# 2016 Displaced Vertex Search

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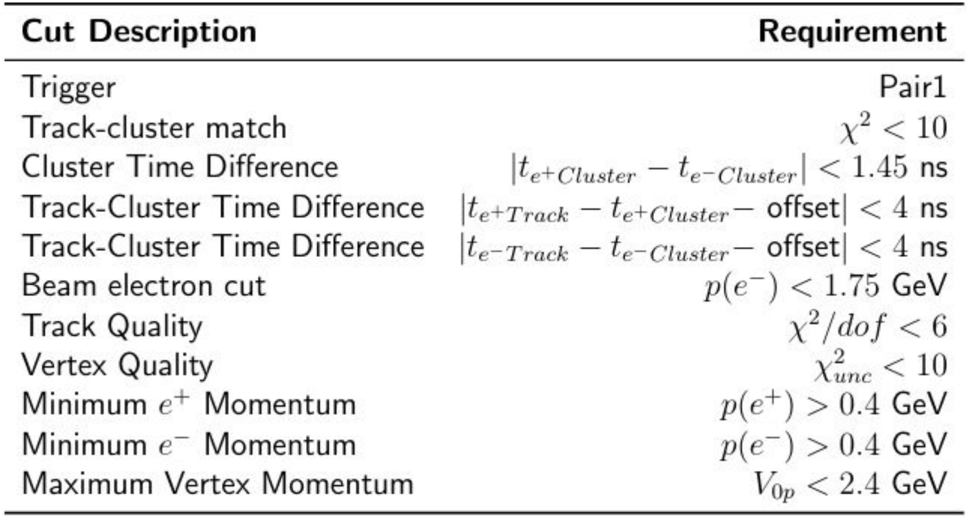
# Introduction

- The latest from the displaced vertexing analysis for 2016 data
- I will show results for 10% of the data. It is pending approval from the analysis committee
  - We are nearly ready to unblind the analysis (at least the L1L1 portion)
- Analysis Note on Overleaf - ask for permission to view
  - Chapters relevant for unblinding are nearly complete
- Presenting a step-by-step guide to the displaced vertex analysis
  - Event selection, signal rates, mass resolution, defining signal regions, computing expected signal yield, setting limits, systematics, and analyzing excess backgrounds

# Preselection Cuts

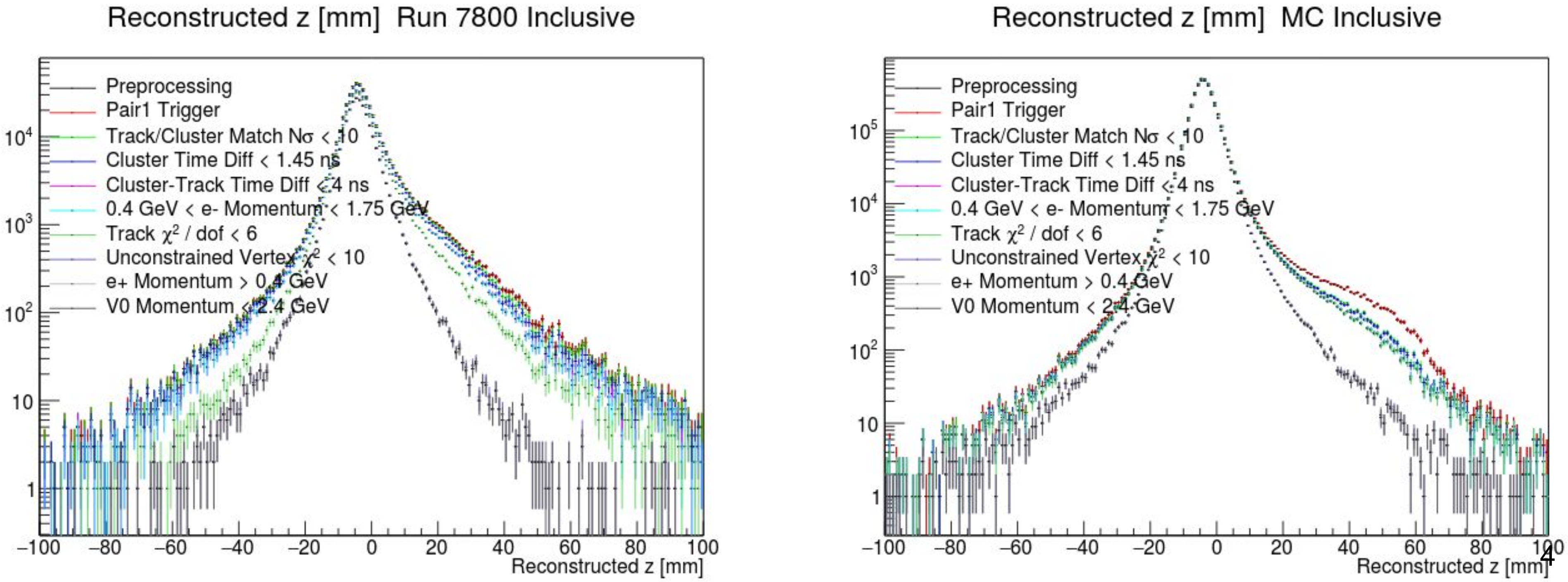
- Cuts are divided into 3 steps - cuts in reconstruction (MOUSE), Preselection, and Tight Cuts
- A preliminary set of cuts is used for initial study called “Preselection”
- Preselection cuts include (right):
    - Track quality
    - Track/cluster timing
    - Track/cluster matching
    - Vertex quality
    - Basic momentum cuts
    - No layer requirements… yet
- These are either loose cuts or based on previous analysis cut values



| Cut Description | Requirement |
|---|---|
| Trigger | Pair1 |
| Track-cluster match | $\chi^2 < 10$ |
| Cluster Time Difference | $\lvert t_{e^+Cluster} - t_{e^-Cluster} \rvert < 1.45$ ns |
| Track-Cluster Time Difference | $\lvert t_{e^+Track} - t_{e^+Cluster} -$ offset$\rvert < 4$ ns |
| Track-Cluster Time Difference | $\lvert t_{e^-Track} - t_{e^-Cluster} -$ offset$\rvert < 4$ ns |
| Beam electron cut | $p(e^-) < 1.75$ GeV |
| Track Quality | $\chi^2/dof < 6$ |
| Vertex Quality | $\chi^2_{unc} < 10$ |
| Minimum $e^+$ Momentum | $p(e^+) > 0.4$ GeV |
| Minimum $e^-$ Momentum | $p(e^-) > 0.4$ GeV |
| Maximum Vertex Momentum | $V_{0p} < 2.4$ GeV |

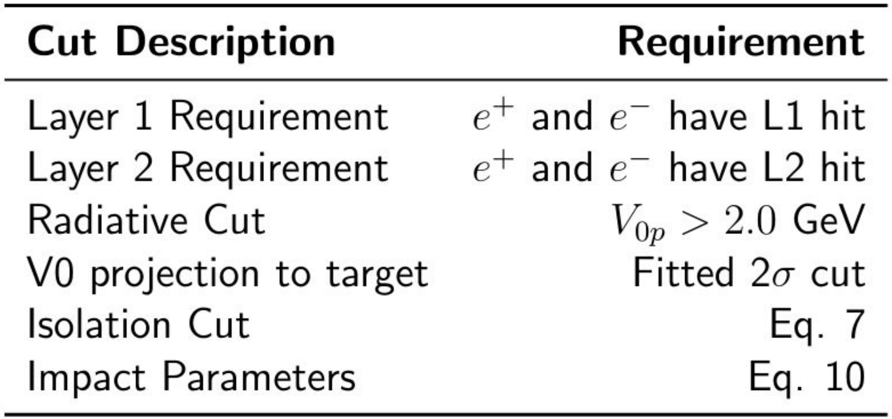
# Preselection Cutflow

- Cutflow for the Preselection cuts for Run 7800 (left) and tritrig-wab-beam (right)



# Tight Cuts L1L1

- “Tight Cuts” are used to further reduce background events at high z
- Require layer hits in layer 1 (L1L1) to start, we will relax this requirement later
- Beyond layer requirements, there are 4 main tight cuts that will be discussed in detail
  - Raditiative cut (V0 momentum)
  - V0 projection to the target
  - Isolation cut (for mistracking)
  - Impact Parameters



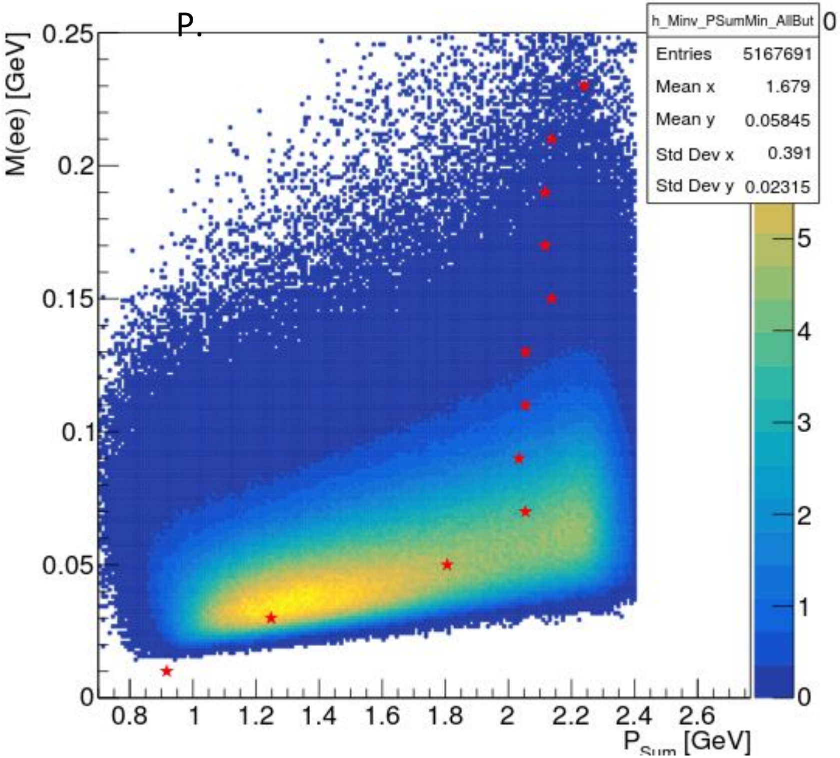
| **Cut Description** | **Requirement** |
|---|---|
| Layer 1 Requirement | $e^+$ and $e^-$ have L1 hit |
| Layer 2 Requirement | $e^+$ and $e^-$ have L2 hit |
| Radiative Cut | $V_{0p} > 2.0$ GeV |
| V0 projection to target | Fitted $2\sigma$ cut |
| Isolation Cut | Eq. 7 |
| Impact Parameters | Eq. 10 |

- Easy to demonstrate cut effectiveness, it is tough to rigorously justify a specific cut value due to lack of precise knowledge of background shape
- Removed V0 position cut and tighter vertex quality cut (redundant with other cuts)

# Radiative Cut

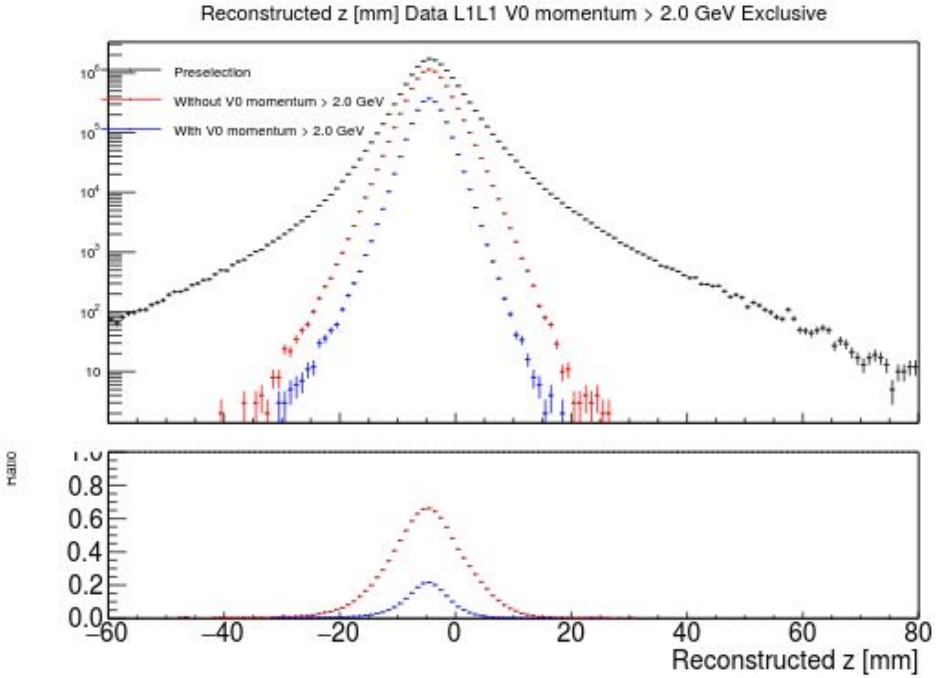
- A minimum cut on the V0 momentum (radiative cut) is warranted since A's take most of the beam energy
- A's are kinematically identical to radiative tridents, thus the Psum cut can be optimized as sqrt(Rad)/Tridents
- This same method is used by the resonance search (cut is at 1.9 GeV)
- Vertexing mass range of interest is ~0.060 GeV - 0.150 GeV, so a minimum cut of **2.0 GeV is selected**

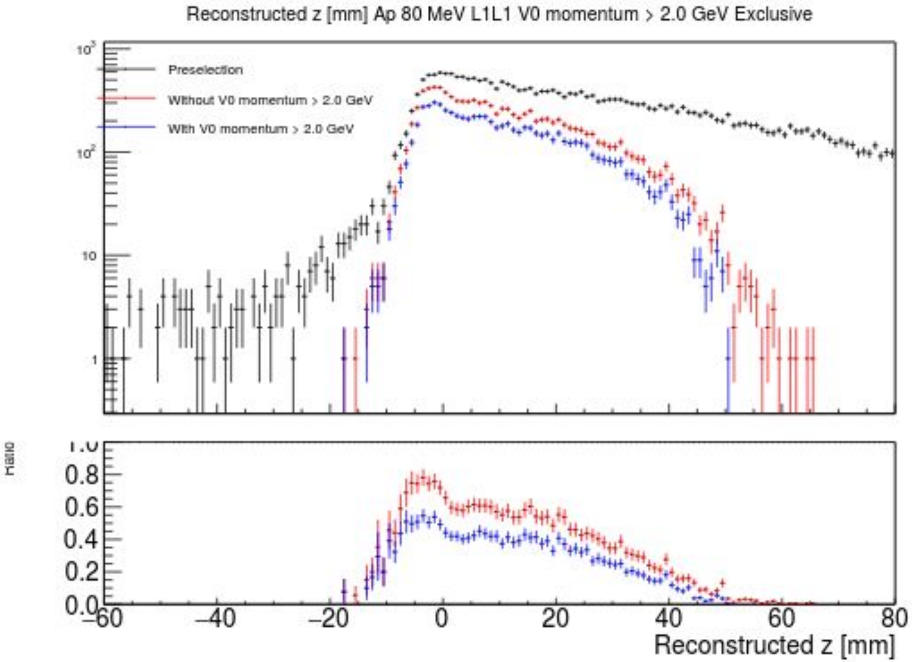
Plot courtesy of Rafo P.



# Radiative Cut

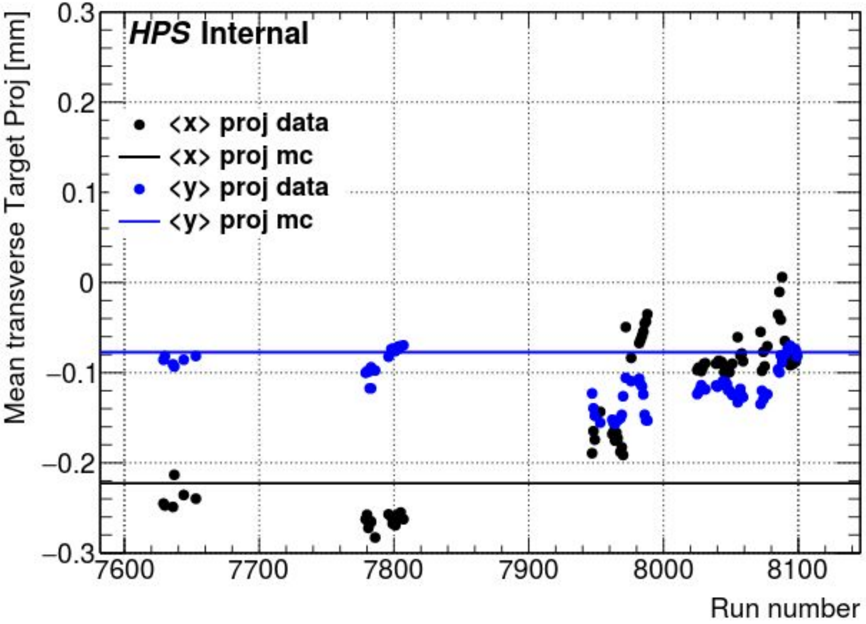
- The effect of the radiative cut on 10% data (left) and 80 MeV A’ (right)

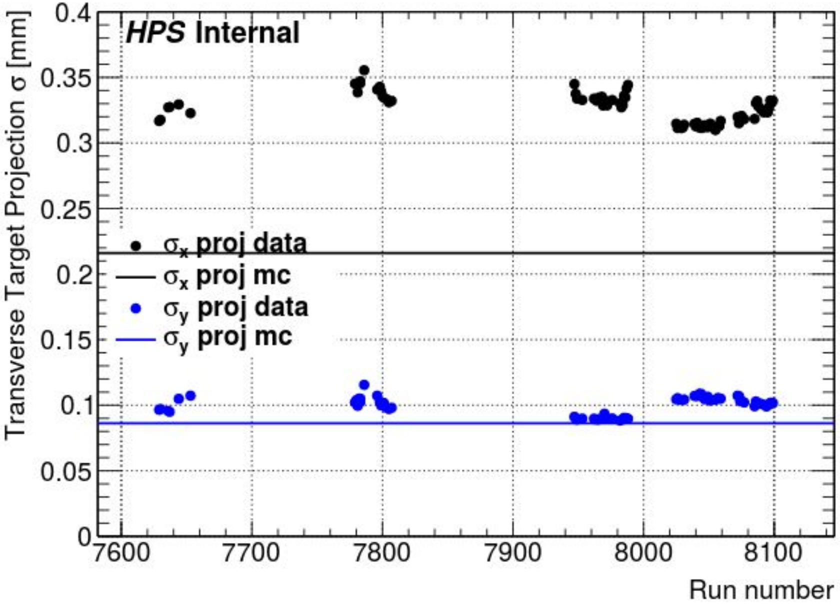




# V0 Projection to the Target

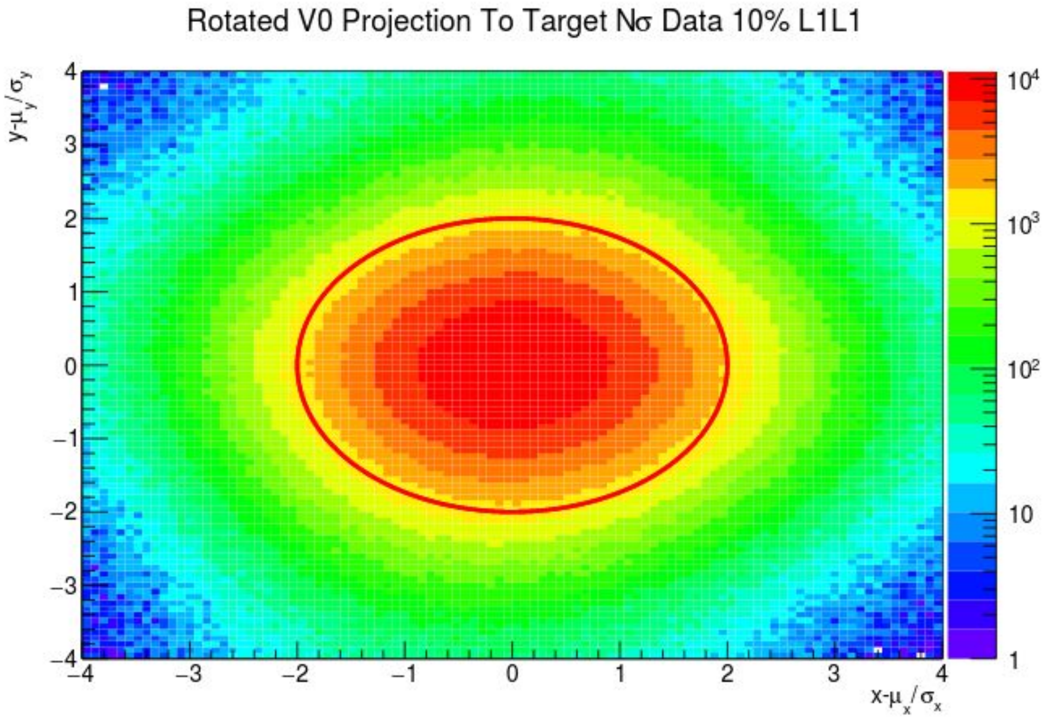
- Signal should have the V0 projection to the target close to the beamspot
- The run-by-run fitted mean and σ, these values are used for a run-by-run cut
- Constant fitted values for mean and σ are used in MC





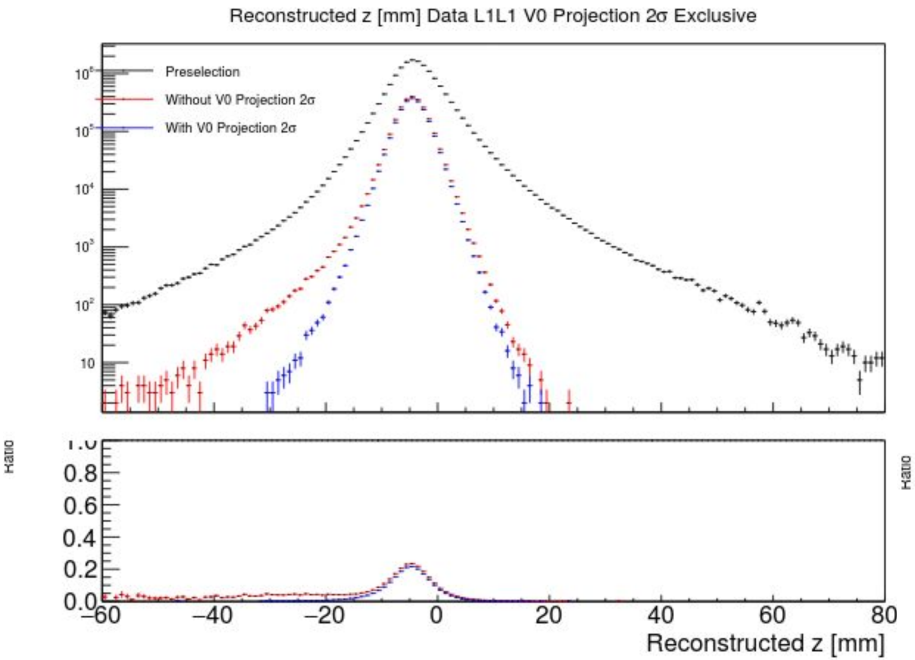
# V0 Projection to the Target

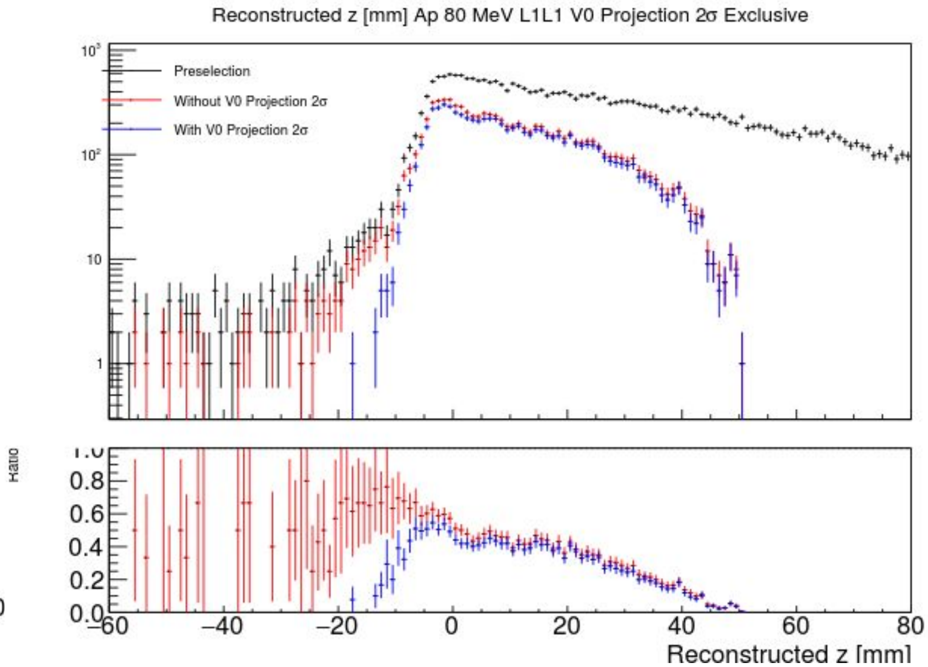
- Coordinates are rotated in order to remove x-y correlation
- The rotated coordinates are transformed into nσ deviation from the mean (significance) using run-by-run values in data
- An elliptical cut is made in this space. Cut value is selected at 2σ
    - (Really this is a circular cut in significance space)



# V0 Projection to the Target

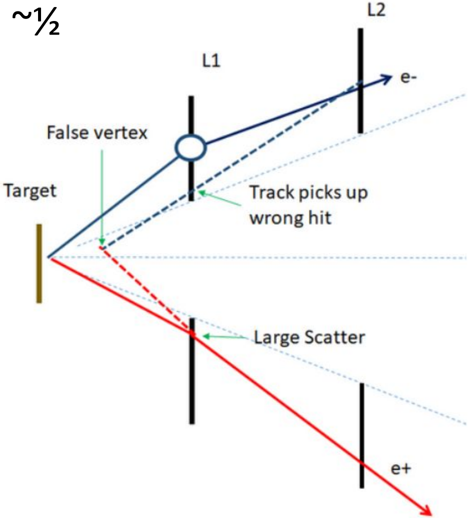
- The effect of the V0 projection to the target on 10% data (left) and 80 MeV A' (right)

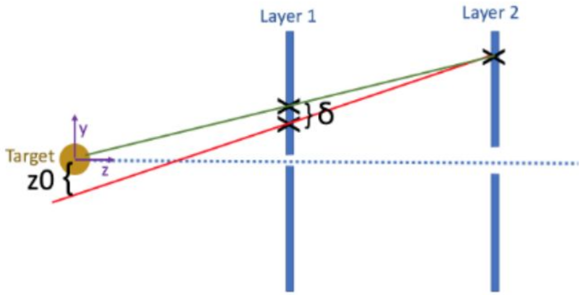




# Isolation Cut

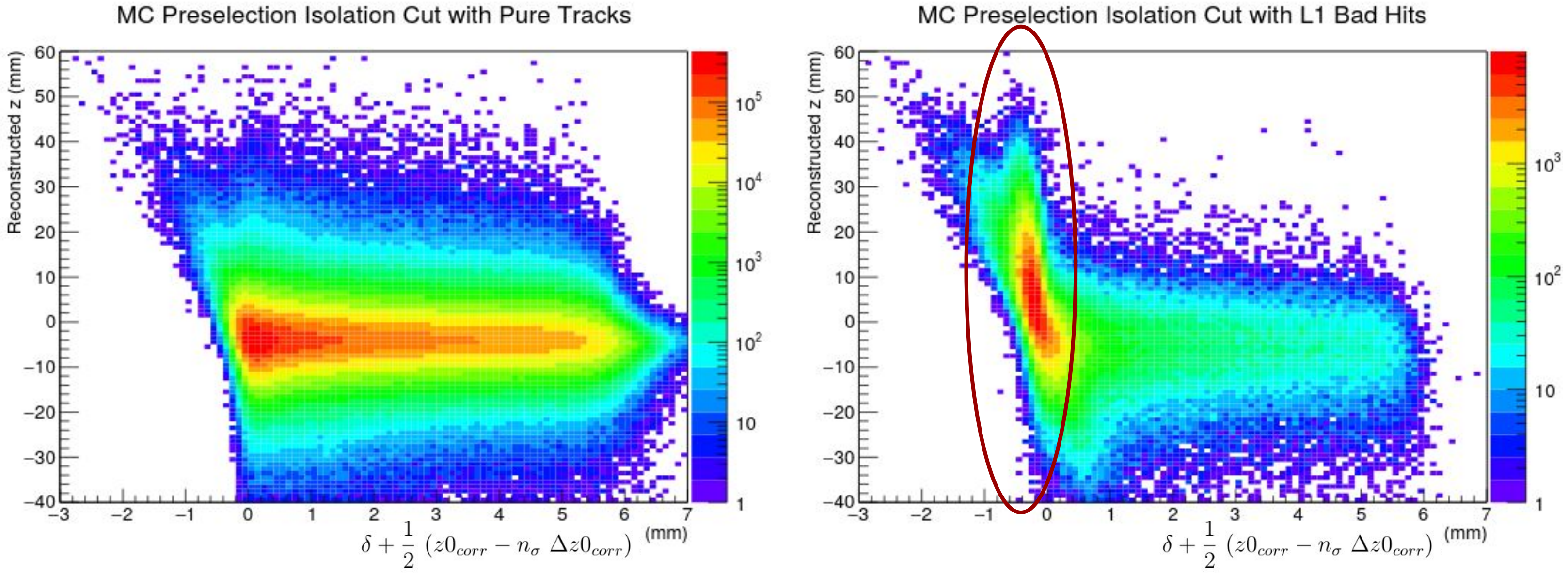
- Isolation cut is designed to eliminate high z events due to mistracking in L1
- This is a simple geometric cut: $\delta + \frac{1}{2} z0_{corr} > 0$
    - z0_corr is the vertical impact parameter at the target, δ is minimum distance between 1D hits
    - The factor of ½ comes from the ratio of the distance between L2 and L1 and L2 and the target is ~½





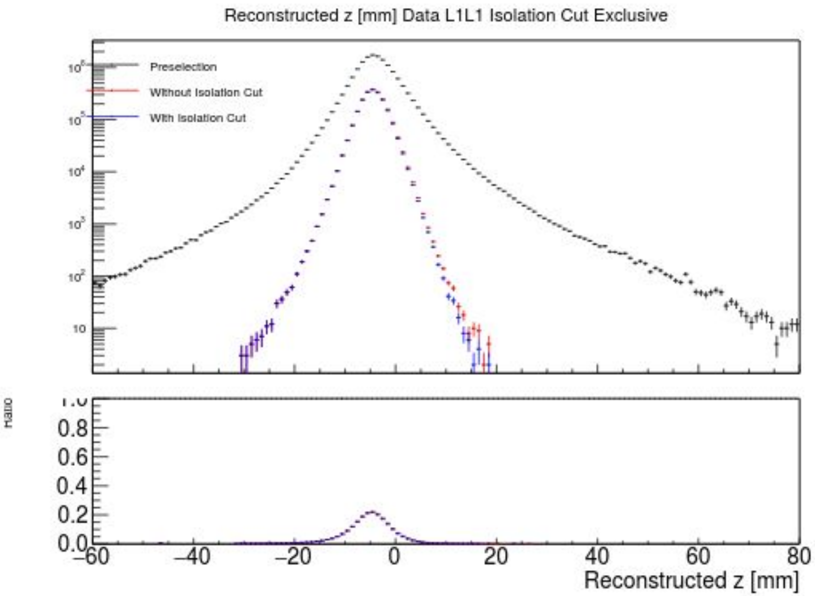
# Isolation Cut

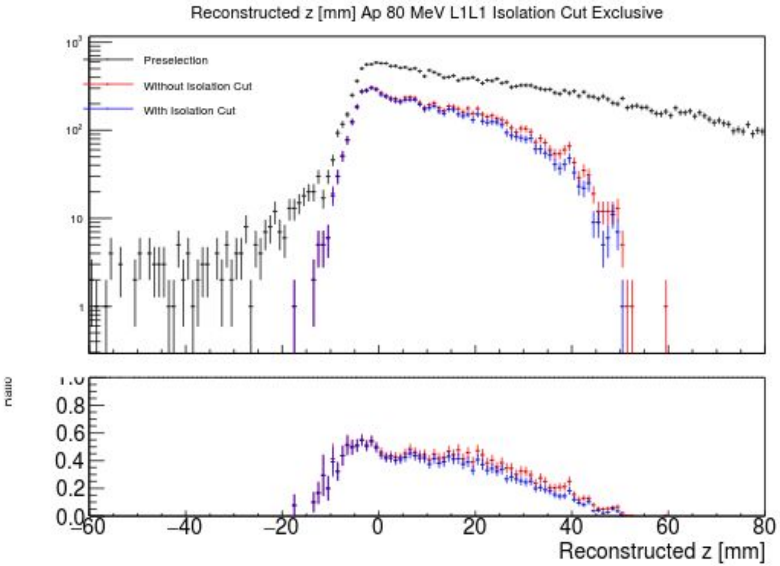
- The simple geometric cut fails to account for multiple scattering. This is a small effect but was enough to be a major source of high z backgrounds in 2015 data
  - Including multiple scattering errors: $\delta + \frac{1}{2} z0_{corr} > 0 \longrightarrow \delta + \frac{1}{2}\left(z0_{corr} - n_{\sigma}\ \Delta z0_{corr}\right) > 0$



# Isolation Cut

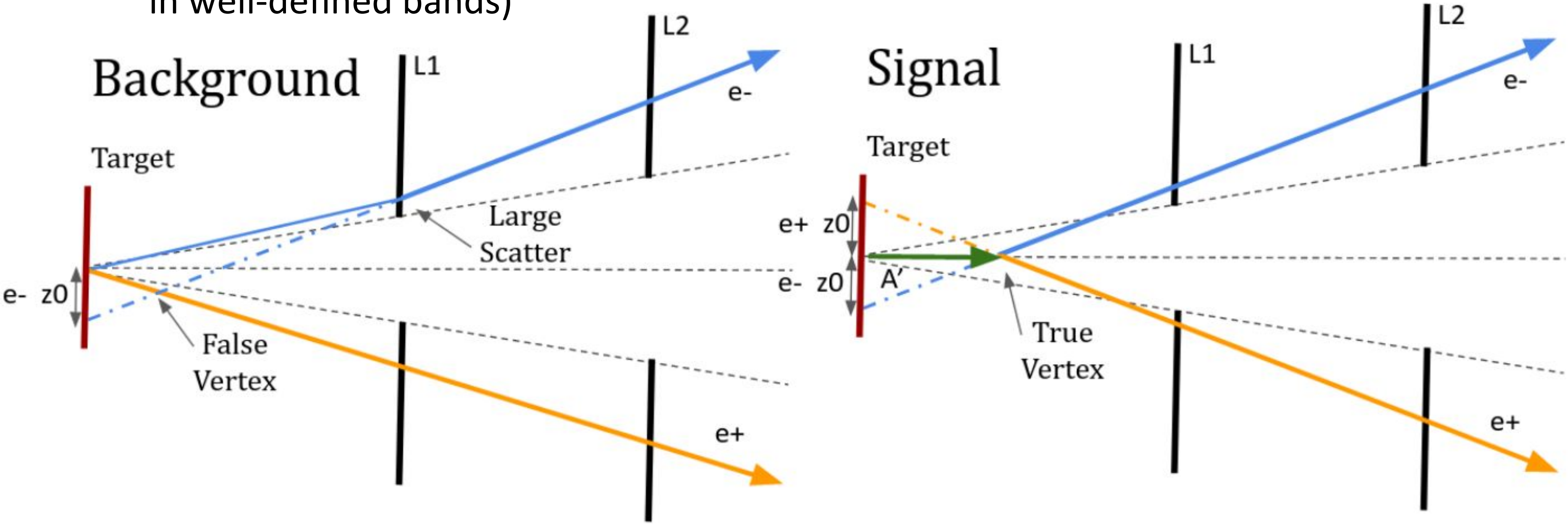
- The effect of the isolation cut on 10% data (left) and 80 MeV A’ (right)
- The signal yield is fairly insensitive to nσ on the track z0 error. 3σ is a reasonable value that eliminates all high z events in MC due to mistracking


Reconstructed z [mm] Data L1L1 Isolation Cut Exclusive


Reconstructed z [mm] Ap 80 MeV L1L1 Isolation Cut Exclusive

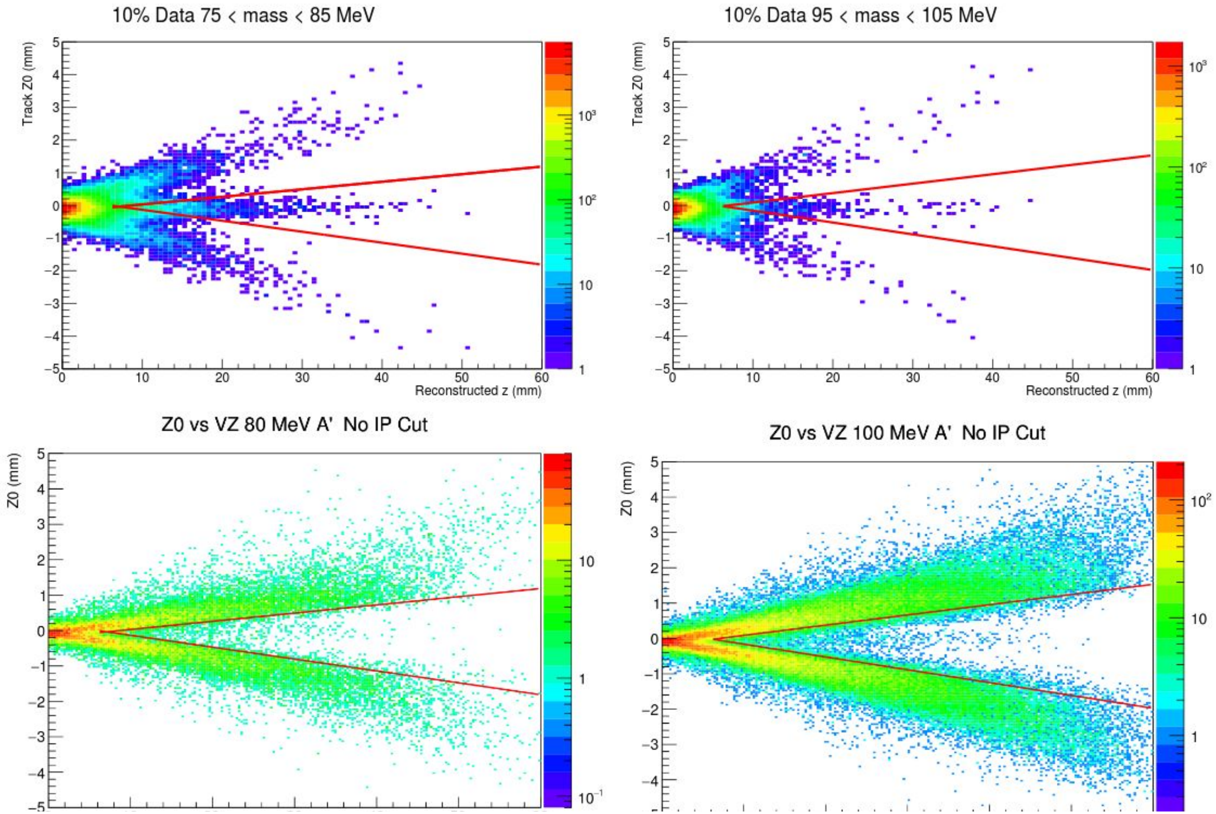
# Impact Parameter Cut

- Background may have only one large impact parameter (IP) due to one large scatter, while long-lived signal typically has large IP for both e+ and e- tracks
- Require both e+ and e- tracks to have large impact parameters (signal shape is in well-defined bands)



# Impact Parameter Cut

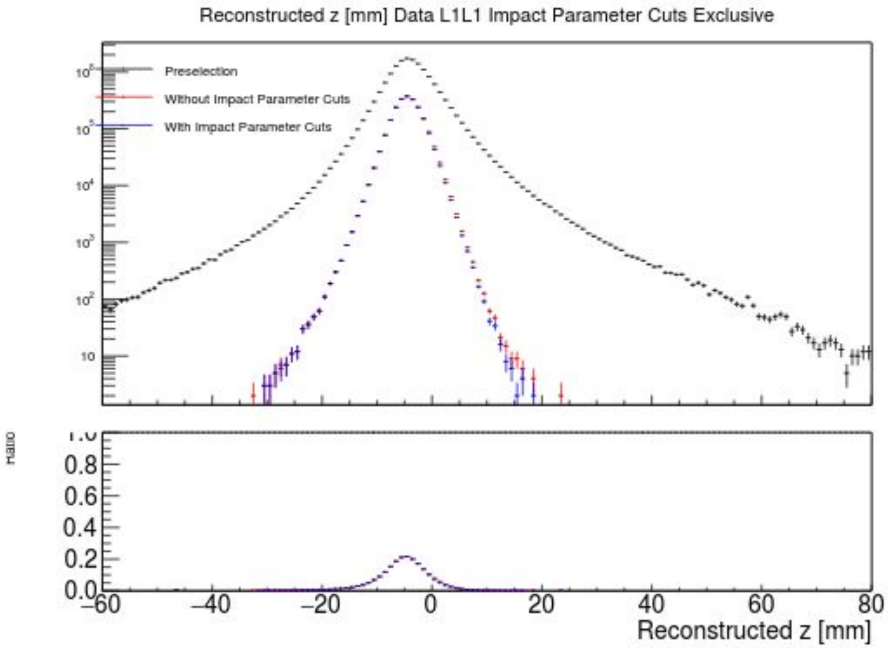
- For a given mass, IP cut is linear in z with one tunable parameter α which sets how much signal to eliminate
- The slope of line is parametrized in mass, different for top/bottom
- One tunable parameter α -> cut defined by 5 parameters

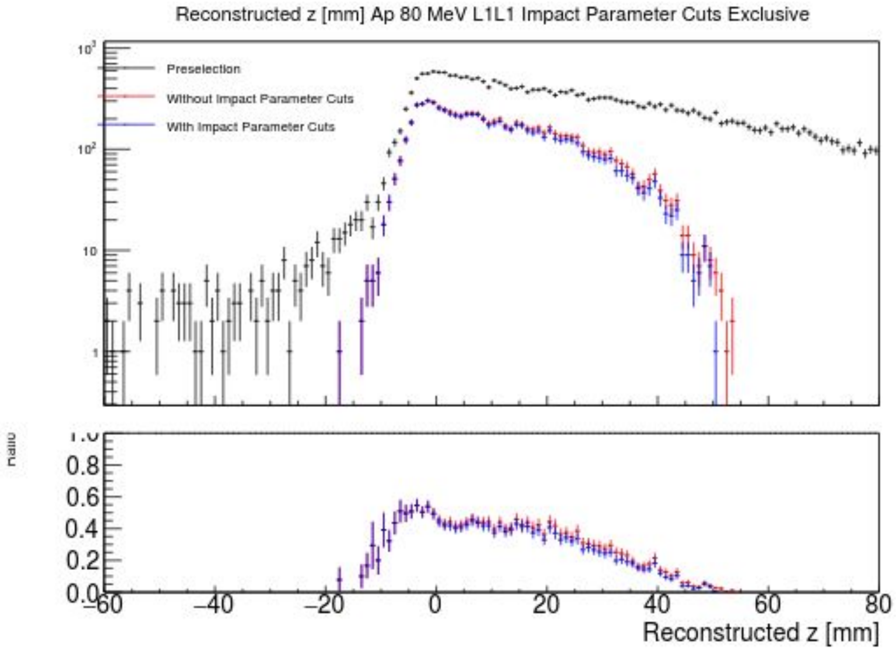


$$z0_{+}(m,z,\alpha) > a(\alpha) + b_{0+}(\alpha)\ z + b_{1+}(\alpha)\frac{z}{m} \text{ or } z0_{-}(m,z,\alpha) < a(\alpha) + b_{0-}(\alpha)\ z + b_{1-}(\alpha)\frac{z}{m}$$

# Impact Parameter Cut

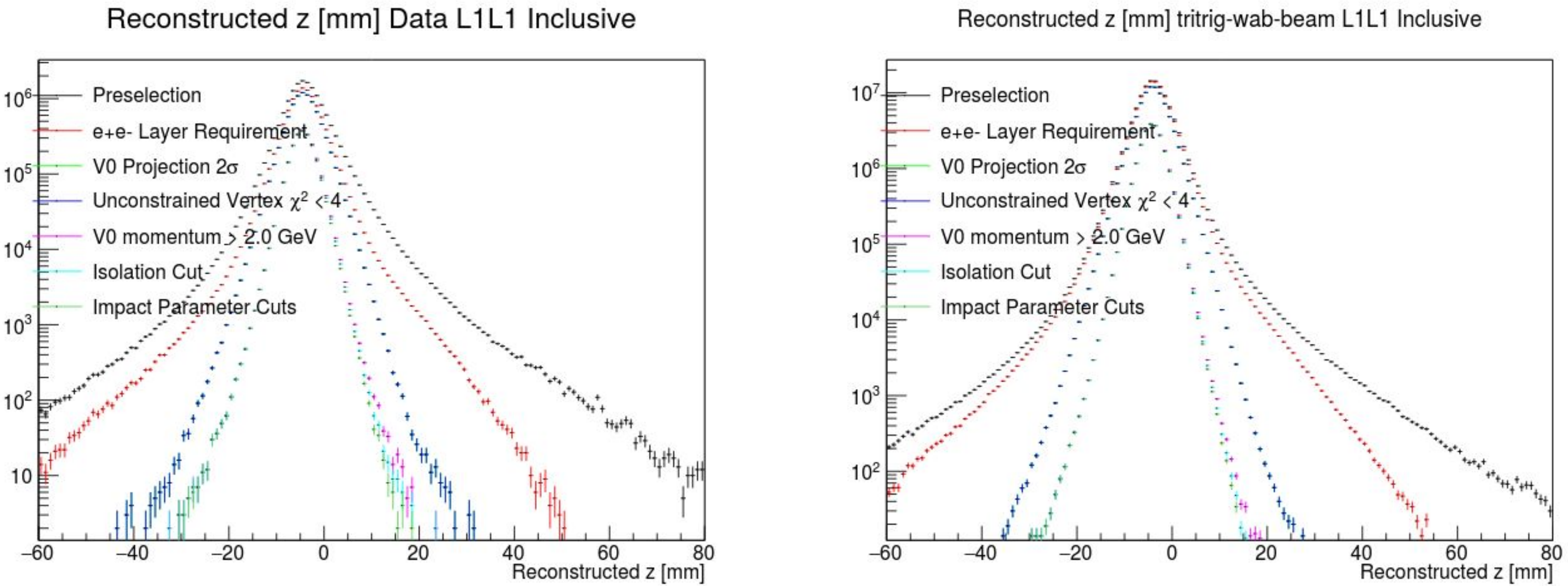
- The effect of the impact parameter cut on 10% data (left) and 80 MeV A’ (right)





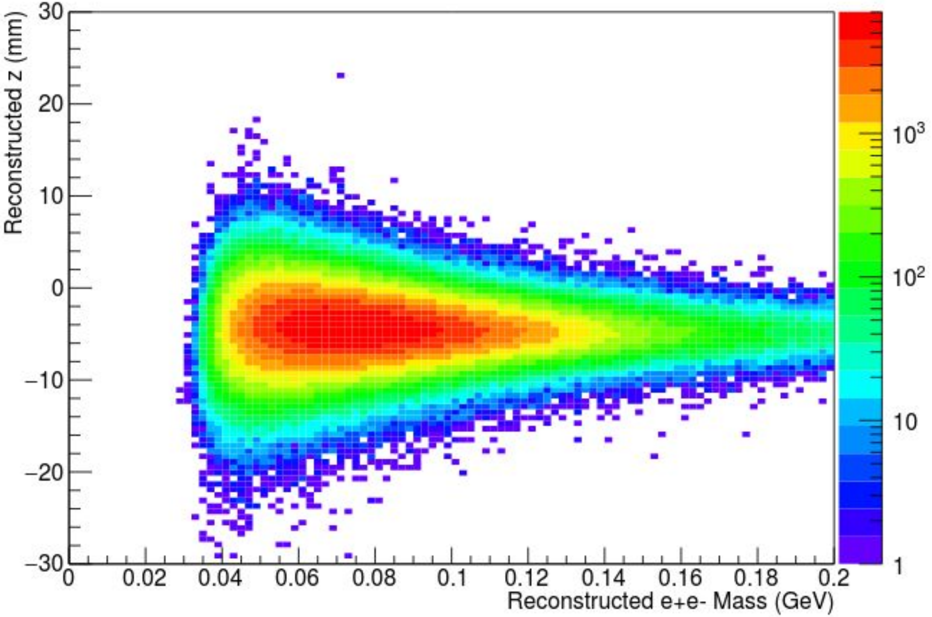
# L1L1 Tight Cuts Cutflow

- Cutflow of the tight cuts in the L1L1 category

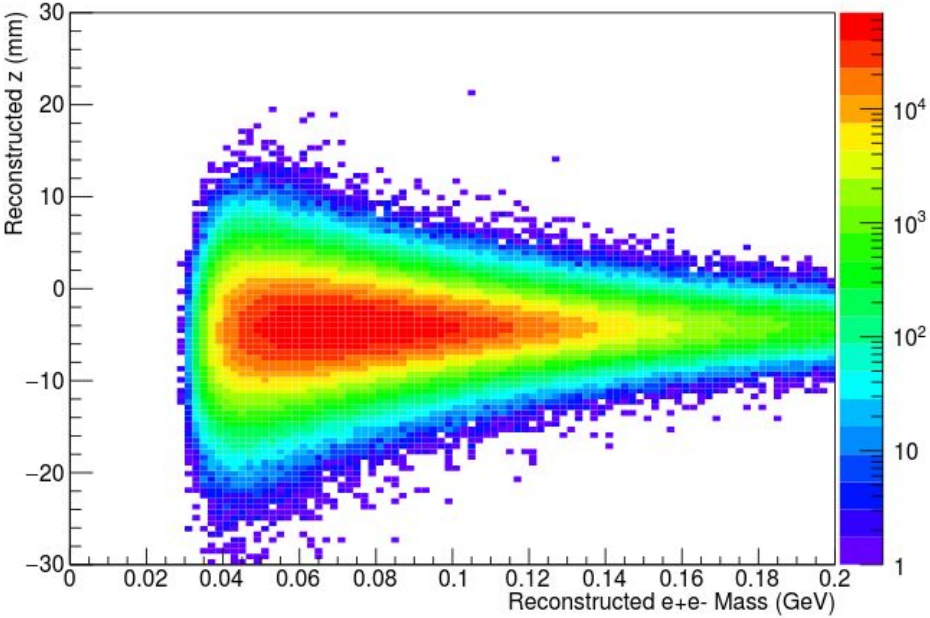


# Final Selection for L1L1

- Finally, remove tracks with shared hits remove duplicate V0s
- Final selection for the L1L1 category for 10% data (right) and MC (right)



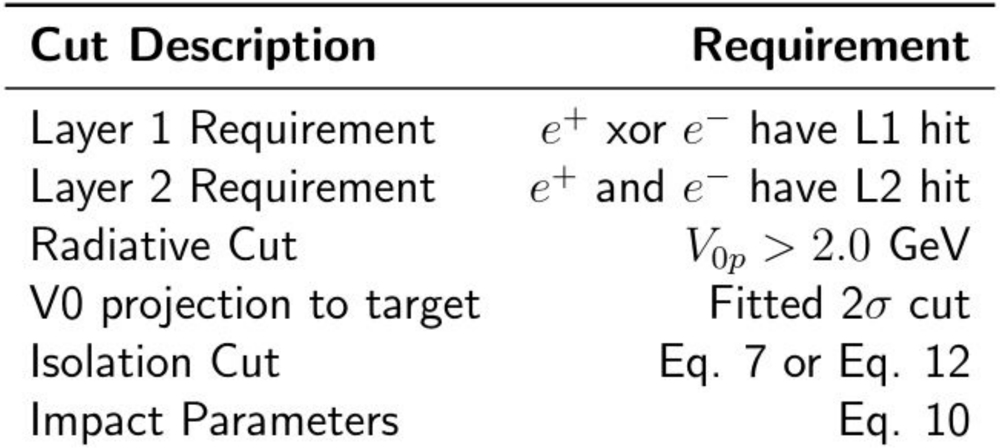
Final Selection 10% Data L1L1



Final Selection 100% tritrig-wab-beam

# Tight Cuts L1L2

- The same method for tight cuts are used as L1L1, but with key differences
- Raditiative cut (V0 momentum)
  - Remains the same
- V0 projection to the target
  - Account for resolution effects
  - Scale resolution from L1L1 by 1.25 for x and 1.5 for y
- Isolation cut (next slide)
- Impact Parameters
  - Same method is used as L1L1, but different 5 parameters
- Require no shared hits and no duplicate V0s as in L1L1

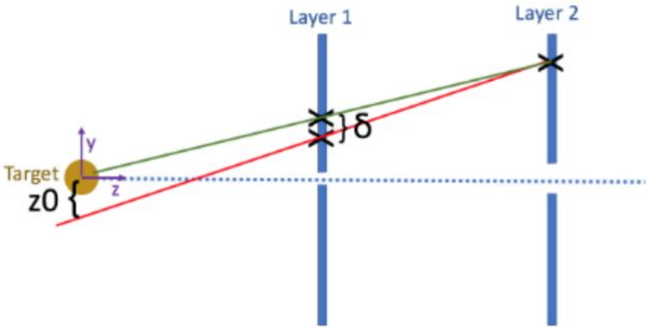


| **Cut Description** | **Requirement** |
|---|---|
| Layer 1 Requirement | $e^+$ xor $e^-$ have L1 hit |
| Layer 2 Requirement | $e^+$ and $e^-$ have L2 hit |
| Radiative Cut | $V_{0p} > 2.0$ GeV |
| V0 projection to target | Fitted $2\sigma$ cut |
| Isolation Cut | Eq. 7 or Eq. 12 |
| Impact Parameters | Eq. 10 |

# Isolation Cut L1L2

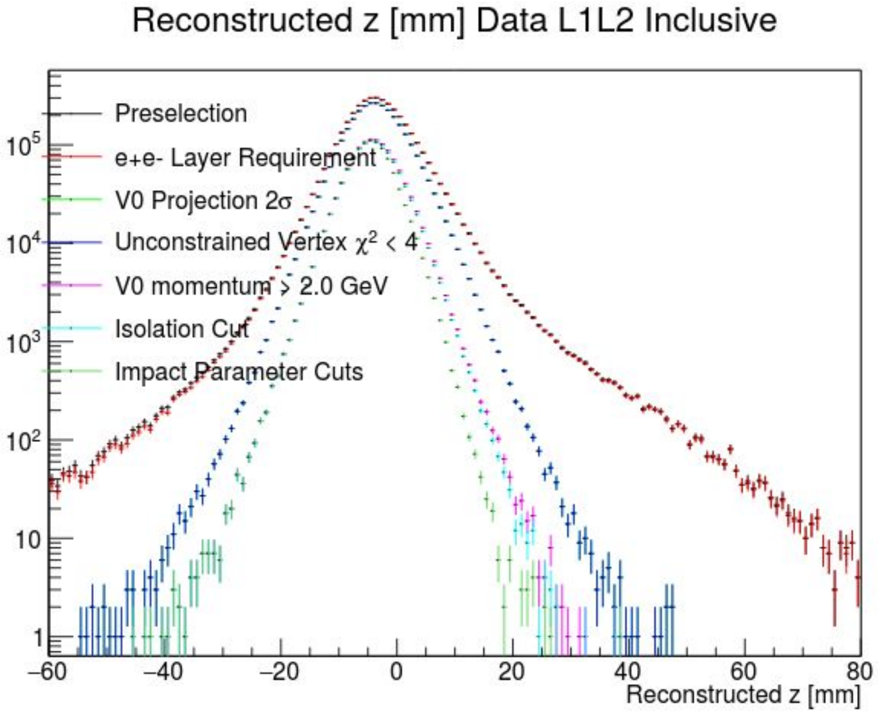
- The L1L2 isolation cut is different since the distance between the the first layer hit and the target are different
- The track with the layer 1 hit has the same isolation cut requirements as L1L1
- The track with the layer 2 hit has a different isolation cut requirement than L1L1
    - The factor of ⅓ comes from the ratio of the distance between L3 and L2 and L3 and the target is ~⅓

$$\delta + \boxed{\frac{1}{3}}(z0_{corr} - 3\ \Delta z0_{corr}) > 0$$

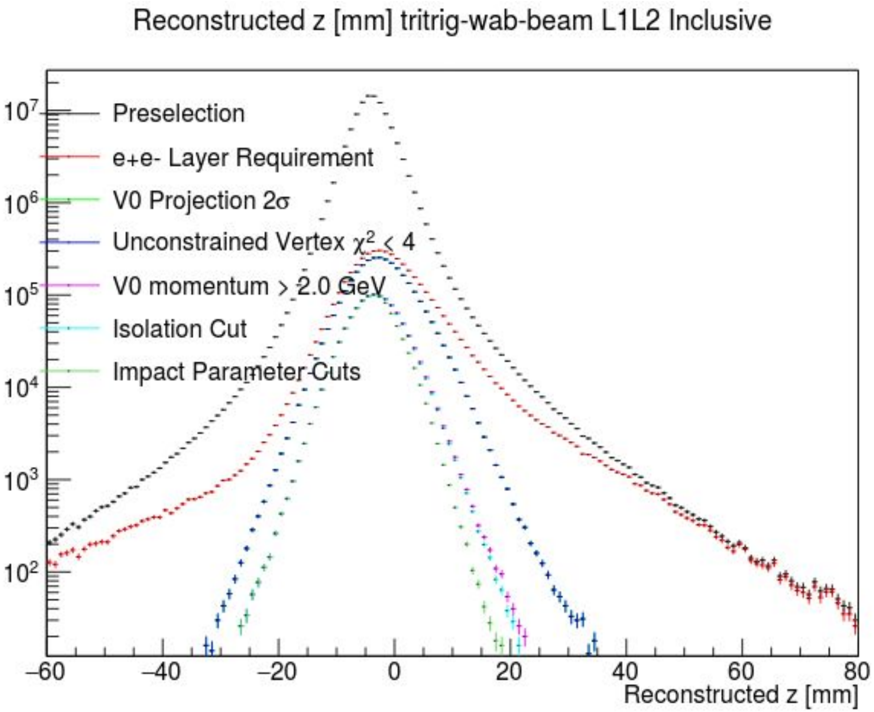


# L1L2 Tight Cuts Cutflow

- Cutflow of the tight cuts in the L1L2 category. Next, remove shared hits and duplicate V0s



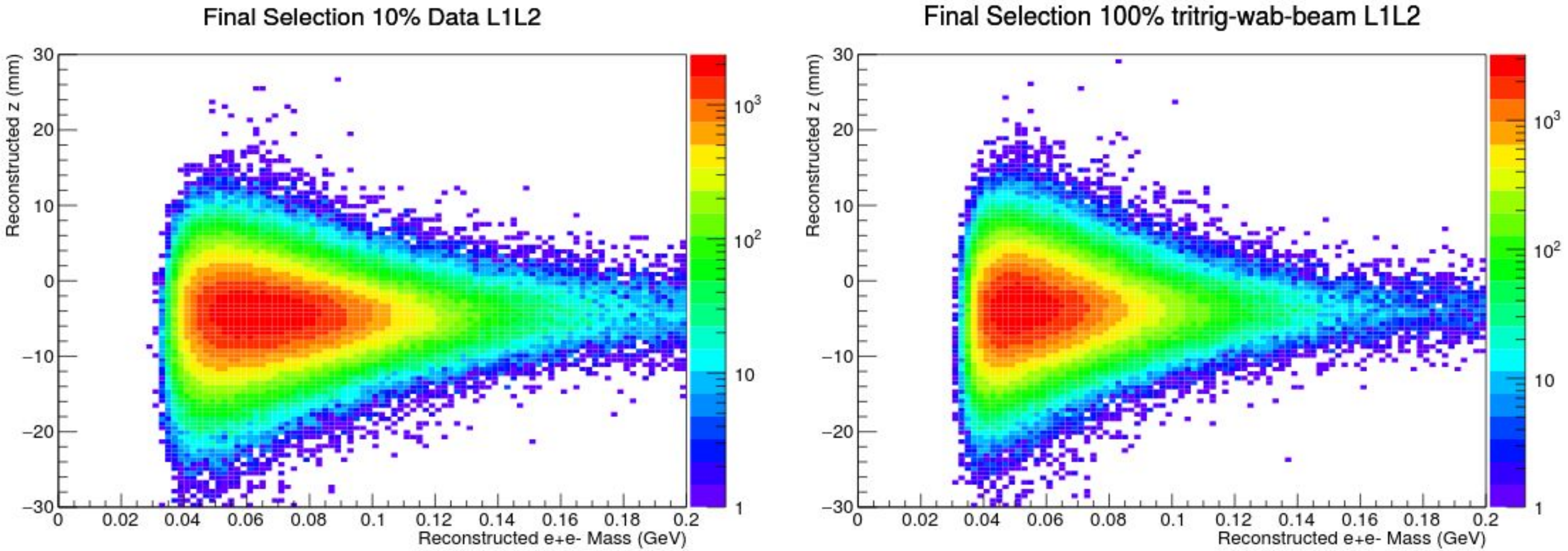
Reconstructed z [mm] Data L1L2 Inclusive



Reconstructed z [mm] tritrig-wab-beam L1L2 Inclusive

# Final Selection for L1L2

- The final selection for the L1L2 category. This still needs more work
- THe L1L2 category is dominated by hit efficiency effects that aren't in the MC
  - To do: Run the hit killing algorithm (explained later) and reconstruct tracks + V0s

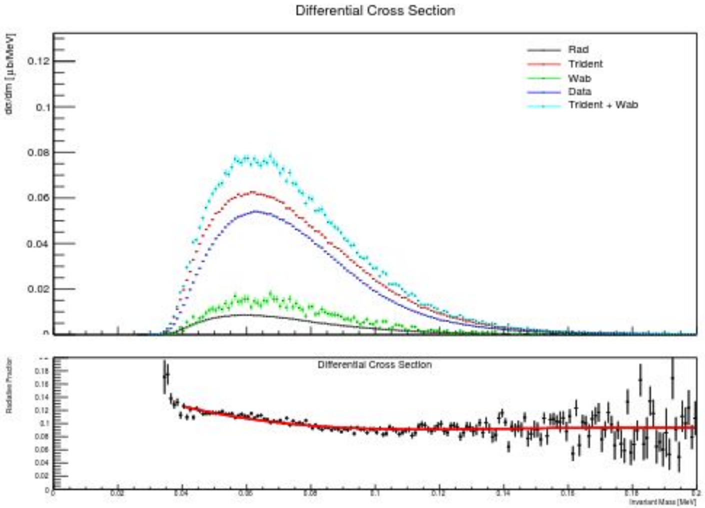


# Signal and Background Rates

- To get the expected signal rate:
  - Get the fraction of radiative tridents from MC (radiative fraction)
  - Obtain number of e+e- pairs from data, compute expected signal as a function of mass and ε
  - Displace the signal over a range of z
- First, find the radiative fraction using preselection + cuts shared with mutually exclusive categories

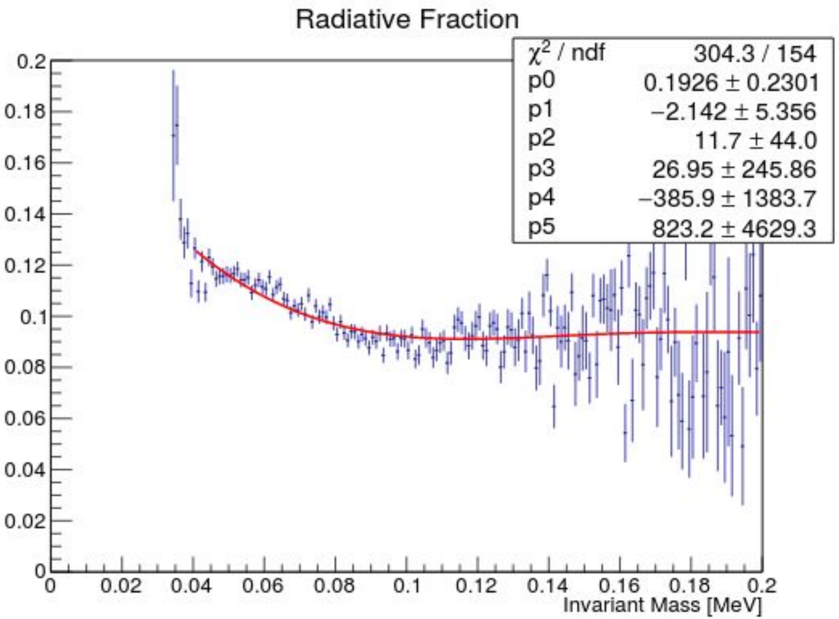
$$f_{rad}(m) = \frac{d\sigma_{rad}/dm(m)}{d\sigma_{tri}/dm(m) + d\sigma_{cWAB}/dm(m)}$$

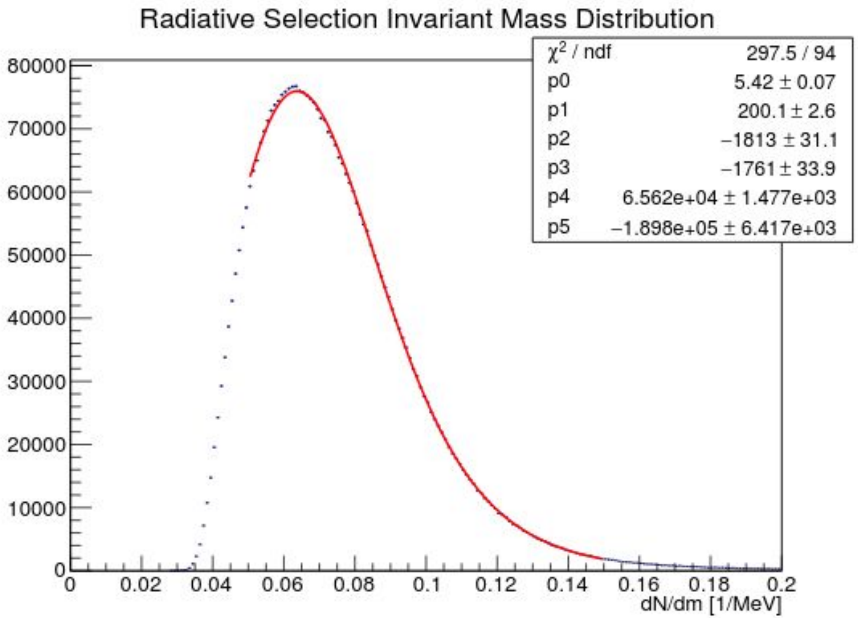
| Cut Description | Requirement |
|---|---|
| Preselection | - |
| Layer 2 Requirement | $e^+$ and $e^-$ have L2 hit |
| Radiative Cut | $V_{0p} > 2.0$ GeV |



# Radiative Fraction

- The radiative fraction is found the same way as bump hunt using the ratio of truth-matched radiatives (using truth mass) to reconstructed mass of tridents + wabs
- To do: Hit efficiency and momentum smearing effects needs to be applied



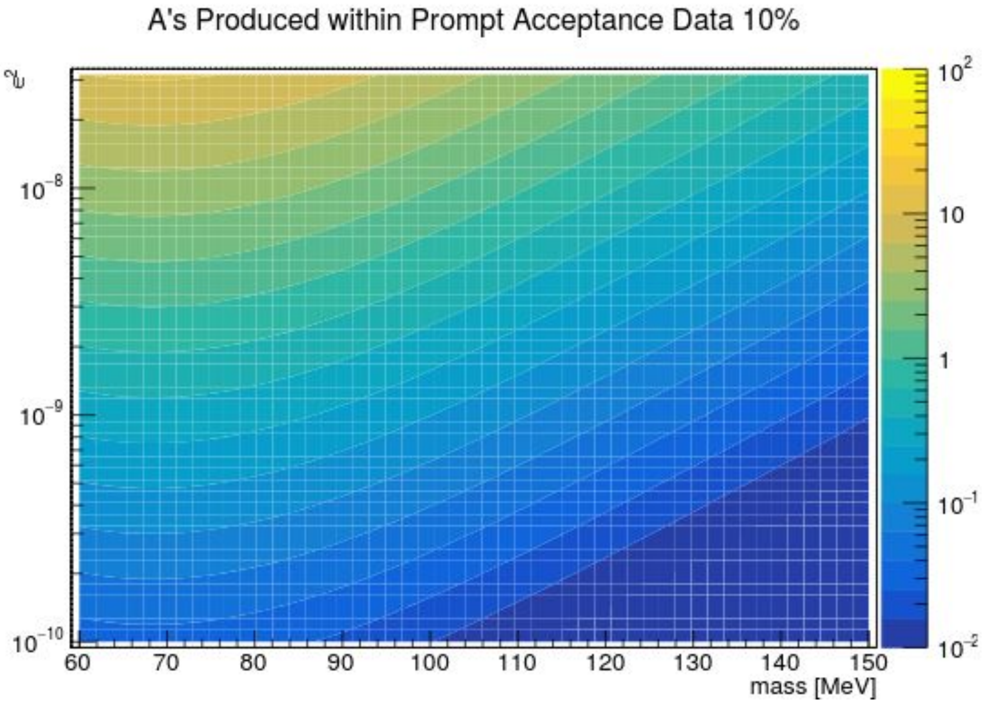


# Expected Signal Produced

- From the radiative fraction $f_{rad}$ and the number of e+e- pairs $N_{bin}$ in a small mass bin of $\delta m_{A'}$ , the number of signal events as a function of mass and ε is

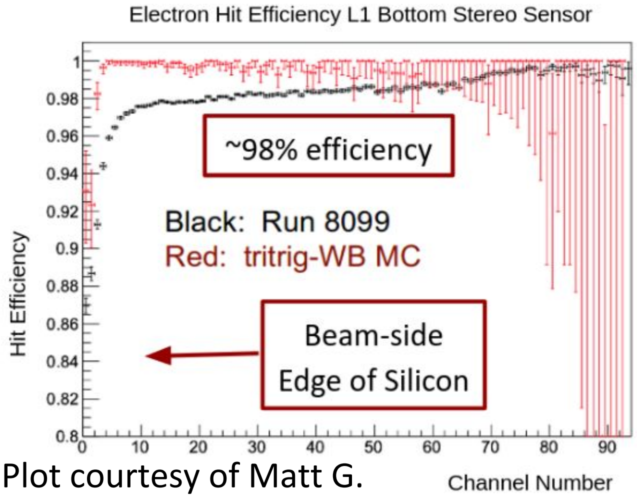
$$S(m_{A'},\epsilon) = f_{rad}N_{bin}\frac{3\pi\epsilon^2}{2N_{eff}\alpha}\frac{m_{A'}}{\delta m_{A'}}$$

- Mass window is 1 MeV
- Plot on the right shows the number of expected A’s in prompt acceptance for 10% data



# Displaced A’ Rates

- Once A’s are produced at the target, they are displaced and end up in 1 of 3 mutually exclusive categories based on the first layer hit on track
    - L1L1, L1L2, and L2L2 (only L1L1 and L1L2 are used in this analysis)
- Data has hit efficiencies, current MC does not
    - Need to incorporate hit killing algorithm as a function of track slope (Matt G.)



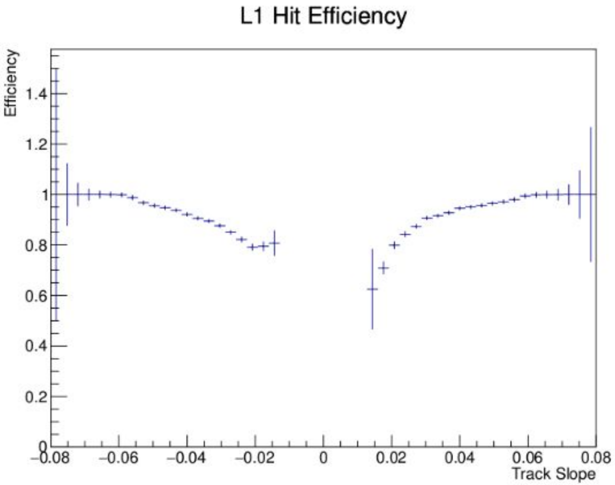
~98% efficiency

Black: Run 8099

Red: tritrig-WB MC

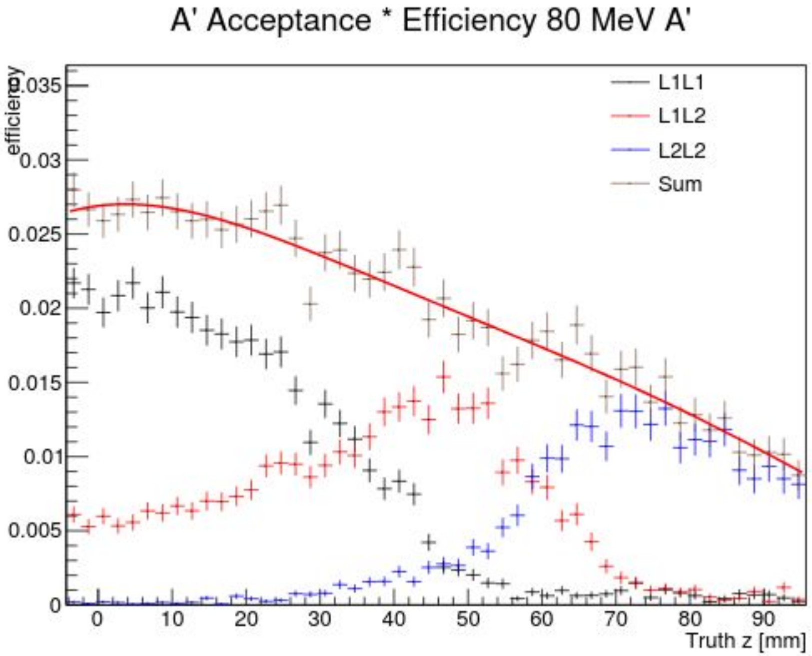
Beam-side Edge of Silicon

Plot courtesy of Matt G.



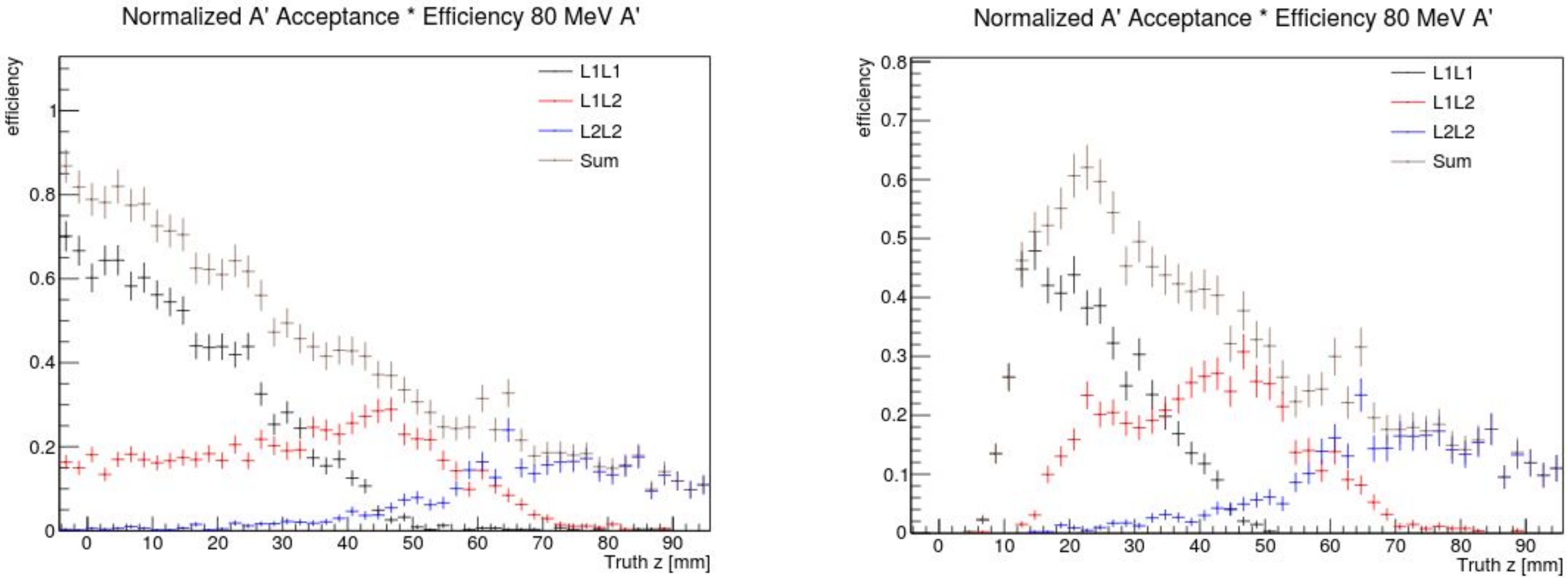
# Displaced A’ Rates

- Several options for tracks using the hit killing algorithm
    - Passes hit killing -> nothing changes
    - Fails hit killing and has 6 hits -> migrates to the appropriate category (e.g. one track in L1L1 fails, event moves to L1L2)
    - Fails hit killing and has 5 hits -> events is eliminated
- Results of hit killing shown to the right
- Fit a function to the sum and normalize it to 1 at the target $\epsilon_{vtx,sum}(z_{targ}, m_{A'}) = 1$



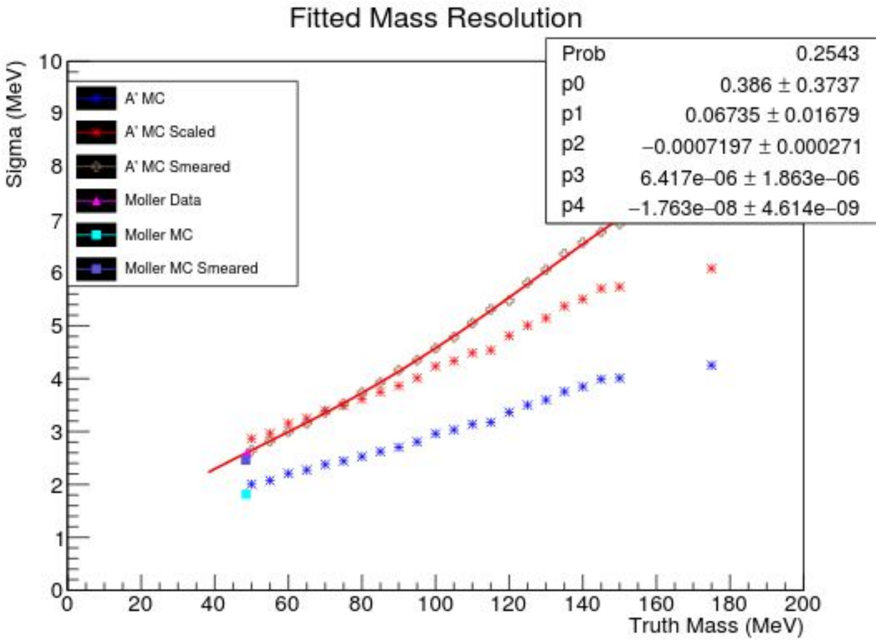
# Displaced A’ Rates

- Left: Apply the normalization factor, and then apply the remaining analysis cuts to each of the individual categories (the sum is no longer 1 at the target)
- Right: Apply the zcut (explained later) to the reconstructed z in each category



# Mass Resolution

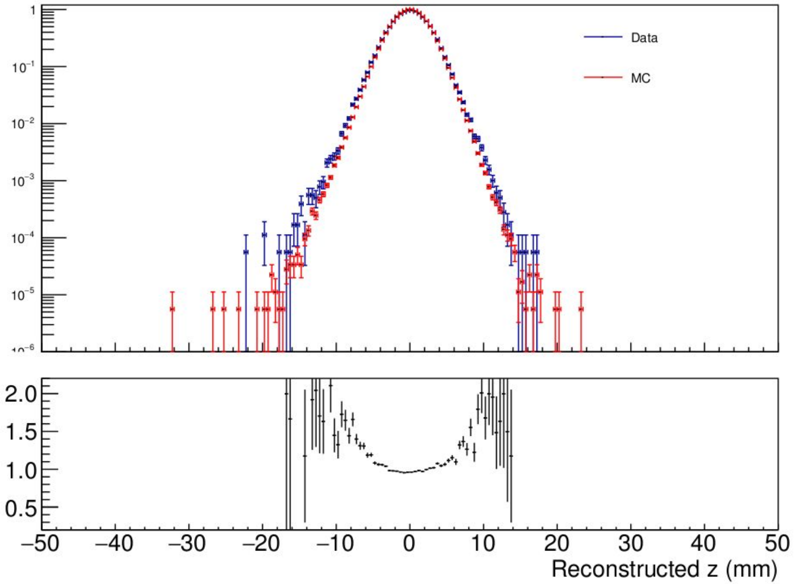
- The same method as bump hunt for mass resolution is used - track momentum smearing and rescaling the mass resolution (except uses unconstrained V0s)
- Scaled and smeared resolution does not agree well
- A’ smeared resolution is parametrized as a function of mass and used as the input to the analysis
- A’ mass resolution is ~independent of z
- Prompt A’s with the same selection as radiative fraction are used for mass resolution (needs to be compared)



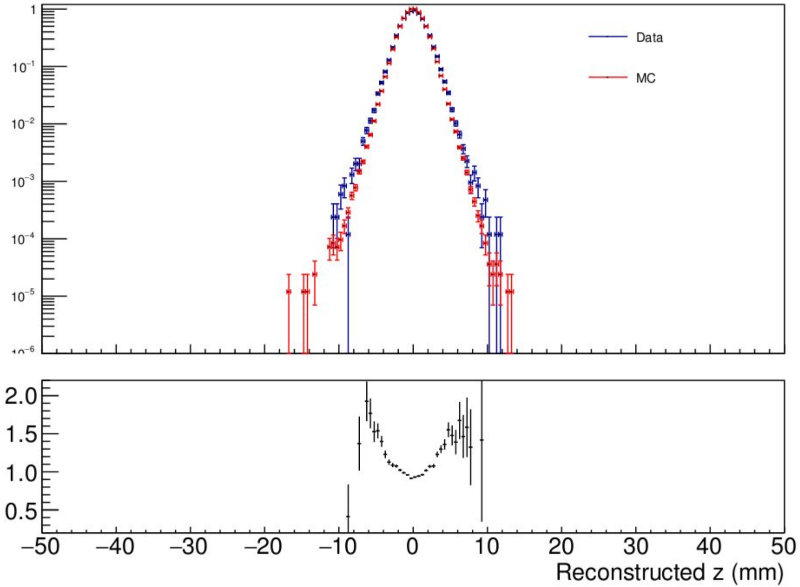
# Mass Slices

- Data/MC are sliced into mass bins of 1.9σ
- Examples at two different mass slice comparisons are shown below (with means shifted). Data is consistently slightly wider than MC

64.5 MeV < Mass < 70.7 MeV: Mean Shifted 10 Percent Data L1L1



114.6 MeV < Mass < 125.2 MeV: Mean Shifted 10 Percent Data L1L1



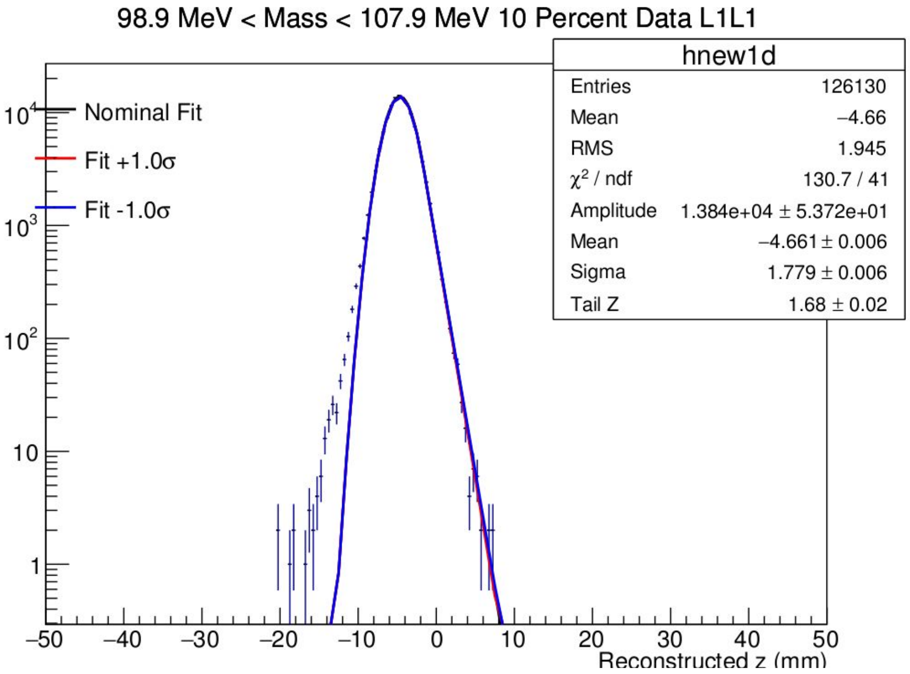
# Mass Slices and Background Fits

- Fit each mass slice with a Gaussian + exponential tail (shown right)

$$F\left(\frac{z-\mu_z}{\sigma_z} < b\right) = Ae^{-\frac{(z-\mu_z)^2}{2\sigma_z^2}}$$

$$F\left(\frac{z-\mu_z}{\sigma_z} \geq b\right) = e^{-\frac{b^2}{2}-b\frac{z-\mu_z}{\sigma_z}}$$

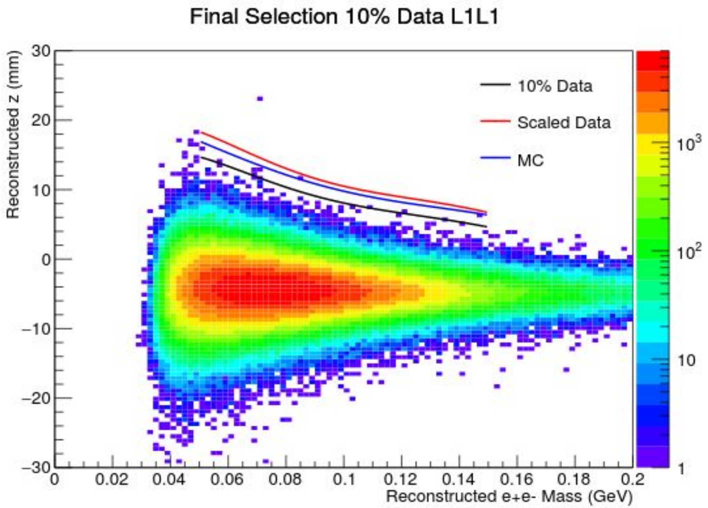
- Zcut defined as the z position past which you expect 0.5 background events. This defines the signal region
- Same fit function is attempted for L1L2 (works well, but with longer tail)

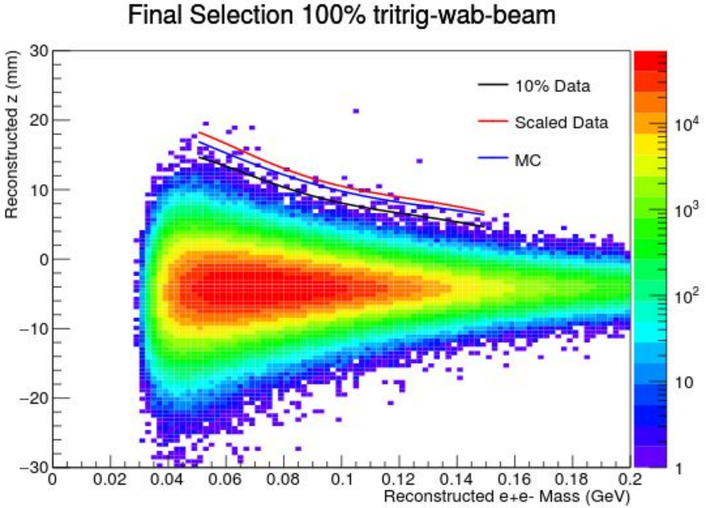


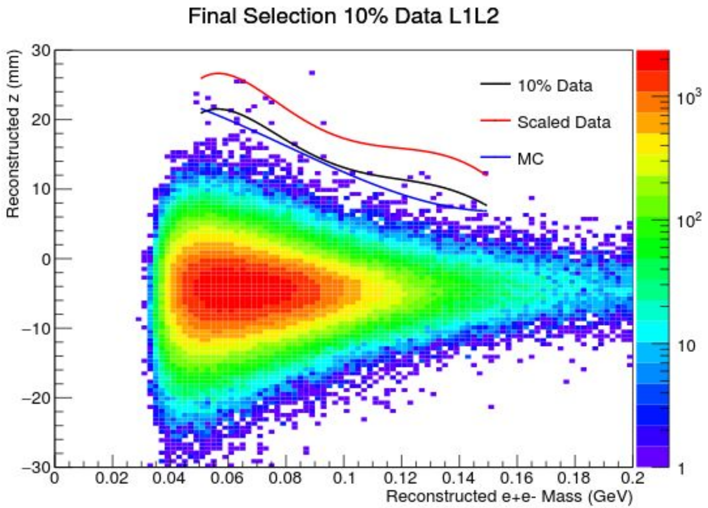
# ZCut

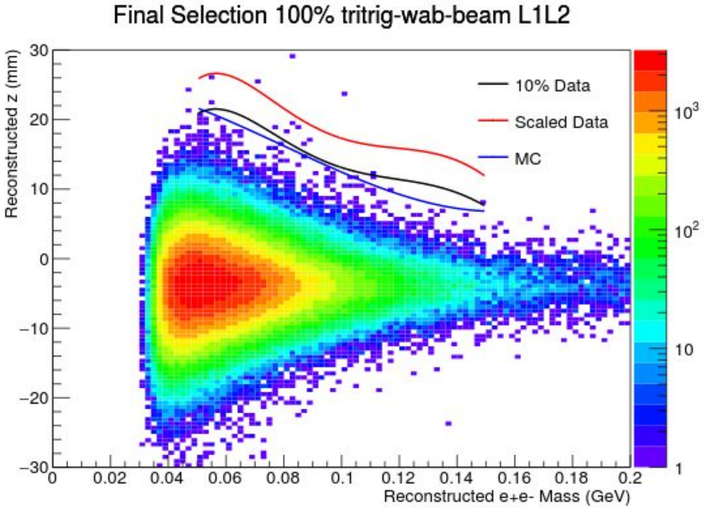
Zcuts overlaid on final selections in data and MC for L1L1 and L1L2 categories

The actual zcuts used are done in an unbiased way using the mass sidebands









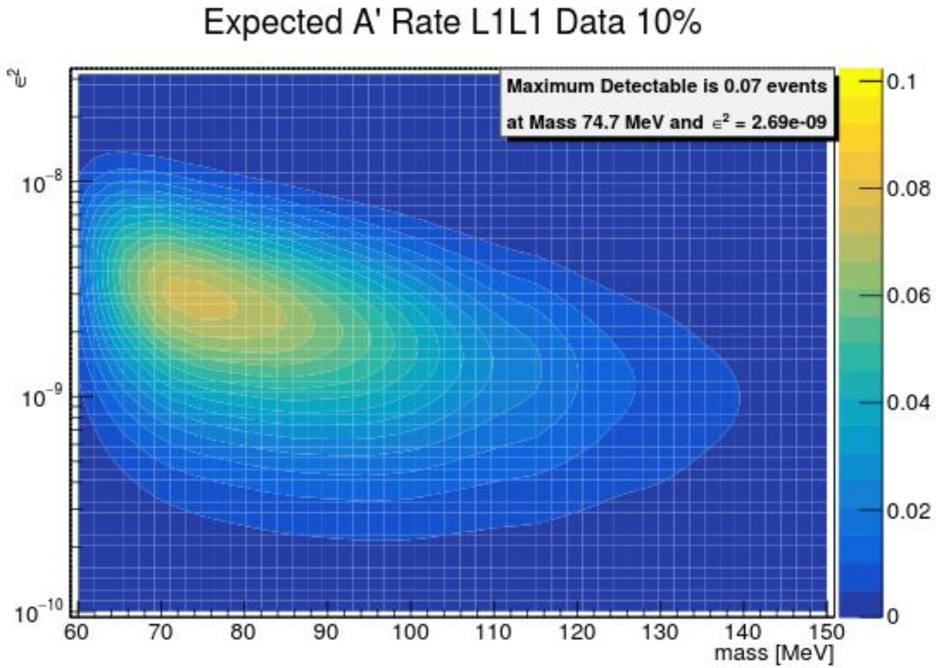
# Computing Expected Signal Rate

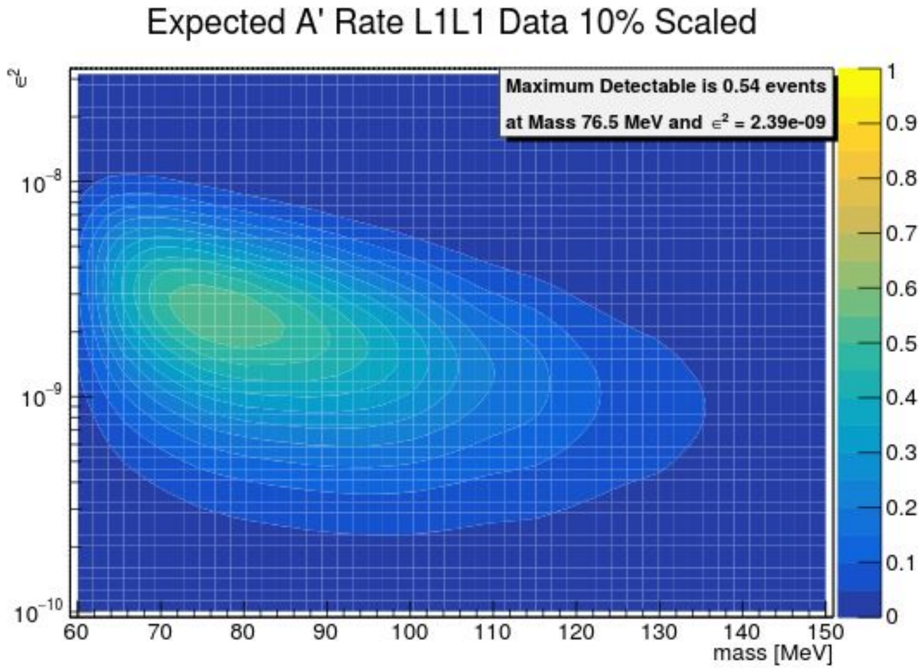
- Number of A's produced in prompt acceptance: $S_{bin}(m_{A'}, \epsilon)$
- Truth signal distribution: $S_{truth}(z, m_{A'}, \epsilon) = \frac{e^{-(z_{targ}-z)/c\tau}}{\gamma c\tau}$
  - Normalized such that $\int_{z_{targ}}^{\infty} S_{truth}(z, m_{A'}, \epsilon) dz = 1$
- Efficiency normalized to 1 at target: $\epsilon_{vtx,sum}(z_{targ}, m_{A'}) = 1$
- Efficiency from layer i and layer j requirements, further cuts, and hit efficiency effects: $\epsilon_{vtx,LiLj}(z, m_{A'})$
- Total acceptance x efficiency: $\epsilon_{vtx,sum}(z, m_{A'})\ \epsilon_{vtx,LiLj}(z, m_{A'})$
- Total expected rate in LiLj category:

$$S_{bin,zCut,LiLj}(m_{A'}, \epsilon) = S_{bin}(m_{A'}, \epsilon) \int_{z_{targ}}^{z_{max}} S_{truth}(z, m_{A'}, \epsilon) \epsilon_{vtx,sum}(z, m_{A'})\ \epsilon_{vtx,LiLj}(z, m_{A'}) dz$$

# Expected Signal Rate L1L1

- Total expected signal in the L1L1 category for 10% data (left) and scaled (right)
- “Scaled” takes into account both increased e+e- pairs and increased zcut

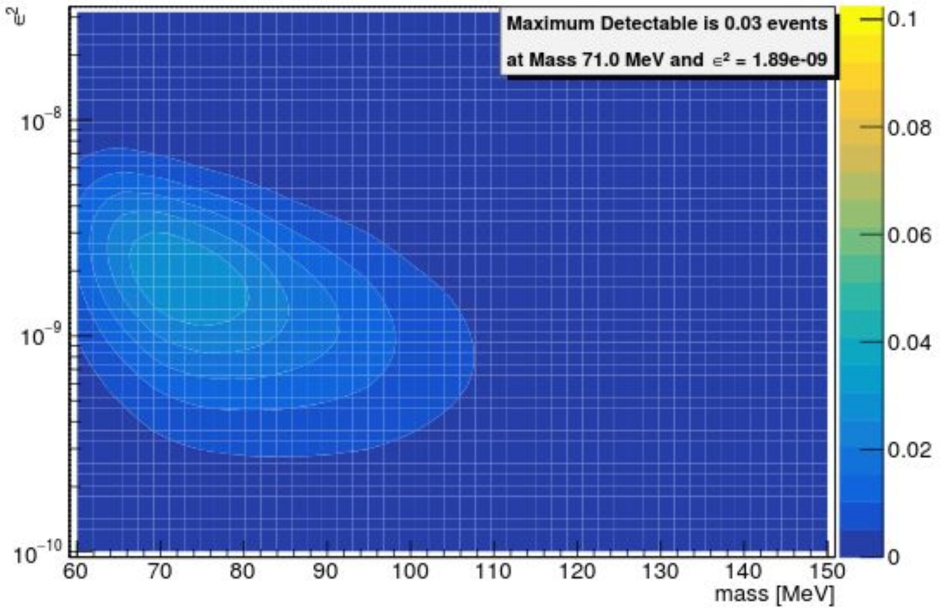

Expected A' Rate L1L1 Data 10%


Expected A' Rate L1L1 Data 10% Scaled

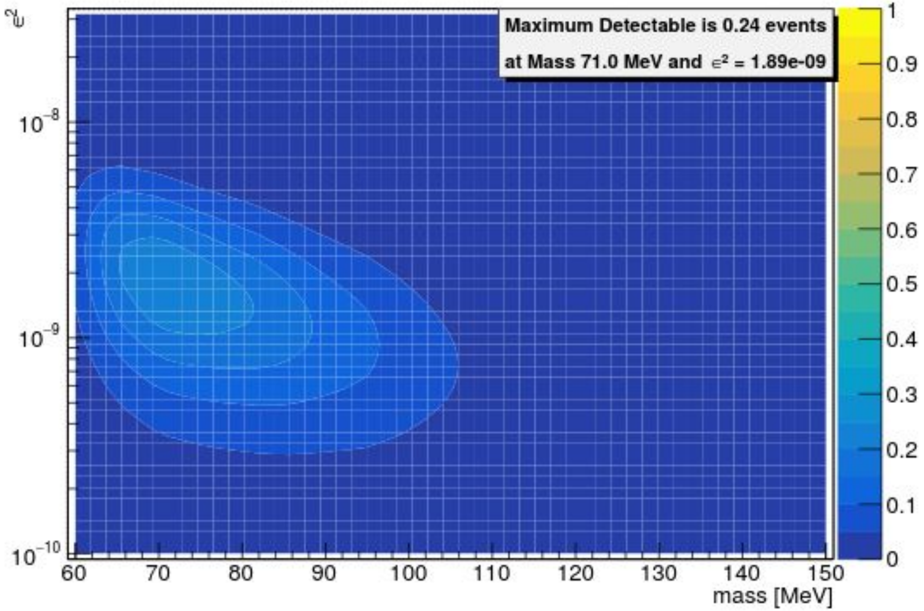
# Expected Signal Rate L1L2

- Total expected signal in the L1L2 category for 10% data (left) and scaled (right)
- The L1L2 category adds ~30-40% in signal expectation

Expected A' Rate L1L2 Data 10%

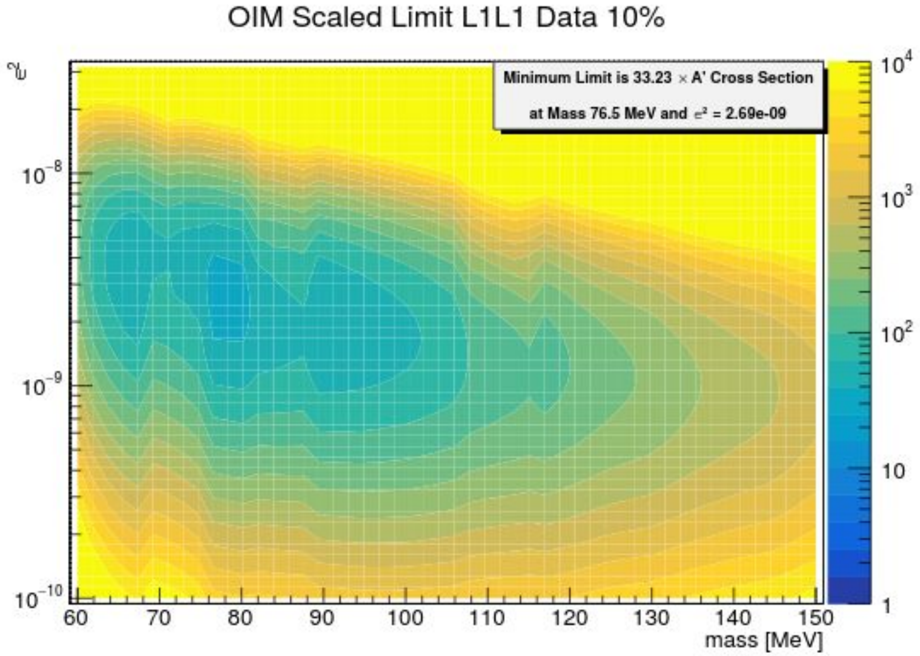


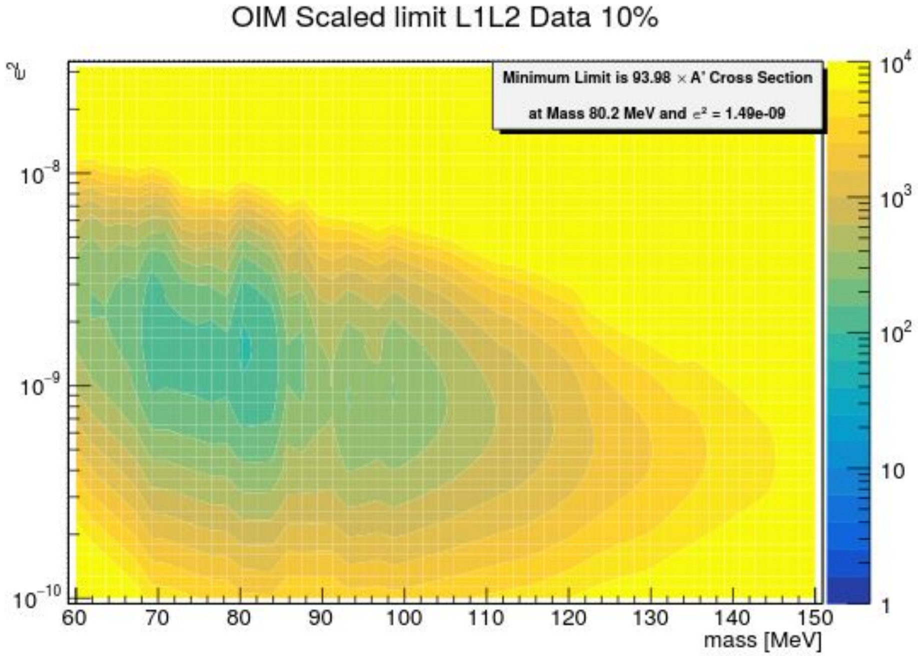
Expected A' Rate L1L2 Data 10% Scaled



# Setting Limits

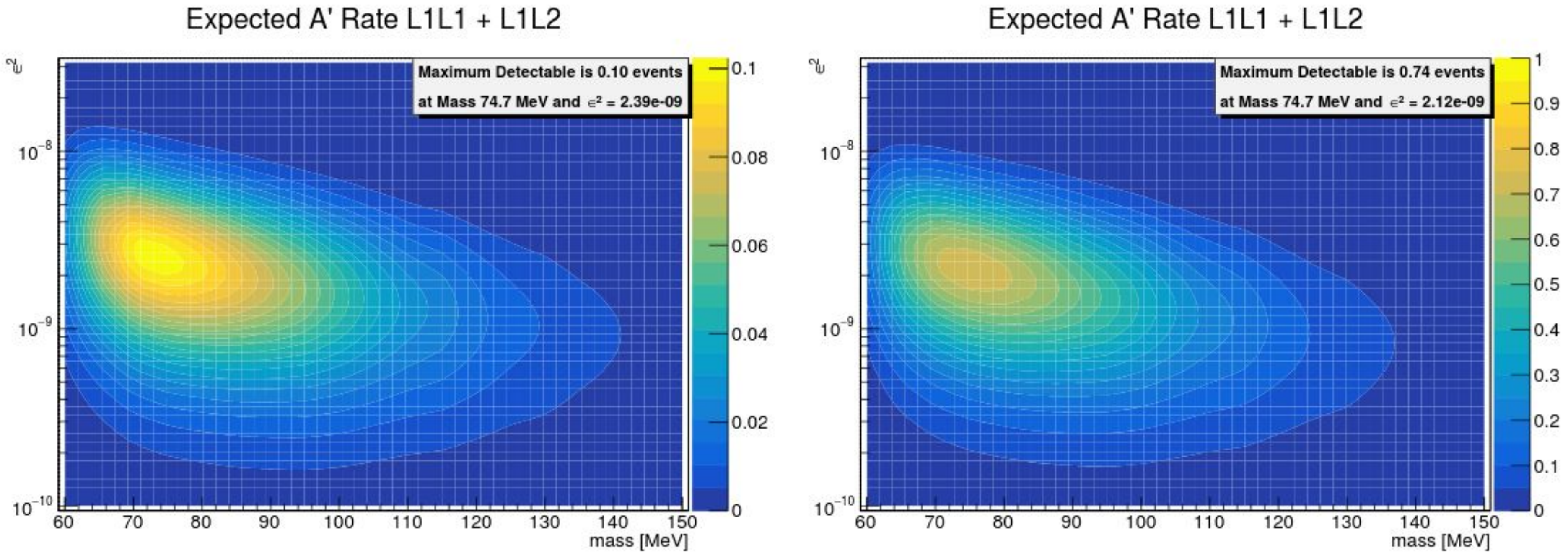
- The Optimum Interval Method (OIM) is used to set a limit
    - With only 10% of 2016 data, we already show a better limit than 2015 full data
- Also working on a method of cut-and-count significance (not ready to show yet)


OIM Scaled Limit L1L1 Data 10%


OIM Scaled limit L1L2 Data 10%

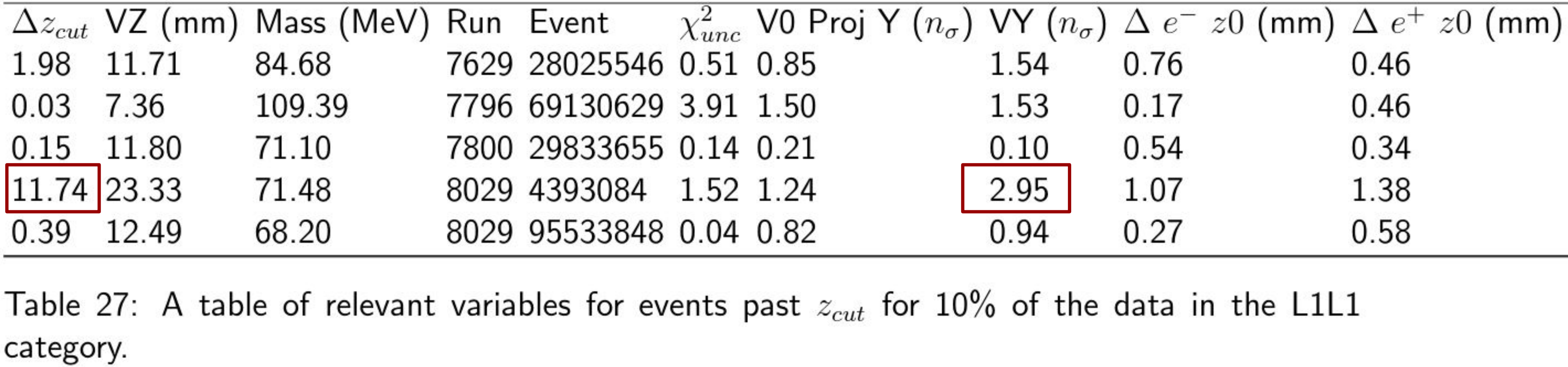
# Combining L1L1 and L1L2

- Combining L1L1 and L1L2 datasets
    - Expected signal rate can be added trivially
    - Combining limits is still being explored



# High Z Events

- Understanding high z events (i.e. those that are significantly past zcut) in both data and MC are important to learn from this analysis
- The strategy is to use all of our tools - look at reconstructed distributions, truth distributions, truth scattering angles (these are correlated), and event displays



| $\Delta z_{cut}$ | VZ (mm) | Mass (MeV) | Run | Event | $\chi^2_{unc}$ | V0 Proj Y ($n_\sigma$) | VY ($n_\sigma$) | $\Delta$ $e^-$ $z0$ (mm) | $\Delta$ $e^+$ $z0$ (mm) |
|---|---|---|---|---|---|---|---|---|---|
| 1.98 | 11.71 | 84.68 | 7629 | 28025546 | 0.51 | 0.85 | 1.54 | 0.76 | 0.46 |
| 0.03 | 7.36 | 109.39 | 7796 | 69130629 | 3.91 | 1.50 | 1.53 | 0.17 | 0.46 |
| 0.15 | 11.80 | 71.10 | 7800 | 29833655 | 0.14 | 0.21 | 0.10 | 0.54 | 0.34 |
| 11.74 | 23.33 | 71.48 | 8029 | 4393084 | 1.52 | 1.24 | 2.95 | 1.07 | 1.38 |
| 0.39 | 12.49 | 68.20 | 8029 | 95533848 | 0.04 | 0.82 | 0.94 | 0.27 | 0.58 |

Table 27: A table of relevant variables for events past $z_{cut}$ for 10% of the data in the L1L1 category.

*This table uses an older zcut, but it still illustrates interesting features of high z events

# Systematics

- Possible sources of systematics include
    - Mass resolution - comparing the amount of signal leaking in/out of a mass bin
    - Radiative fraction and e+e- composition - method can be shared with bump hunt
    - Target position at +/- 0.5 mm - comparing the truth distributions for different target positions
    - Analysis cuts - IP cut, isolation cut, and V0 projection to target
    - Fit to the background distribution and zcut - estimated to be very small
    - A' efficiency curves - both the interpolation method and the fit used for normalization

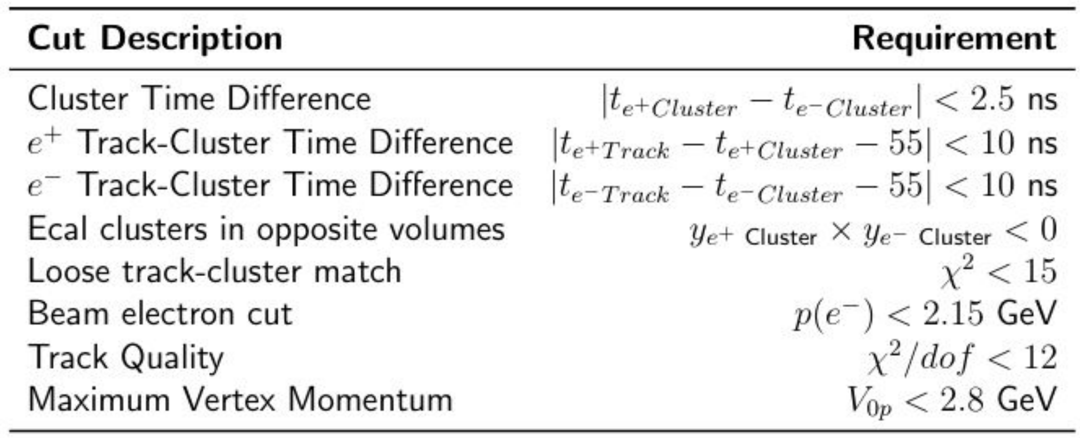
# Future of Displaced Vertexing Analysis

- Require e+e- to both miss layer 1 (L2L2 category) in 2016 Data
    - I will do the same method as L1L1 and L1L2 - apply tight cuts, compute zcut and expected signal yield, compute limit, and explore high z events (L1 trident production?)
    - This will not be a part of the standard analysis. Preliminary estimates show that is will add ~15% to the analysis. It will be in my thesis and important for future analysis
- SIMPs in 2016 Data (see Stany’s talk) or Generalized Displaced Vertices
    - A similar method to the “standard” analysis can be performed
    - The key difference is lower V0p (below the radiative cut) due to the missing energy of the dark pion (mutually exclusive with A’ analysis)
    - Added difficulties: model is 6 parameters and increased high z backgrounds at low V0p
- 2019 Displaced Vertexing Analysis (see Cameron’s projections)

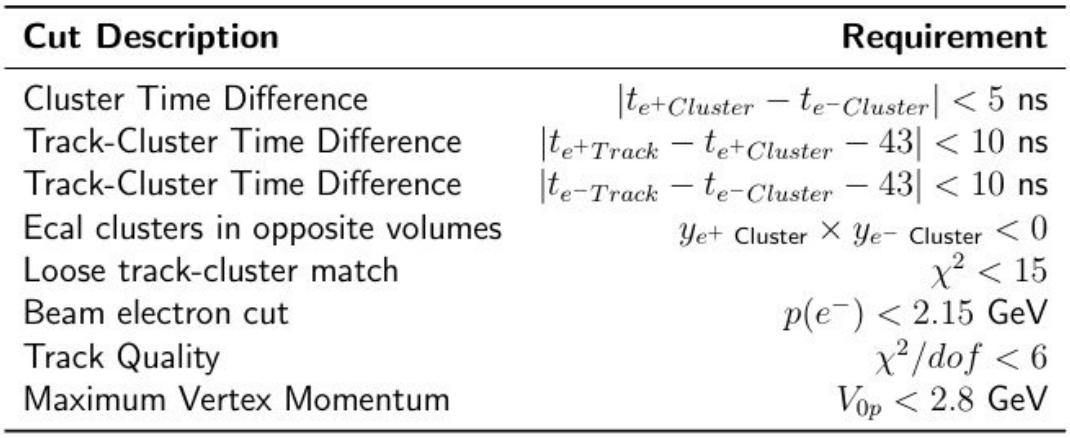
# Conclusion

- 2016 Displaced Vertex Search is showing significant progress
  - L1L1 is almost ready to unblind, I am still working with the analysis committee to finalize the last details of the analysis. Expect these results soon
  - L1L2 needs some more work to understand backgrounds - incorporate hit inefficiencies in MC indirectly
  - We are on pace to be ready to complete the analysis (and graduate!) by the July/August time frame
- Results on 10% of the data for L1L1 is nearly complete and presented here
  - These results are already comparable to the full dataset of 2015 in both signal expectation and exclusion

# MOUSE Cuts



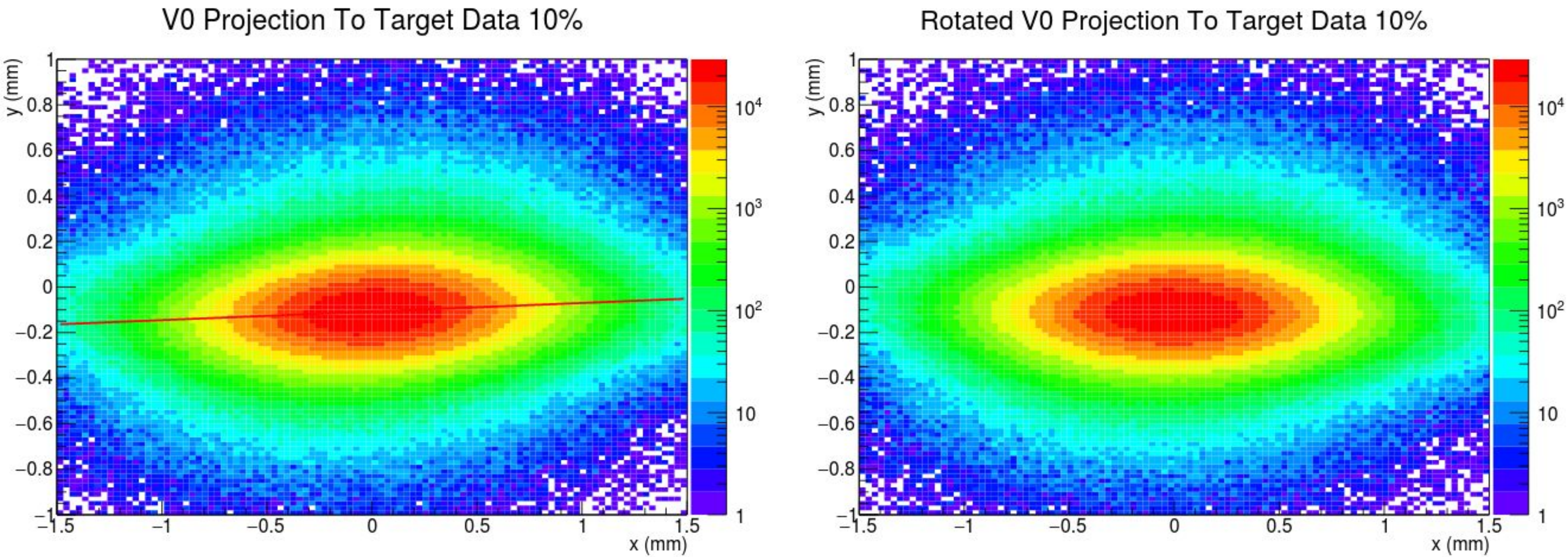
| **Cut Description** | **Requirement** |
|---|---|
| Cluster Time Difference | $\lvert t_{e^+Cluster} - t_{e^-Cluster}\rvert < 2.5$ ns |
| $e^+$ Track-Cluster Time Difference | $\lvert t_{e^+Track} - t_{e^+Cluster} - 55\rvert < 10$ ns |
| $e^-$ Track-Cluster Time Difference | $\lvert t_{e^-Track} - t_{e^-Cluster} - 55\rvert < 10$ ns |
| Ecal clusters in opposite volumes | $y_{e^+\text{ Cluster}} \times y_{e^-\text{ Cluster}} < 0$ |
| Loose track-cluster match | $\chi^2 < 15$ |
| Beam electron cut | $p(e^-) < 2.15$ GeV |
| Track Quality | $\chi^2/dof < 12$ |
| Maximum Vertex Momentum | $V_{0p} < 2.8$ GeV |



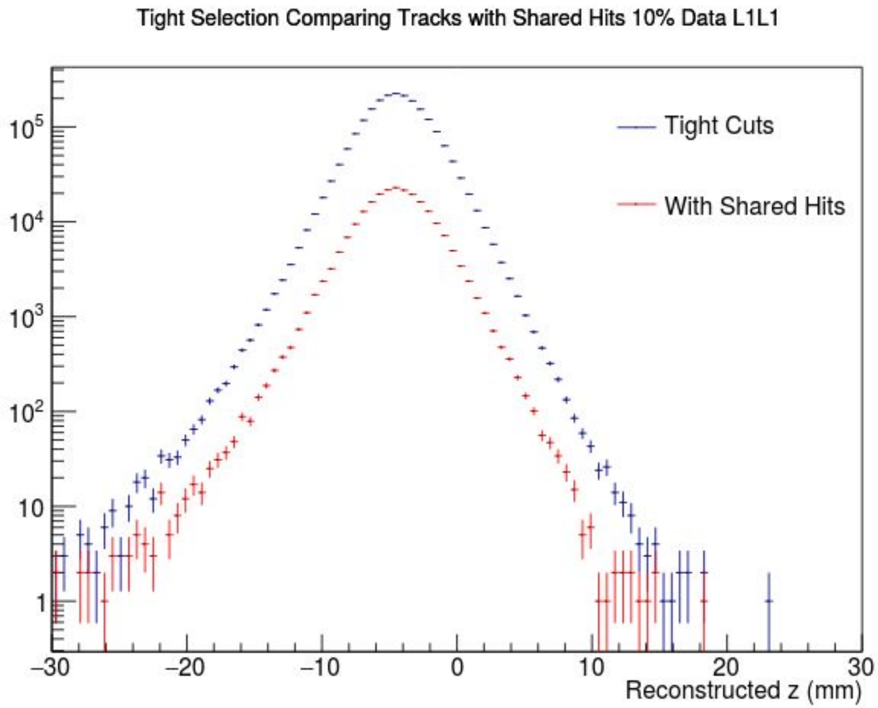
| **Cut Description** | **Requirement** |
|---|---|
| Cluster Time Difference | $\lvert t_{e^+Cluster} - t_{e^-Cluster}\rvert < 5$ ns |
| Track-Cluster Time Difference | $\lvert t_{e^+Track} - t_{e^+Cluster} - 43\rvert < 10$ ns |
| Track-Cluster Time Difference | $\lvert t_{e^-Track} - t_{e^-Cluster} - 43\rvert < 10$ ns |
| Ecal clusters in opposite volumes | $y_{e^+\text{ Cluster}} \times y_{e^-\text{ Cluster}} < 0$ |
| Loose track-cluster match | $\chi^2 < 15$ |
| Beam electron cut | $p(e^-) < 2.15$ GeV |
| Track Quality | $\chi^2/dof < 6$ |
| Maximum Vertex Momentum | $V_{0p} < 2.8$ GeV |

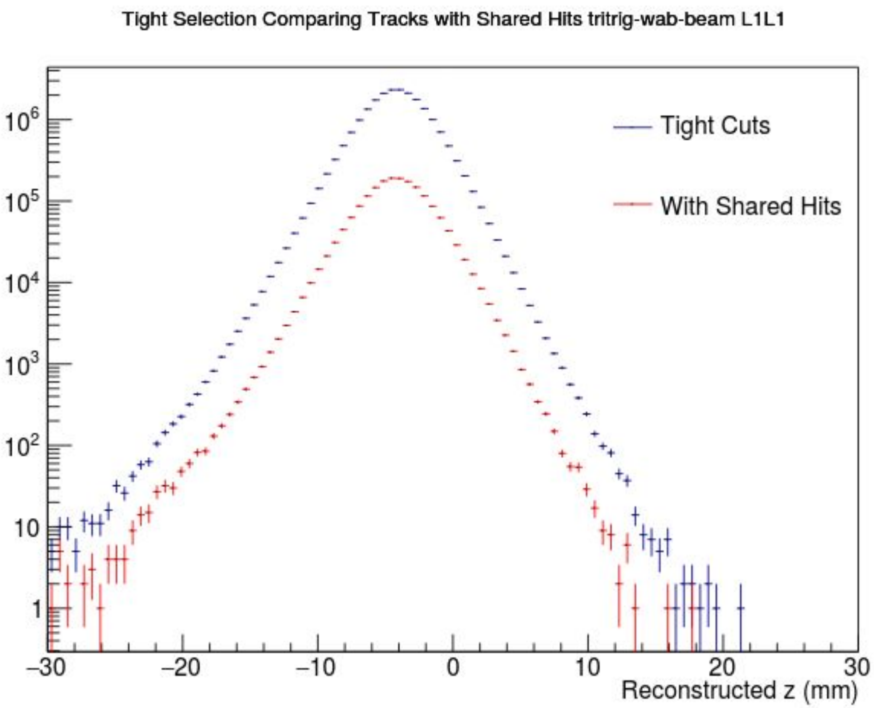
# V0 Projection to the Target

- There is an x-y correlation in both data (~2.2 degrees) and MC (~6.4 degrees)
- Coordinates are rotated in order to remove this correlation

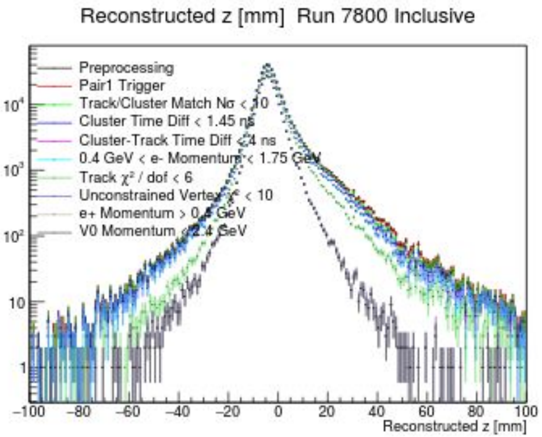


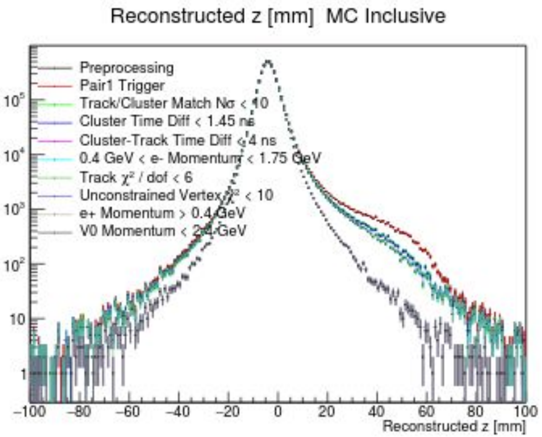
# Duplicates Tracks and V0s

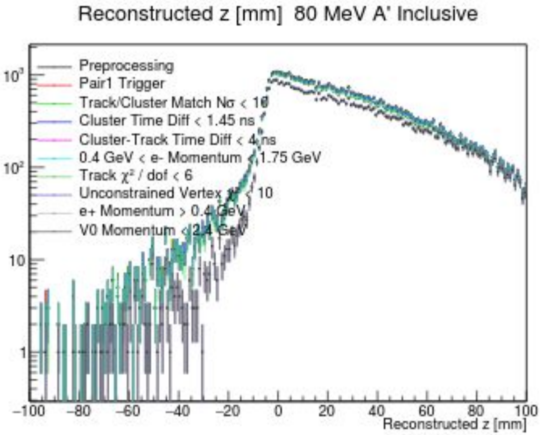


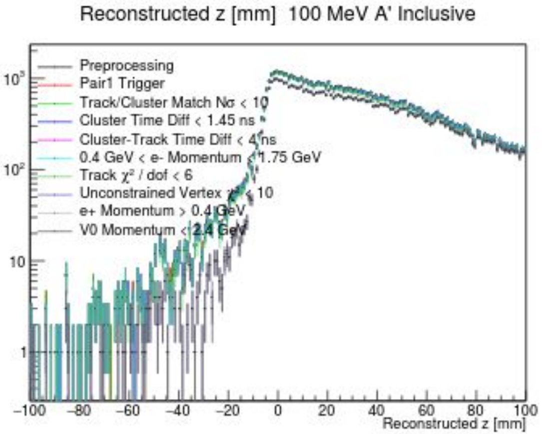


# Preselection Cut Flow

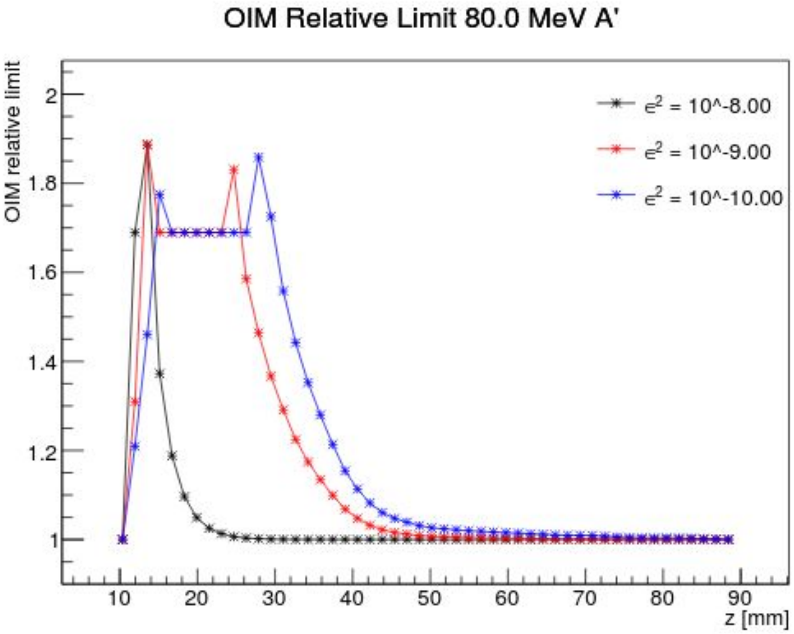


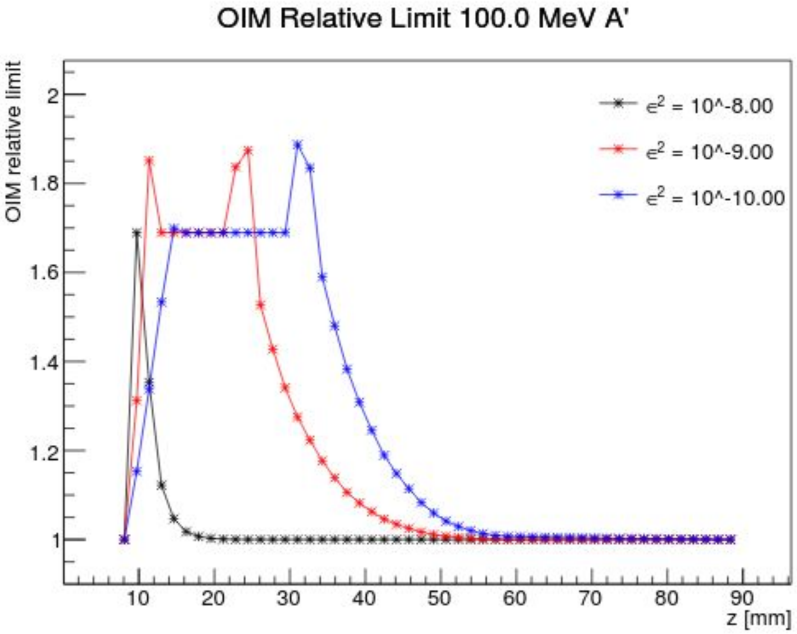






# Optimum Interval Method Dummy Event


OIM Relative Limit 80.0 MeV A'


OIM Relative Limit 100.0 MeV A'