# Weekly Update

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July 19, 2017

# Outline

- Some more info on how BdNMC calculates # of signal events
- Reproducing some plots from the paper ("Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP")

# How BdNMC calculates # of signal events

- For each production channel i: $\texttt{signal\_events}[i] = \frac{\texttt{ninteractions}[i]}{\texttt{trials}} \times \texttt{vnumtot} \times \texttt{pmax} \times \textbf{efficiency},$
- **Signal_events : "the total number of signal events that the experiment would observe given some number of protons on target, POT"** [1]
- ninteractions[i] = number of scatterings by DM originating from production channel i
- Sum of ninteractions[i] over all production channels = samplesize
- Pmax is the maximum scattering probability
- Efficiency =detector efficiency
- vnumtot is the total number of DM particles produced
- $\texttt{vnumtot} = \sum_i \texttt{vnum[i]}$ where vnum[i] is the number of dark matter particles produced by each channel [1]
- Vnum is the total number of V mediators produced by POT protons that will decay into dark matter particles [1]
- The terminology is a bit confusing, but basically the POT enters the signal_events equation as

**Vnum= (something) * POT**

[1] From the "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and ShiP" , has the BdNMC appendix

# Cont.

- Eg, for a pseudoscalar meson X (eg pion, eta, etc): [1]

$$\texttt{vnum} = \mathrm{Br}(X \to \chi\bar{\chi}\gamma) \times \mathbf{meson\_per\_pi0} \times \mathbf{pi0\_per\_POT} \times \mathbf{POT}$$

Where $\mathrm{Br}(X \to \chi\bar{\chi}+\gamma)$ has to be numerically integrated for off-shell V production

For vector meson mixing, $\texttt{vnum} = \mathrm{Br}(X \to \chi\bar{\chi}) \times \mathbf{meson\_per\_pi0} \times \mathbf{pi0\_per\_POT} \times \mathbf{POT}$

For p-Bremsstrahlung, the total number of V's produced, $N_V$ is $N_V = \mathbf{POT}\int_0^{\mathbf{ptmax}^2} dp_\perp^2 \int_{\mathbf{zmin}}^{\mathbf{zmax}} dz \frac{d^2 N_V}{dz\,dp_\perp^2}$

[1] From the "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and ShiP" , has the BdNMC appendix

# Reproducing some plots from the paper

- Want to reproduce figure 1.0 of “Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP”:

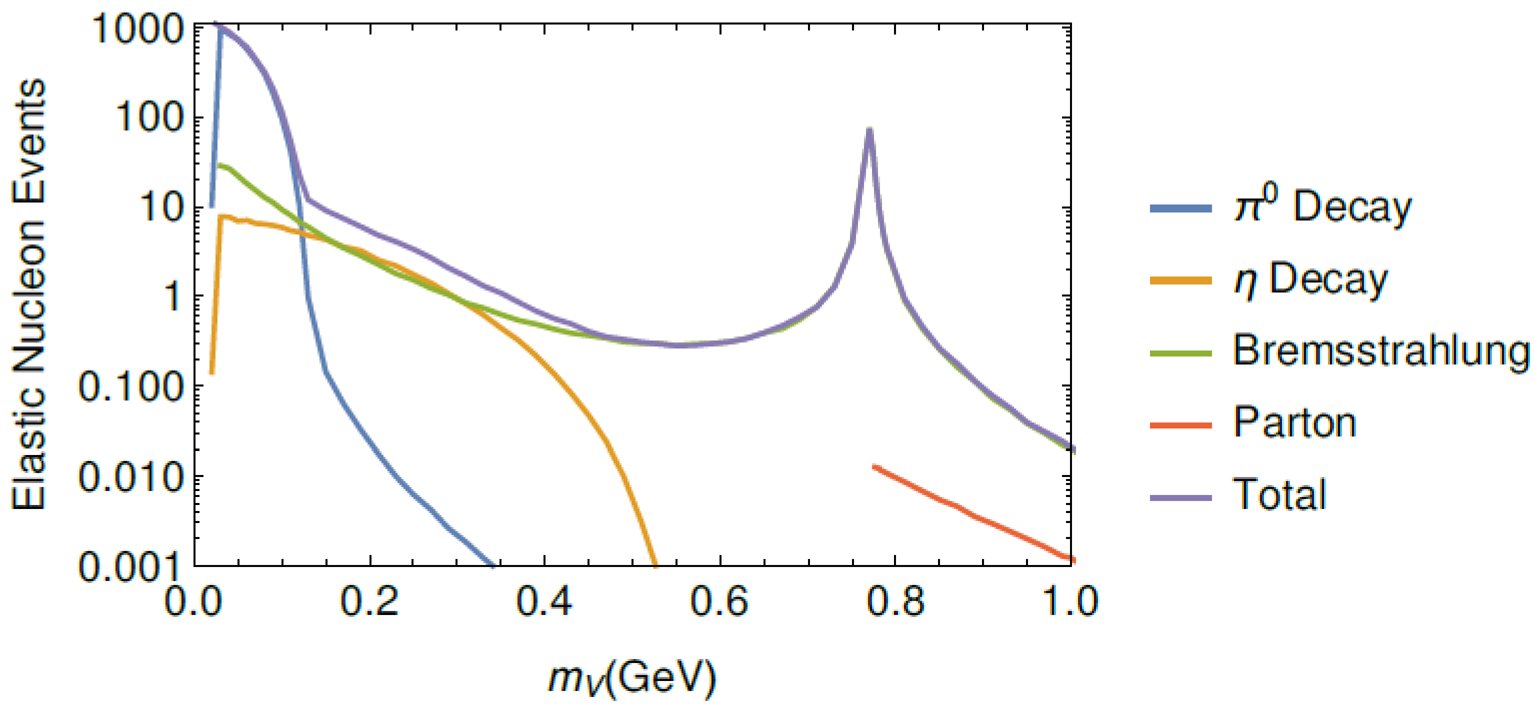



FIG. 1. A plot illustrating the distinct contributions to DM production (coupled through the vector portal), as discussed in the text, using the 9 GeV proton beam at MiniBooNE as an example. The rate of elastic scattering events on nucleons is plotted versus the vector mediator mass. From smaller to larger values of $m_V$, the dominant channels are $\pi^0$ decays, $\eta$ decay, bremsstrahlung, which becomes resonant near the $\rho/\omega$ mass region, and finally direct parton-level production. The plot uses $m_\chi = 0.01$ GeV, $\epsilon = 10^{-3}$ and $\alpha' = 0.1$.

**Reproducing figure 1.0 of “Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP”:**

- I run BdNMC ~20 times for m_V in [0.005, 0.75] for the production channels pi0 decay, eta decay, and proton bremsstrahlung (can't easily do parton production, but it doesn't matter for m_v<~0.75GeV) and signal channel NCE_nucleon.
- Parameters:

$m_\chi = 0.01$ GeV, $\epsilon = 10^{-3}$ and $\alpha' = 0.1$.

- Figure's caption says plot is for 9 GeV beam energy, but it's actually 8.9 GeV, they rounded.
- 2e20 POT
- Efficiency = 0.35
- 0.9 pi0_per_POT (pi0_per_POT is the number of pi0's expected per proton on target)
- Using production distributions pi0_sanfordwang for pi0 decay and k0_sanfordwang for eta decay (Sanford-Wang distributions appropriate for MiniBooNE energies)
- Production distribution proton_brem and ptmax = 0.2 , zmin = 0.3 , zmax = 0.7, which are appropriate for MiniBooNE
- Continued on next slide...

## Reproducing figure 1.0 of “Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP”:

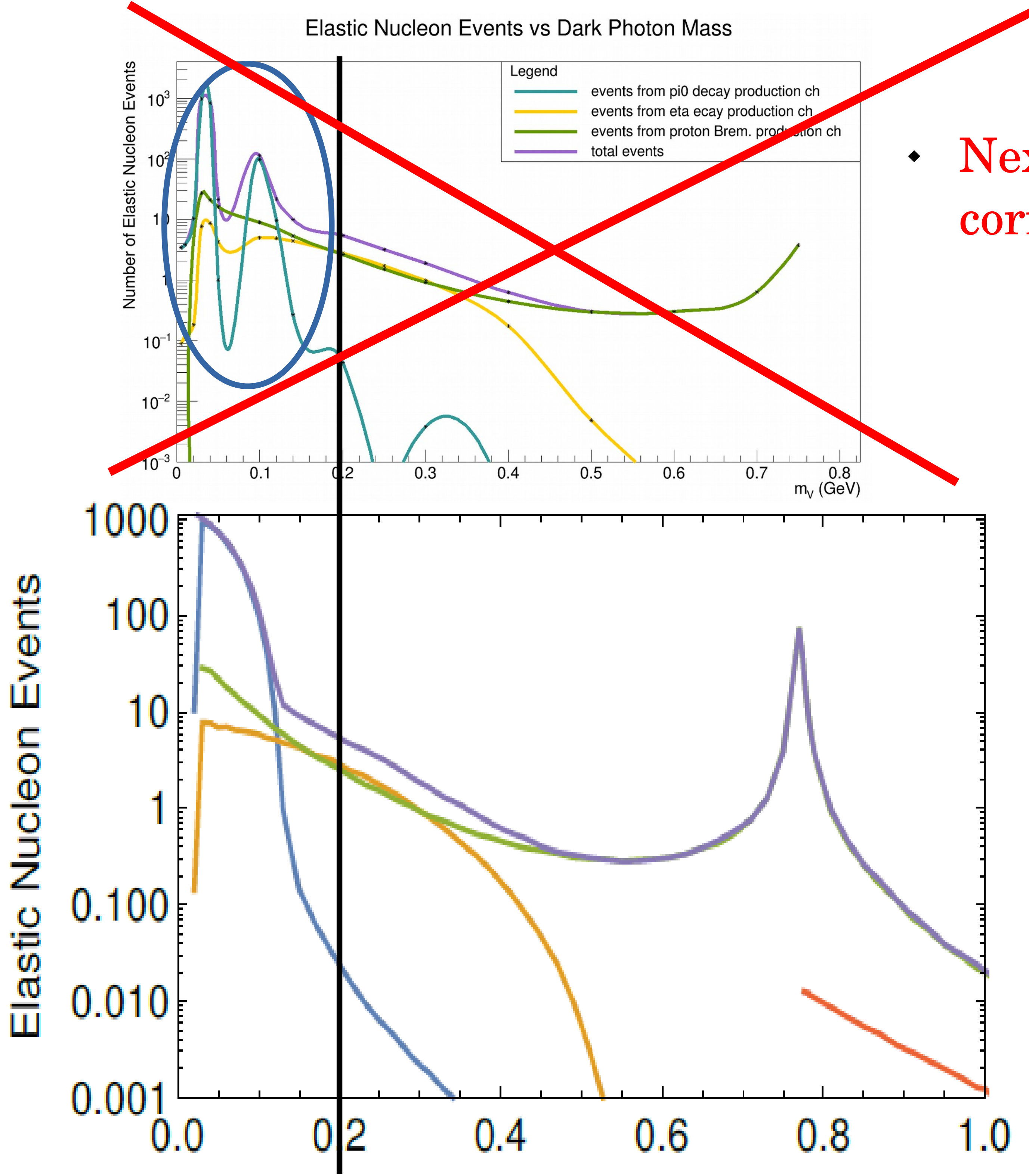
- Cuts on the kinetic energy of outgoing nucleon, default to min=0 and max=1e9 GeV:
- Initially Patrick said he used min=0.35 GeV and max=1 GeV
- Sensitivity section of paper says they use the same cuts (page 10)
- Using these cuts, my plot was off (~100 times fewer events than figure 1.0)
- I saw the paper “Dark Matter Search in a Proton Beam Dump with MiniBooNE” (arXiv:1702.02688v2) used 0.035 GeV as the lower cut in their analysis, do I used this as the lower cut
  - No longer off by a factor of 100, still a bit off.
  - Asked Patrick → 0.35 is a type, **it is actually 0.035GeV!** (upper energy cut is still 1.0 GeV)
- I'm also using the same value for the detector geometry as Patrick used (a bit different than values in the tables in paper):

  x = 0.0 m

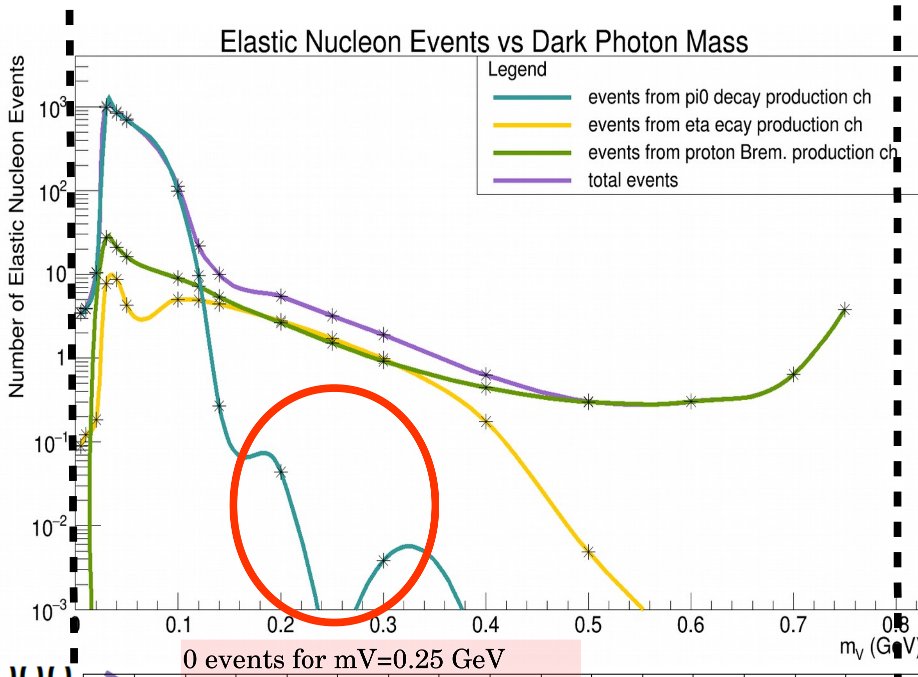
  y = -1.9 m

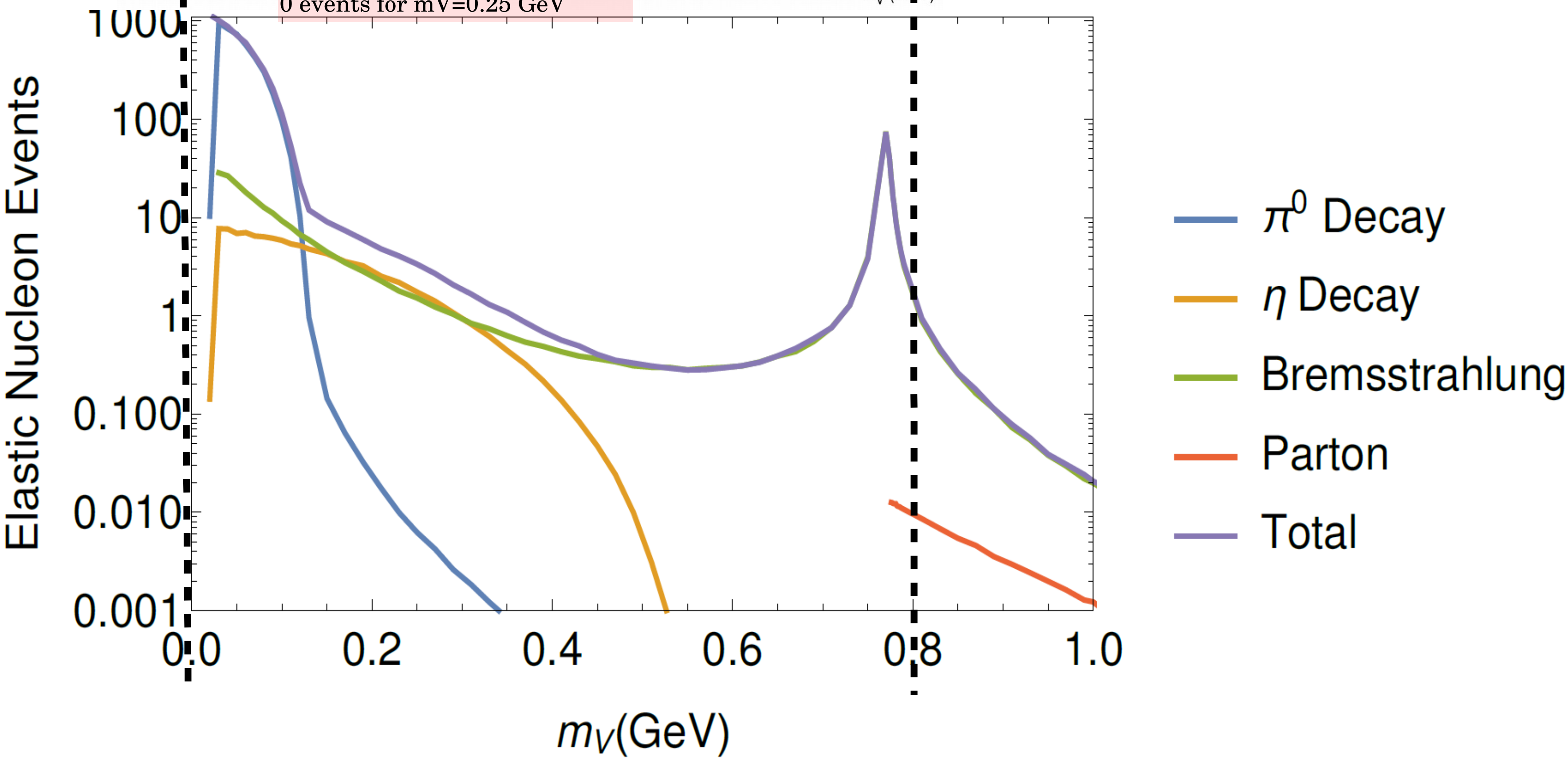
  z = 491 m

  r = 5 m
- My plot is on the next page (only 1000 entries for each BdNMC run, am currently running it with 20000 entries but that will take a few hours)



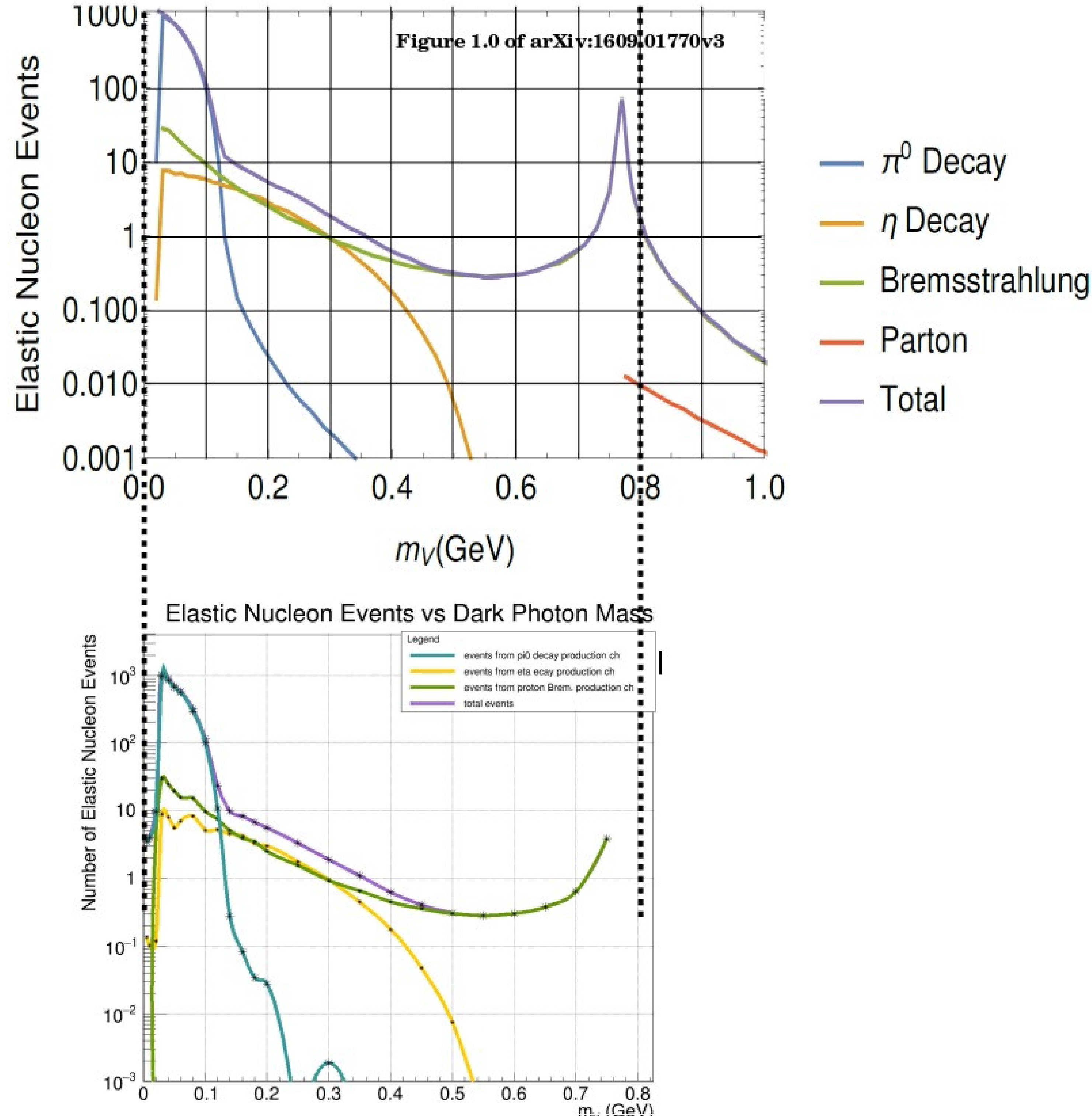

- Next slide has corrected graph




- Looks almost the same
- **My plot has 0 pi0 events at 0.25 GeV ->discrepancy**
- **Samplesize of each BdNMC run is only 1000 …**

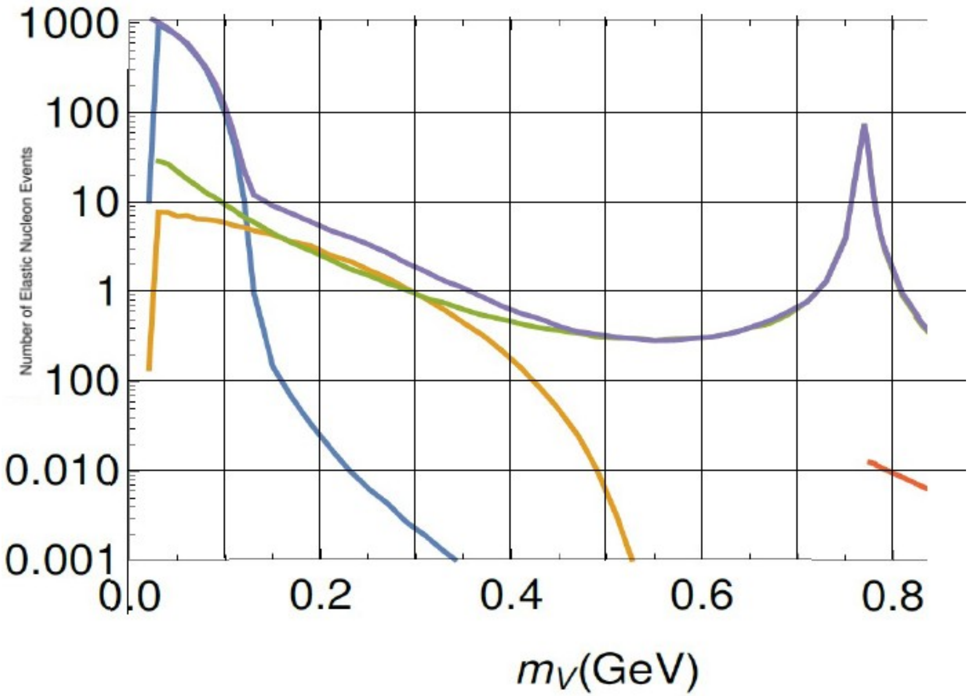
**Figure 1.0 of arXiv:1609.01770v3**

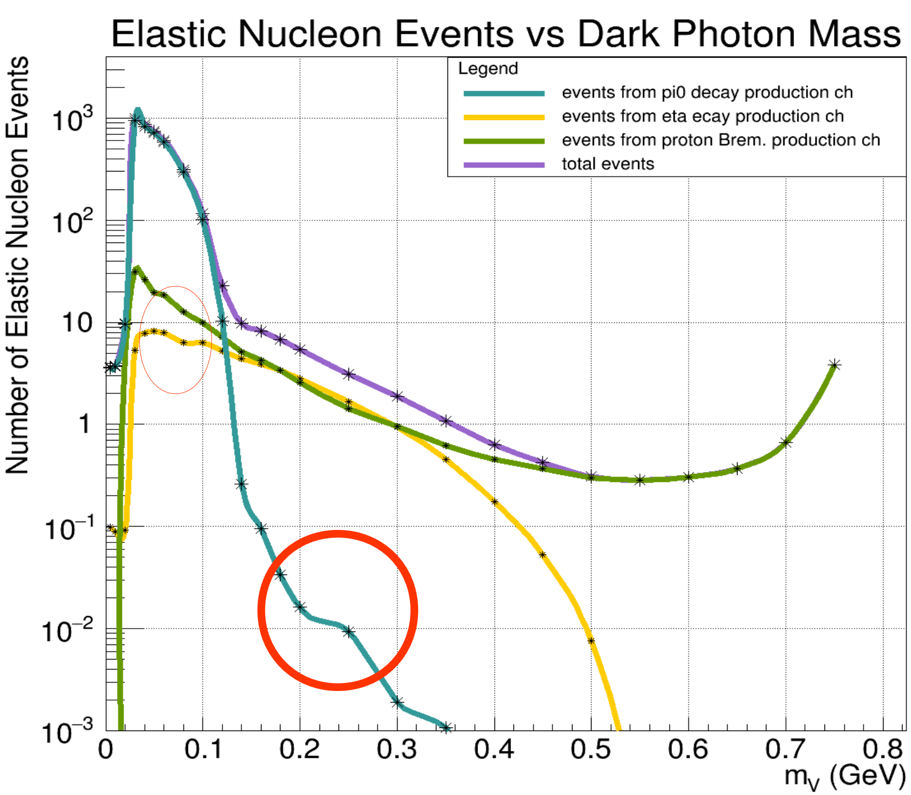



**My plot: each BdNMC run has a sampelsize of 1000**

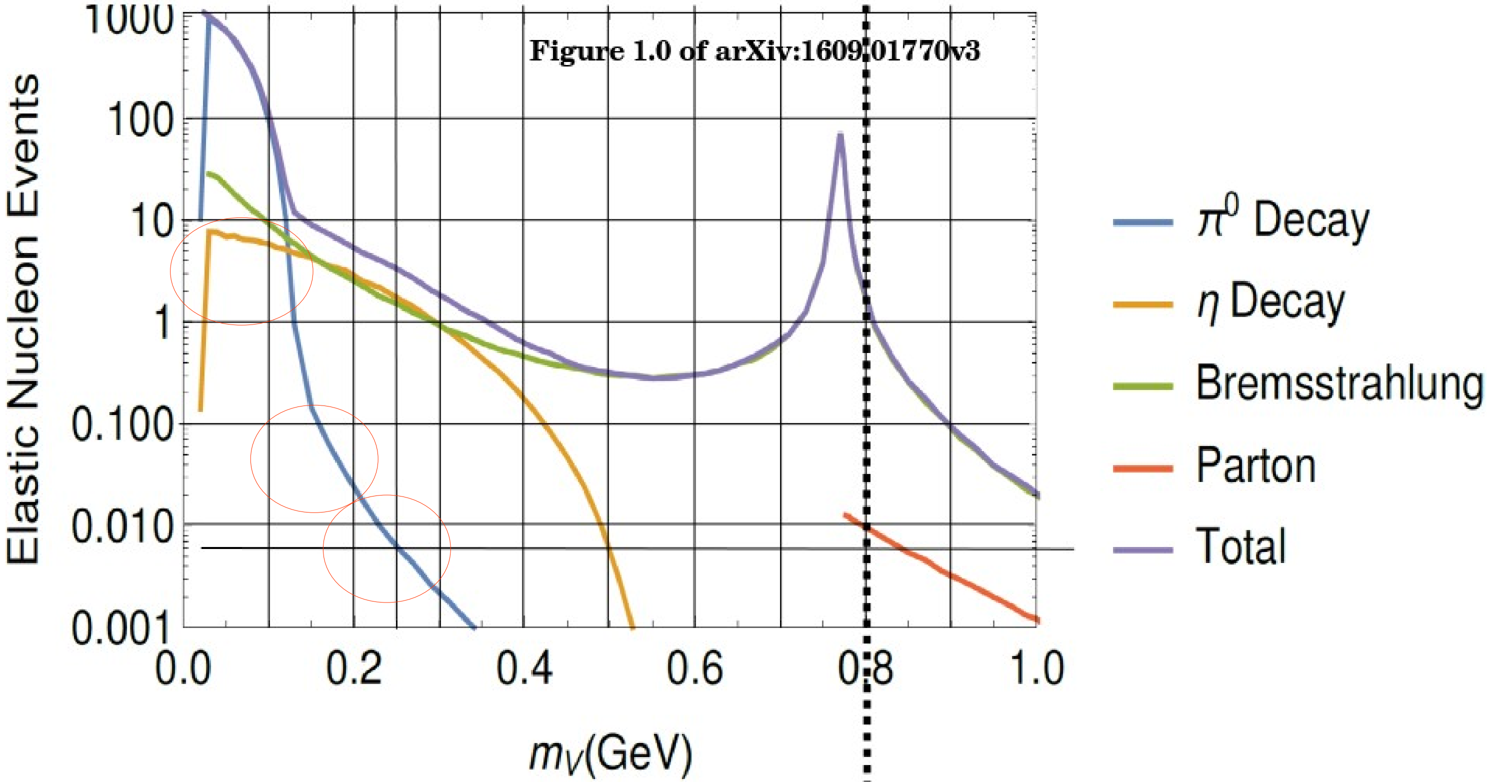
- Each BdNMC run has 1000 events (again)
- I still get 0 events for mV=0.25 GeV
- Tried samplesize = 2000, results on next slide

Figure 1.0 of arXiv:1609.01770v3



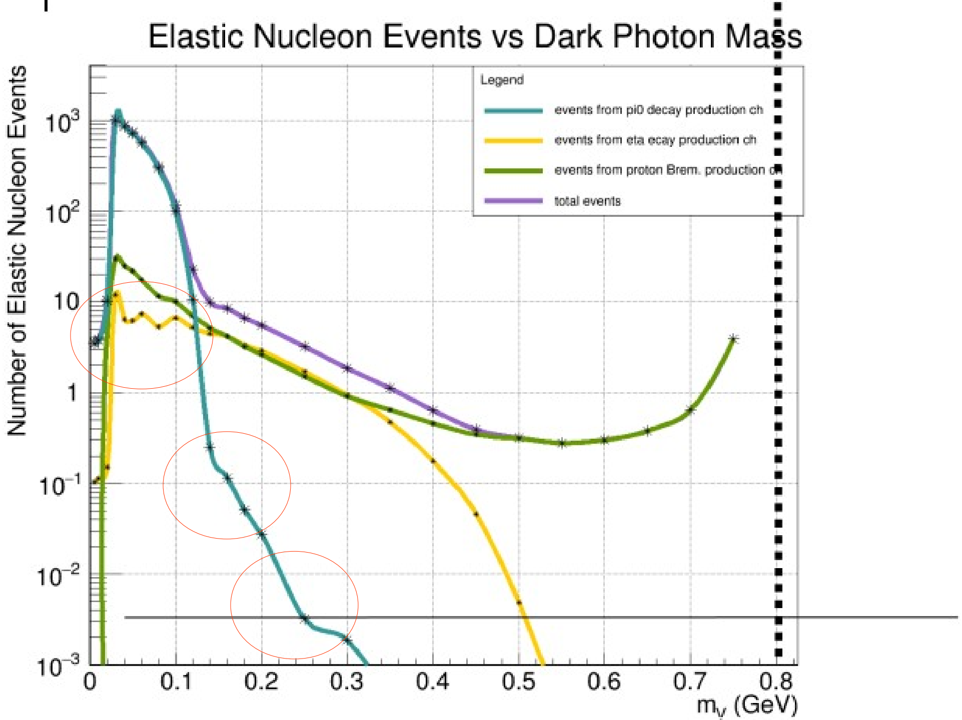

- Each BdNMC run has 2000 events
- My plot looks ~ same, some small differences (outlined in red)




Each BdNMC run has 3000 events

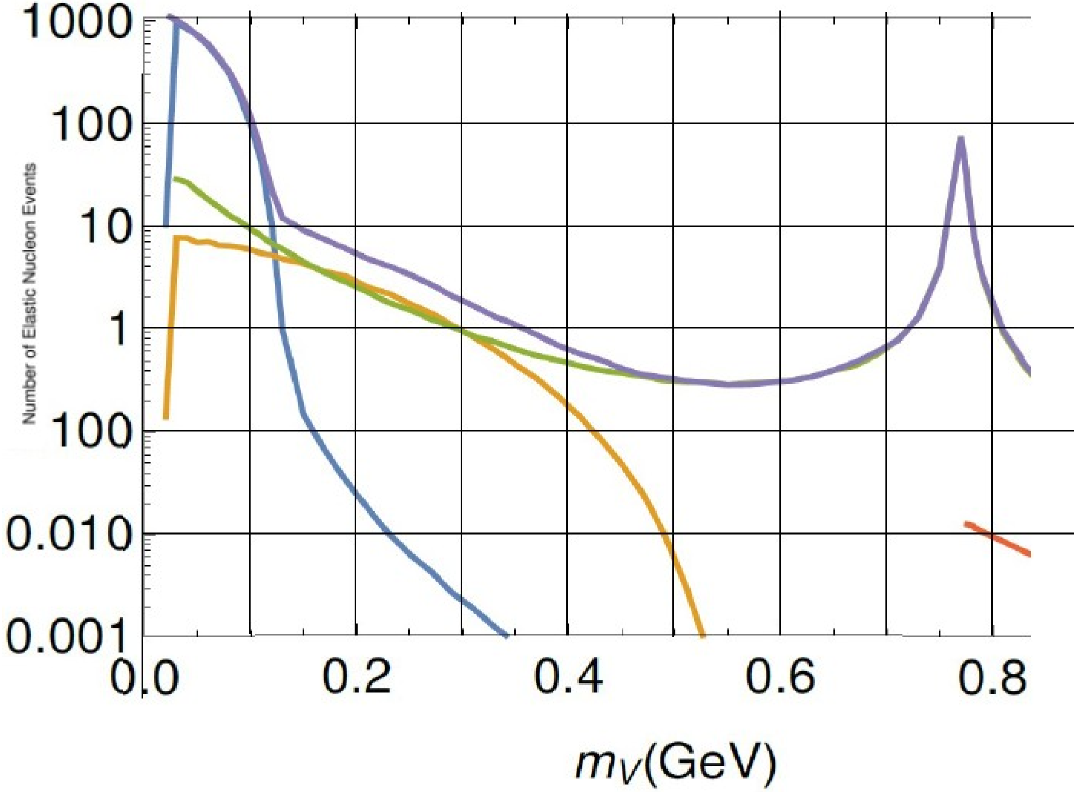
Still some minor differences:

Figure 1 has ~0.0065 events at mV=0.25 GeV, my plot has ~0.002 events

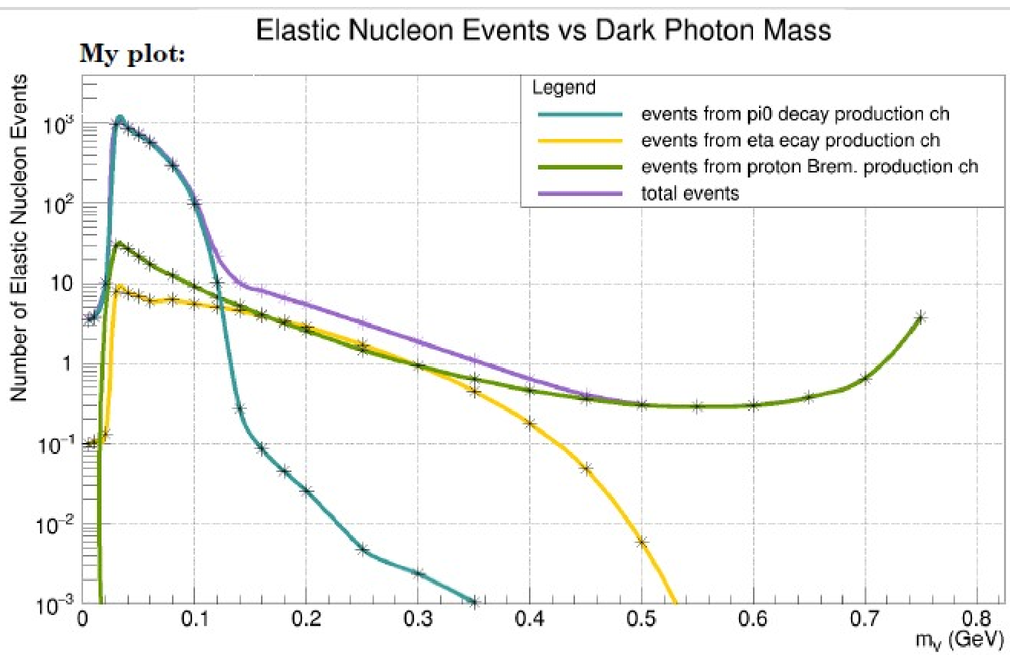



**My plot: each BdNMC run has a sampelsize of 3000**

**Figure 1.0 of arXiv:1609.01770v3**




**My plot:**




- Ran BdNMC run with a **samplesize of 20000** for each run
- **My plot (bottom plot) matches the paper's**

# Reproducing the paper's sensitivity plots

- Went on to reproduce this plot (figure 7 of arXiv:1609.01770v3):

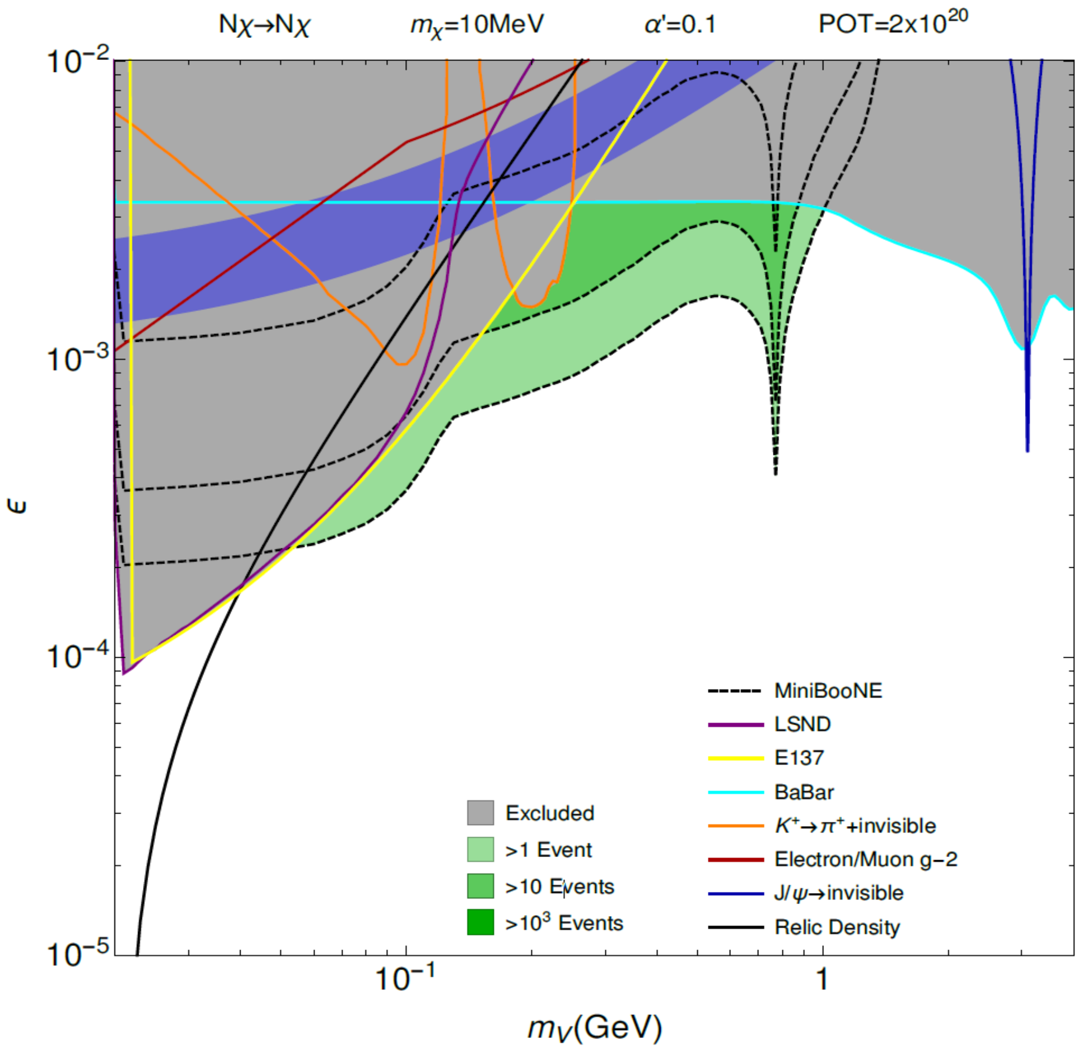



**FIG. 7. Plots showing the MiniBooNE yield of light dark matter scattering events in nucleon elastic scattering. In this plot and the others to follow, the gray regions are excluded by existing constraints, while the green contours indicate 1, 10 and 1000 events.**

- Note: I will only do $m_V$<1 GeV for now because paper says partonic production is relevant for >1GeV

# Reproducing paper's sensitivity plots:

- The paper (arXiv:1609.01770v3) says they use the following information:

| Name | Energy | POT | Detector Mass | Material | Distance | Angle | Efficiency |
|---|---|---|---|---|---|---|---|
| MiniBooNE-Beam Dump | 8 GeV | $2 \times 10^{20}$ | 400 tons | $CH_2$ | 490 m | 0 | 0.35 |
| T2K-ND280 (P0D) | 30 GeV | $5 \times 10^{21}$ | 6 tons | $H_2O$,Plastic | 280 m | $2.5^o$ | 0.35 |
| T2K-Super-K | 30 GeV | $5 \times 10^{21}$ | 50 kilotons | $H_2O$ | 295 km | $2.5^o$ | 0.66 |
| SHiP | 400 GeV | $2 \times 10^{20}$ | 10 tons | LAr | 100 m | 0 | 0.5 |

TABLE I. A summary of the relevant characteristics of the experiments considered. The listed detector mass is the fiducial mass, when available. Note that SHiP is still in the proposal and planning stage, and the design has not been finalized, so the detector material and mass have been chosen for illustration (the final fiducial mass may be larger).

- Nucleon recoil energy $E_R$ in [0.35, 1] GeV **(it's actually 0.035 not 0.35)**

- **The next slide lists all the parameters I used to create the sensitivity plot**

```
#Model Parameters
epsilon .0029
dark_matter_mass 0.01
dark_photon_mass .79
alpha_D 0.1

#Run parameters
POT 2e20
pi0_per_POT 0.9
samplesize 2000
```

These values change

```
beam_energy 8

################################
#Production Channel Definitions#
################################

#Production Parameters
#Currently pi0_decay,  eta_decay, V_decay and phi_decay, are supported.
#For baryonic, we support pi0_decay_baryonic, eta_decay_baryonic, V_decay_baryonic, phi_decay_baryonic, piminus_capture
production_channel pi0_decay

#Choosing a production distribution is optional, but it must be grouped with the relevant production_channel entry
production_distribution pi0_sanfordwang
```

```
#Here we also call a second production mode.
production_channel eta_decay
production_distribution k0_sanfordwang

#This invokes the bremsstrahlung production channel. This works, but may be
#unreliable around the rho resonance. The zmin/zmax values seem reasonable
#for MiniBooNE energies. ptmax could be as large as the proton mass, but
#probably would not change signal much.
production_channel V_decay
production_distribution proton_brem
ptmax 0.2
zmin 0.3
zmax 0.7

############################
#END OF PRODUCTION CHANNELS#
############################
```

**CONT. ON NEXT SLIDE**

*Parameter card: /home/atashi/updated_patrick_code/BdNMC-3.2.0/base_card4fig7.dat*

```
################
#SIGNAL CHANNEL#
################

#Scattering Parameters
#Choose from NCE_nucleon, NCE_electron, Pion_Inelastic, Inelastic_Delta_to_Gamma or NCE_nucleon_baryonic.
signal_channel NCE_nucleon
```

```
########
#OUPTUT#
########

#Where to write events.
output_file Events/events.dat
#Where to write a summary of the run with number of events and paramaters in the format: channel_name V_mass DM_mass num_events epsilon 0.0
summary_file Events/checking_peaks_fig7runs_summary.dat

#In comprehensive mode, all particles that make up an event are written to the output file. This overwrites the output file.
output_mode comprehensive
#summary suppresses output to output_file (no event list), while still writing to the summary file.
#output_mode summary

#Generate a particle_list file of length samplesize by writing to output_file for use in production_distribution particle_list.
#output_mode particle_list

#Cuts on the kinetic energy of outgoing nucleon or electron. These default to min=0 and max=1e9 GeV
max_scatter_energy 1.0
min_scatter_energy 0.035
#Decreasing the resolution increases setup time but improves accuracy of scattering cross sections
#dm_energy_resolution 0.01

#####################
#DETECTOR DECLARATION#
#####################

#Detector Parameters
detector sphere
x-position 0.0
y-position -1.9
z-position 491
radius 5.0
```

*Parameter card: /home/atashi/updated_patrick_code/BdNMC-3.2.0/base_card4fig7.dat*

```
#Material parameters
#Mass is set in GeV.
#mass is only important for coherent scattering, can be set to anything.
#anything not defined will be set to zero.
material Carbon
number_density 3.63471e22
proton_number 6
neutron_number 6
electron_number 6
mass 11.2593

material Hydrogen
number_density 7.26942e22
proton_number 1
neutron_number 0
electron_number 1
mass 0.945778


efficiency 0.35
```

*Parameter card: /home/atashi/updated_patrick_code/BdNMC-3.2.0/base_card4fig7.dat*

# Code(s) that create the sensitivity plots

- Wrote bash code that changes the values of epsilon, mass_V, mass_DM (if necessary) in the main parameter card, then runs BdNMC.
- Another code reads the summary.dat file and stores the values of epsilon, mass_V, and signal events.
  - Puts these into three different array for events with signal events >1, >10, and >1000
  - Draws these three tgraphs

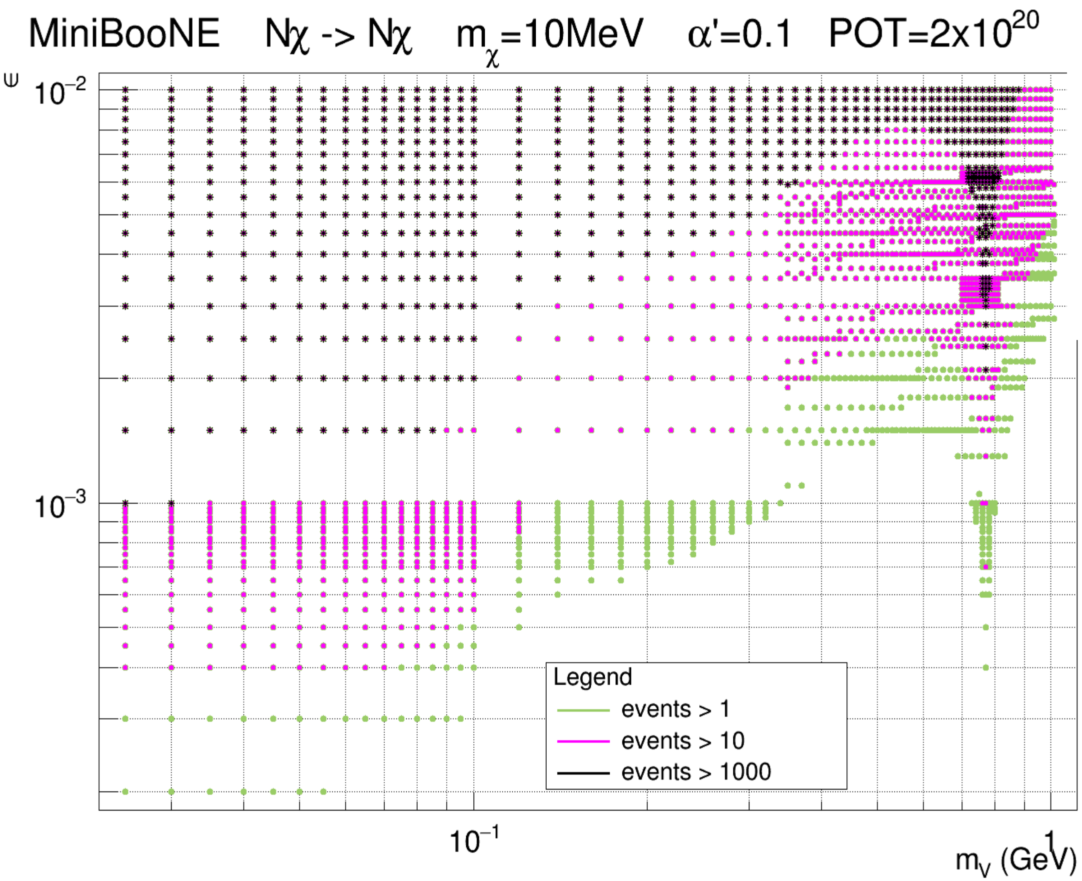
Technical details:

- Bash code: /home/atashi/updated_patrick_code/BdNMC-3.2.0/more_automated_run_BdNMC_4fig7.sh
- Have to specify the main parameter card in the bash code (I have base_card4fig7.dat)
- Specify the range of the values of epsilon and dark photon mass → code creates an array of epsilon and an array of mass_V
- For each value in (epsilon_array) X (mass_V) array:
  - code changes the values in the parameter card
  - Runs BdNMC with that parameter card
- Note: these runs should be put in a separate summary.dat file, which is later read by anotehr code

Code that creates plots: (/home/satashi/local_code/BdNMC_related_code/make_sensitivity_plots)

- Set f_input in make_sensitivity_plots to the path of the run summary data file
- Run it

*My plot:*



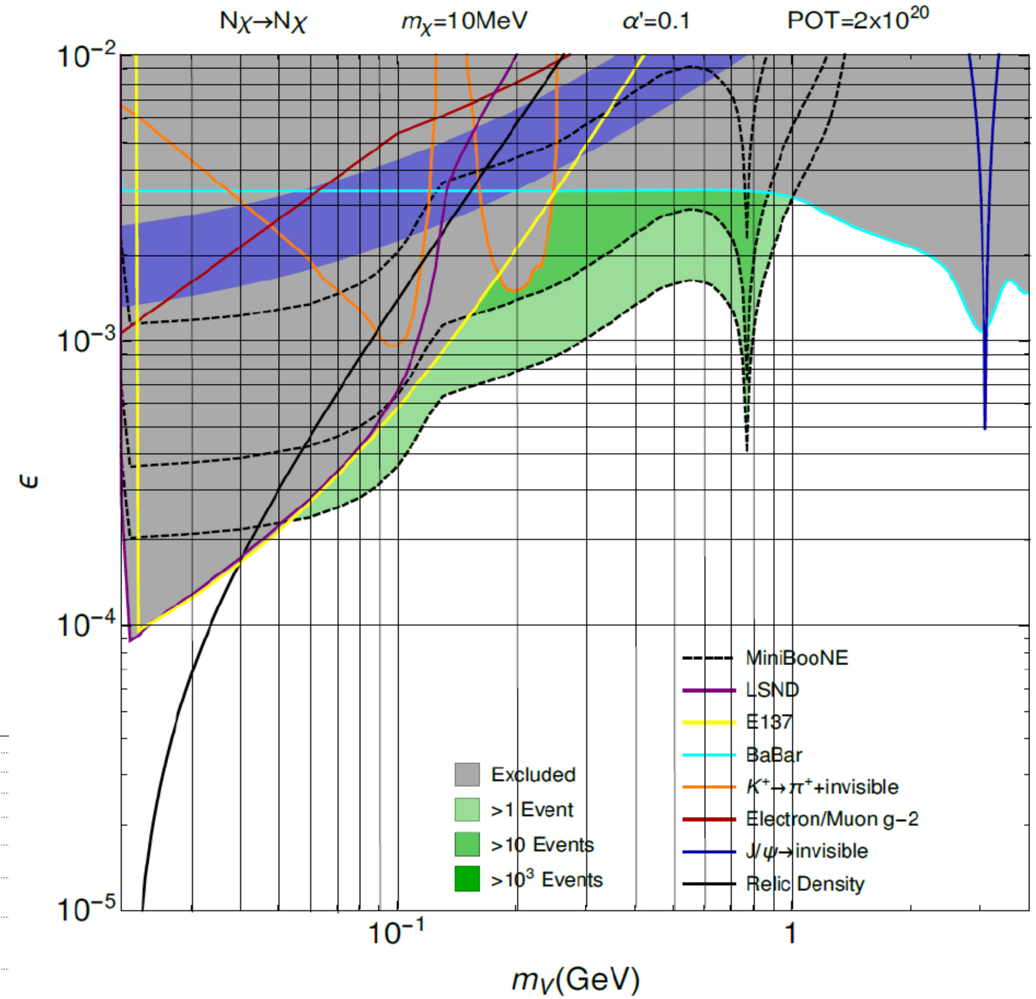
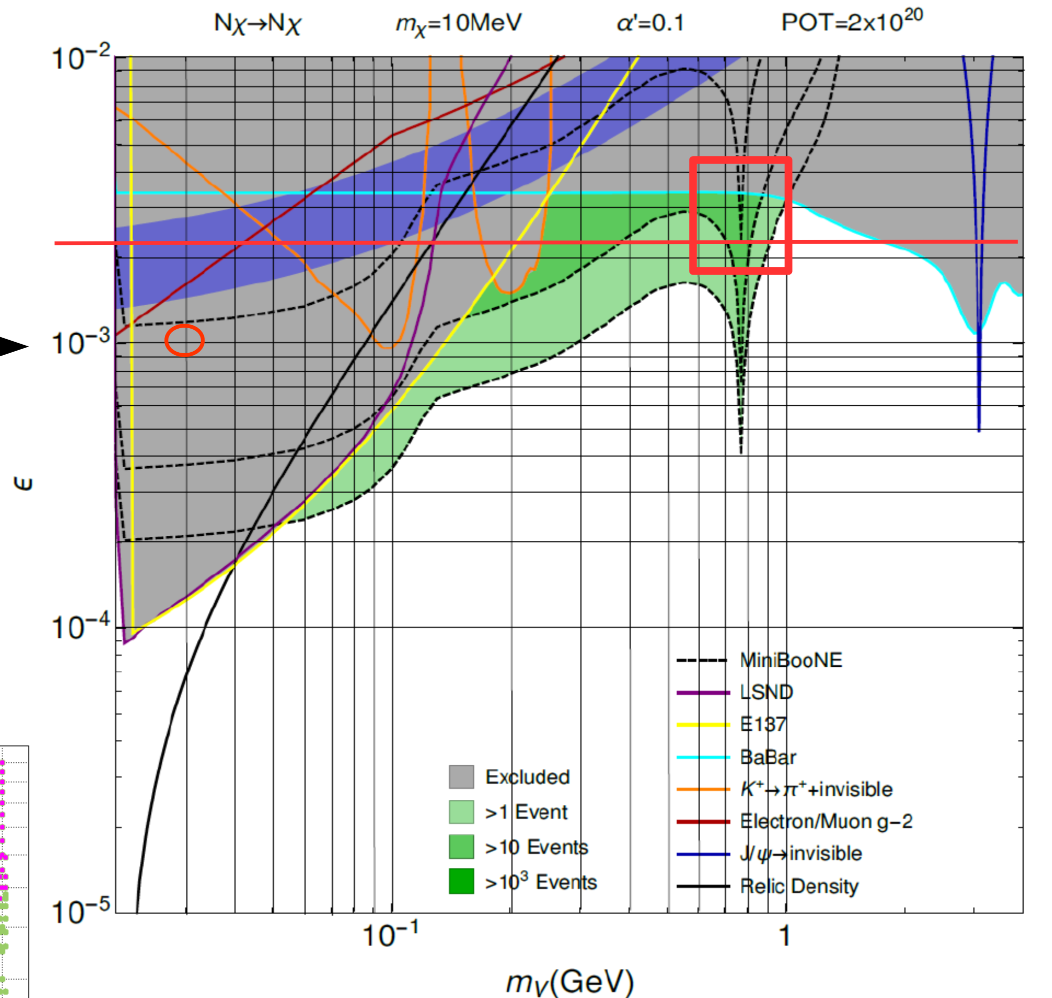



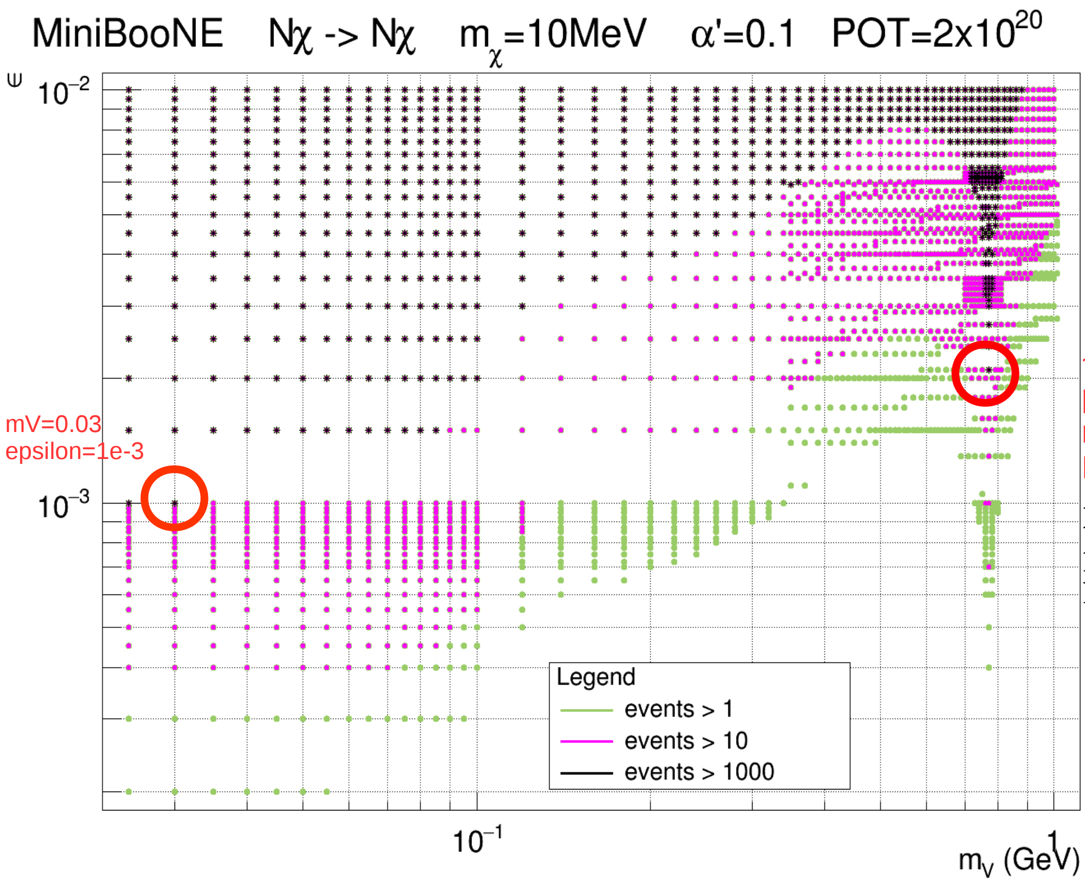

*Figure 7 of arXiv:1609.01770v3*

...

At mV=0.03, epsilon = 1e-3,

paper says 10<events<1000,
my plot says events >1000




~looks wrong at point
mV=0.77 GeV
Epsilon=0.0021

My plot says ~1100 events,
paper's plot says it should be
less than 1000, greater than 10

- At the point mV=0.77 GeV, epsilon=0.0021, my plot says ~1100 events, paper's plot says it should be less than 1000, greater than 10)
- Ran BdNMC for this point again:

  signal_events = 1199.78

  signal_events=  1224.35

  signal_events=1187.56

  - I'm slightly overestimating the events ...
- Ran BdNMC for the point mV=0.77 GeV, epsilon=0.002
- Figure 7 says 10<signal_events <1000

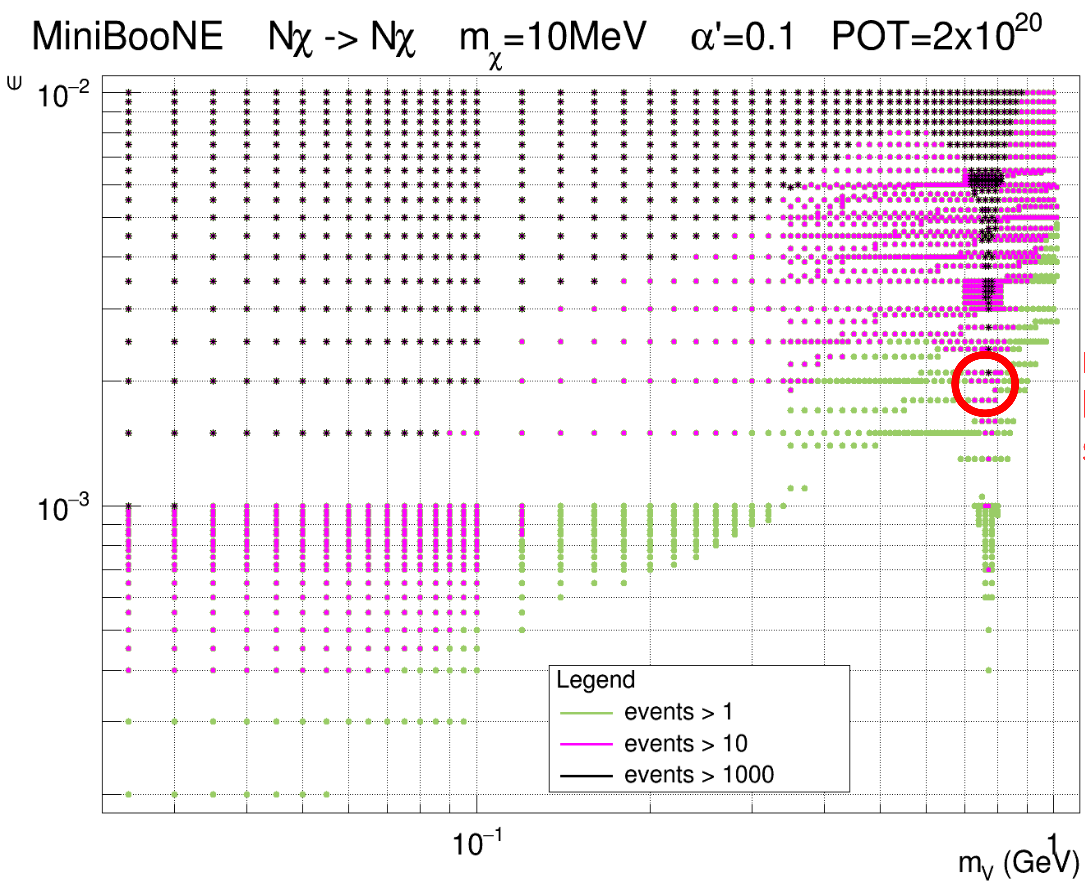
    I get:

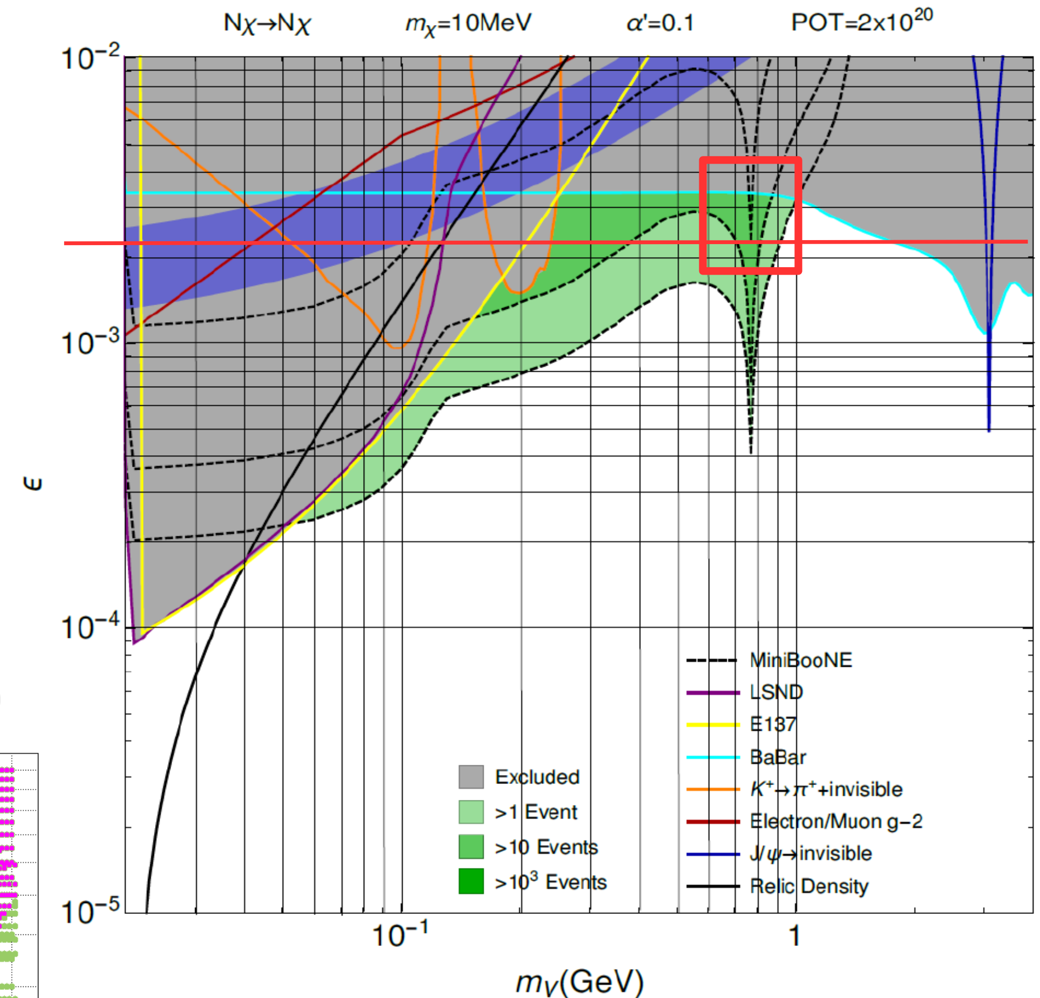
    signal_events = 970.105

    signal_events=  938.08

    signal_events= 995.897

    signal_events =  948.825




**mV=0.77 GeV**
**Epsilon=0.0021**
**signal_events ~ 1100**

- Ran BdNMC for this point again (mV=0.03 GeV, epsilon=0.001)
  - Figure 7 says 10<signal_events <1000

    I get:

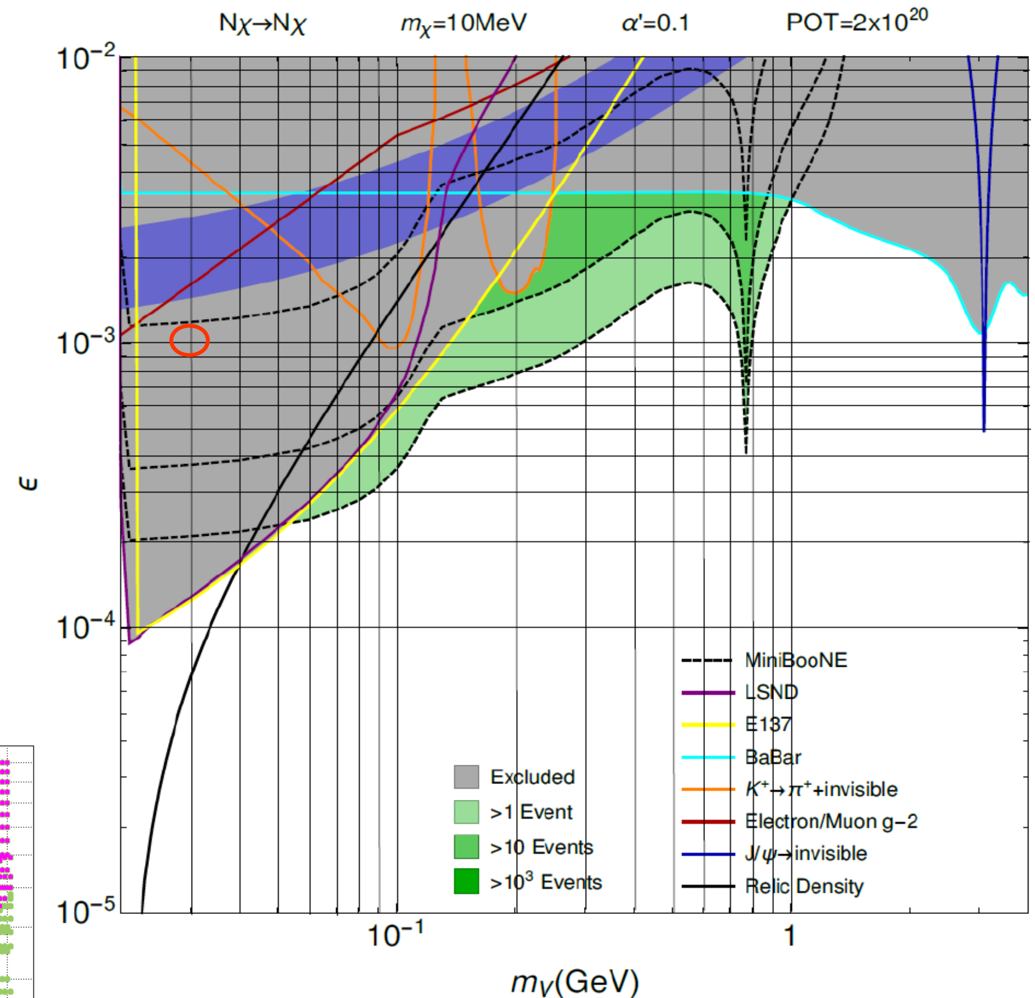
    signal_events = 1003.48

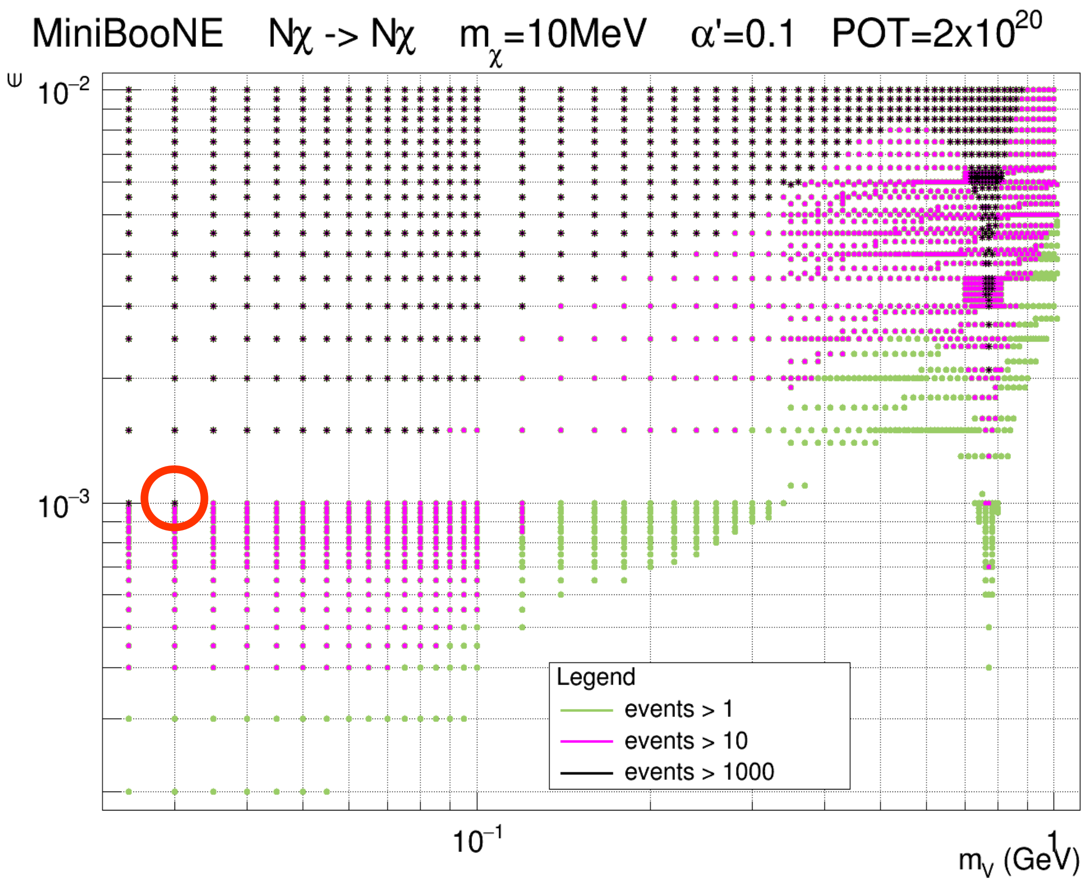
    signal_events= 1022.2

    signal_events= 987.447

    signal_events = 1038.27

    signal_events=990.734



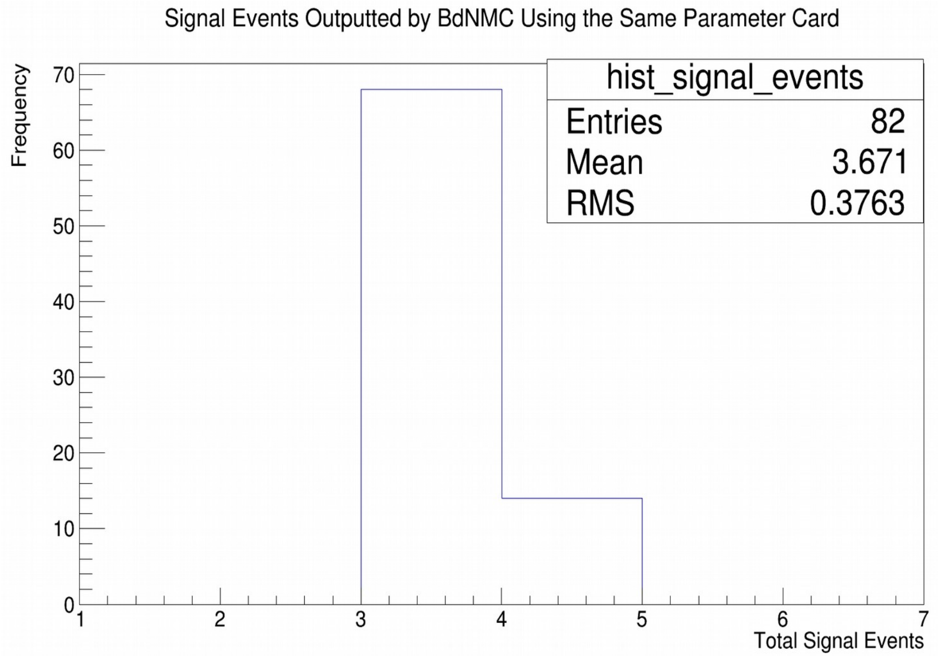




mV=0.03, epsilon=1e-3
signal_events=1003.32

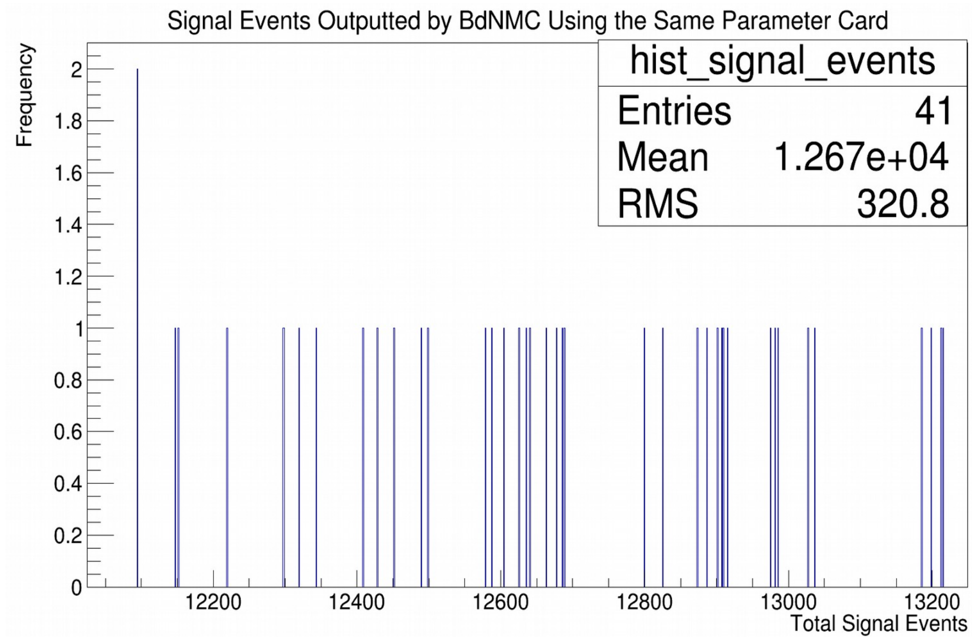
# Errors in signal_events outputted by BdNMC

- Simulation doesn't output errors
- Wanted to get a sense of the error in signal_events
- Ran BdNMC with the same parameter card a few times

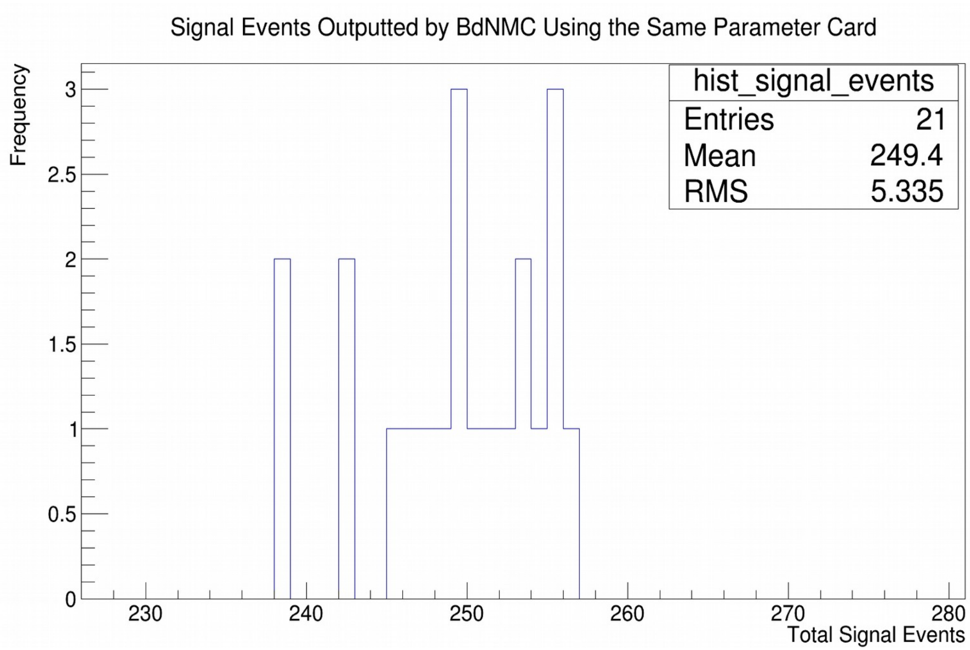
# Errors in signal_events outputted by BdNMC




*Same parameters as described on slides 18-19 BUT epsilon = 0.002, dark_matter_mass = 0.01 GeV, dark_photon_mass = 0.6 GeV*




*Same parameters as described on slides 18-19 BUT epsilon = 0.008, dark_matter_mass = 0.01 GeV, dark_photon_mass = 0.75 GeV*




*Same parameters as described on slides 18-19 BUT epsilon = 0.003, dark_matter_mass = 0.01 GeV, dark_photon_mass = 0.75 GeV*

I'll have to think about errors more ...

# Next steps

- Error in signal events
- Reproducing fig 8 of the paper

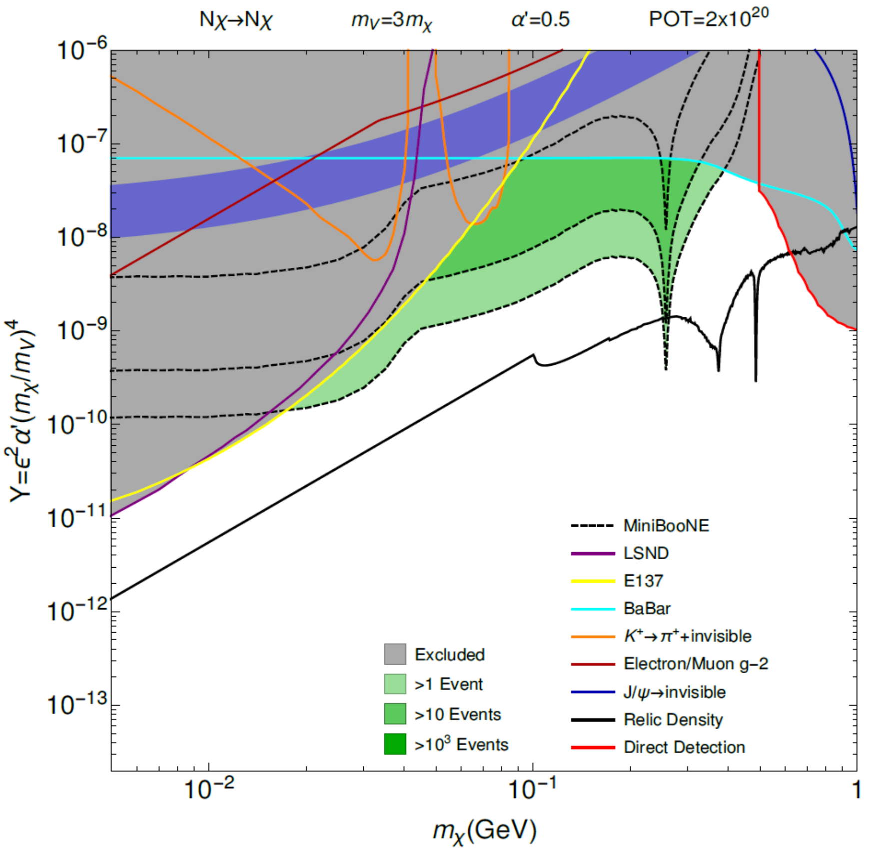



Fig 8.0 of arXiv:1609.01770v3: Further plots showing the MiniBooNE yield of light dark matter scattering events in various channels, now using
mV = 3m with 0 = 0:5, and using the variable Y for the vertical scale. In these plots and below the black dotted line shows
the parameters required to achieve the dark matter relic density, so smaller values of Y are excluded due to over-production of
dark matter.

# Next steps cont.

- Maybe it's better to shift my focus to running BdNMC with SK's parameters (the most accurate ones, not necessarily the ones used in the paper to make the SK sensitivity plots) ?
- The partonic production channel's dependence on beam energy (i.e. its relevance to T2K SK)
- Study the patterns I saw in the dark photon distributions (from a few weeks ago)

# Backup

null