True Muonium Acceptance at 6.6 GeV

a true underdog story

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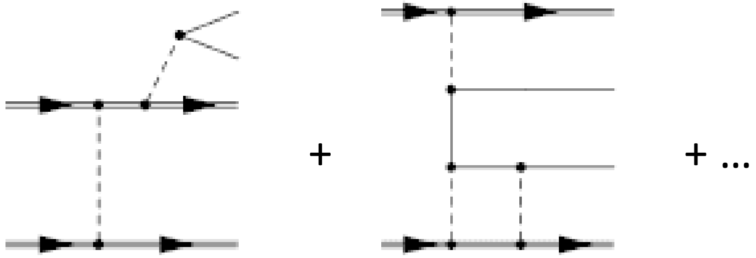
True Muonium Production

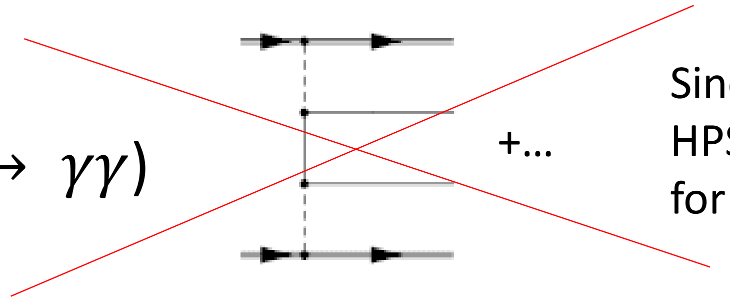
- Muon-antimuon bound state
  - Two spin ½ fermions, total spin can add to either 0 or 1

- Two mechanisms for production:
  - Odd # of photons, spin-1 triplet states, “ortho” ($TM \rightarrow e^+e^-$)



The 1-photon mechanism is identical to brems-like A’ production, and peaks in the radiative energy region. The 3-photon mechanism peaks in the BH region, so difficult to search for.

  - Even # of photons, spin-0 singlet states, “para” ($TM \rightarrow \ \gamma\gamma$)



Since para-TM decays into photons, HPS is currently unequipped to search for them.

True Muonium Production

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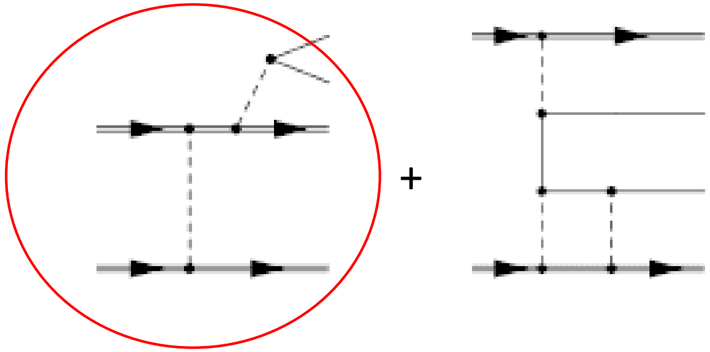
  - Two spin ½ fermions, total spin can add to either 0 or 1

- Two mechanisms for production:
  - Odd # of photons, spin-1 triplet states, “ortho” ($TM \rightarrow e^{+}e^{-}$)

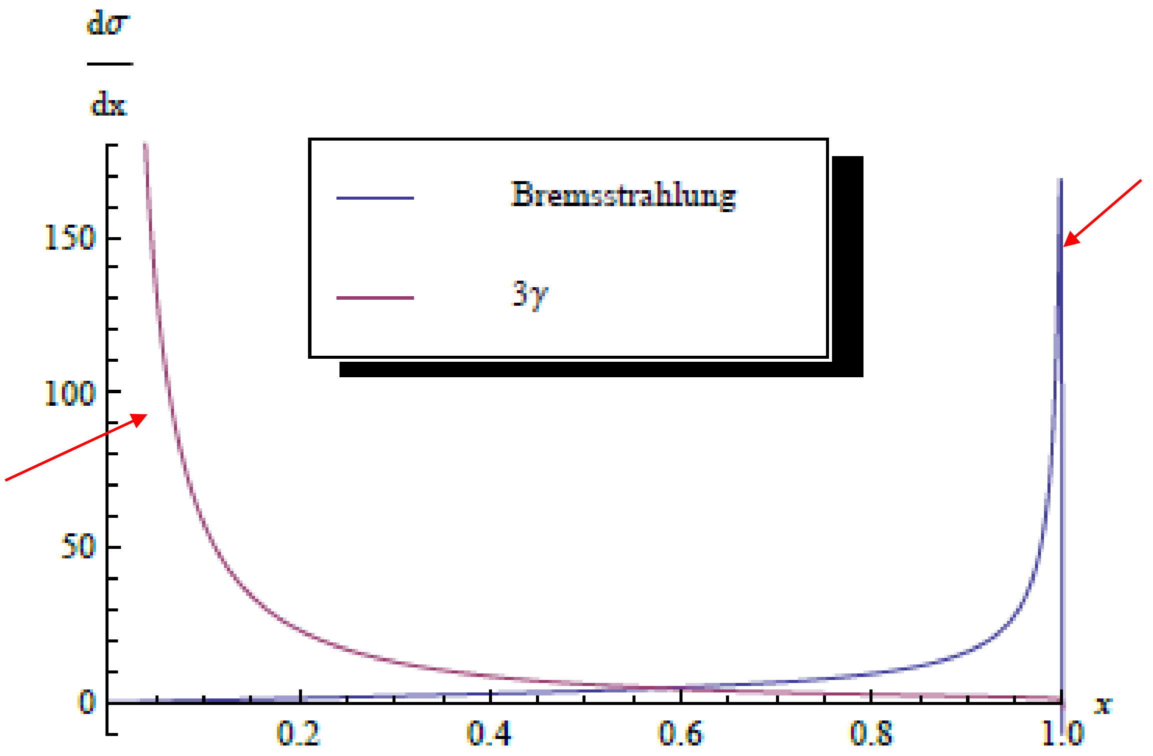


  - The 1-photon mechanism is what HPS is most capable of searching for
  - Effectively an A’ with known mass and decay length

TM Production Cross sections (1 vs. 3 photon)

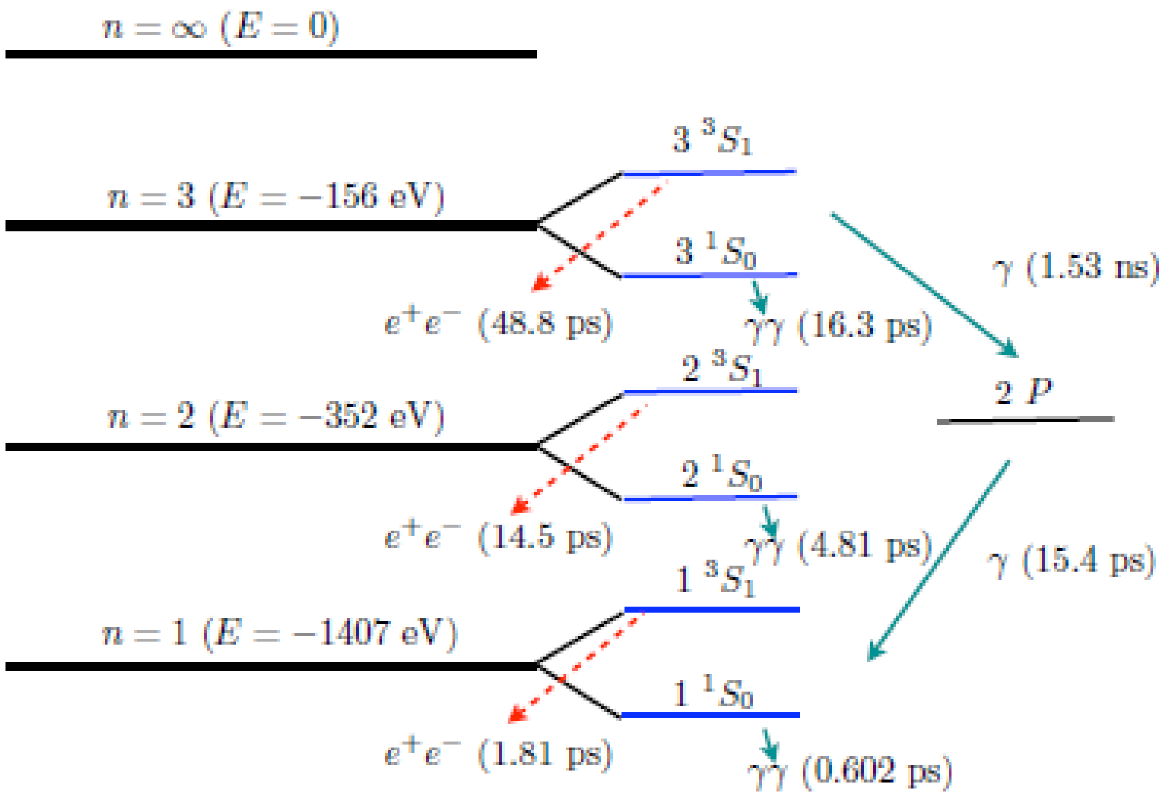
- $x = E/E_{beam}$

3-photon mechanism peaks below likely pair1 trigger thresholds



Radiative mechanism peaks at beam energy (“A’-like”)

True Muonium Energy Levels and lifetime



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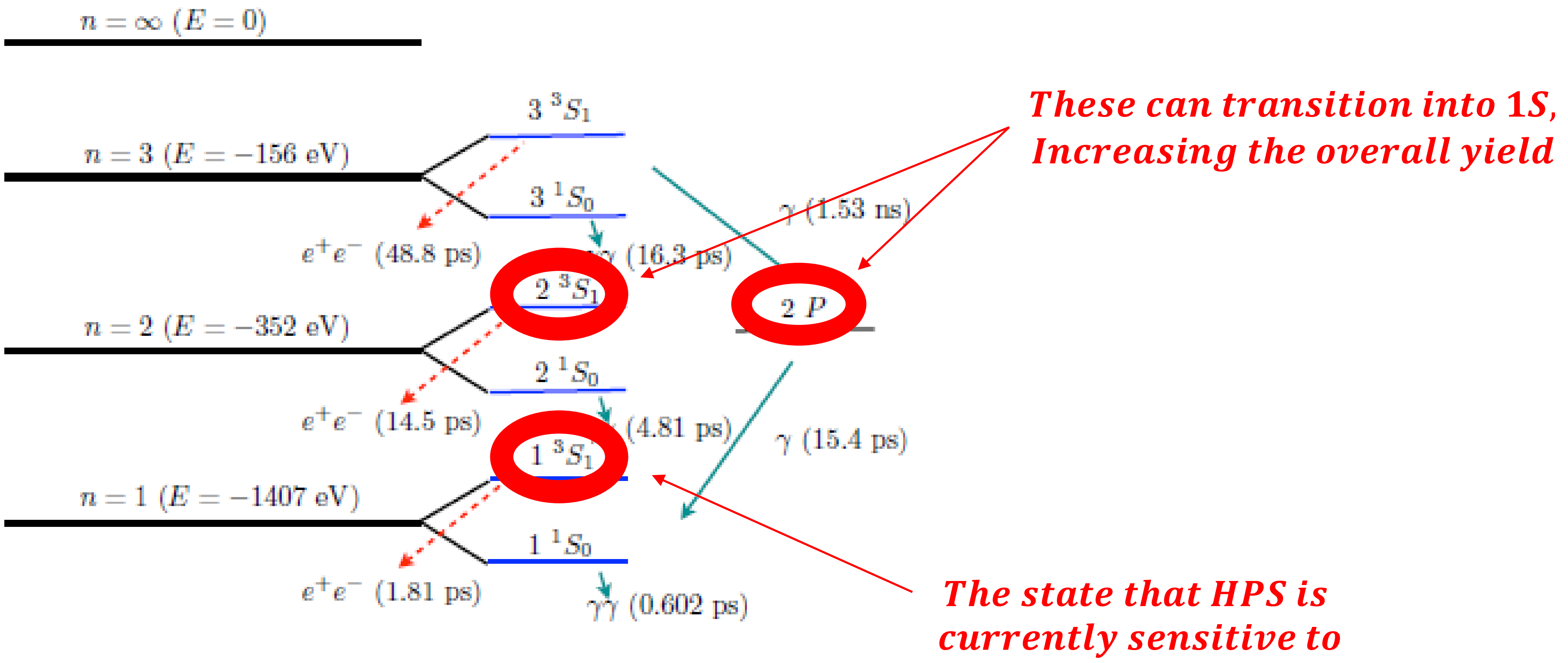

Part I: True Muonium Production Rate

- To estimate how many detectable True Muonium events will be produced, both the production and dissociation cross sections must be calculated

- Total 1S produced = produced $1S + [(2S, 2P) \to 1S\ ] -$ dissociations

- The small production rate and extremely high dissociation in the target is what makes these events so difficult to detect

Primary Production Cross Section (radiative)

- Banburski Schuster - arXiv:1206.3961v1 [hep-ph] 18 Jun 2012

$$\left(\frac{d\sigma}{dx}\right)_{rad\ 1S} = \frac{1}{4}\frac{\alpha^7 74^2}{\left(m_\mu\right)^2}\frac{x(1-x)}{\left(1-x+\left(m_e/\left(2m_\mu\right)\right)^2\right)^2}\left(1-x+\frac{1}{3}x^2\right) * \left(2\mathrm{Log}[E_{Beam}/m_\mu]+2\mathrm{Log}[1-x]-\mathrm{Log}\left[1-x+\left(m_e/\left(2m_\mu\right)\right)^2\right]-1\right)$$

- Integrate (up to $x = 1 - m_e/E_{beam}$ where $\frac{d\sigma}{dx} = 0$)

$\sigma(\mathbf{4.4\ GeV})_{rad\ 1S} =$ **0.113724 pb**
$\sigma(\mathbf{6.6\ GeV})_{rad\ 1S} =$ **0.26614 pb**

1S production cross section for radiative process only

Secondary Production/Dissociation (target interaction)

- Transition cross section (to all other bound states + dissociation)

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

= 5.67937×10^{16} pb

1S state-> all states + dissociation ("X")

Transfer matrix elements

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

Thomas-Fermi-Moliere FF

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

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

$$b_1 = 6.0, b_2 = 1.2, b_3 = 0.3,$$
$$\alpha_1 = 0.10, \alpha_2 = 0.55, \alpha_3 = 0.35$$

Dissociation Cross Section (1S)

- Transition cross section (bound state to another bound state)

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

- To get dissociation, $\sigma_{trans+diss.} - \sigma_{transition}$ $=$ **2.21044 $\times 10^{16}$ pb**

Published value for Pb (Schuster): 2.65 $\times 10^{16}$ pb

- Note that σ_{diss} is ***17*** orders of magnitude greater than σ_{prod}!

Expected True Muonium Rate (1S)

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

- Solving

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

1-photon mechanism

Proposed 6.6 GeV target

$$= \left(\frac{5625\ electrons}{2ns}\right)\left(\frac{0.26614\ pb}{5.67937 * 10^{16}\ pb}\right)\left(1 - e^{-\frac{8.750\mu m}{2.792\mu m}}\right)$$

$$= \mathbf{33.13\ events/month}$$

(6.6 GeV, 1S state only)

The number of radiative 1S TM events before HPS acceptance

Expected True Muonium Rate (1S)

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

- Solving

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

1-photon + 3-photon

Proposed 6.6 GeV target

$$= \left(\frac{5625\ electrons}{2ns}\right)\left(\frac{1.27455\ pb}{5.67937 * 10^{16}\ pb}\right)\left(1 - e^{-\frac{8.750\mu m}{2.792\mu m}}\right)$$

$$= \mathbf{168.36\ events/month}$$

(6.6 GeV, 1S state only)

Add to this the transitions from 2S,2P to 1S…

Expected True Muonium Rate (1S,2S,2P)

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

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

- 2P yield:

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

Expected True Muonium Rate (1S,2S,2P)

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

  $\sigma(e^- \to 1S)$: $1.27455\ pb\ (1 + 3\ photon\ mechanisms)$

  $\sigma(1S \to X)$: $5.67937 * 10^{16}\ pb$

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

  $\sigma(2S \to X)$: $4.90741 \times 10^{17}\ pb$

  $\sigma(2P \to 2S)$: $3.1625 \times 10^{17} pb$

  $\sigma(e^- \to 2S)$, $\sigma(e^- \to 2P)$: $0.0332675\ pb$ $= \sigma(e^- \to 1S)/8$

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

  $\sigma(1S \to 2P)$: 2.6437×10^{16}

  $\sigma(2S \to 2P)$: $3.1625 \times 10^{17} pb$

  $\sigma(2P \to X)$: $6.30545 \times 10^{17}\ pb$

Solving the coupled DE's…

- In one month of running at 6.6 GeV:

  - N_{1S} = 168.36 ← from both production diagrams
  - N_{2S} = 9.46
  - N_{2P} = 15.37

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- If only considering radiative events:
  - N_{1S} = 33.13

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- If only considering radiative events:
  - N_{1S} = 33.13

- What about acceptance?

Part II: Simulating True Muonium events

- Lifetime depends on energy level n

$$\tau(n^3S_1 \rightarrow e^+e^-) = \frac{6\hbar n^3}{\alpha^5 mc^2}$$

= 1.81 ps for 1S

$$\Gamma = \frac{6.582*10^{-25}GeVs}{1.81*10^{-12}s}$$

$$= \ 3.627 * 10^{-13}GeV$$

Only used to calculate cross section, so we don't really need this…

- These parameters can be used by MadGraph/stdhep to generate the 1^3S state.
- The idea is to find the acceptance of a known # of events, to scale the theoretical yield

True Muonium Acceptance @ 6.6 GeV

- Initial 6.6 GeV trigger cuts (scaled up from 2.3 GeV)

<seedEnergyLow> 300 MeV
<minHitCount> 2
<pairCoincidence> 3ns

<clusterEnergyLow> 150 MeV
<clusterEnergyHigh> 4.2 GeV

<energySumLow> 1.800 GeV
<energySumHigh> 6 GeV
<energyDifferenceHigh> 3.3 GeV

<coplanarityHigh> 35 deg
<energySlopeParamF> 0.0055 GeV/mm
<energySlopeLow> 700 MeV

6.6 GeV Layer-0 detector used:
HPS-Proposal2017-Nominal-v2-6pt6-fieldmap

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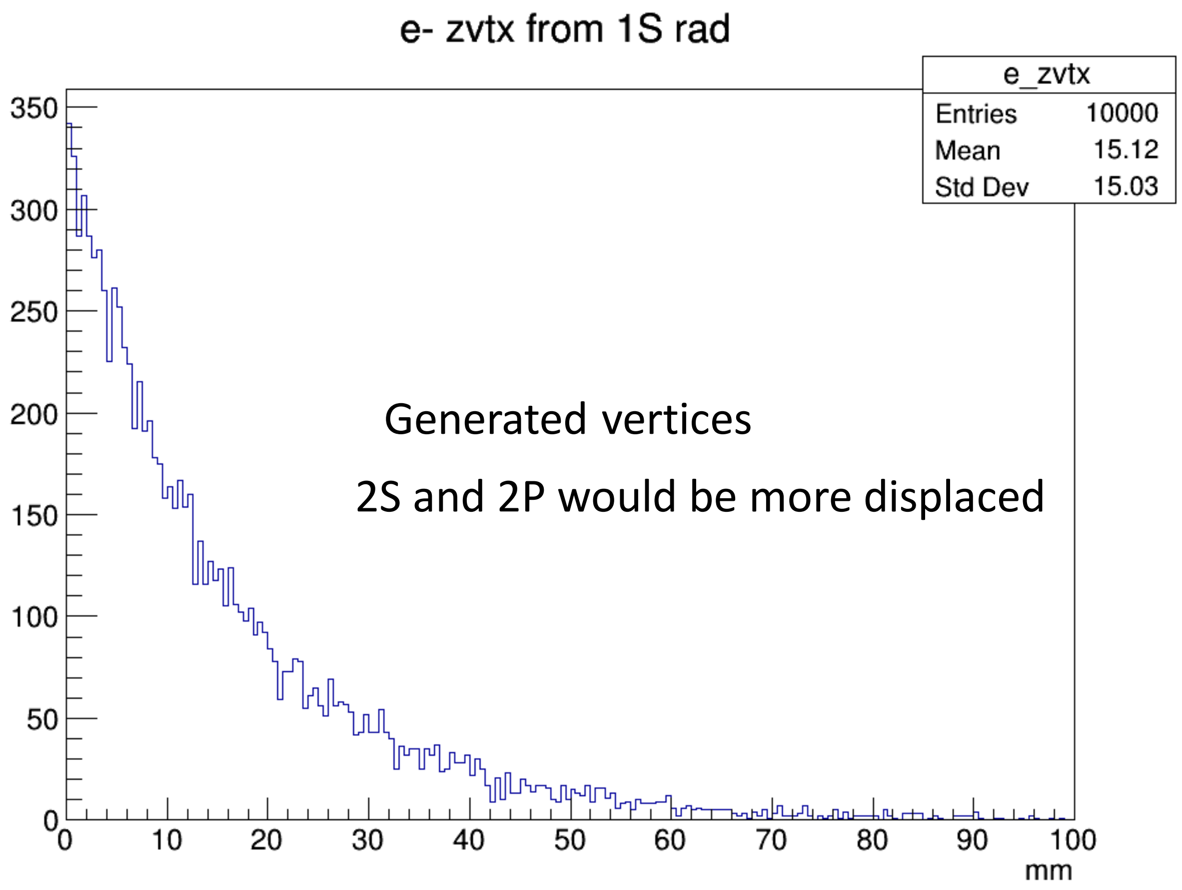
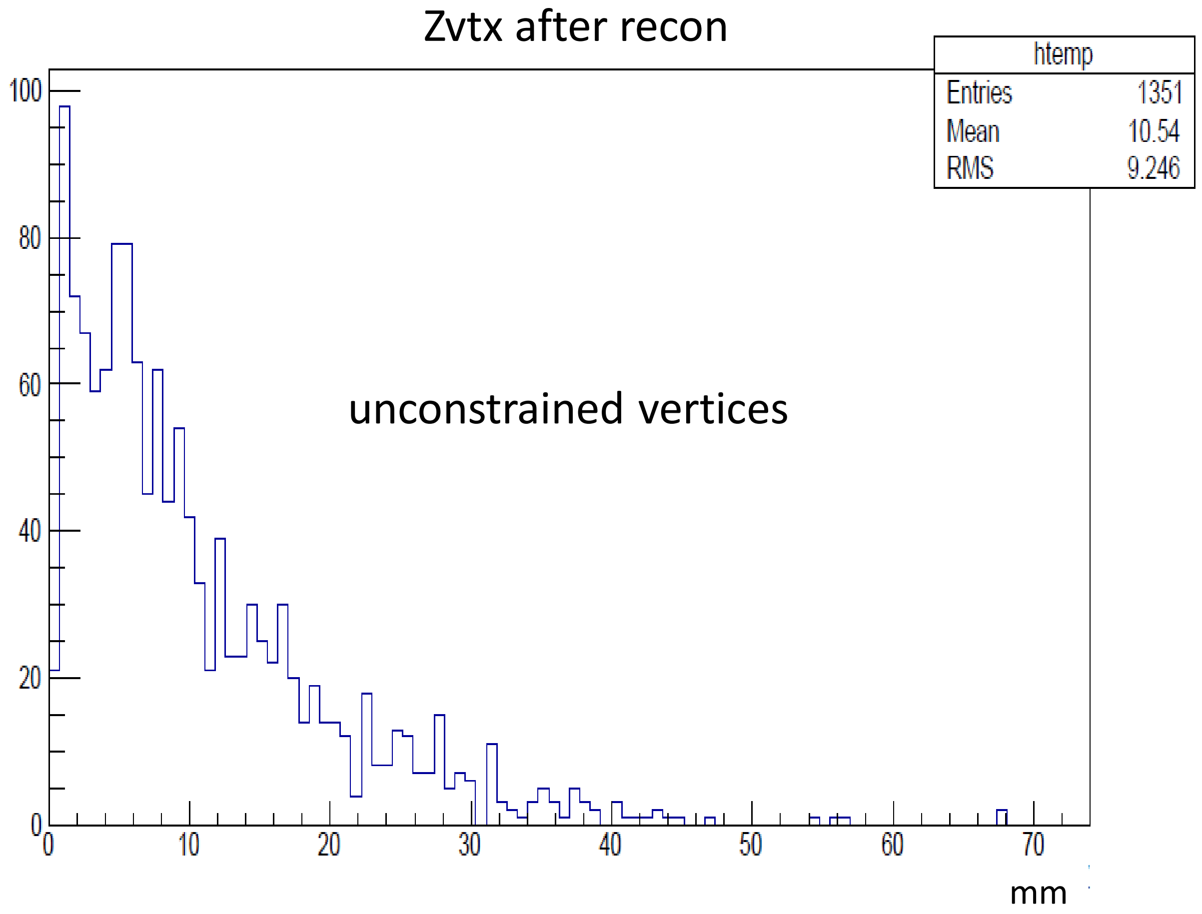
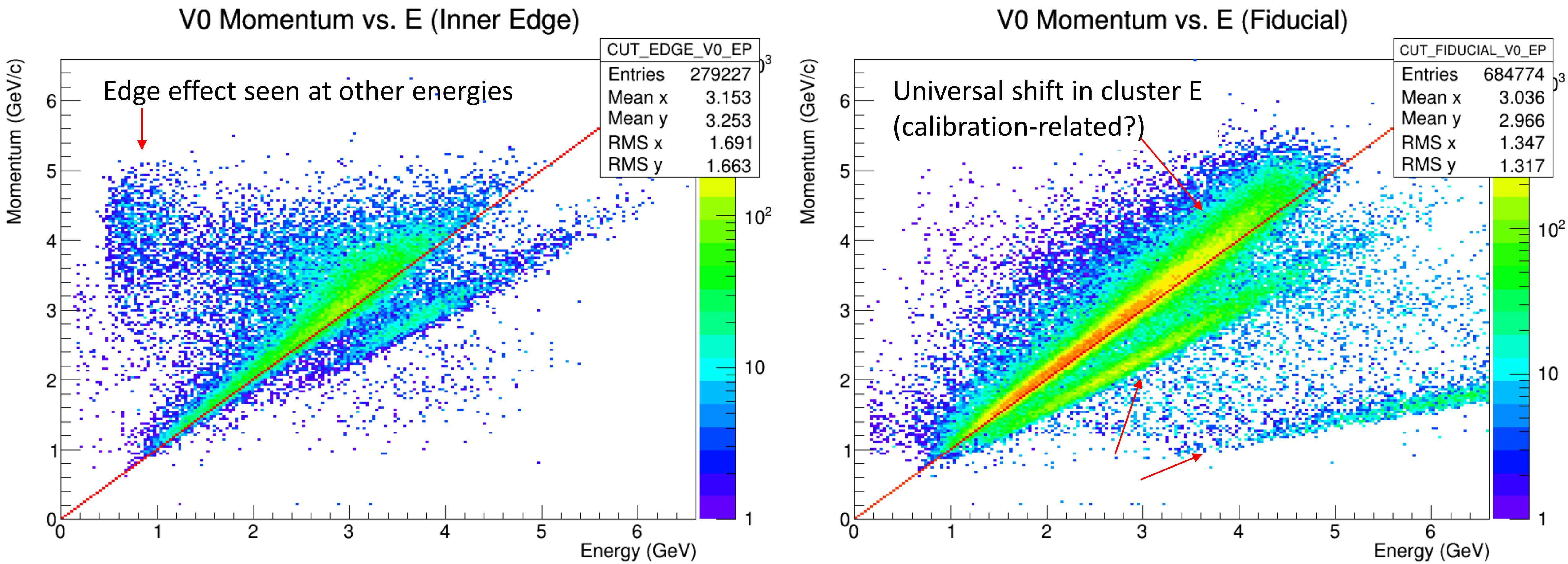
Quick check of the events…

TM Vertex Acceptance (1S)

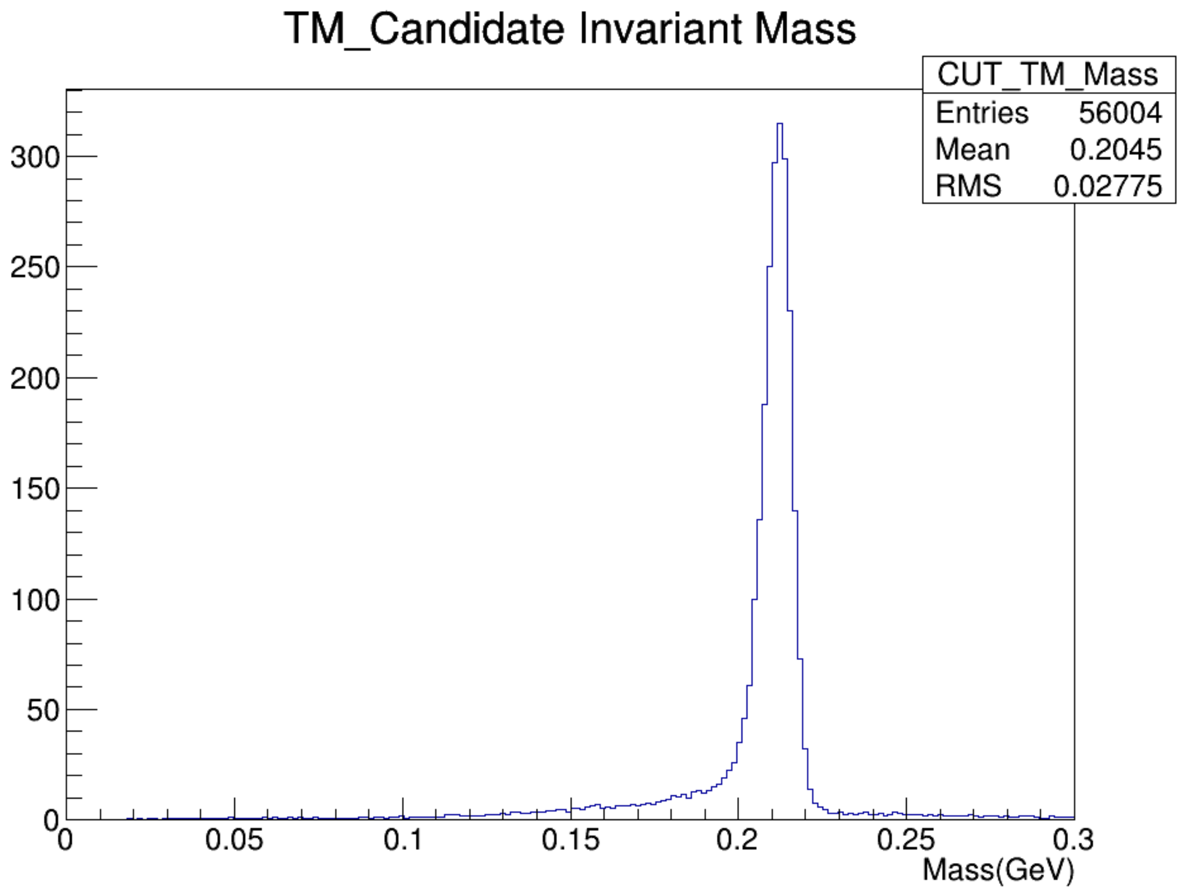


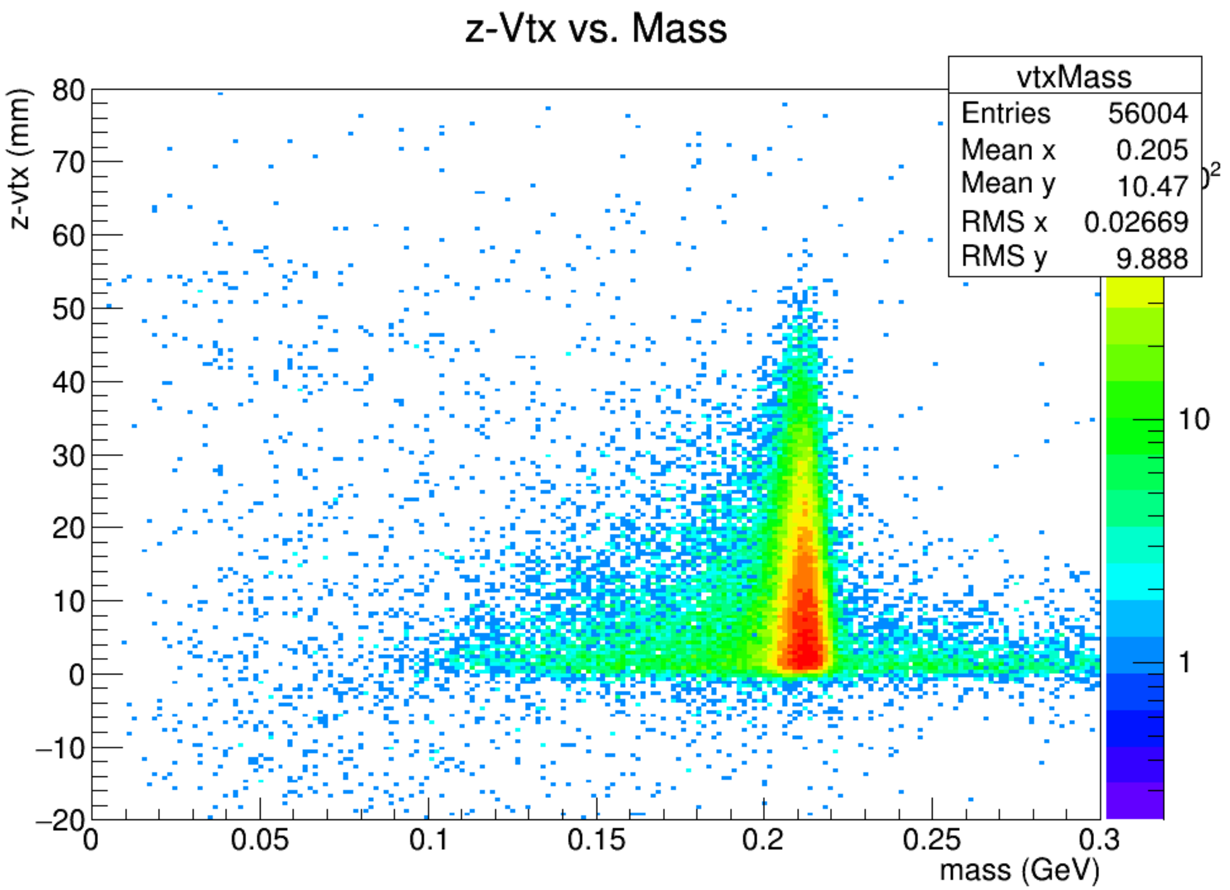


Momentum vs. Cluster Energy

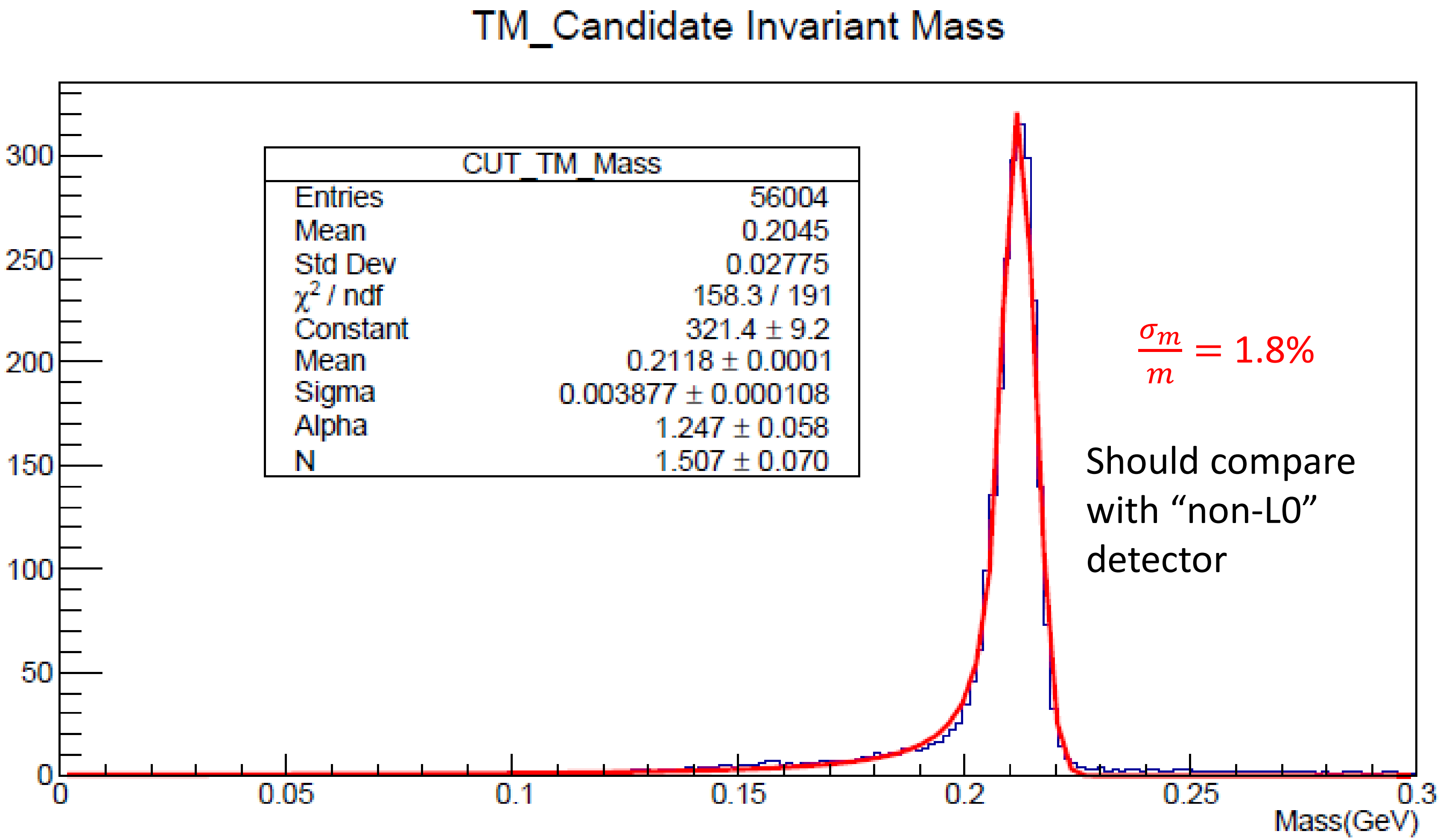


Invariant Mass





(Very) preliminary 6.6 GeV MC resolution



$\frac{\sigma_m}{m} = 1.8\%$

Should compare with “non-L0” detector

Estimated TM Yield @ 6.6 GeV

- Initial 6.6 GeV trigger cuts

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Radiative + 3g: 168.36 events

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True Muonium trigger acceptance
91355/470000 = 19.43%

+ Tracking/Vertexing acceptance
56004/470000 = **11.91%**

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Number of analyzable TM events/month:
Radiative 1S only: **3.94 events**
Radiative + 3g: up to **20.06 events**

This assumes a similar acceptance for 3-photon events, which we can't actually know without a generator…

Summary and future plans

- The bad news
  - < 4 events/month accepted, if only looking for the radiative 1S1 state
    - We are currently only sensitive to the radiative 1S1 state.
  - This doesn’t even include analysis cuts
  - We don’t have a generator for the 3-photon diagram

- The good news
  - Since the mass is known, the search itself becomes much easier
    - Analysis can be tuned to a single mass
    - No “look-elsewhere effect”
    - More efficient background studies
      - Generator mass cut can be exploited

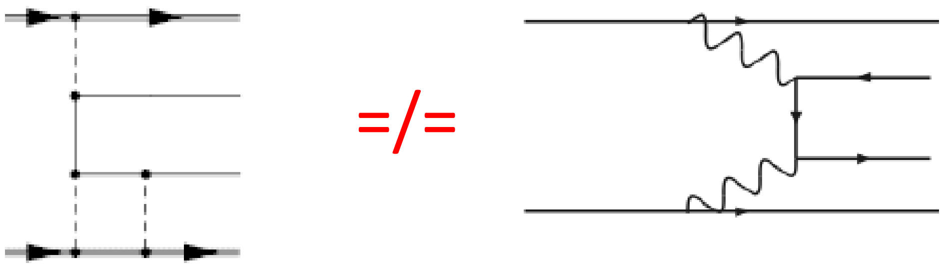
  - The 2S and 2P states can possibly add a few events
    - only differ by decay length (8x larger lifetime)

  - Probing the BH (low x) region would cement the feasibility of the TM search

Summary and future plans

- What is needed
  - 6.6 GeV background to analyze, mix, find cuts, etc.
  - See if the hodoscope geometry picks up additional events

- What is probably also needed
  - A way to conduct a search in the Bethe-Heitler region
  - simulation of 3-photon events (not trivial)



Bonus Slides

True Muonium Production

- Muon-antimuon bound state
  - Two spin ½ fermions, total spin can add to either 0 or 1

- Two mechanisms for production:
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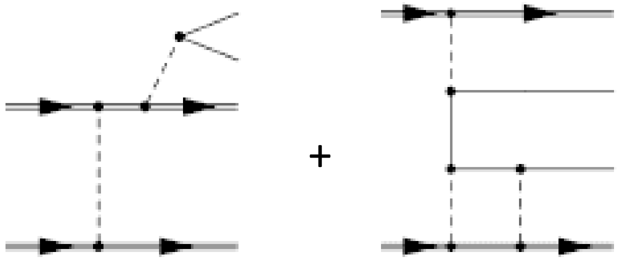


  - 1-photon: “radiative-like”, 3-photon: “Bethe-Heitler-like” kinematics
  - Branching ratio beyond 3-photon diagram makes those yields negligible.

Primary Production Cross Sections

- Banburski Schuster - arXiv:1206.3961v1 [hep-ph] 18 Jun 2012

Radiative (1-photon) mechanism:

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

3-photon mechanism:

Additional Z^2 dependence

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

Expected True Muonium Rate (1S)

- Using the production and dissociation cross sections for the 1S state

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

(dissociation length, to all final states)

Where $z = \frac{l}{l_{1^1S \rightarrow X}}$

(average distance traveled before breakup)

$$l_{1S \rightarrow X} = \frac{1}{N\sigma_b} = \frac{1}{(6.306 * 10^{22} cm^{-3})(5.67937 * 10^{-20} cm^2)} = 2.792\ \mu m$$

(atomic density) (breakup cross section)

$8\mu m\ W$ HPS target is ~3x the 1S dissociation length

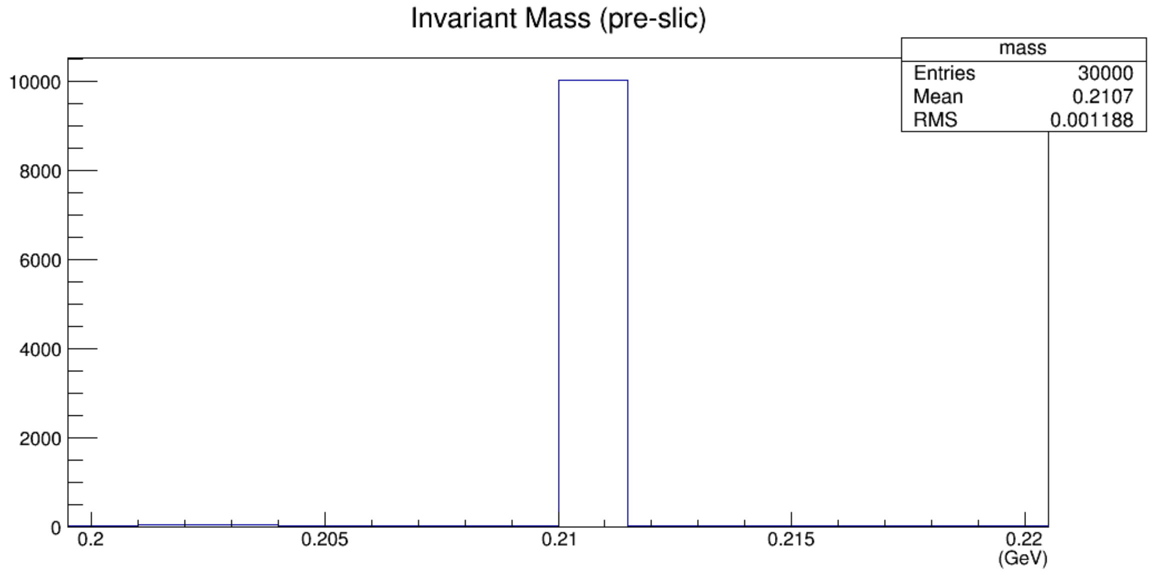
2S and 2P dissociate more easily in target, by an order of magnitude.

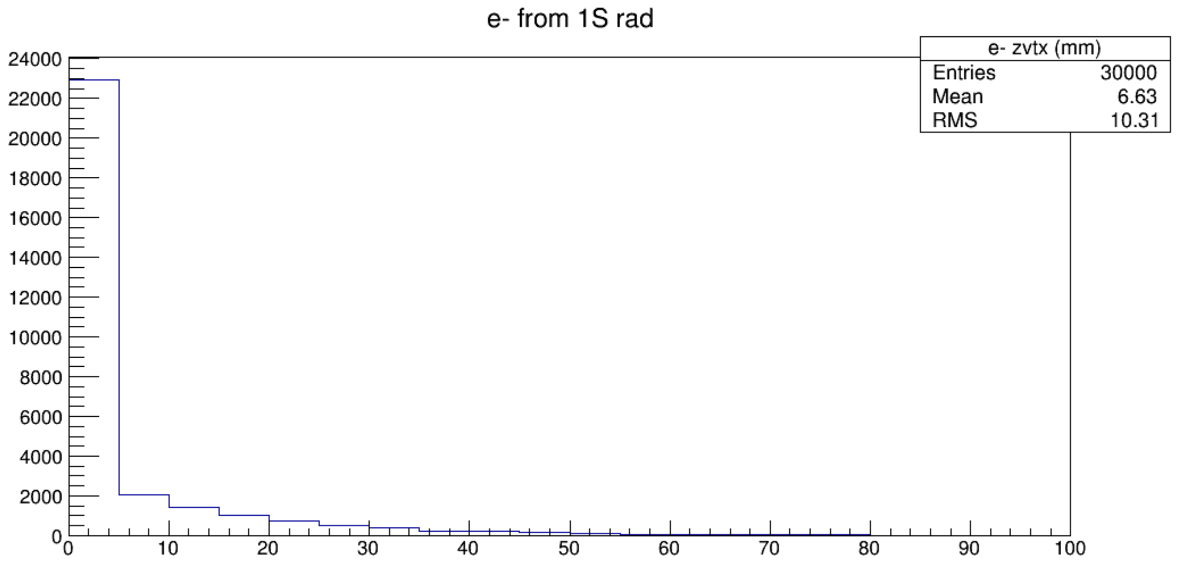
$$N_e(z) \approx N_e = \frac{5625\ electrons}{2ns}$$

450 nA for 6.6 GeV

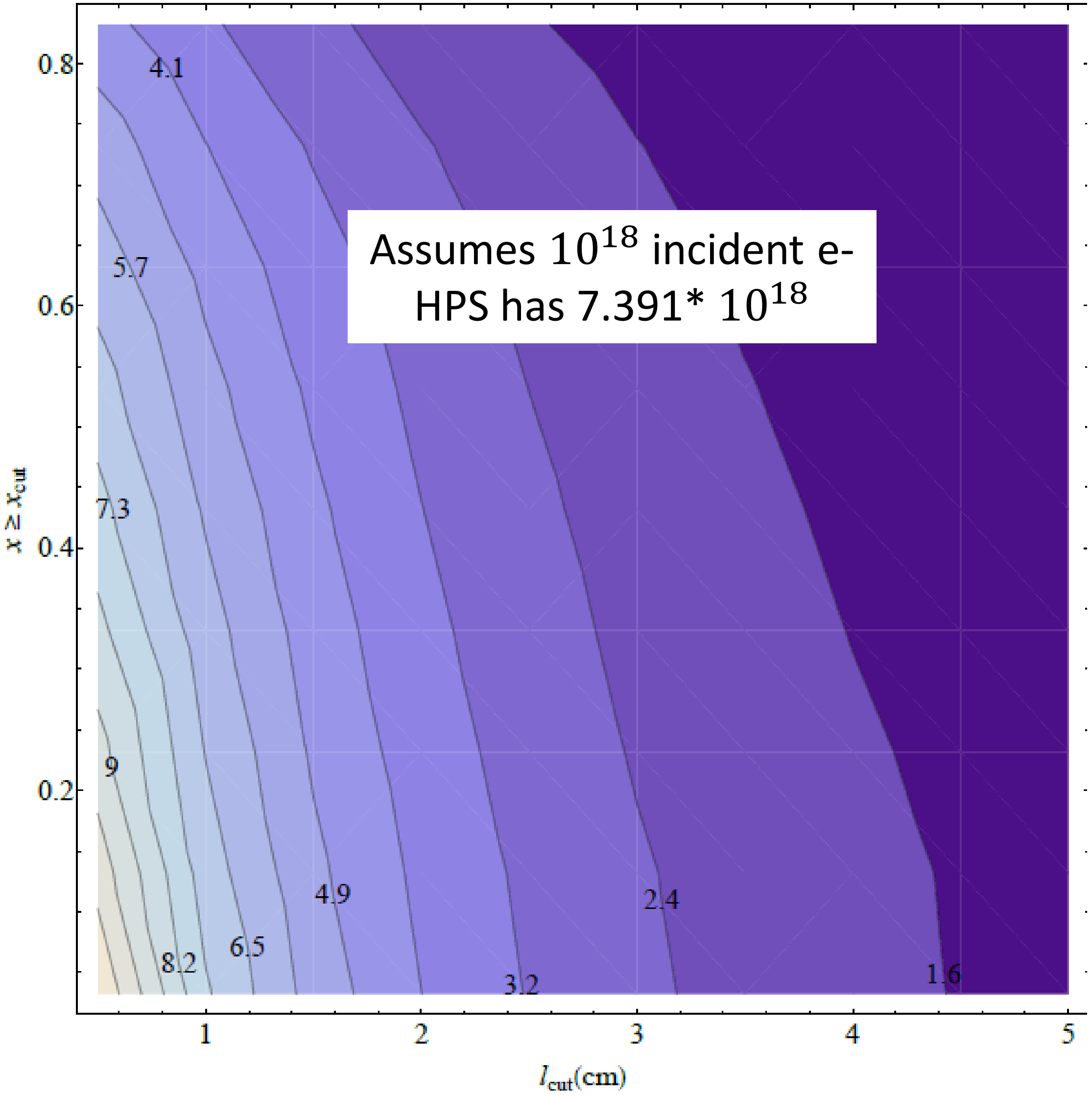
Generated True Muonium 1^3S events

$MadGraph4\ A'\,generator\ (> e^+e^-), Alpha\ correction$
$Mass = 0.211\ GeV$
: $Width = 3.627 * 10^{-13}\ GeV$ = **4.9349×10[17] pb**
$Epsilon = 1$





Banburski-Schuster TM Yield (corrected)



Secondary Production/Dissociation (target interaction)

- Transfer matrix elements

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

- Transition cross section (to all other bound states + dissociation)

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

2S state-> all states + dissoc.

$\int_0^\infty diffTotE1Ground[Z,q]\, dq$

$:= \int_0^\infty Z^2\alpha^2/\pi\ (1-F[\mathbf{2},0,0,\mathbf{2},0,0,q])\ 1/\boldsymbol{a_{TM}^2} \Delta[q,Z]\ \Delta[q,Z]\ q dq$ = **4.90741×10^17 pb**

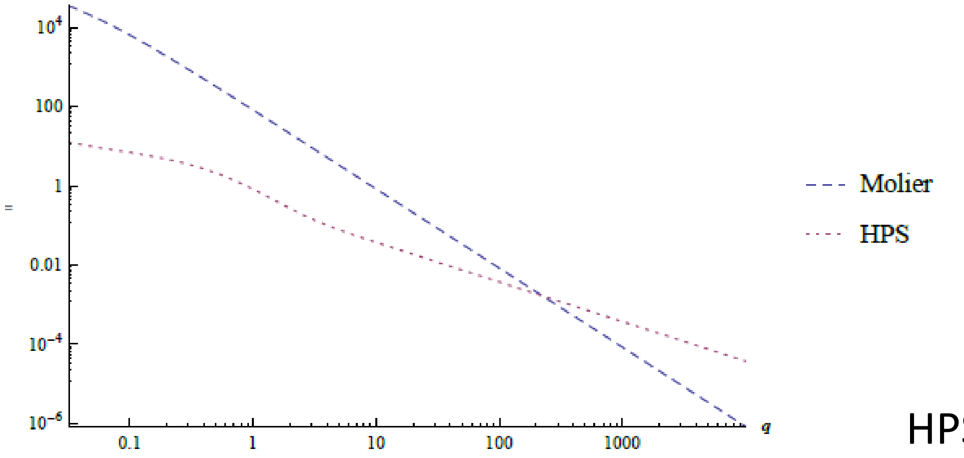
$MadGraph4\ A'generator\ (> e^+e^-), Alpha\ correction$

$: \begin{array}{c} Mass = 0.211\ GeV \\ Width = 3.627 * 10^{-13}\ GeV \\ Epsilon = 1 \end{array}$ | = **4.9349×10^17 pb**

Similar for 4.4 and 6.6 GeV

Thomas-Fermi-Molier vs. HPS G2 Factors

- Form Factors



Thomas-Fermi-Molier:

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

$$\Delta[q\_, Z\_] := 4\pi \left(\frac{0.1}{q^2/a^2 + \beta1[Z]^2} + \frac{0.55}{q^2/a^2 + \beta2[Z]^2} + \frac{0.35}{q^2/a^2 + \beta3[Z]^2} \right)$$

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

HPS G2 elastic form factor (used by MG4, $\propto d\sigma/dx$):

```
Anuc = 184;
aval := 111 / (0.0005111 * 74^(1 / 3));
dval = 0.164 / Anuc^(2 / 3);
apval = 773 / (0.0005111 * 74^(2 / 3))
ΔHPS[q_, Z_] :=
  ((Z^2) * (aval^4) * (q^2) / ((1 + aval^2 * q) * (1 + q / dval))^2 + Z * (apval^4) *
      q^2 * (1 + 1.9276 * q)^2 / ((1 + apval^2 * q) * (1 + 1.40845 * q)^4)^2)^0.5;
```

2S and 2P True Muonium States

- Unlike the “primarily produced” 1S state, which survives the target, the 2S and 2P dissociate far more easily in the target.
- Their primary production yields are also an order of magnitude lower.
- The displaced 2S and 2P states will then come from a 1S state transitioning into them within the target (“secondary production”).
- While these states are difficult to detect, the 2P state is able to transition to additional 1S states that may survive the target, contributing to its overall yield.

Secondary Production/Dissociation (target interaction)

- Transfer matrix elements

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

- Transition cross section (to all other bound states + dissociation)

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

$\int_0^\infty diffTotE1Ground[Z,q]\, dq$:=

$\int_0^\infty$ $Z^2\alpha^2/\pi$ (1−F[1,0,0,1,0,0,q]) $1/\boldsymbol{a^2_{TM}}$Δ[q,Z] Δ[q,Z] qdq **= 5.67937×10^{16} pb**

$\int_0^\infty$ $Z^2\alpha^2/\pi$ (1−F[1,0,0,1,0,0,q]) $1/\boldsymbol{a_0^2}$ **Δ$_0$[q,Z] Δ$_0$[q,Z]** q **/(127.9/137)^2**qdq

= 6.88469 ×10^{18} pb

Secondary Production/Dissociation (target interaction)

- Transfer matrix elements

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

- Transition cross section (to all other bound states + dissociation)

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

$\int_0^\infty diffTotE1Ground[Z,q]\, dq$:=

$\int_0^\infty Z^2\alpha^2/\pi\ (1-F[1,0,0,1,0,0,q])\ 1/\boldsymbol{a_{TM}^2}\Delta[q,Z]\ \Delta[q,Z]\ q\,dq$ = **5.67937×10^16 pb**

$\int_0^\infty Z^2\alpha^2/\pi\ (1-F[1,0,0,1,0,0,q])\ 1/\boldsymbol{a_0^2}\ \boldsymbol{\Delta_0[q,Z]\ \Delta_0[q,Z]} * \boldsymbol{\Delta HPS[q,Z]\ /(127.9/137)^{\wedge}2}\ q\,dq$

= **4.13904×10^18 pb**

Secondary Production/Dissociation (target interaction)

- Transfer matrix elements

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

- Transition cross section (to all other bound states + dissociation)

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

$\int_0^\infty diffTotE1Ground[Z,q]\, dq$:=

$\int_0^\infty$ Z$^2\alpha^2$/π (1−F[1,0,0,1,0,0,q]) 1/$\boldsymbol{a_{TM}^2}$Δ[q,Z] Δ[q,Z] qdq **= 5.67937×10^{16} pb**

$\int_0^\infty$ Z$^2\alpha^2$/π (1−F[1,0,0,1,0,0,q]) 1/$\boldsymbol{a_{TM}^2}$Δ[q,Z] Δ[q,Z] $*$ **ΔHPS[q,Z] /(127.9/137)^2** qdq

= **2.34739×10^{17} pb**

Secondary Production/Dissociation (target interaction)

- Transfer matrix elements

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

- Transition cross section (to all other bound states + dissociation)

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

1S state-> all states + dissoc.

$\int_0^\infty diffTotE1Ground[Z,q]\, dq$

$:= \int_0^\infty Z^2 \alpha^2/\pi\ (1-F[\mathbf{1},0,0,\mathbf{1},0,0,q])\ 1/\boldsymbol{a_{TM}^2} \Delta[q,Z]\ \Delta[q,Z]\ q\,dq$ = **5.67937×10^{16} pb**

$MadGraph4\ A'generator\ (> e^+e^-), Alpha\ correction$

$Mass = 0.211\ GeV$

$:\ Width = 3.627 * 10^{-13}\ GeV$ | = **4.9349×10^{17} pb**

$Epsilon = 1$

Similar for 4.4 and 6.6 GeV

TM Theory vs. MadGraph A’ generator XS

- If MadGraph assumes no state transitions, only 1S production and dissociation of a hydrogen-like atom, correcting for α in MadGraph4:

$$\frac{MG4\ generated}{TM\ Theory\ (1S \rightarrow e^{+}e^{-})} = \frac{4.9349 * 10^{17}\ pb}{2.21044 * 10^{16}\ pb} = 22.32$$

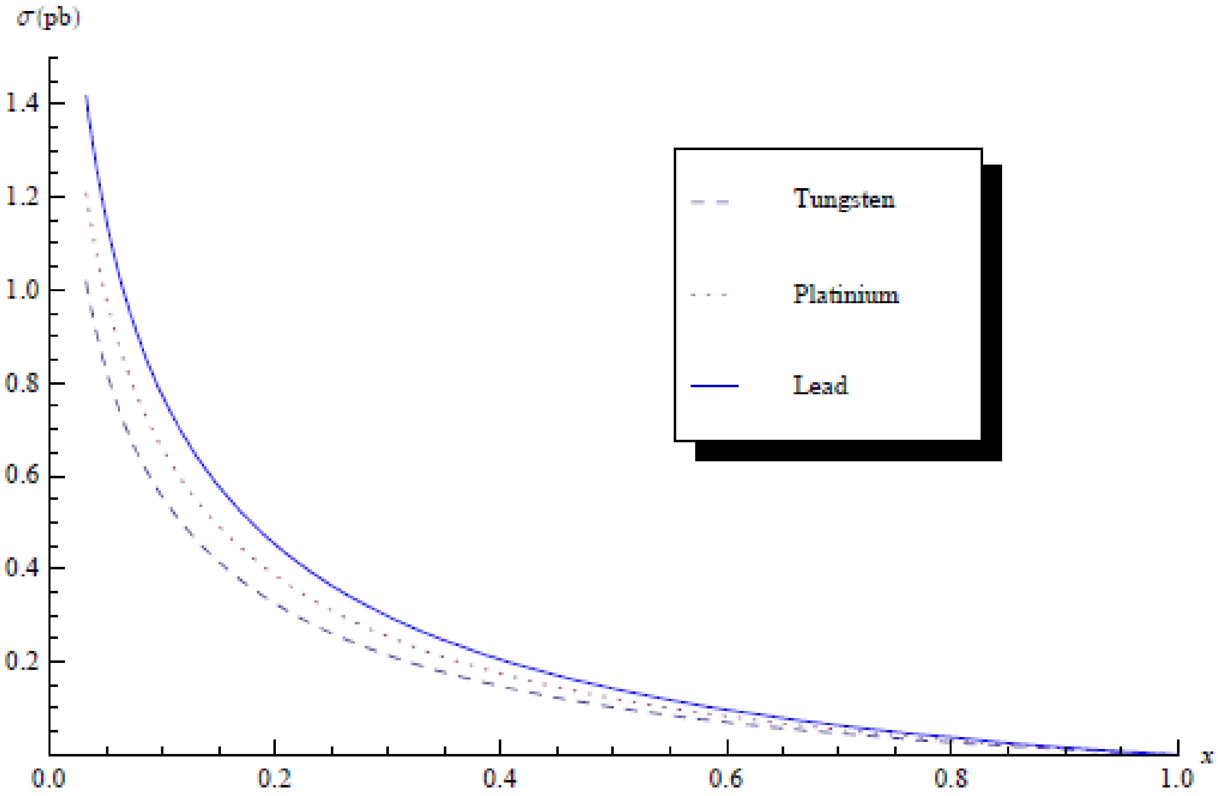
- If also using HPS’s G2 form factor for A’ production:

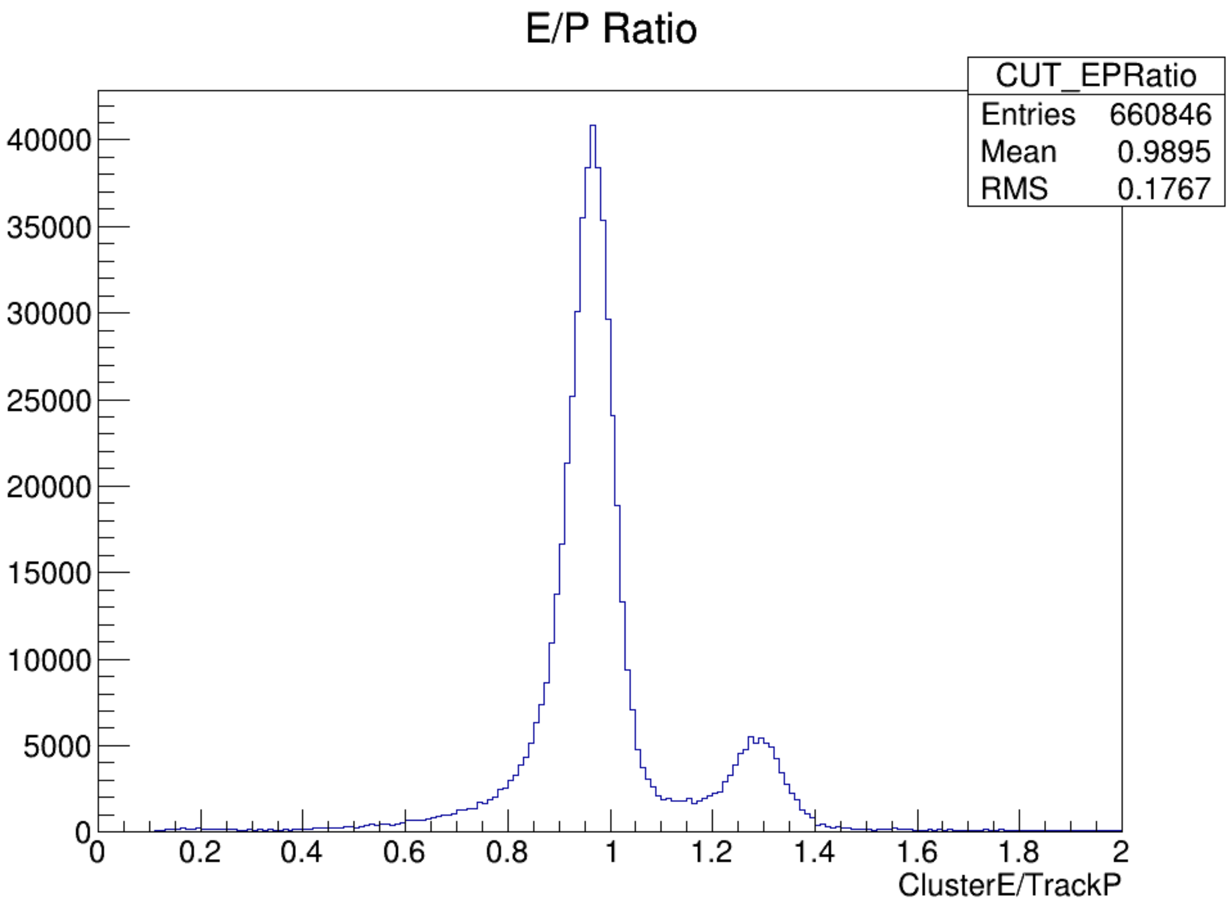
$$\frac{MG4\ generated}{TM\ Theory\ (1S \rightarrow e^{+}e^{-})) + HPS\ FF} = \frac{4.9349 * 10^{17}\ pb}{2.0005 * 10^{17}\ pb} = 2.466$$

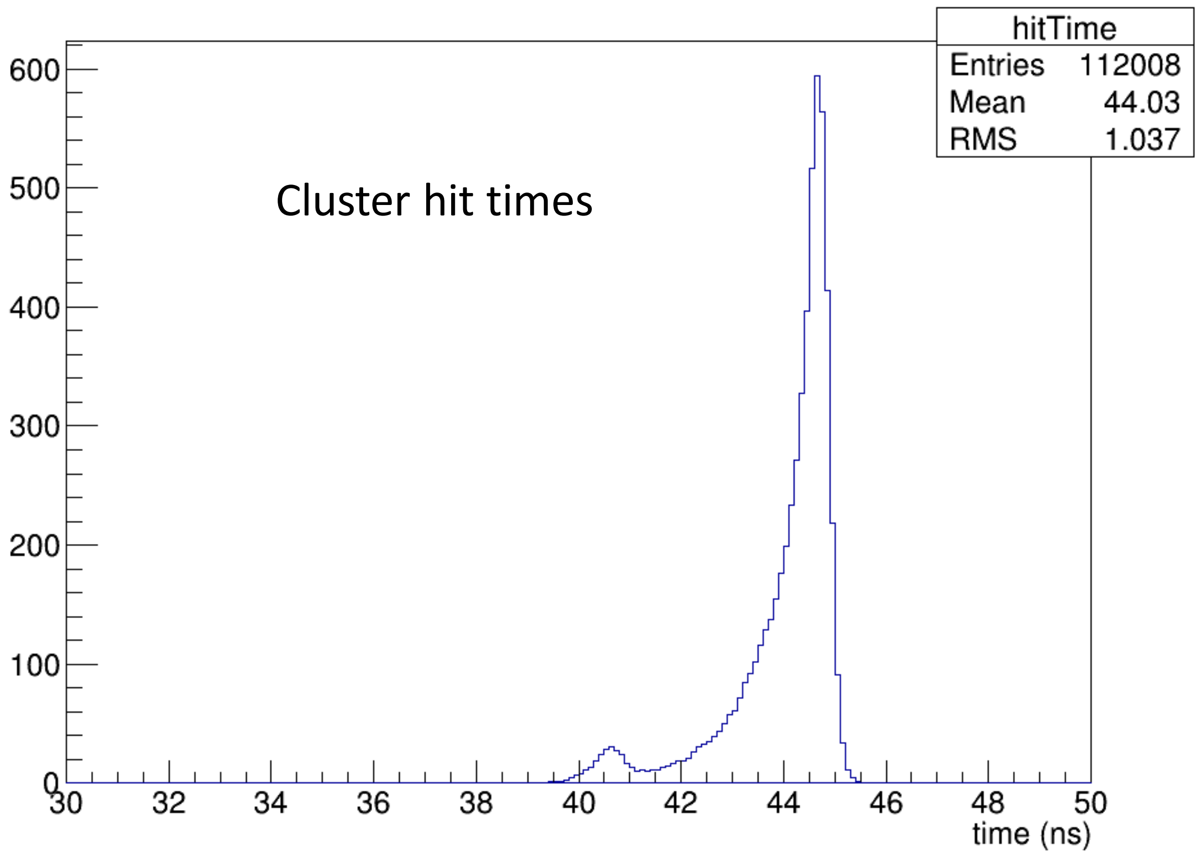
- If Assuming all state transitions + dissociation, not just 1S

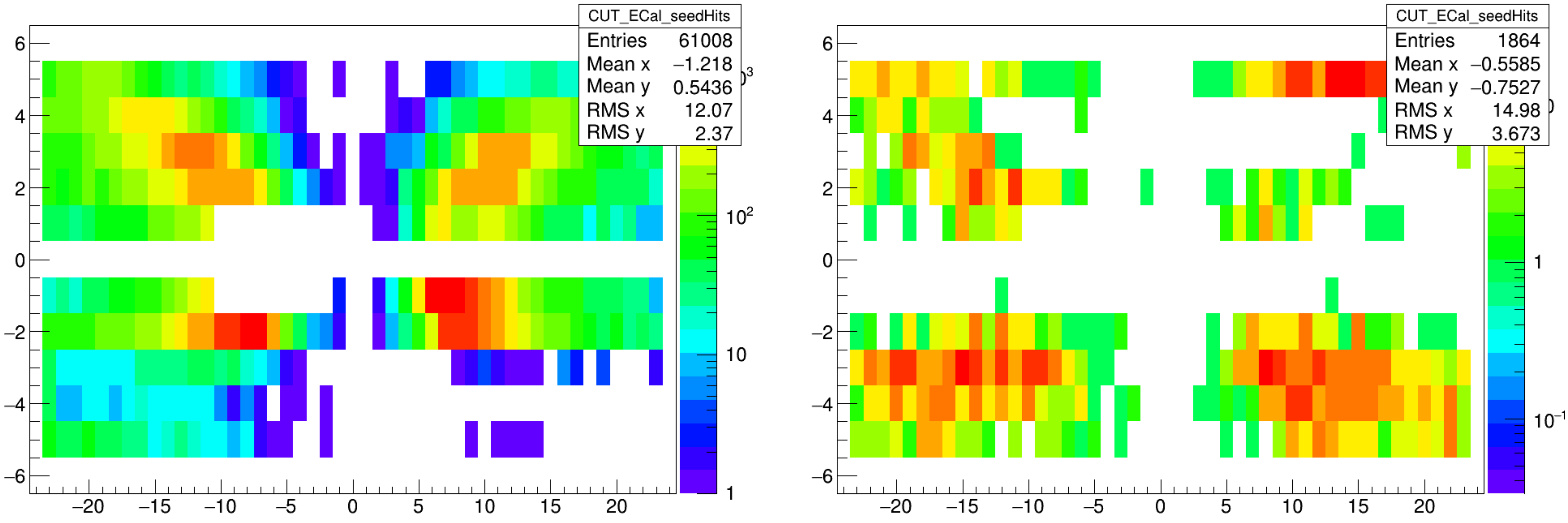
$$\frac{MG4\ generated}{TM\ Theory(All \rightarrow e^{+}e^{-}) + HPS\ FF} = \frac{4.9349 * 10^{17}\ pb}{2.34739 * 10^{17}\ pb} = 2.10$$

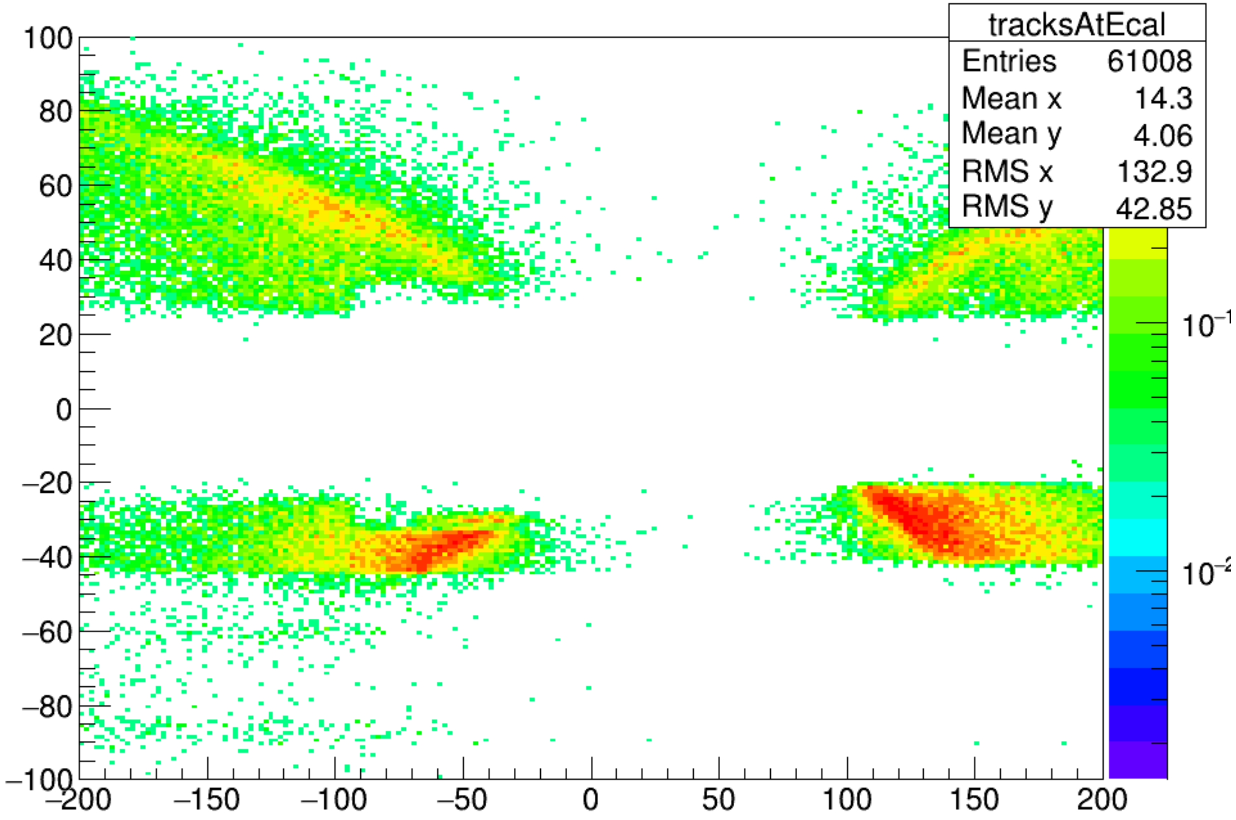
Integrated Production Cross Section (radiative)

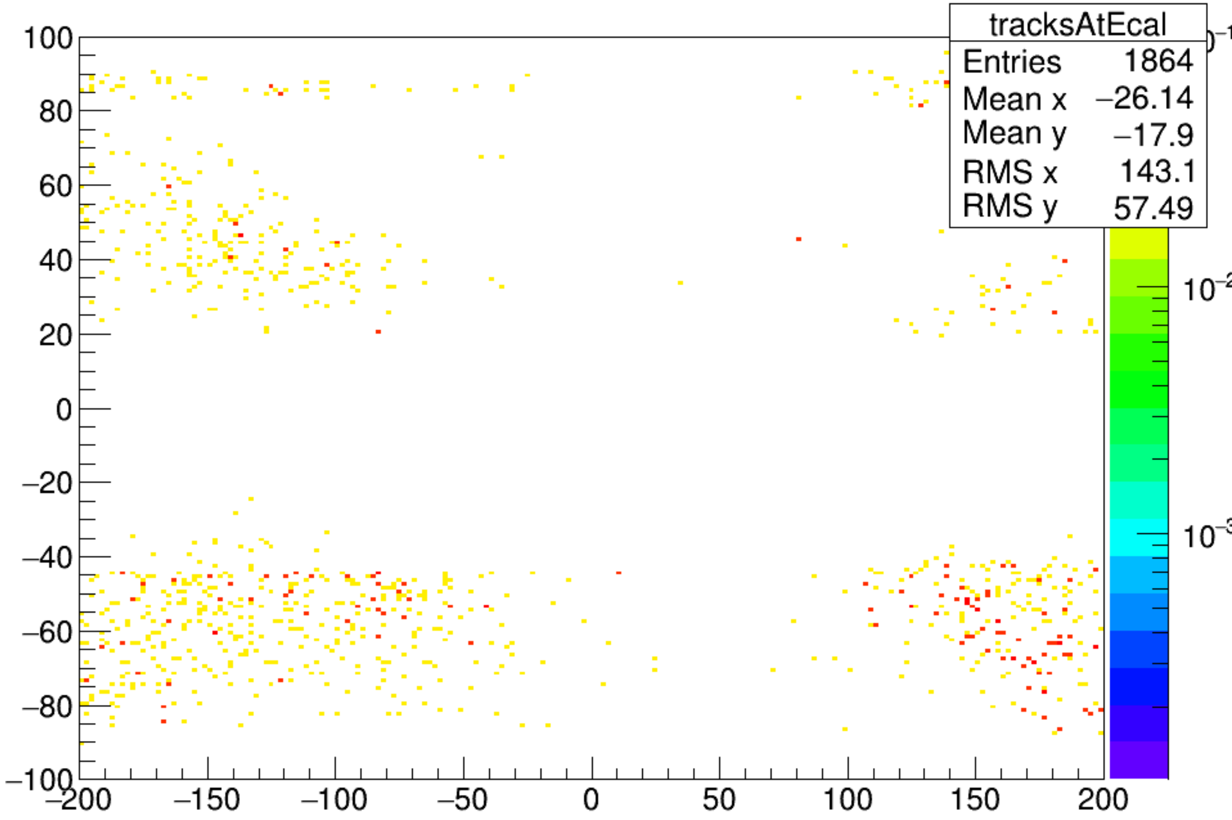


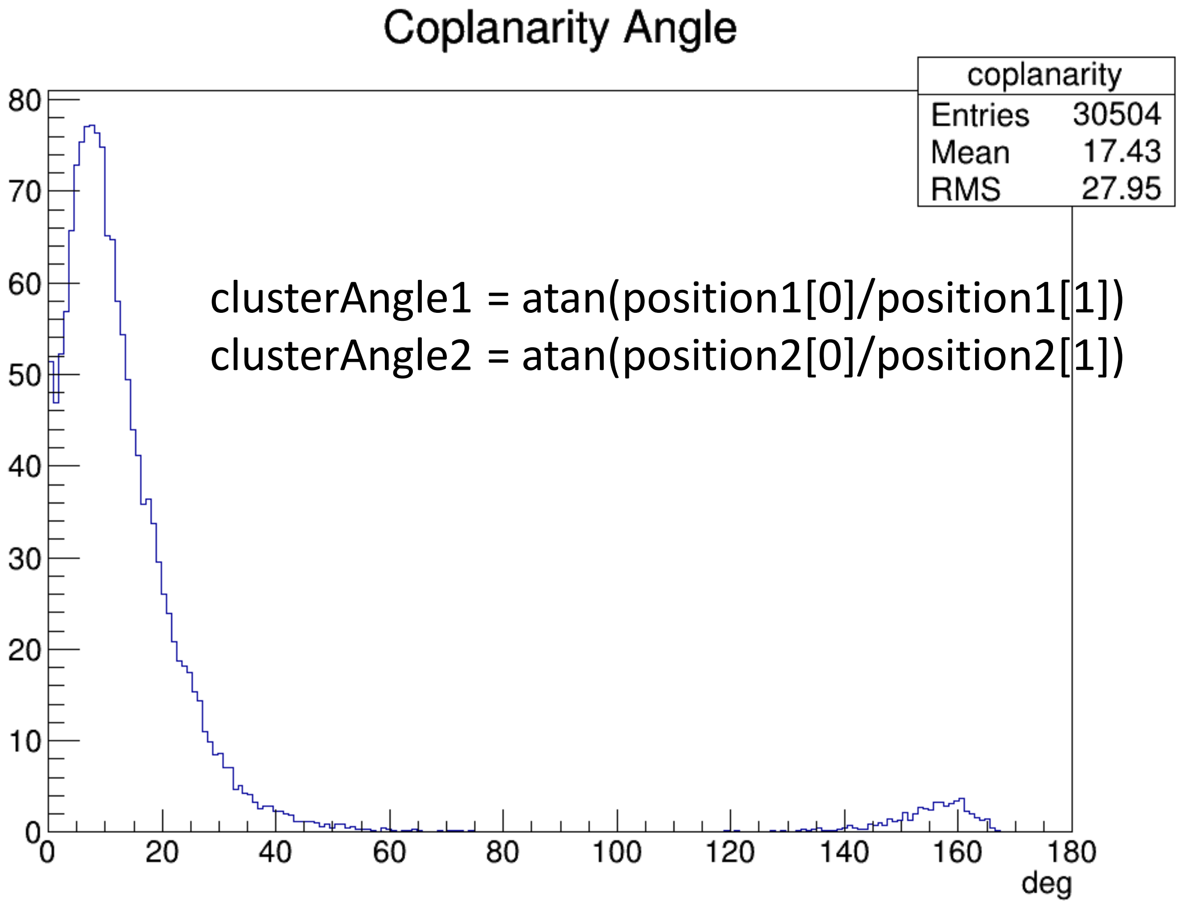

E/P Ratio
CUT_EPRatio
Entries 660846
Mean 0.9895
RMS 0.1767
ClusterE/TrackP

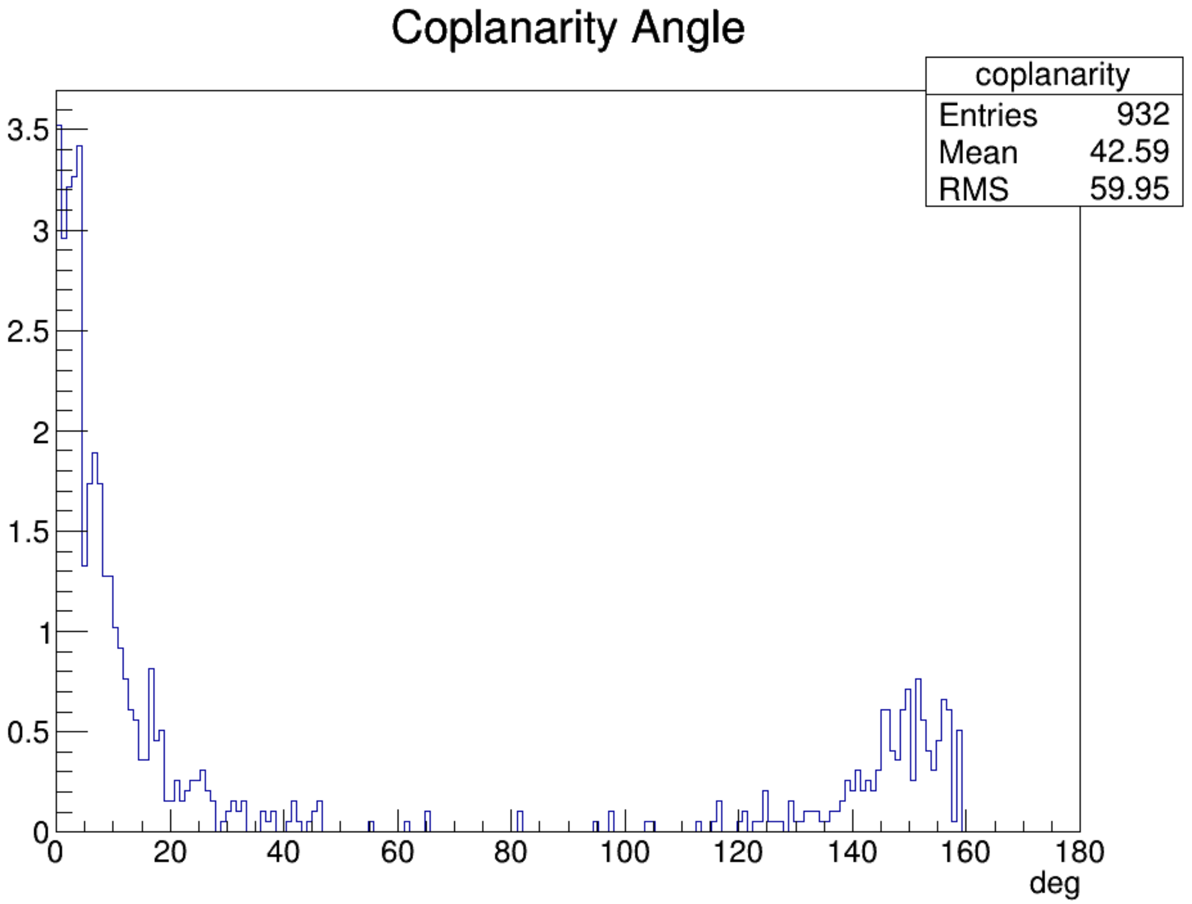

hitTime
Entries 112008
Mean 44.03
RMS 1.037
Cluster hit times
time (ns)


CUT_ECal_seedHits
Entries 61008
Mean x −1.218
Mean y 0.5436
RMS x 12.07
RMS y 2.37
CUT_ECal_seedHits
Entries 1864
Mean x −0.5585
Mean y −0.7527
RMS x 14.98
RMS y 3.673


tracksAtEcal
Entries 61008
Mean x 14.3
Mean y 4.06
RMS x 132.9
RMS y 42.85
100
80
60
40
20
0
−20
−40
−60
−80
−100
−200 −150 −100 −50 0 50 100 150 200
10^{-1}
10^{-2}


tracksAtEcal
Entries 1864
Mean x −26.14
Mean y −17.9
RMS x 143.1
RMS y 57.49
100
80
60
40
20
0
−20
−40
−60
−80
−100
−200 −150 −100 −50 0 50 100 150 200
10^{-2}
10^{-3}


Coplanarity Angle
coplanarity
Entries 30504
Mean 17.43
RMS 27.95
clusterAngle1 = atan(position1[0]/position1[1])
clusterAngle2 = atan(position2[0]/position2[1])
deg


Coplanarity Angle
coplanarity
Entries 932
Mean 42.59
RMS 59.95
deg