Weekly Update

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August 02, 2017

From last time: Reproducing the paper's sensitivity plots

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

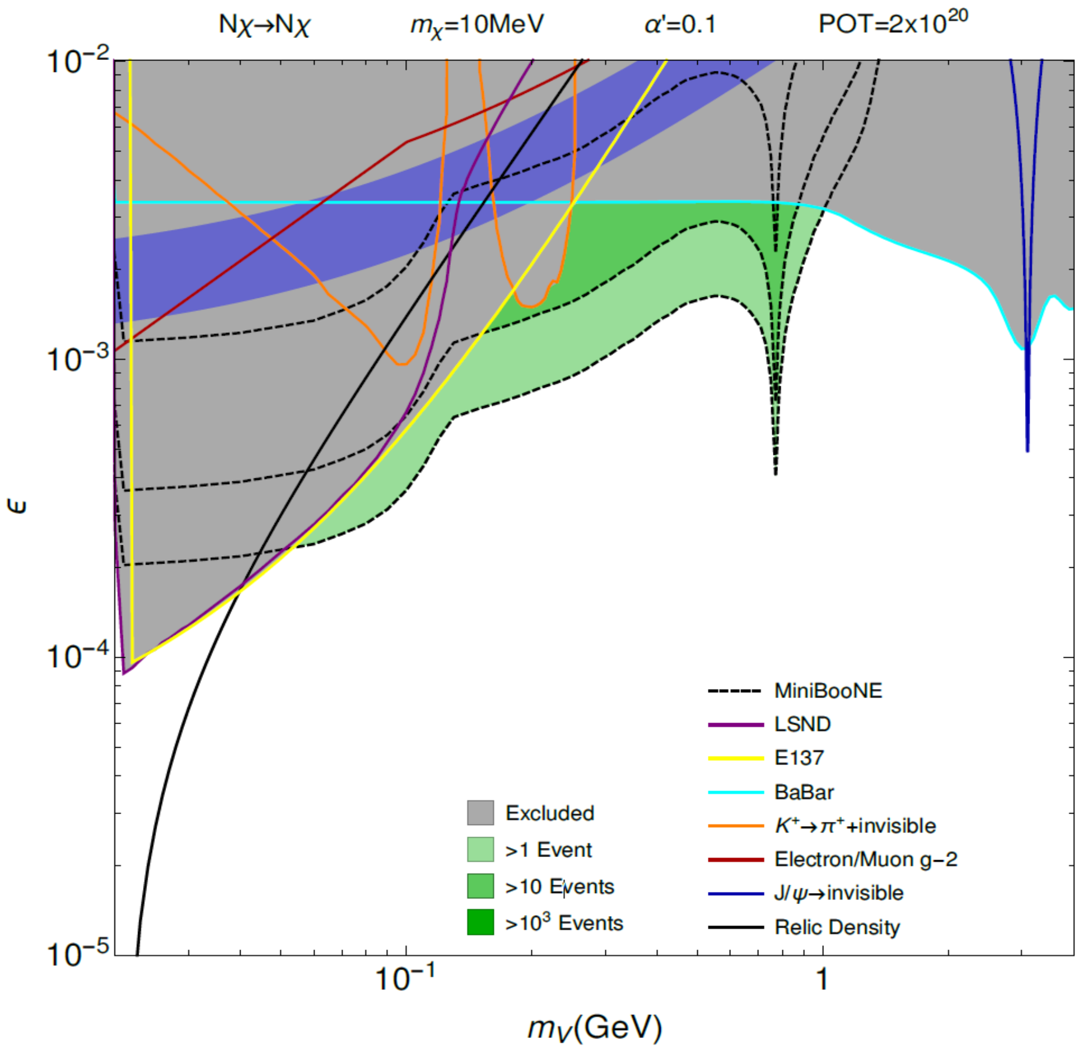


FIG. 7. Plots showing the MiniBooNE yield of light dark matter scattering events in nucleon elastic scattering. In this plot and the others to follow, the gray regions are excluded by existing constraints, while the green contours indicate 1, 10 and 1000 events.

Paper's plot:

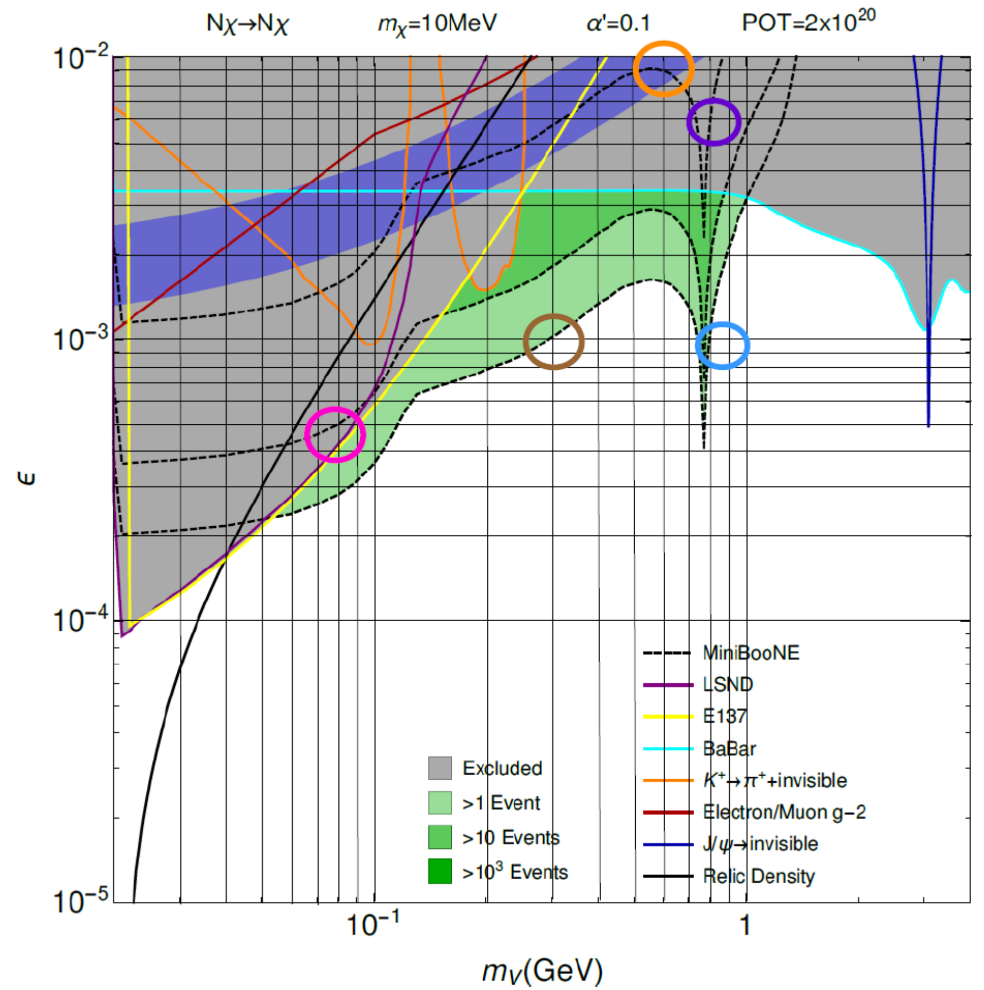
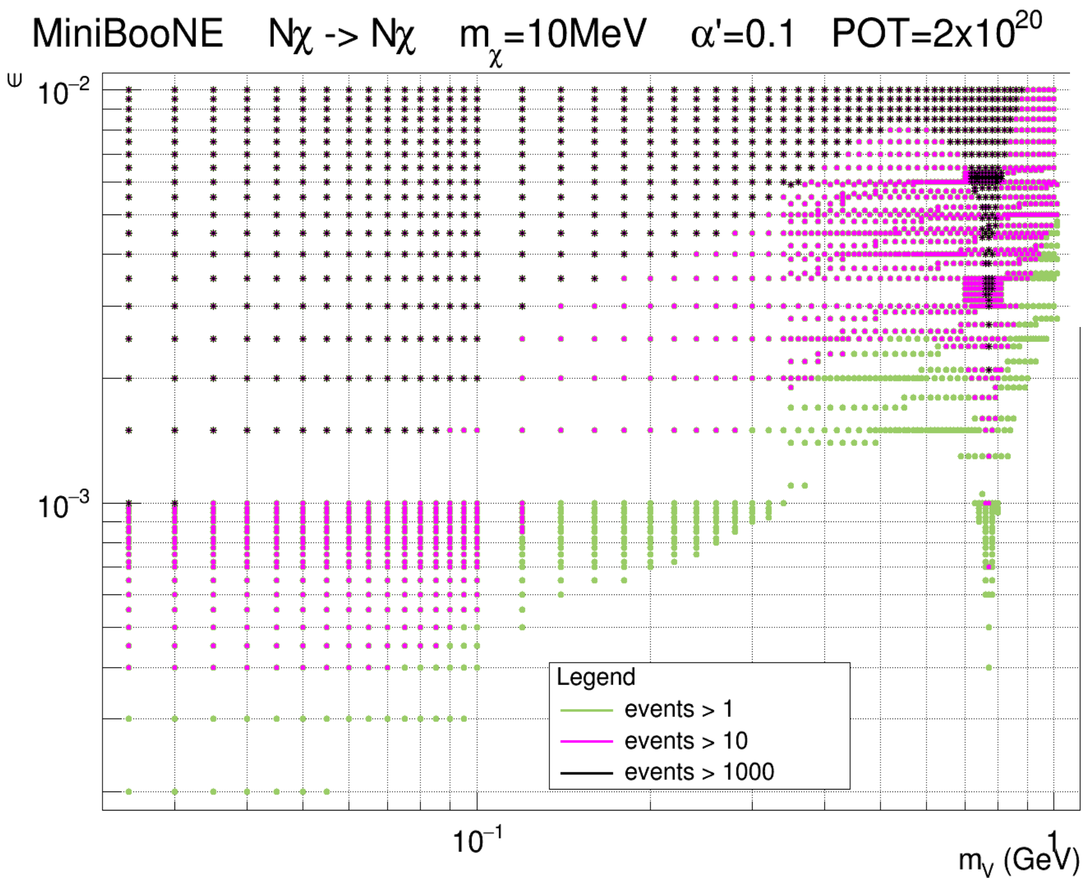


FIG. 7 of ***arXiv:1609.01770v3:*** **Plots showing the MiniBooNE yield of light dark matter scattering events in nucleon elastic scattering. In this plot and the others to follow, the gray regions are excluded by existing constraints, while the green contours indicate 1, 10 and 1000 events.**

My plot:



- It seems like at some points, I'm getting more events than the paper's plot, next slide →

Update on reproducing figure 7

mV	epsilon	#events from paper's plot	What I get for #events with samplesize=2000
0.08	0.0005	10	19.7047 +/- 0.014
0.3	0.001	1	1.7586 +/- 0.0042
0.6	0.009	1000	1625.62 +/- 0.13
0.8	0.006	1000	1591.48 +/0.13
0.8	0.001	1	1.2306 +/- 0.0035

- Asked Patrick to tell me the exact values for these points
- "My m_V = 0.08 GeV number almost exactly matches with yours, but the others diverge. **It seems like the plot is off by a factor of 2 for some reason.** I'll need to look into it further, but it may just be that the plot was using out-of-date settings."

  The m_V=0.3 GeV and 0.6 GeV are off, but that's my fault as the table lists the 8 GeV kinetic energy rather than the 8.9 GeV total MiniBooNE energy for some reason. So you should get 2 and 2000 events respectively. Above m_rho, your numbers should diverge somewhat from the plot as parton-level production starts to contribute.
- I ran the mV=0.3 and 0.6 points with beam energy=8.9 GeV, got 1.89838+/- 0.00001 and 1989.34 +/0 0.0004 →
  - Asked Patrick, he said these are close enough to his values

mV	epsilon	#events from Patrick	What I get for #events with samplesize=2000 and beam energy=8.9 GeV instead of 8 GeV	What I get for #events with samplesize=20,000 and beam energy=8.9 GeV instead of 8 GeV
0.3	0.001	2	1.89485 +/- 0.0043	1.89838+/- 0.00001
0.6	0.009	2000		1989.34 +/0 0.0004

I run BdNMC with POT=2x10^{30}

$$\#\ signal\ events\ with\ 2x10^{20}\ POT = \frac{\#\ signal\ events\ with\ 2x10^{30}\ POT}{10^{10}}$$

$$error\ in\ \#\ signal\ events\ with\ 2x10^{20}\ POT = \sqrt{\frac{\#signal\ events\ with\ 2x10^{30}\ POT}{10^{10}}}$$

Update on Resonant Vector Meson Mixing Discussion from last Time

- From page 28 of 2017 paper [1]:

The simulation of vector meson mixing is quite similar to that of the pseudoscalar meson decays, but the calculation of vnum is slightly different,

$$\texttt{vnum} = \mathrm{Br}(X \to \chi\bar{\chi}) \times \textbf{meson\_per\_pi0} \times \textbf{pi0\_per\_POT} \times \textbf{POT}. \qquad (8)$$

The kinematics of this process are simulated as an off-shell vector meson X oscillating into an on-shell V, which then decays normally into a $\chi\bar{\chi}$ pair. This channel is normally paired with a pion production distribution to generate a somewhat reasonable set of three-momenta from which to sample. Note that this channel overlaps with, and has now been replaced by, bremsstrahlung production which also receives a significant contribution from resonant vector meson mixing.

Vector meson mixing is :

- P + P → vector meson → V → chi + chi [dagger]
- Included in the proton bremsstrahlung production channel via the form factor
  - Differential V production rate:

5

$$\frac{d^2N_V}{dz\,dp_\perp^2} = \frac{\sigma_{pA}(s')}{\sigma_{pA}(s)} F_{1,N}^2(q^2)\, w_{ba}(z, p_\perp^2),$$

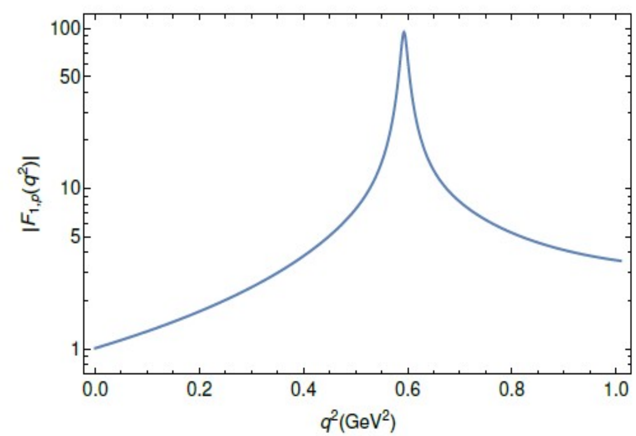


FIG. 3. The timelike form factor $F_{1,p}(q^2)$ from [56]. The resonant enhancement around the ρ/ω region is not fully resolved in the fit.

[1] "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP" by deNiverville et al. (arXiv:1609.01770v3)

Question: should we use the direct partonic production channel for SK analysis?

"Signatures of sub-GeV dark matter beams at neutrino experiments" (arXiv:1205.3499v1) by Patrick, McKeen, and Rtiz (reference in the main paper [1] when they talk about the DM model)

. talks about direct production (P+P → V → chi + chi$^{\text{dagger}}$) at MINOS and T2K (near detectors)

→ direct partonic production channel relevant for T2K energies, but *how relevant?*

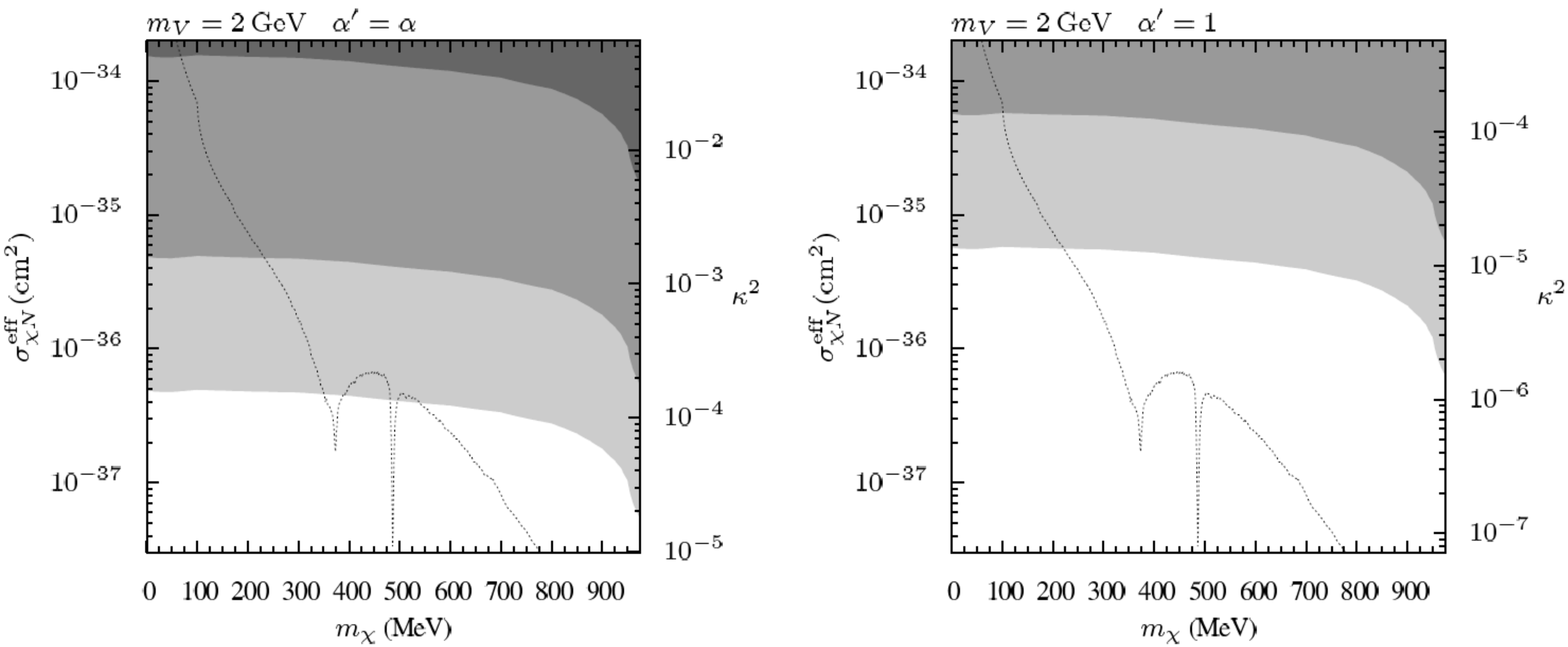


FIG. 13. Expected number of neutral current-like dark matter nucleon scattering events from direct V production with the INGRID detector at T2K, comparing two different α values ($\alpha' = \alpha$ on the left and $\alpha' = 1$ on the right) for a 2 GeV Vector mediator. The contours are described in Fig. 8.

The regions show greater than 10 (light), 1000 (medium) and 106 (dark) expected events. The dashed curve indicates the value of required for the dark matter annihilation cross section in the early universe to equal 1 pb.

[1] "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP" by deNiverville et al. (arXiv:1609.01770v3)

Direct partonic production at SK?

- Would be nice to know partonic production channel's contribution compared to other production channels, at T2K energies (something like figure 1 [1]below at 30 GeV proton beam energy)

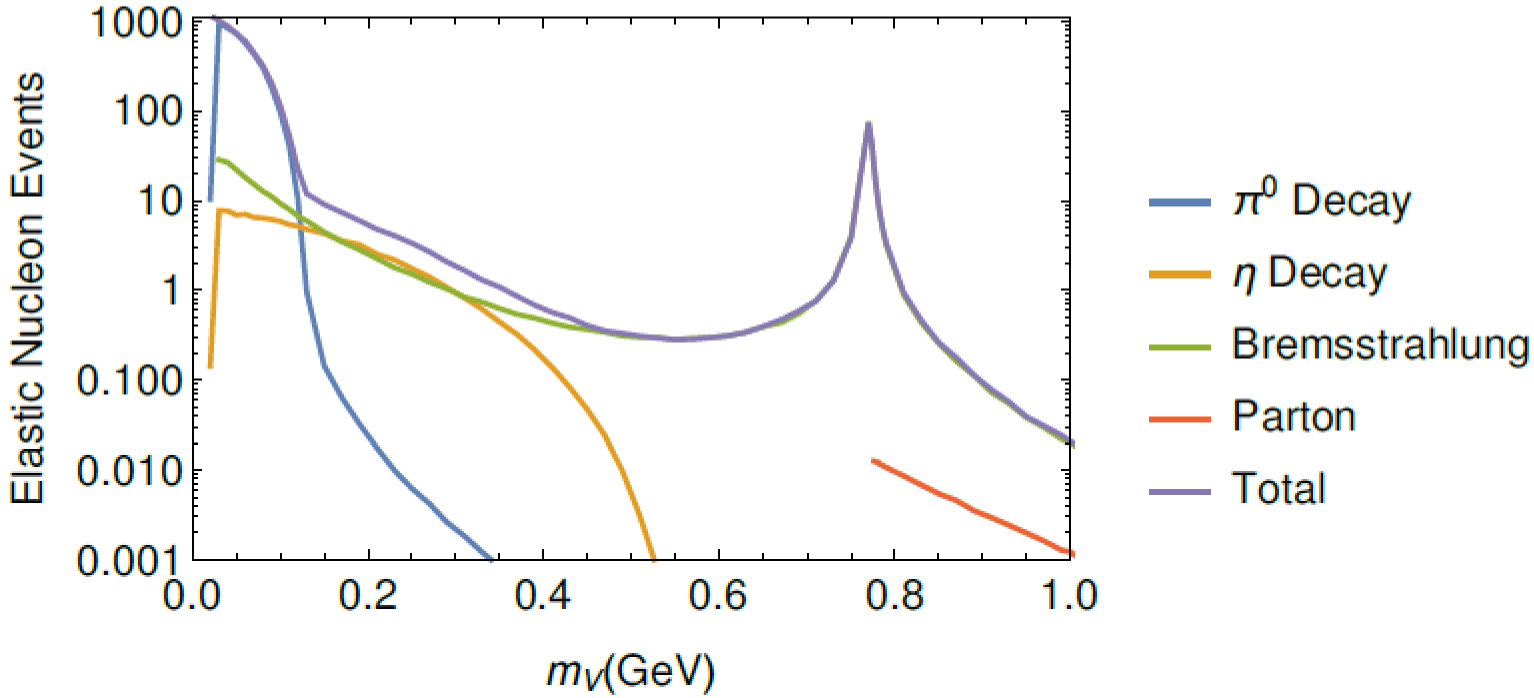


FIG. 1. A plot illustrating the distinct contributions to DM production (coupled through the vector portal), as discussed in the text, using the 9 GeV proton beam at MiniBooNE as an example. The rate of elastic scattering events on nucleons is plotted versus the vector mediator mass. From smaller to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

[1] "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP" by deNiverville et al. (arXiv:1609.01770v3)

Direct partonic production at SK?

- Looked over some papers to see if I can a discussion of the aprtonic production channel's contirbution at 30 GeV beam energy
  - Main paper [1] says they use CTEQ6.6 PDF's from “Implications of CTEQ global analysis for collider observables” by Nadolsky, Lai, Cao, etc (arXiv:0802.0007v3) for their direct partonic production channel estimates
    - Didn't find anything useful

- Going to carefully look over “Signatures of sub-GeV dark matter beams at neutrino experiments” (2012 paper by Patrick, McKeen, and Ritz: arXiv:1205.3499v1) again.

- 2012 paper says their work extends their earlier analysis of MeV-scale dark matter in the following papers:
- “Exploring Portals to a Hidden Sector Through Fixed Targets” (2009 paper by Batell, Pospelov, and Ritz: arXiv:0906.5614v2)
- and “Observing a light dark matter beam with neutrino experiments” (2013 paper by Patrick, Pospelov, and Ritz: arXiv:1107.4580v3)
    - Going to quickly look over these

- Will ask Patrick about the direct partonic production channel's contribution to NCE nucleon scattering compared to the other production channels, at T2K energies and m_V below the mass of rho

[1] “Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP” by deNiverville et al. (arXiv:1609.01770v3)

Coherent scattering option in BdNMC + relevance to SK

- *I was trying to figure out if I should use coherent NCE nucleon scattering for SK analysis*
- Reminder: Coherent scattering is an added feature of BdNMC 3.1.5 (I'm running BdNMC 3.2.0)
  - Available for signal channels NCE_nucleon, NCE_nucleon_baryonic, piminus capture signal channels; will be ignored for signal channels that do not support coherent scattering.
  - Enabling coherent scattering in the code: add “coherent true” to parameter card
- Plots I've shown so far have been with incoherent scattering
- Paper's [1] section “SIGNATURES AT MINIBOONE, T2K AND SHIP” talks about this: (next slide)

[1] “Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP” by deNiverville et al. (arXiv:1609.01770v3)

- Under the section "signatures at miniboone, t2k, and ship", they give a generic formula for the number of signal events calculated by the simulation:

A. Simulation

The total number of signal events can be written generically in the form

$$N_{A\chi\to A^{(*)}\chi} = n_A \epsilon_{\rm eff} \sum_{\substack{\rm prod.\\ \rm chans.}} \left(\frac{N_\chi}{2N_{\rm trials}} \sum_i L_i \sigma_{A\chi,i} \right).$$

In this expression, n_A denotes the number density of target atoms in the detector, $\epsilon_{\rm eff}$ is the corresponding detection efficiency, and the outer sum refers to the relevant production channels. The total number of dark matter particles N_χ is determined according to the relevant production channel, while $N_{\rm trials}$ refers to the number of trajectories generated by the production Monte Carlo. The inner sum is over all dark matter 4-momenta p_i generated by the production Monte Carlo, and L_i is the length of the intersection between the dark matter trajectory (with momentum p_i) and the detector. Finally, the scattering cross section was computed in the form

$$\sigma_{A\chi}(E) = \int_{E_\chi^{\rm min}}^{E_\chi^{\rm max}} dE_\chi \sum_{\alpha=p,n,e} f_\alpha \frac{d\sigma_{\chi,\alpha}}{dE_\chi}, \quad (19)$$

where E is the incoming kinetic energy, and $E_\chi^{\rm max/min}$ are determined by the experimental cuts on the nucleon/electron recoil momentum $q = \sqrt{2M(E-E_\chi)}$, while the sum is over the relevant scattering channels. For elastic or quasi-elastic nucleon scattering, we take $f_{p,n} = Z, A-Z$ for the vector portal and $f_{p,n} = A$ for the baryonic portal, since scattering is incoherent for the momentum transfers $q^2 > (50\,{\rm MeV})^2$ of interest, and nuclear binding effects (e.g. Pauli blocking) are subleading for the cuts on recoil energy (and thus momentum transfer) that are relevant for the experiments studied here. For electron scattering, we necessarily take $f_e = Z$.

The results presented below were computed using the Monte Carlo simulation tool BdNMC, developed by one of the authors (P.dN.). It is now publicly available, and full documentation is provided in the Appendix.

→ Use incoherent NCE nucleon scattering for SK studies

[1] "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP" by deNiverville et al. (arXiv:1609.01770v3)

Cont. Coherent scattering option in BdNMC + relevance to SK

- *How can you have incoherent elastic nucleon scattering?*
  - Found a nice thesis paper that describes *elastic/inelastic, coherent/incoherent neutrino nucleon scatterings (Daniel Scully's T2K thesis: "Neutrino Induced Coherent Pion Production"):*
- Elastic interactions: nucleon recoils from the interaction intact, except the change of charge in CC (quasi-elastic) interactions
    - dominate at small Q^2
- Inelastic interactions:
  - lower Q^2 region is dominated by resonance production: nucleon excited into a baryonic resonance (eg a delta) before decaying
  - higher Q^2 region is dominated by deep inelastic scattering (DIS), where the neutrino scatters directly off a constituent quark, fragmenting the original nucleon.
- Coherent scattering: nucleus recoils as a whole, un-fragmented particle, in the same state as before the interaction. This can only be achieved if the four-momentum transfer to the nucleus is small [2]
  - Doesn't tell me much about incoherent elastic scattering...
- Read some online notes on neutron scattering: elastic scattering cross section can be separated into a coherent and an incoherent scattering part [3]

[2] Daniel Scully's T2K thesis: "Neutrino Induced Coherent Pion Production"

3 NIST online course "PROBING NANOSCALE STRUCTURES USING SANS- Fall 2016" chapter 9 notes on "COHERENT AND INCOHERENT NEUTRON SCATTERING"

Cont. Coherent scattering option in BdNMC + relevance to SK

How can you have incoherent elastic nucleon scattering?

- Incoherent scattering refers to DM scattering off a nucleon (T2K can detect the de-excitation gammas when DM knocks out a nucleon from ^{16}O)
- Coherent scattering considers the whole nucleus. Our experiment is not able to detect coherent scattering, so **we only consider incoherent NCE nucleon scattering**

What coherent scattering events look like in the events.dat file

```
Run 1501526425
event 1
eta             0.176922        -0.0868606      4.73635         4.77201
V               0.0291613       -0.0554874      4.37933         4.38434
DM              -0.0201811      -0.0177601      3.97866         3.97877
Carbon          0.279413        0.88549         0.155876        11.2986         -2.48021        -2.18267        488.967         1.63106e-06

endevent 1

event 2
eta             0.122861        -0.329529       1.55813         1.68867
V               -0.0326418      0.0397699       0.852966        0.87761
DM              0.00285028      -0.00714244     0.792703        0.792803
Carbon          0.402485        -0.621651       0.630205        11.3012         1.7659          -4.42512        491.121         1.63841e-06

endevent 2

event 3
V               0.052567        -0.0314566      5.00205         5.00642
DM              0.0121831       0.0153156       4.55052         4.55057
Hydrogen        0.0373849       -0.272185       0.0495434       0.98612         1.30803         1.64434         488.56          1.62968e-06
```

From some weeks ago: patterns in angular distributions of dark photons from an example MinoBooNE experiment

- MiniBooNE like example (from sample parameter card in the paper)

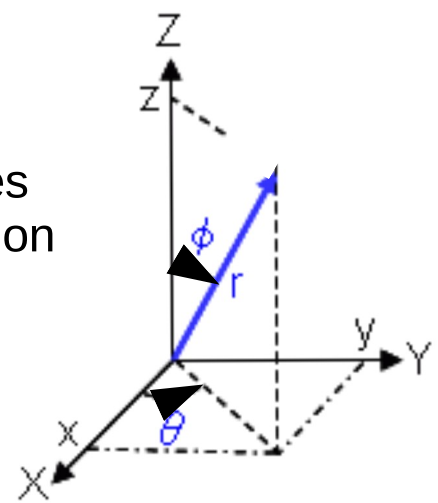
Parameters:

- MiniBooNE-like experiment

epsilon = 1e-3 dark_matter_mass= 0.01 GeV alpha_D = 0.1
POT= 2e20 beam_energy = 8.9 GeV
Production_channel: pi0_decay
Signal_channel: NCE_nucleon
Detector parameters:
Sphere at x=0, y=0, z=500 m, radius=5 m

- Geometry for the angular distributions:

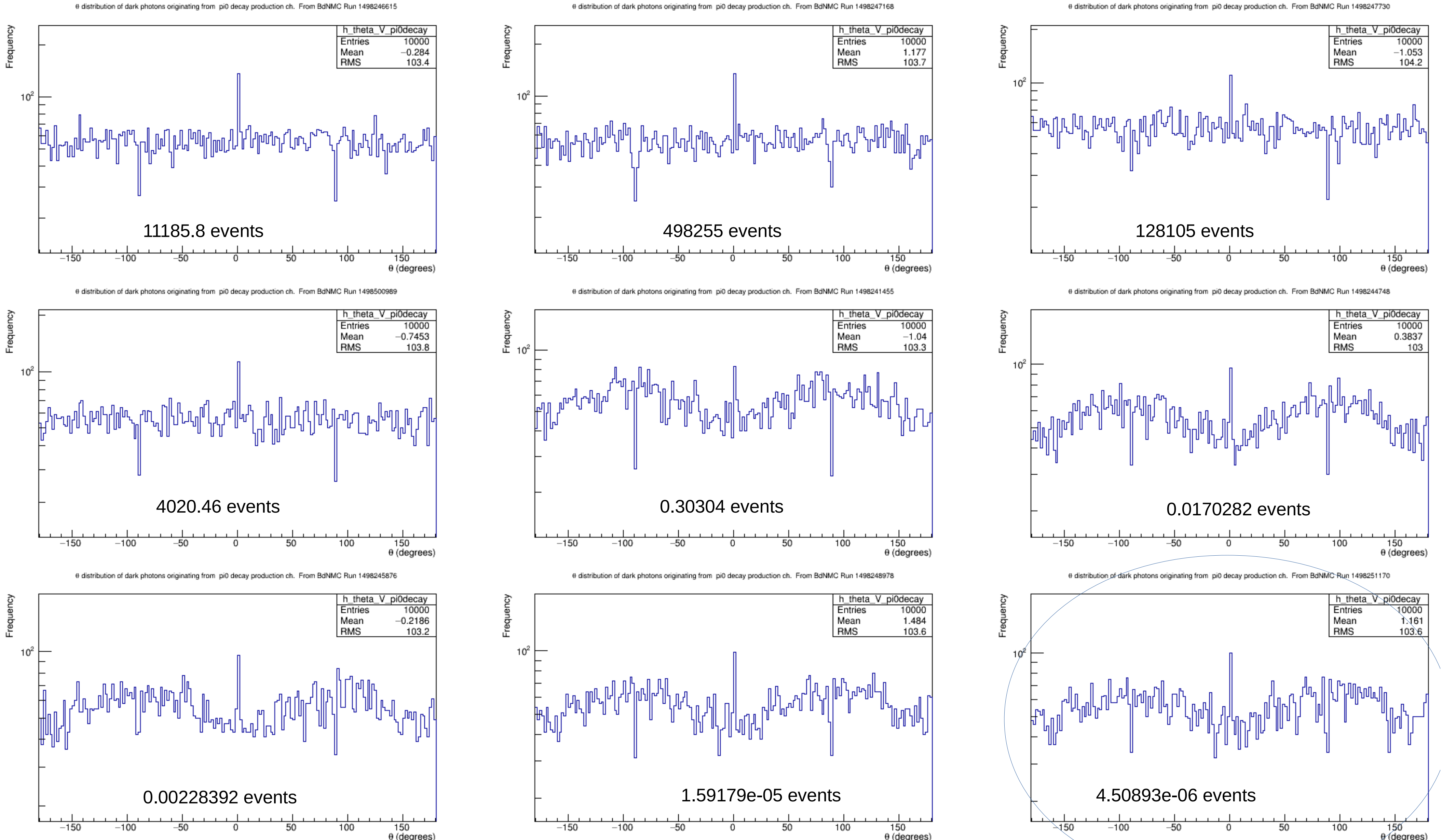
Beam goes in z direction



$$\theta = tan^{-1}\frac{y}{x}$$

$$\phi = tan^{-1}\frac{\sqrt{x^2+y^2}}{z}$$

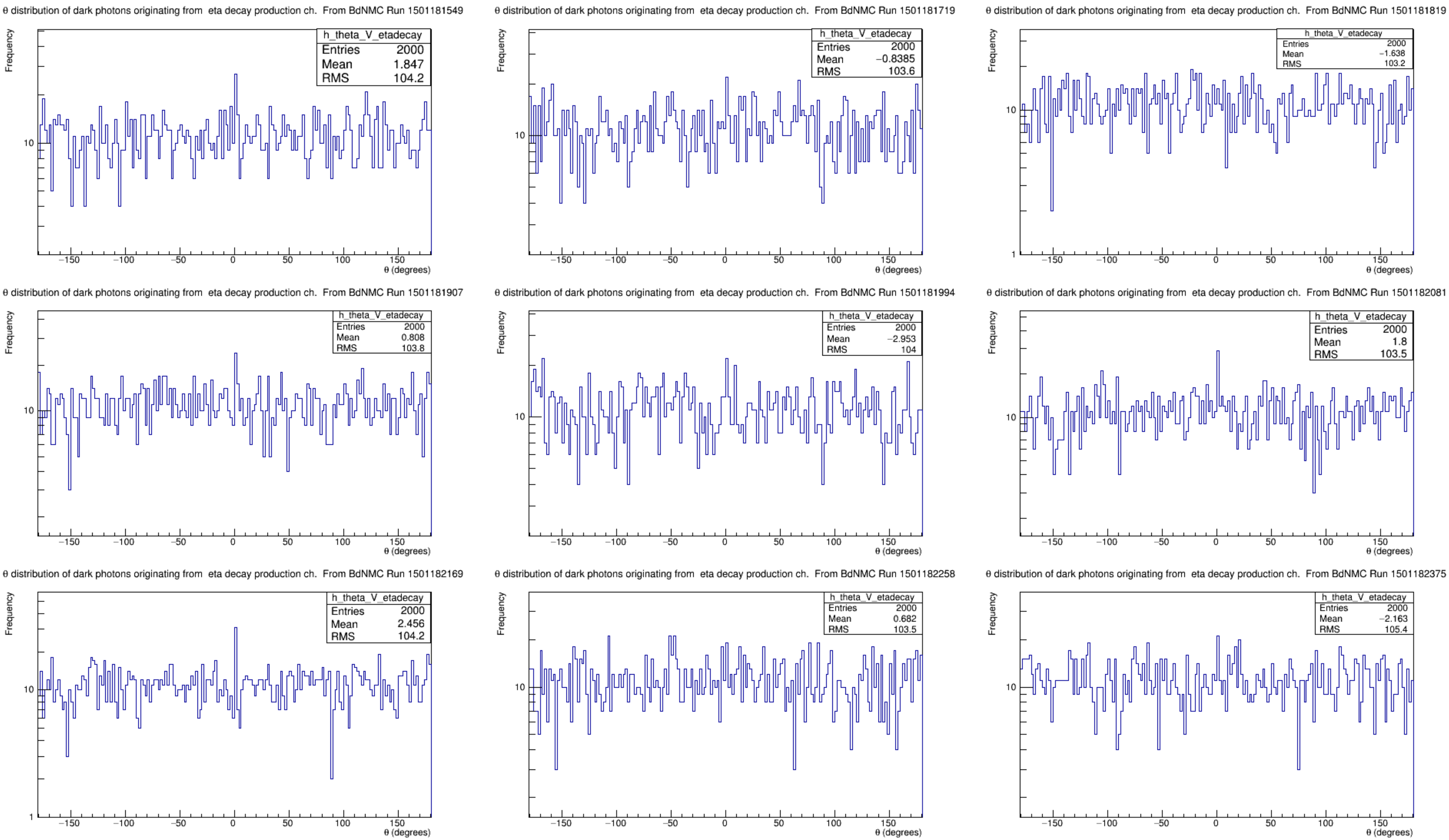
Theta distribution of dark photons originating from the pi0 decay production channel



Run1498246615, mass_V=0.02 GeV
Run1498247168, mass_V=0.03 GeV
Run1498247730 mass_V=0.05 GeV
Run1498500989, mass_V= 0.1 GeV
Run 1498241455, mass_V= 0.2 GeV
Run1498244748 , mass_V = 0.3 GeV 17
Run1498245876, mass_V = 0.4 GeV
Run1498248978, mass_V = 0.8 GeV
Run1498251170, mass_V = 0.95 GeV

Theta distribution of dark photons originating from the eta decay production channel

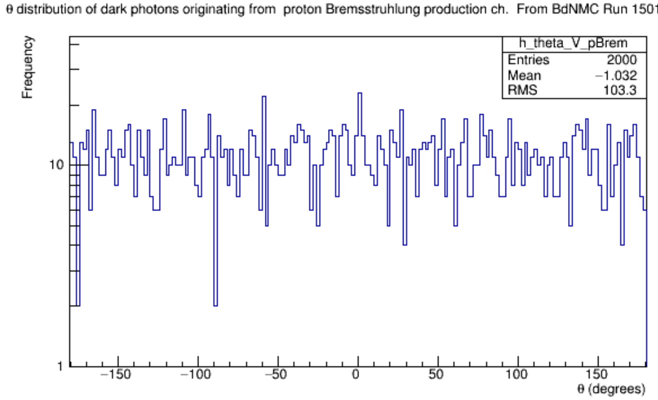
Run 1501181549, m_V=0.02 GeV
Run 1501181719, m_V= 0.03 GeV
Run 1501181819, m_V= 0.05 GeV
Run 1501181907, m_V= 0.1 GeV
Run 1501181994, m_V= 0.2 GeV
Run 1501182081, m_V= 0.3 GeV
Run 1501182169, m_V= 0.4 GeV
Run 1501182258 , m_V= 0.8 GeV
Run 1501182375 , m_V= 0.95 GeV

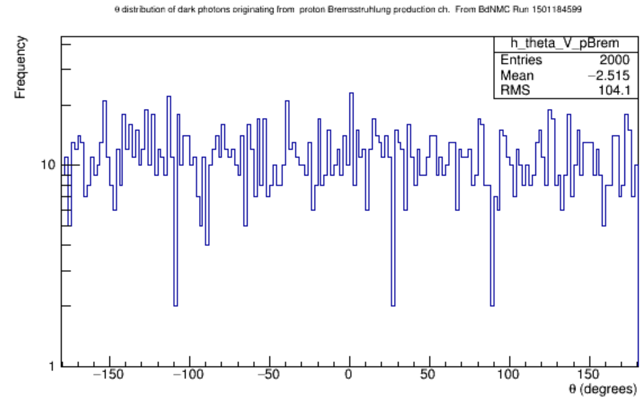


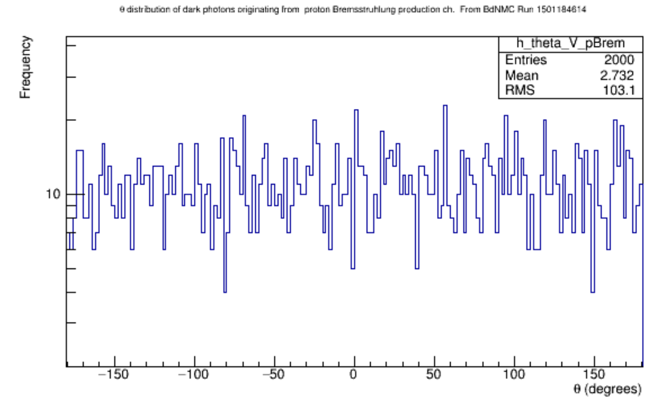
→ **No sinusoidal pattern here**

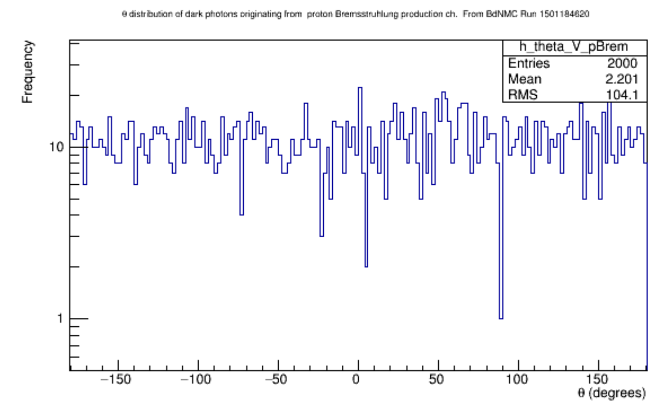
Theta distribution of dark photons originating from the proton bremsstuhlung production channel

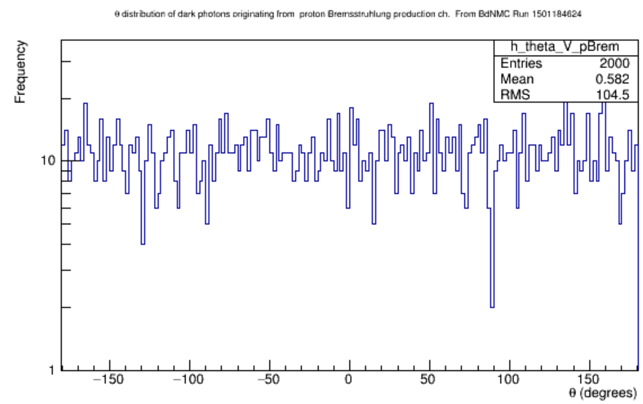
Run 1501184569, m_V= 0.03 GeV
Run 1501184599, m_V= 0.05 GeV
Run 1501184614, m_V= 0.1 GeV
Run 1501184620, m_V= 0.2 GeV
Run 1501184624, m_V= 0.3 GeV
Run1501184628 , m_V= 0.4 GeV
Run 1501184632, m_V= 0.8 GeV
Run 1501184641 , m_V= 0.95 GeV

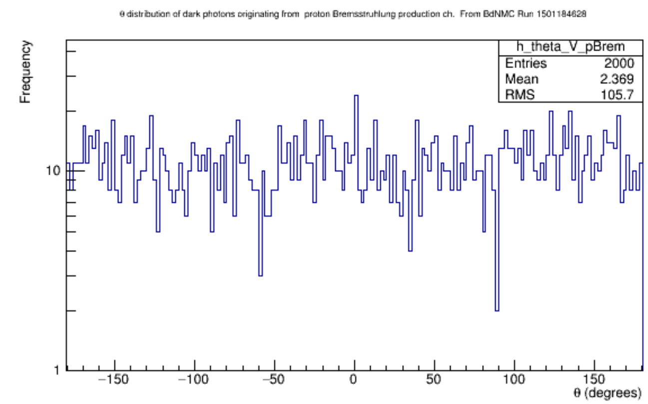


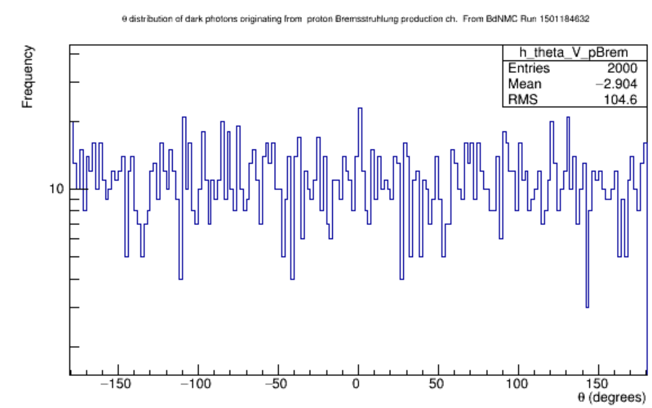


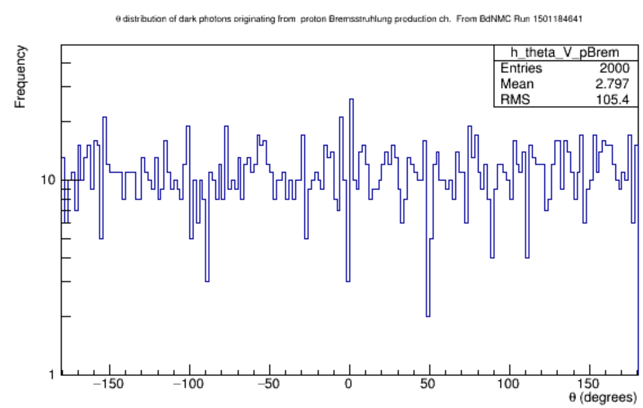












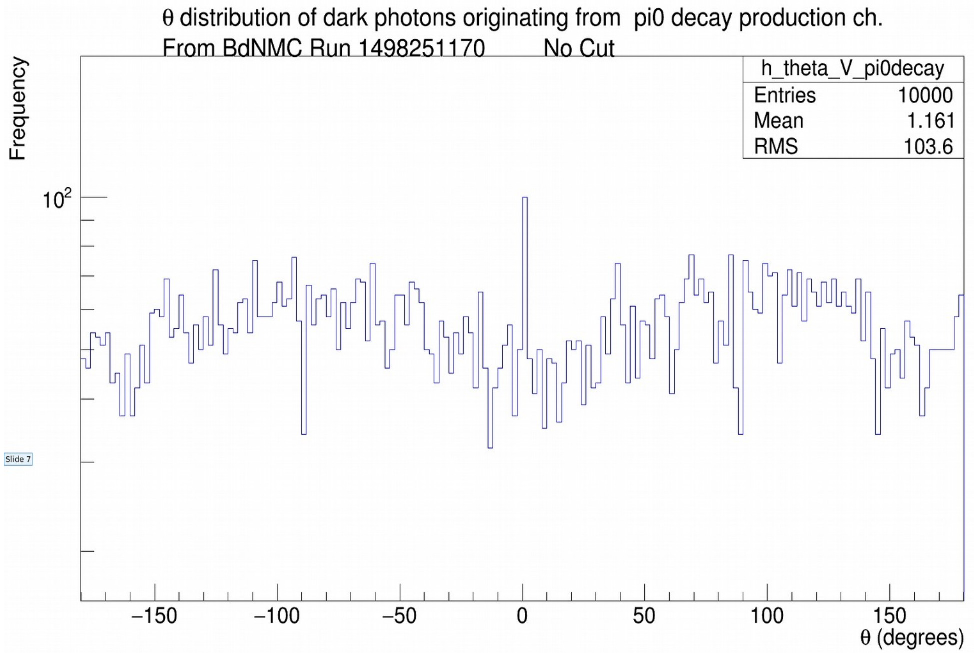
→ No sinusoidal pattern here

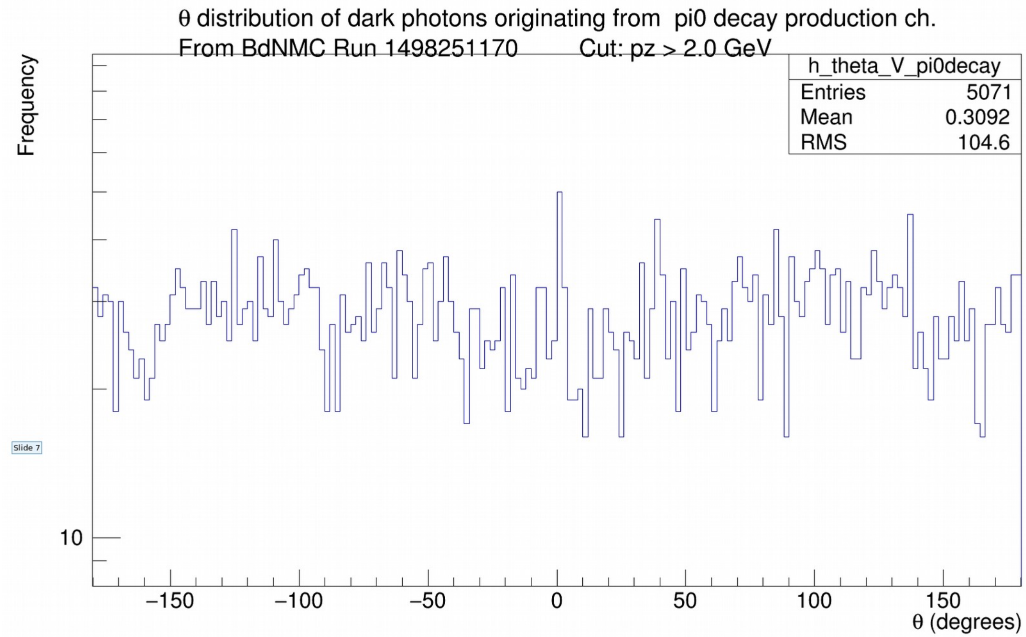
Some thoughts

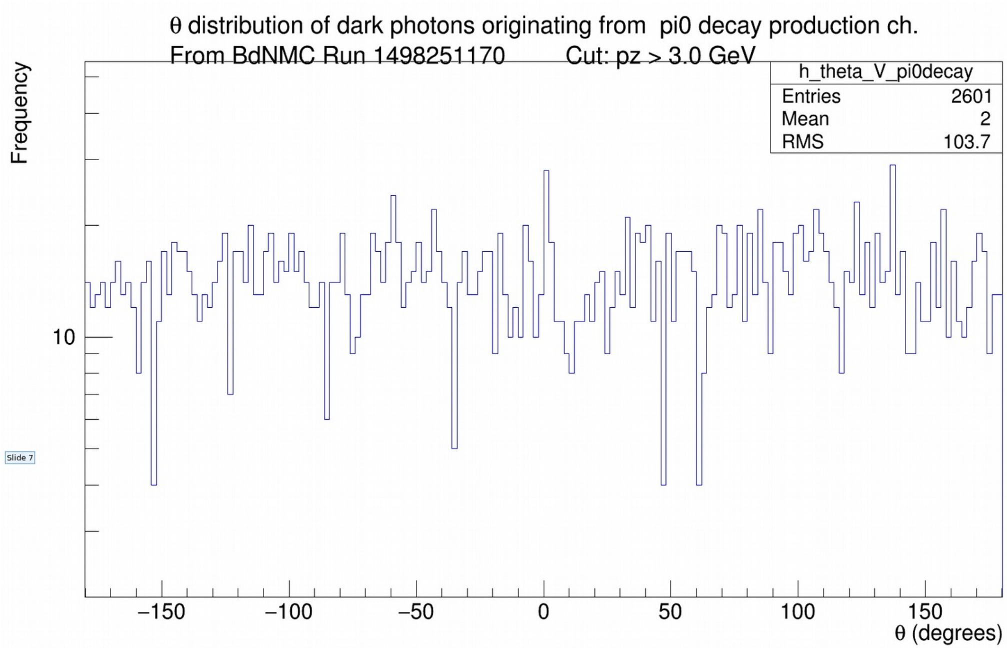
- The decay of pseudoscalar meson to V (dark photon) is isotropic in the parent particle's rest frame.
- After performing the X → V + \gamma decay, the V is Lorentz boosted from the pseudoscalar meson's rest frame to the lab frame (page 28 of [1])
- Thought: patterns in V distributions arise when V is Lorentz boosted, px py distributions are symemtroc around 0,

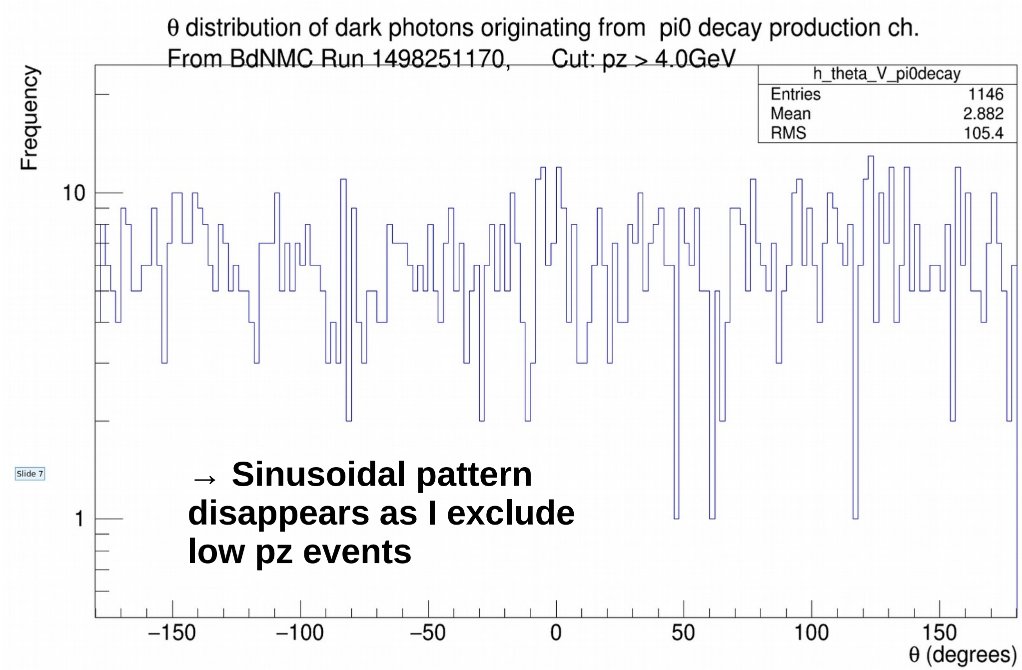
  → see difference in patterns with different cuts of pz , next slides

[1] "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP" by deNiverville et al. (arXiv:1609.01770v3)





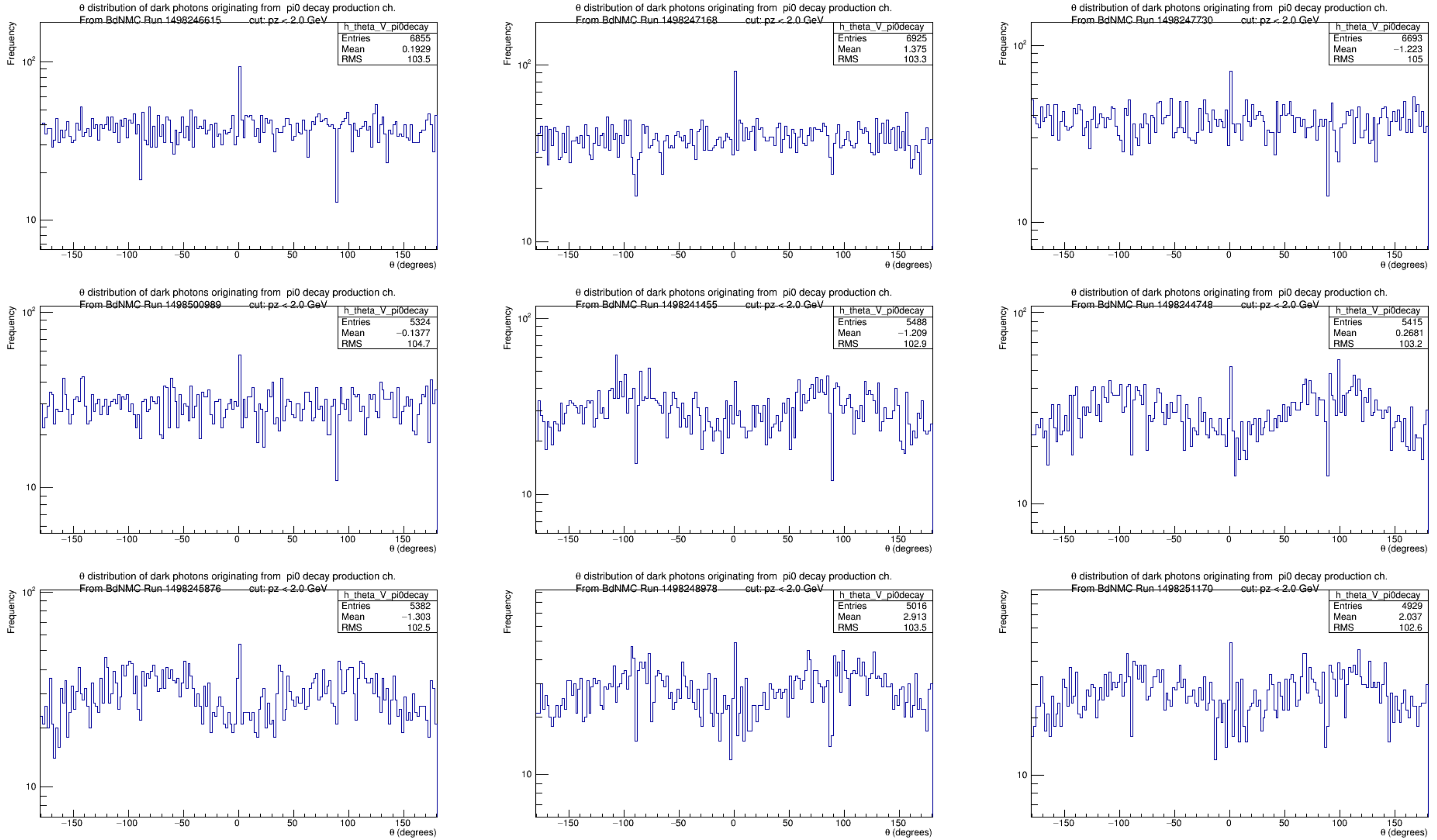




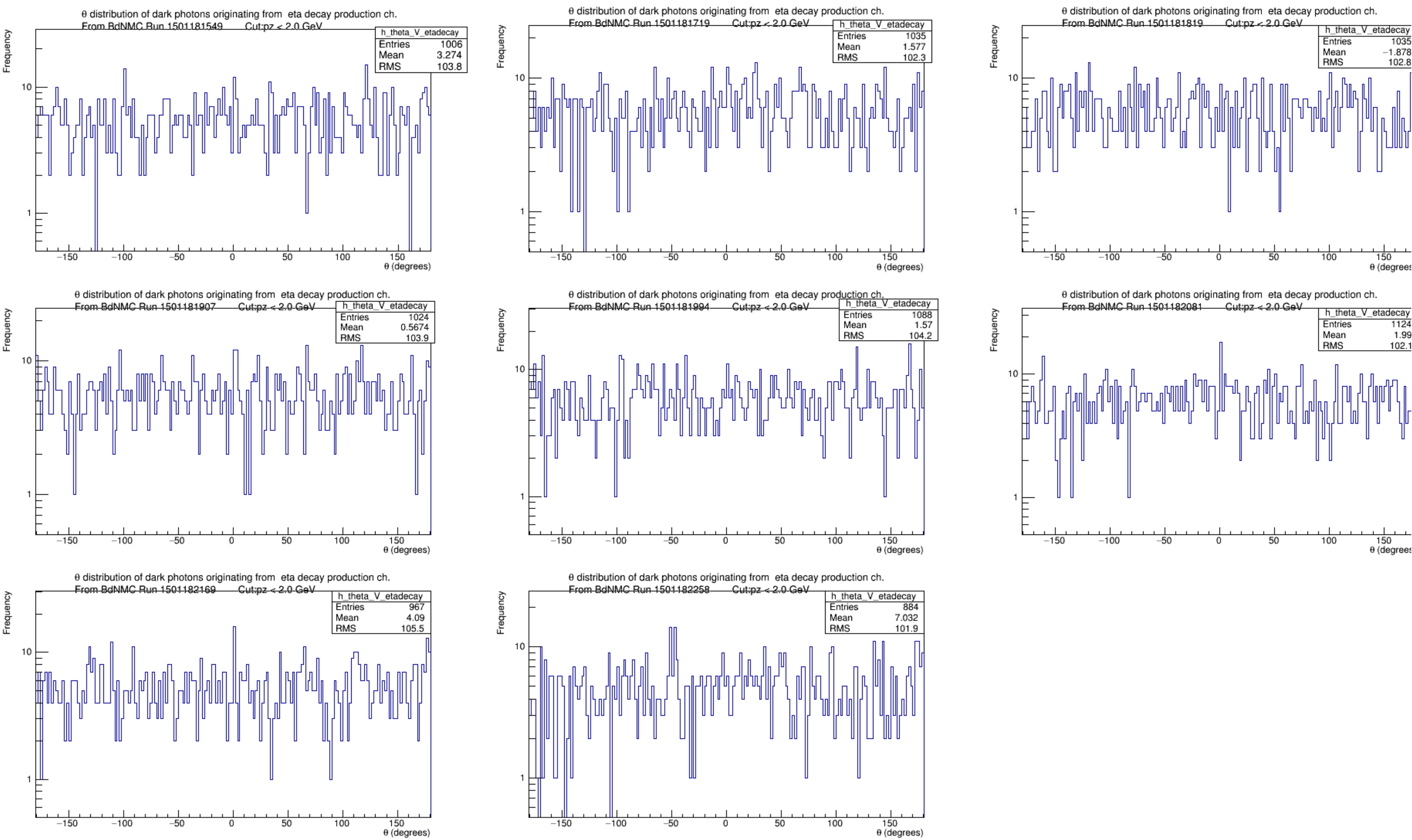
→ Sinusoidal pattern disappears as I exclude low pz events

→ **Showing events with pz of V < 2.0 GeV: sinusoidal pattern visible**

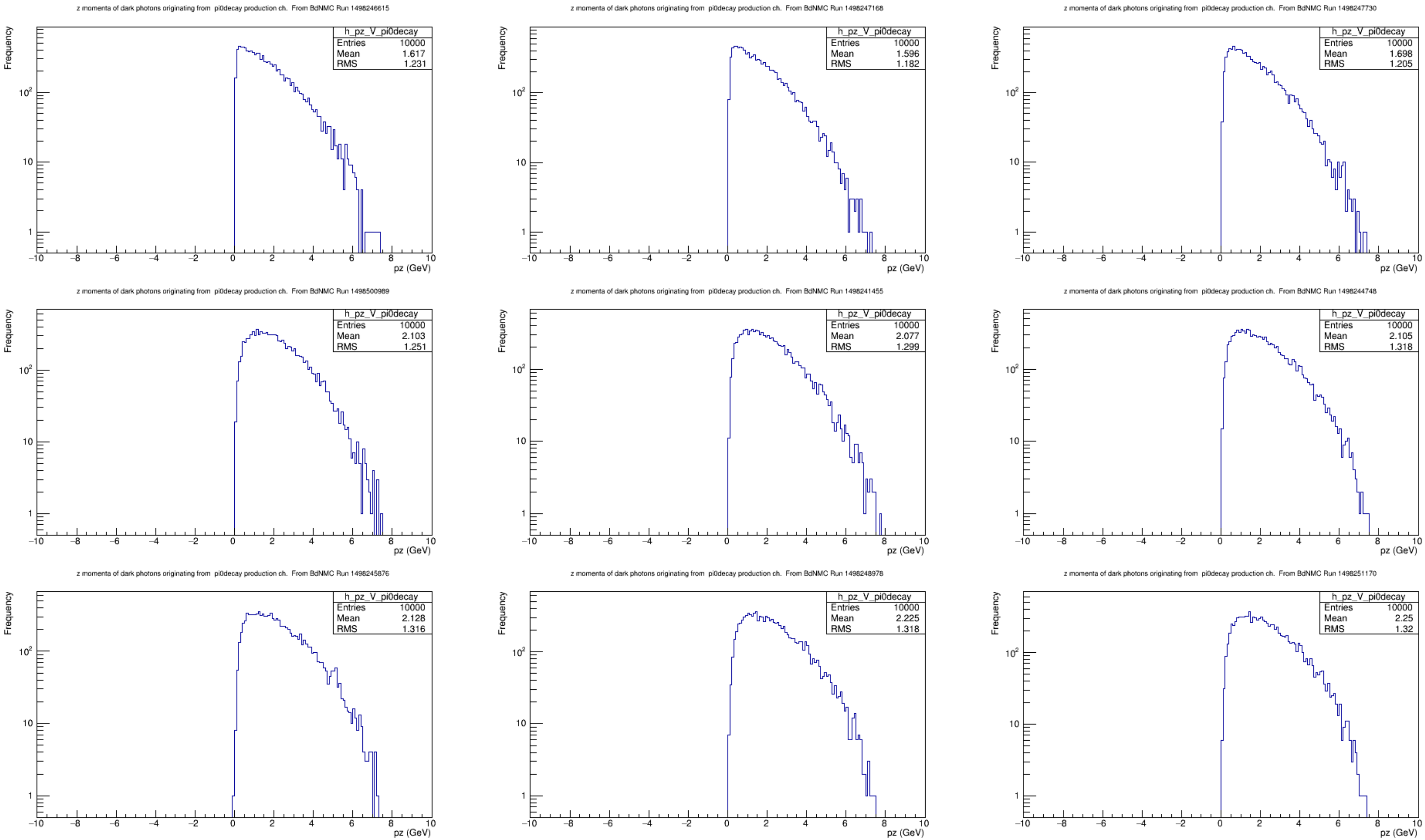
- Next slide: shows the same thing for V's originating from eta production channel



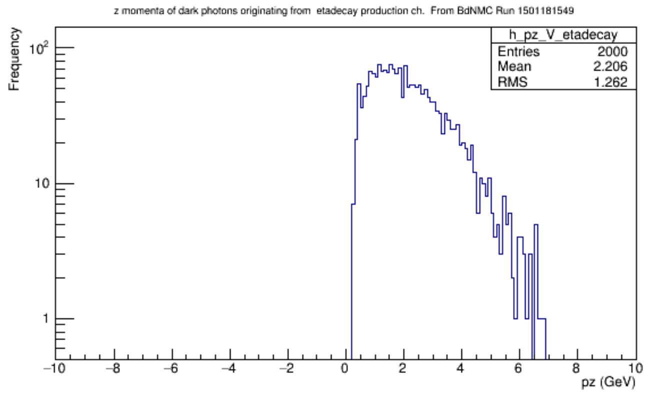
→ **Showing events with pz of V < 2.0 GeV for V originating from eta decay: no sinusoidal pattern**

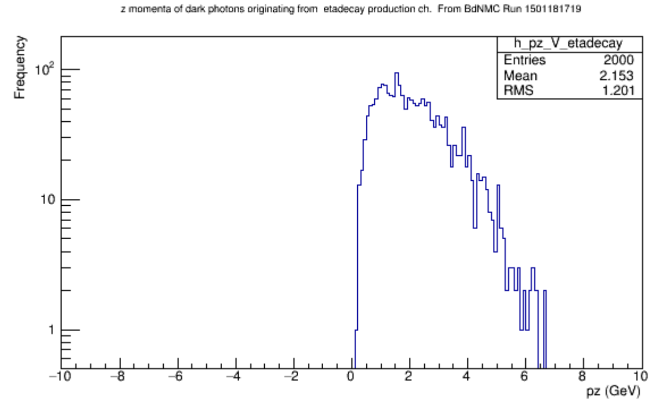


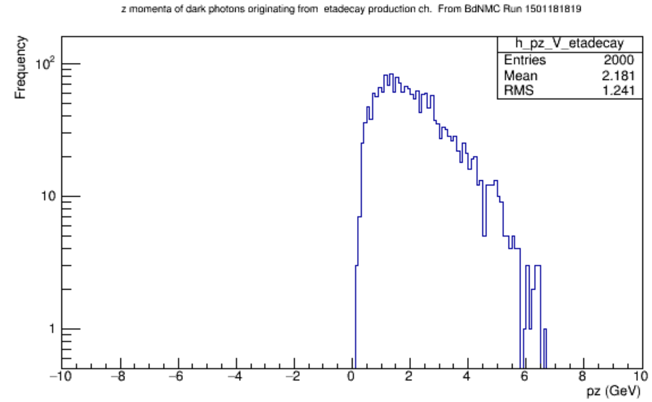
Looking at the V pz distributions for V's originating form pi0 decay

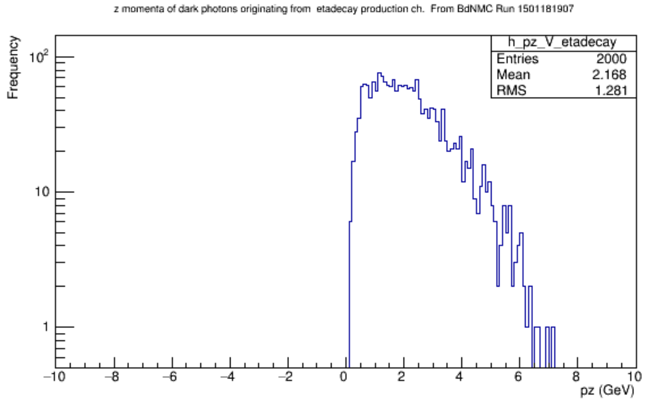


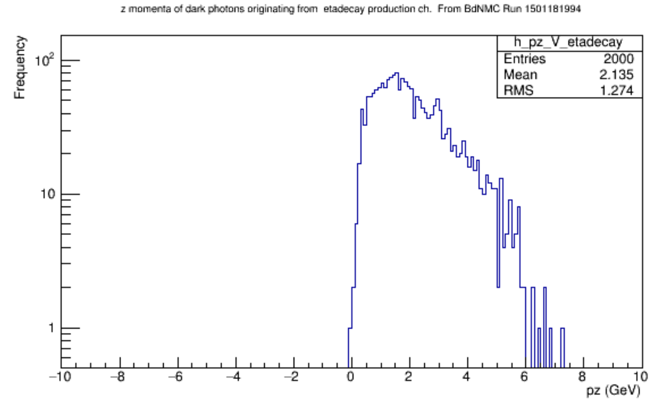
Looking at the V pz distributions for V's originating from eta decay

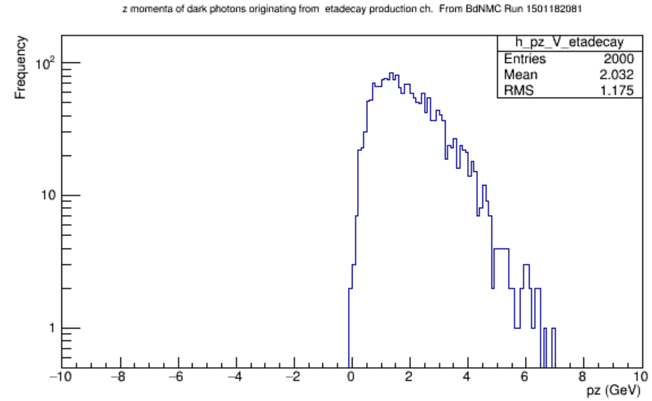


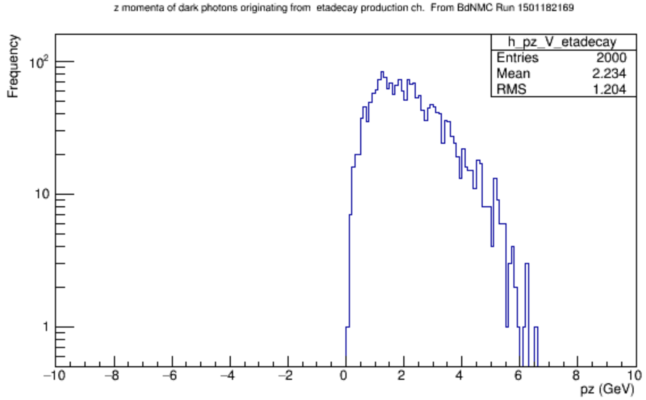


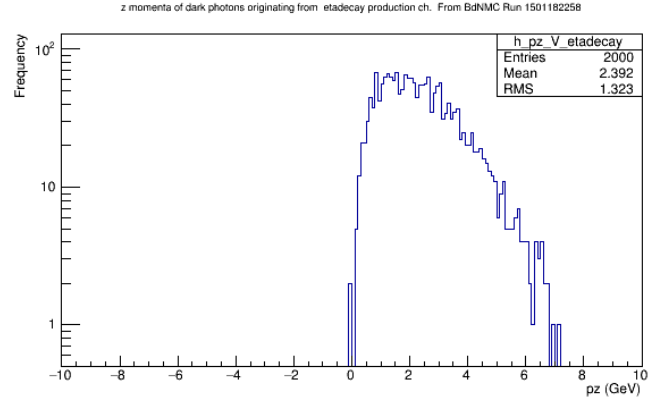








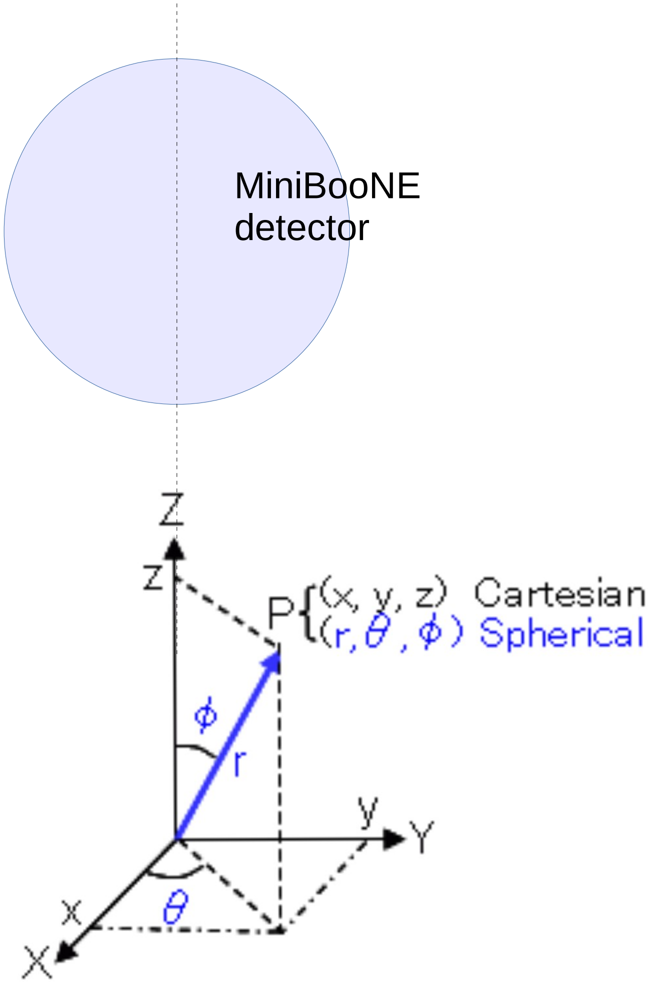




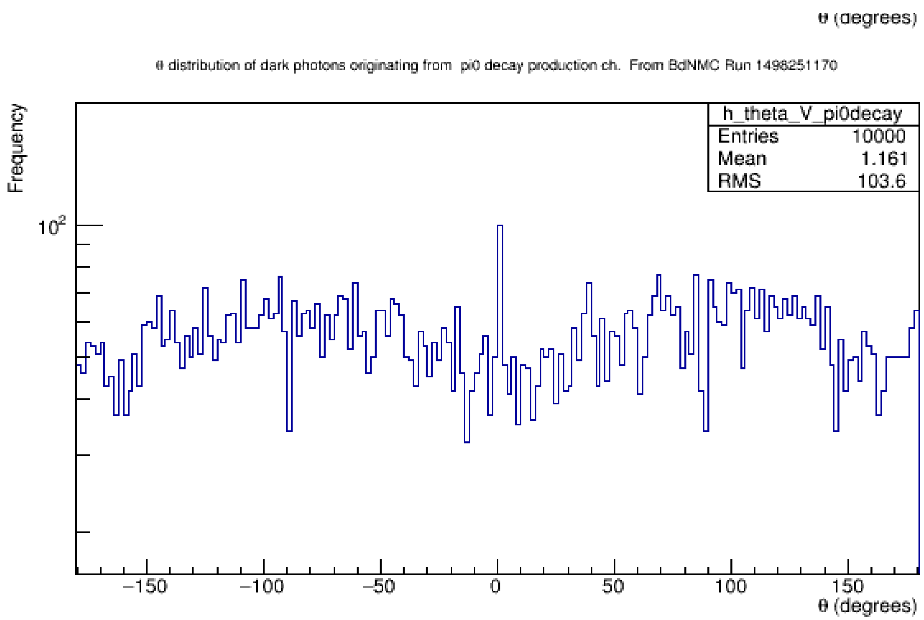
→ Not too different from the V pz distributions of V's originating from the pi0 decay production channel

Some thoughts

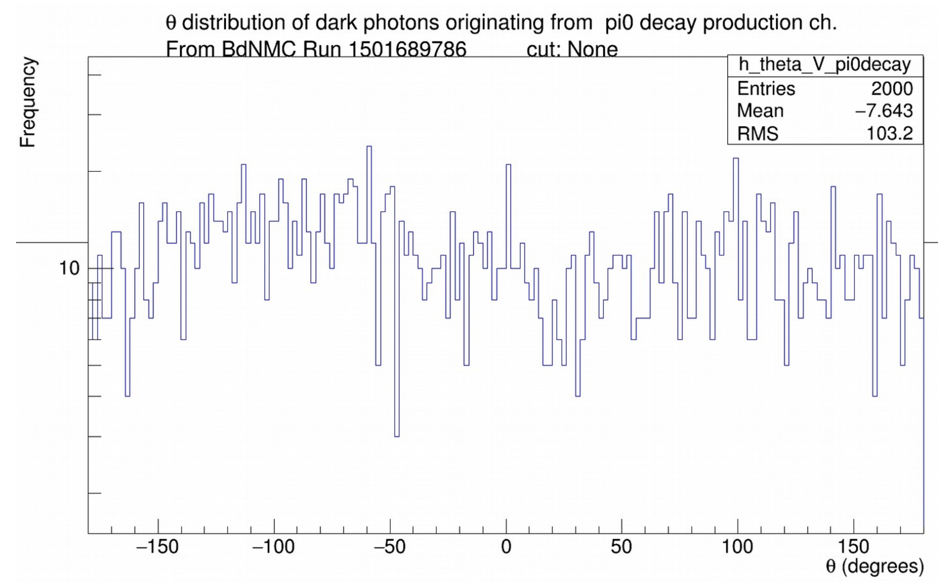
. Check detector geometry, make sure detector's center is positioend porperly



With x=0m, y=0m, z=500m



With x=0m, y=-1.9m (used by Patrick in MiniBooNE plots), z=500m

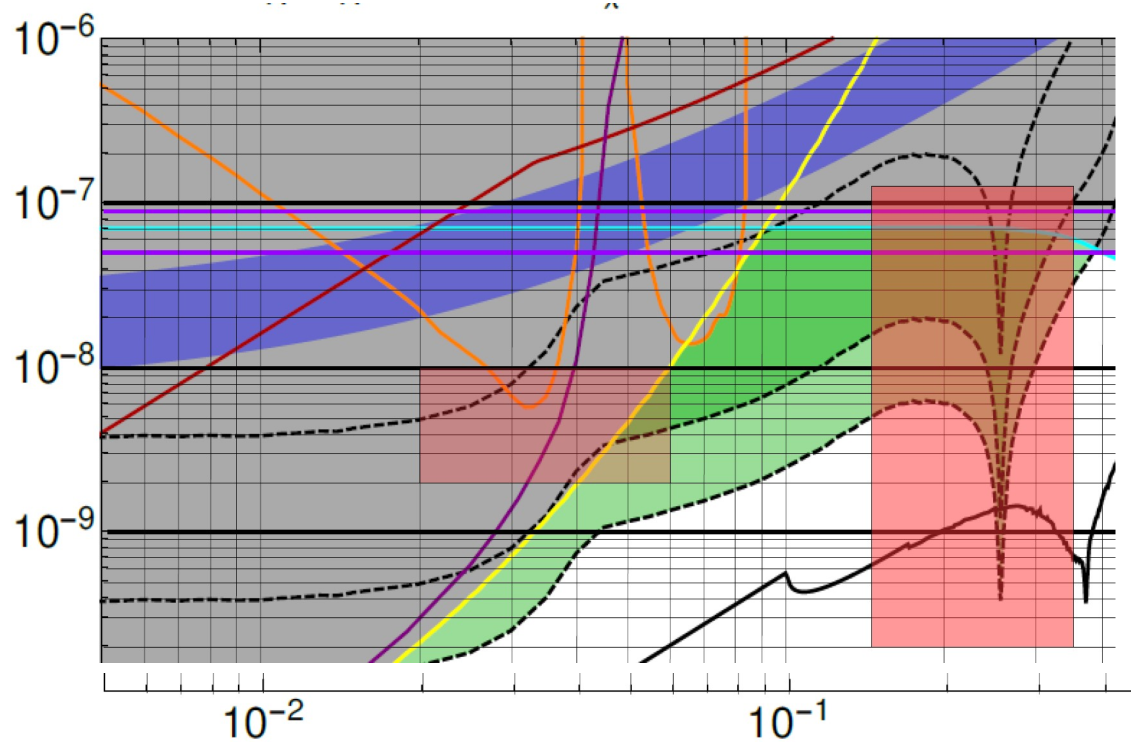


Work in progress ...

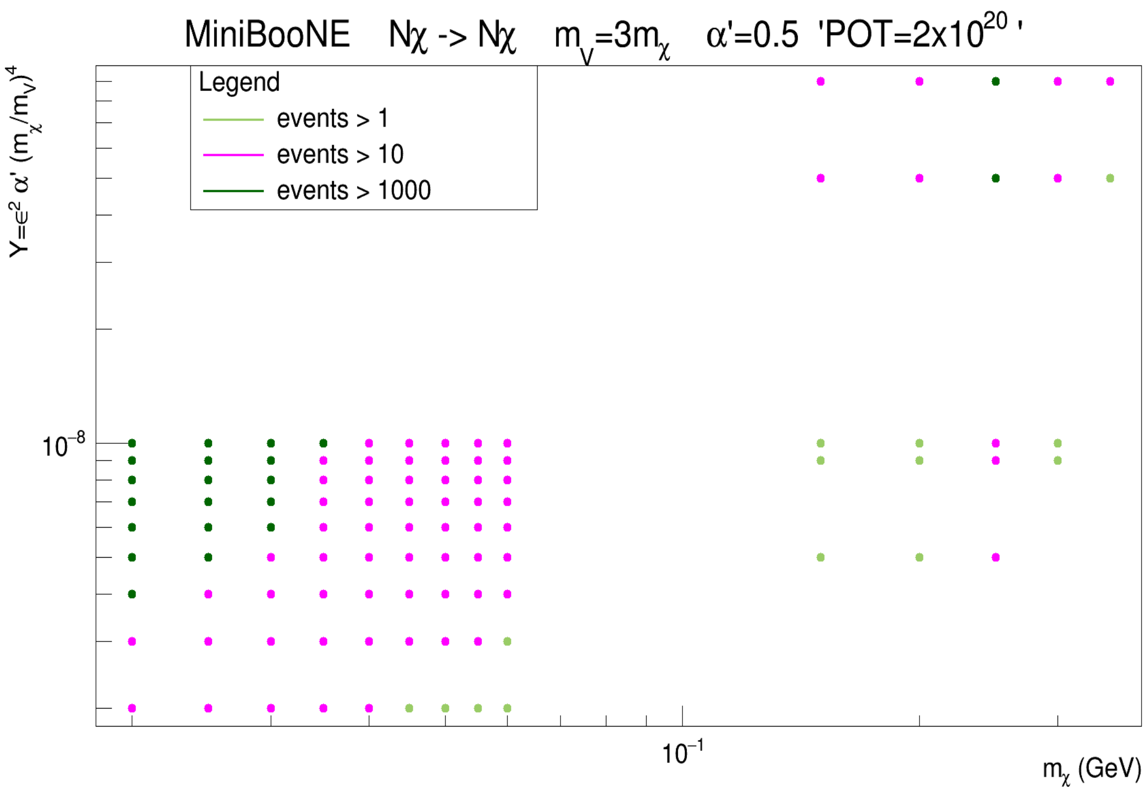
Backup

•

Zoomed in section of figure 8 from last slide



My plot:

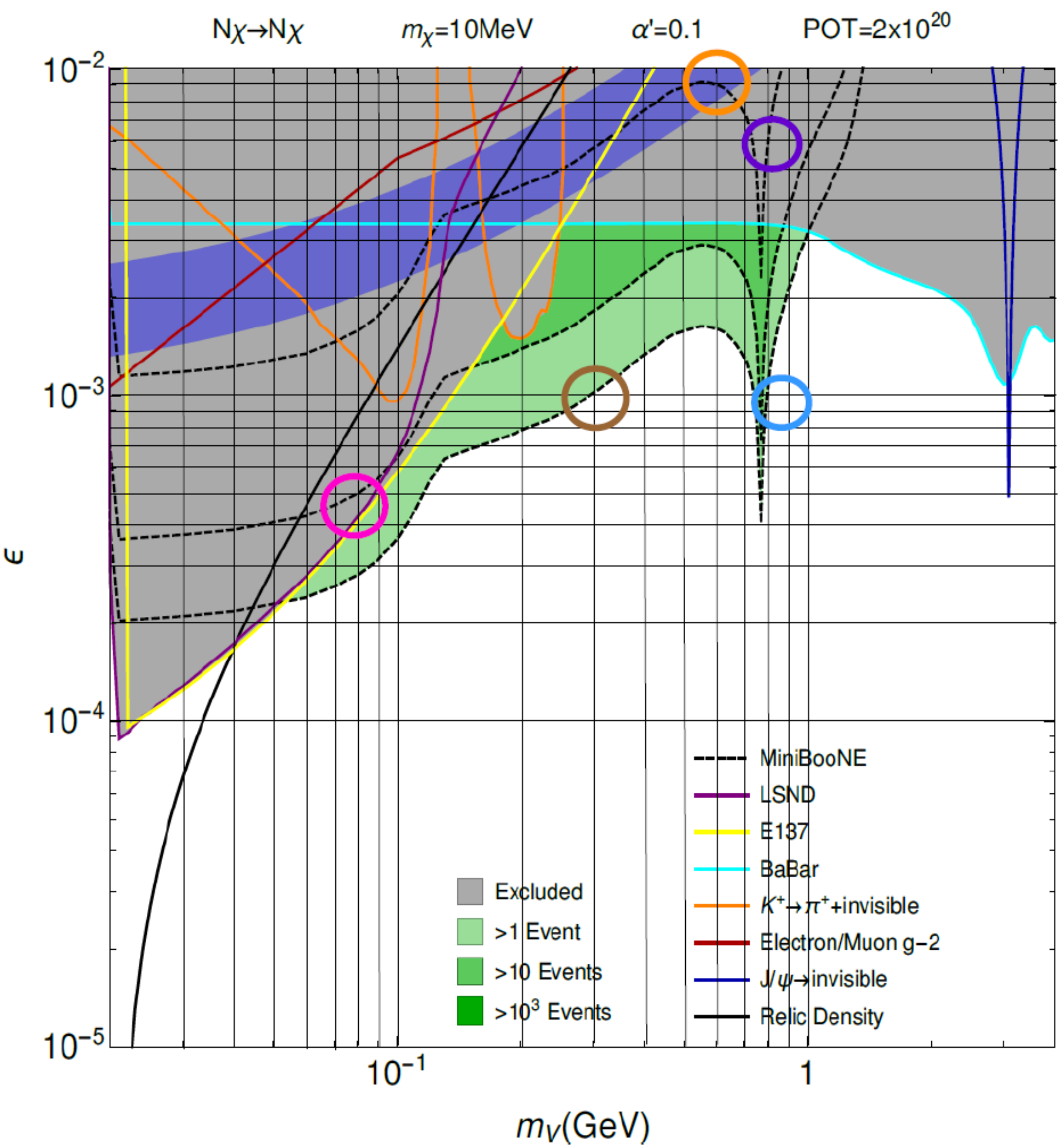


On-Shell/Off-shell

On-shell: mV > 2m and mV < mX [1]

[1] "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP" by deNiverville et al. (arXiv:1609.01770v3)

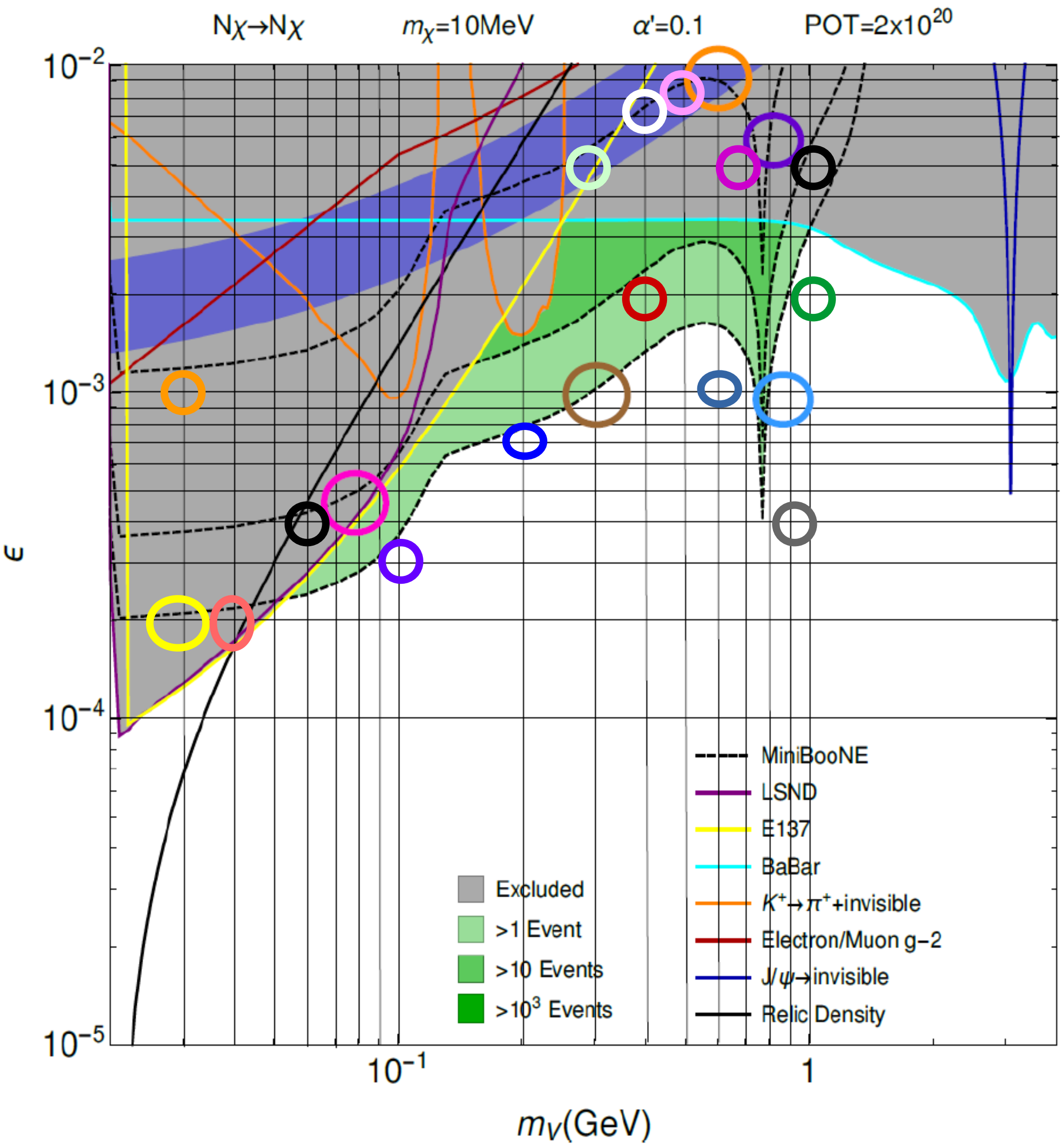
- Did what hiro suggested, ran BdNMC with POT=2x10^{25}, then divided #signal events by 10^{5}
  Did this for some points on the curves corresponding to events>1, events>10, events>1000



mV	epsilon	#events from paper's plot	What I get for #events with samplesize=2000
0.08	**0.0005**	**10**	**19.7047**
0.3	**0.001**	**1**	**1.7586**
0.6	**0.009**	**1000**	**1625.62**
0.8	**0.006**	**1000**	**1591.48**
0.8	**0.001**	**1**	**1.2306**

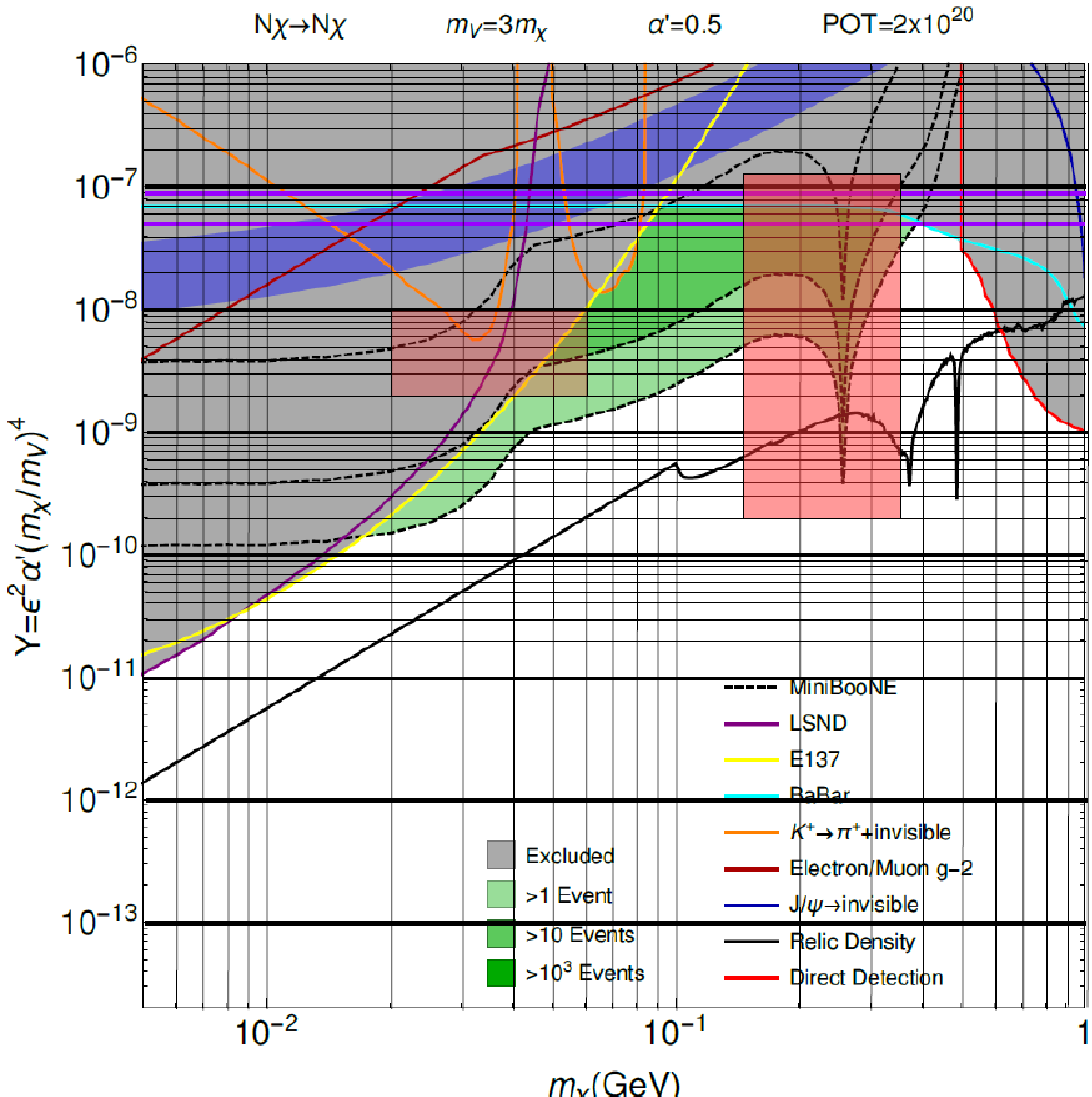
- Values don't agree (my #signal events are higher), even when considering the statistical error of my # of signal events

- Did this for some more points
  I'm getting more events than the paper for points near the boundries of the regions



mV	epsilon	#events from paper's plot	What I get for #events with samplesize=1000
0.08	0.0005	10	19.6593
0.03	0.0002	events<1	1.53437
0.04	0.0002	Events < 1	1.46220
0.1	0.0003	events<1	0.866641
0.2	0.0007	events<1	1.14948
0.6	0.001	events<1	0.243613
0.9	0.0004	events<1	0.00206906
1.0	0.002	events<1	0.28754
0.06	0.0004	1<events<10	14.7441
0.4	0.002	1<events<10	8.69028
1	0.005	1<events<10	12.0527
0.03	0.001	10<events<1000	975.59
0.3	0.005	10<events<1000	1047.9
0.4	0.007	10<events<1000	1280.88
0.5	0.008	10<events<1000	1034.59
0.7	0.005	10<events<1000	341.881

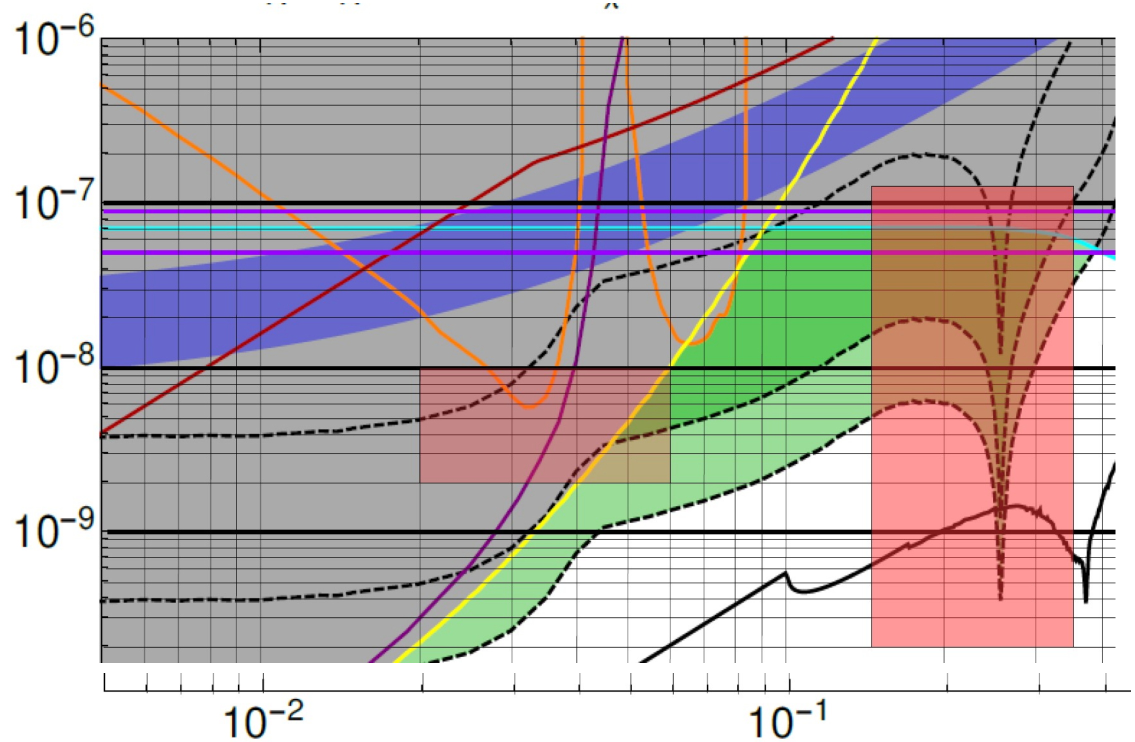
0.08	0.0005	10	19.7047
0.3	0.001	1	1.7586
0.6	0.009	1000	1625.62
0.8	0.006	1000	1591.48
0.8	0.001	1	1.2306



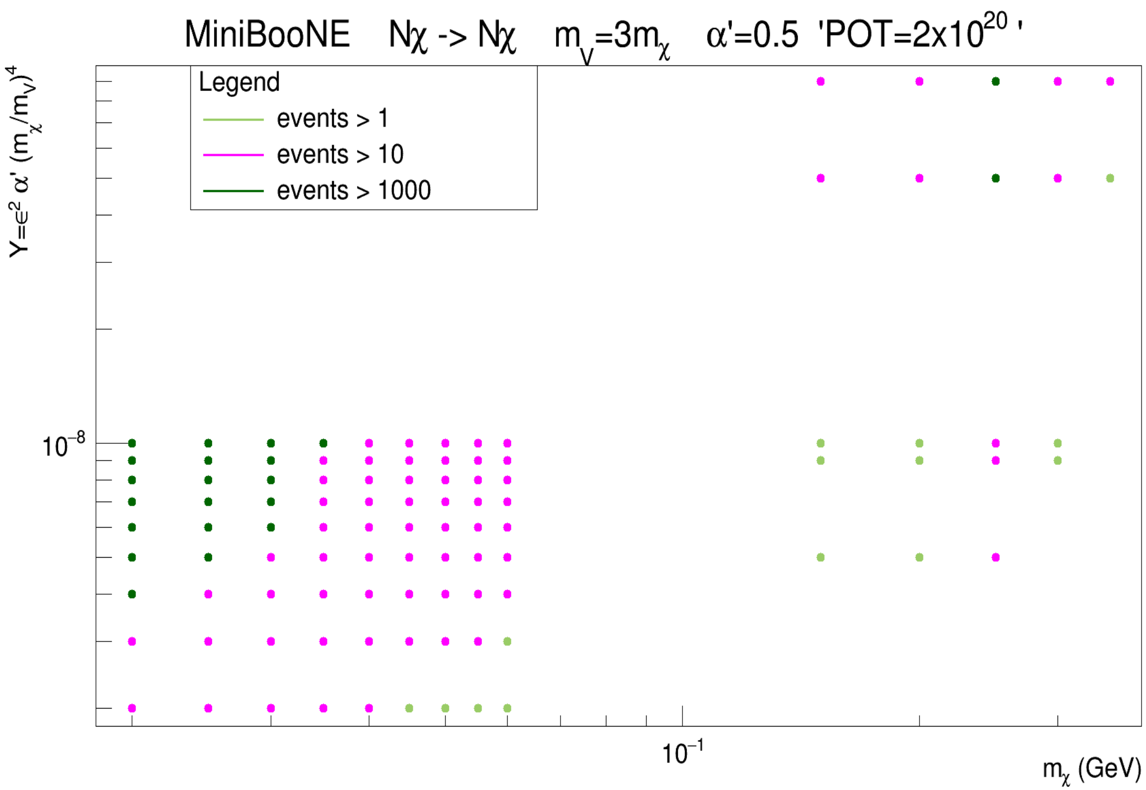
- Next: replicated some points (in red) in this plot. Checked the number of signal events for each point: same 'issue' as figure 7: # signal events agree, but I get (a few) more signal for some points

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 = 3mX with alpha' = 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.

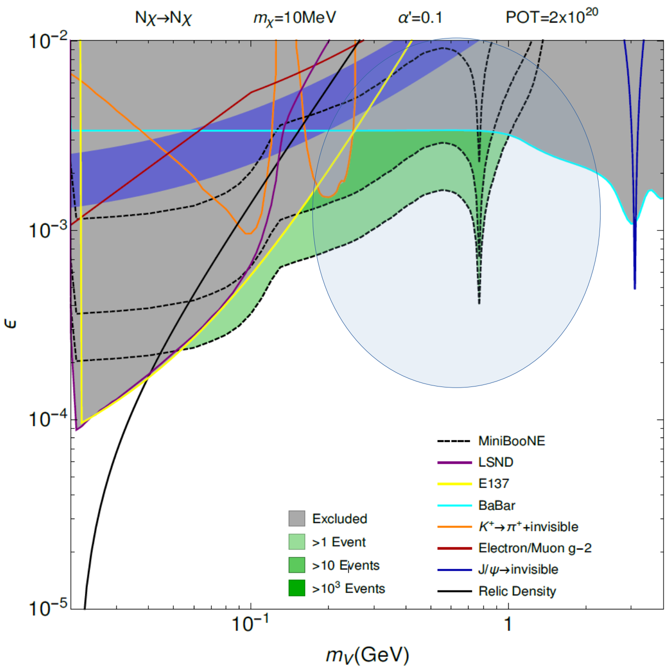
Zoomed in section of figure 8 from last slide



My plot:



Resonant Vector Meson Mixing



← Causes this peak

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

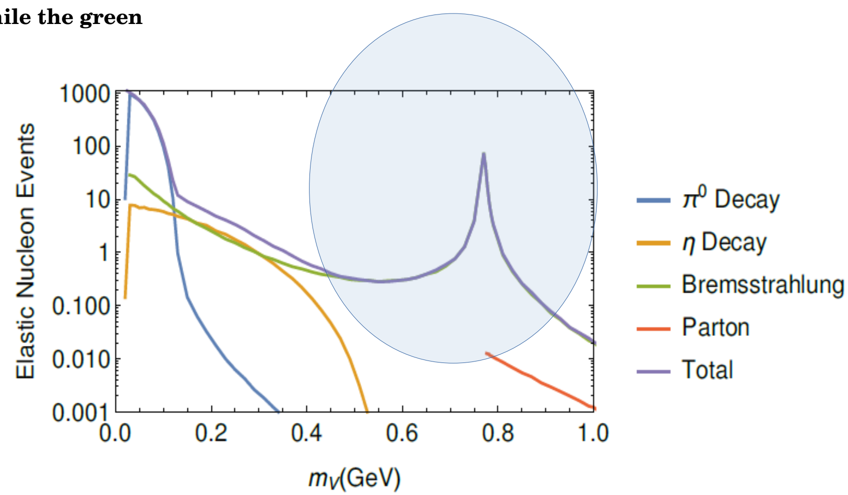


FIG. 1. A plot illustrating the distinct contributions to DM production (coupled through the vector portal), as discussed in the text, using the 9 GeV proton beam at MiniBooNE as an example. The rate of elastic scattering events on nucleons is plotted versus the vector mediator mass. From smaller to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

- In the earlier paper, 'leptophobic dark matter at neutrino factories' (2014), they have the production channels secondary meson decay, direct QCD production, and vector meson mixing ('for mV close to the mass of a vector meson rho, omega, phi, resonant production via mixing can be important ...')
  - “Although beyond the scope of this work, one can also contemplate production of DM through **bremsstrahlung**-like radiation of the vector mediator from the proton beam, and it would be worthwhile to investigate this mechanism in the future.”

(ii) *Vector meson mixing*: For m_V close to the mass of a vector meson $X = \rho, \omega, \phi$, resonant production via mixing can be important [31]. In principle, this requires an off-shell treatment of both X and V_B, to account for the full spectral shape. However, there is little (e.g. Drell-Yan) data available for the relevant kinematic range, and we will focus on one tractable contribution that corresponds to taking $\sigma(pp(n) \to V_B^* + \cdots) \sim \sigma(pp(n) \to X + \cdots) \times \mathrm{Br}(X \to V_B^* \to \chi\chi^\dagger)$. This relation can be derived in the narrow-width approximation for the vector meson resonance, and one can compute the branching ratio

$$\frac{\mathrm{Br}(X \to \chi\bar{\chi})}{\mathrm{Br}(X \to e\bar{e})} = r_\chi \left(c_X \frac{g_B}{e} - \kappa \right)^2 \left(\frac{g_B q_B}{e} \right)^2 \times \frac{m_X^4}{(m_X^2 - m_V^2)^2 + m_V^2 \Gamma_V^2} \times \left(1 + a_\chi \frac{m_\chi^2}{m_X^2} \right) \left(1 - \frac{4 m_\chi^2}{m_X^2} \right)^{1/2}, \quad (9)$$

where $c_X = \{0, 2, -1\}$ for $X = \{\rho, \omega, \phi\}$, while $r_\chi = 1$, $a_\chi = 2$ (Dirac fermion χ), or $r_\chi = 1/4$, $a_\chi = -4$ (scalar χ). In practice, the X width is usually much larger than the V_B width, so to better approximate the spectral shape we will broaden the effective resonance width, $\Gamma_V \to \Gamma_{\mathrm{eff}} \sim \Gamma_X$. (In the case of ρ, we also modify the spectral shape as a Breit-Wigner distribution does not provide a good fit to higher energy Drell-Yan data.) Further calculational details are presented in Appendix A 2. Estimated production rates for the vector mesons are again summarized in Table I.

→ Vector meson mixing is
$P+P(N) \to X \to V^*_B \to DM + DM_{\mathrm{dagger}}$
Where X is the rho, omega, or phi meson.