2021 Møllers Overview

HPS Collaboration Meeting – June 2025

Lewis Wolf

Introduction

- Møllers are a two-body interaction which has a fixed invariant mass based on beam energy
  - Serves as a good way to get a handle on detector mass resolution, since the Møller invariant mass spectrum is a spike without width.

$$M(e^- e^+) = \sqrt{S} = \sqrt{2m_{e^-}^2 + 2E_{\text{beam}} m_{e^-}} \approx \sqrt{2E_{\text{beam}} m_{e^-}}$$

- For 2016, Ebeam = 2.3GeV and M(ee) = 48. 498MeV
- For 2021, Ebeam = 1.92GeV and M(ee) = 44.309MeV

Talk organization:

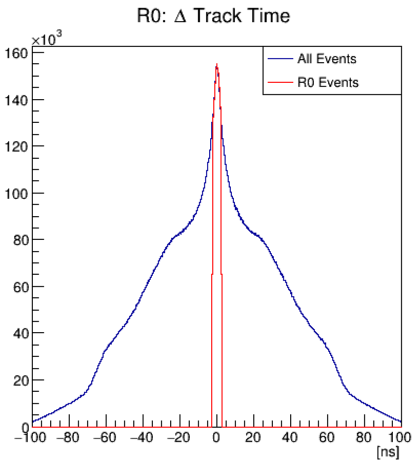
- Cuts & event selection
- V7 detector efforts and fits
- Angular quantities and dependency
- Cluster requirement and distributions
- Beam Direction

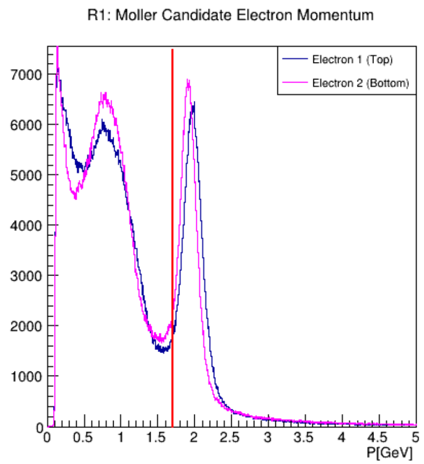
- Previous talks for more detail
- FALL24 Collaboration Meeting Talk
- Moller Angular Dependence I
- Moller Angular Dependence II

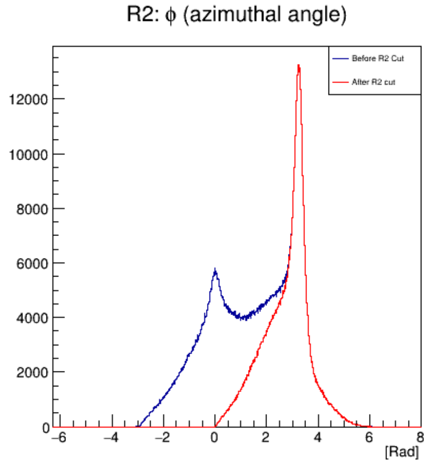
2021 Cuts for Møller Selection

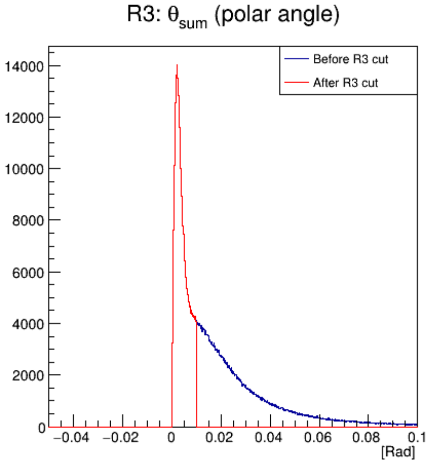
- 5 “R-series” cuts are applied sequentially:

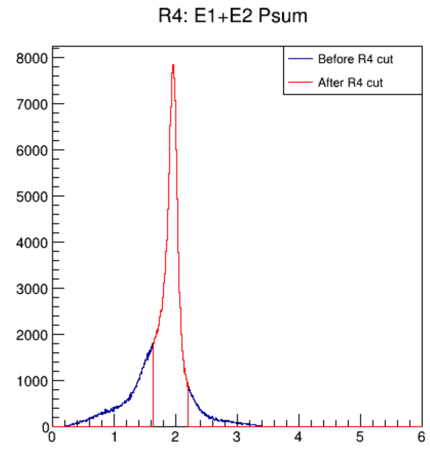
- R0 - Cut on track time: $|\Delta TrackTime| < 2.5ns$
- R1 - Cut on individual electron momenta: $|p_e| < 1.7GeV$
- R2 - Cut requiring electrons to be in opposite volumes of HPS
- R3 - Cut on calculated beam angle: $(\vec{p}_{e1} + \vec{p}_{e2})_\theta < \theta_{max}$
- R4 - Cut on the 3-momentum sum of the two electrons: $0.85E_b < |\vec{p}_{e1} + \vec{p}_{e2}| < 1.15E_b$



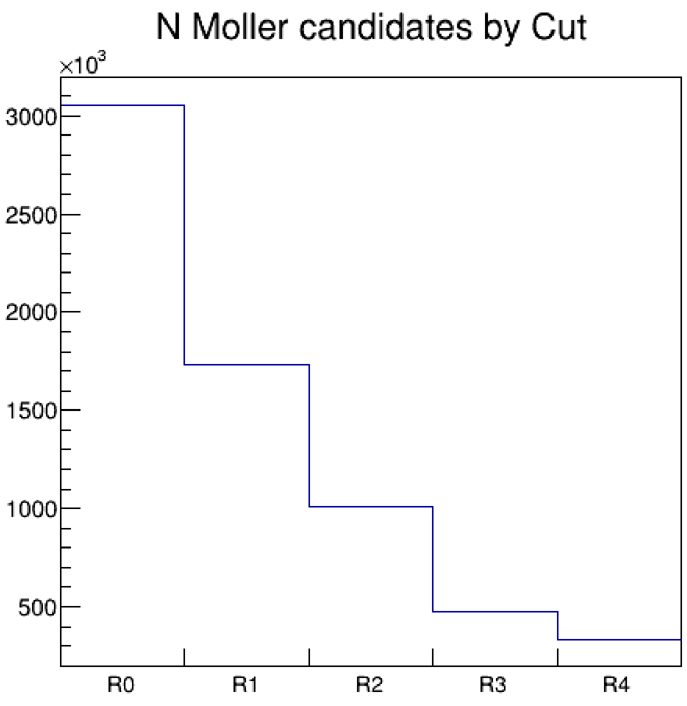


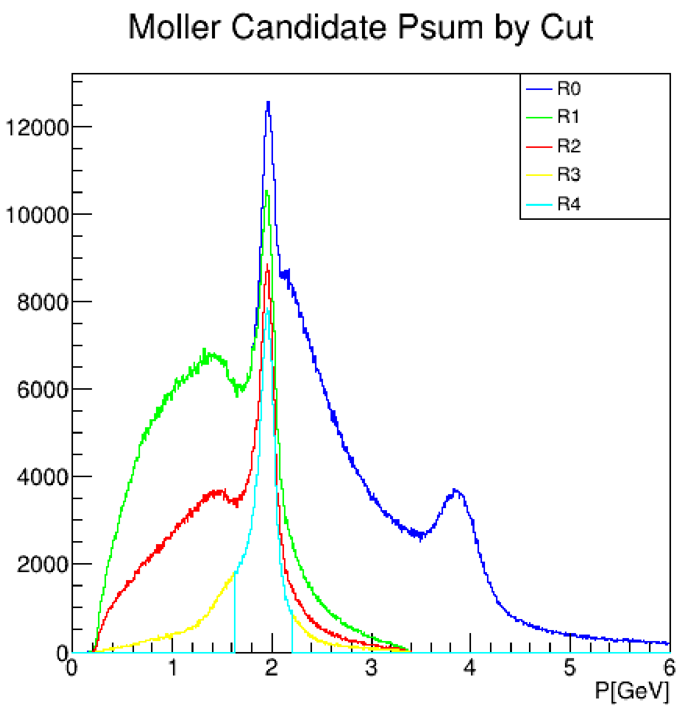


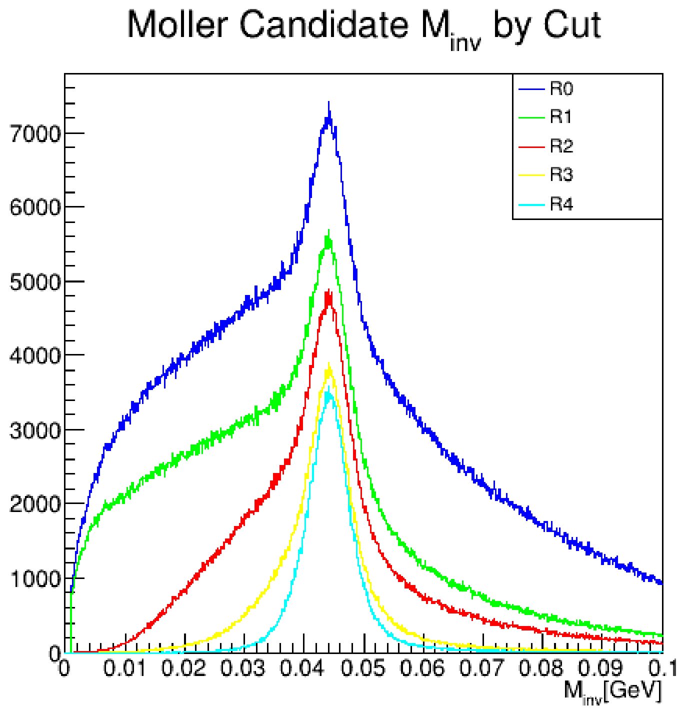




2021 Cuts for Møller Selection

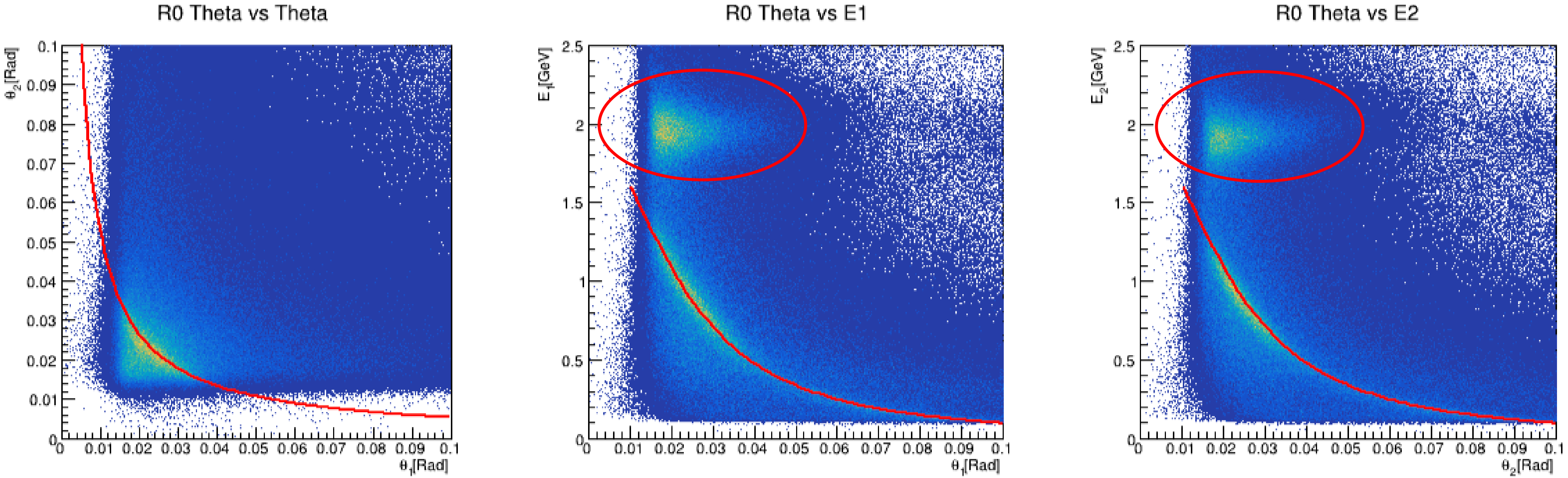






- Visualization of Møller candidate momentum sum (middle) and invariant mass distribution (left) after each cut applied sequentially.
- Roughly 1% efficiency after applying all cuts.

2021 Cuts for Møller Selection

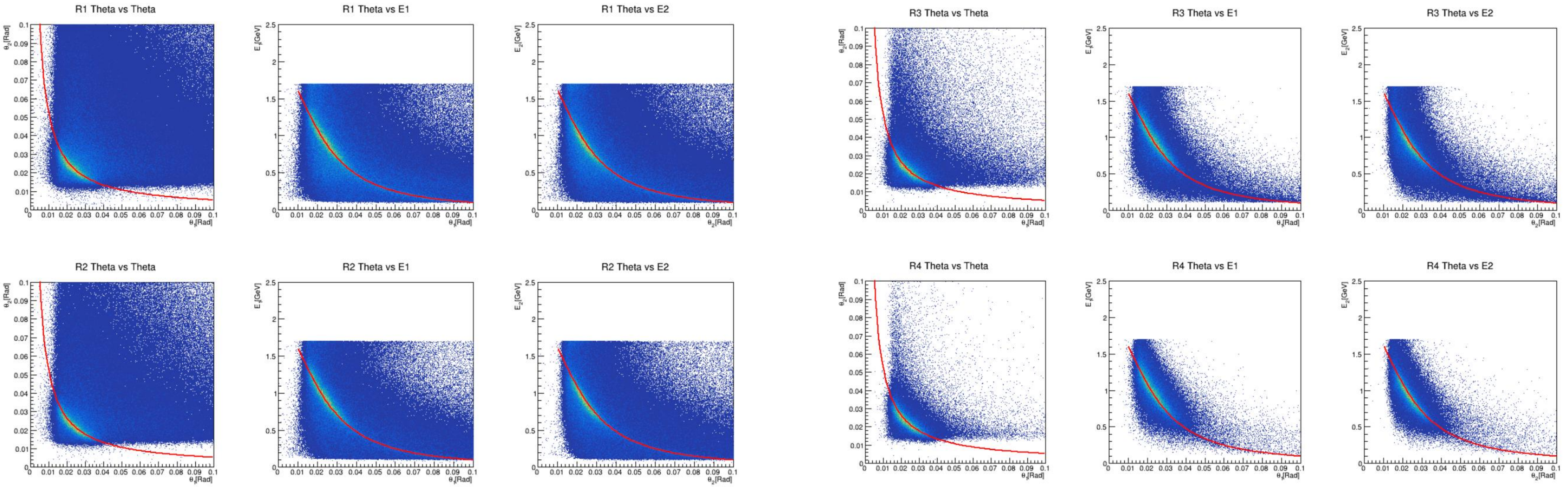


$$\theta_2(\theta_1) = 2\sin^{-1}\left(\frac{m_e}{2E_{beam}}\csc\frac{\theta_1}{2}\right)$$

$$E(\theta) = \frac{E_{beam}}{1 + \frac{2E_{beam}}{m_e}\sin^2(\theta/2)}$$

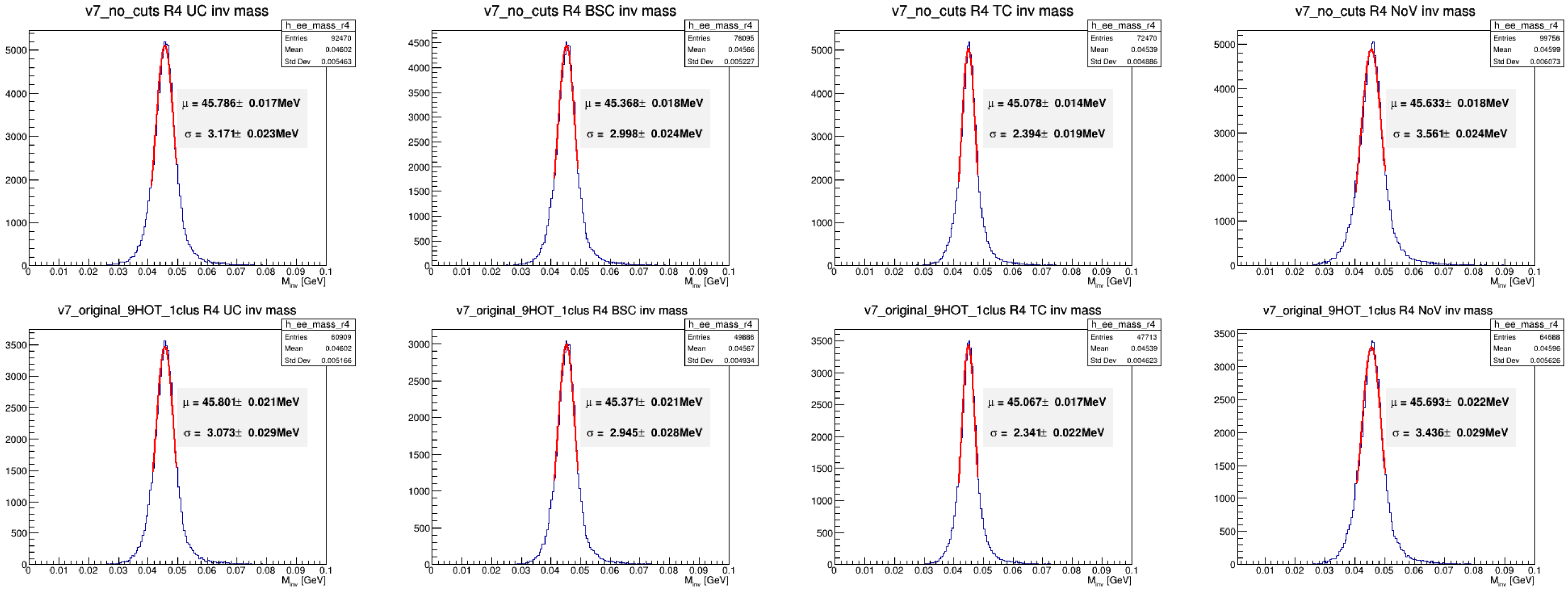
- Explicit relations between scattering angle and energy exist, and the data follows these curves well.
- FEEs are clearly seen here as well after only applying the timing cut.

2021 Phase Space by Cut



- Top left: R1, cuts out FEES
- Bottom left: R2, requires electron 1 and electron 2 to be in opposite tracking volumes. This is what labels el1 as the 'top' electron, and el2 as the 'bottom' electron.
- Top right: R3, cut on 'parent' or virtual photon angle W.R.T the beam.
- Bottom right: R4, cut on electron momentum sum.

2021 Invariant Mass Distributions

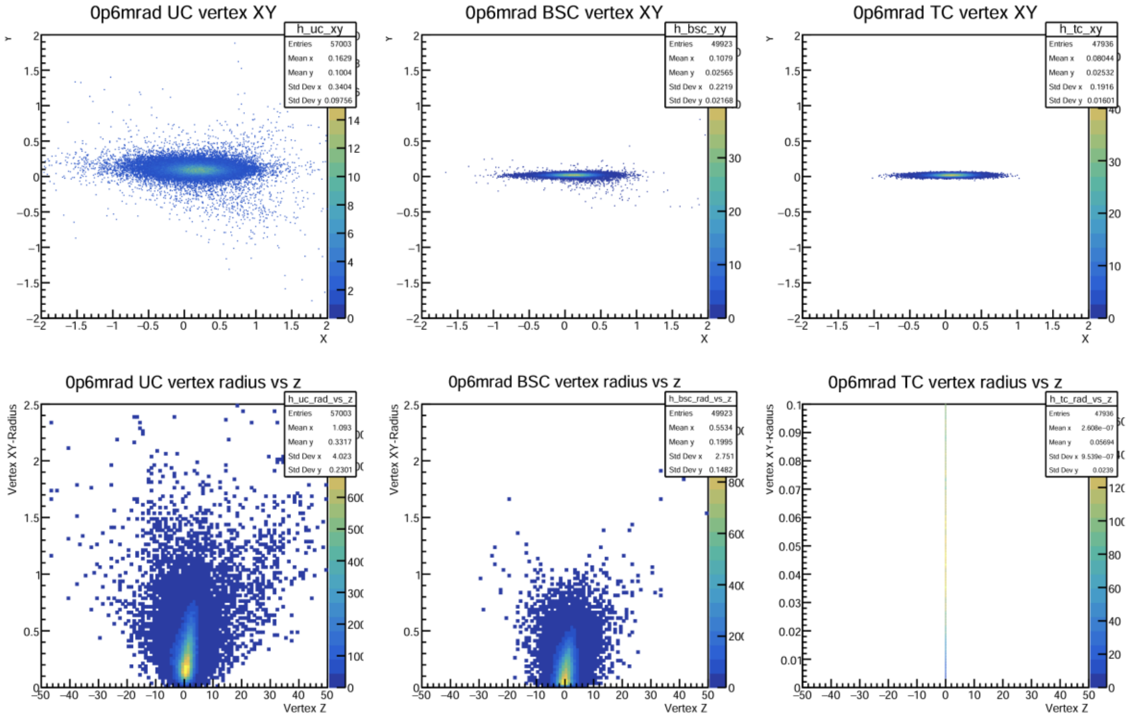


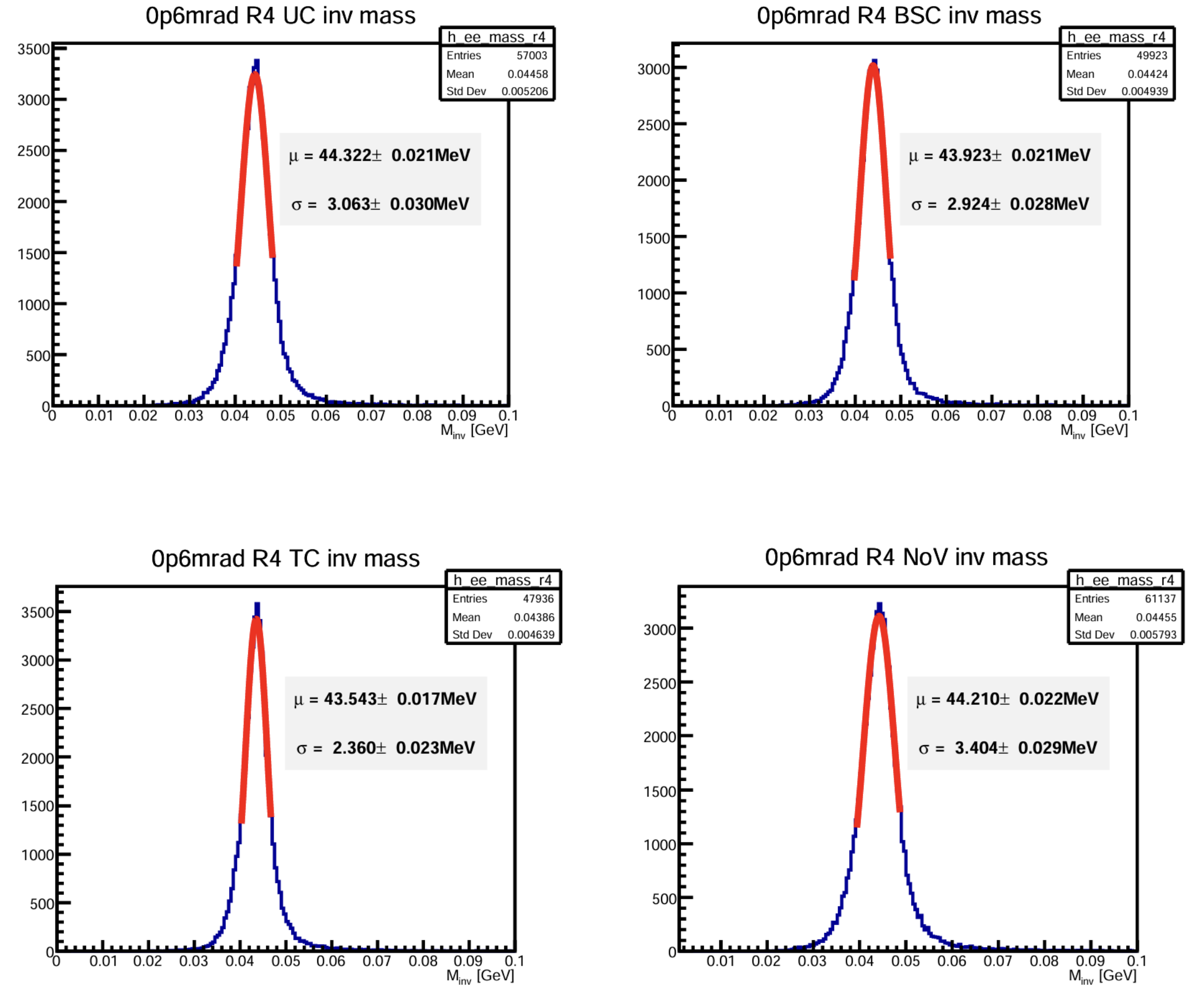
- Matthew Gignac put a lot of effort into tuning the so-called ‘V7’ detectors to get the correct mean value of the Møller peak. The first V7 detector, using the same cuts, appeared to produce a Møller peak that was a few MeV higher than the theoretical value.

- I checked to see if requiring 9 hits on track or adding ECal cluster requirements would improve this, but it did not seem to have a significant impact.

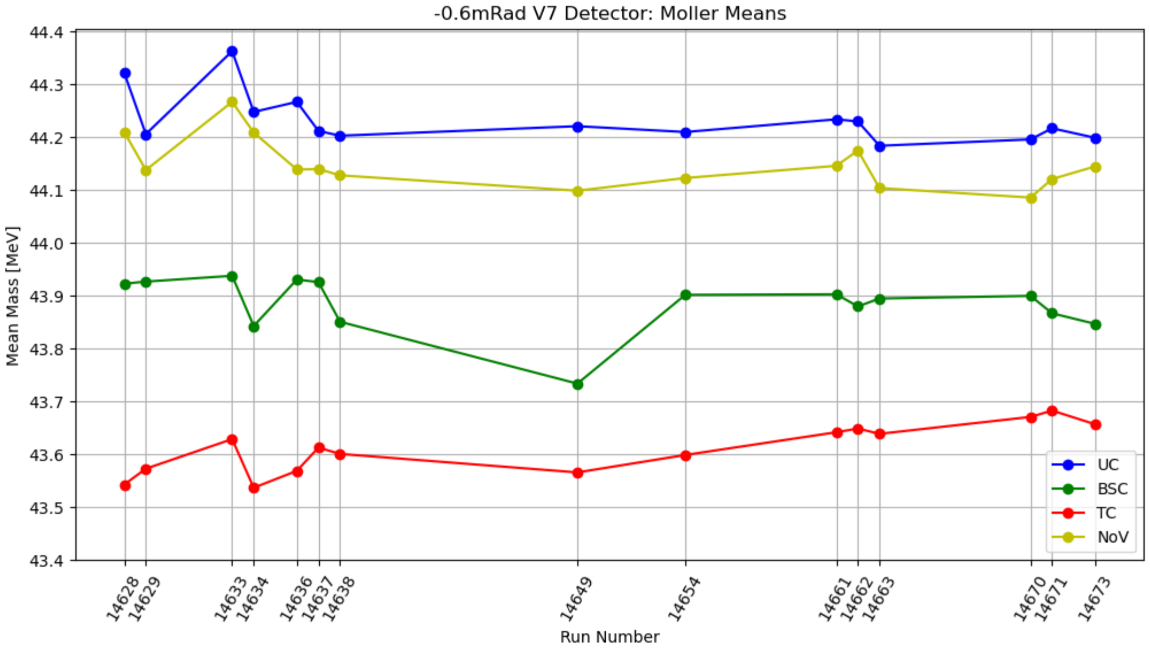
2021 Invariant Mass Distributions

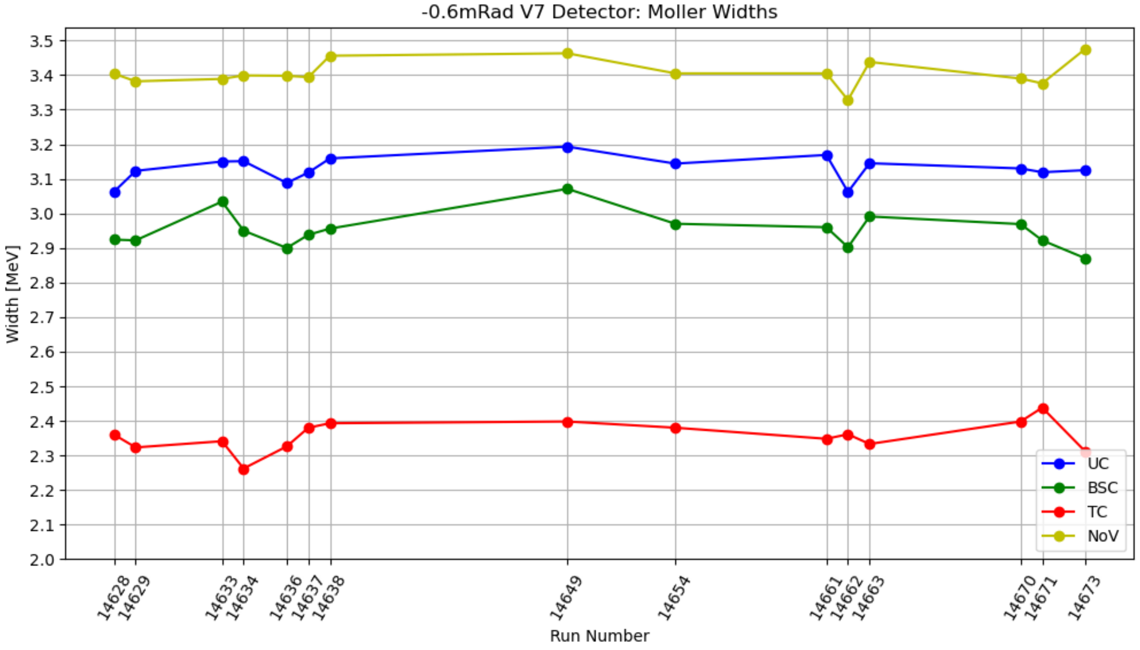
- Matthew Gignac put a lot of effort into tuning the so-called ‘V7’ detectors to get the correct mean value of the Møller peak. Many detectors were made with various opening angles, all resulting in different mean values for the Møller peak.
- Extrapolating the opening angle vs Møller mean to the correct value resulted in a -0.6mrad correction





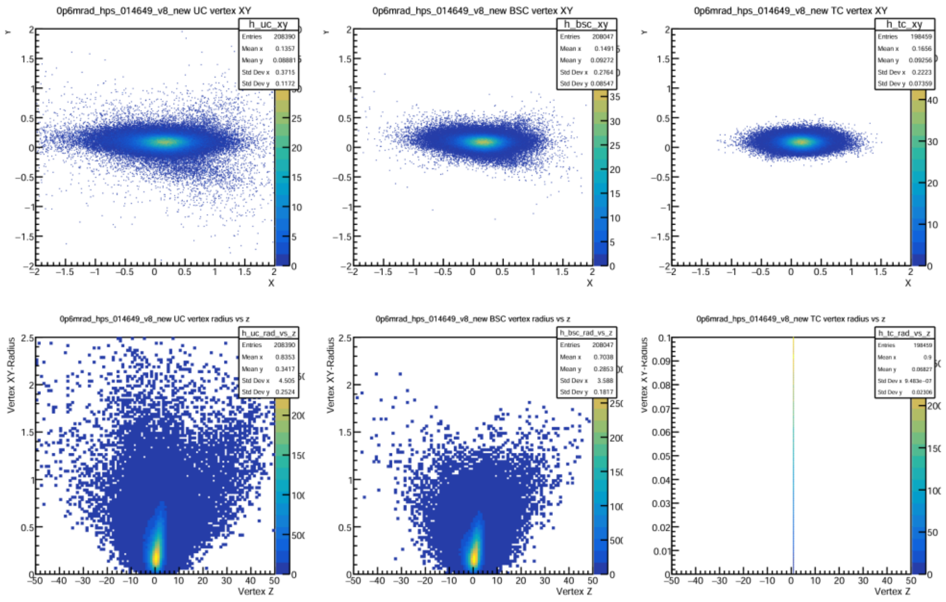
2021 Invariant Mass Distributions

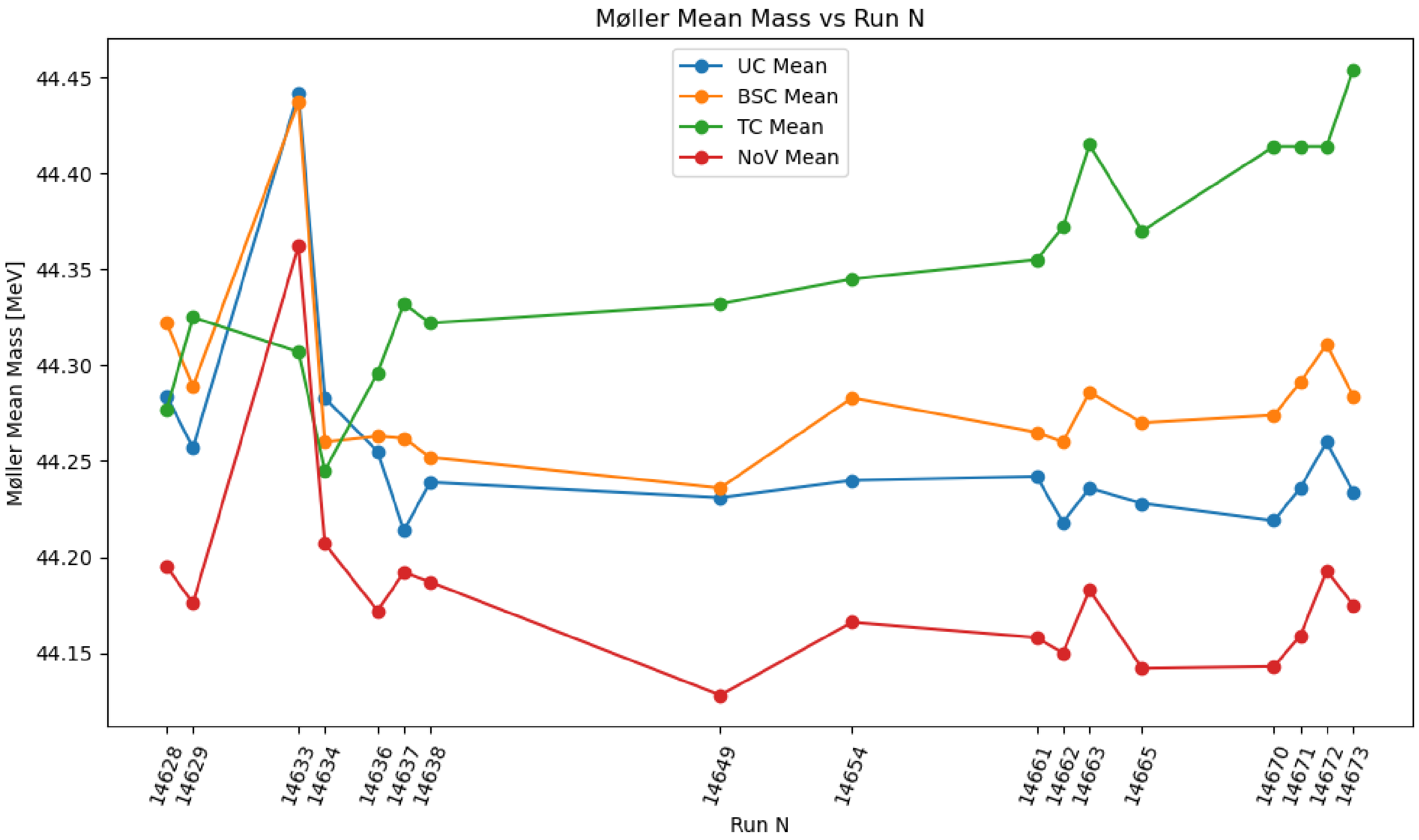




- This -0.6mrad correction was derived using unconstrained vertices, so though UC Møller V0s look quite stable and just under the theoretical value of 44.309MeV, the beamspot and target constrained V0s are still a bit off.

2021 Invariant Mass Distributions

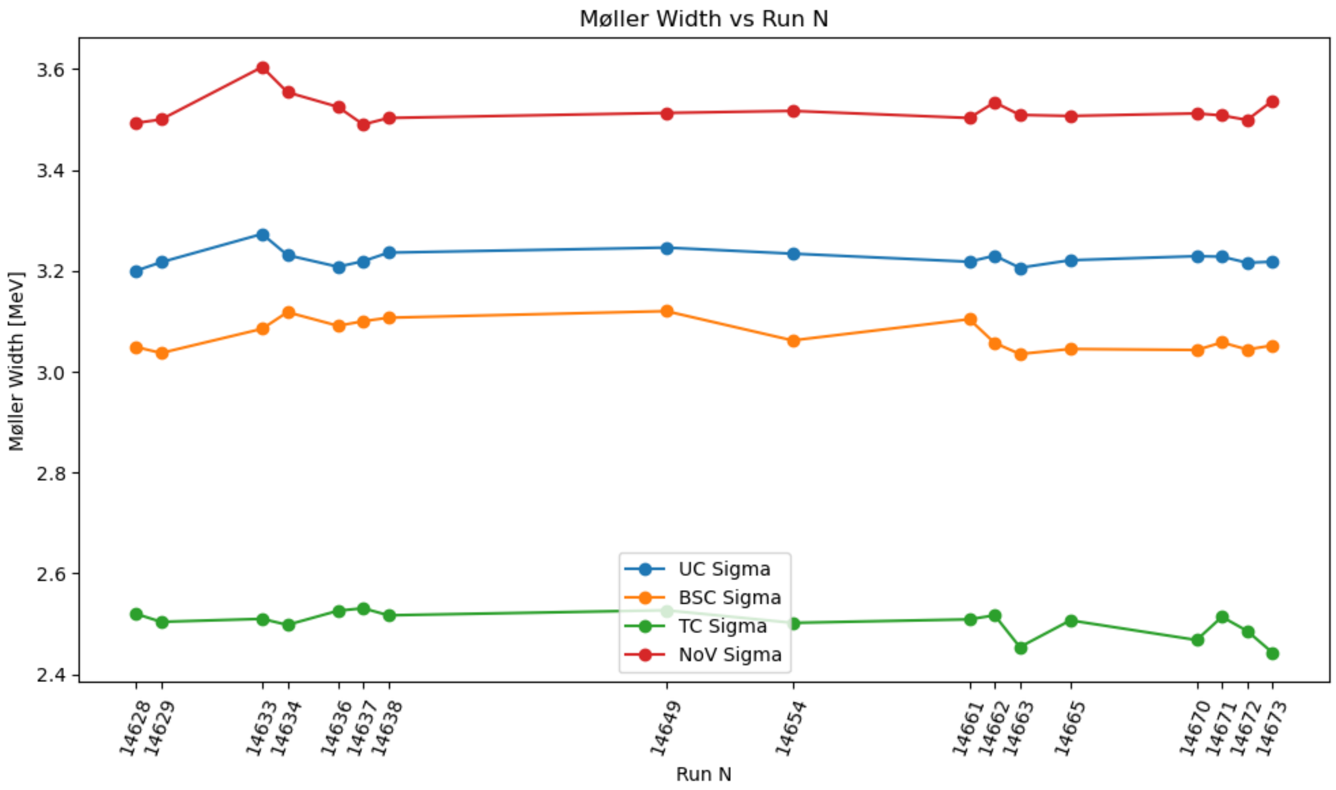


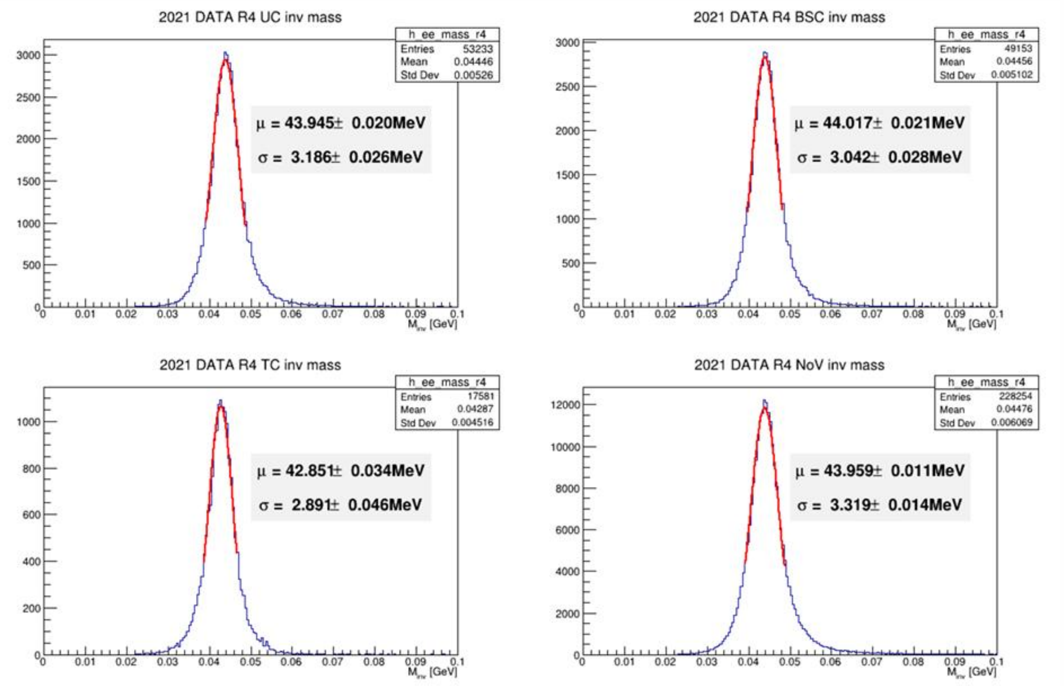


- After some more tweaking by Matt Gignac using vertex position information, this is the latest result using 10% of the data across the Møller runs. Note that y-axis range is only 0.3MeV. The mean values are in good shape. Theoretical value is 44.309MeV.

10% Møller runs Fits

OLD



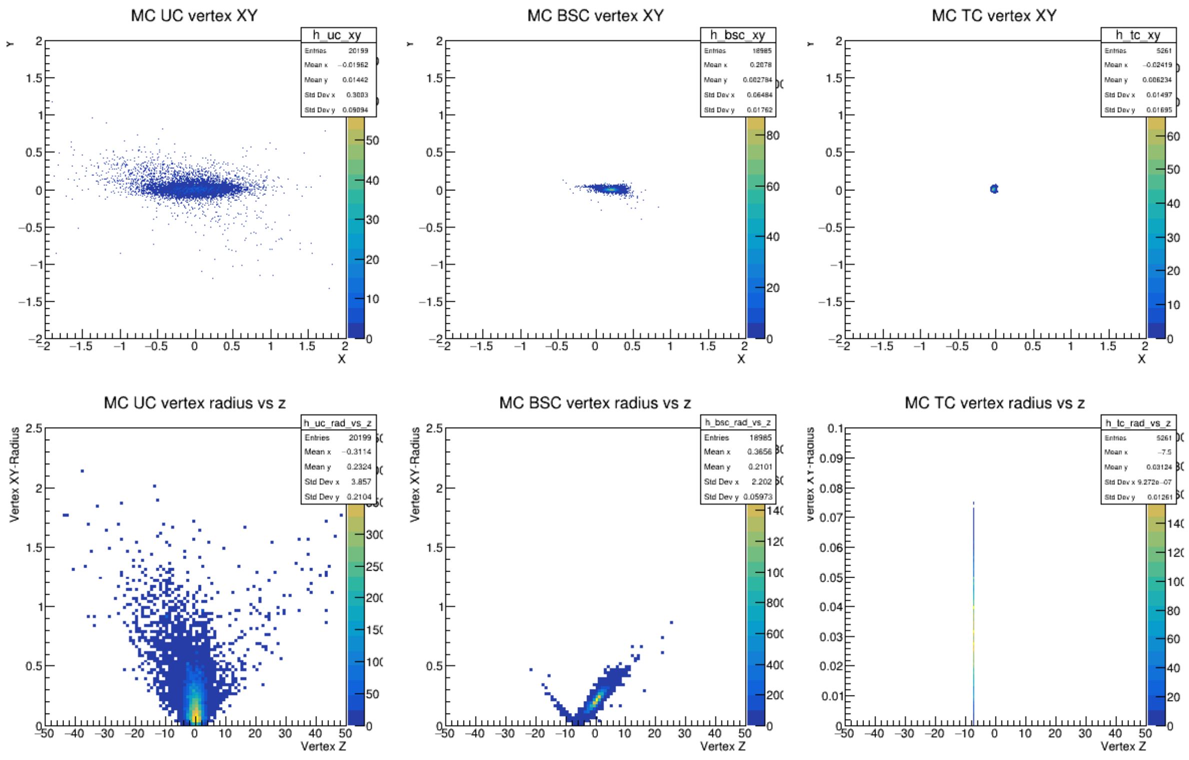


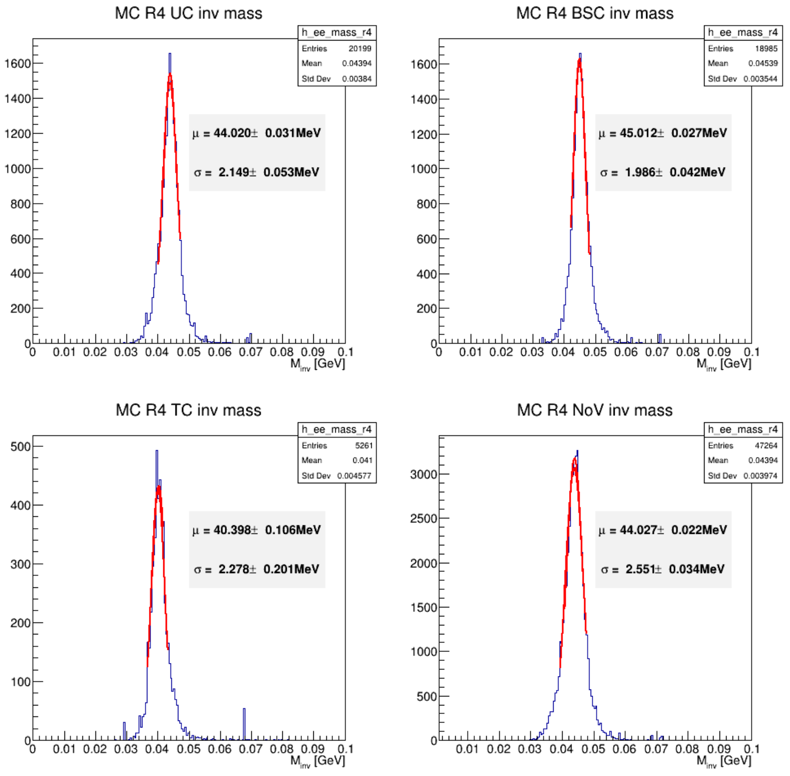
- Widths are slightly higher with the new detectors than when compared to the old detectors (v4/v5) with the exception of TC V0s.

2021 Møller MC

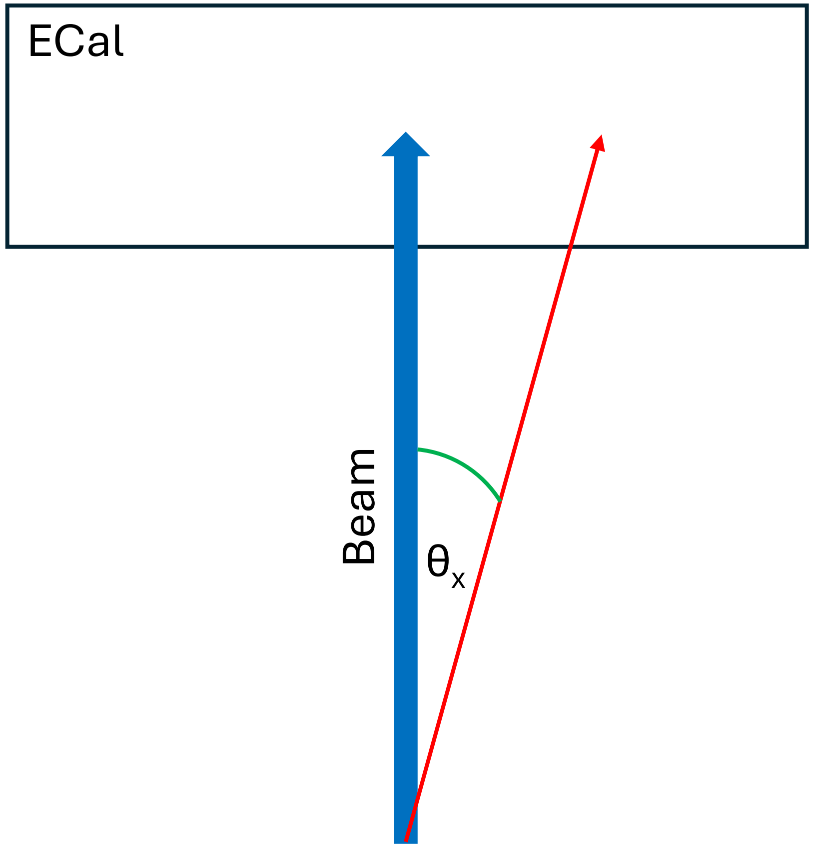
- Compared to the Møller MC + beam overlay sample, the data is about an MeV wider, except for TC V0s, which also suffer from an inaccurate target position.

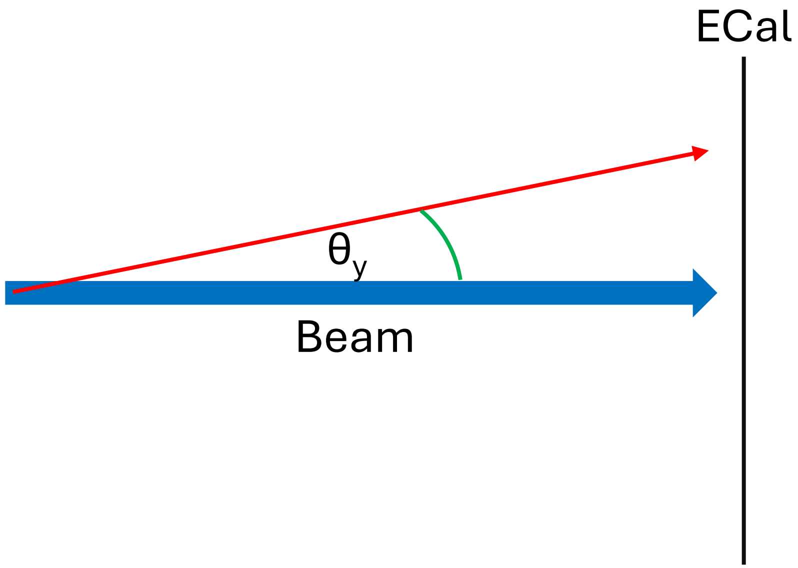
UC R4 Fits	μ [MeV]	σ [MeV]	σ_{err} [MeV]
Data	44.322	3.063	0.030
MC	44.020	2.149	0.053





Møller Mean Angular Dependence





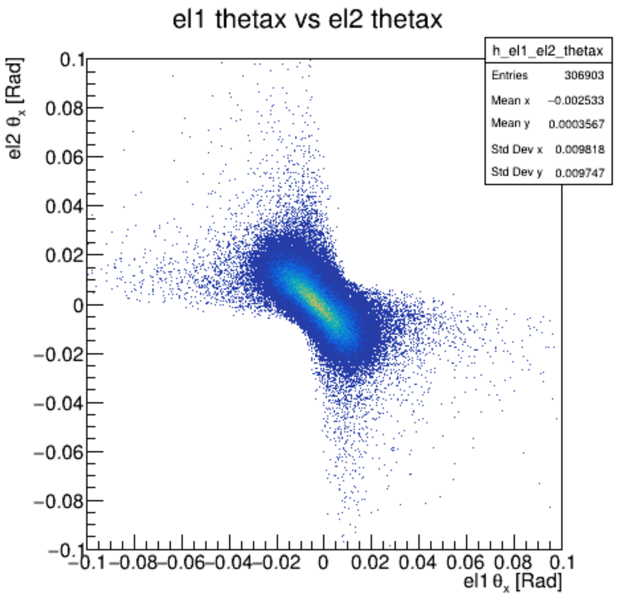
θ_x defined as arctan(px/pz)

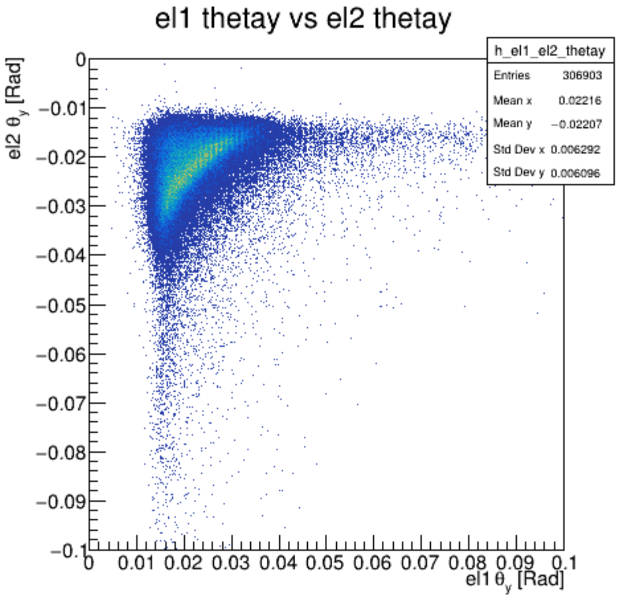
Phi0 equiv.

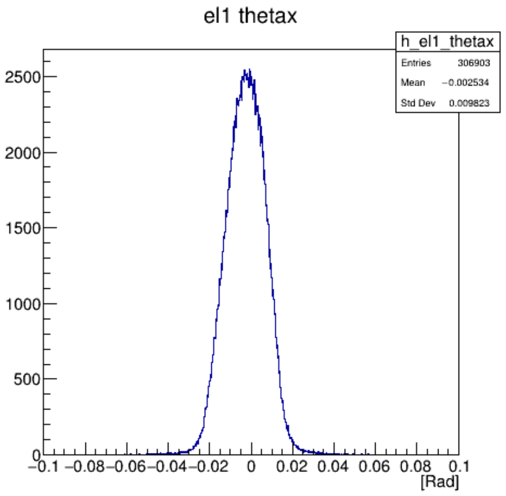
θ_y defined as arctan(py/pz)

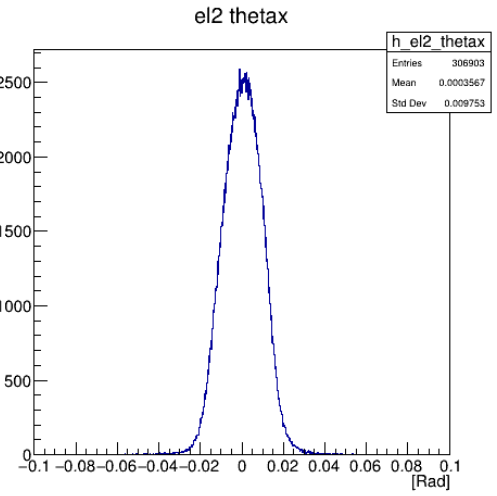
TanL equiv.

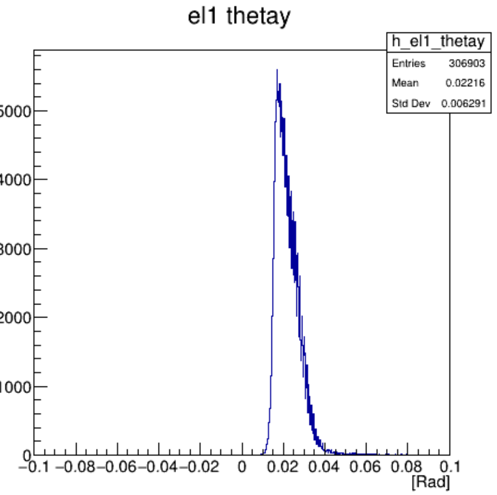
Møller Mean Angular Dependence

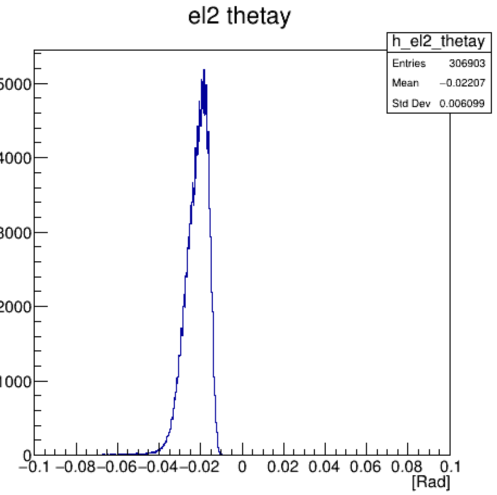






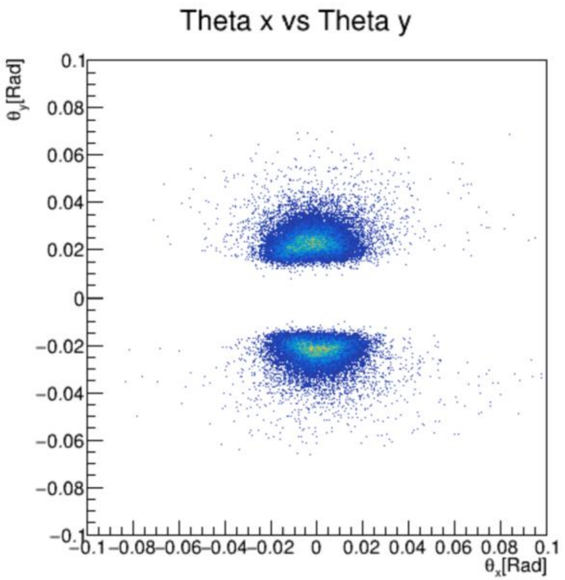




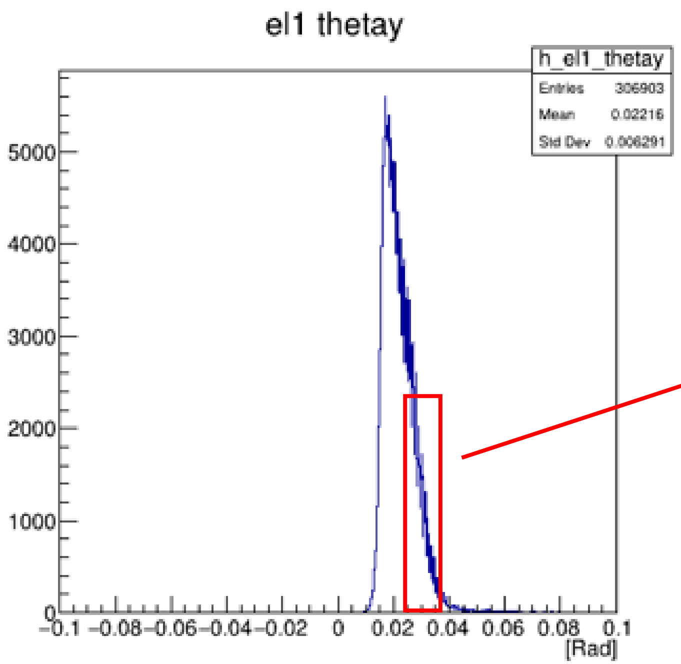


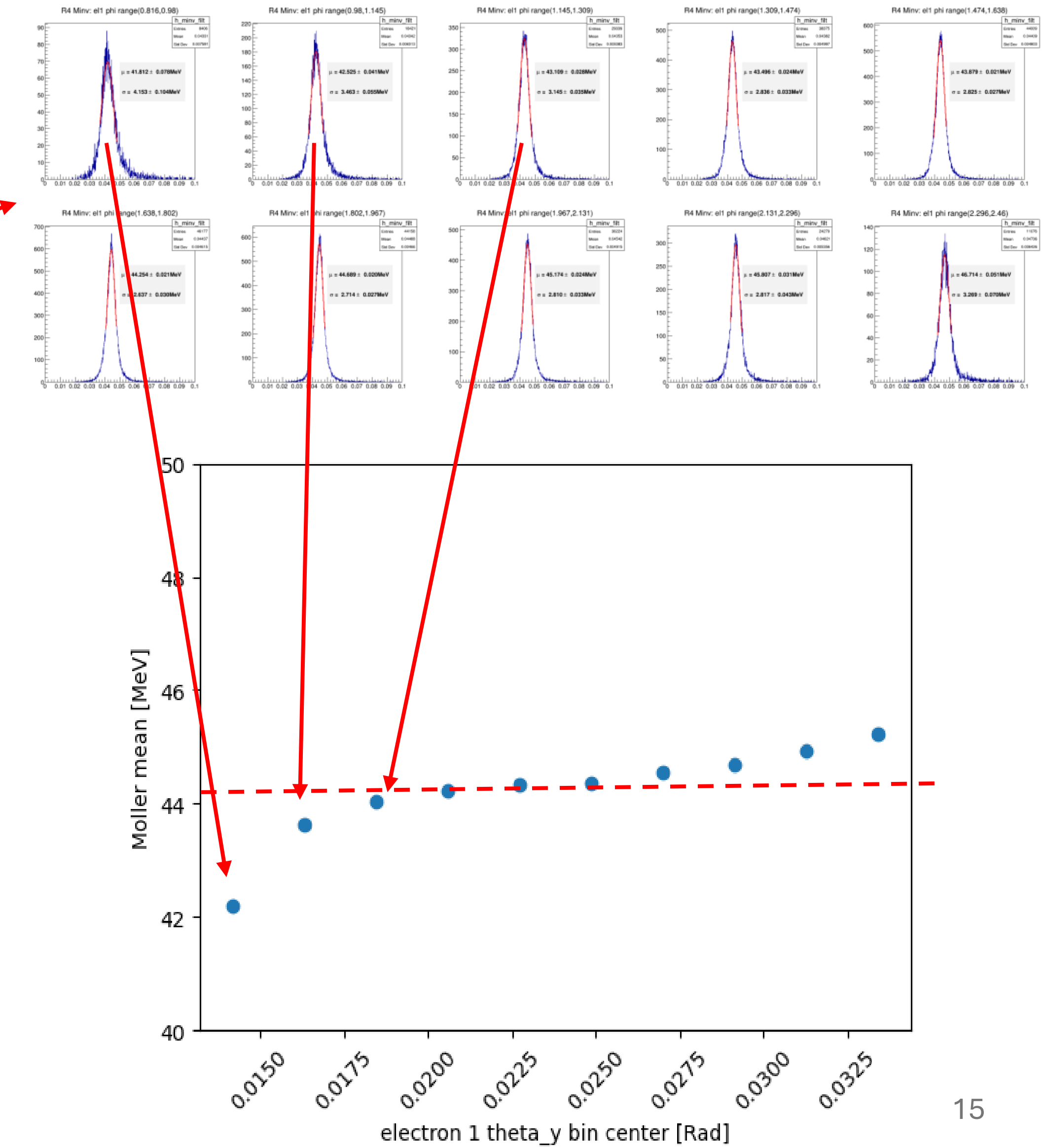
- Electron 1 theta y is always positive, as it is defined as the positive volume electron; electron 2 theta y is always negative by definition as well.

- These include the 30mRad rotation into the beam frame.



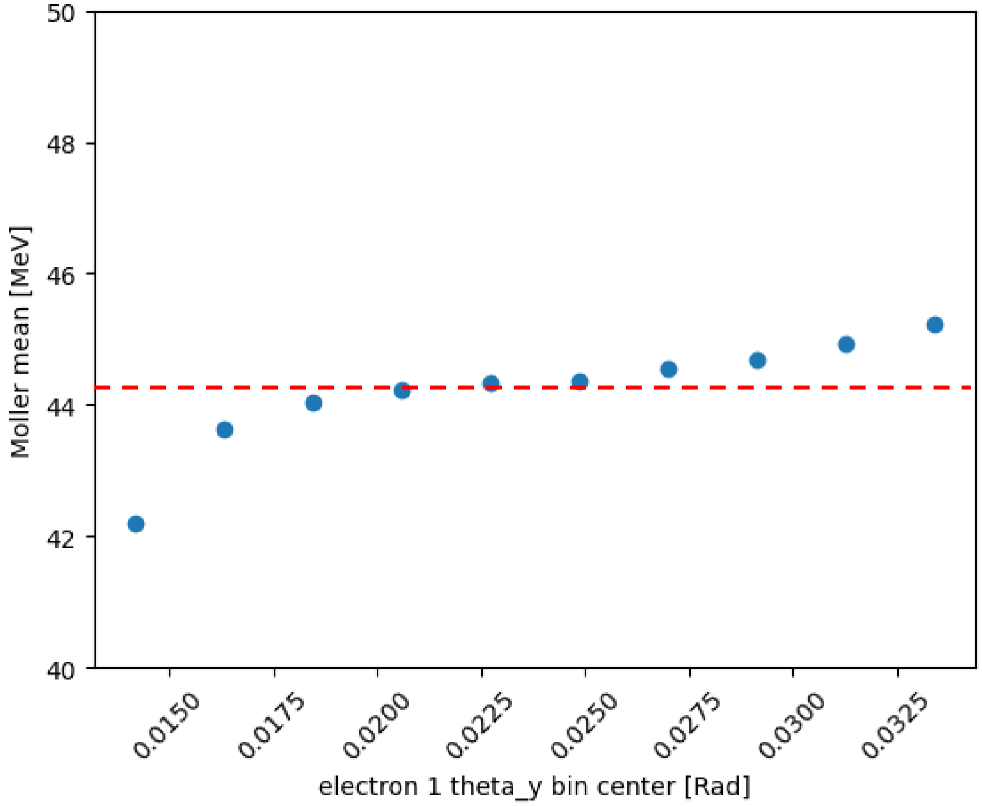
Procedure

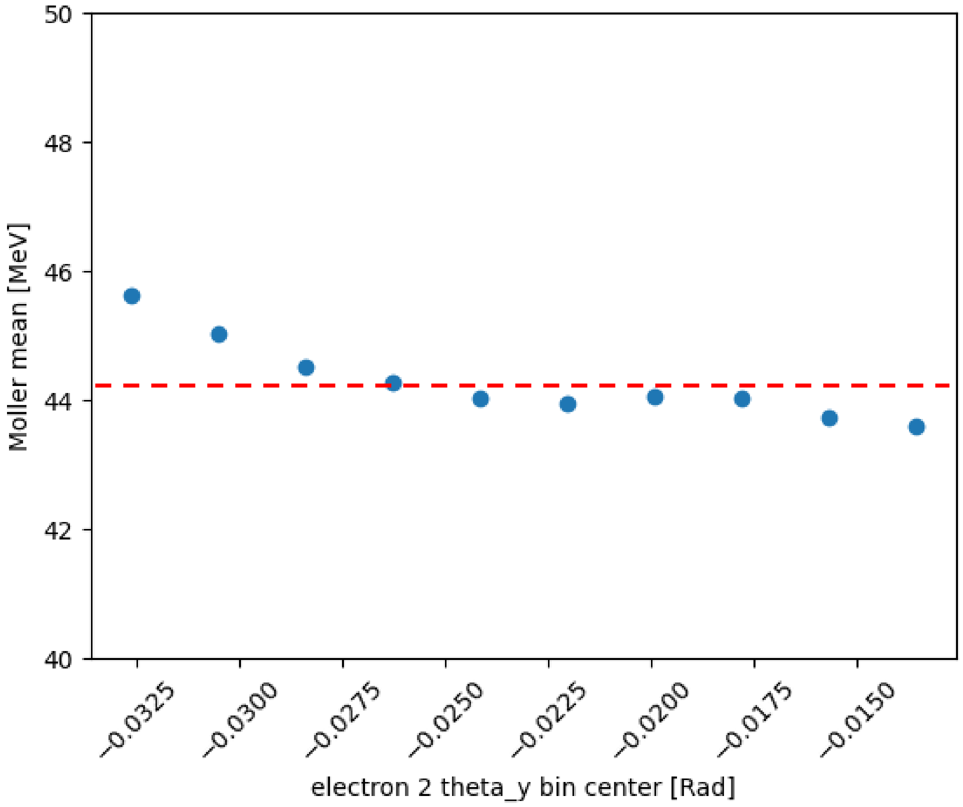




- Overall goal here is to examine the Møller mass as a function of various angular variables. We ideally want to see *no* dependence on angular quantities.
- I start with the Møllers' thetax and thetay distributions and then split these plots into 10 bins.
  - Then calculate the invariant mass of the Møller events in this bin.
- This method is statistically limited, but the fits here look alright. The error bars are present, but too small to be visible.

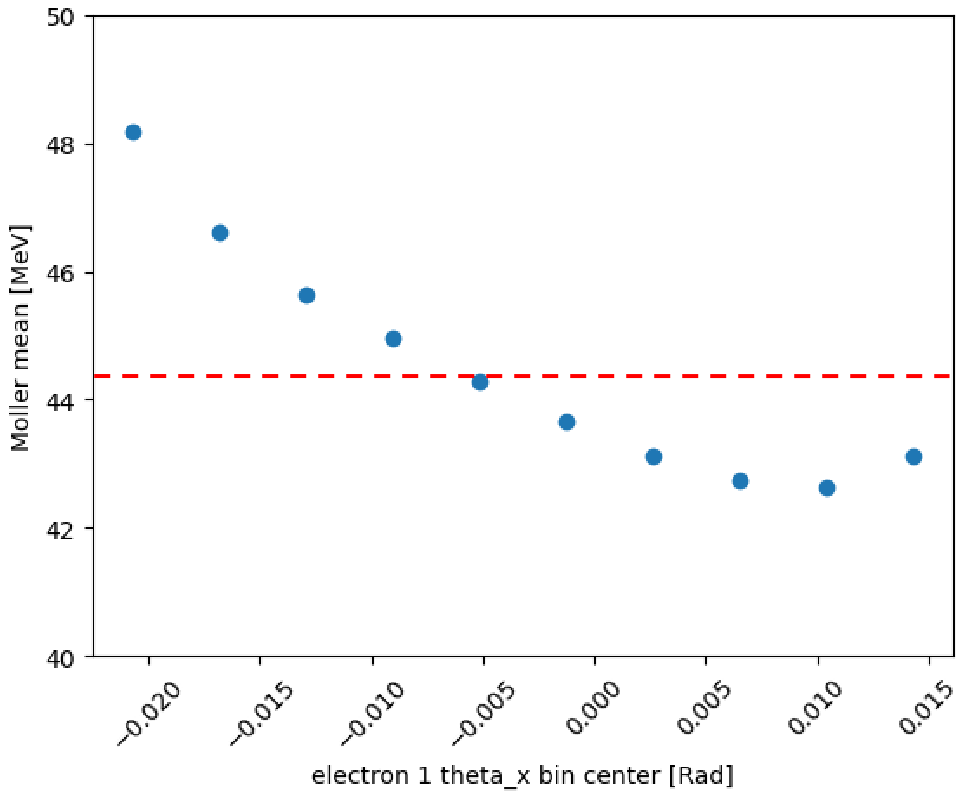
Møller Mass Dependence: Theta y (tanL)

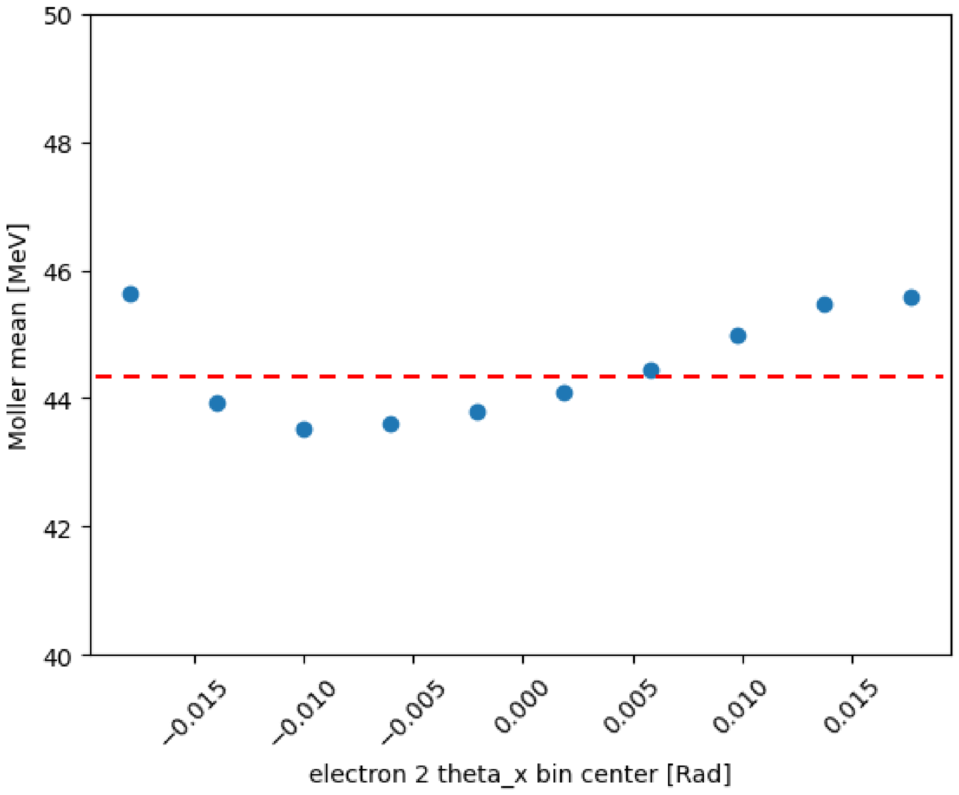




- Theta y dependence isn’t very significant.

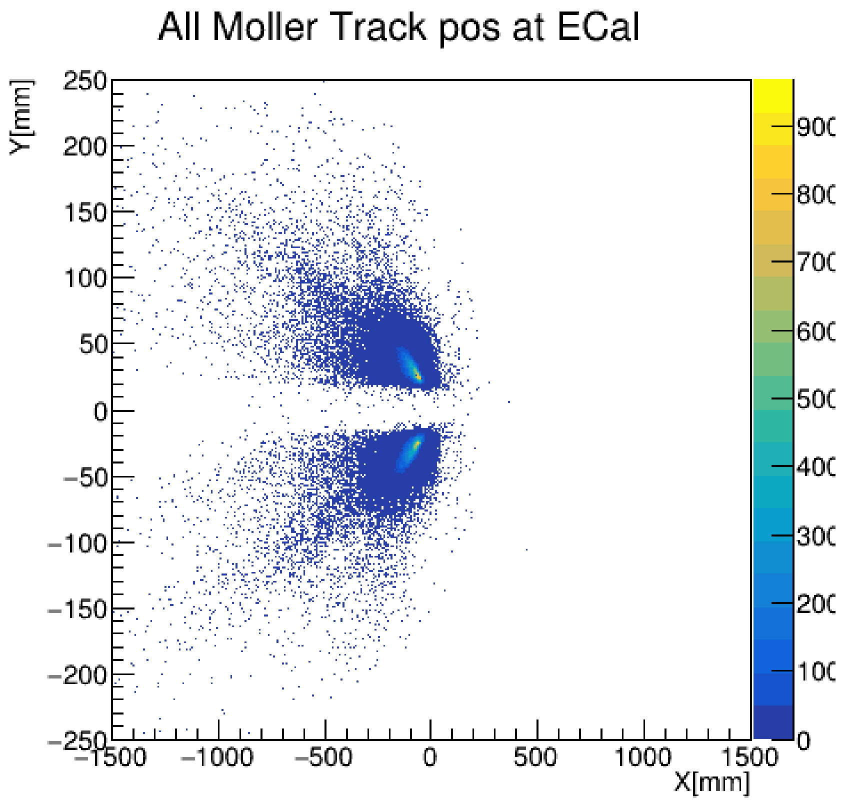
Møller Mass Dependence: Theta x

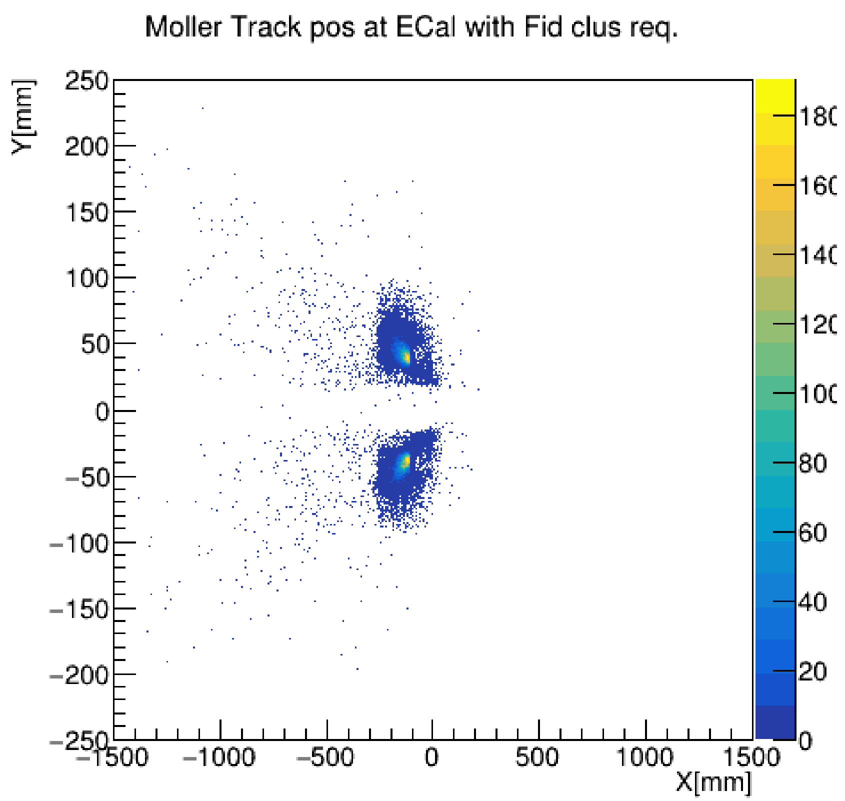




- Theta x dependence is very strong for electron 1.
- Less so for electron 2 but still present with an oscillatory behavior.

Cluster Requirements



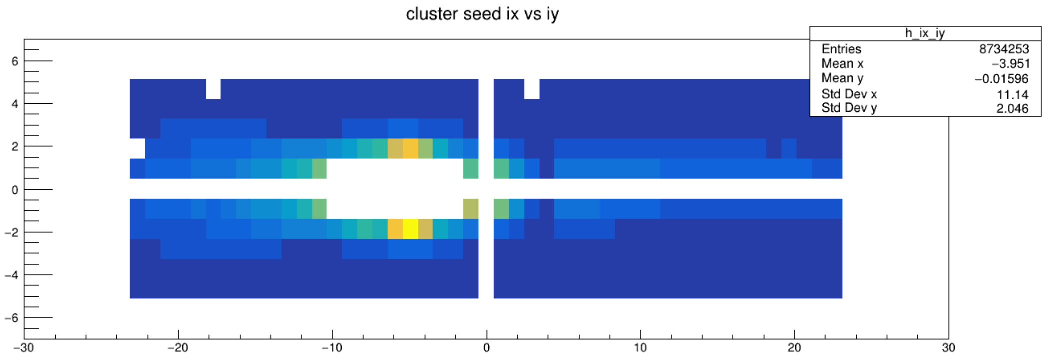


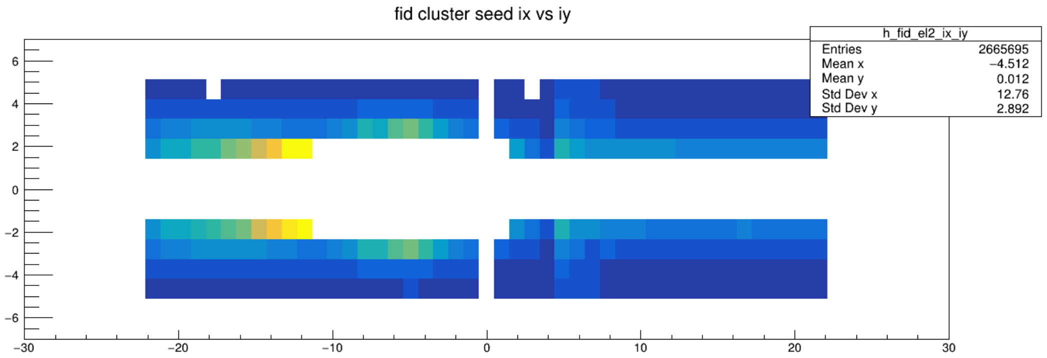
- These plots are the electron tracks extrapolated to the ecal face. The right plot has the standard fiducial cut applied.

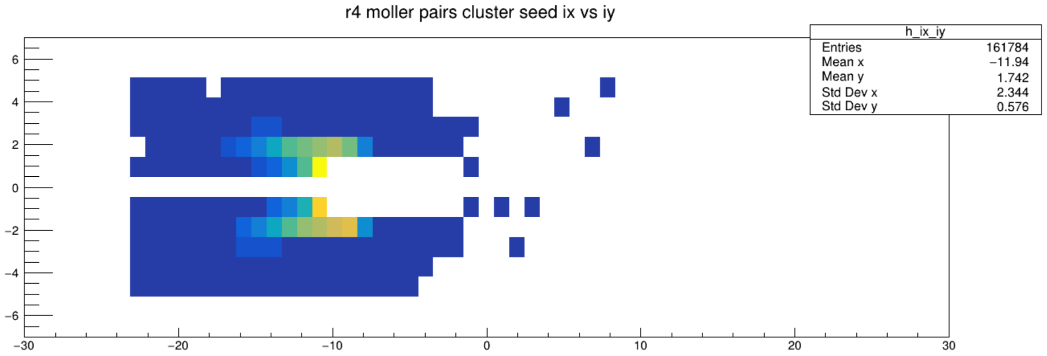
- Note: I don't have enough statistics to require both el1 and el2 make a fiducial cluster, so I consider the two separately, i.e. el1 makes a fid cluster and no requirement on el2 and vice versa.

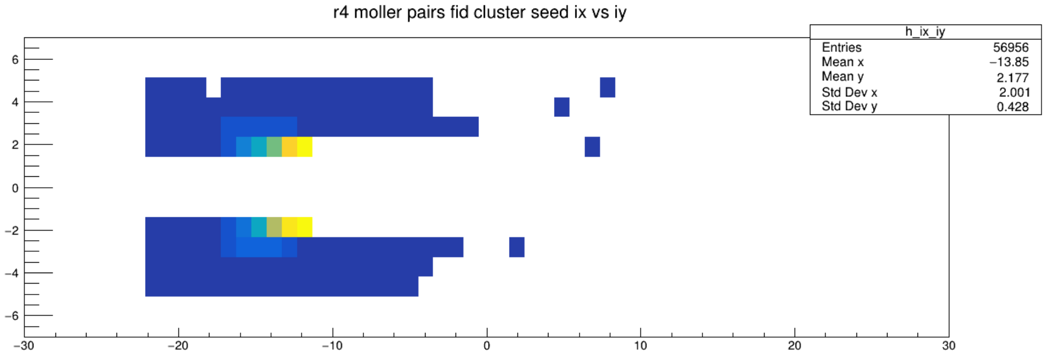
```
n total moller events : 317390
n moller events where el1 makes a cluster : 161411
n moller events where el2 makes a cluster : 165652
n moller events where el1 makes a fid cluster: 56873
n moller events where el2 makes a fid cluster: 60419
n moller events where both have an ecal cluster: 56609
n moller events where both make a fid cluster: 355
```

Cluster Positions





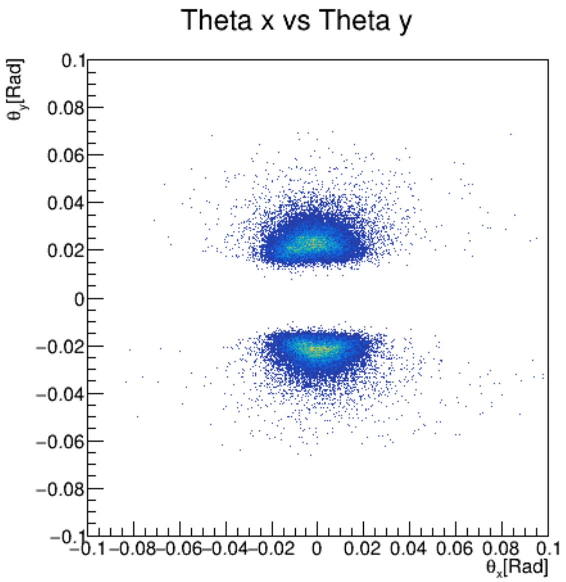


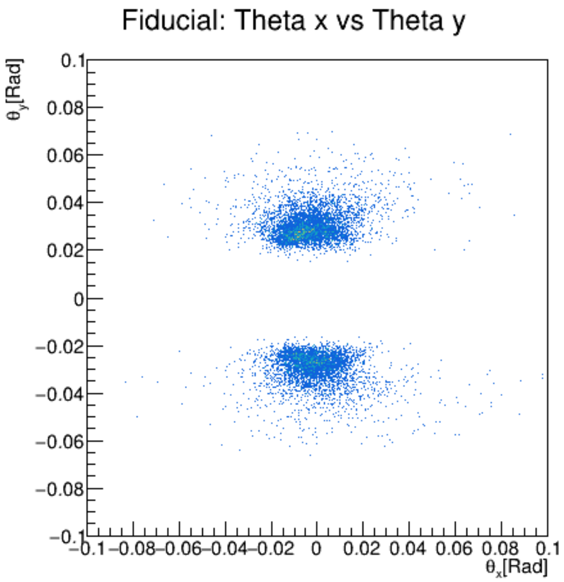


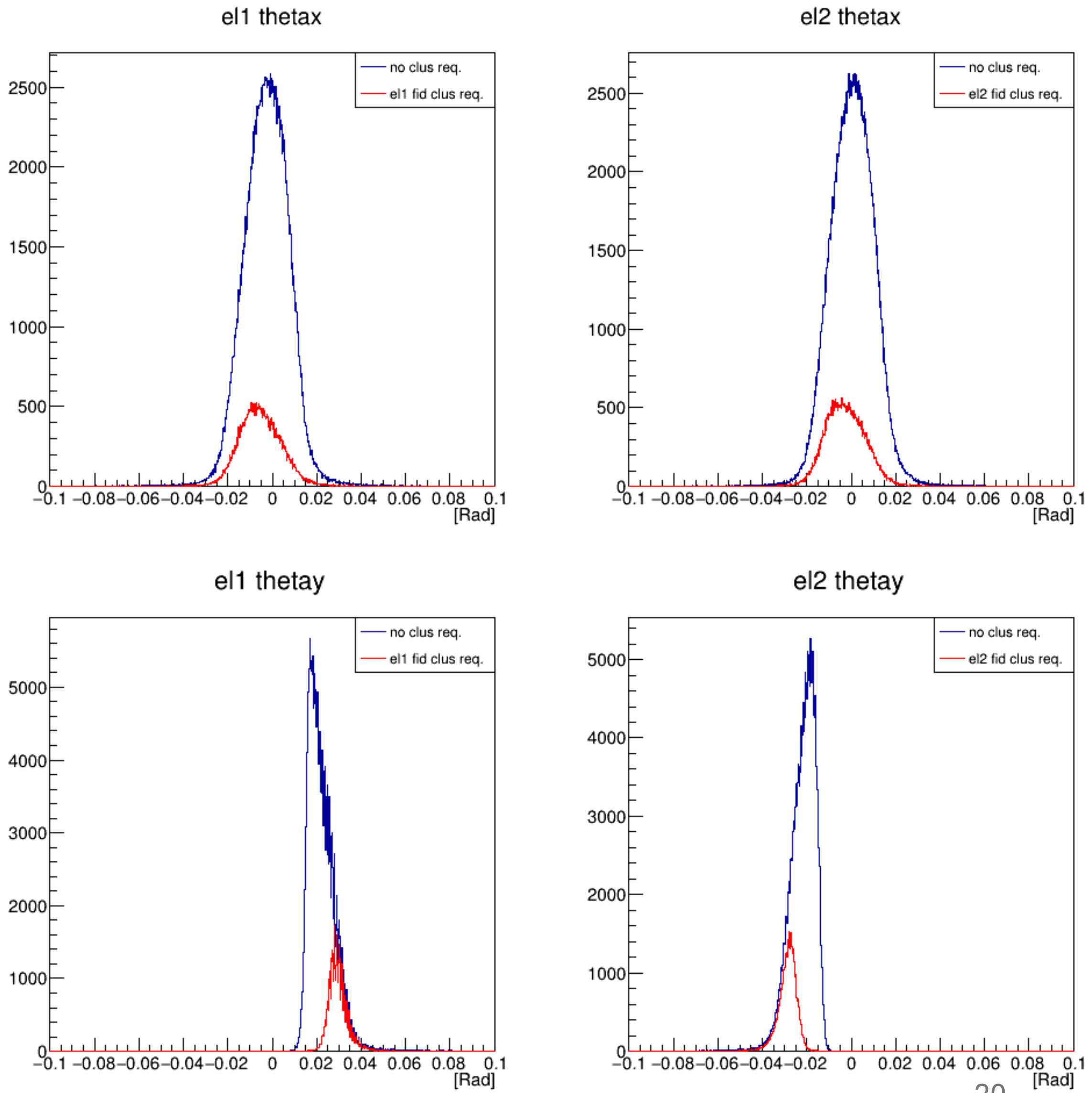
- Top left: all ecal cluster seed ix vs iy
- Top right: all ecal fiducial cluster seed ix vs iy
- Bottom left: all R4 Møller pair cluster seed ix vs iy
- Bottom right: all R4 Møller pair fiducial cluster seed ix vs iy

Cluster Requirements

- Left plots require el1 to make a fiducial cluster, right plots require el2.
- Skewing to higher thetay’s due to the fiducial cut as expected is apparent in bottom plots .

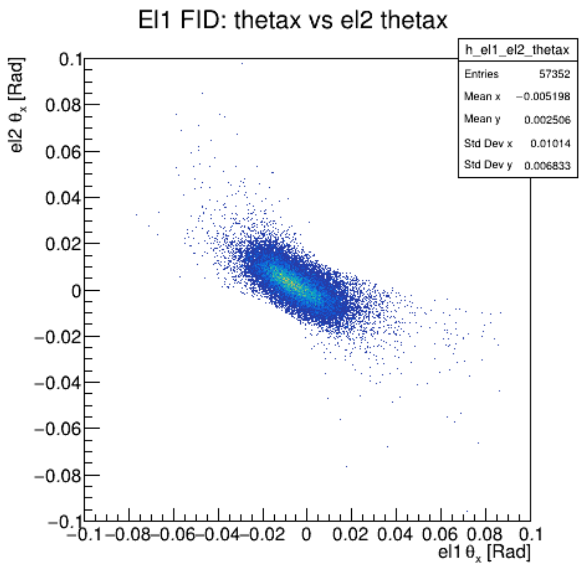


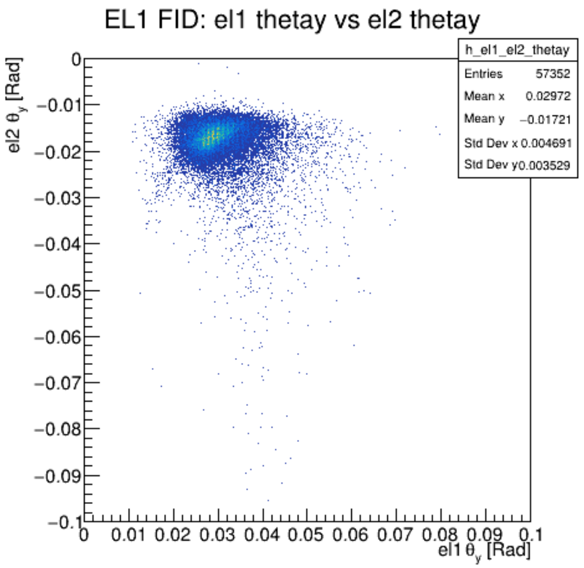


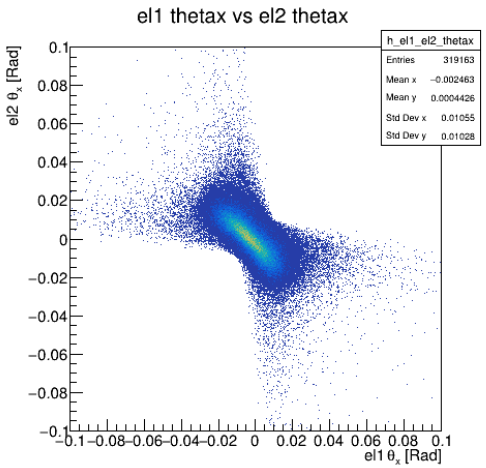


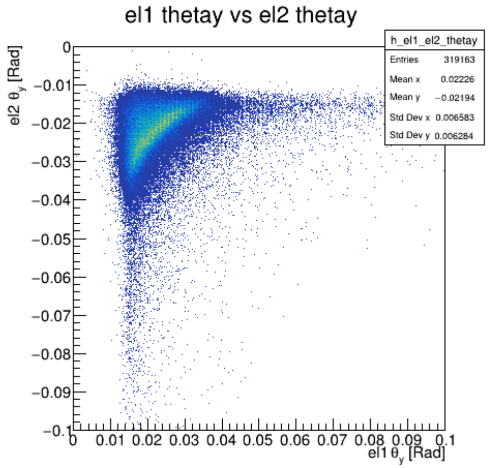
Fiducial Region Distributions

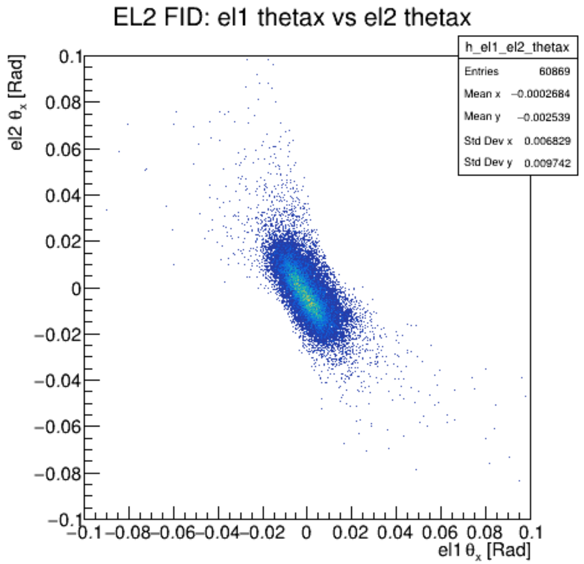
- Requiring **either** el1 making a fid cluster or el2 making a fid cluster changes the shape of the theta-theta distributions
- As expected, the electron with the fiducial cluster requirement has higher thetay.

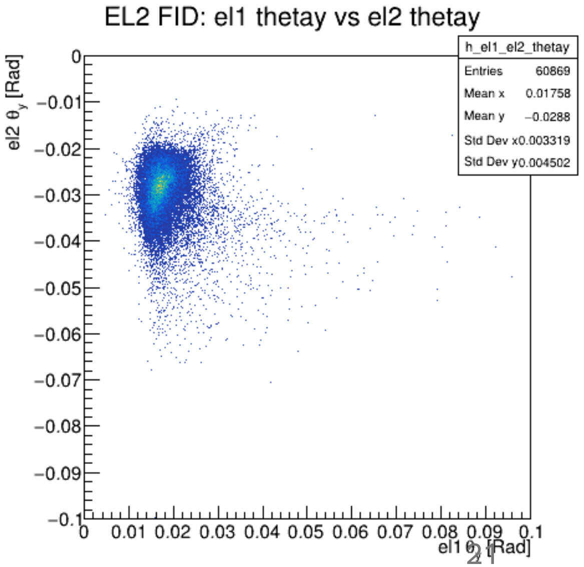






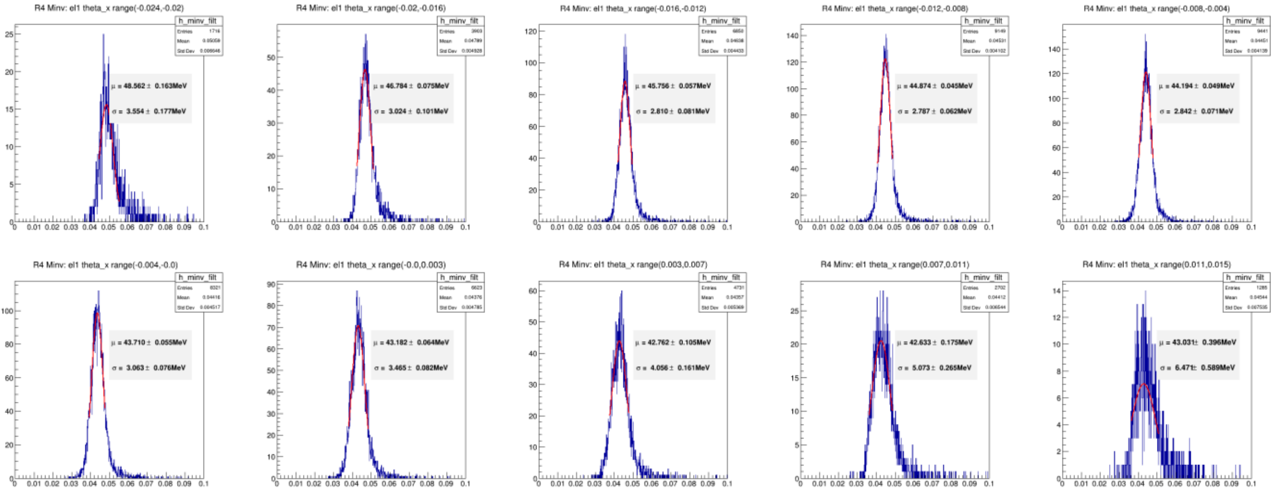


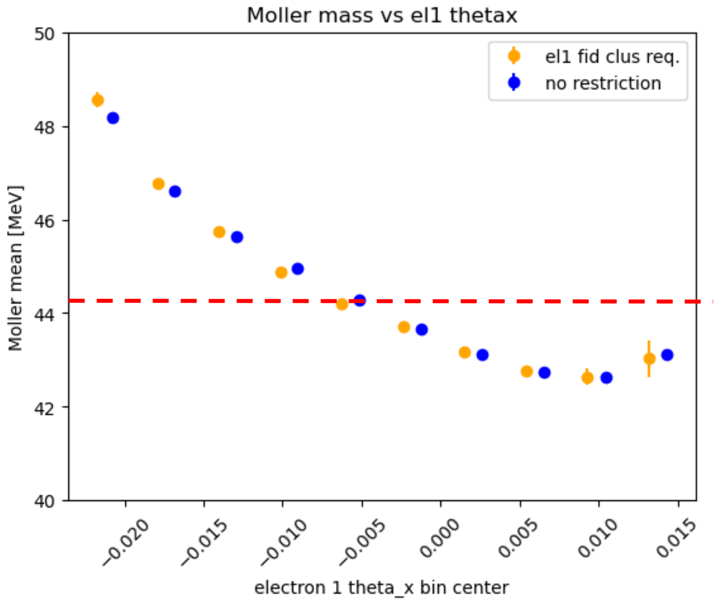


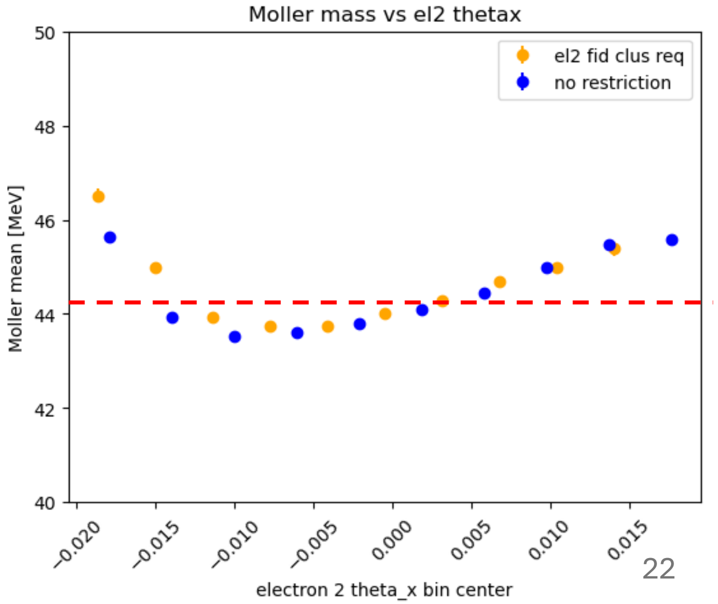


Plots from before without any cluster requirements

Møller Mass Dependence: Theta x, el1 fid clus



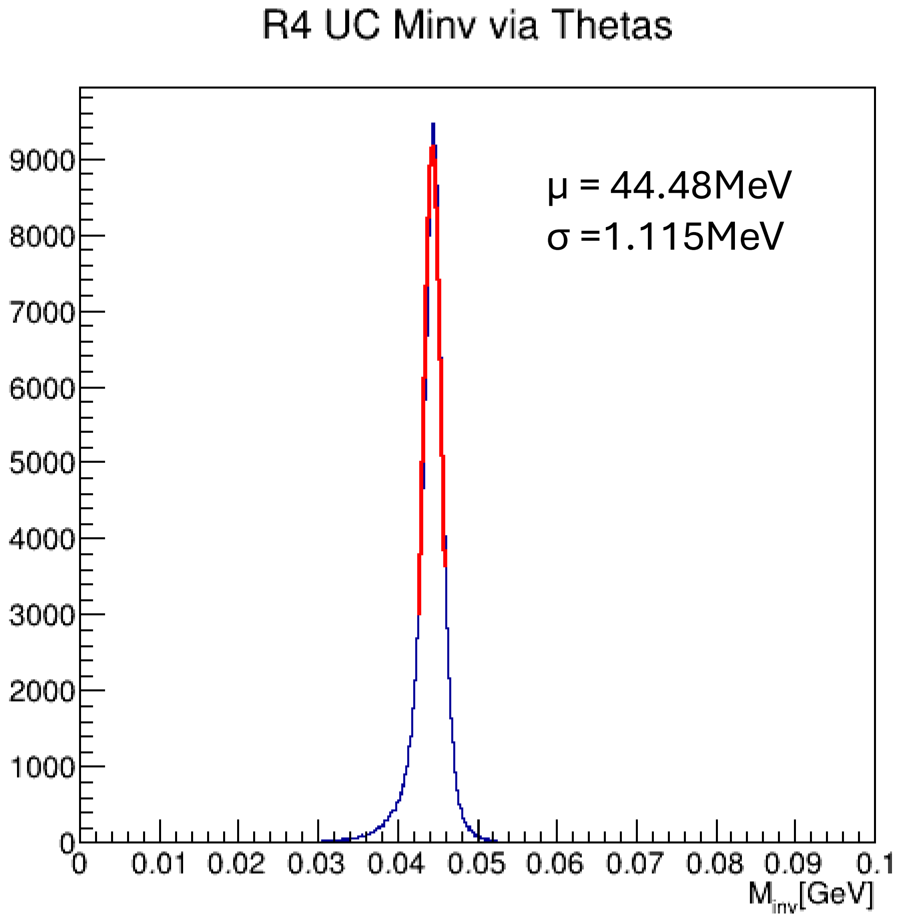




- Require electron 1 to make a fiducial cluster, no requirement on el2 at all.
- Select bins of fiducial el1 theta_x, make the usual invariant mass distributions
- Møller mean mass still shows a strong dependence!

An Aside: Moller Minv via Theta Calculation

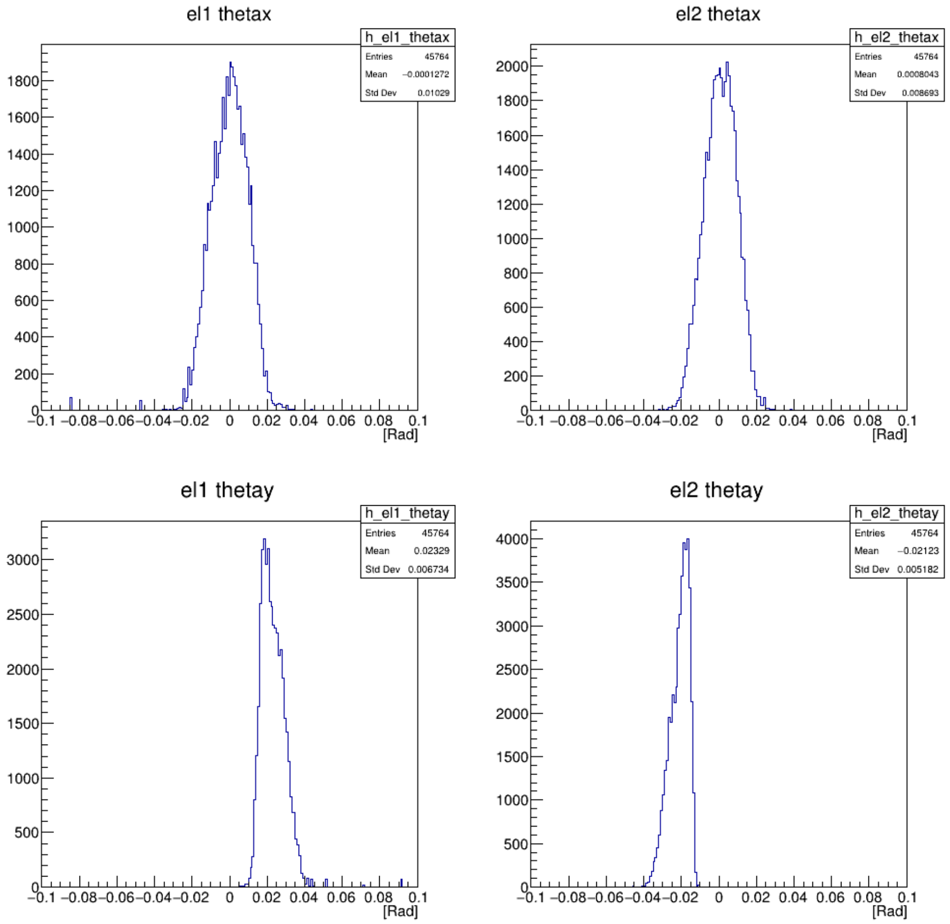
- If you calculate the invariant mass distribution using theta1 and theta2 (scattering angles) only (so no momentum information at all), you get quite a narrow peak.
- The widening of the Møller peak here is only due to angular resolution of the detector. This gives us a handle on how much the mass resolution for Møllers is impacted by the angular and momentum resolution separately.

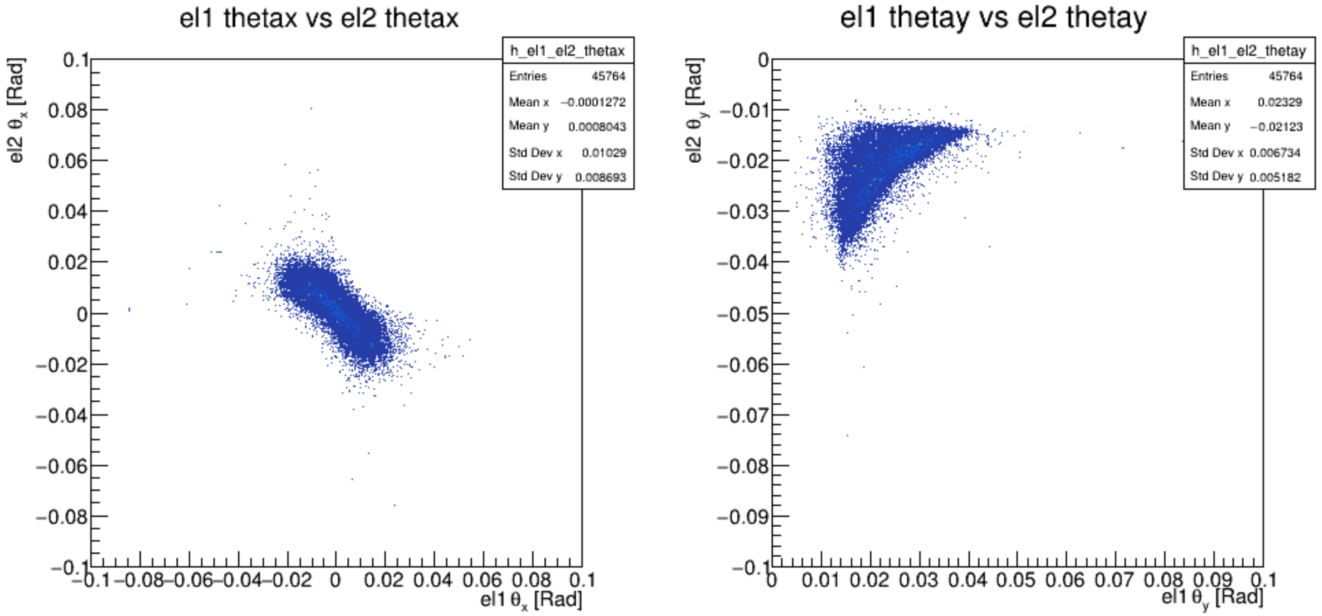


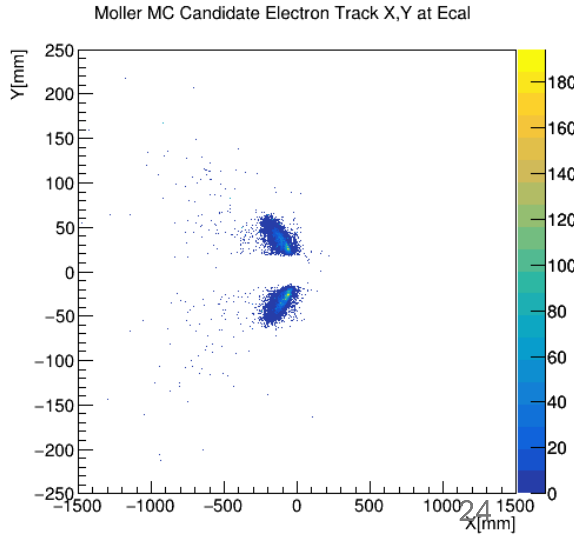
- We know that:
  - $E1 + E2 = Ebeam$
  - $M(e^- e^-) = \sqrt{S} = \sqrt{(2m_e^2 + 2Ebeam\, m_e)}$
  - $E1(\theta 1) = E\_beam / [1 + (2Ebeam / m_e) \cdot \sin^2(\theta 1 / 2)]$
  - $E2(\theta 2) = E\_beam / [1 + (2Ebeam / m_e) \cdot \sin^2(\theta 2 / 2)]$

  - → $M(e^- e^-) = \sqrt{(2m_e^2 + 2\,(E1 + E2)\, m_e)}$

MC Møller with beam overlay (v4 Detector)



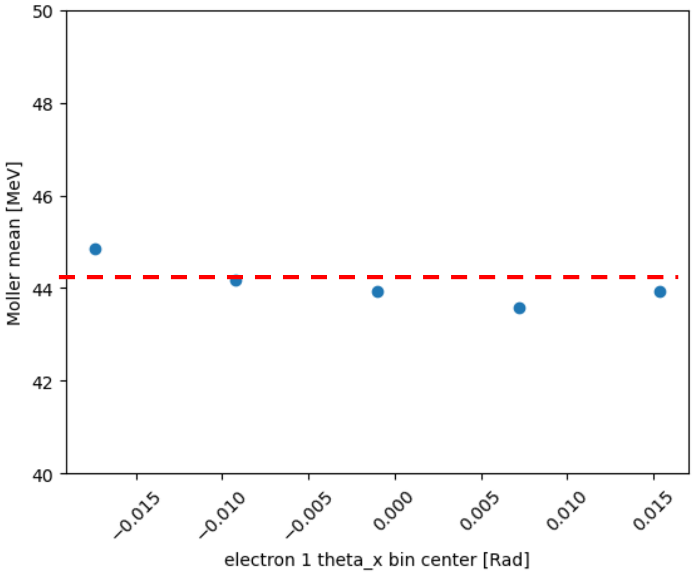


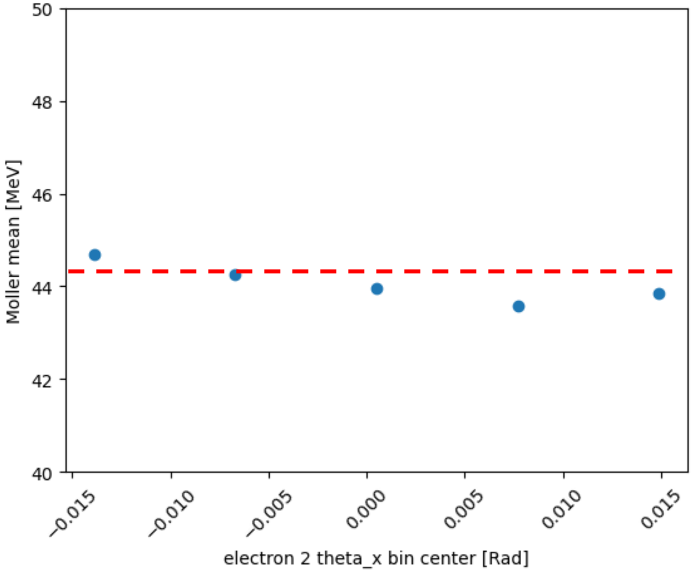


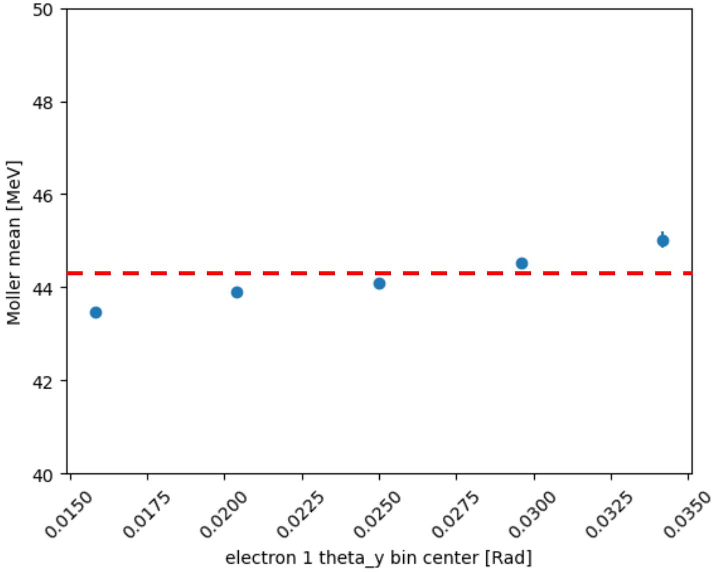
- Quickly examined the Møller + beam overlay sample I used for the original 2021 Møller studies last Fall. Far fewer total events to use for a differential analysis like this.

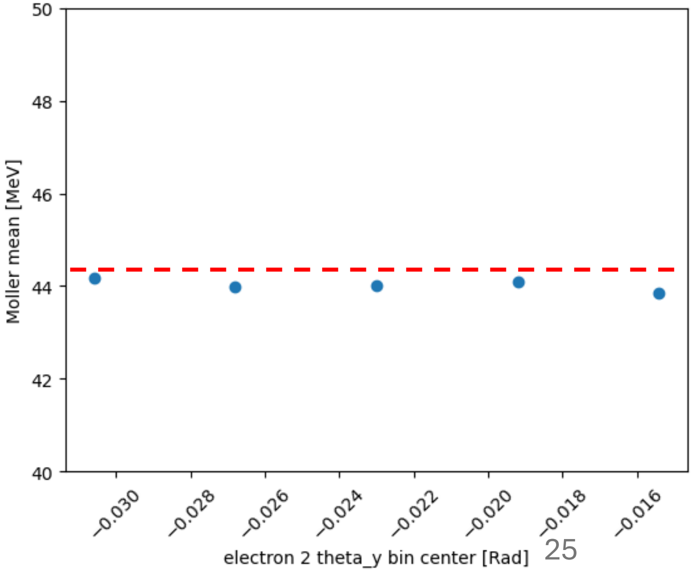
MC Møller with beam overlay

- These look quite a bit flatter than what is seen in data using the same analysis.
  - Decreased to 5 angular bins to get better fits.









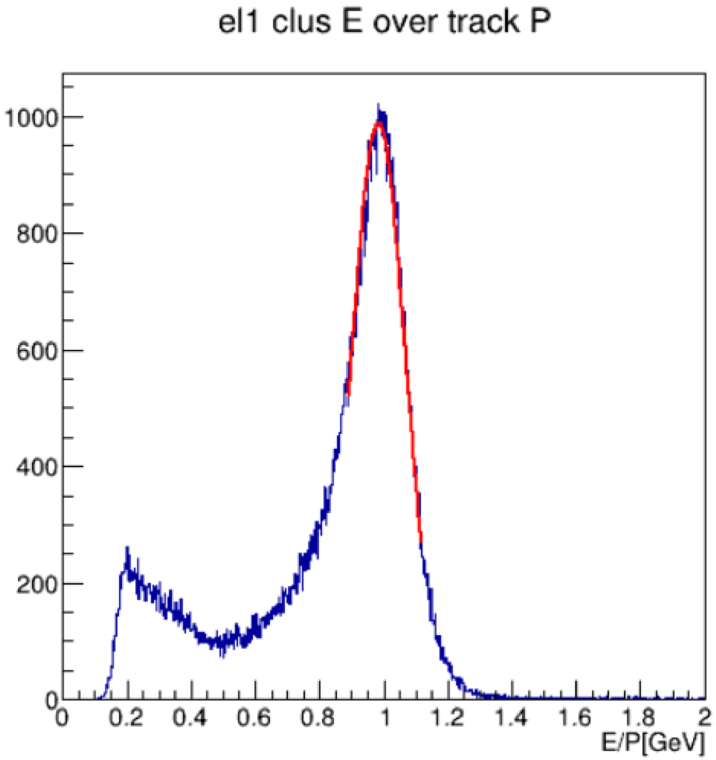
Cluster Requirements

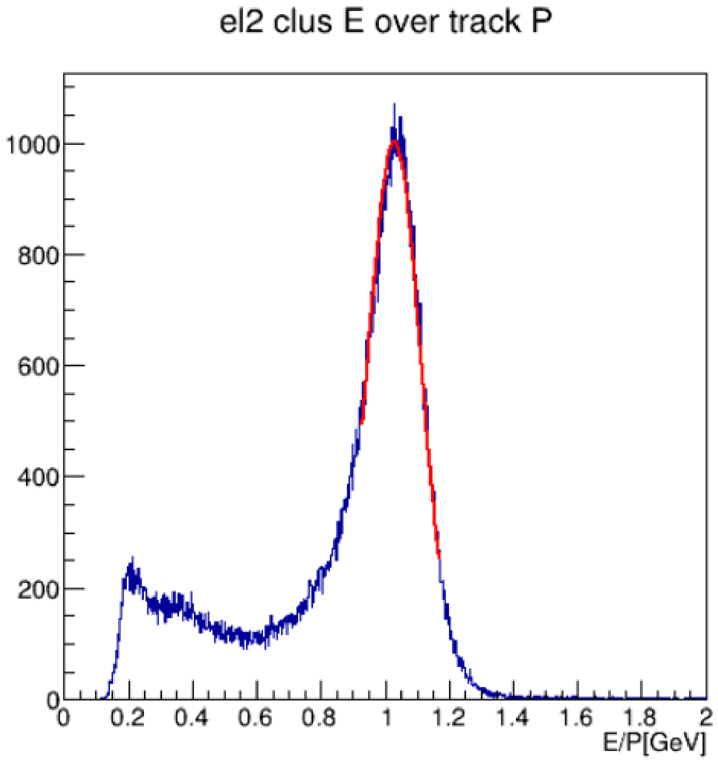
- As one more check, I looked at Ecal Energy / Track Psum for Møller candidates to see if this might explain the dependence on thetax.

- Fitting the core of the peaks give:

- El1 (top volume):
- Mean = 0.985
- Sigma = 0.083

- El2 (bottom volume):
- Mean = 1.031
- Sigma = 0.084





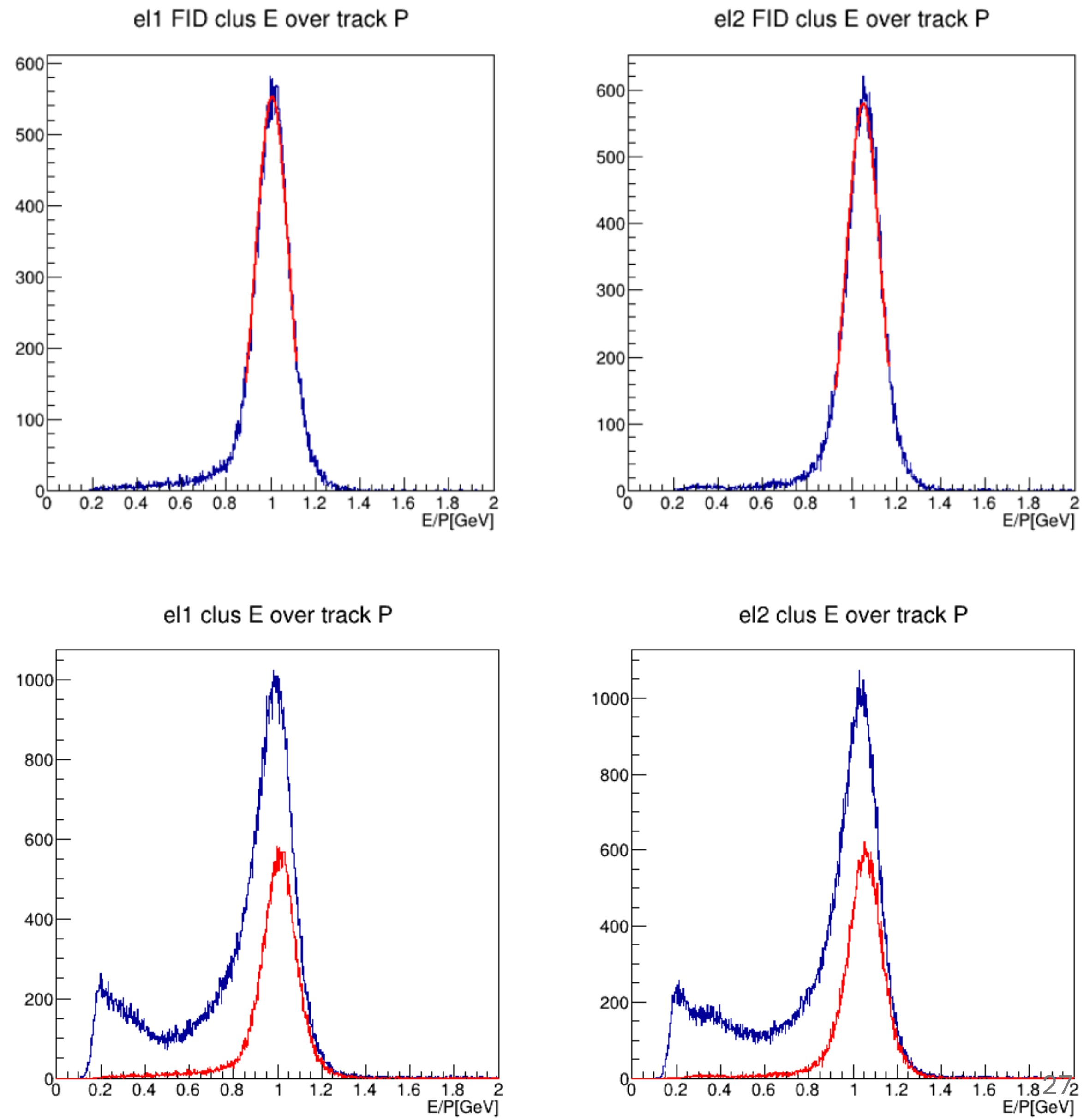
Cluster Requirements

- Requiring the cluster to be in the fiducial region cleans the plots up nicely.

- Fitting the core of the peaks give:
  - El1 FID (top volume):
  - Mean = 1.009
  - Sigma = 0.074

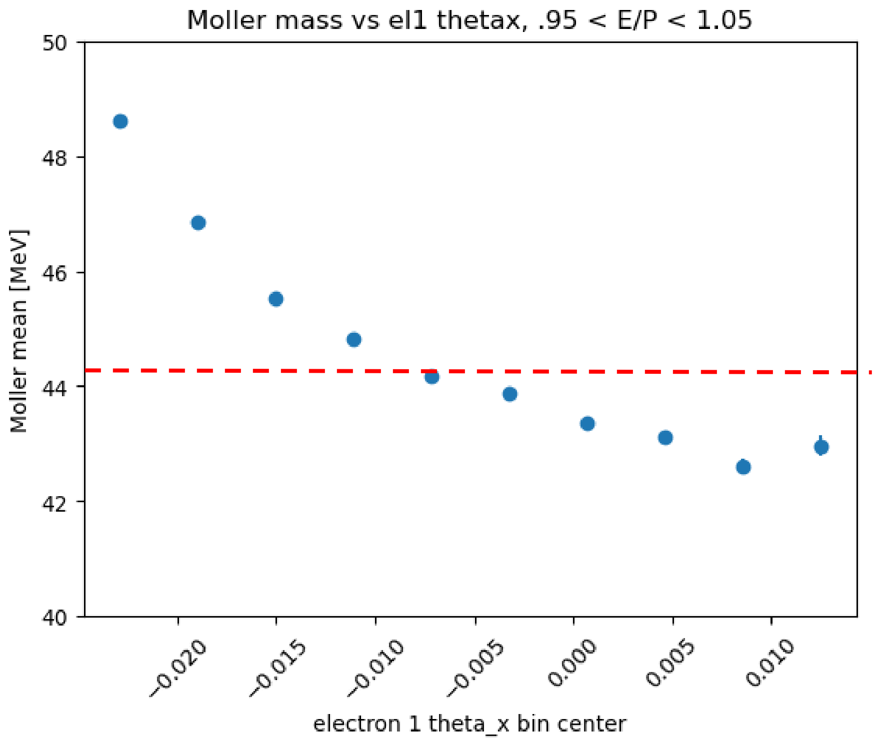
  - El2 FID (bottom volume):
  - Mean = 1.055
  - Sigma = 0.076

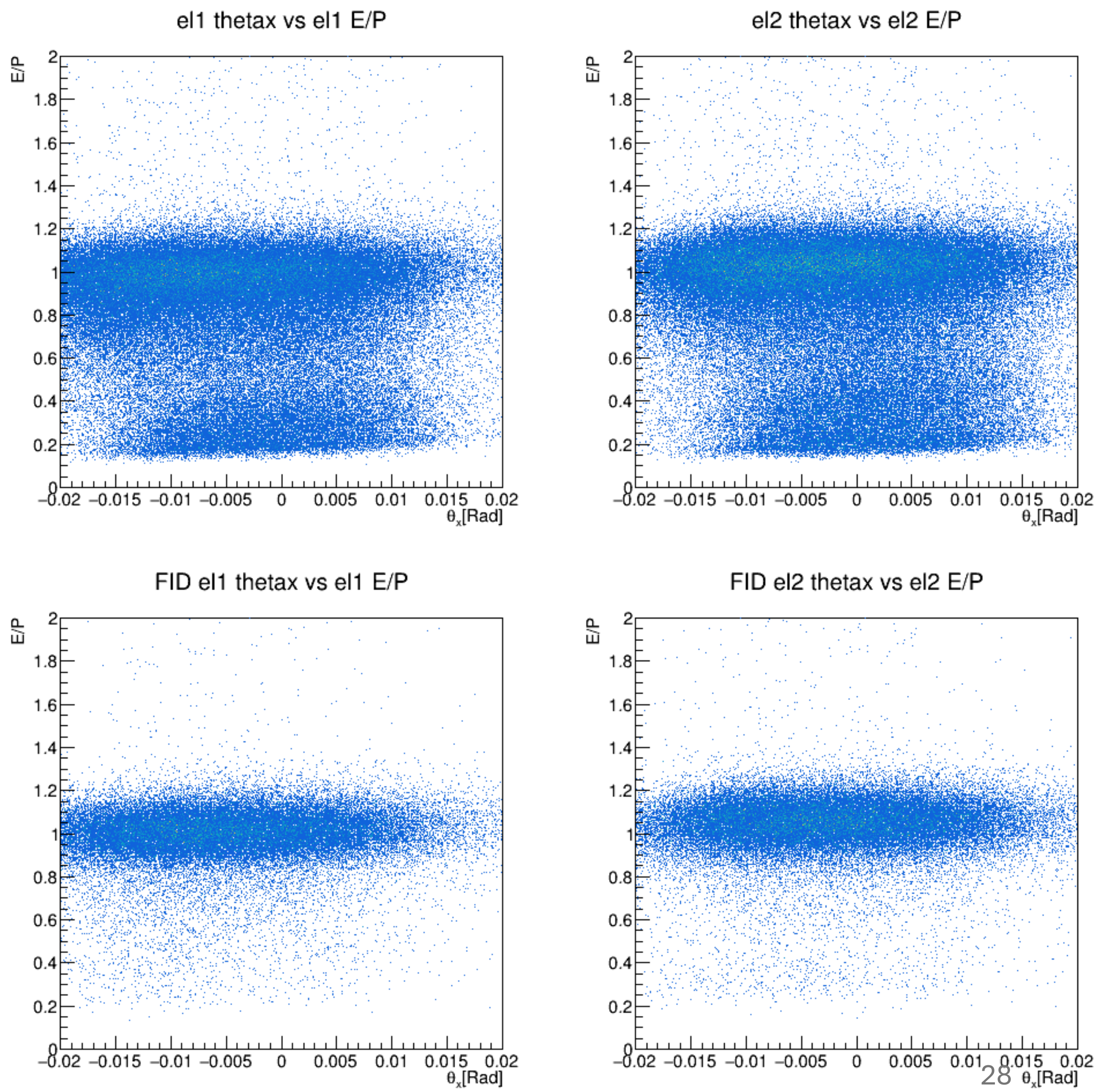
- Bottom plot shows fid vs all on the same plot for reference.



Cluster Requirements: Theta X

- No strong dependence of E/P on theta x from a quick visual check, but I checked to see the impact of a tight E/P cut might have on the el1 thetax depdendence. It is still present

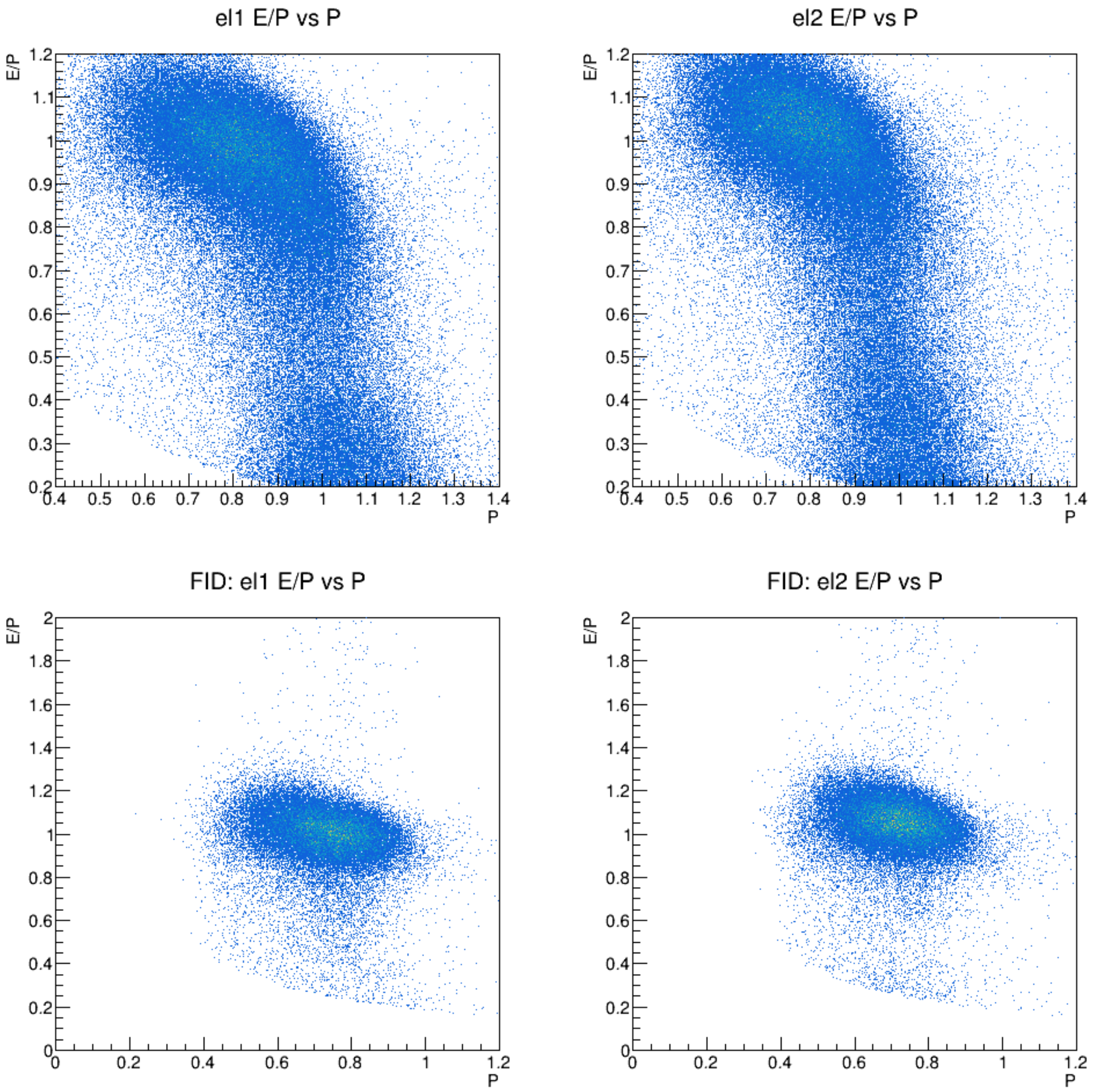




Cluster Requirements: E/P vs P

- Plotting E/P vs P shows something a bit more interesting. There appears to be a small negative slope present even after applying the fiducial cut.

- Fitting the fiducial plots with a line gives confirms this.



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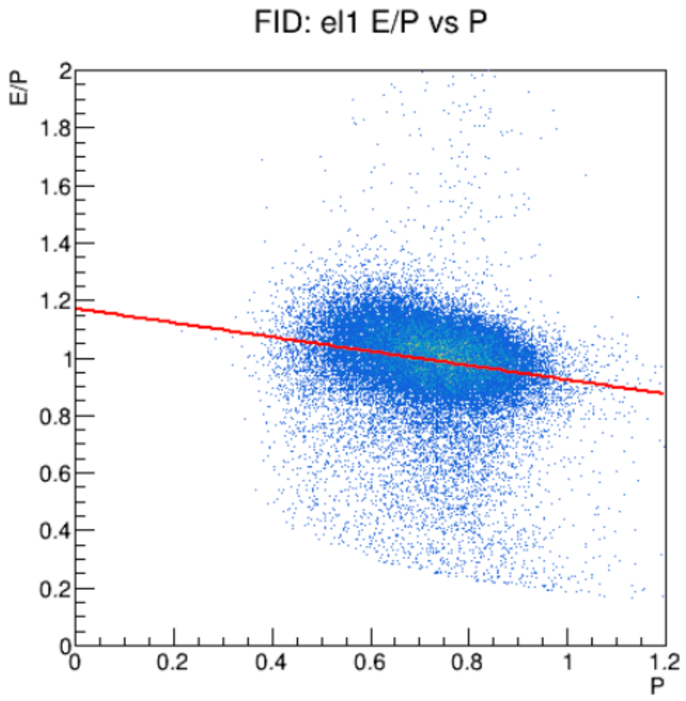
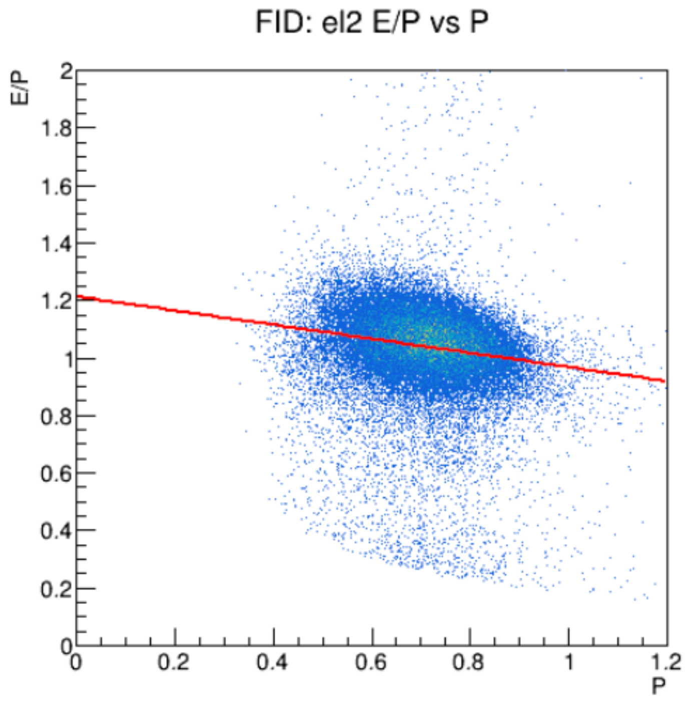
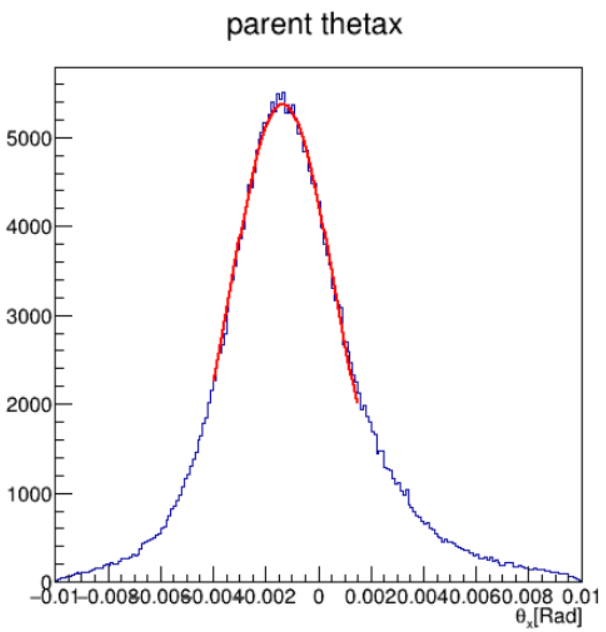



```
Minimizer is Minuit2 / Migrad
Chi2                      =   2.49665e+08
NDf                       =         35039
Edm                       =   1.60557e-15
NCalls                    =            38
p0                        =       1.16936   +/-   0.00494638
p1                        =     -0.247224   +/-   0.00671392
```

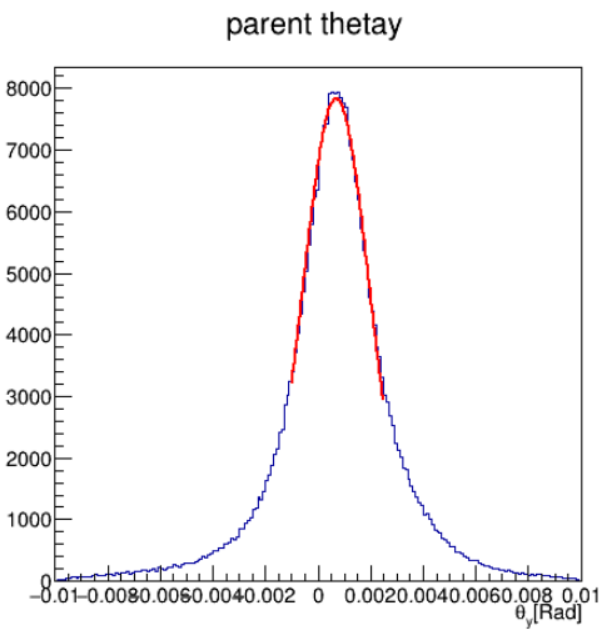



```
Minimizer is Minuit2 / Migrad
Chi2                      =   2.58339e+08
NDf                       =         35042
Edm                       =   6.27544e-14
NCalls                    =            34
p0                        =       1.21114   +/-   0.00513341
p1                        =     -0.244712   +/-   0.0071503
```

Beam Direction



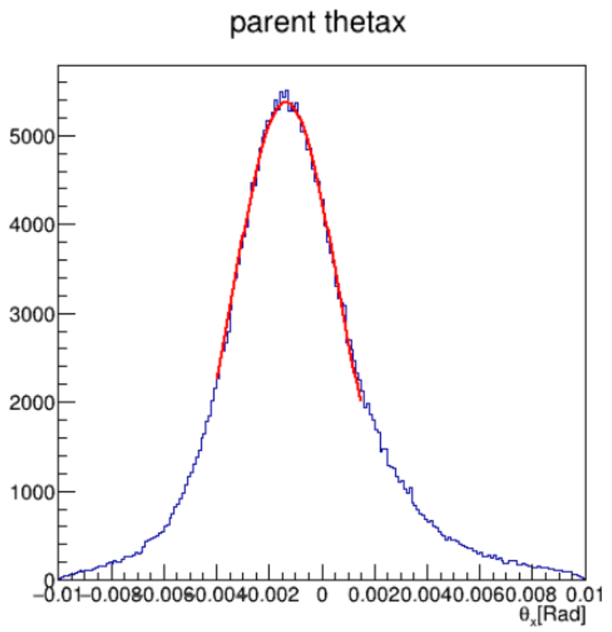

```
Minimizer is Minuit2 / Migrad
Chi2                      =      137.146
NDf                       =           52
Edm                       =  1.12858e-08
NCalls                    =           83
Constant                  =      5368.55   +/-    15.8643
Mean                      =  -0.00133859   +/-    6.11532e-06
Sigma                     =   0.00200891   +/-    8.58685e-06
```

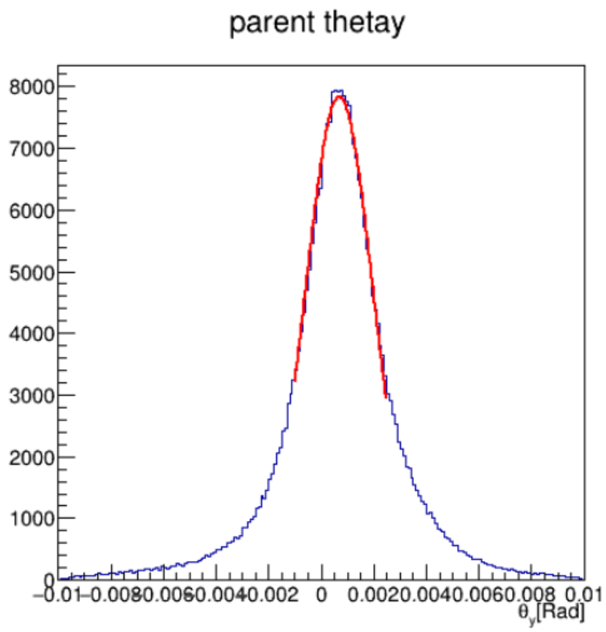


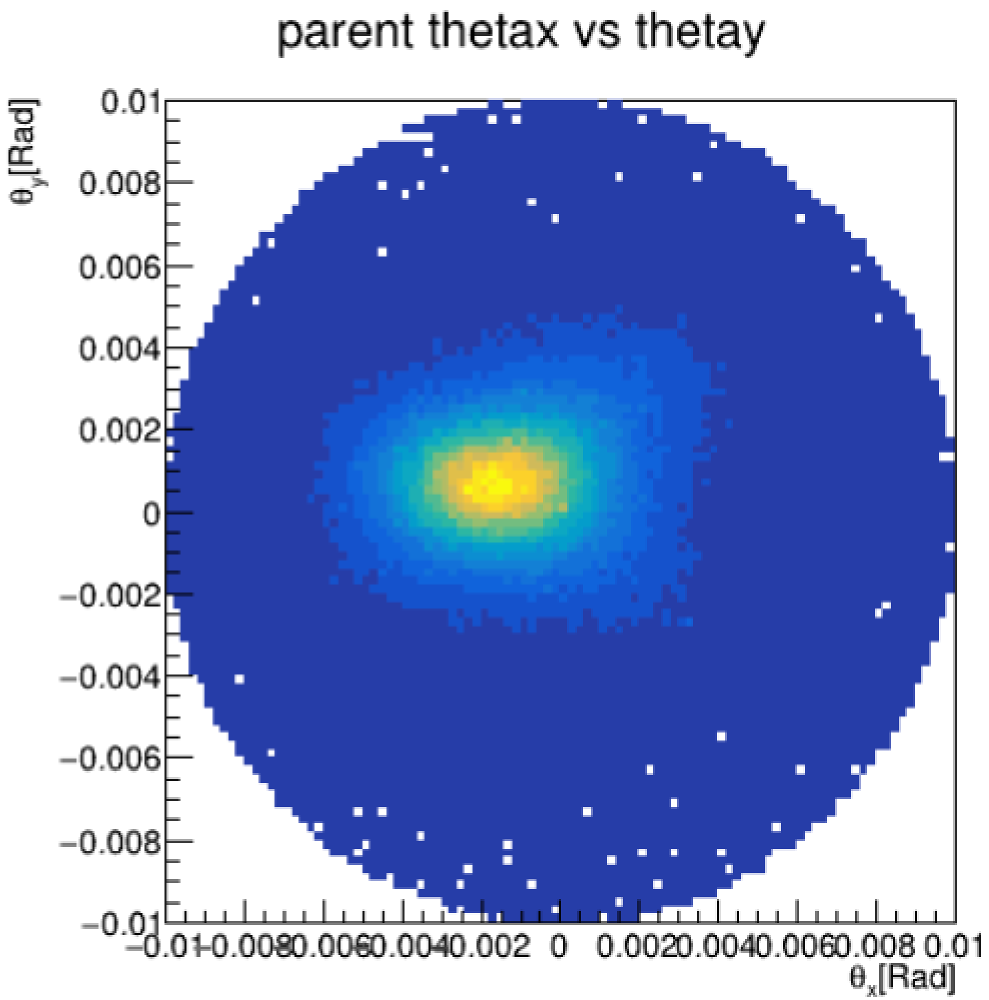

```
Minimizer is Minuit2 / Migrad
Chi2                      =      117.457
NDf                       =           32
Edm                       =  6.48087e-09
NCalls                    =           83
Constant                  =      7826.52   +/-    24.1327
Mean                      =  0.000709731   +/-    3.99459e-06
Sigma                     =   0.00126946   +/-    5.62274e-06
```

- We can get the beam direction from calculating the theta_x and theta_y of the Møller electron’s parent particle– which must come from the beam. This is done by adding the four vectors of the two Møller candidate electrons and calculating the theta x and theta y of the this summed 4-vec.

Beam Direction







- These fits yield a slightly negative theta x and a slightly positive thetay, which is more easily seen in this 2D plot.

Summary & Moving forward

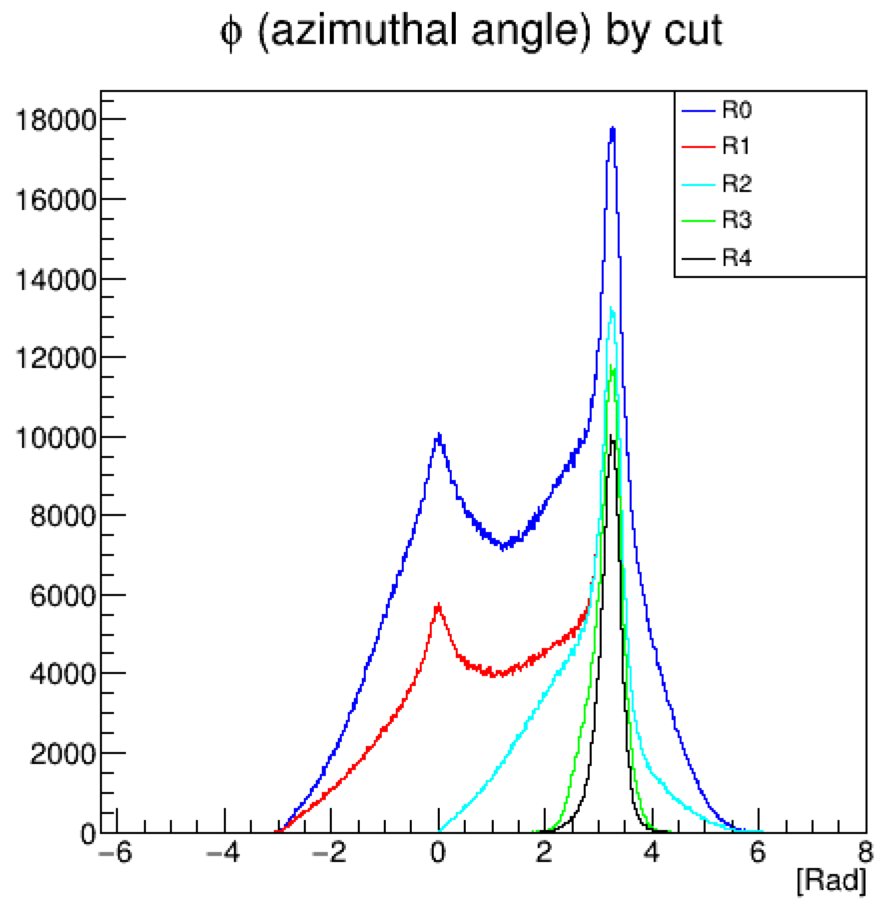
- Møller mean values are in good shape, and widths are comparable (~marginally higher) when compared to old (v4/v5) detectors.

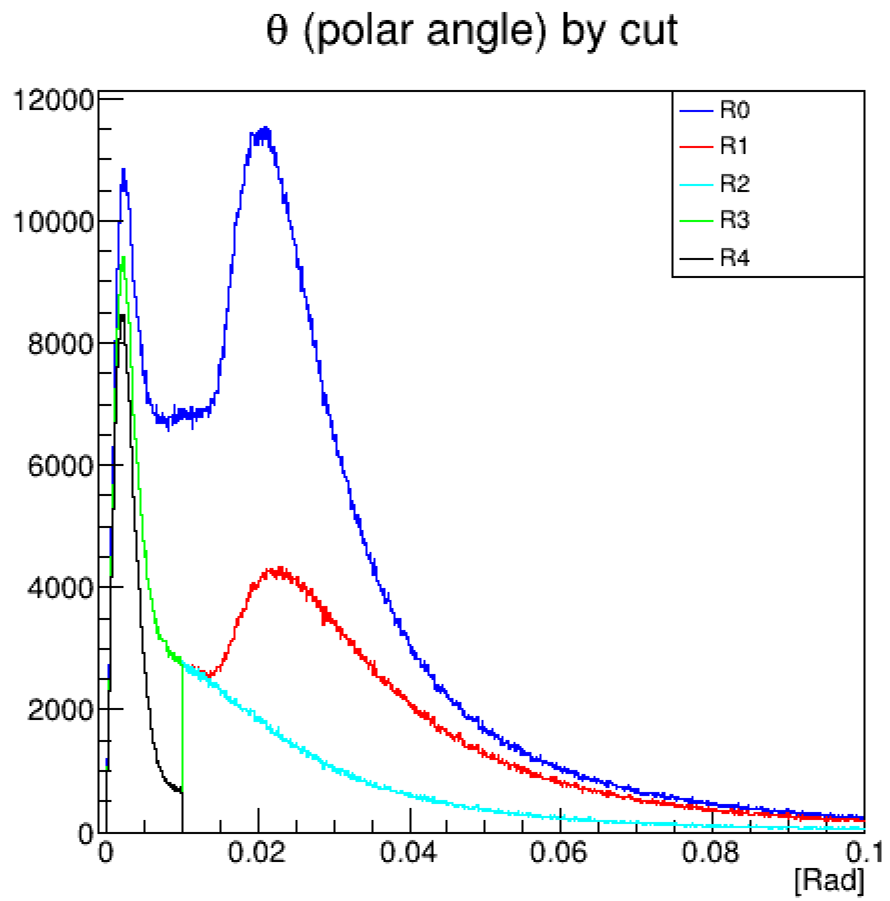
- Moller mean dependence on thetax is puzzling and need more investigation. Requiring fiducial clusters and placing a strict cut on E_ecal / P_track does not appear to remedy this.
    - What other quantities could I look at?

- Compared to MC (really only UC's and NoV's), the the distributions in data are ~1MeV wider.
    - Would be nice to have a larger mc sample where target position is fixed to see how BSC and TC V0s look.

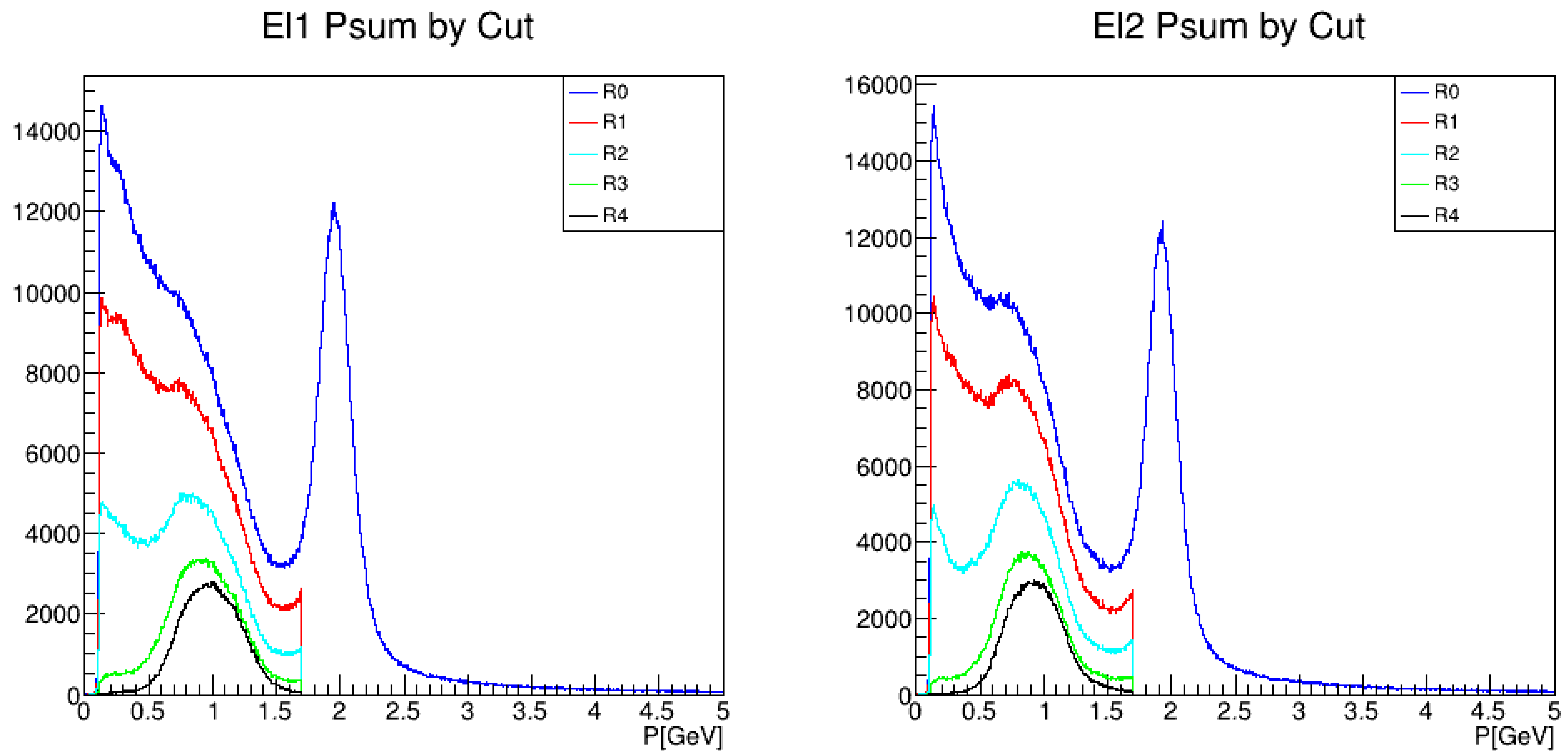
- Can look at tridents next. Maurik is working on some MC for this, in combination with the existing 2021 sample with beam background.

Backup: Phi and Theta (spherical) angle by cut



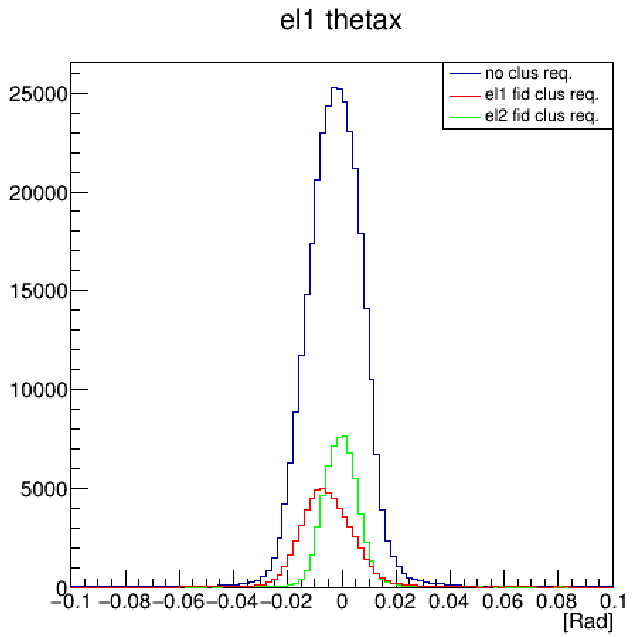


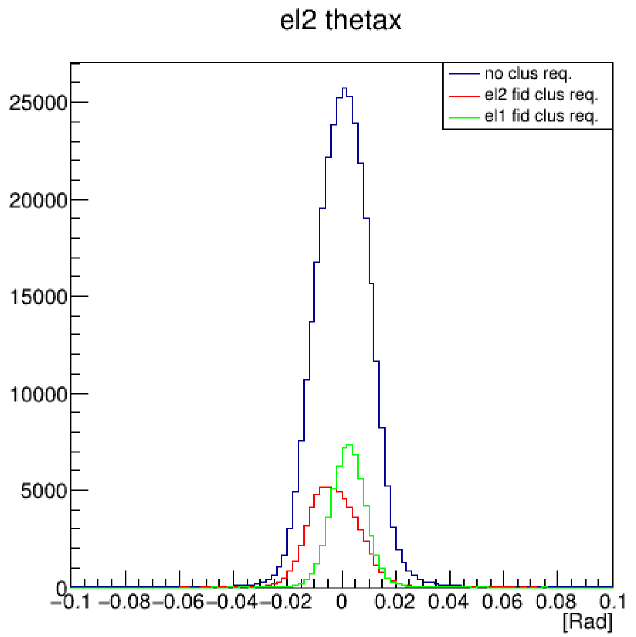
Backup: El1 & El1 psum by cut

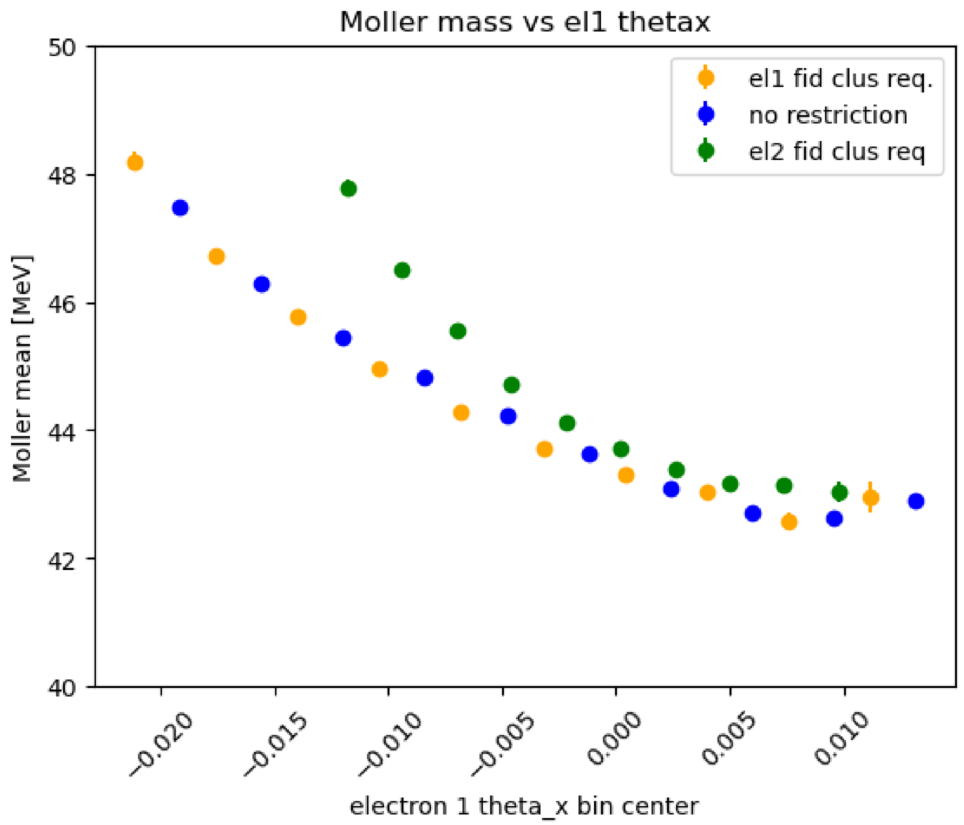


- Note: top/bottom labels do not match E1/E2 here.

Backup: El1 thetax with el2 Fid. Cluster







- The moller mass dependence on electron 1 thetax is present when requiring electron 2 to make a fiducial cluster.