Preliminary

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True Muonium: A Unique Opportunity for the HPS Collaboration

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05/10/2023

Preliminary

U.S. DEPARTMENT OF ENERGY

Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Road Map

True Muonium

- Brief TM primer
- Summary of Previous Research
- Bottom Line
- TM as ideal BSM Probe
- Next Steps

Additional Slides

- Calculating primary production cross section (3photon and radiative)
- HPS-mc studies

Production of True Muonium

SLAC

$M_{TM} \sim 2\, M\mu\ (2\, M\mu$ - Binding)

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

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

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

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

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

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

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

Production mechanism we care about

Production of bound $\mu^+\mu^-$ systems in relativistic heavy ion collisions

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

Fool's Intersection Storage Rings - Brodsky

DIMUS: Super-Compact Dimuonium Spectroscopy Collider at Fermilab **March 2022 Proposal**

Production of True Muonium

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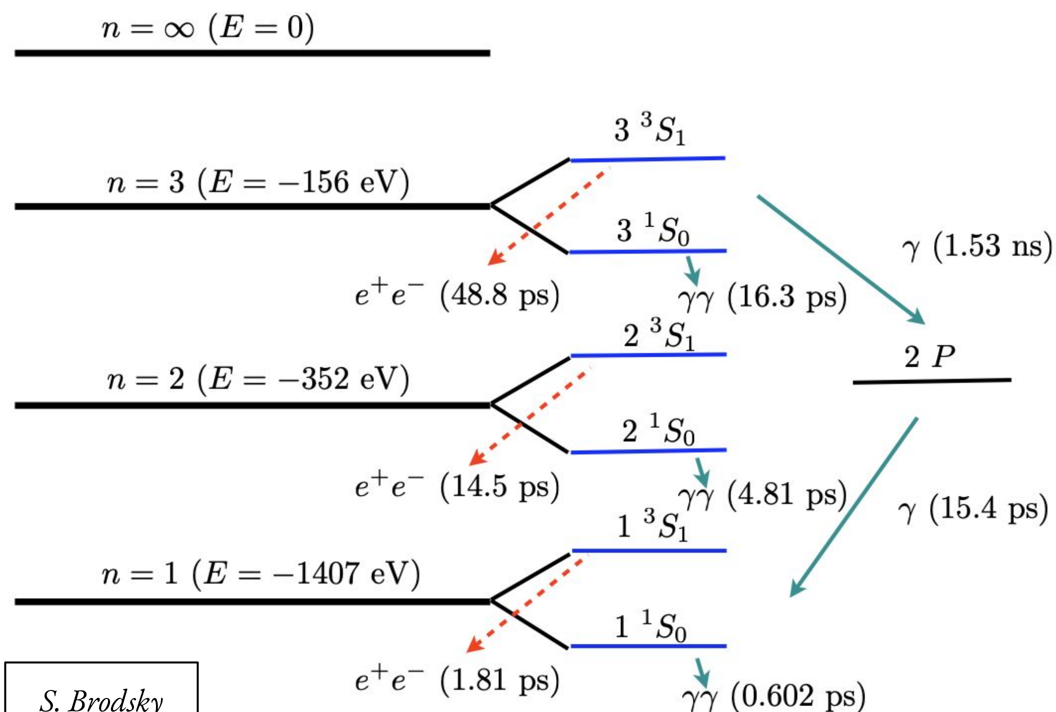
Production mechanism we care about

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

Production of True Muonium

True Muonium Level Diagram



S. Brodsky

Electro Production of Dimuonium

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

TABLE I: True fermionium decay times and their ratios.

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

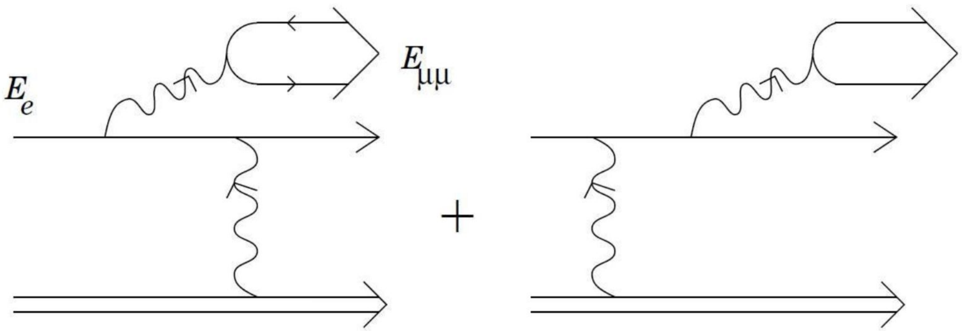
$$\tau(2P \to 1S) = \left(\frac{3}{2}\right)^8 \frac{2\hbar}{\alpha^5 mc^2}\ ,\ \tau(3S \to 2P) = \left(\frac{5}{2}\right)^9 \frac{4\hbar}{3\alpha^5 mc^2}\ ,$$

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

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

Primary Production Modes of Orthodimuonium

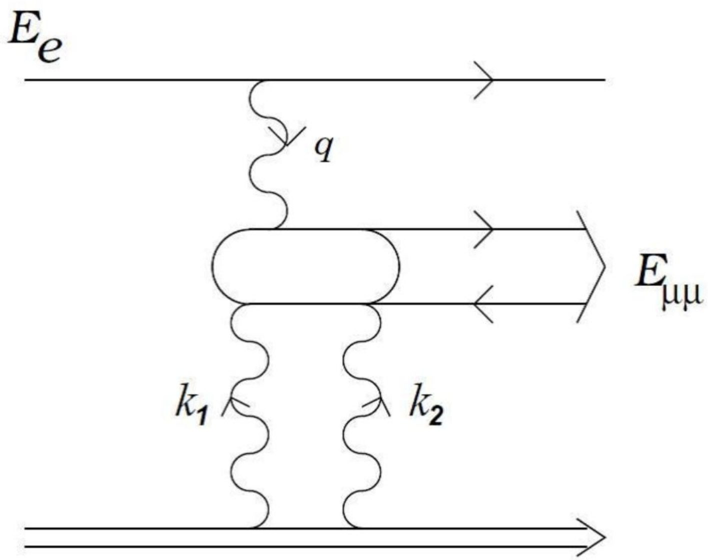
One photon (radiative) mode



Similar Kinematics to A' !

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

Three photon mode



Oppressed by Bethe-Heitler Background

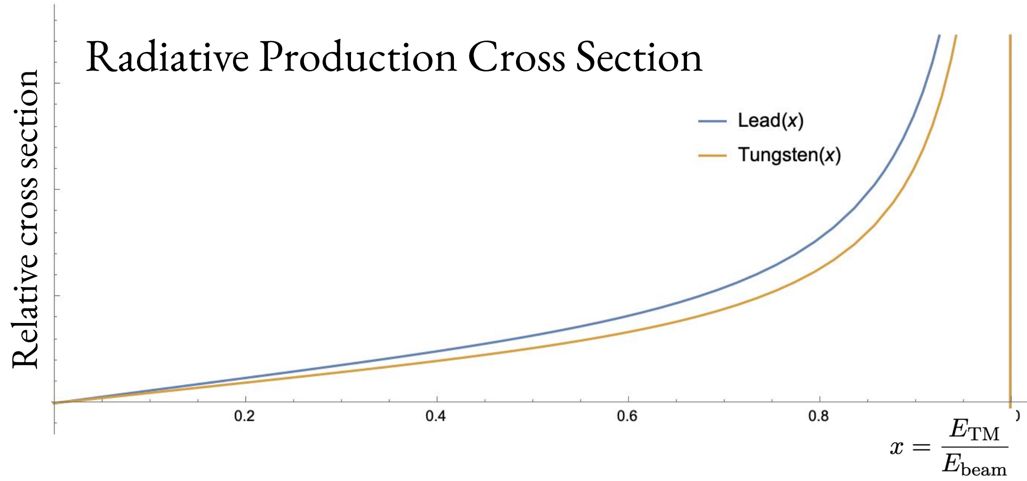
Scattering Angle: $\theta_{3\gamma} \sim \frac{\Lambda}{xE_0}$ $\Lambda = \frac{405}{A^{1/3}}$ MeV

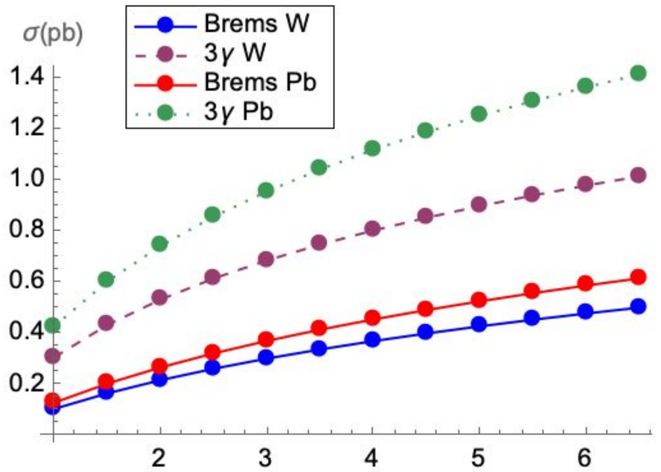
Summary of different production modes

Radiative
- Well understood within HPS framework
- Peaks at High Efrac

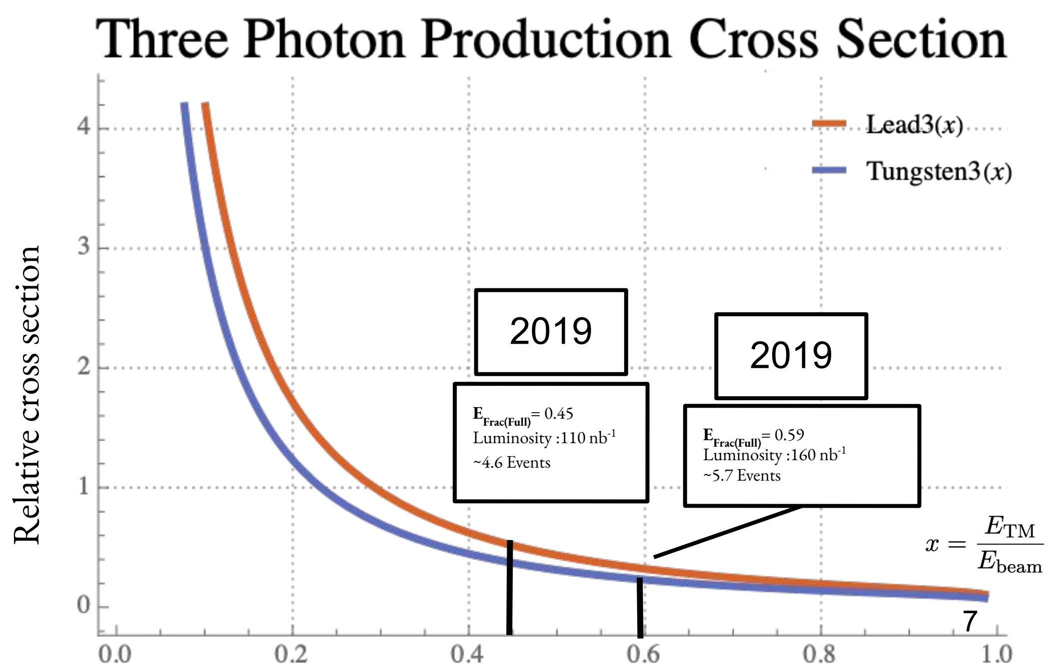
Three Photon
Many challenges
- Kinematics need to be better understood
- vertex acceptance study necessary

Peaks at low Efac ⇒ we cut a lot of this with triggers





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



Broad Summary of Previous Work (as fleshed out in additional slides)

- Calculated dissociation lengths of (1S) state for various materials
- Determined total yield for radiative (1S) state excluding extra gained from "reverse dissociation" (does include loss from (1S) dissociation)
- Determined first order approximation of total three photon (1S) yield (taking into consideration positron trigger turn on)
- Conducted HPS-mc study to determine 4.55 GeV vertex acceptance result of TM radiative events (7.9-9.5)% depending on mom cuts used
- Began study for 6.6 GeV vertex acceptance

True Muonium: Bottom Line

In 2019/2021:

[3photon/radiative]

- 16.1* detectable (1S) TM particles produced [10.37/5.77] (*total higher from 3photon but cut by trig)
- ~1.4 Events Accepted [1.10/0.30]**

  (anticipated after all cuts, assuming uniform acceptance for production mechanisms and beam energies – **not necessarily true)

In 2025:

- opportunity to change trigger thresholds or add dedicated trigger and Pb target

  (as proof of concept test for dedicated run)
- **higher energy** $\Rightarrow$ more TM produced $\Rightarrow$ shorter path to 5σ

Dedicated 1 month 6.6 GeV run:

(450 nA, 8.75 um target, similar trigger cuts for 3Photon and similar acceptance)

- 63 Total (1S) Events [32/31]
- 5.04 Events Accepted [2.56/2.48]

Lead target $\Rightarrow$ **91 total – 7.3 accept** (proportionally determined, need to verify further)

True Muonium: Beyond the Discovery

With current experimental configuration, HPS will not be able to do much more than discover TM. That is fine.

- By following through on our unique opportunity for discovery, however, we may be well suited to lead the charge on utilizing TM as a probe for BSM physics through next generation silicon vertex tracking detectors or development of spectroscopic instrumentation and phenomenology.
- With current SM discrepancies pertaining to muons, HPS will not always have a competitive edge.

TM, by means of QED precision measurements, offers an exciting and perhaps bountiful window into BSM physics.

- TM is directly below the dimuon threshold (-binding energy of ~1.4 keV)
- TM can be considered analogous to positronium (bound leptonic pair)

True Muonium as an Ideal BSM Probe Candidate

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Heaviest possible metastable pure-QED system for QED precision tests

- $(\mu+\ \mu-) >_{\text{inv mass}} (\mu+\ e-)$, $(e+\ e-)$, $(\mu-\ e+)$
- $\mu-$ [(2.2 e -6) s] >> $(\mu+\ \mu-)_{(1S)}$ [~1 ps]
  - True Muonium decays far sooner than constituents.
- $\tau-$ [291 fs or 146 fs] ~~ $(\tau+\ \tau-)_{(1S)}$ [36 fs or 107 fs]
  - This implies competition between $(\tau+\ \tau-)$ annihilation channel and weak decay of constituent τs. $\Rightarrow$ **not pure QED system**
- $(\mu-\ \tau+)$, $(\mu+\ \tau-)$ decay too quickly and are not true bound states (quasibound/resonant states)

USEFUL: A short review about some exotic systems containing electrons, muons, and tauons

Smallest radius possible pure QED system

- Radius (512 fm) < hydrogen atom (526 fm), positronium (~1050 fm)

True Muonium as an Ideal BSM Probe Candidate

Studies exist for positronium! But discovery potential exists outside **the muonic sector** and is further constrained by low electron rest mass

- **Precise measurement of positronium**
- An Improved Limit on Invisible Decays of Positronium
- First search for invisible decays of ortho-positronium confined in a vacuum cavity
- Current and future perspectives of positronium and muonium spectroscopy as dark sectors probe

TM , a purely muonic system, may offer insights into:

- anomalous magnetic moment aμ
- proton's charge radius from muonic hydrogen
- D meson and B meson decay to leptons

True Muonium: Future Work

- 3 photon production kinematics study to determine detector overlap **(PRIORITY)**
- 4.55 GeV Vertex Acceptance for 3Photon
- 3.74 GeV Vertex Acceptance for 3Photon, radiative
- 6.6 GeV Vertex Acceptance for 3Photon, radiative
- Verify lead doesn’t melt in beam

- Begin working on dedicated run proposal for TM

- Would like to lead more regular TM (bi or tri weekly) meeting to regularly update collaboration on progress, solicit feedback, and hold dedicated discussions [if people are interested, no one required to show up, everyone welcome]
    - may highlight different papers to discuss if progress slow
    - as this work does not neatly fit in any particular scheduled meeting time (summer thing Matt mentioned??)

Concluding Remarks

Discovery of true muonium will be an important milestone in the future of particle physics, as either the end of a QED era or the beginning of something else entirely.

HPS is in the unique position to prove predictive and detection capabilities by leveraging a dedicated case study of our vertex tracking methods.

Worthwhile Resources

- 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)

- H. Lamm. True Muonium: the atom that has it all.

ADDITIONAL SLIDES

(basically entirety of Fall 2022 Collab Meeting)

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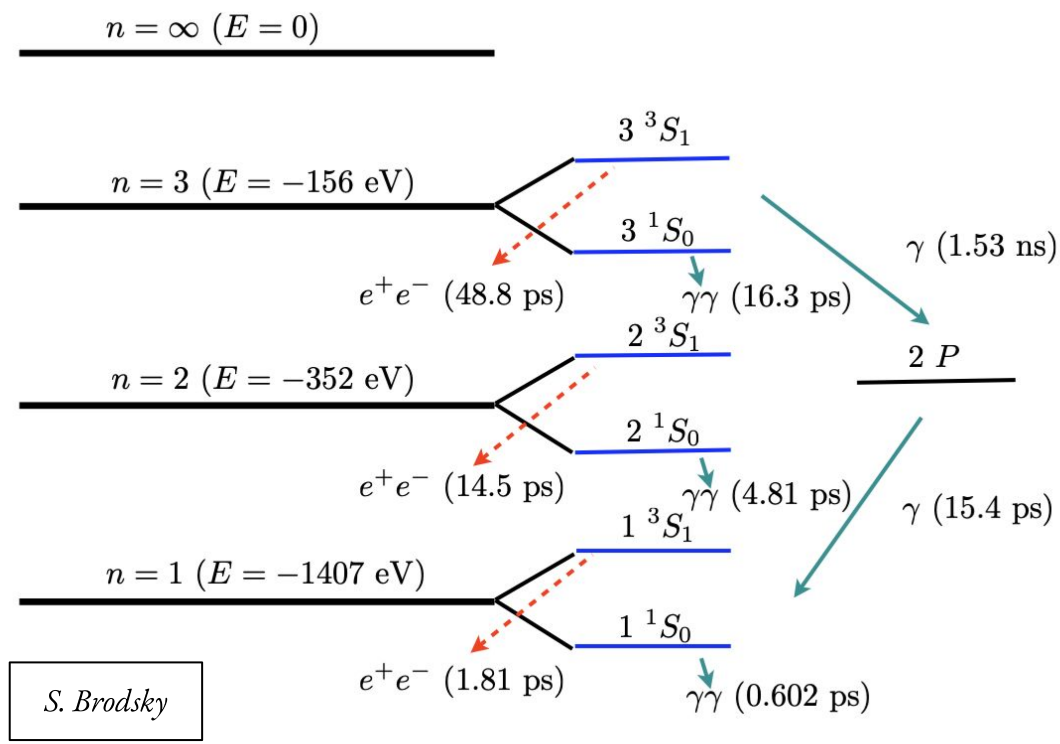
True Muonium Level Diagram



Production of True Muonium

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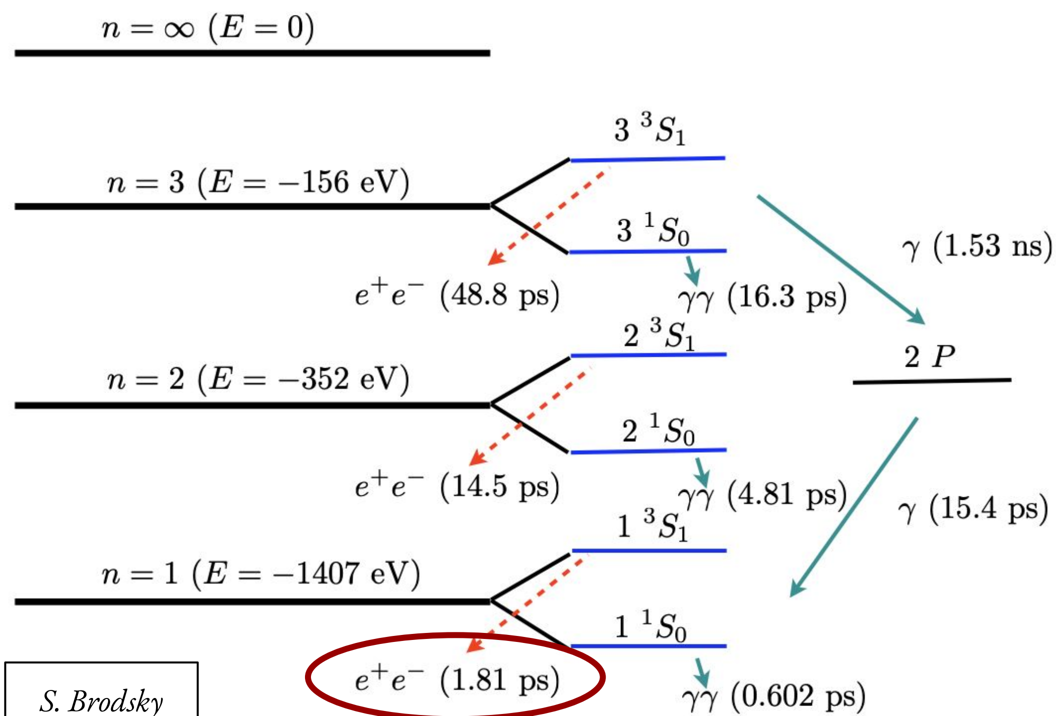

S. Brodsky

Electro Production of Dimuonium

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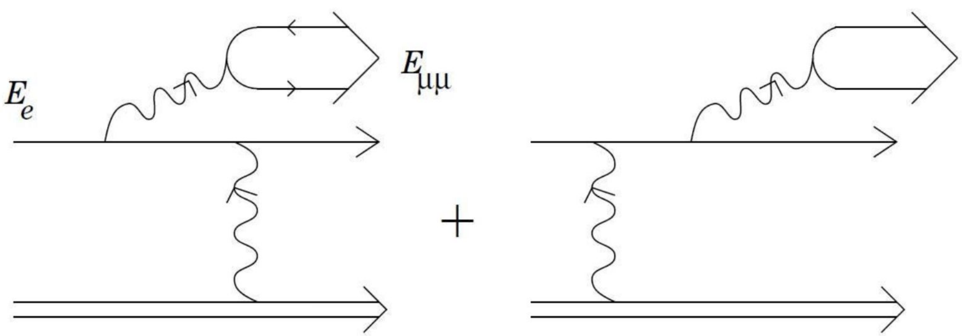
Decay Length of Interest

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

Primary Production Modes of Orthodimuonium

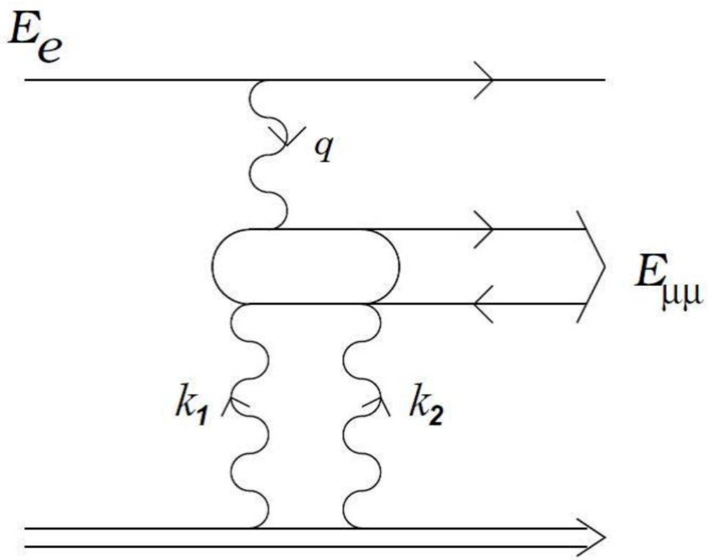
One photon (radiative) mode



Similar Kinematics to A' !

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

Three photon mode

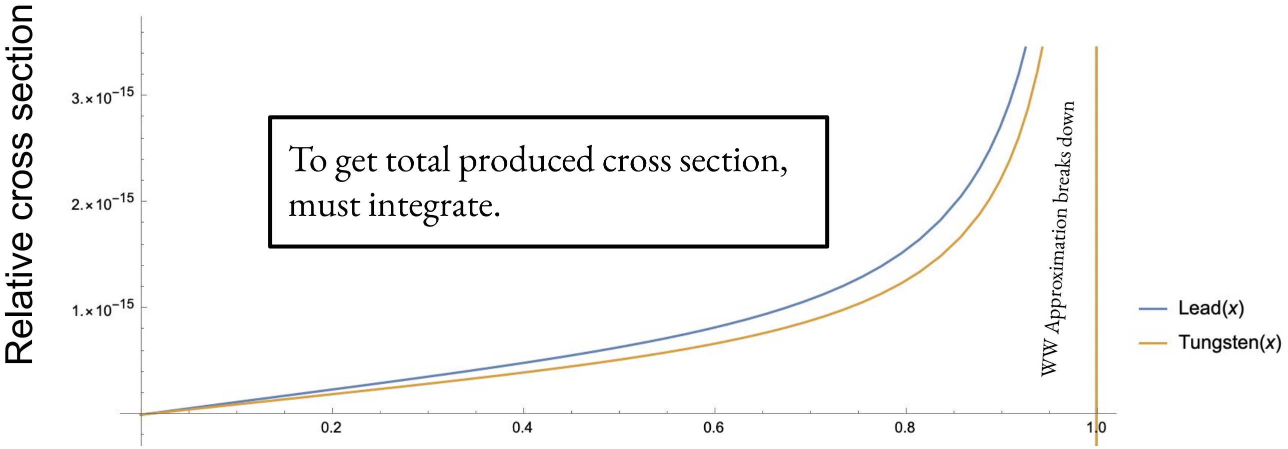


Oppressed by Bethe-Heitler Background

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

Calculating Radiative Production Cross Section

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



To get total produced cross section, must integrate.

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

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

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

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

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

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SLAC

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Dissociation Length of Interest

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

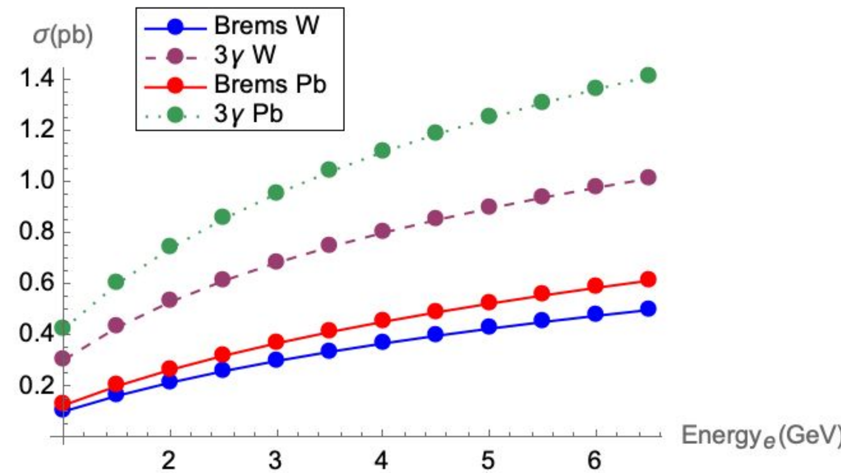
Note: more complete calculation in [Contribution of α2-terms to the total interaction cross sections of relativistic elementary atoms with atoms of matter]

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

- 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)

SLAC

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

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

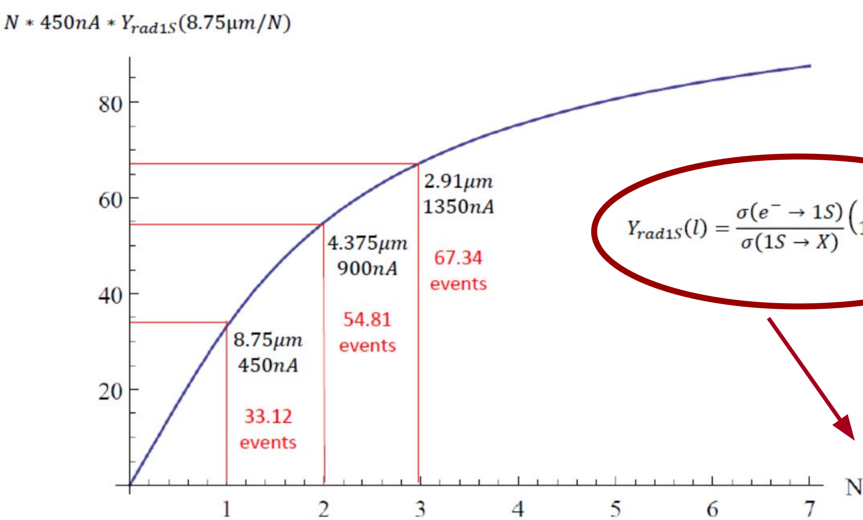
$$\frac{dN_{2P}}{dz} = N_e \frac{\sigma(e^- \to 2P)}{\sigma(1S \to X)} - N_{2P} \frac{\sigma(2P \to X)}{\sigma(1S \to X)} + N_{1S} \frac{\sigma(1S \to 2P)}{\sigma(1S \to X)} + N_{2S} \frac{\sigma(2S \to 2P)}{\sigma(1S \to X)}$$

Calculating Yield (in progress)

Primary Contribution

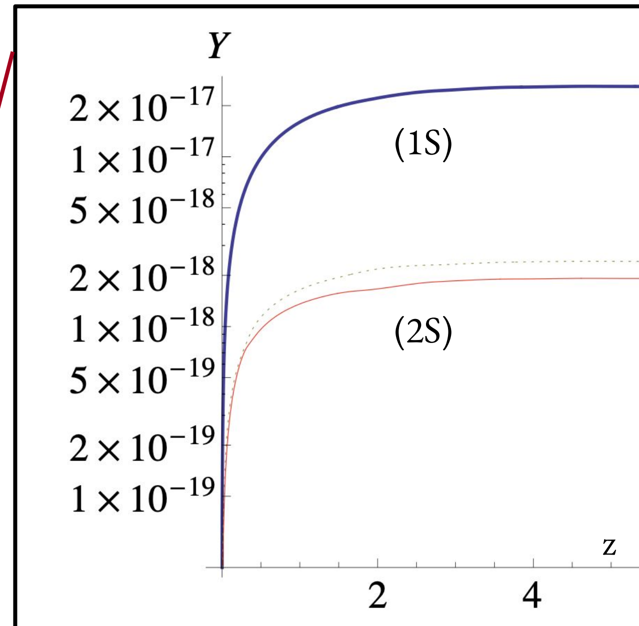
$$\frac{dN_{1S}}{dz} = N_e \frac{\sigma(e^- \to 1S)}{\sigma(1S \to X)} - N_{1S}$$

Rad. 1S generated per month



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

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.

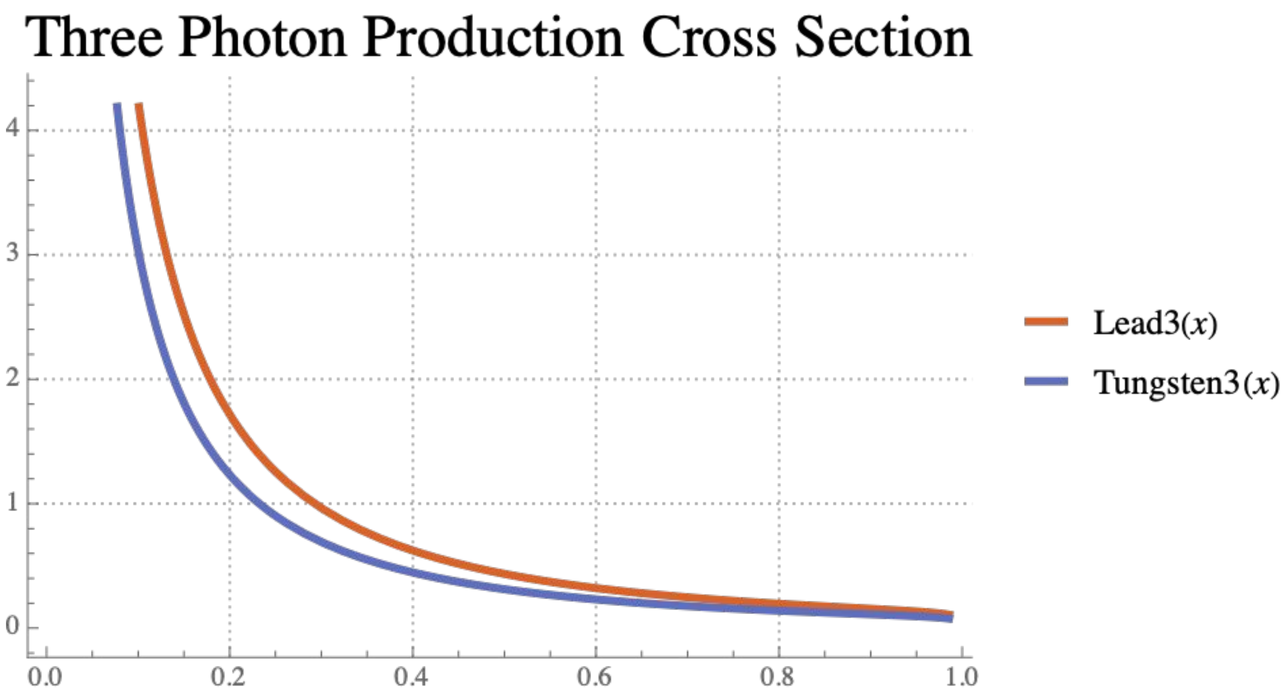
Calculating Yield (in progress)

- 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 would 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 discussed here: [Production of the bound triplet μ+ μ- system in collisions of electrons with atoms]

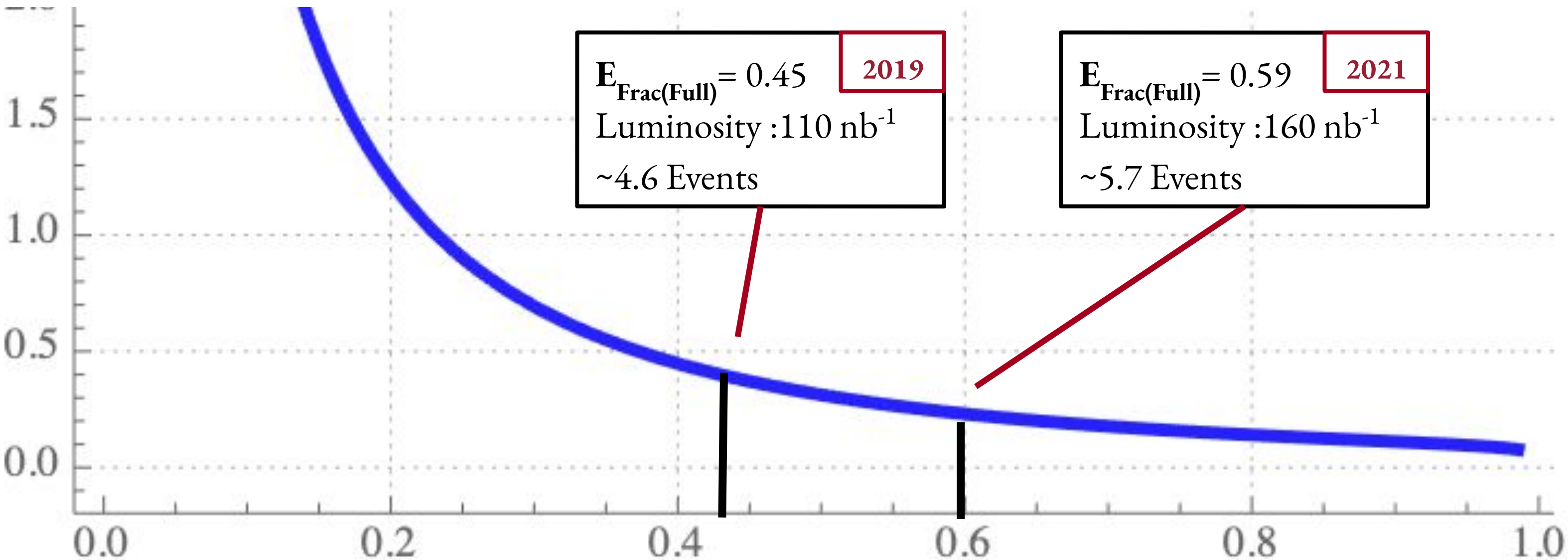
Prospects of 3 Photon Events in Previous Data (Without Acceptance Cuts)

Triggers used during runs limit number of potential events.

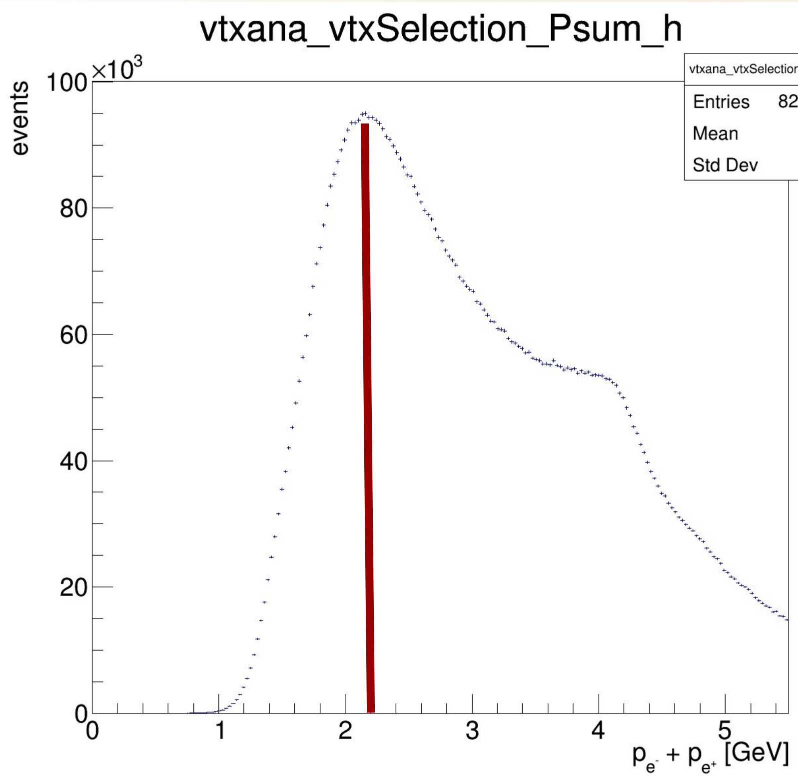
- 2019 and 2021 trigger reach full sensitivity at ~2.2 GeV,
- we are sensitive to ~½ events from 1 GeV - 2.2 GeV

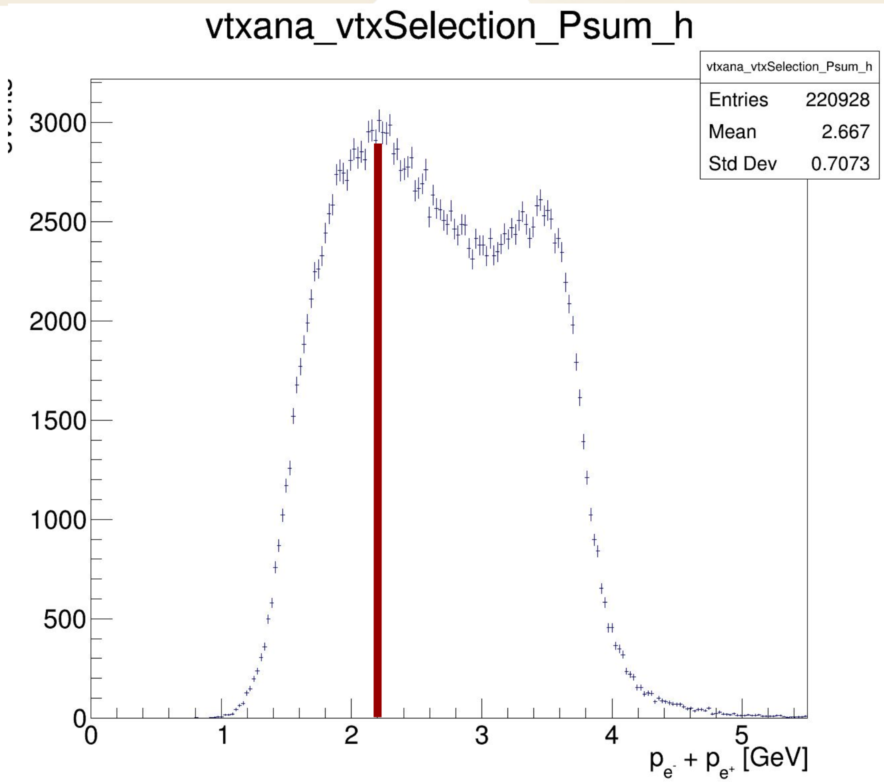
Year	$E_{Frac(partial)}$	$E_{Frac(Full)}$
2019	0.22	0.46
2021	0.27	0.59

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	0.090	0.157	2.48	2.16
2021	2.47E+18	0.059	0.141	2.65	3.09



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.

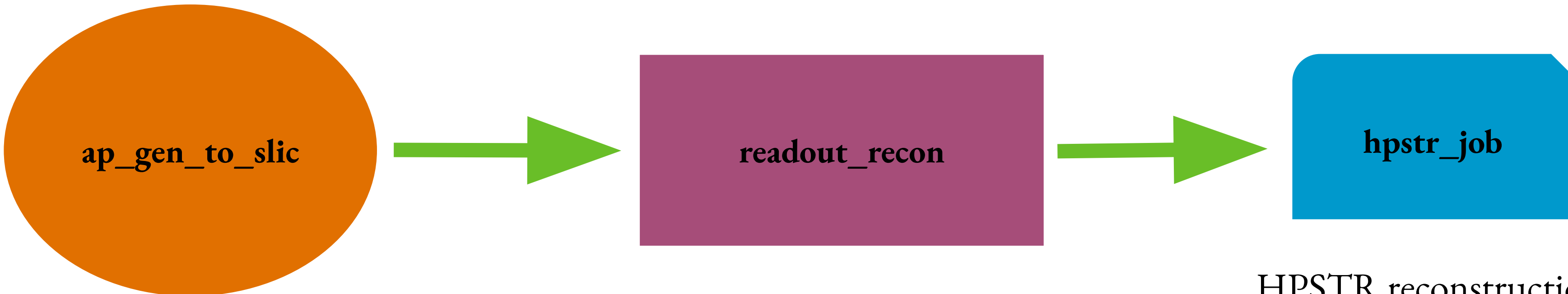
Summarizing Three Photon Production

- Total Events from 2019/2021 ~ 10.37
  - 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



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

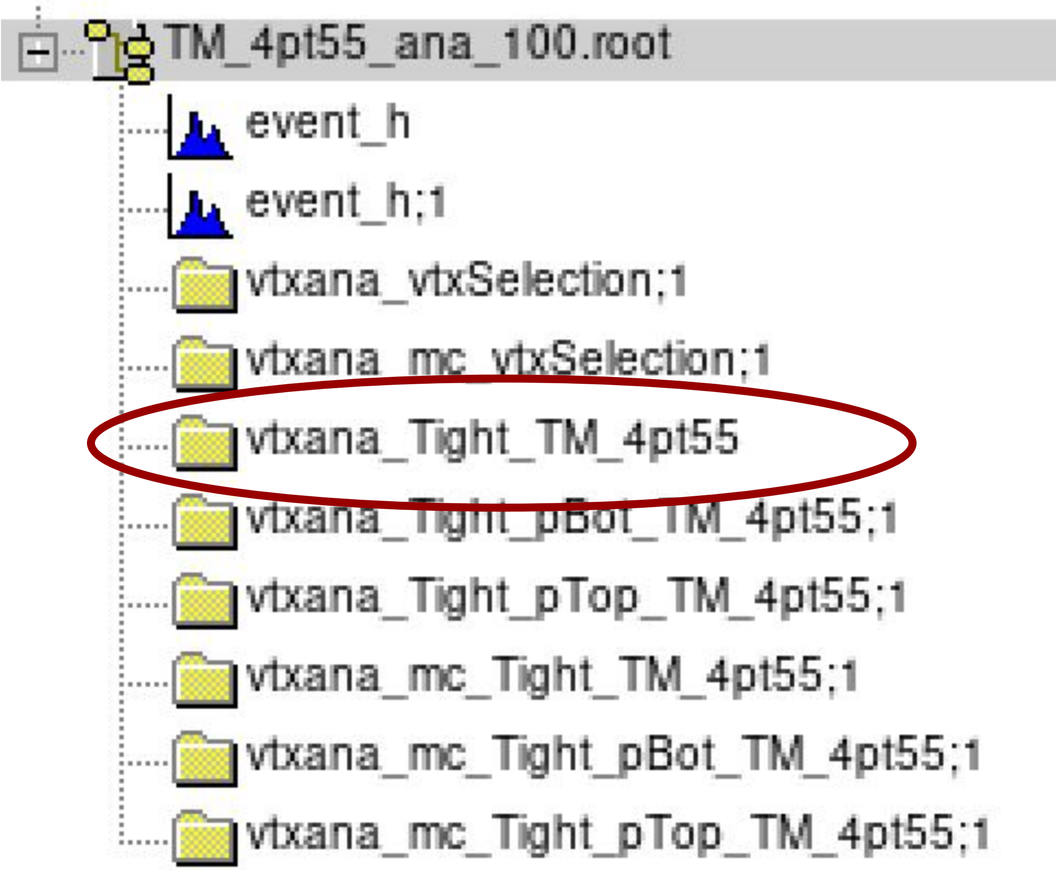
- subArray.sh (using hpstr type)

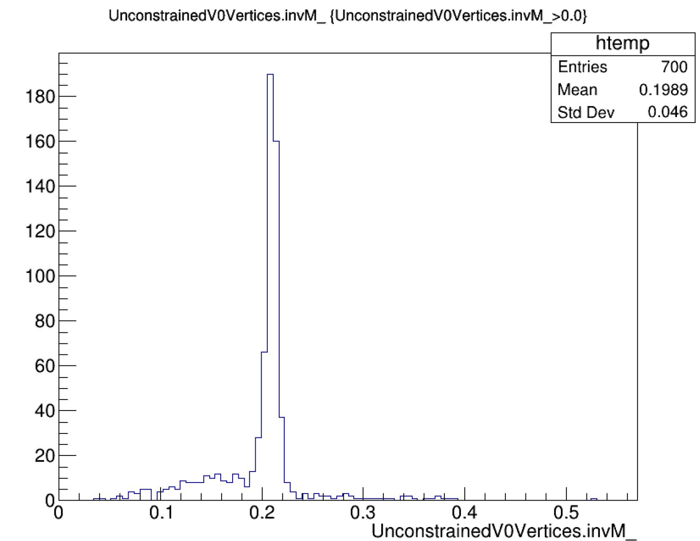
Added following files to hpstr:
- /analysis/selections/vertexSelection_TM_4pt55.json
- /analysis/selections/Tight_TM_4pt55.json
- /analysis/selections/Tight_pTop_TM_4pt55.json
- /analysis/selections/Tight_pBot_TM_4pt55.json
- /analysis/plotconfigs/tracking/vtxAnalysis_TM_4pt55.json

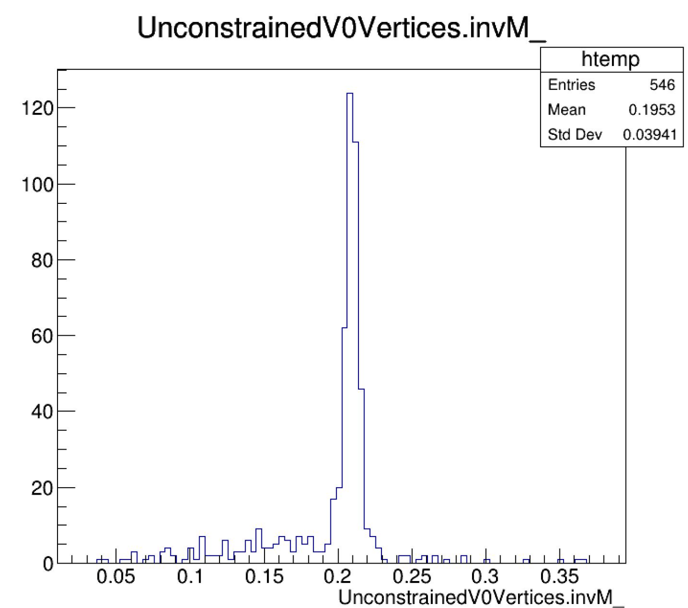
Config: anaTMTuple.py (added into hpstr/processors/config)
Run_mode: 0
Year: 2019

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

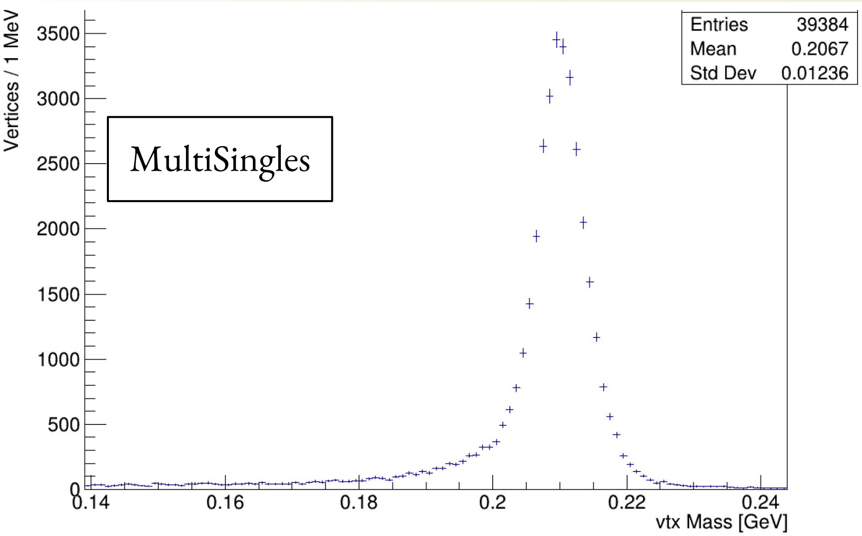
4.55 GeV (Preliminary)

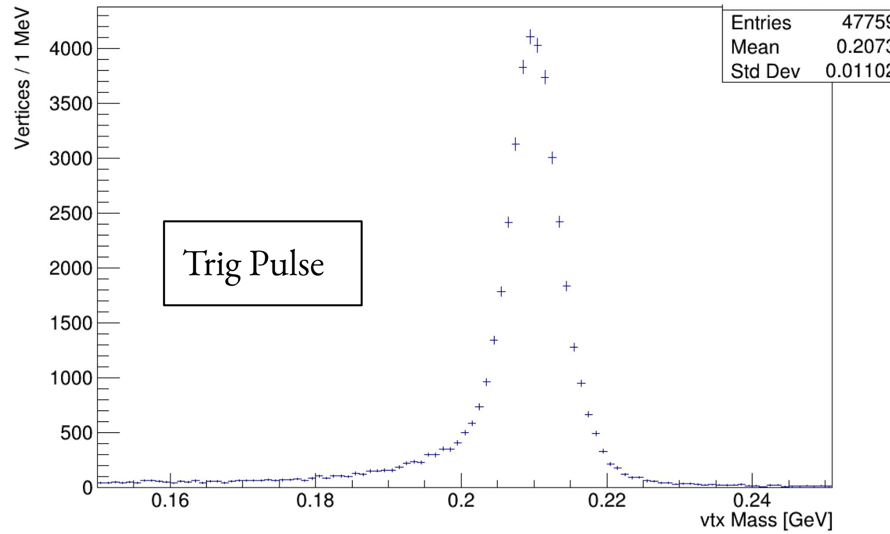


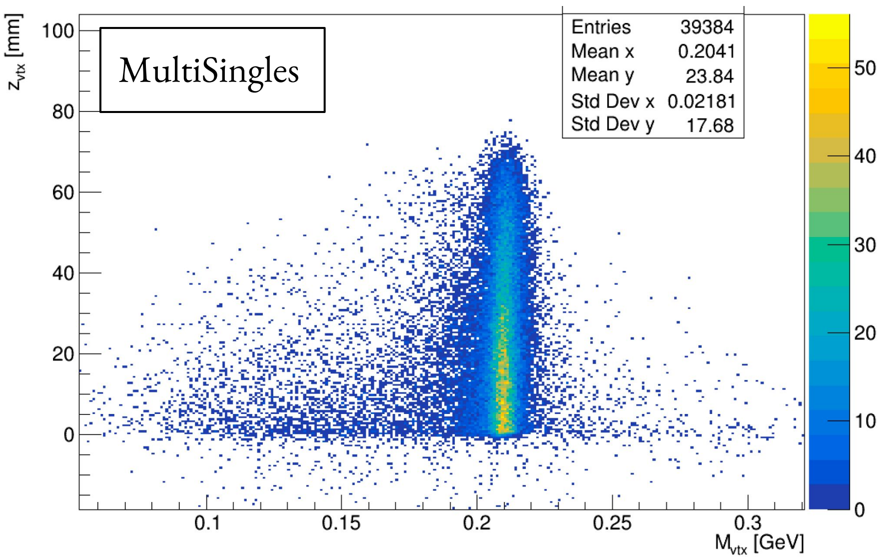


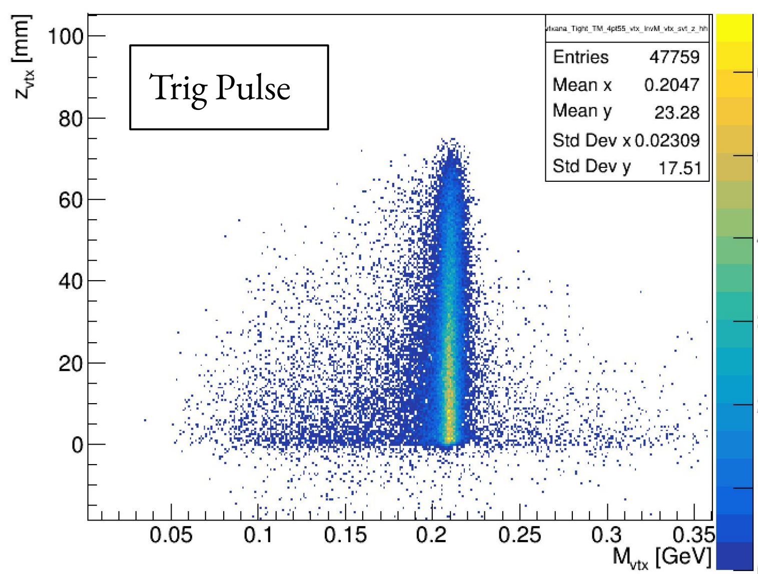


4.55 GeV Plots (1/2)

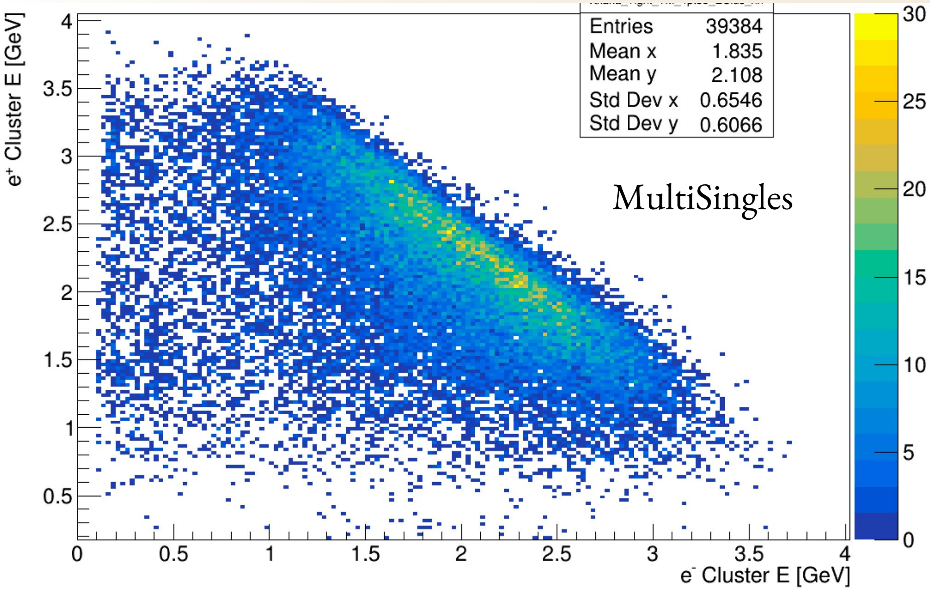


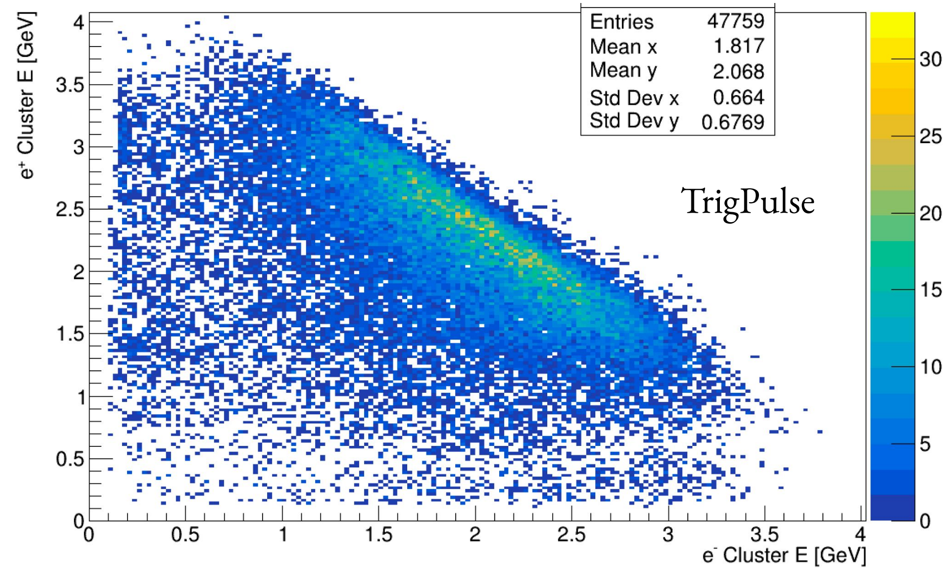




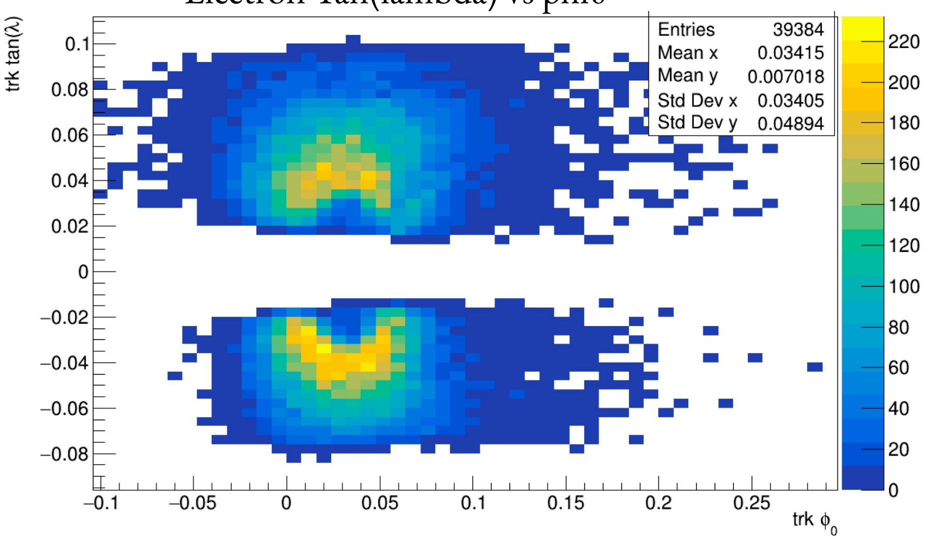


4.55 GeV Plots (1/2)

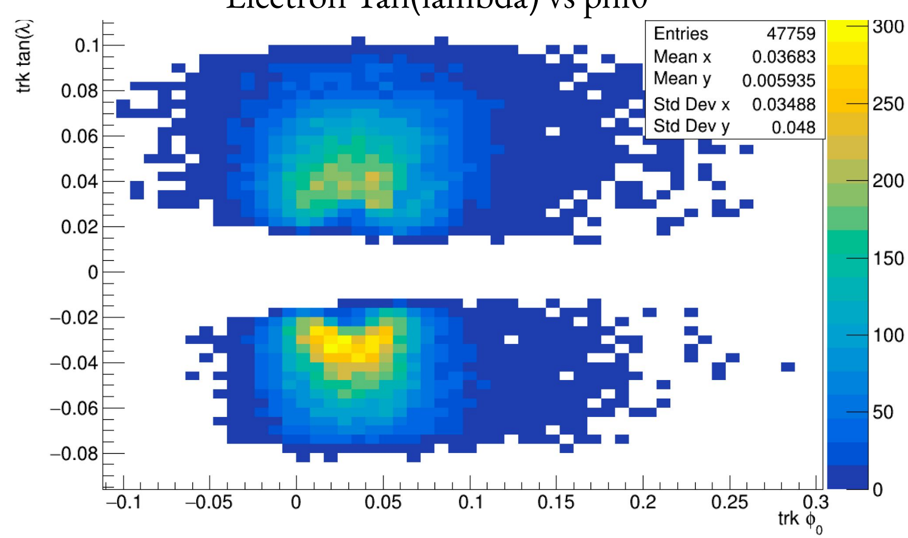




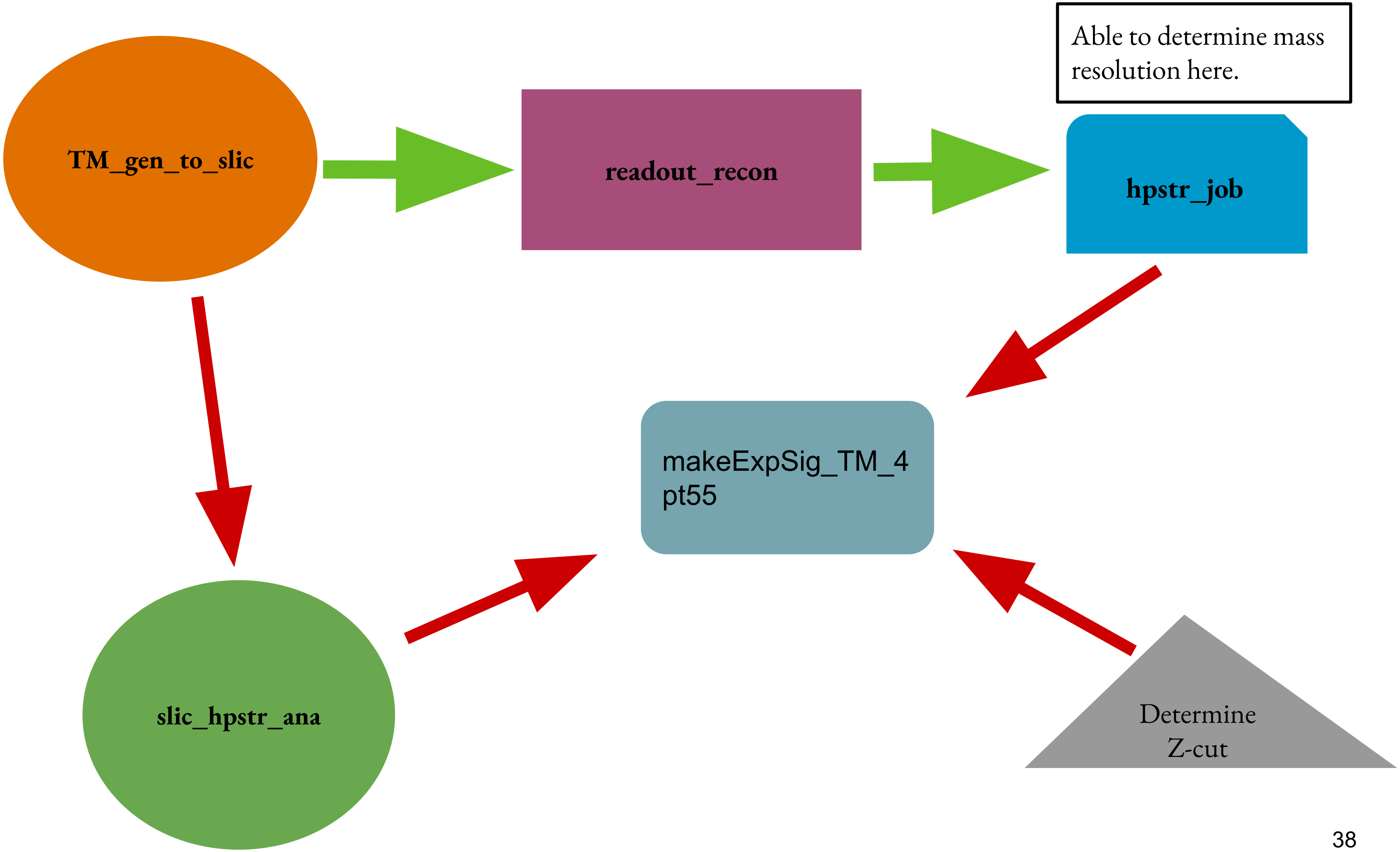
Electron Tan(lambda) vs phi0



Electron Tan(lambda) vs phi0

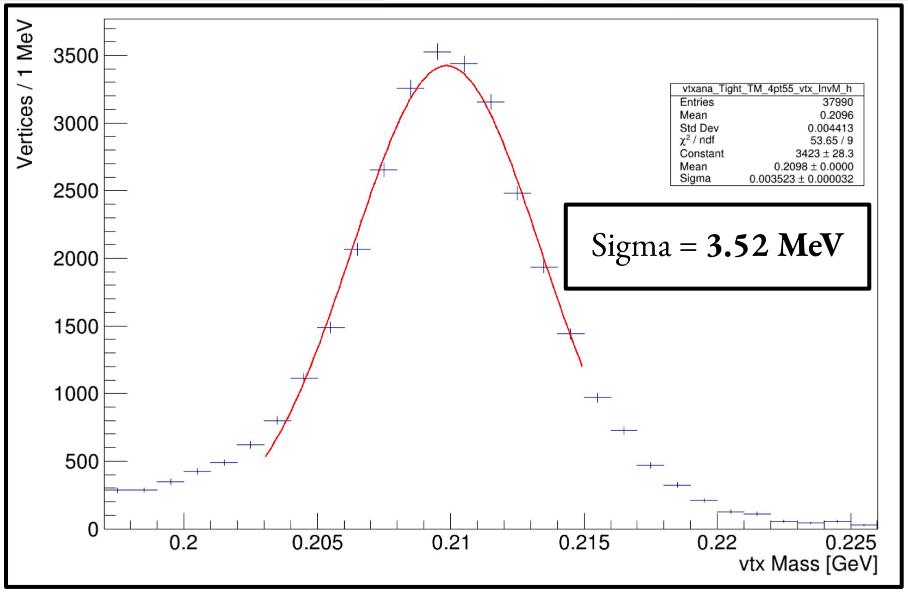


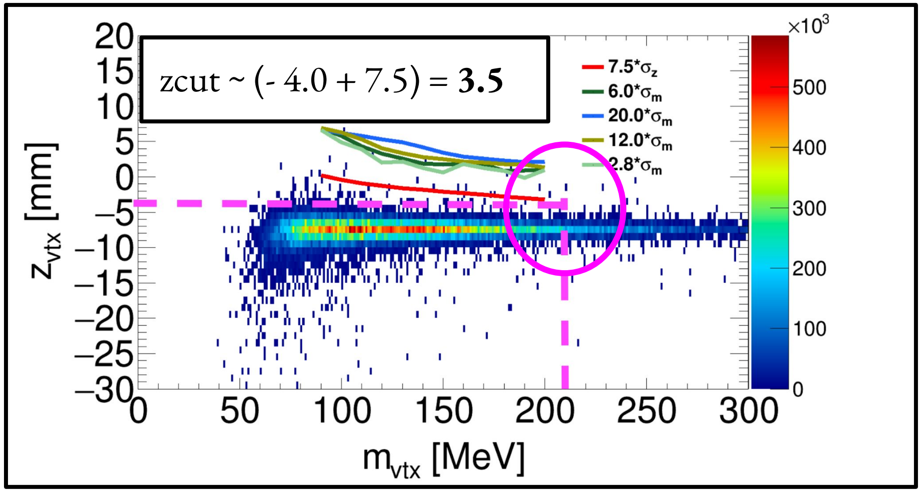
Vertex acceptance flow using /hps-mc/python/jobs



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





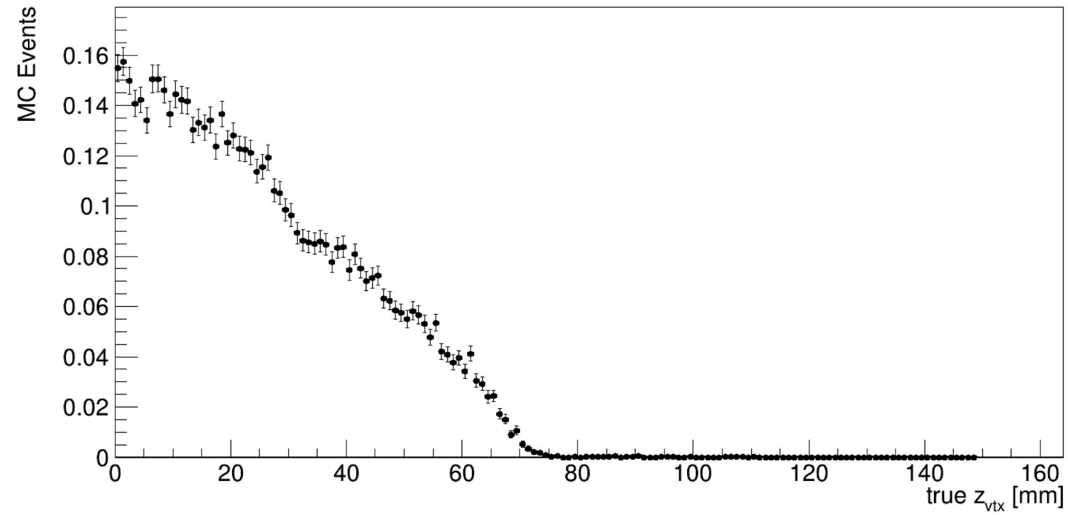
C. Bravo. *Comparison of Zcuts for 2019 Reach.*

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.

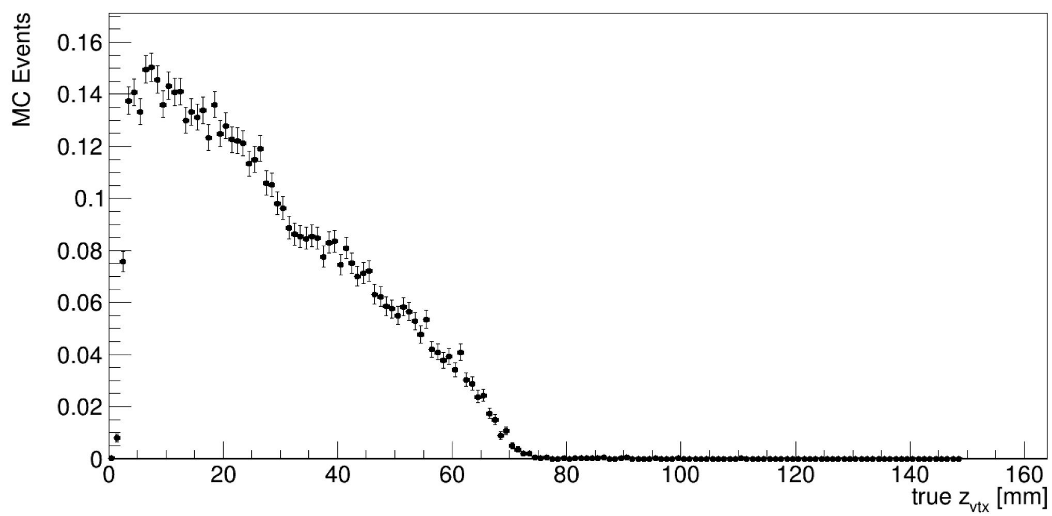
Calculating Vertex Acceptance for Radiative (1S) [2/2]

- 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	Yes	7.97%
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	(7.97 - 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: 2.29
  - anticipate accepting (0.15 - 0.18) events.
- Lower energy seems to marginally help with acceptance of TM as the on average decay length is shorter

Total (1S) Produced

Total Radiative Events	Total 3Photon Events	Anticipated Yield	Optimistic Accepted Events****
5.77	10.37	16.13	(1.29 - 1.54)

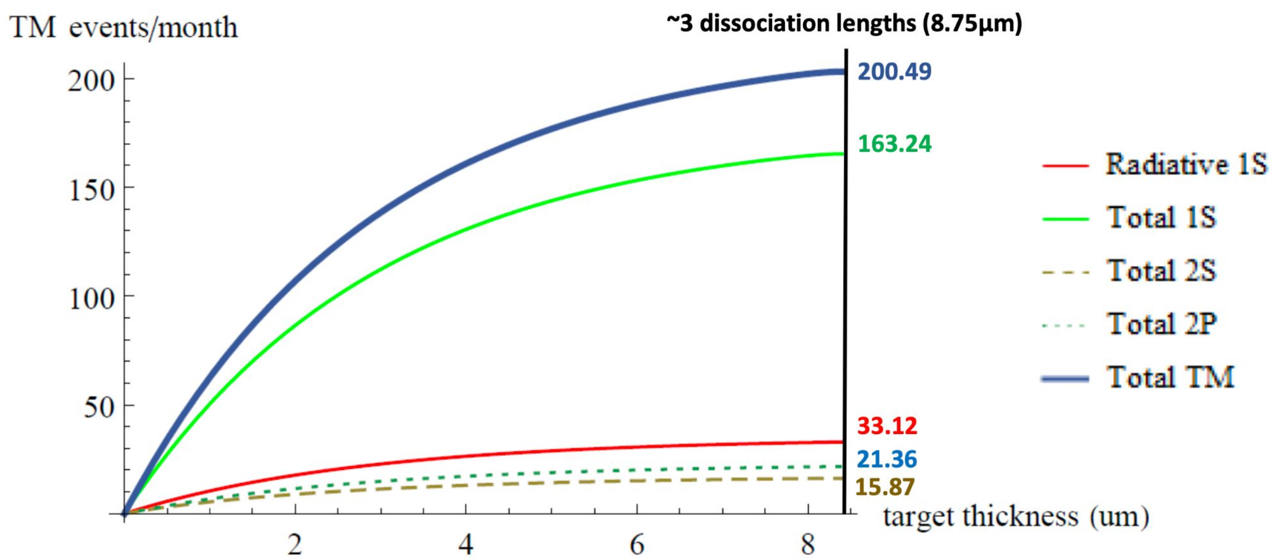
****Need to determine efficiency for radiative 3.74 GeV and 3 photon events to rigorously determine this.

6.6 GeV Future run?

True Muonium Generated (450nA)

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

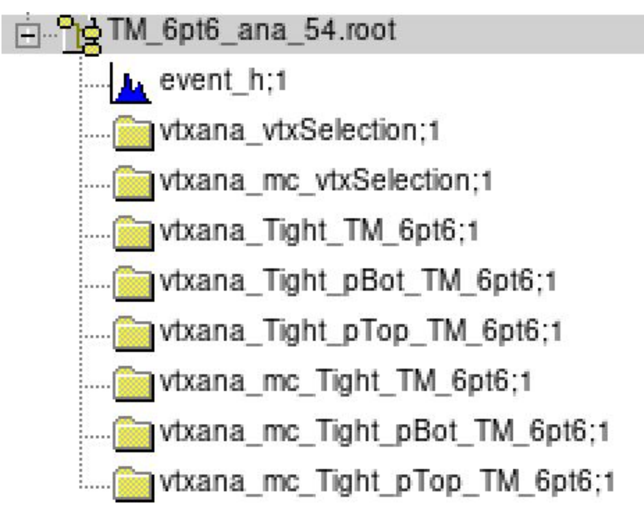
- 32 Three photon events
- 31 Radiative events



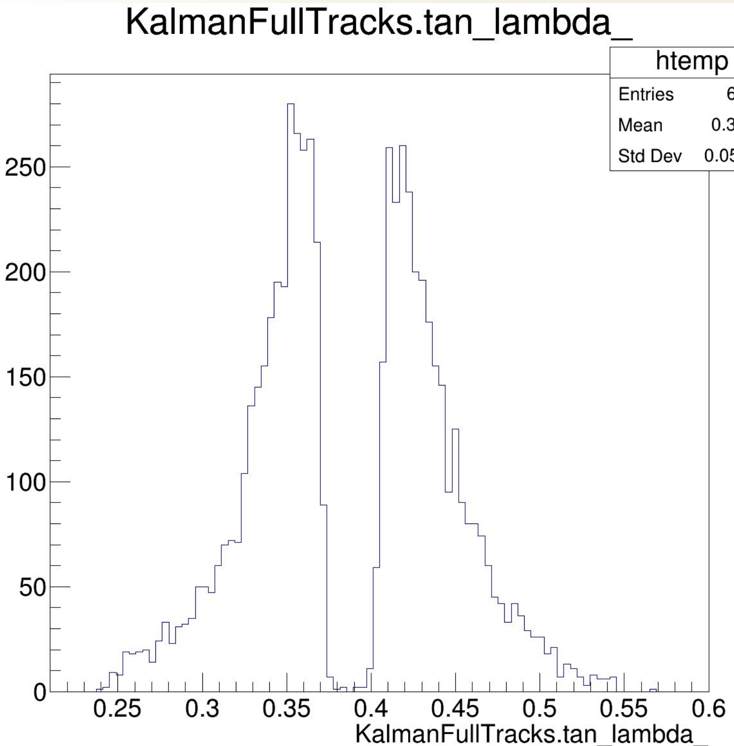
B. Yale. On the generation of true muonium.

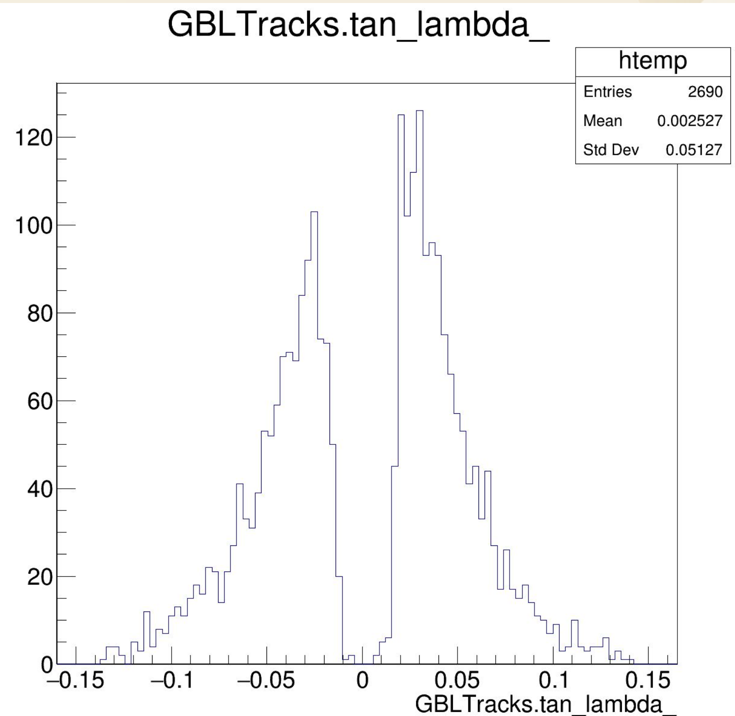
6.6 GeV (Preliminary)

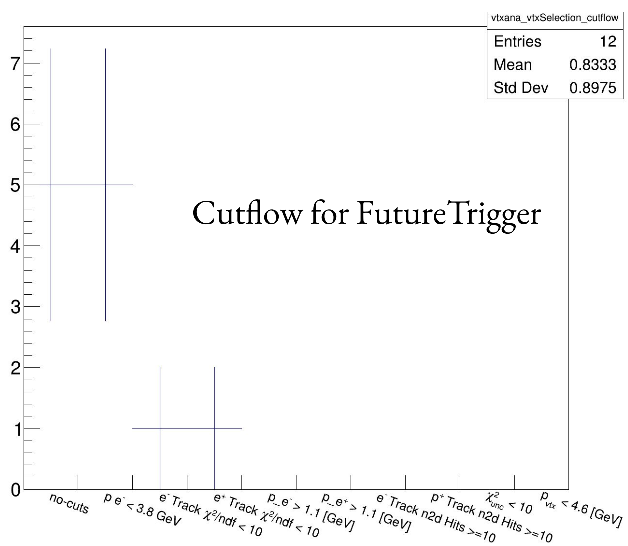
- Tongtong made a new steering file that set DAQ configuration for a 6.6 GeV Beam **Future6pt6TrigSingles.lcsim** – thanks!
- Was able to go through the same procedure as for the 4.55 GeV
    - Tm_gen_to_slic → readout_recon → hpstr_ana
- Noticed a print statement still set to 4.55 GeV (need to figure out where this is coming from)
- Have been stonewalled, next slide illustrates dilemma **UPDATE 2023 BUG FIXED**

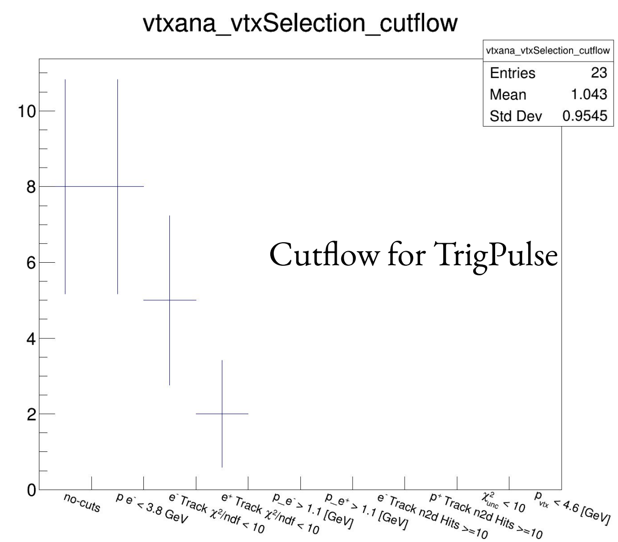


6.6 GeV Plots


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
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

SLAC

- 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)
- H. Lamm. True Muonium: the atom that has it all.

Slides in progress

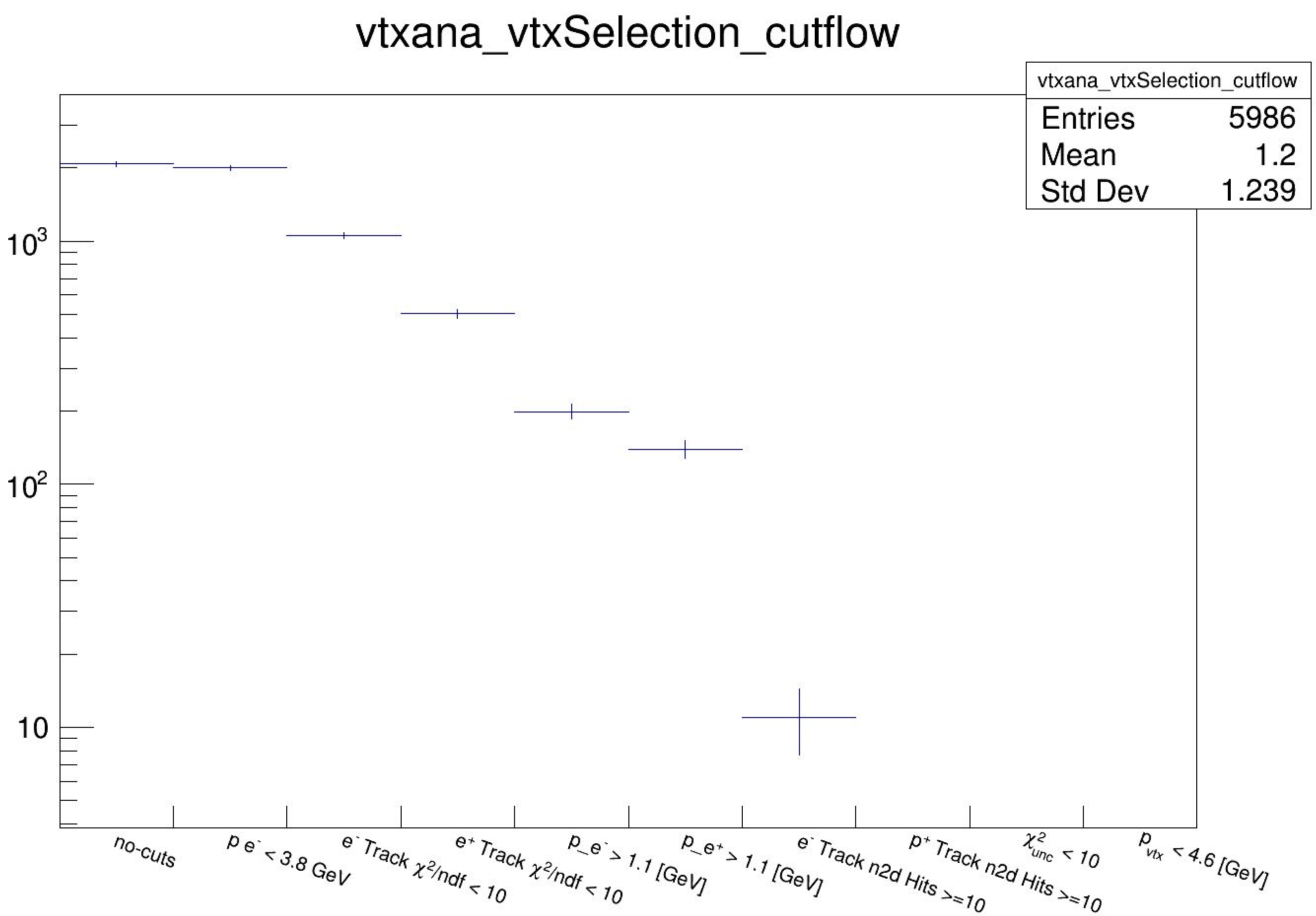
Considering form factor B

$$\frac{\mathrm{d}\sigma}{\mathrm{dx}} = \frac{1}{4n^3} Z^2 \frac{\alpha^7}{m_\mu^2} \left(\frac{Z\alpha\Lambda}{m_\mu} \right)^2 \frac{4B}{x} \ldots$$

Accounting for B = 0.85 → 0.93
Yield → 17.65
Accepted** (1.41-1.68)
Zcut of 0.89 → (2.01 - 2.21)

Paper fully deriving three photon mechanism is:
Production of bound $\mu1\mu2$ systems in relativistic heavy ion collisions

Cutflow for 6pt6 TrigPulse with default cuts



Three Photon Production Mechanism Diagram