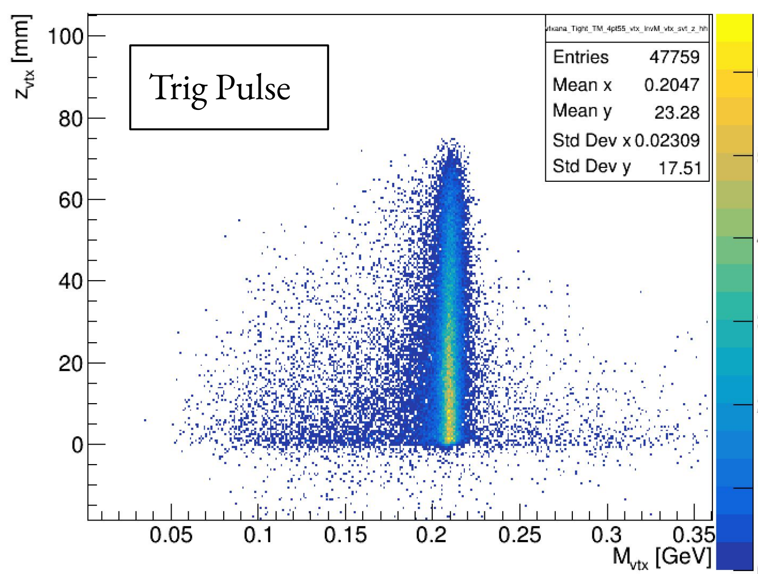


4.55 GeV Plots (1/2)

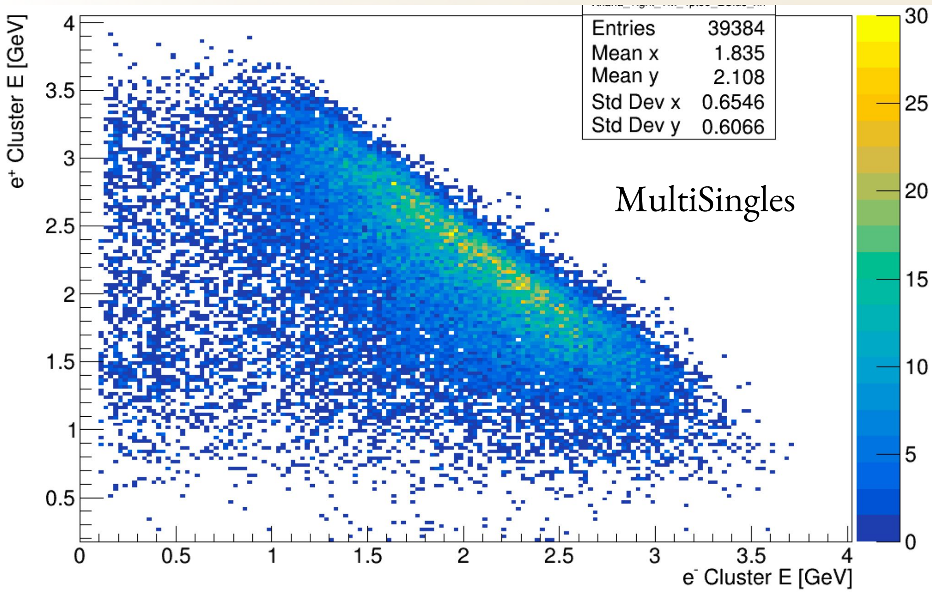


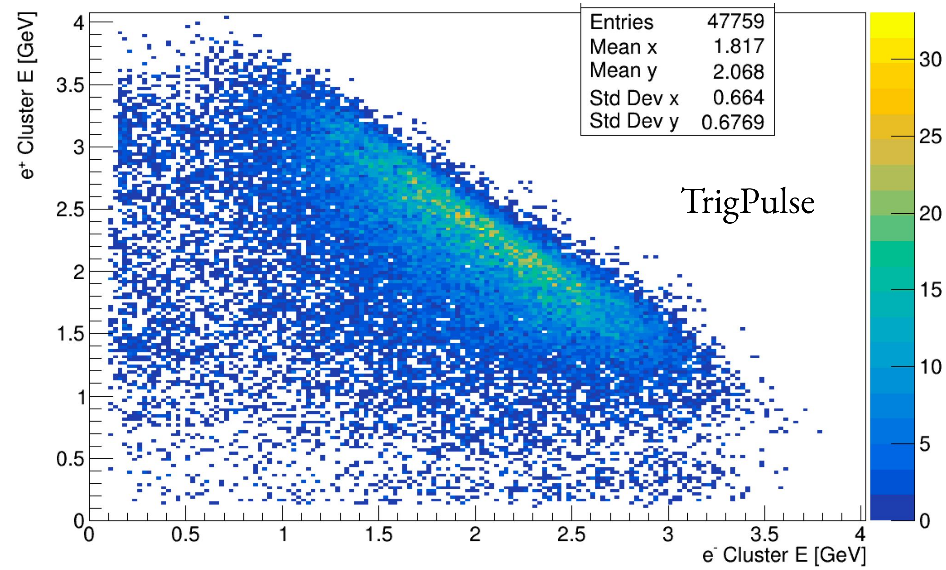




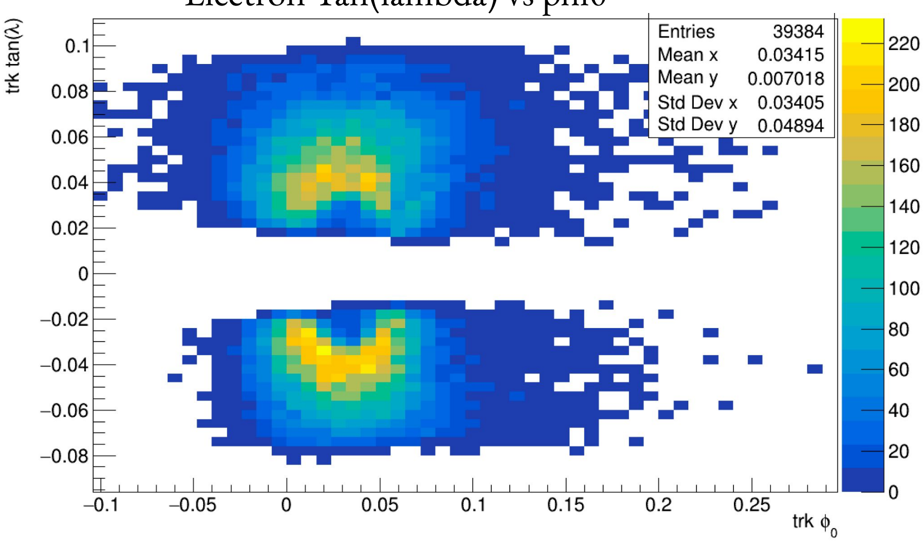


4.55 GeV Plots (1/2)

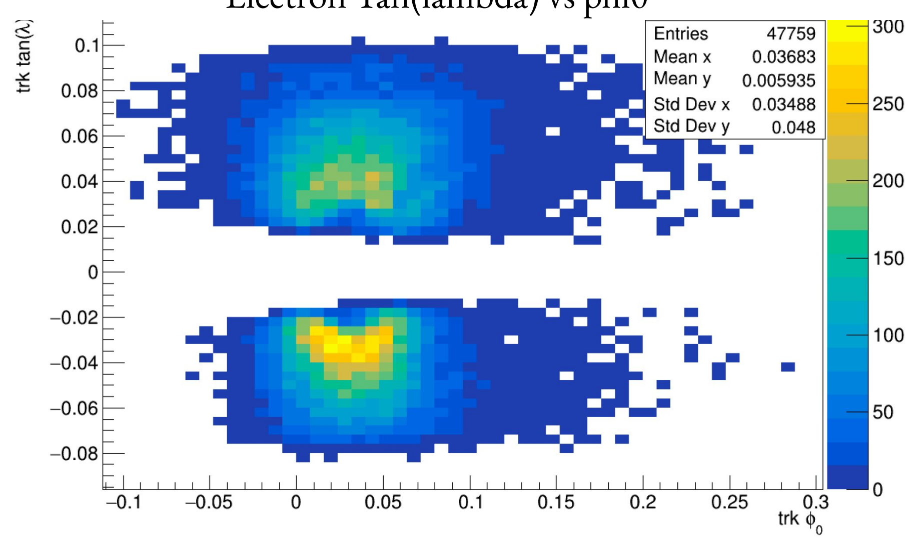




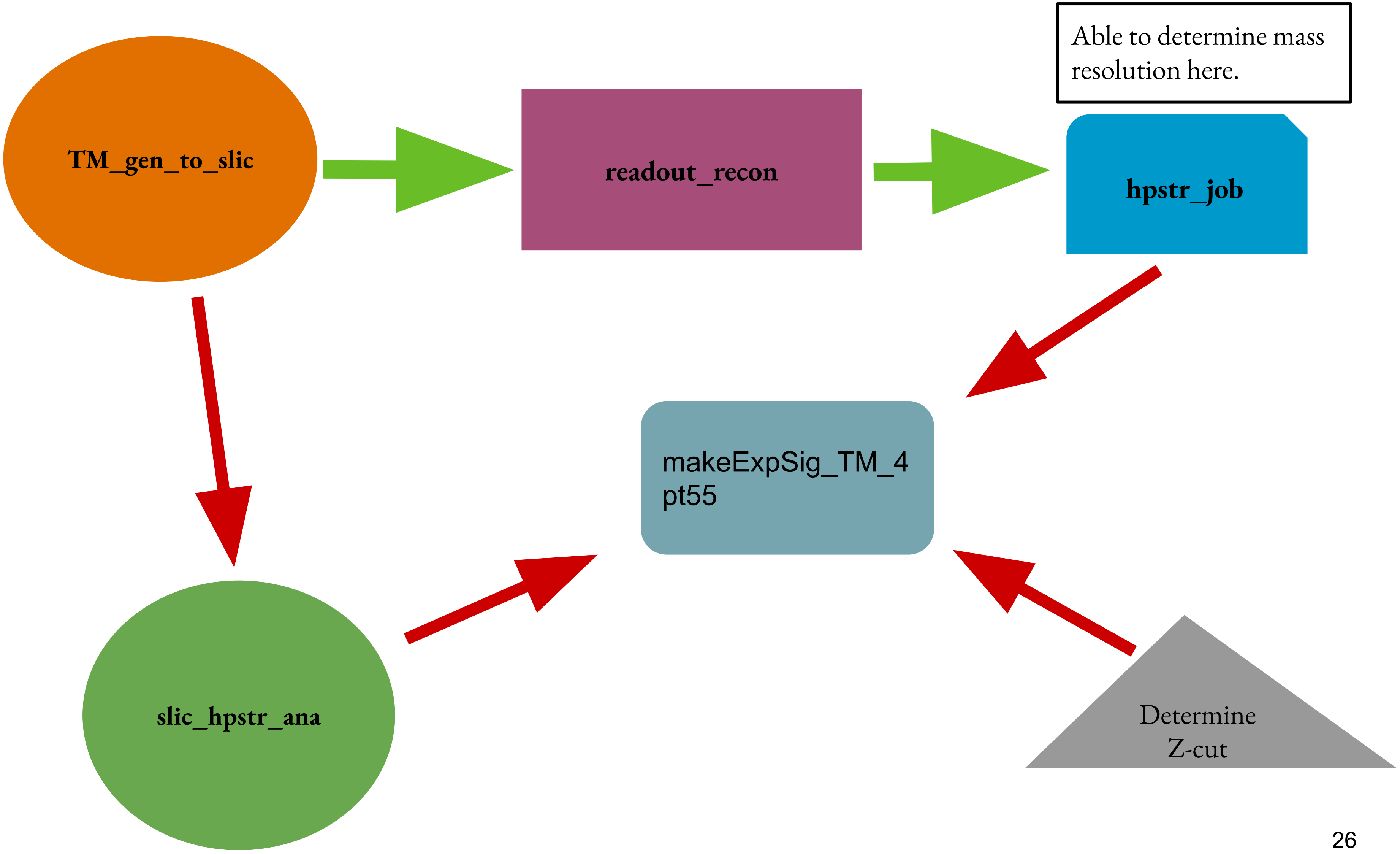
Electron Tan(lambda) vs phi0



Electron Tan(lambda) vs phi0

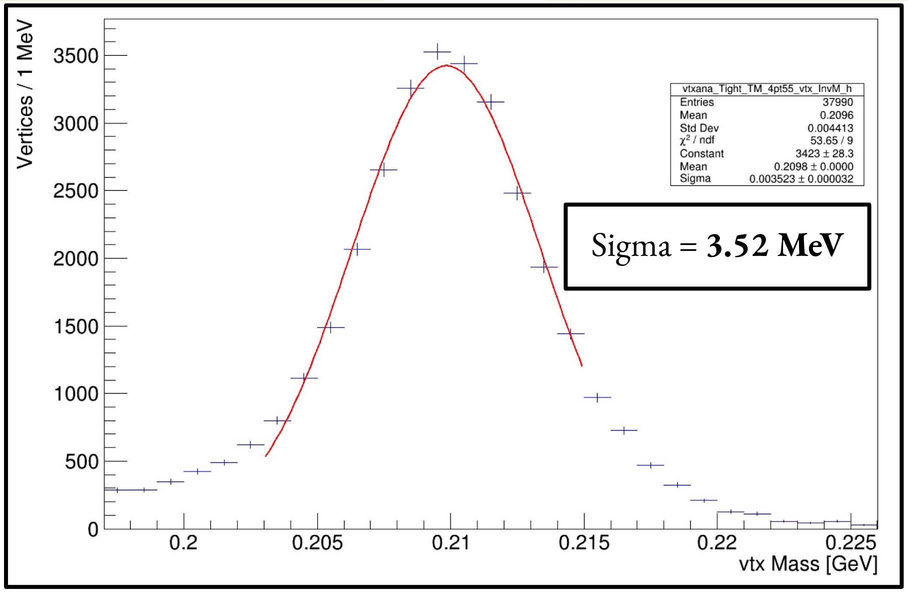


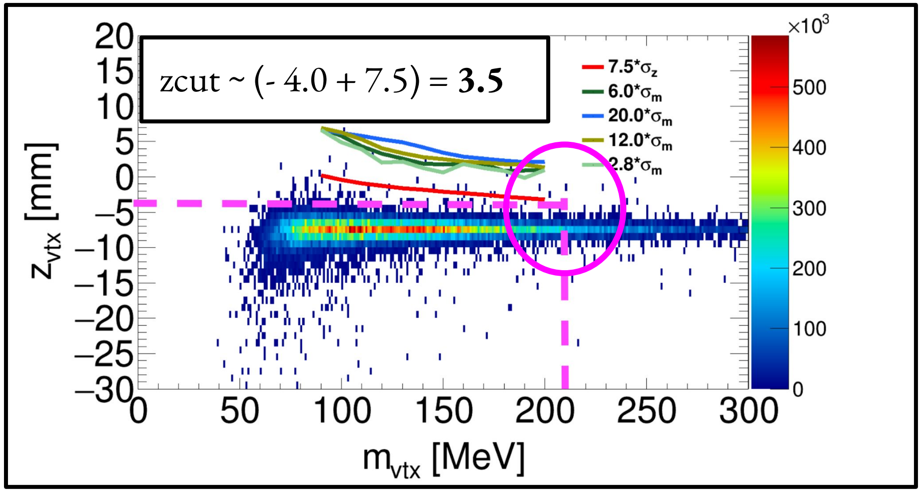
Vertex acceptance flow using /hps-mc/python/jobs



Calculating Vertex Acceptance for Radiative (1S) [1/2]

- Determine mass resolution of TM
  a. Fit gaussian to invariant Mass plot of hpstr TrigPulse output and determine sigma
- Determine ZCut for TM for each beam energy (using 0.0 as origin)
  a. If good stats for WAB and tritrig, use hpstr/plotUtils/reach/makeZcuts.py
  b. For 2019, sufficient to use Cam's reach estimate to determine zcut





C. Bravo. *Comparison of Zcuts for 2019 Reach.*

Using makeZcuts.py gave a zcut of 0.89, but input file stats were low and ultimately need to be redone to be thorough.

Sigma without PSum cuts was improved at 3.39 MeV.

Calculating Vertex Acceptance for Radiative (1S) [2/2]

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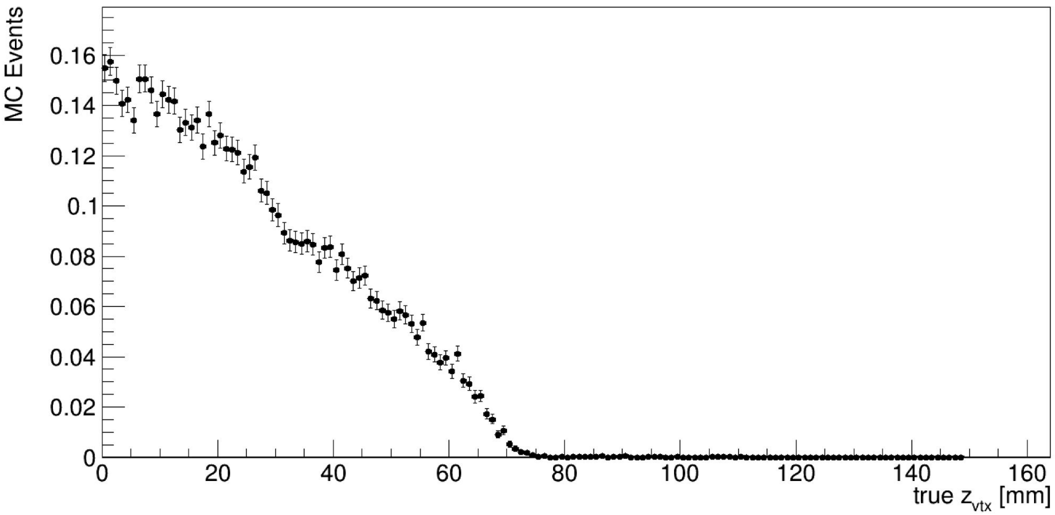
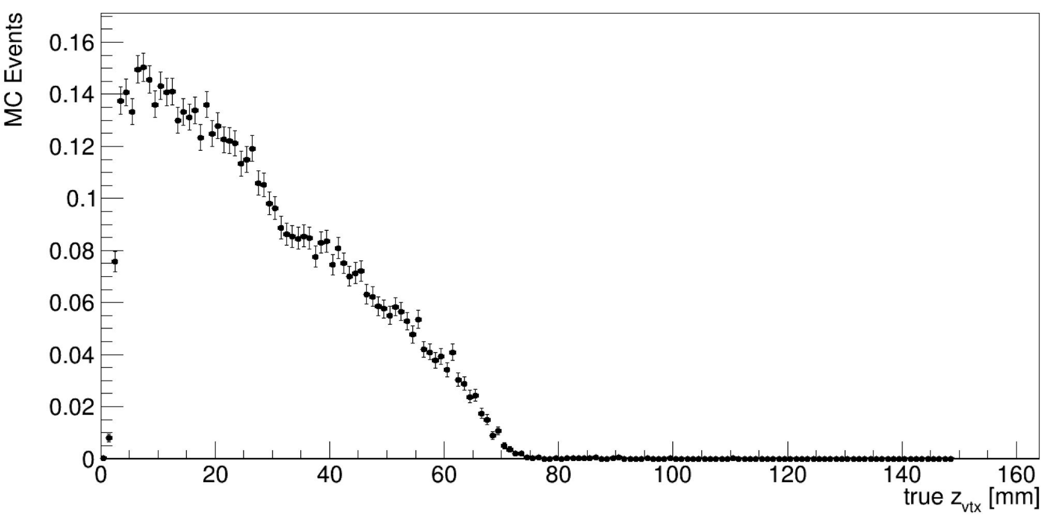
- Reformat / repurpose /hpstr/plotUtils/reach/summer20/makeExpSig2019.py to only use a single invariant mass (211 MeV) and
    a. use mass resolution and zcut determined previously
    b. Input files:
        i. hpstr output of the slic data
        ii. hpstr output of readout_recon (vtxana_Tight_TM_4pt55/vtxana_Tight_TM_4pt55_tree)
- Signal efficiency and normalized vertex selection gives vertex acceptance



Vertex Acceptance for Radiative (1S)

ZCut Applied	Momentum Cuts Applied?	Vertex Acceptance
0.89	No	12.50%
2.50	Yes	8.80%
2.50	No	10.50%
3.50	No	9.50%
4.50	No	8.60%



Radiative (1S) True Muonium Event (s) from Previous Data

Integrated Cross Section	Total Radiative Events	Zcut	Vertex Acceptance	Accepted Events
0.126 pb	3.5	3.5	(7.8 - 9.5)%	0.27 - 0.33

Must still determine consequences of removing psum cuts from Tight.json files to determine this.

This should motivate an acceptance study on 3.7 GeV.

- Radiative events from 2021: 1.92 anticipate accepting (0.61 - 0.77) events.
- Lower energy seems to marginally help with acceptance of TM as the on average decay length is shorter

Total Radiative Events	Total 3Photon Events	Anticipated Yield	Optimistic Accepted Events****
5.37	9.82	15.19	(1.18 - 1.44)

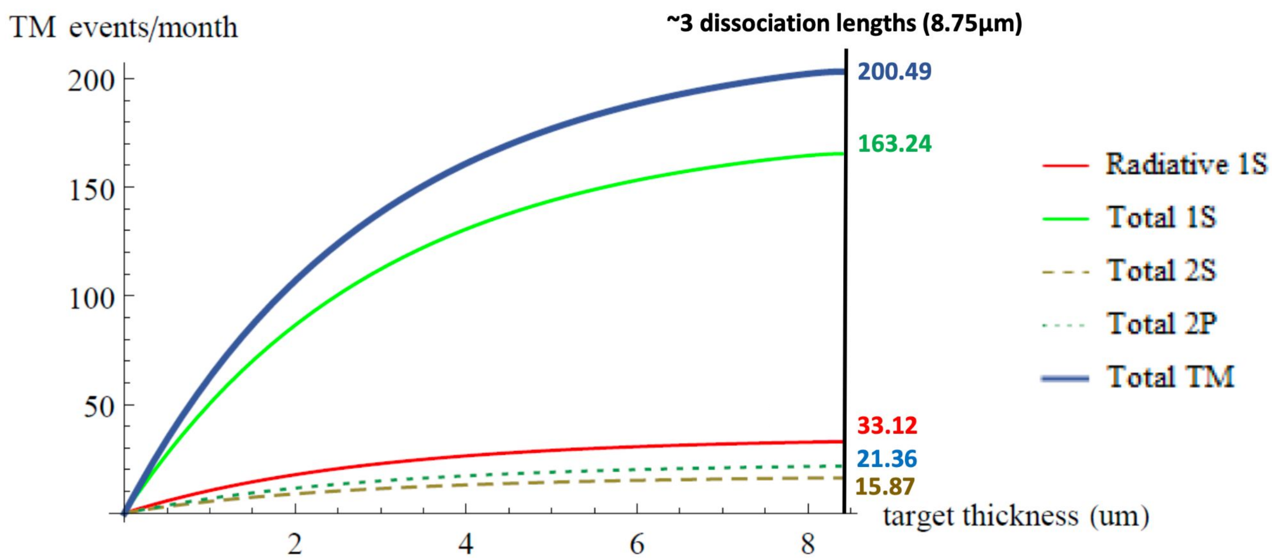
****Need to determine efficiency for radiative and 3 photon events to rigorously determine this.

6.6 GeV Future run?

True Muonium Generated (450nA)

Assuming current trigger cuts on three photon events and equivalent target, HPS would likely generate:

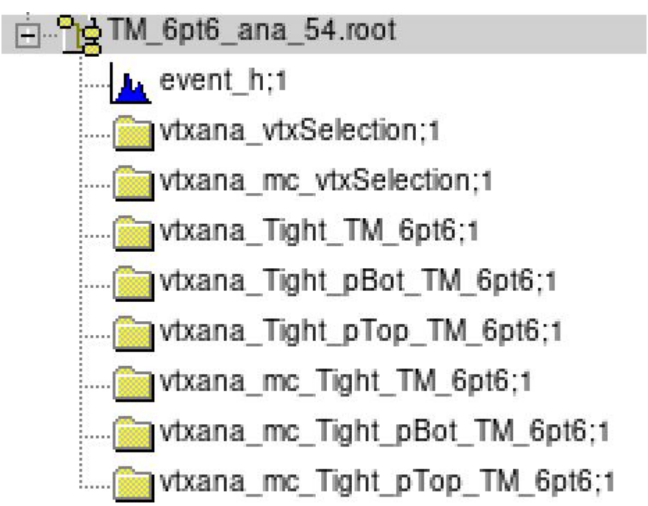
- 32 Three photon events
- 31 Radiative events



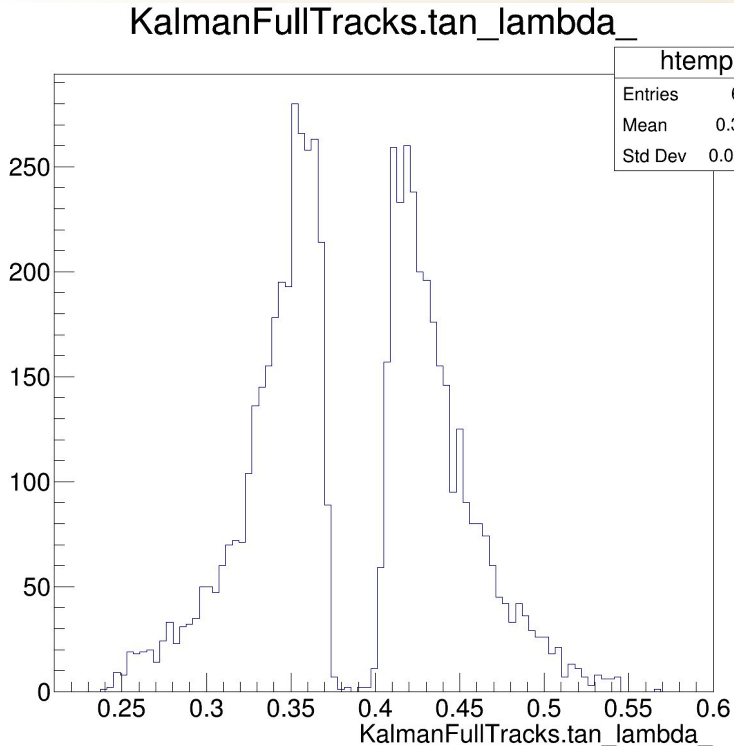
B. Yale. On the generation of true muonium.

6.6 GeV (Preliminary)

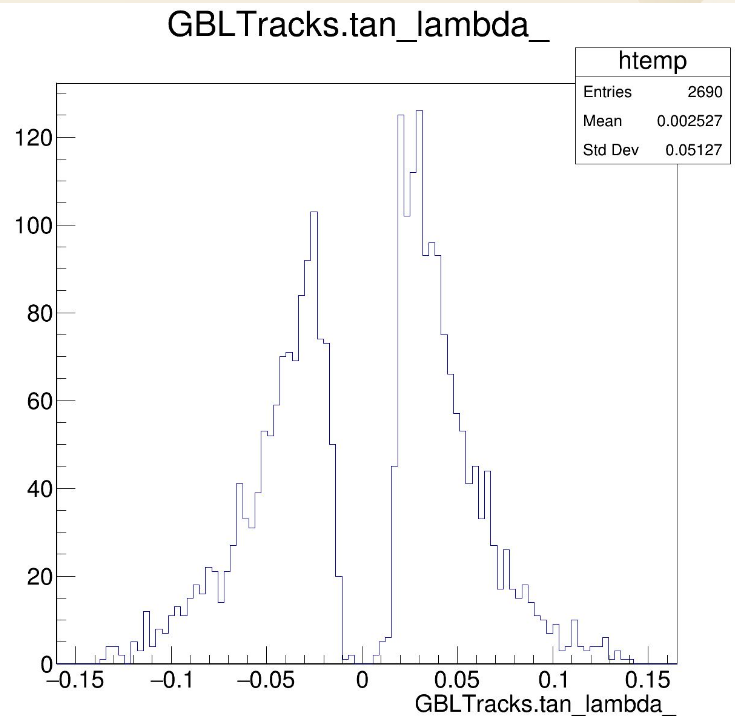
- Tongtong made a new steering file that set DAQ configuration for a 6.6 GeV Beam **Future6pt6TrigSingles.lcsim** – thanks!
- Was able to go through the same procedure as for the 4.55 GeV
    - Tm_gen_to_slic → readout_recon → hpstr_ana
- Noticed a print statement still set to 4.55 GeV (need to figure out where this is coming from)
- Have been stonewalled, next slide illustrates dilemma



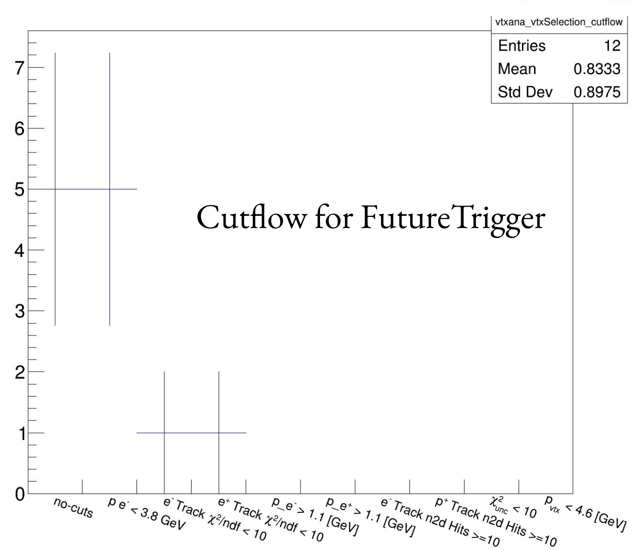
6.6 GeV Plots



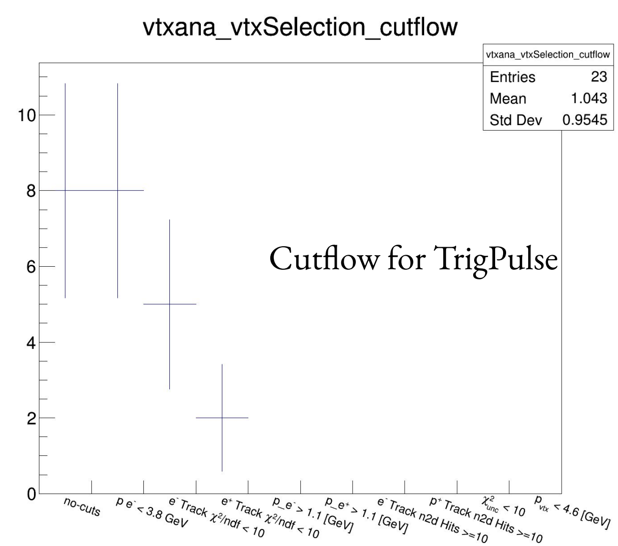
KalmanFullTracks.tan_lambda_
htemp
Entries 6279
Mean 0.3875
Std Dev 0.05681
KalmanFullTracks.tan_lambda_



GBLTracks.tan_lambda_
htemp
Entries 2690
Mean 0.002527
Std Dev 0.05127
GBLTracks.tan_lambda_



vtxana_vtxSelection_cutflow
Entries 12
Mean 0.8333
Std Dev 0.8975
Cutflow for FutureTrigger
no-cuts



vtxana_vtxSelection_cutflow
vtxana_vtxSelection_cutflow
Entries 23
Mean 1.043
Std Dev 0.9545
Cutflow for TrigPulse
no-cuts

Next Steps

- Finish acceptance study for 6.6 GeV
- Study kinematics of three photon mechanism
        - Then determine efficiency if these particles go through detector
- Determine temp of target during run (dependent on E)
- Determine optimal run parameters for 6.6 GeV beam
    - lead and tungsten comparative study
    - optimized trigger?

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)