iDM Readout-Level Acceptance

Tom Eichlersmith

he/him/his

University of Minnesota

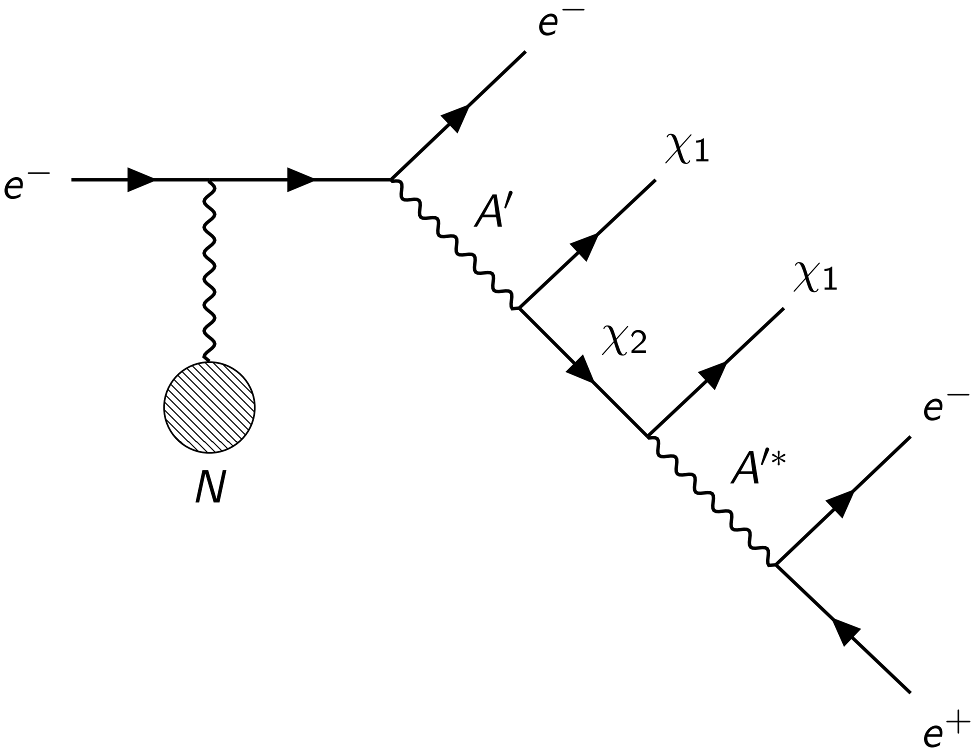
eichl008@umn.edu

September 12, 2023

Status

Signal Sample Generation

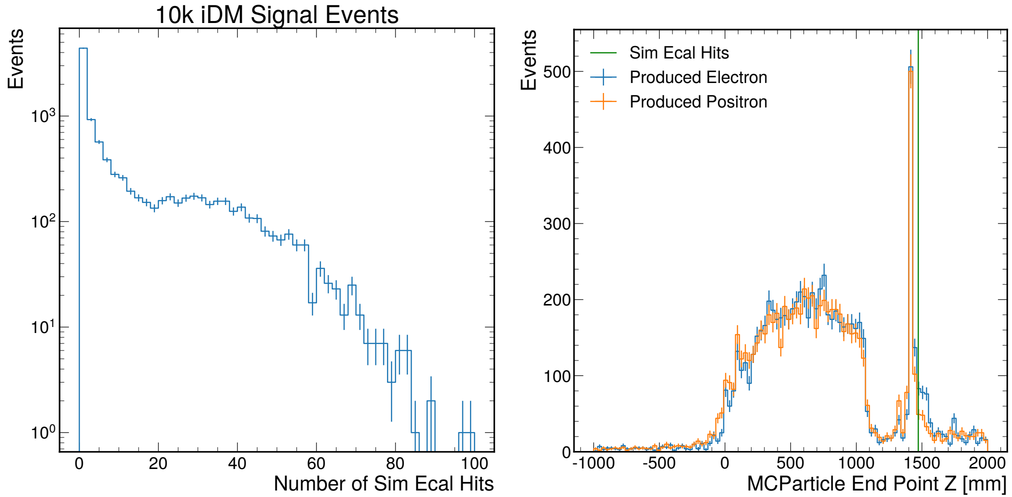
- Have MadGraph model that calculates this diagram.
- Model now integrated into and being run from hps-mc
- Events displaced randomly and simulated
- Readout and reconstructed with standard 2016 steering files

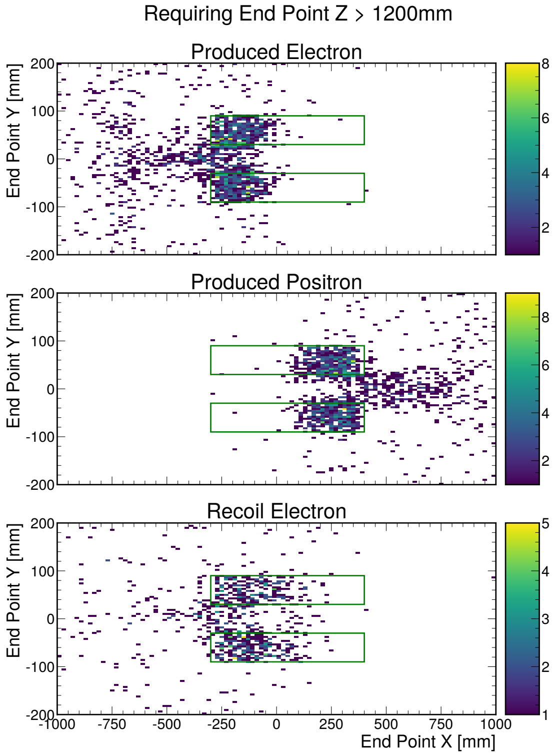


Woes Continue

The number of events being output by the full chain is $\sim$ 10 out of the input 10k.

This can be understood by looking at the truth-level information.

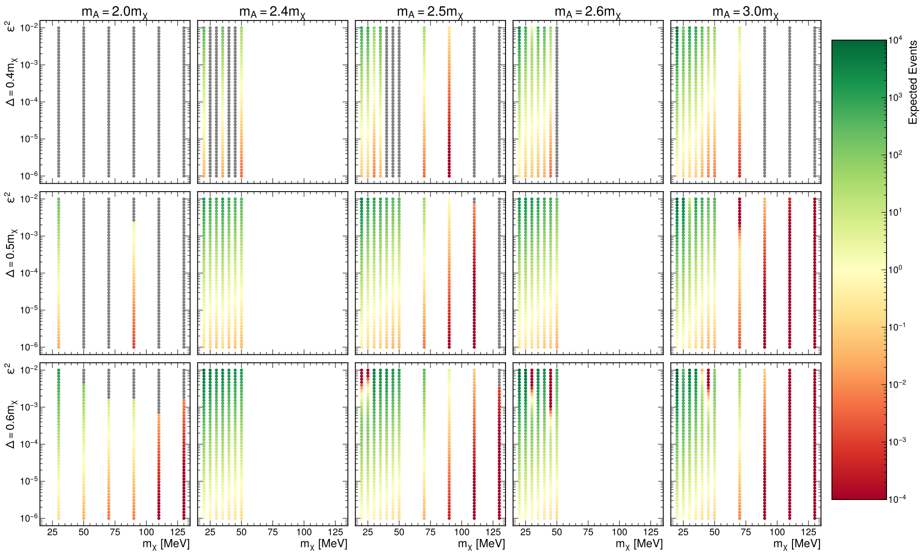




Same Side Vertex

What if we look at same-side vertices?

i.e. a vertex where both the e^- and e^+ are in the same half. Also called "conversion" vertices since they are also formed when a photon converts to e^+e^- in a detector layer.

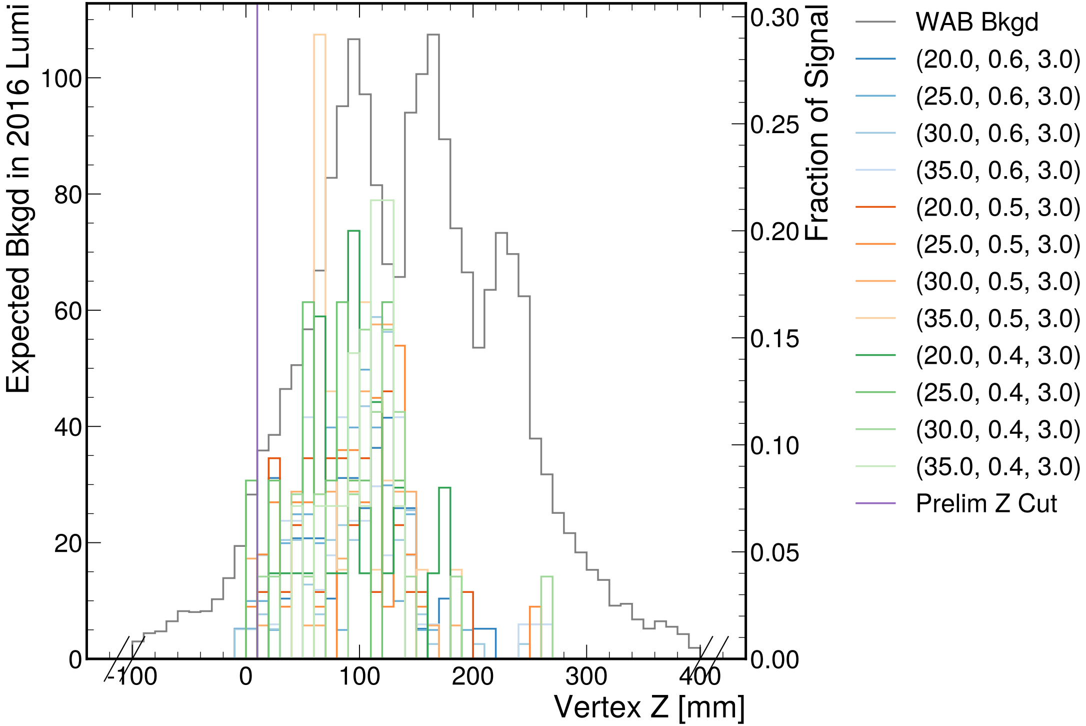


- Require existence of same-side vertex and an electron track in the other half.
- Using a flat **10mm** z cut for this reach

Displacement Difficulties (again)

Caused by Conversion

While the same-side vertices *do* pick out the displaced vertex for signal better, they *do not* reject a reasonable amount of WAB background.



Example Background-Reducing Cuts

There are several different variables that have been suggested as useful tools for reducing this background distribution.

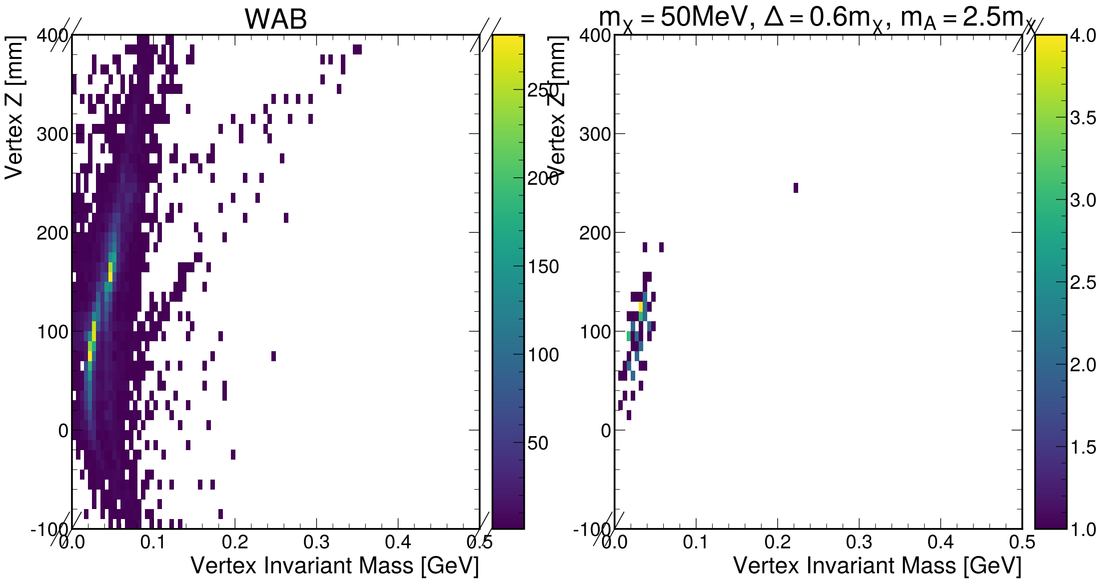
- Invariant mass
- Opening angle (total and delta-tan-lambda)
- y_0 of the vertex
- Momentum magnitude sum (shows separation but unsure if physical)

Currently, these plots are strongly limited by the sample size of the signal distributions. I chose one of the signal points which shows O(1k) expected events (near maximum).

Caveat

The number of expected events is higher than the number of events actually in the sample. This is generally worrisome and could producing a “vanishing” of acceptance while implementing background cuts. Currently at ≈ 0.0001 selection efficiency.

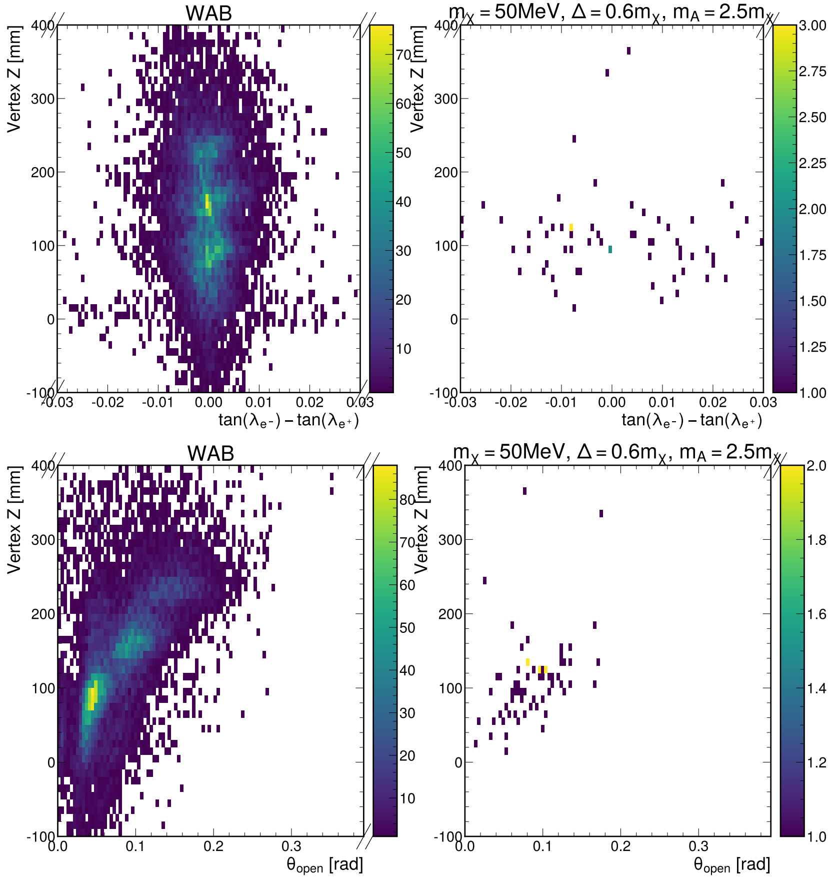
Invariant Mass



Not seeing statistically-significant separation between the two distributions.

Invariant mass of the vertex as calculated during reconstruction.

Opening Angle

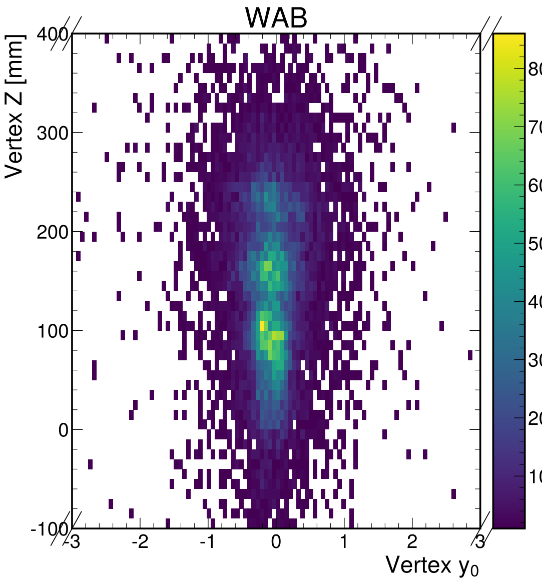


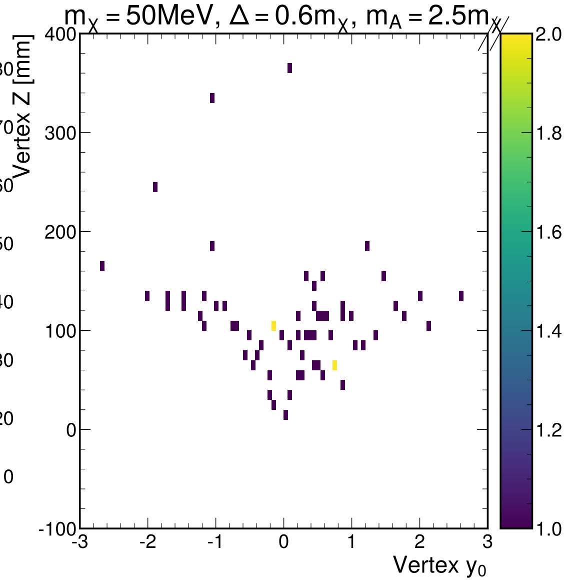
Top: Track $\Delta \tan(\lambda)$

Bottom: Angle Between Reconstructed Momentum Vectors

Both Calculations Show Lack of Separation

Vertex Pointing At Origin





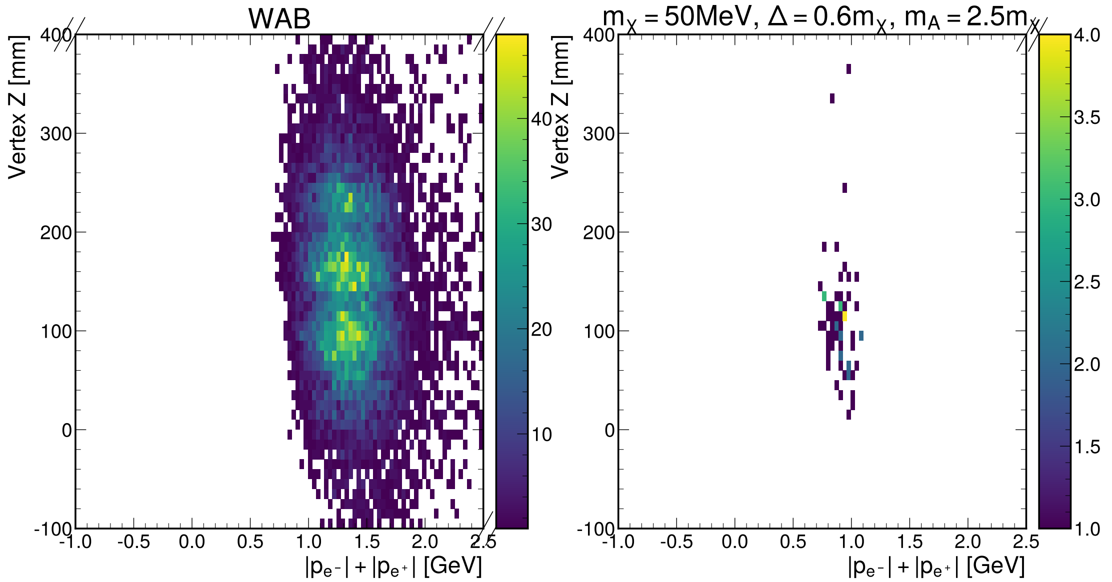
Not seeing statistically-significant separation between the two distributions.

y_0 is the vertical displacement of the vertex at the origin.

$$y_0 = y - \frac{p_y}{|p|} z$$

where position and momentum are *for the vertex*.

Momentum Magnitude Sum



Sum of momentum magnitudes of the two tracks in the conversion vertex.

Saved until last because this distribution shows the most separation.

Caveat

The WAB sample I'm using was designed for the standard, displaced vertex analysis. The drop off near 1GeV could very easily be non-physical.

Summary and Plans

Summary

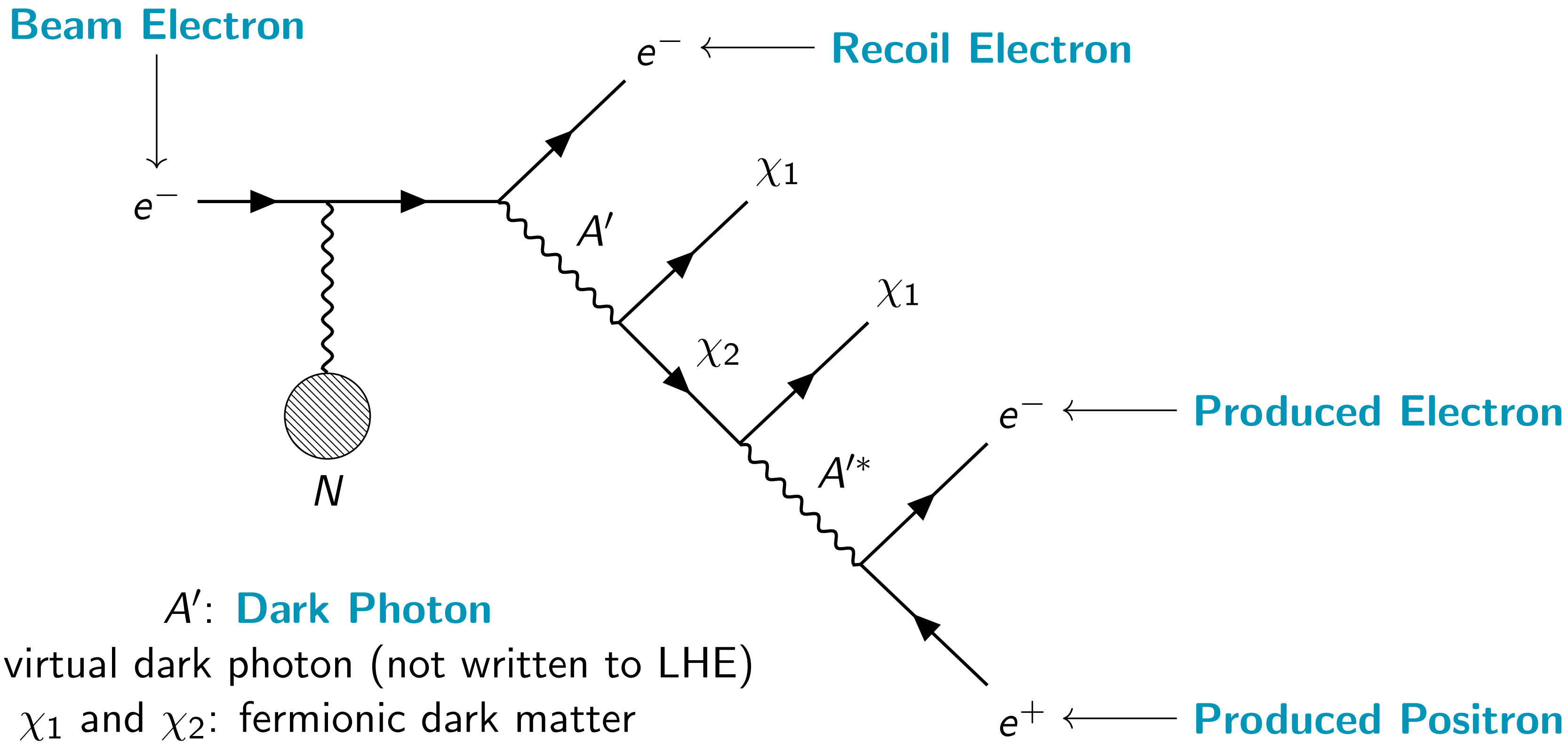
- Moved to used recon-level determination of acceptance to be more realistic
- Observing competition between production rate wanting low m_χ and kinematics wanting high m_χ
- **No "goldilocks" zone is observed for 2016.** The readout efficiency is too poor, the reconstruction does not observe the produced electron, or the production rate is too low compared to the expected background.

Next

- Write these conclusions and steps to reproduce into internal note for future reference
- Do similar analysis over 2019/2021 detector configurations (early study is seeing more than an order-of-magnitude improvement in trigger efficiency)

Questions

Vocabulary



A': **Dark Photon**

A'^* : virtual dark photon (not written to LHE)

χ_1 and χ_2: fermionic dark matter

χ_2 width is what causes the displacement

MG iDM Model History

Mixed-Up Notation $A' \equiv Z' \equiv Z_D$

1. Model provided to me by Stefania Gori – able to generate iDM from pp collisions in that state.
2. Updated the model for eN fixed target by porting over the `frblock` parameters and couplings from the *dark photon MG4 model* in hps-mc.
3. Observed issues with phase space accessibility as the dark photon mass was lowered.
4. Conferred with Tim and Stefania who confirmed this was non-physical behavior and most likely a bug.
5. Removed dark photon – standard nucleus coupling which resolved this phase space issue.[1]
6. Integrated the model into hps-mc to share with collaboration.
7. Update/patch to set $\epsilon = 1$ in the model so it can be included in displacement studying later

[1] I suspect that the way I put in the nucleus-photon interaction caused interference between the dark photon and the standard photon diagrams, leading to a closing of the phase space as the dark photon mass was lowered and began to appear more like a standard photon.

Parameters

Parameter	Block	Default	Description
Mchi	dm	0.1	m_χ Average fermion dark matter mass in GeV
dMchi	dm	0.02	Δ Difference between fermion DM masses in GeV
Map	hidden	1	$m_{A'}$ dark photon mass in GeV
Fixed by HPS Design			
GAN	frblock	~ 0.3	SM photon-nucleon coupling
GZPN	frblock	~ 0.3	Dark photon-nucleon coupling
Anuc	frblock	184	atomic weight of nucleus in amu
Znuc	frblock	74	atomic number of nucleus
Disconnected from Rate in HPS			
MHSinput	hidden	200	dark higgs mass in GeV
epsilon	hidden	0.01	SM-dark photon mixing strength
kap	hidden	10^{-9}	quartic dark higgs interaction strength
aXM1	hidden	127.9	$1/\alpha_D$

Table: Relevant MadGraph/MadEvent parameters available in `param_card.dat`

Parameters

What are some limitations on these parameters?

Kinematic

Avoid kinematic, cosmological limits and/or degeneracy into different model.

$$2m_e < \Delta < \frac{2}{3} m_\chi \qquad m_{A'} > 2m_\chi$$

Lifetime

A DM survey paper ArXiV 1807.01730 Eq (24)

$$\Gamma(\chi_2 \to \chi_1 \ell^+ \ell^-) \propto y \left(\frac{\Delta}{m_1}\right)^5 m_1 \qquad y \equiv \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4$$

Technically, we don't actually use this equation for any calculations since it has pretty strict requirements on the parameters (mainly Δ we wish to avoid). In reality, I use MadGraph/MadEvent to calculate the width of χ_2 and then scale that width linearly with ϵ^2.

iDM Parameter Limitations

- $\Delta > 0$ so χ_1 and χ_2 are actually different mass states
- $\Delta > 2m_e$ so χ_2 will decay to $\chi_1 e^+ e^-$
- $\Delta < m_\chi$ so that the mass of χ_1 is real $m_1 > 0$
- $\Delta < \frac{2}{3} m_\chi$ so $\Delta \lesssim \mathcal{O}(1) m_1$ so "DM freezeout is dominantly controlled by SM fermions"[2]
- $m_{A'} > 2m_\chi$ so a real A' decays to $\chi_2 \chi_1$
- $m_{A'} < E_{\mathrm{beam}}$ so a real A' can be produced
- $m_{A'}/m_\chi$ upper limit is defined by cross section – too high and the cross section is too low for it to be produced within HPS's data set
- $m_\chi > 0$ obviously the dark fermions need to be massive
- $m_\chi < 2m_\mu$ to avoid losing cross section to muon pairs compared to electron pairs

[2] ArXiV 1807.01730 Section III.5

Sample Detail

TriTrig and WAB

Produced by Cam and available at SLAC.
/sdf/group/hps/mc/2pt3GeV/HPS-PhysicsRun2016-Pass2/{tritrig,wab}/ecal_trig_res

Signal

Used ▸ tomeichlersmith/hps-prod container release ▸ 2023-07-10

- $m_{A'} = 3m_\chi$, $\Delta = 0.6m_\chi$, $m_\chi = 30\text{MeV}$ and $m_\chi = 100\text{MeV}$
- Run the `idm` job in `hps-mc` 200 times (iterating the random seed)
  - Note: Only 122 runs of the 100MeV mass point succeeded, the failures were due to slurm evacuating my jobs so a user with higher prio could run.
- Merge resulting reconstructed slcio files into a single file
- Tuplize reconstructed slcio file with ▸ hpstr:ptrless

Opposite-Side Vertex Analysis

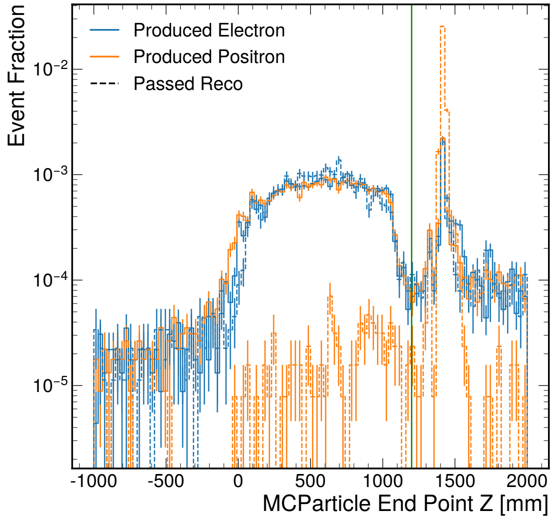
Soldier On

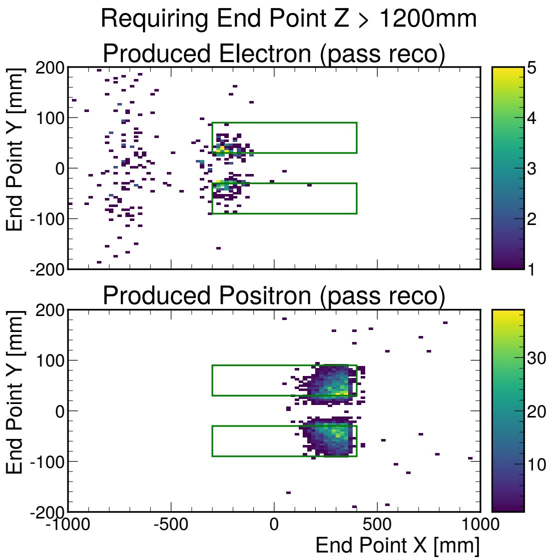
So what if our rate is small, it's still non-zero.

Generate a large (200 run) signal sample with $\Delta = 0.6 m_\chi$, $m_{A'} = 3 m_\chi$, $m_\chi = 30\mathrm{MeV}$

Readout+Reco Selection

The standard steering files appear to be selecting the appropriate events.



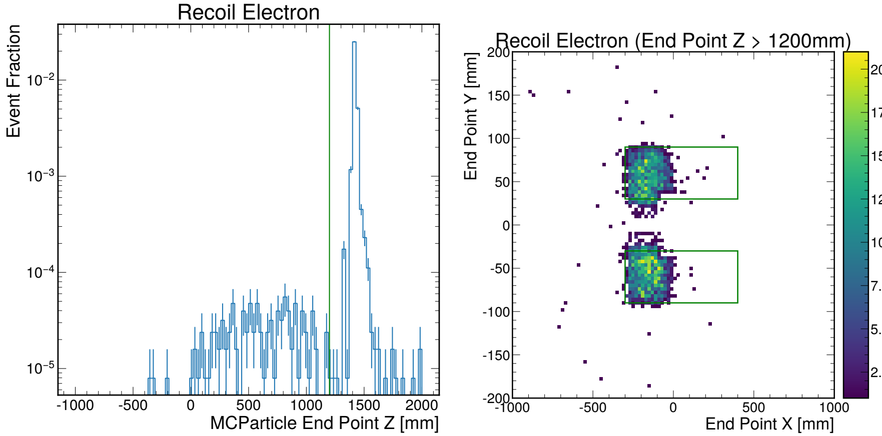


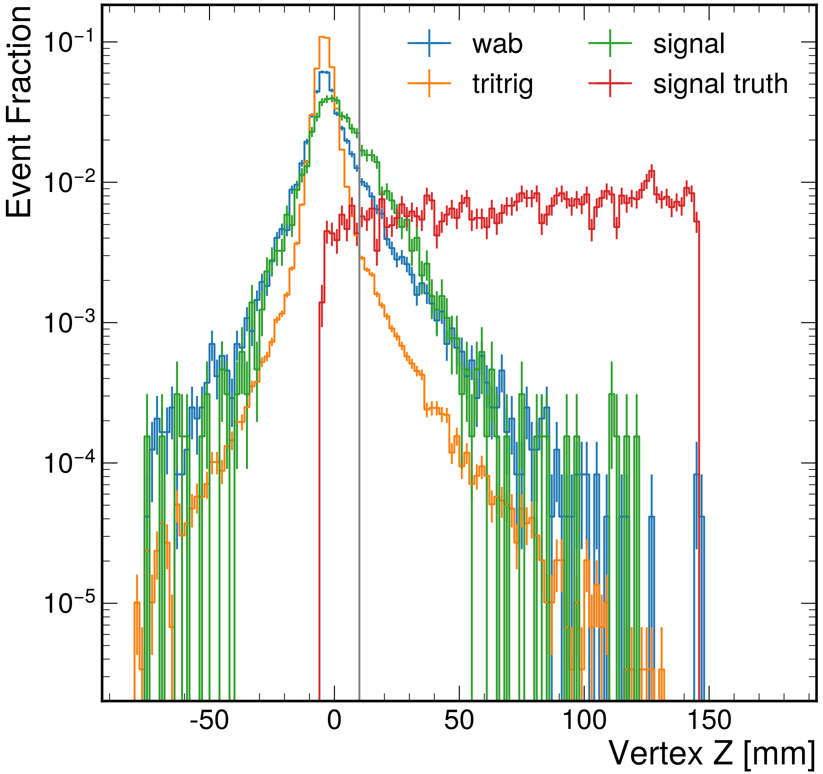
- Events selected have produced positron mostly ending in ECal volume
- Produced electron still smeared pretty widely

Uh Oh

This is a hallmark sign of the detector "choosing" the wrong electron.

Inspect the Recoil



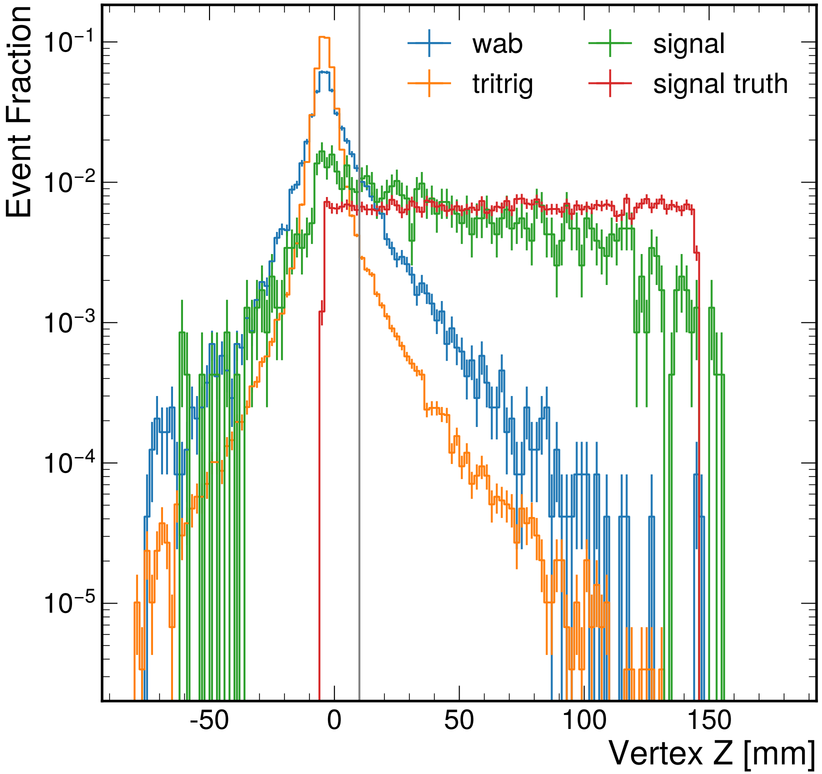


Large Fraction

A majority of the events accepted by the readout+reco chain have the recoil electron be *the* electron in the event.

Raise m_χ to 100MeV

- Increasing m_χ has the kinematic benefit of getting more energy to the produced pair at the downside of production rate loss
- The approximate uniformity of the reconstructed signal (as compared to the signal truth) is encouraging – move forward using this parameter set to study the expected number of events.

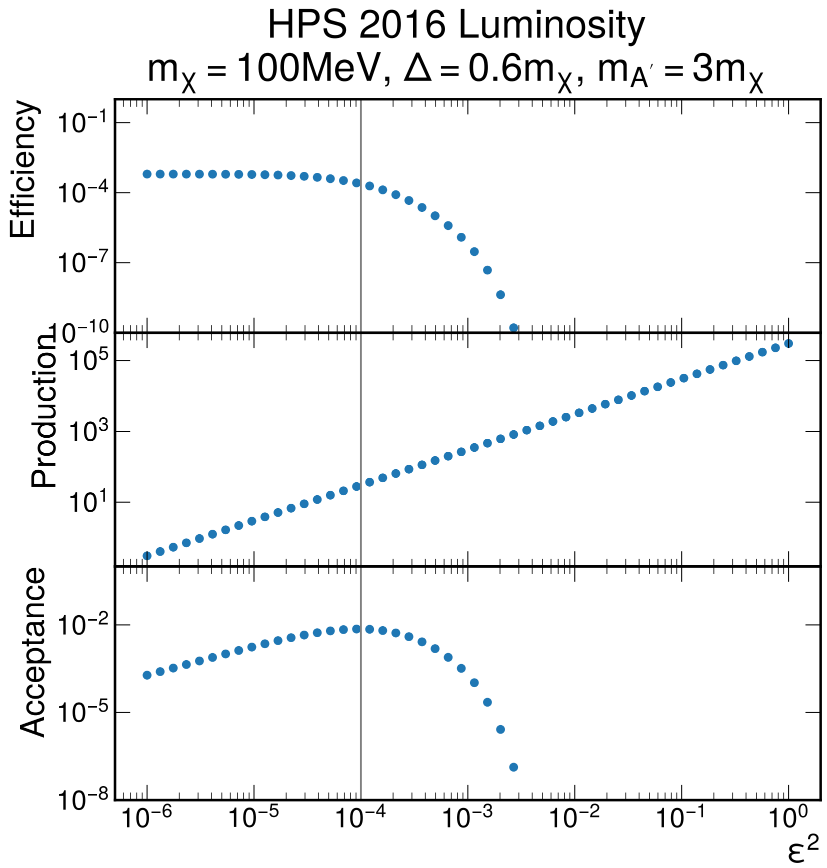


Expected Number of Events

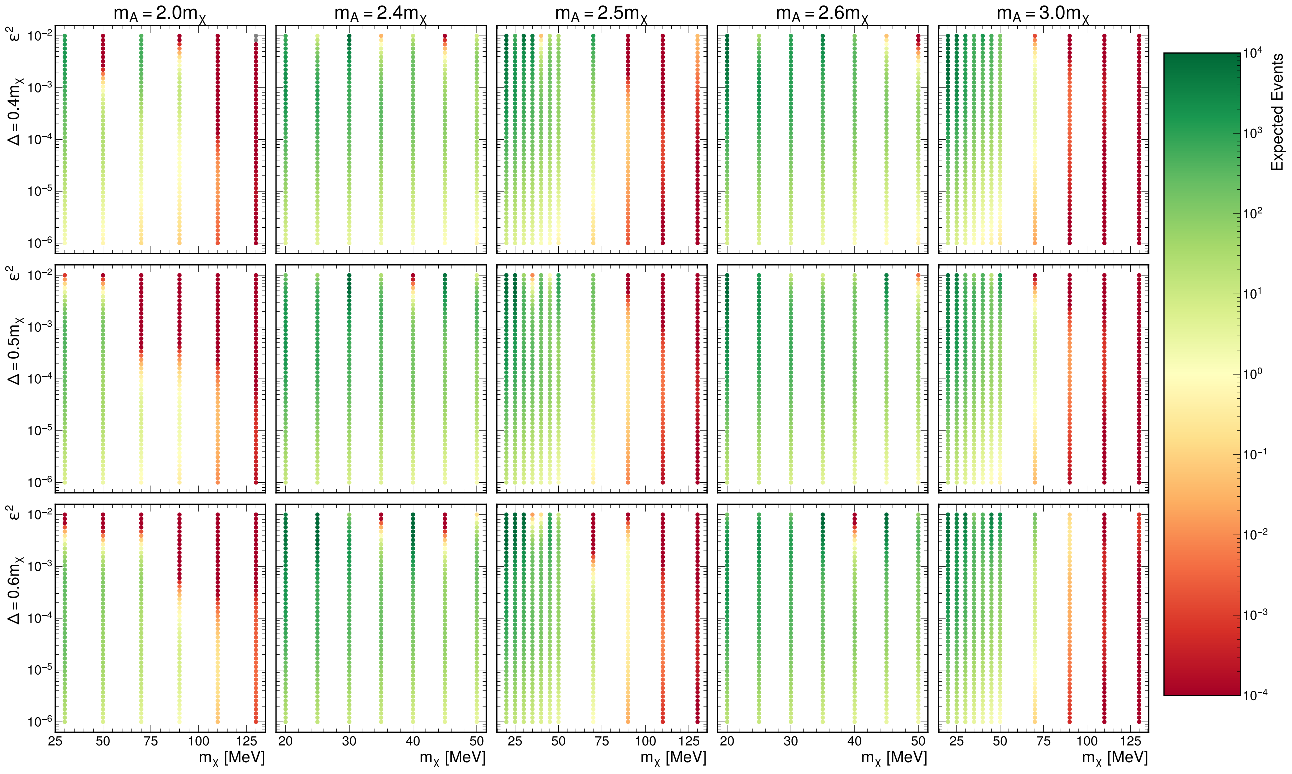
Y Axes

- **Efficiency** – efficiency of entire analysis chain (including z-cut and reweighting for ϵ dependence)
- **Production** – total events produced with HPS 2016 Lumi and beam
- **Acceptance** – product of efficiency and production, estimate of expected events in analysis

See the characteristic “bump”. Yay!



Broaden this Search



- $m_{A'} \in \{2.0, 2.4, 2.5, 2.6, 3.0\} m_\chi$
- $\Delta \in \{0.4, 0.5, 0.6\} m_\chi$
- $m_\chi \in (20, 130)\mathrm{MeV}$
- **fixed z cut at 10mm**

Torn between high-mass helping improve acceptance and low-mass improve production rate.

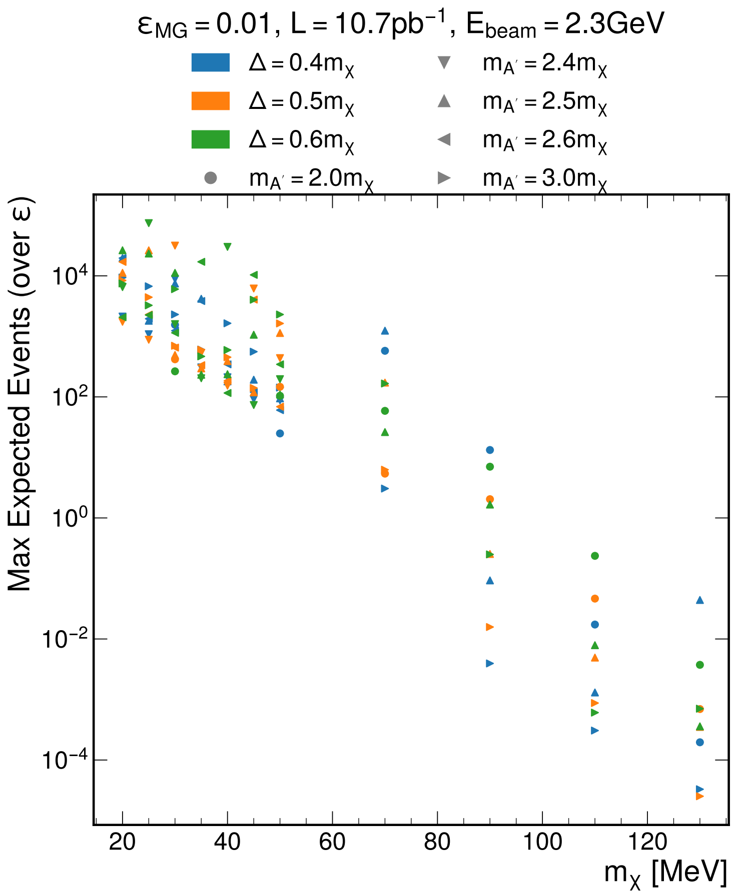
Best We Could Do

Condense this heat-map by getting maximum possible over ϵ.

Qualitative Conclusions

- Low-Mass Production Rate is "winning" the tug-of-war
- Higher mass dominated by decreasing production rate

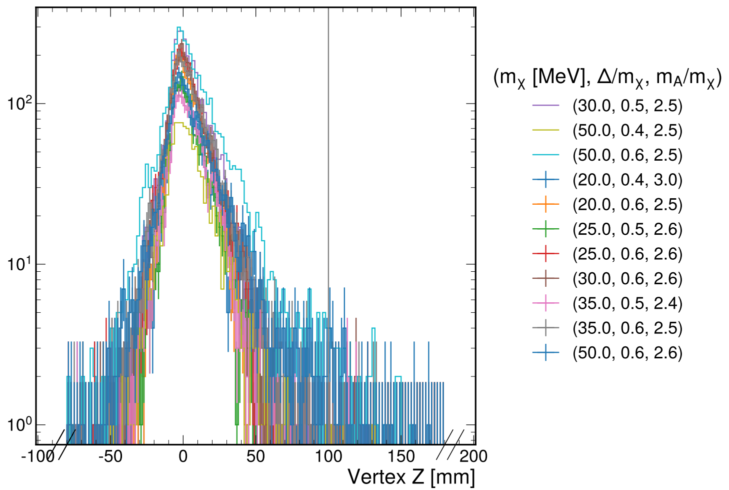
What if we try to look for these few events?

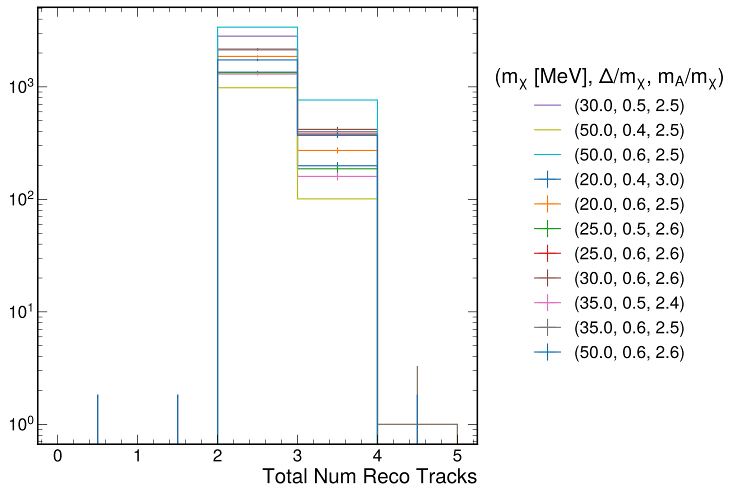


Displacement Difficulties

Appears that these samples simply lucked into higher reach.

Few events at high z. Only $\sim 1/4$ have another reconstructed track.





These are all the samples whose expected number of events have a maximum above one thousand for some choice of ϵ.