Weekly Update

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August 17, 2017

A summary of the production channels as described in the 2012, 2014, and 2017 papers

- .
- 2012 paper “signatures of seb-GeV dark matter beams at neutrino experiments”:
  - - indirect production: prouction of V via the decay of hadronic states (includes scalar and pseudoscalar mesons)
  - - direct production: hadron level processes like pp(n)-> V* → chi + chi + chi^ dagger
    - Thisdoes not include proton bremsstrahlung
- 2014 paper “leptophobic dark matter at neutrino factories”:
  - - secondary meson decay: pseudoscalar meson decaying into dark photon
  - - vector meson mixing: when mV close to the mass of rho, omega, phi mesons, we get a contribution from the decay of these mesons to a dark photon
  - - direct QCD production
  - - they say in the future: worthwhile to investigate production of DM through bremsstrahlung radiation of the vector mediator from the proton beam”
- 2017 paper:
- - pi0 decay
- - eta decay
- - proton Bremsstrahlung, which also includes resonant meson mixing

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)

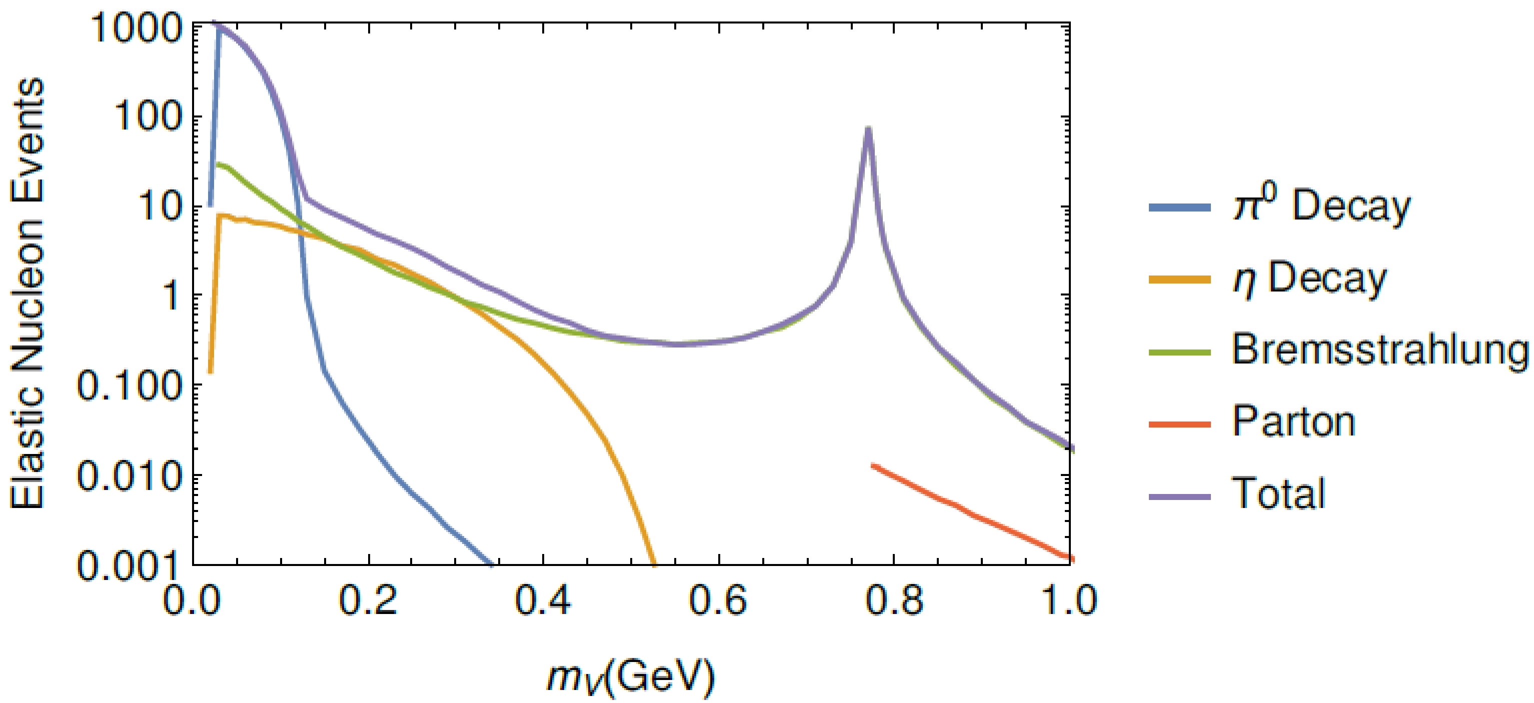


FIG. 1. A plot illustrating the distinct contributions to DM production (coupled through the vector portal), as discussed in the text, using the 9 GeV proton beam at MiniBooNE as an example. The rate of elastic scattering events on nucleons is plotted versus the vector mediator mass. From smaller to 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

    → X

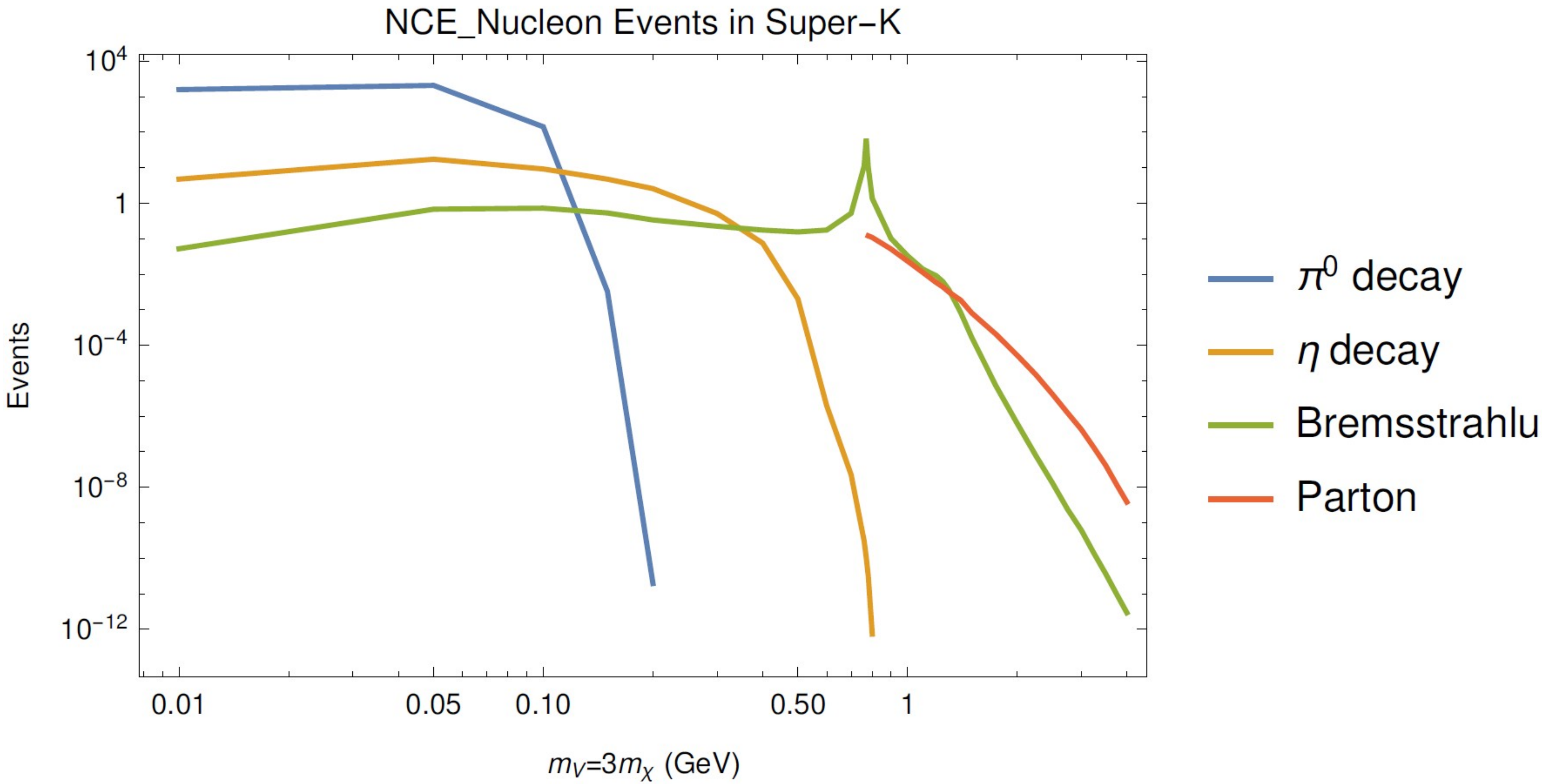
- Going to carefully look over “Signatures of sub-GeV dark matter beams at neutrino experiments” (2012 paper by Patrick, McKeen, and Ritz: arXiv:1205.3499v1) again. → X

- 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)

  → X

- asked Patrick → 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)



Parton level production only starts to dominate past m_V=1 GeV, though this calculation only includes the lowest order diagram.

→ small contribution

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)

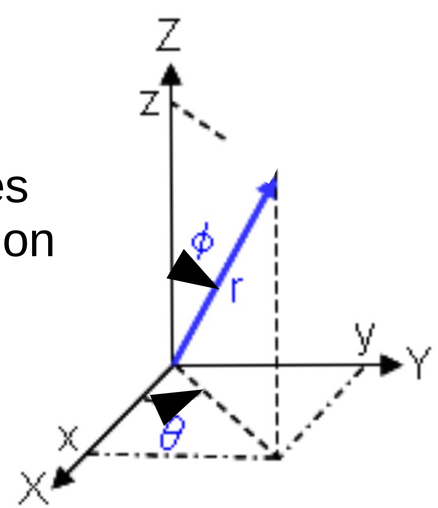
Parameters:

- 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

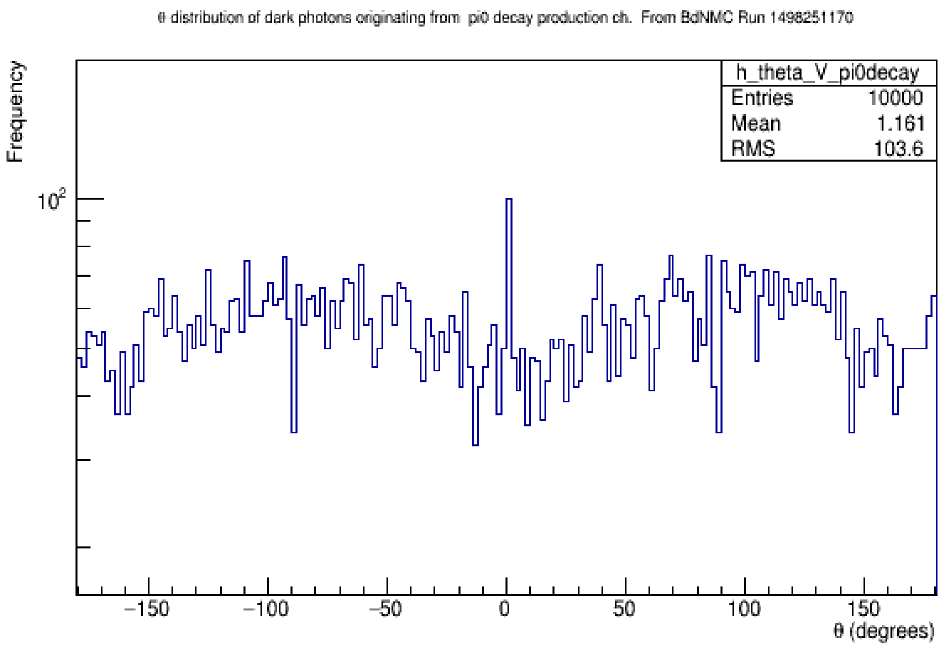


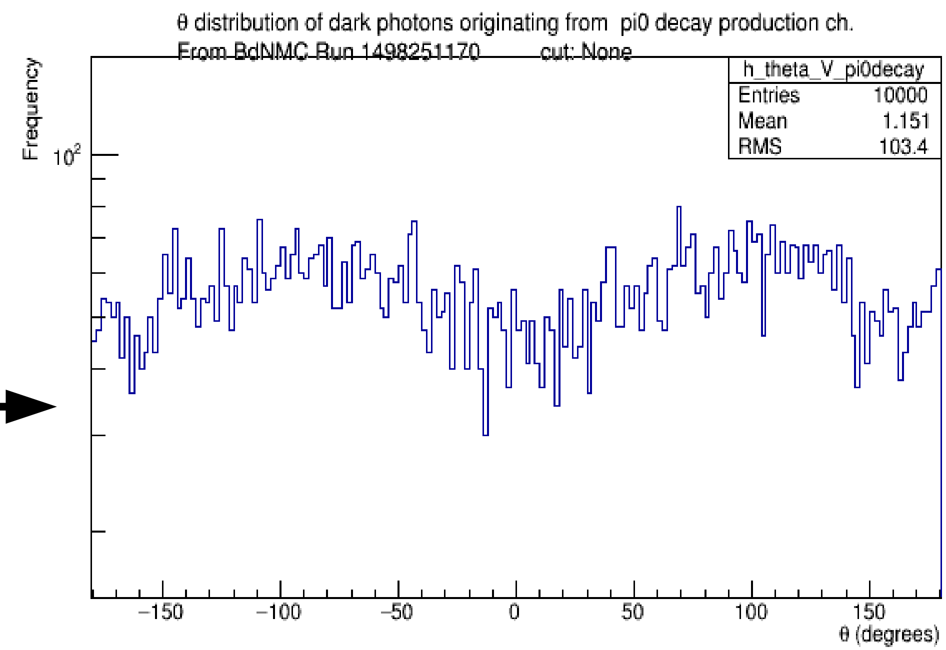
$$\theta = \tan^{-1}\frac{y}{x}$$

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

Some minor updates to code that makes these distributions

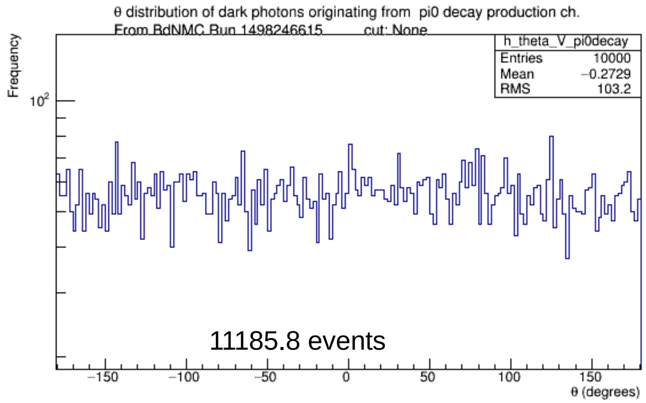
- For atan(), I have to manually determine which quadrant the angle is in. In this process, I had < and > instead of <= nad >=
  - Fixed this
- Apparently, abs() in ROOT returns an integer, TMath::Abs() returns a positive decimal → replaced abs() by Tmath::Abs()
- With these things fixed:

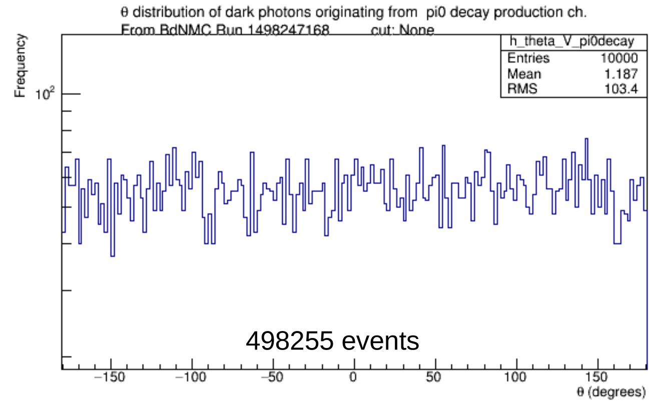


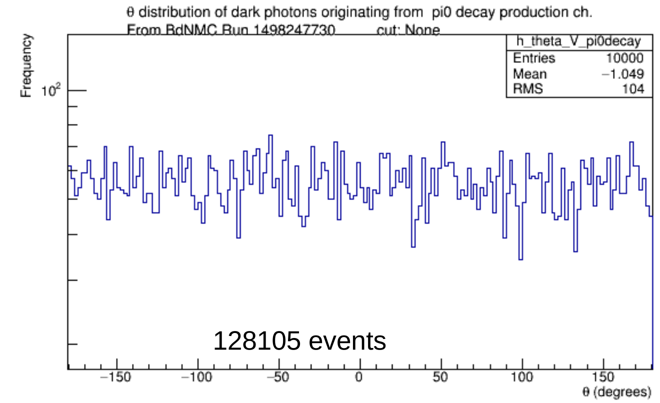


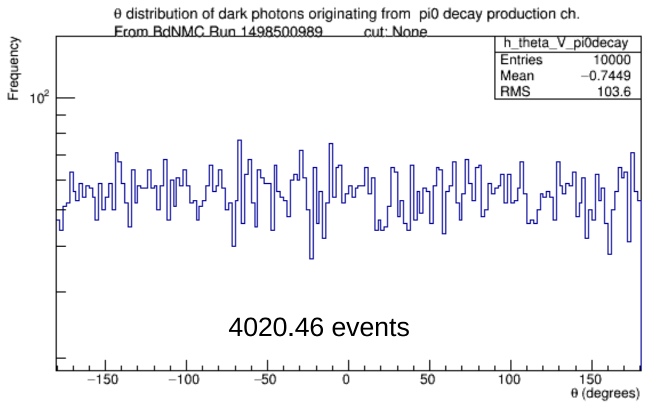
- Next few sildes show the updated plots.
  - Dips at -90/90 gone, no peak at 0, but sinusoidal pattern is still there

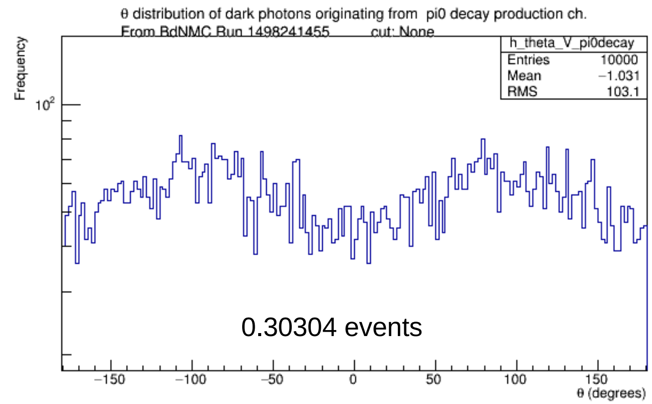
Theta distribution of dark photons originating from the pi0 decay production channel

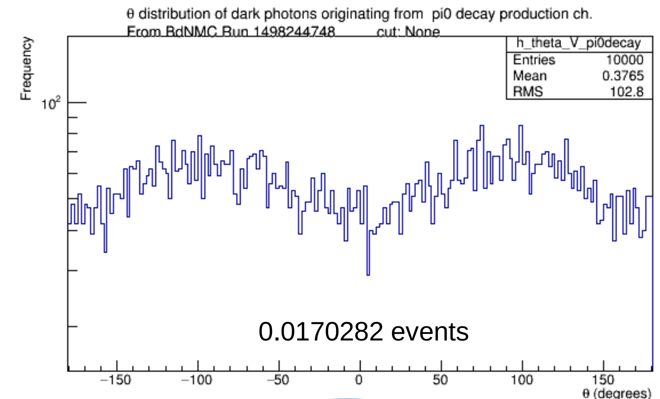


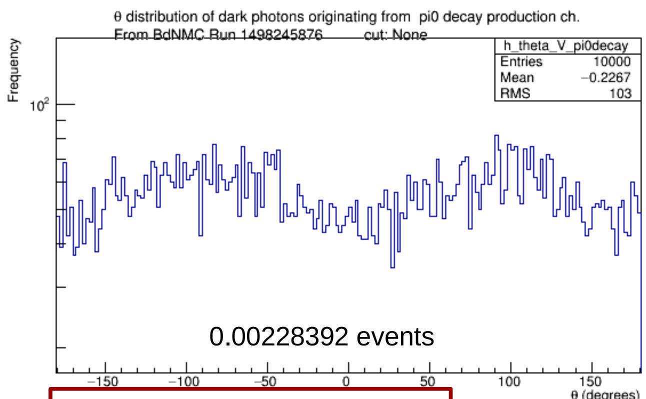


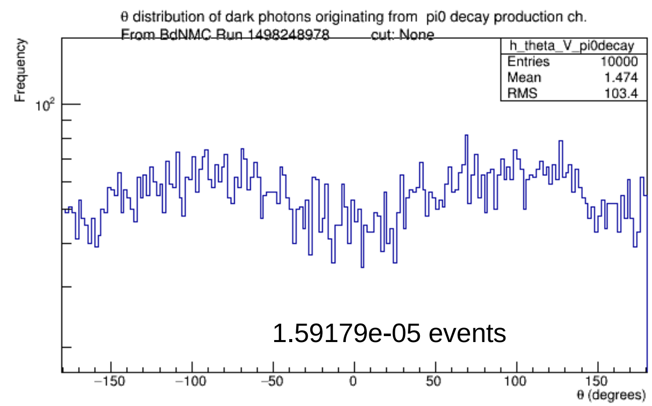


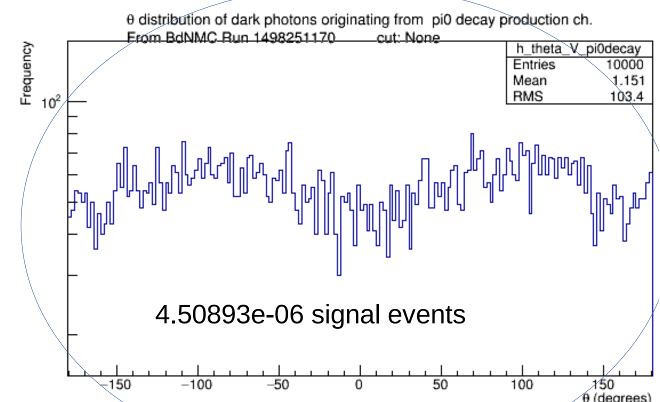








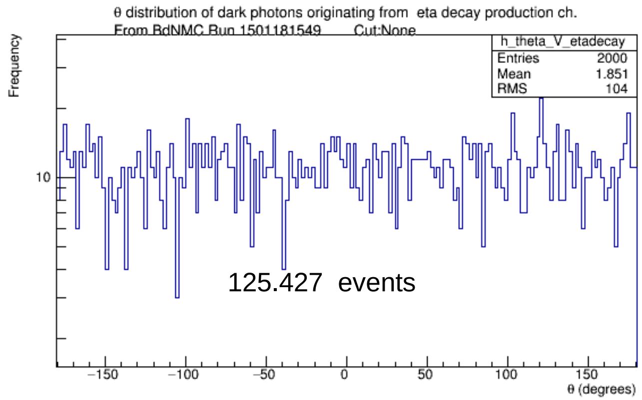


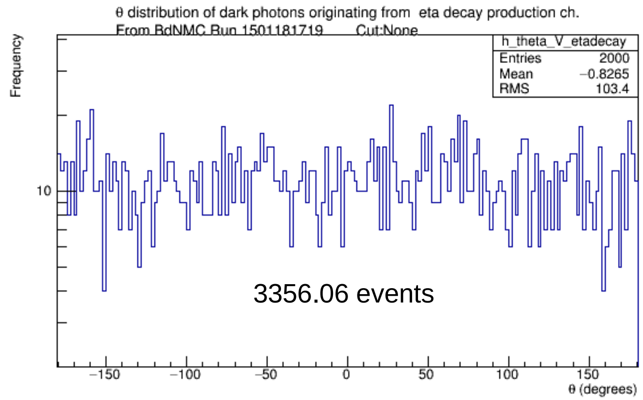


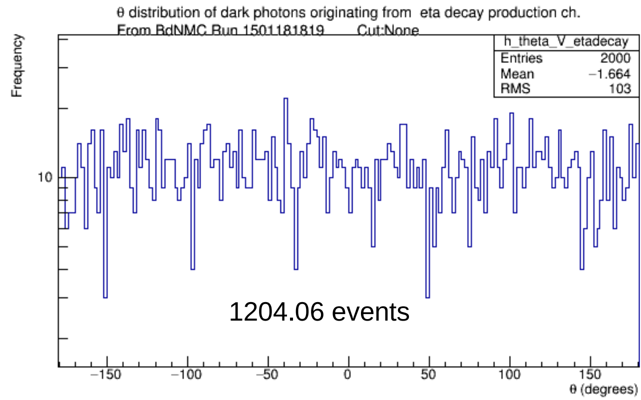
Run1498246615, mass_V=0.02 GeV
Run1498247168, mass_V=0.03 GeV
Run1498247730 mass_V=0.05 GeV
Run1498500989, mass_V= 0.1 GeV
Run 1498241455, mass_V= 0.2 GeV
Run1498244748 , mass_V = 0.3 GeV
Run1498245876, mass_V = 0.4 GeV
Run1498248978, mass_V = 0.8 GeV
Run1498251170, mass_V = 0.95 GeV

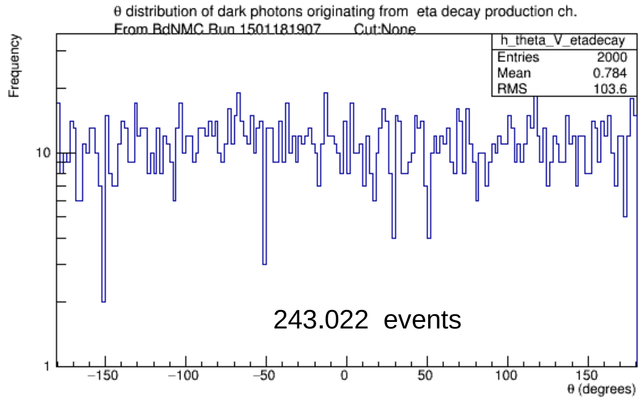
Theta distribution of dark photons originating from the eta decay production channel

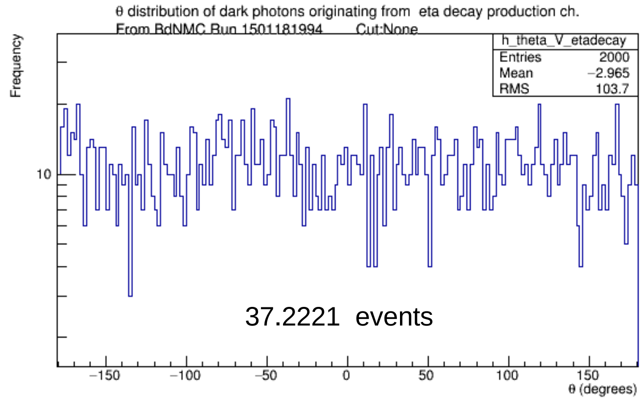
Run 1501181549, m_V=0.02 GeV Run 1501181719, m_V= 0.03 GeV Run 1501181819, m_V= 0.05 GeV
Run 1501181907, m_V= 0.1 GeV Run 1501181994, m_V= 0.2 GeV Run 1501182081, m_V= 0.3 GeV
Run 1501182169, m_V= 0.4 GeV Run 1501182258 , m_V= 0.8 GeV Run 1501182375 , m_V= 0.95 GeV

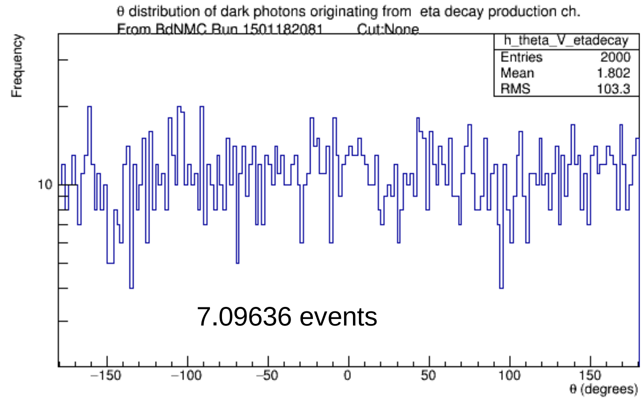


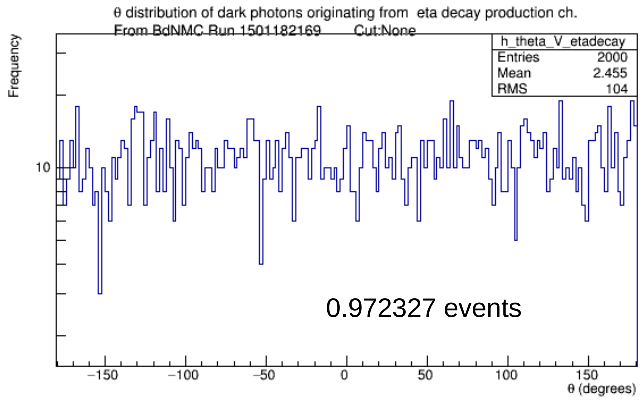


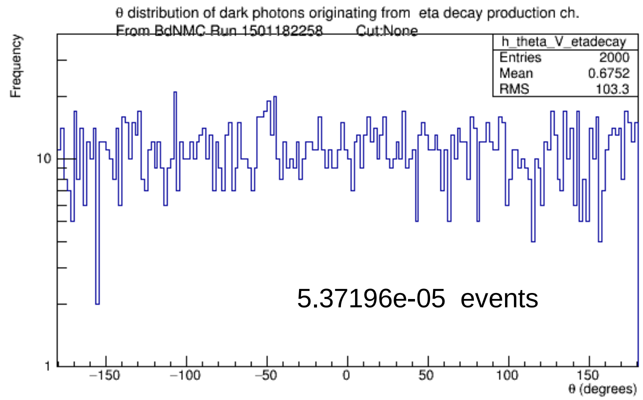








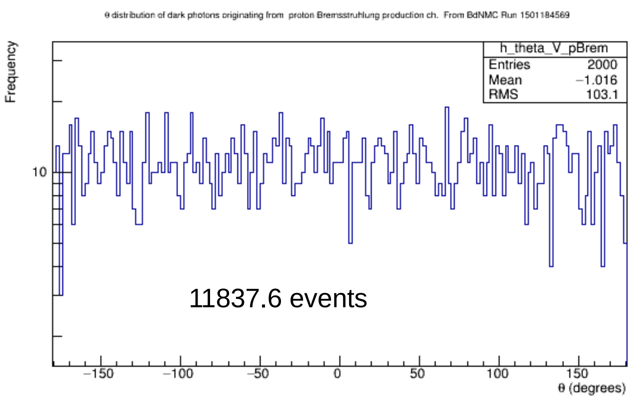


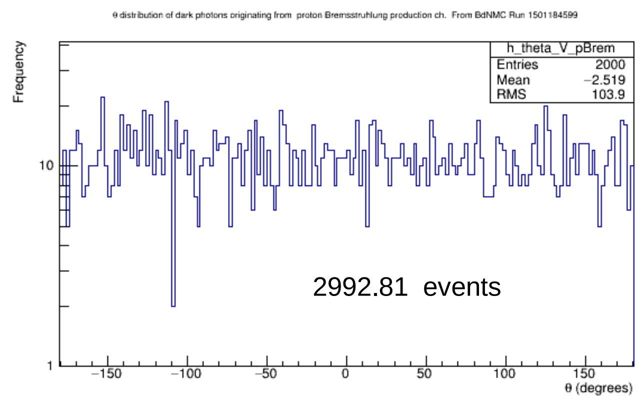


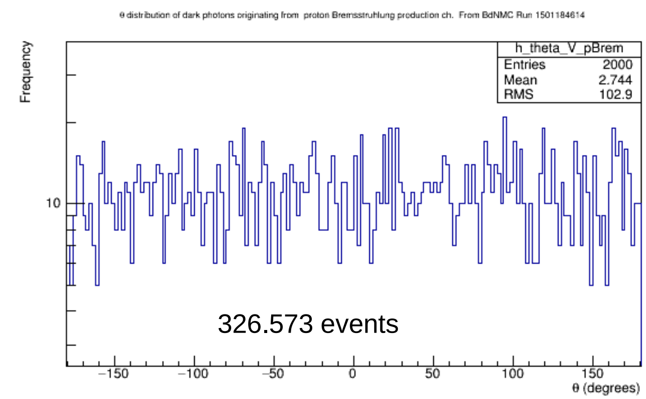
→ **No sinusoidal pattern here**

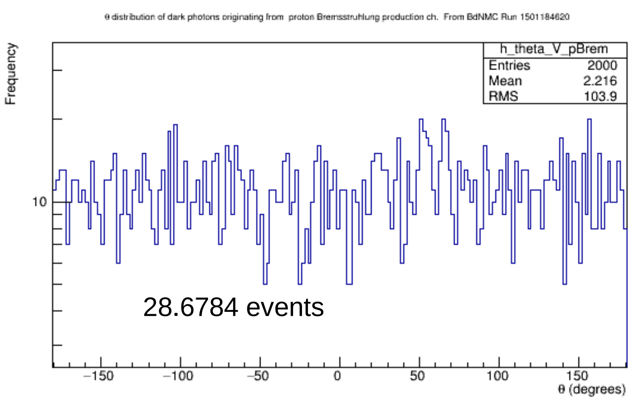
Theta distribution of dark photons originating from the proton bremsstuhlung production channel

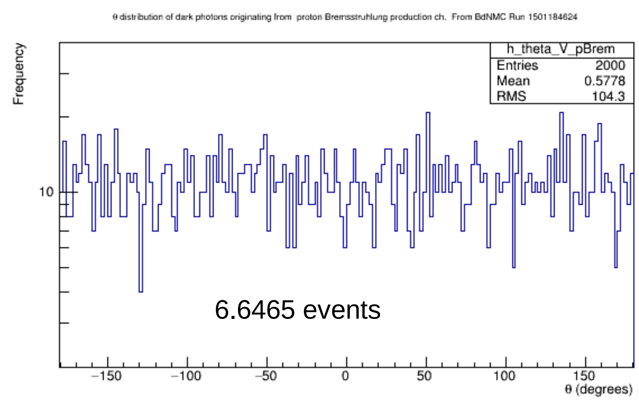
Run 1501184569, m_V= 0.03 GeV
Run 1501184599, m_V= 0.05 GeV
Run 1501184614, m_V= 0.1 GeV
Run 1501184620, m_V= 0.2 GeV
Run 1501184624, m_V= 0.3 GeV
Run1501184628 , m_V= 0.4 GeV
Run 1501184632, m_V= 0.8 GeV
Run 1501184641 , m_V= 0.95 GeV

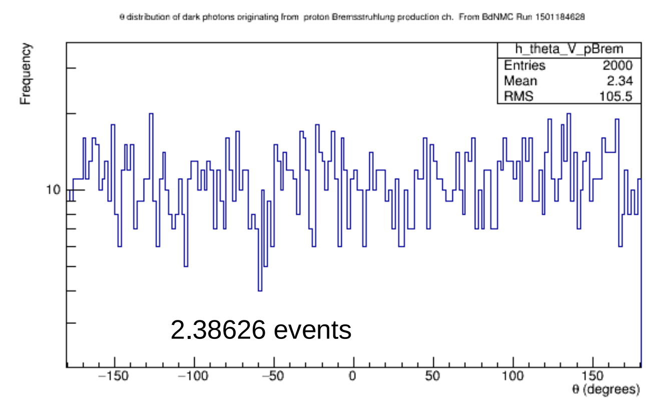


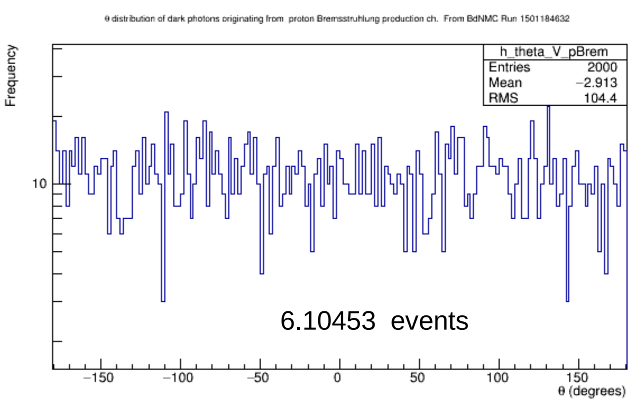


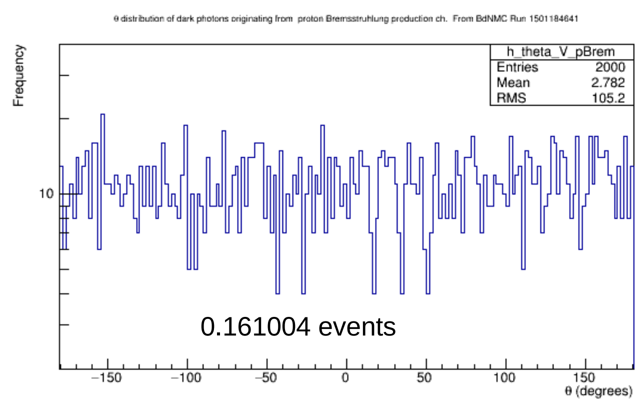










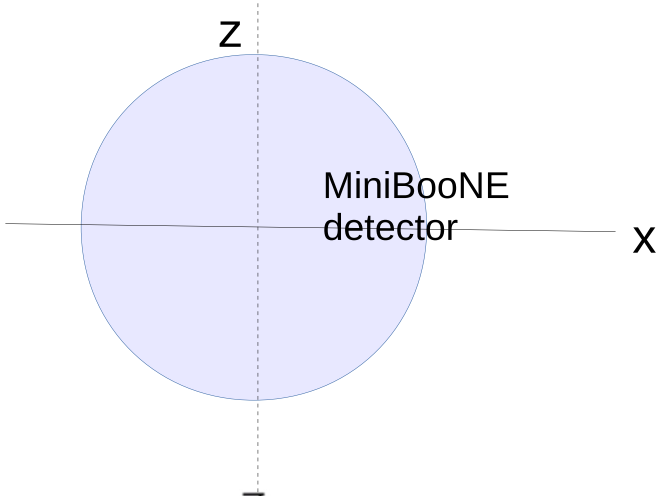


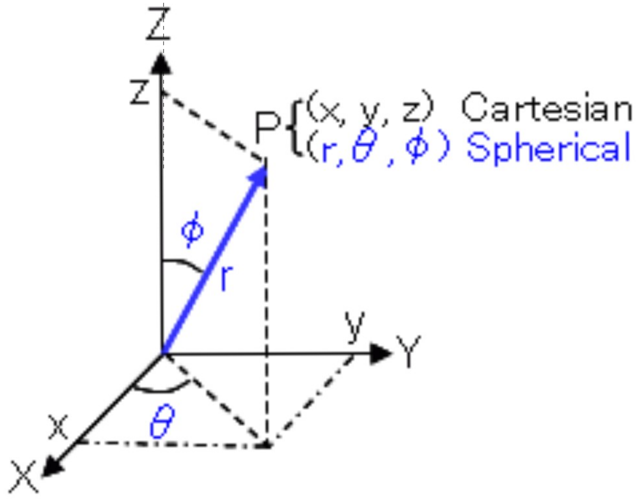
→ No sinusoidal pattern here

Some thoughts

. I thought maybe the detector was not at x=y=0 m → gave rise to patterns in the azimuthal angle distributions

- Nope: detector was at x=y=0 m
- I'll go back and look at this





Moving on to DM production and scattering at T2K (scattering at SK)

Relevant parameters:

- beam energy: 30 GeV
- efficiency: This is an overall factor which accounts for the percentage of signal events the experiment successfully detects and for any differences between the detector's fiducial volume and the geometry used in the simulation.
  - Can scale signal_events by the efficiency at the end since $\texttt{signal\_events}[i] = \frac{\texttt{ninteractions}[i]}{\texttt{trials}} \times \texttt{vnumtot} \times \texttt{pmax} \times \textbf{efficiency},$

    (efficiency=detector efficiency)
- pi0 per POT: The number of pi0's expected per proton on target. As many of the other meson production estimates are scaled relative to that of the pi0, it is important to have a good estimate of this quantity. Defaults to 0.9, which is appropriate for MiniBooNE, with beam on-target.
  - I use 1.0 since Patrick uses 1.0 in his SK parameters cards.
- Dm energy resolution: 0.01 (Patrick uses this value in his SK parameter cards)
- max dm energy: Used in creating interpolation functions for scattering cross sections. This can be safely set equal to the beam energy as an upper limit, at the cost of slowing the initialization of the simulation slightly. Defaults to beam energy.
  - default (Patrick also uses the default)
- max,min scatter angle: Cuts on the scattering angle of the outgoing visible particle (e.g. nucleon, electron) in an interaction event. This defaults to 2.1 pi radians and 0.0 radians respectively, which amounts to no cut on the angle.
- max,min scatter energy: Place cuts on the energy of the outgoing visible particle (e.g. nucleon, electron) in an interaction event. Defaults to 109 GeV and 0.0 GeV, respectively.
- N num target: 6 (graphite target); The number of neutrons per atom in the target. Defaults to 0.
- n density target: 9.02516e22 atoms/cm cubed (2011 t2k nim paper says target is a 1.8g/cm^3 graphite rod) The number density of atoms in the target. Defaults to 0.
- p num target: 6 ; The number of protons per atom in the target. Defaults to 0.

Relevant parameters cont:

POT: 5e21 (from table 1 in the 2017 patrick paper, can scale signal_events for different POT). The total number of protons on target over the duration of the experiment. This value must be supplied or an error will be thrown.

proton target cross section:The total scattering cross section of protons on the target. Used to normalize the V production rate for partonic V production. Defaults to 0. (I use 1.5e-30 from Patrick's value in his parameter cards.

signal channel: NCE nucleon

target length: The length of the target in meters. Default is 0.

timing_cut: The length of the time delay required to register as an event. This currently calculates a timing efficiency

$$t_{\text{efficiency},i} = \begin{cases} 1 & t_{\text{delay},i} \gtrsim t_{\text{cut}}, \\ \frac{t_{\text{cut}} - t_{\text{delay},i}}{t_{\text{cut}}} & t_{\text{delay},i} < t_{\text{cut}}, \end{cases} \tag{1}$$

where $t_{\text{delay},i}$ is the delay between the travel time of a neutrino moving between the target and the detector at c and a dark matter particle. The mean of 1 over all dark matter particles i produced by a given production channel is used to calculate the timing efficiency of that channel, and the total signal is multiplied by this efficiency to determine the event rate after timing cuts. The default value is 0.0, which results in a timing efficiency of 1.0.

Meson per pi0 for pi0decay production channel :1.0

meson per pi0 for eta production channel:0.0333333333333 (Patrick)

Relevant parameters cont. :

- Ptmax: The maximum transverse momentum which a produced V mediator may possess. The minimum is assumed to be 0.
  - 1.0 (from patrick)
- Zmin: The minimum value of z = p_Vz / P , where pV_z is the momentum of the V parallel to the z axis, and P is the total momentum of a beam proton incident on the target. I use 0.2 (from patrick)
- Zmax: The maximum value of z, defined as in the zmin. (I use 0.8, from patrick)

Relevant parameters., detector geometry

Note: off-axis angle: 2.504 +/- 0.004 degrees [1] . The off-axis angle is used to calculate the position of the detector.

- Detector: cylinder
- x-position: 12902.9391 m (to get an off-axis angle of 2.504 degrees) [4]
- y-position: 0
- z-position: 295053.2063 m [4]

  (in his Sk parameter card, Patrick has x-position 12867.7 , z-position 294719 ; gives an angle of 2.5 degrees)
- radius 14.9 [5]
- length 32.2
- det-theta 1.5707963
- det-phi 0

[1] "The T2K experiment" K.Abe et al. arXiv:1106.1238v2 [physics.ins-det] 8 Jun 2011

[4] The T2K 2011 paper says the distance from the target to the center of SK is 295335.2 m, and the off-axis angle is 2.504 degrees, so x is 12902.9391 m and z = 295053.2063 m , y is zero.
Note that x and y are not interchangeable because by default, the detector's length is parallel to the beam direction (z axis), and det-phi defines rotations about the y axis. So the SK detector needs to have a det-theta of pi/2. Refer to figure 1.0

[5] The 2011 NIM paper (reference 1) says the diameter of inner detector is 33.8 m, total detector diameter is 39 meters; inner detector length is 36.2 m, and total detector length is 42 m. But I use the radius and length corresponding to the fiducial volume: The paper
"The Super-Kamiokande detector" by S. Fukuda et al. (Nuclear Instruments and Methods in Physics Research A 501 (2003) 418–462)
says standard fiducial volume is defined as the region inside a surface drawn 2.00m from the ID wall, i.e., a centered cylinder of ***diameter 29.8m and height 32.2 m***.

Relevant parameters., detector geometry

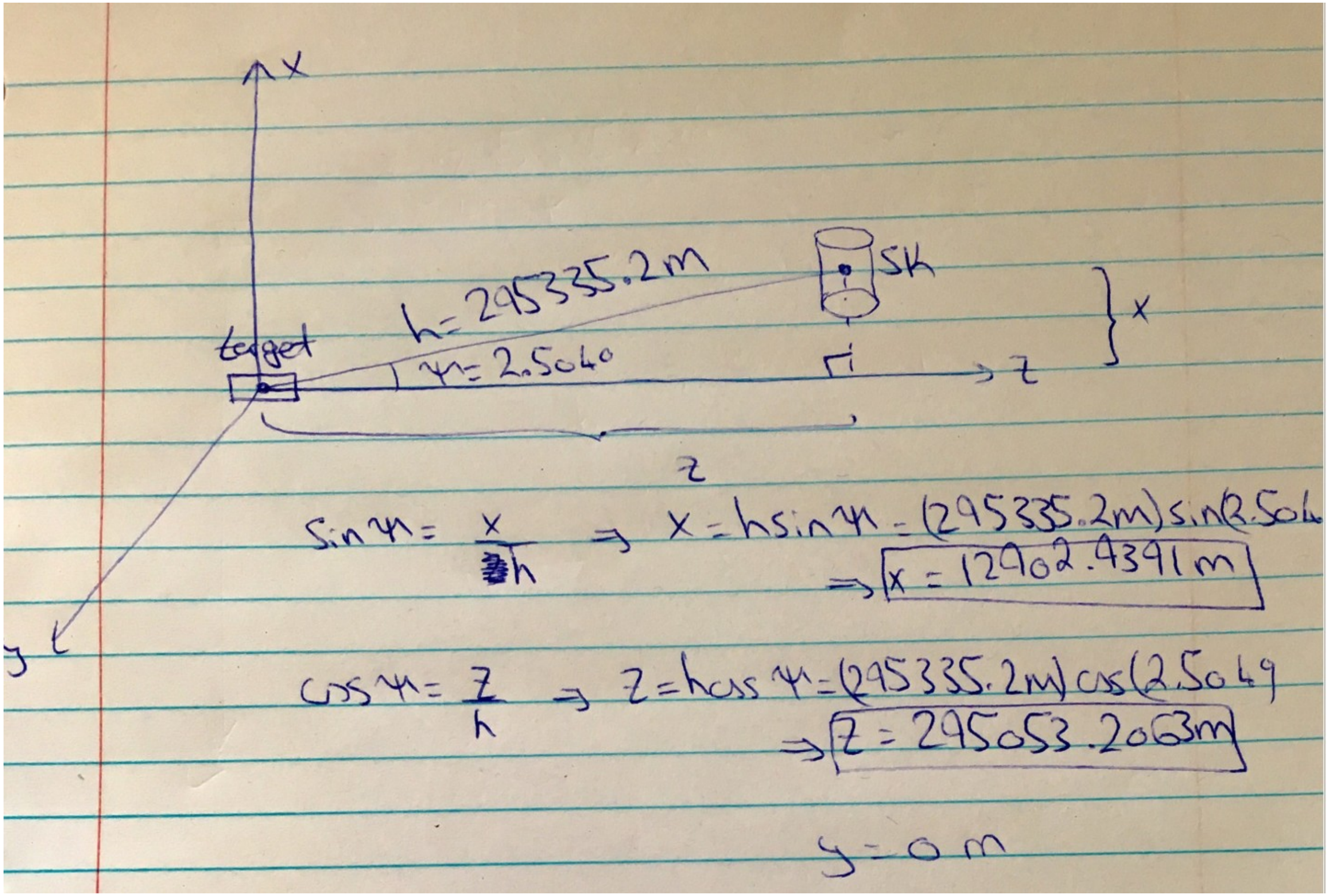


Figure 1.0 : *Calculating the position of the SK detector*

Relevant parameters, material parameters

“Material parameter description from BdNMC: A material is defined by providing a material < name> , and then providing the **number density** in particles per cm3 (note that this is one of the few areas where we do not use meters), **proton number , neutron number , electron number and mass in GeV.”**

material Oxygen

Patrick has number_density 3.34184e22

proton_number 8

neutron_number 8

electron_number 8

material Hydrogen

Patrick has number_density 6.68368e22

proton_number 1

neutron_number 0

electron_number 1

Relevant parameters, meson distributions

- Patrick uses a particle list for the 4-momenta of pions and eta particles for his SK parameter cards.
- In the future: we'll use particle lists that we generate specific to T2K.
- What distribution do I use for now? The default, or bmpt?
  - BMPT:
  - 2012 paper says they use an analytic fit f^{BMPT}(theta, p) to data for (average pi+and pi-) pion production obtained over a range of energies.
  - Bmpt: Utilizes the general pion distribution determined in [52] for a range of multi-GeV beam energies) This channel also requires p num target and n num target to be set.
  - Default: paper doesn't say what this is, but I can plot p versus theta (phi in my geometry) for pi0 and eta to see what they look like.

- (Reference 52: “On particle production for high energy neutrino beams” by M. Bonesini et al.)

What do default distributions for pi0 and eta look like?

Ran bdnmc at 30 GeV beam energy:

- pi0 bmpt: Run 1502818965
- Pi0 default: Run 1502829091
- Eta bmpt: Run 1502819084
- Eta default: Run 1502819130

At 9 GeV beam energy, eta default: Run1502830499

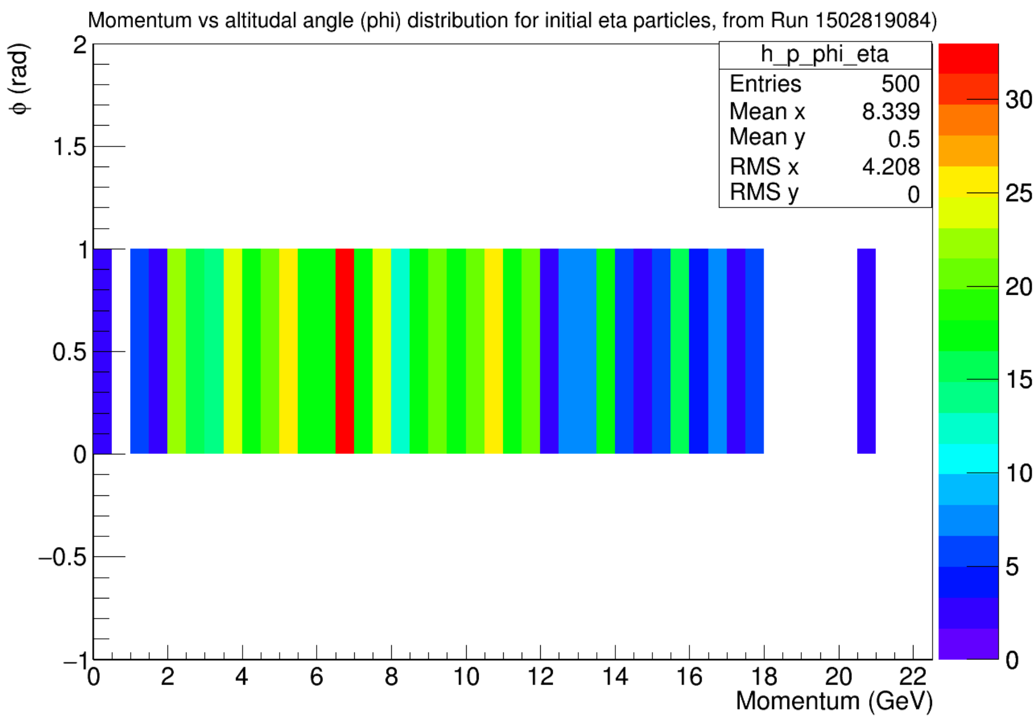
At 80 GeV beam energy, eta default: Run1502830538

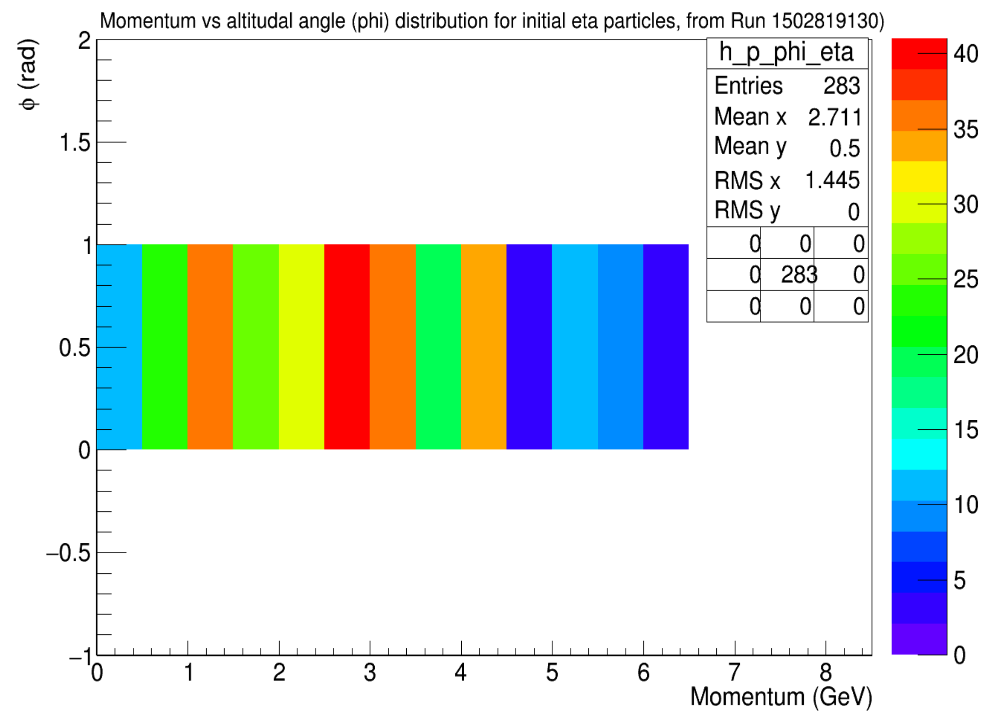
- Next slide:

Default distributions

- Eta bmpt: Run 1502819084 beam energy = 30 GeV

Eta default: Run 1502819130, beam energy = 30 GeV





At 30 GeV beam energy

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- Pi0 default: Run 1502829091
- Eta bmpt: Run 1502819084
- Eta default: Run 1502819130

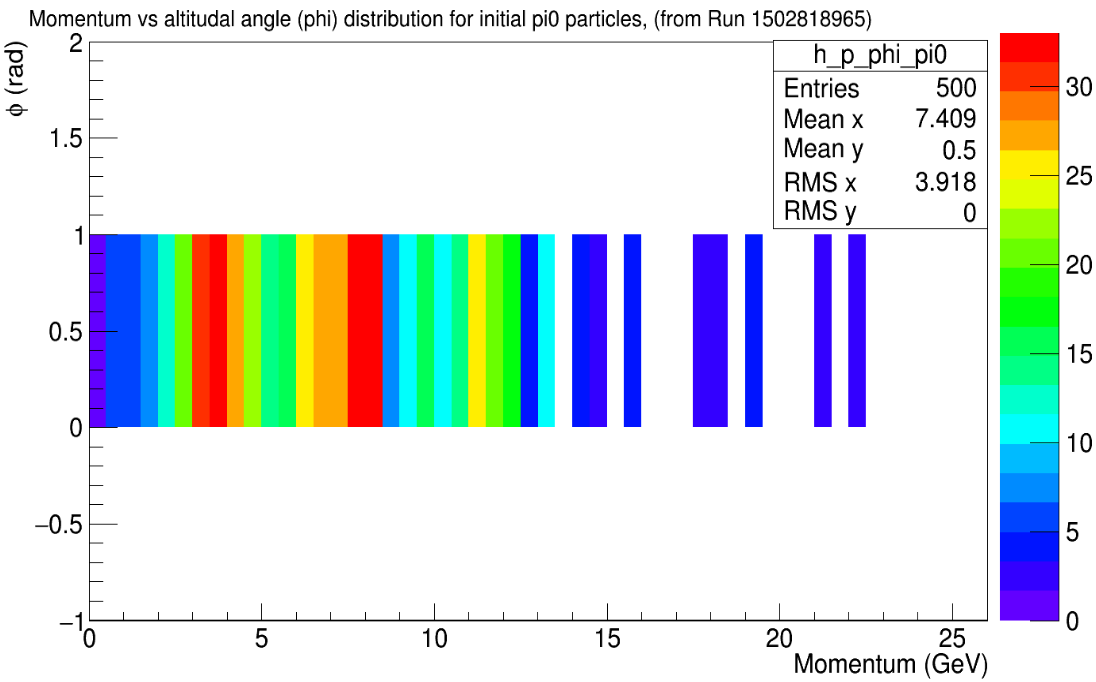
At 9 GeV beam energy, eta default: Run1502830499

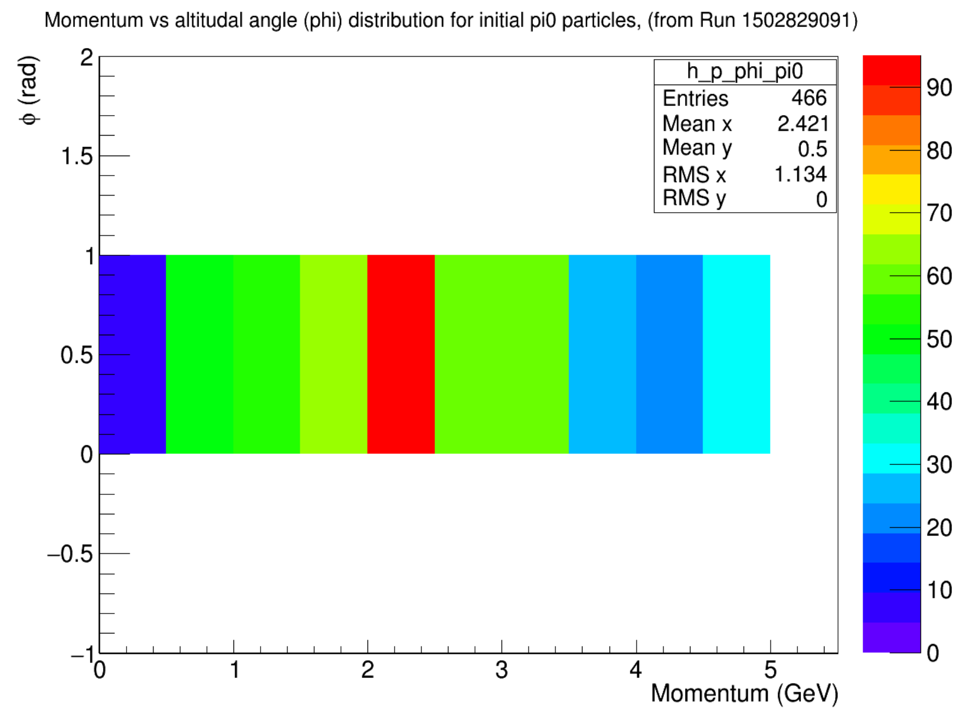
At 80 GeV beam energy, eta default: Run1502830538

Default distributions

- pi0 bmpt: Run 1502818965, 30 GeV

pi0 default: Run 1502829091, 30 GeV





At 30 GeV beam energy

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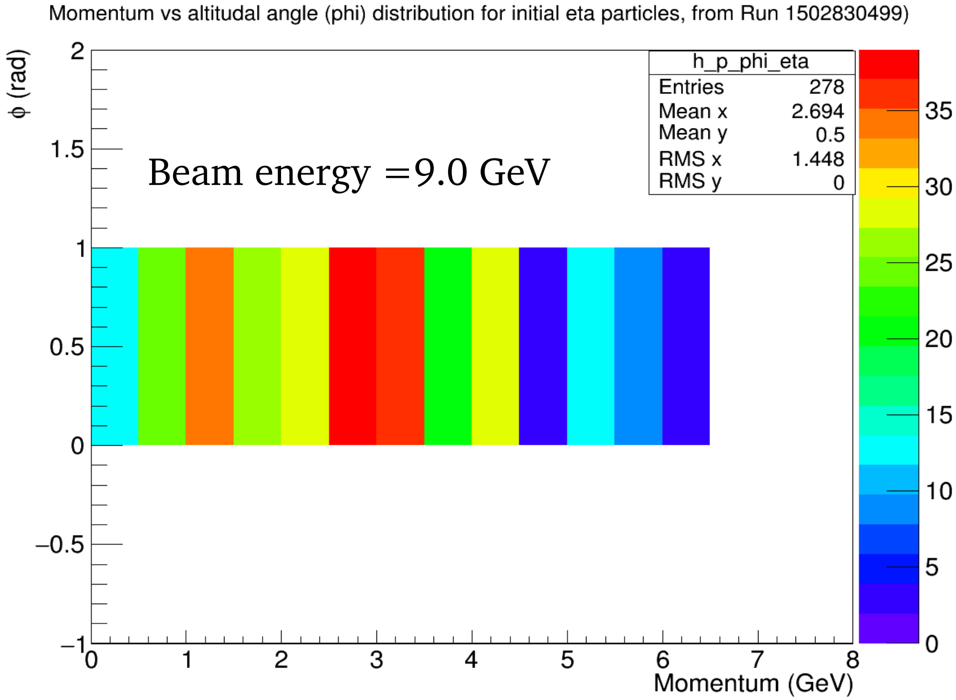
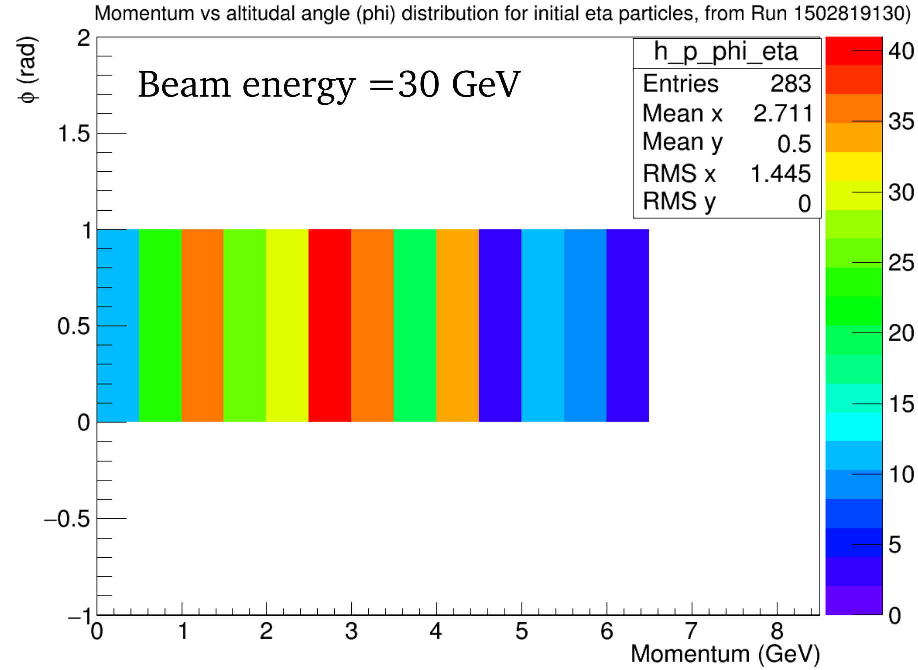
- Pi0 default: Run 1502829091
- Eta bmpt: Run 1502819084
- Eta default: Run 1502819130

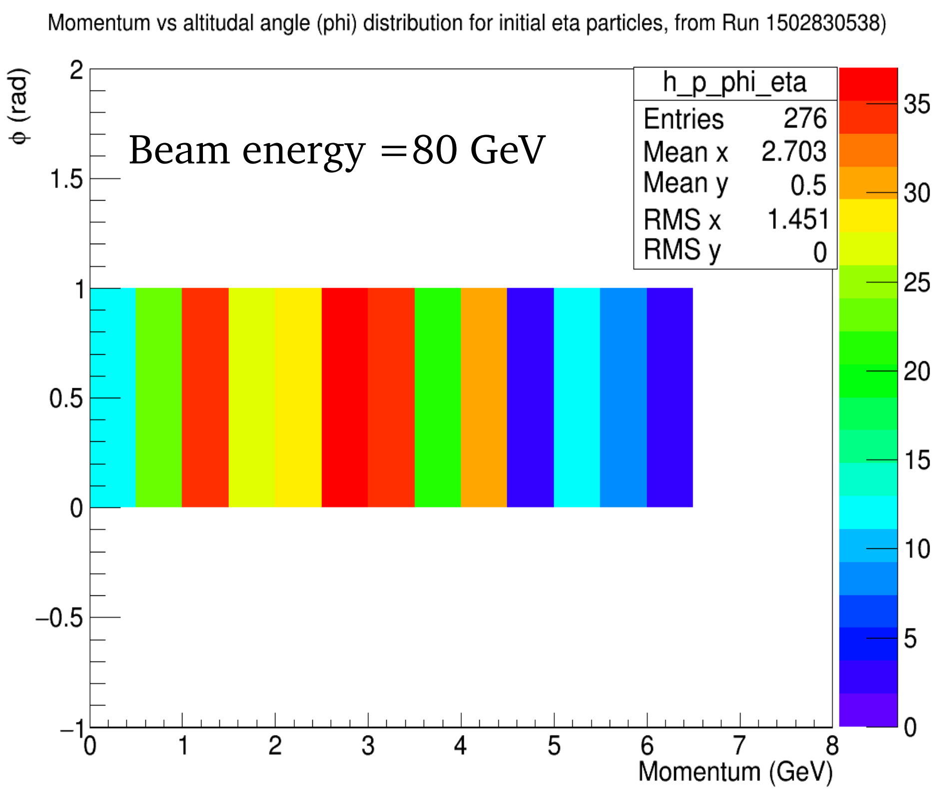
At 9 GeV beam energy, eta default: Run1502830499

At 80 GeV beam energy, eta default: Run1502830538

Default distributions for eta particles







Default distribution independent of beam energy?

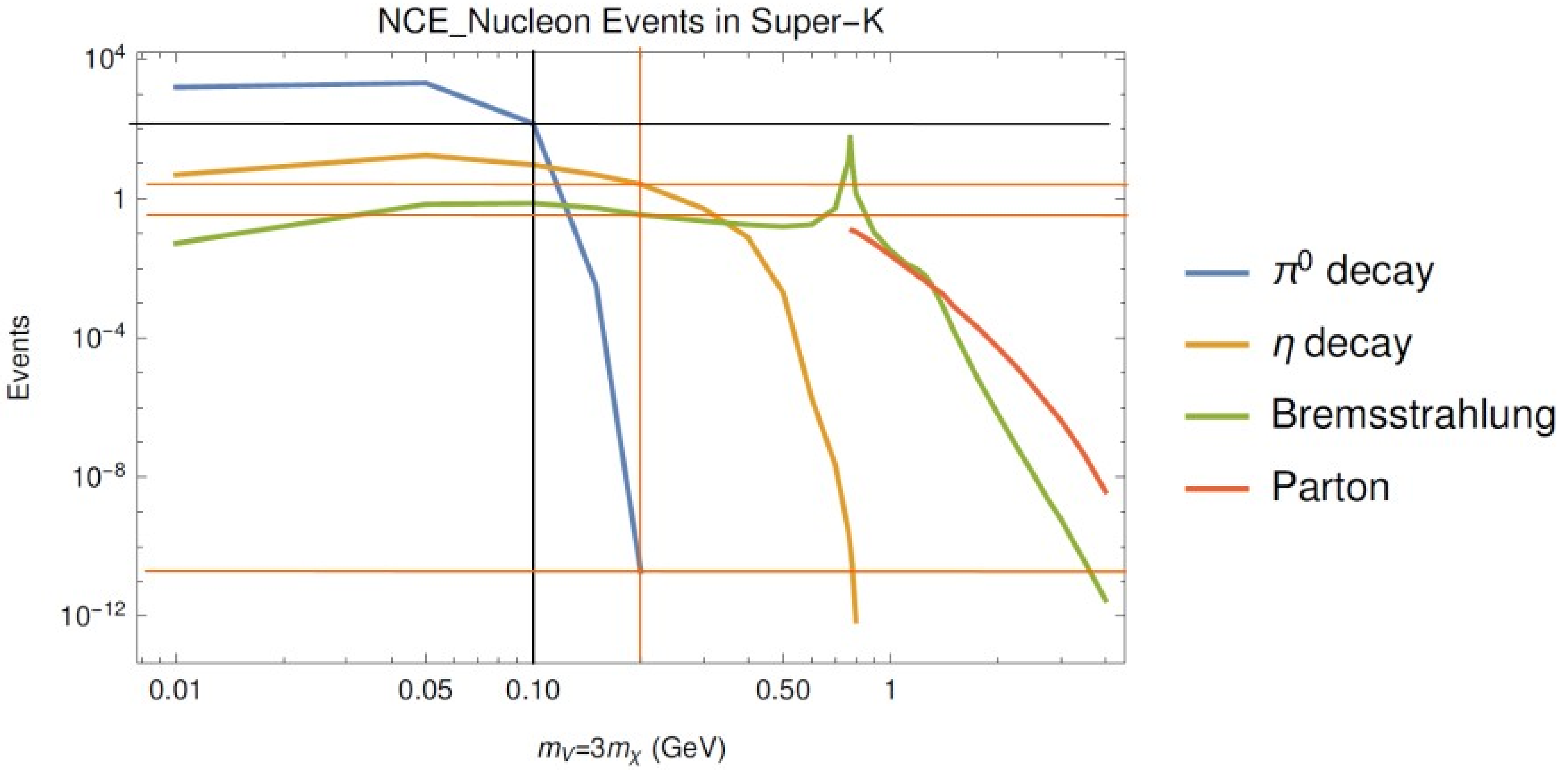
At 30 GeV beam energy

- pi0 bmpt: Run 1502818965
- Pi0 default: Run 1502829091
- Eta bmpt: Run 1502819084
- Eta default: Run 1502819130

At 9 GeV beam energy, eta default: Run1502830499

At 80 GeV beam energy, eta default: Run1502830538

By the way,



Ran BdNMC with Patrick's parameters, used bmpt distribution for pi0 and eta decay (Patrick used particle lists). POT is 8e+21 (same as Patrick)

Black pi0 133.11
orange pi0 2.92945e-11
orange eta 2.07862
orange pBrem 0.36335

→ I use bmpt for pi0 and eta particles (for now)

Patrick's cuts:

- He uses scatter_energy cuts of [0.0014, 1000]
  - We're not sure why he uses this cut, I asked him: came from akira some time ago
  - His timing_cut is 5e-8s. He says it ensures that the dark matter events are out-of-time with the neutrino events (reduce background)

I run BdNMC with no cuts :

- Ran BdNMC with SK-parameters. SK specific values from 2011 T2K and 2003 SK NIM papers. Some other parameters:

Model parameters:

- m_V=0.2 GeV, m_X=m_V / 3
- alpha'=0.5
- Y = 10^{-8} , so epsilon = 0.00127279

Some other parameters:

- pi0_per_POT=1.0 (from Patrick's SK parameter cards)
- Proton_target_cross_section = 1.5e-30 (from Patrick's SK parameter cards)
- POT=5e21
- Efficiency = 100 %
- Production channels: pi0 decay, eta decay, proton bremsstrahlung
- meson_per_POT for eta_decay production channel:0.0333333333333 (from Patrick's SK parameter card)
- Signal channel: nce_nucleon
- With bmpt distribution for pi0 and eta particles
- Ptmax=1.0, zmin=0.2, zmax=0.8 for proton Bremsstrahlung channel

Cuts:

- No scattering angle and energy cuts (cuts on outgoing nucleon)
- No timing cuts

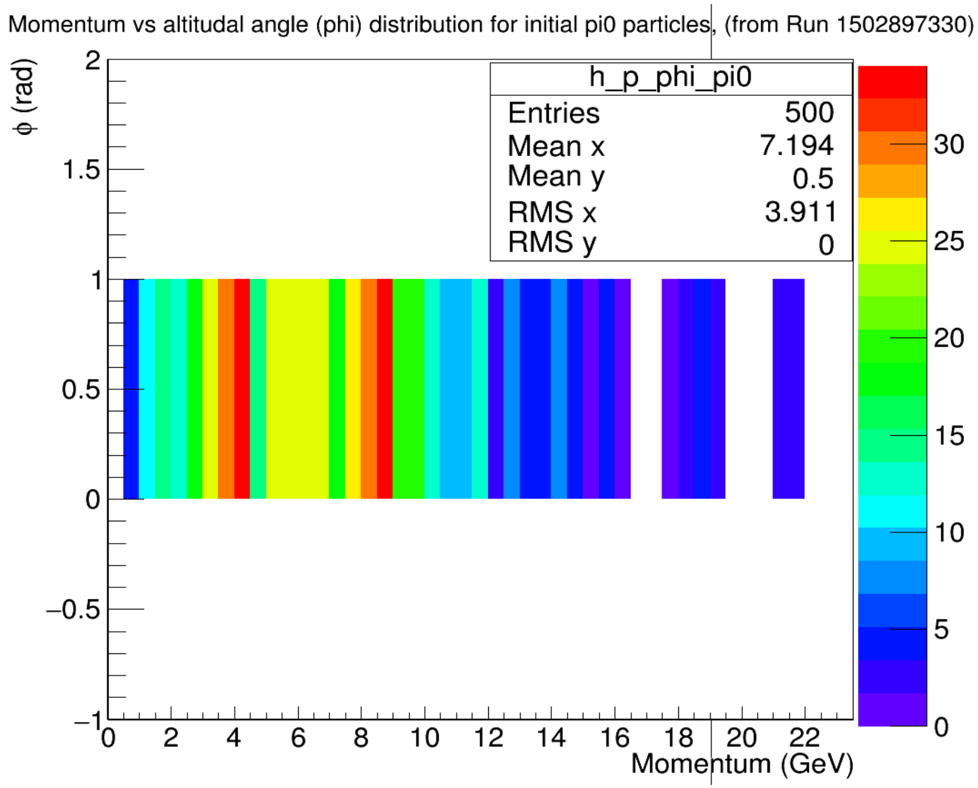
Simulation parameters:

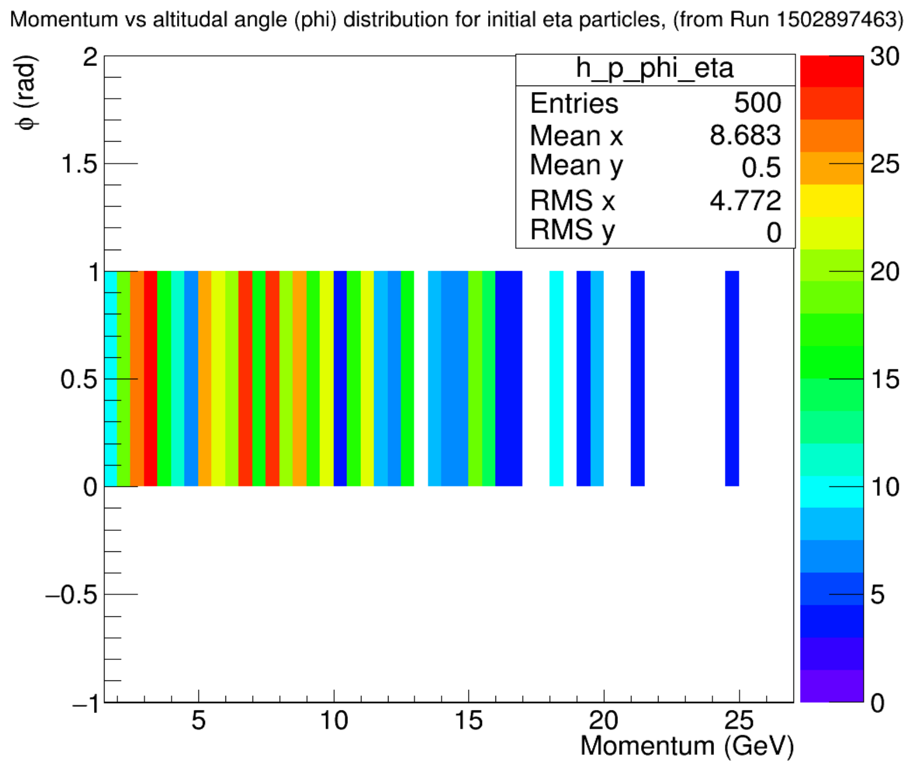
- max_trials 800000000.0
- dm_energy_resolution = 0.01

Some distributions for SK

- Run 1502895571: all three production channels
- Run   1502897330: pi0 productin channel only
- Run 1502897463: eta production channel only
- Run 1502897552 : proton Bremsstrahlung channel only

The momentum angle distributions for production channel particles (this is bmpt for now)



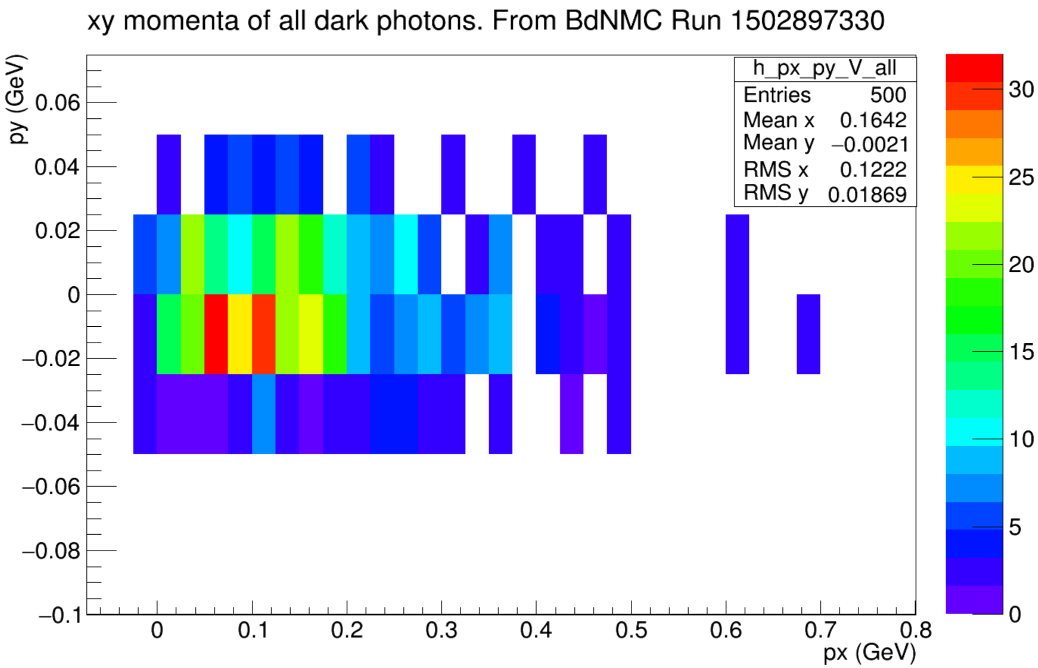


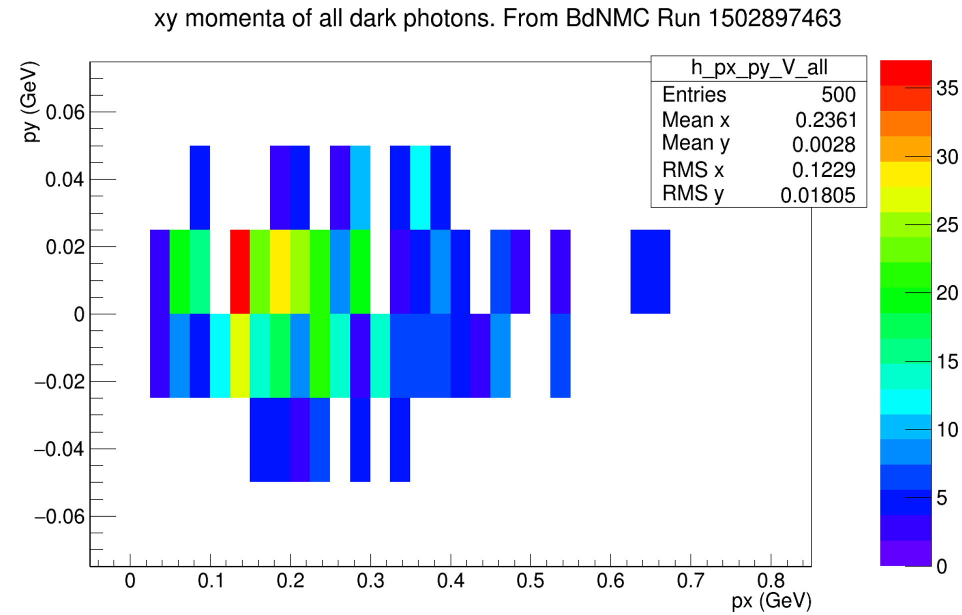
Run 1502895571: all three production channels

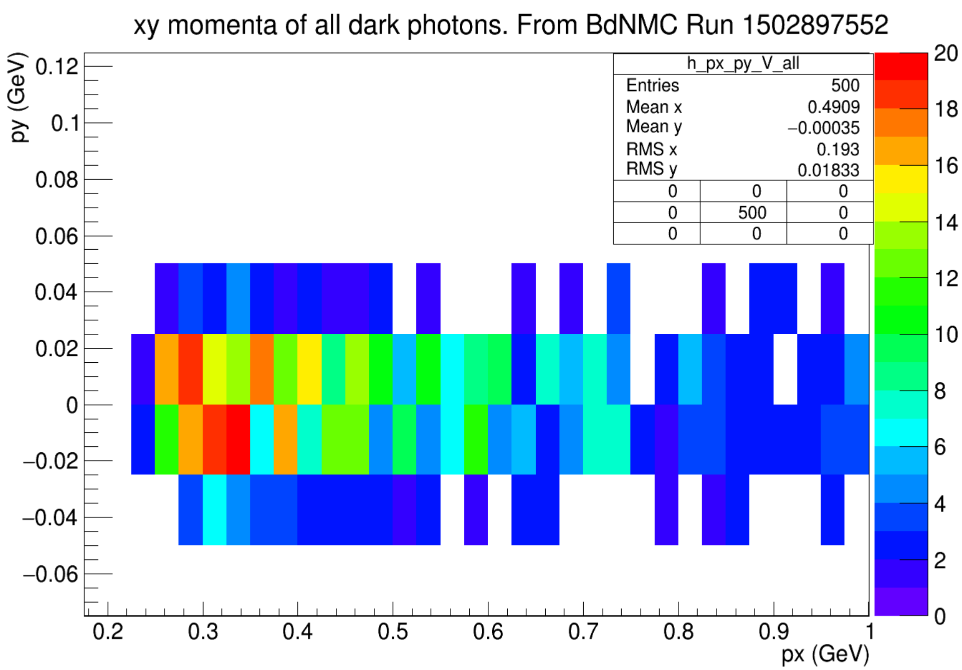
Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only

Run 1502897552 : proton Bremsstrahlung channel only





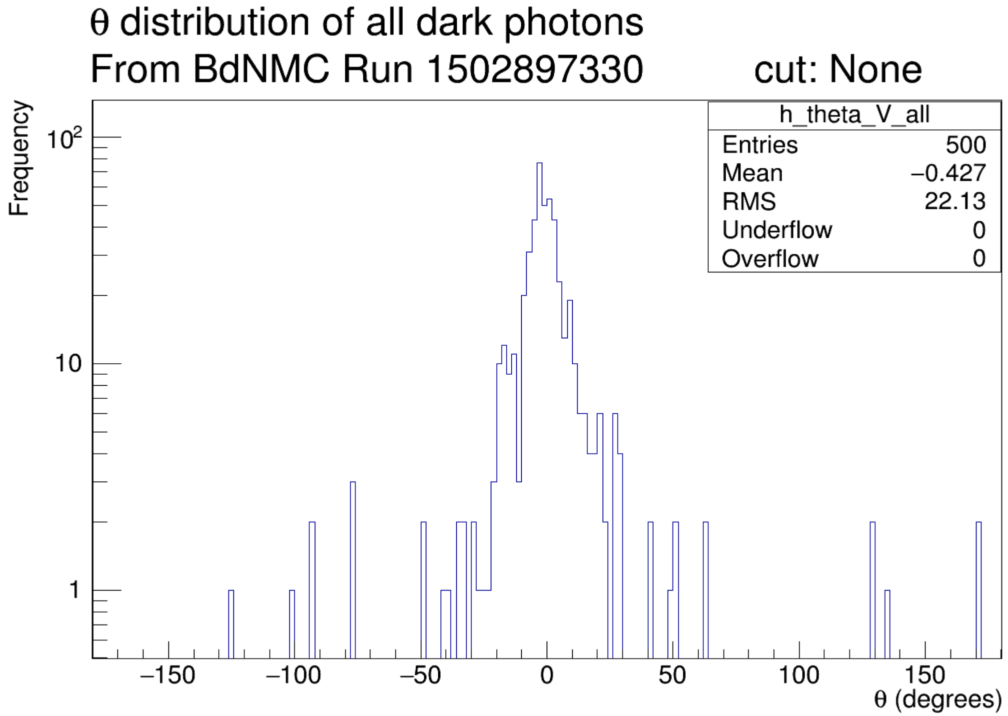


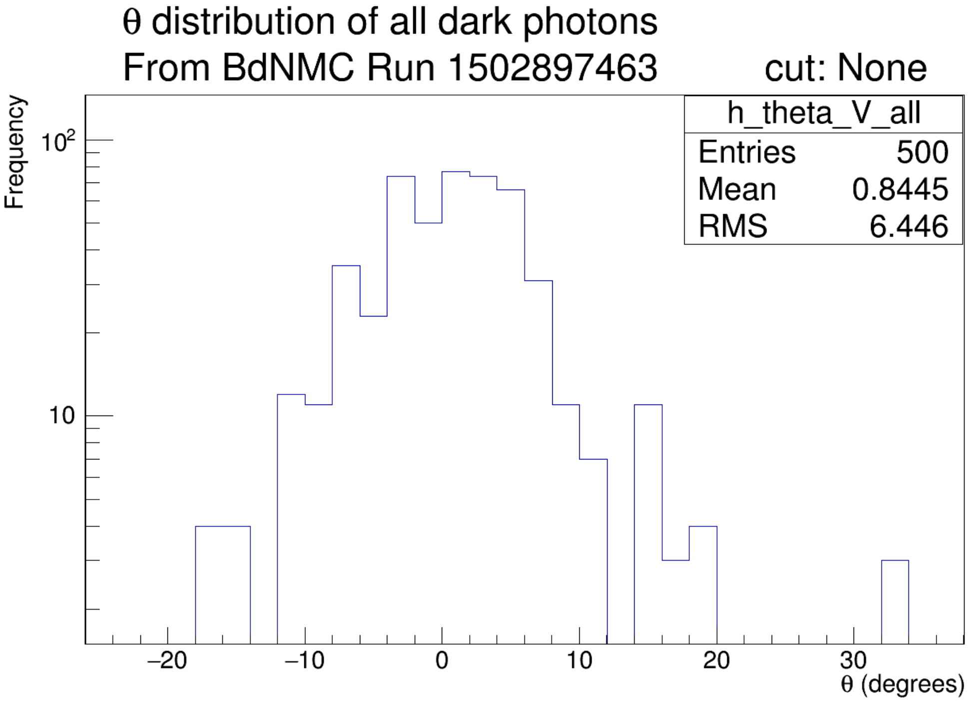
Run 1502897463: eta production channel only

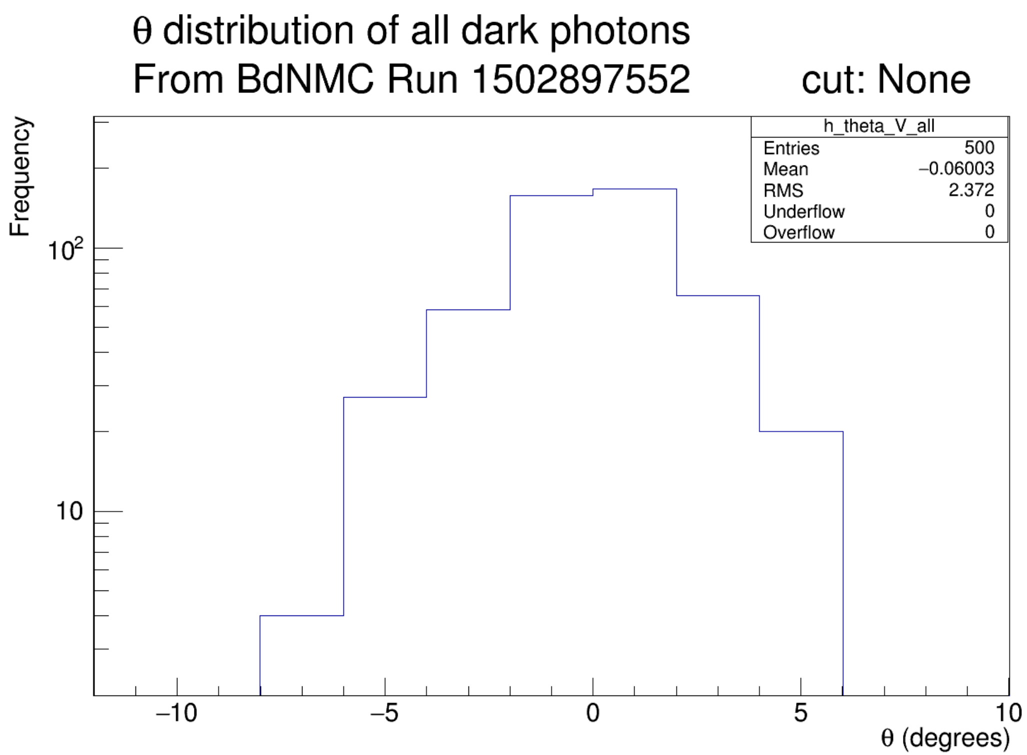
Run 1502897552 : proton Bremsstrahlung channel only

Some notes:

- Px distribution shifts to the right for eta and pBrem.
- x=y=z=0 corresponds to the position of the target.
- Off-axis angle of 2.5 degrees, so x- position of detector is ~12900 m =>particles with negative x momenta won't intersect detector





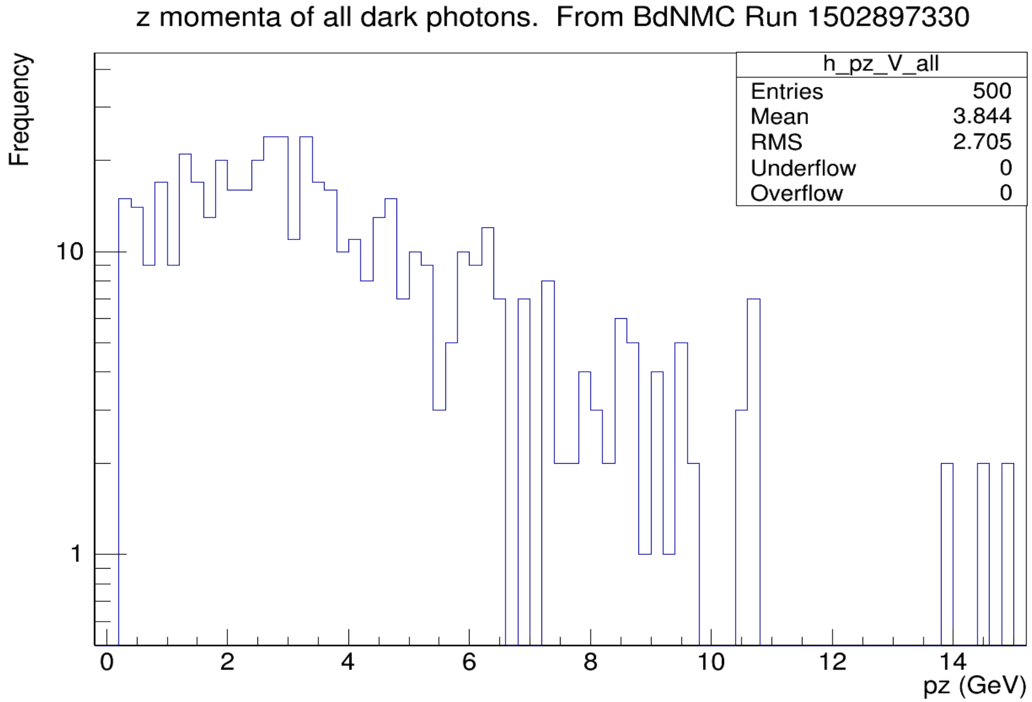


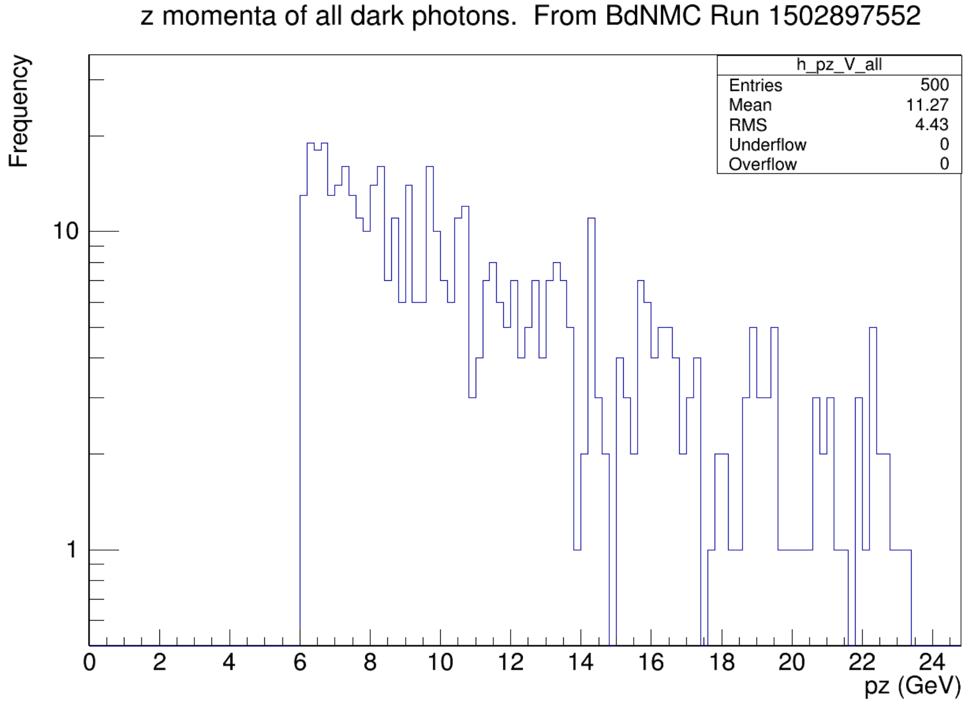
Run 1502895571: all three production channels

Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only

Run 1502897552 : proton Bremsstrahlung channel only





Some notes:

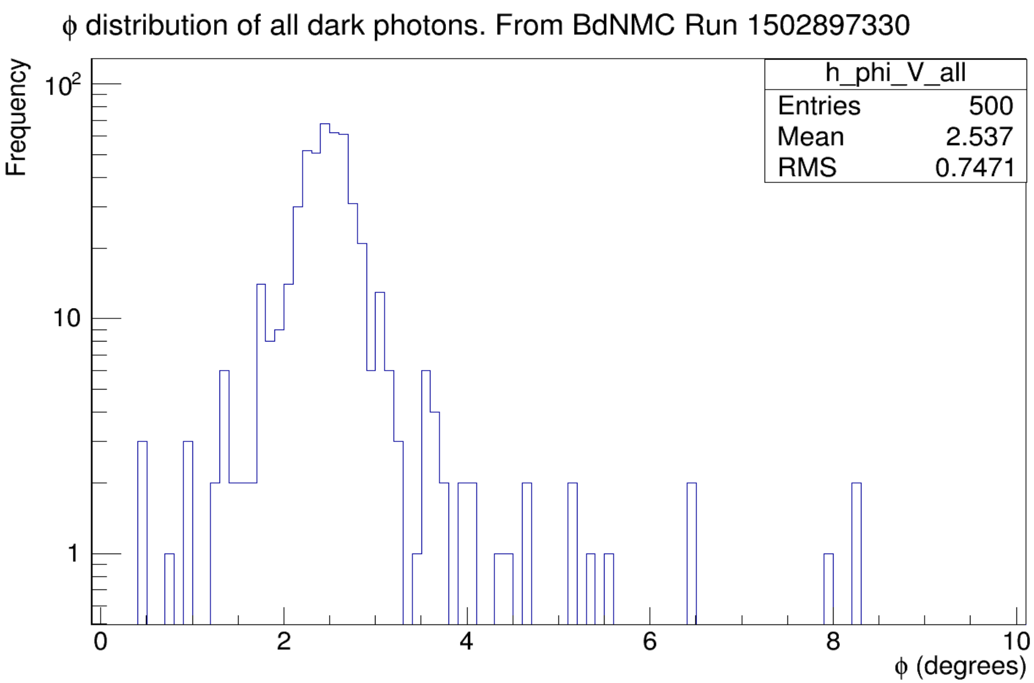
- The distribution for V's coming from eta decay production channel is similar to that of the pi0

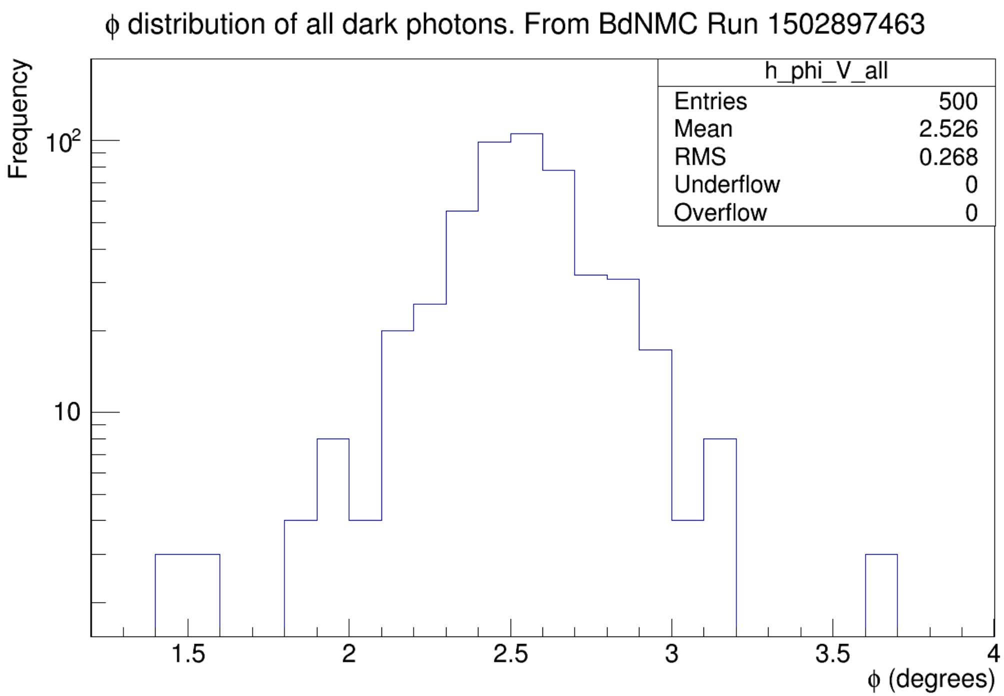
Run 1502895571: all three production channels

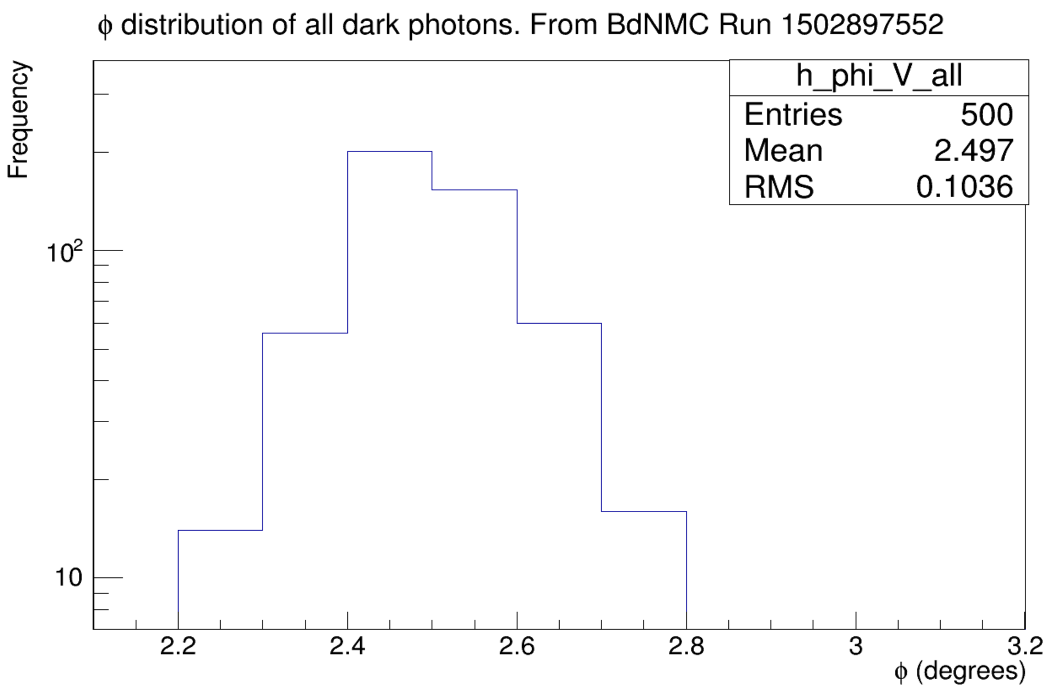
Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only

Run 1502897552 : proton Bremsstrahlung channel only





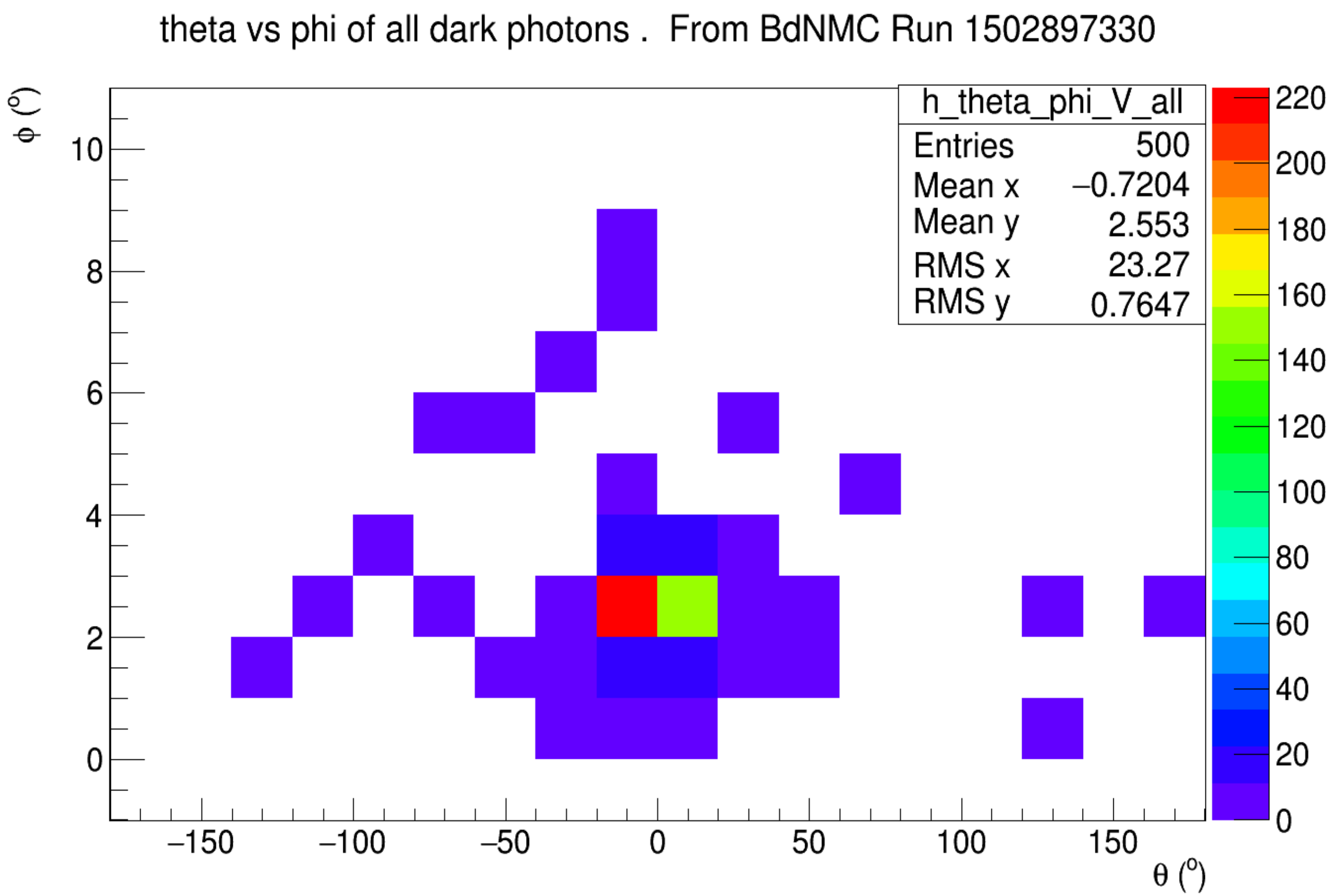


Run 1502895571: all three production channels

Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only

Run 1502897552 : proton Bremsstrahlung channel only



Some notes:

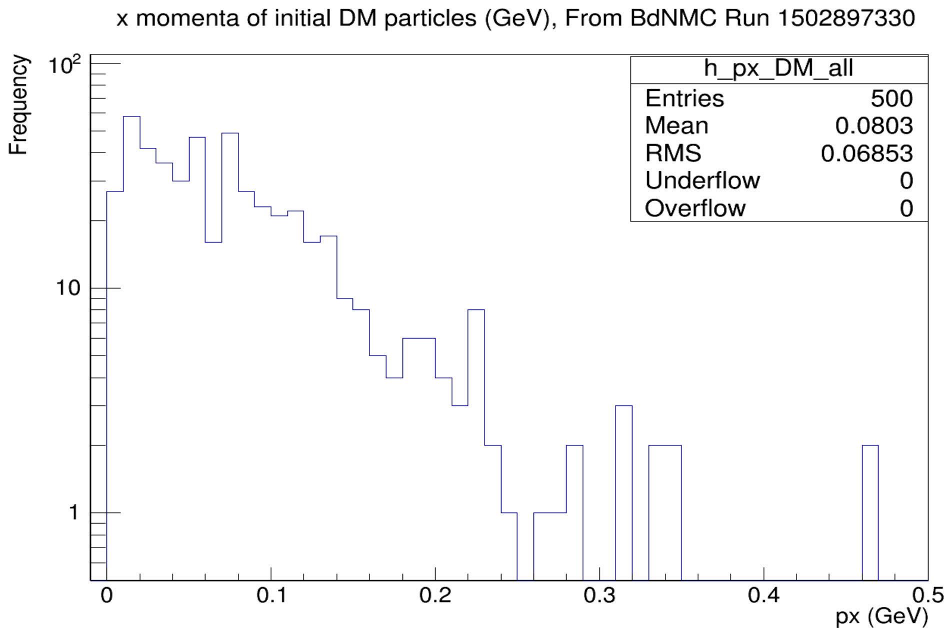
- The distribution for V's coming from eta decay and proton Bremsstrahlung production channels is similar (but with less spread)

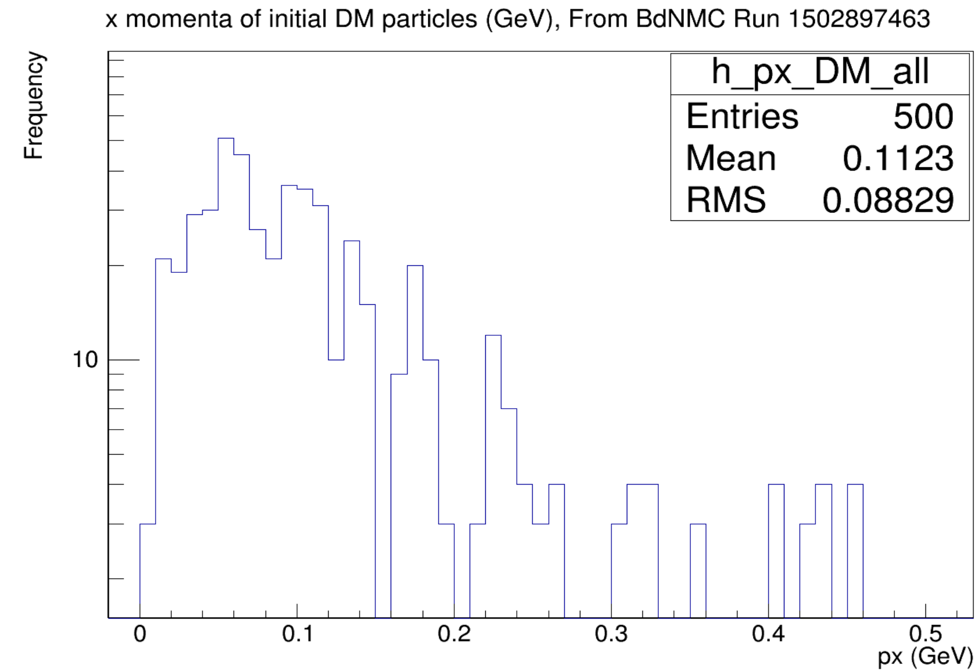
Run 1502895571: all three production channels

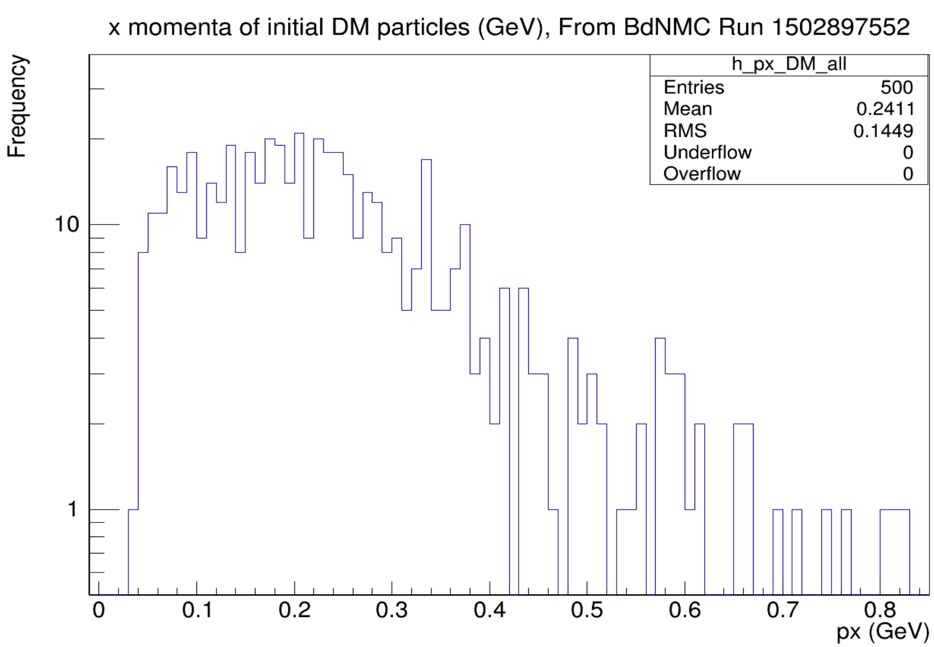
Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only

Run 1502897552 : proton Bremsstrahlung channel only







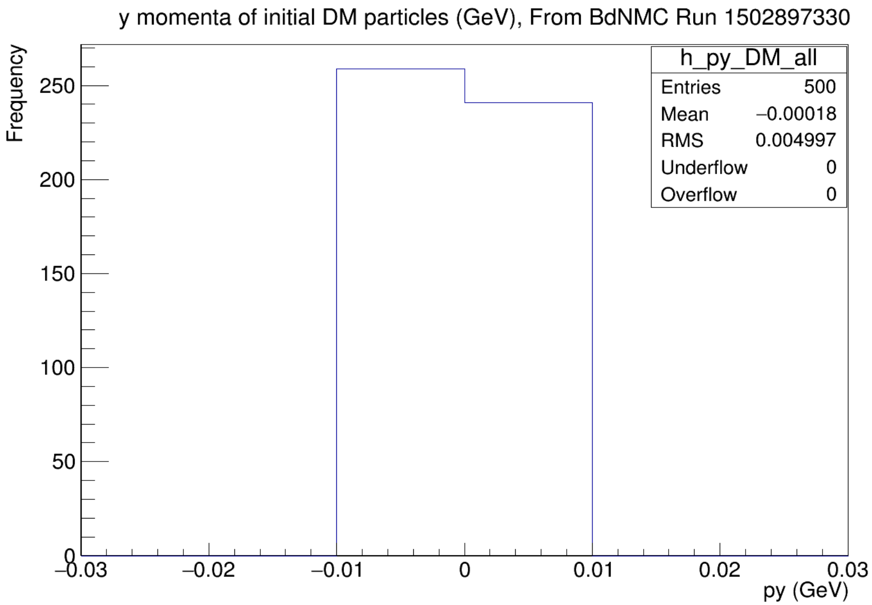
Note: the distributions of the dark matter particles have less spread than the dark photons

Run 1502895571: all three production channels

Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only

Run 1502897552 : proton Bremsstrahlung channel only



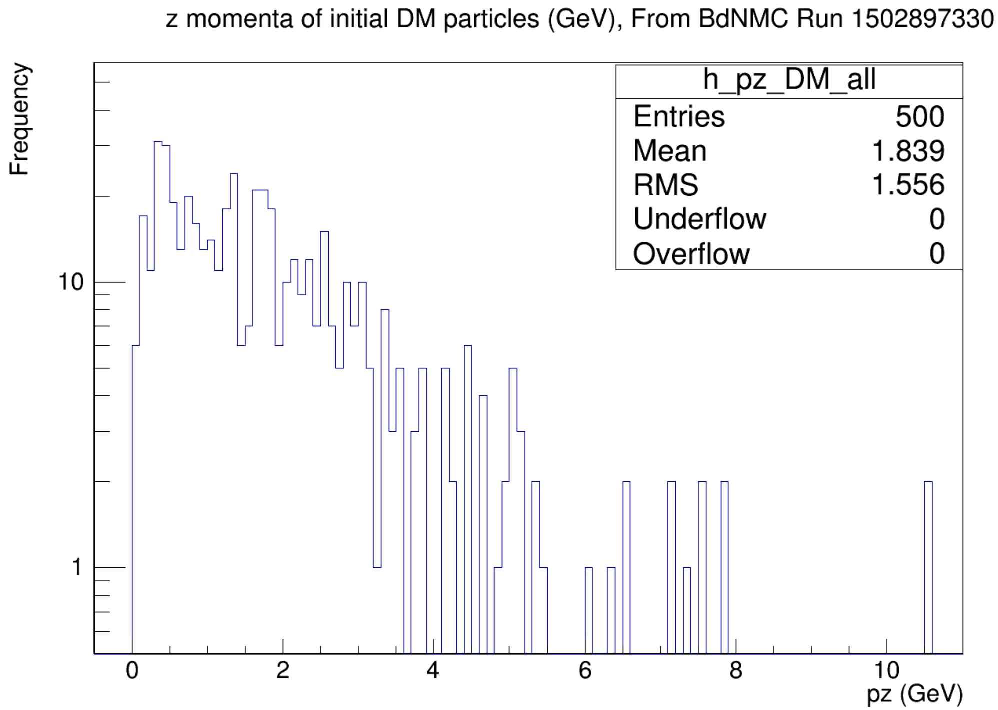
Note: the py distribution for other production channels are ∼ the identical

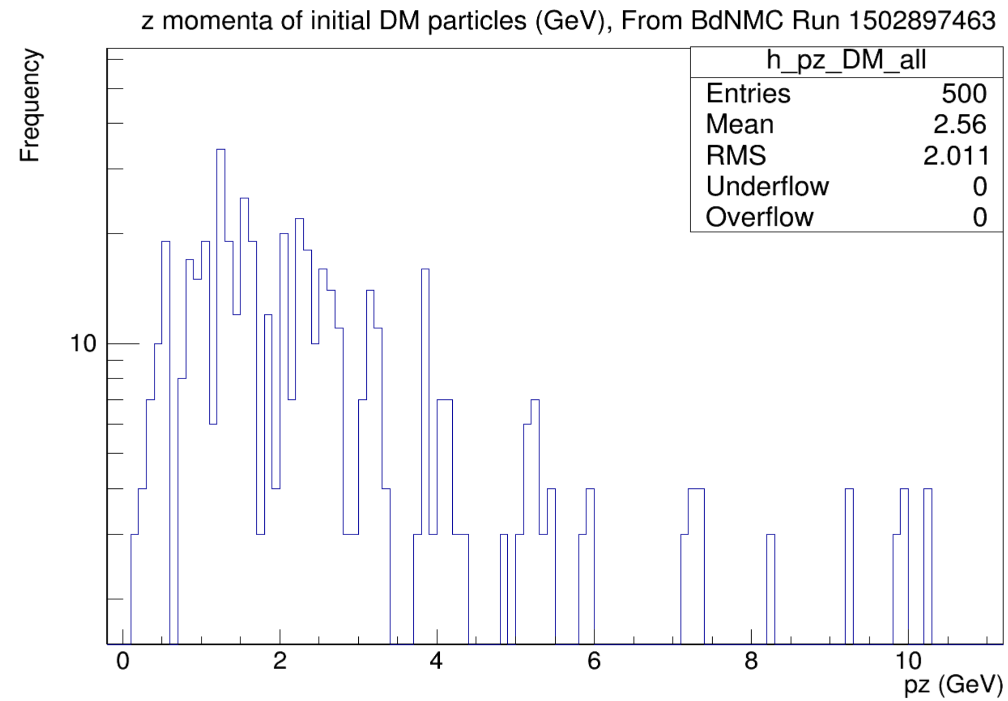
Run 1502895571: all three production channels

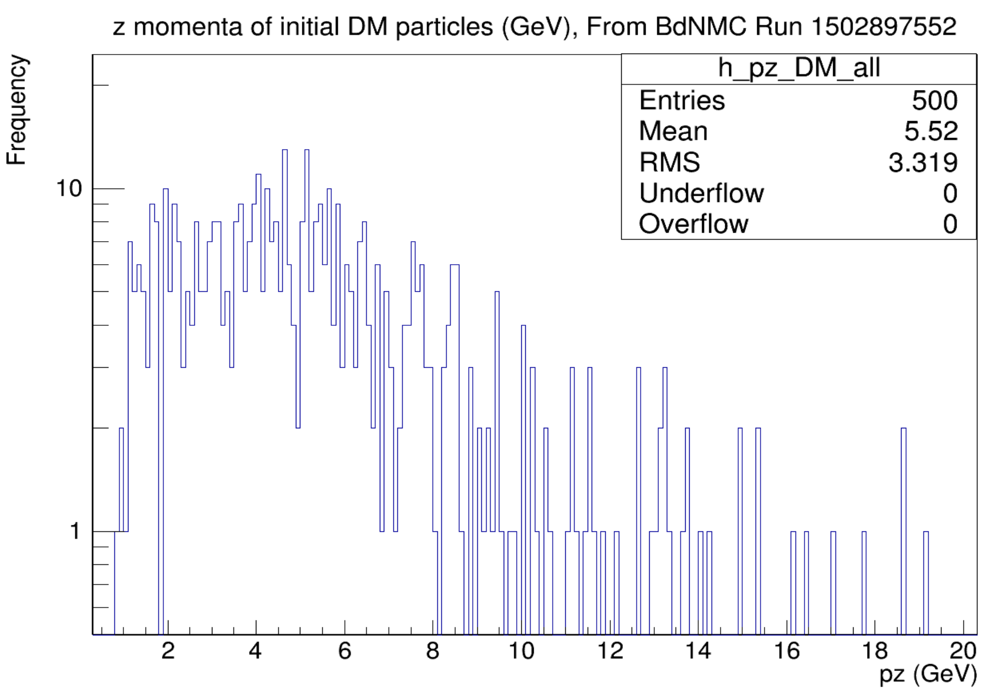
Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only

Run 1502897552 : proton Bremsstrahlung channel only







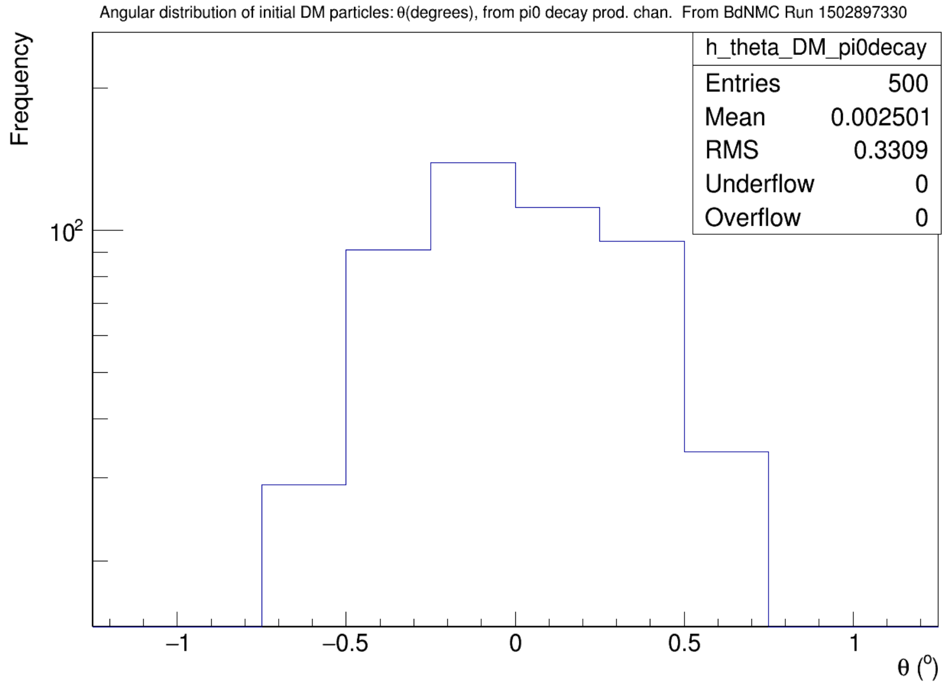
Eta, pBrem shifted to the right

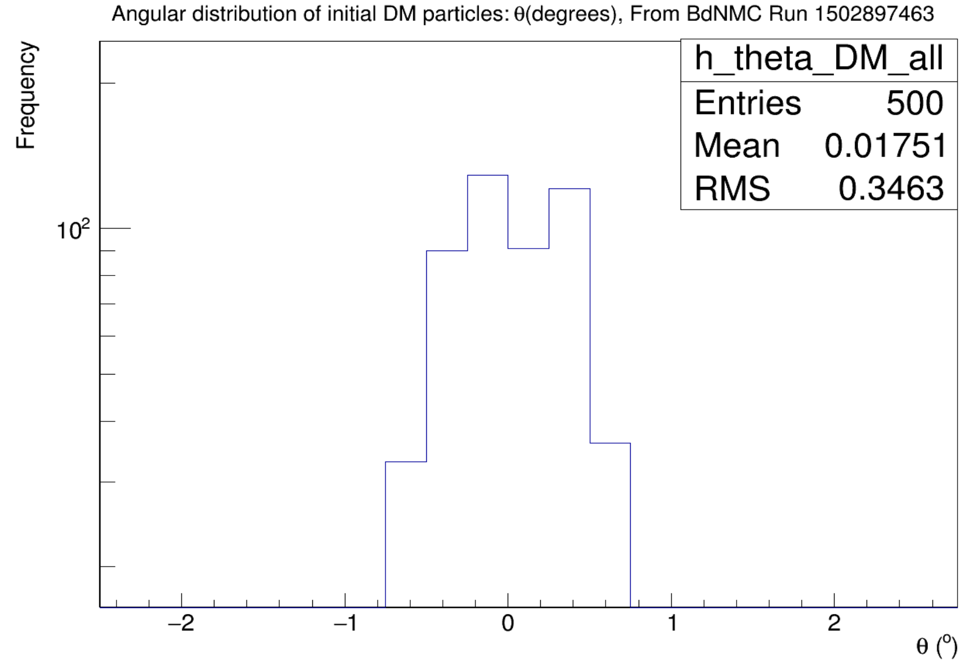
Run 1502895571: all three production channels

Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only

Run 1502897552 : proton Bremsstrahlung channel only



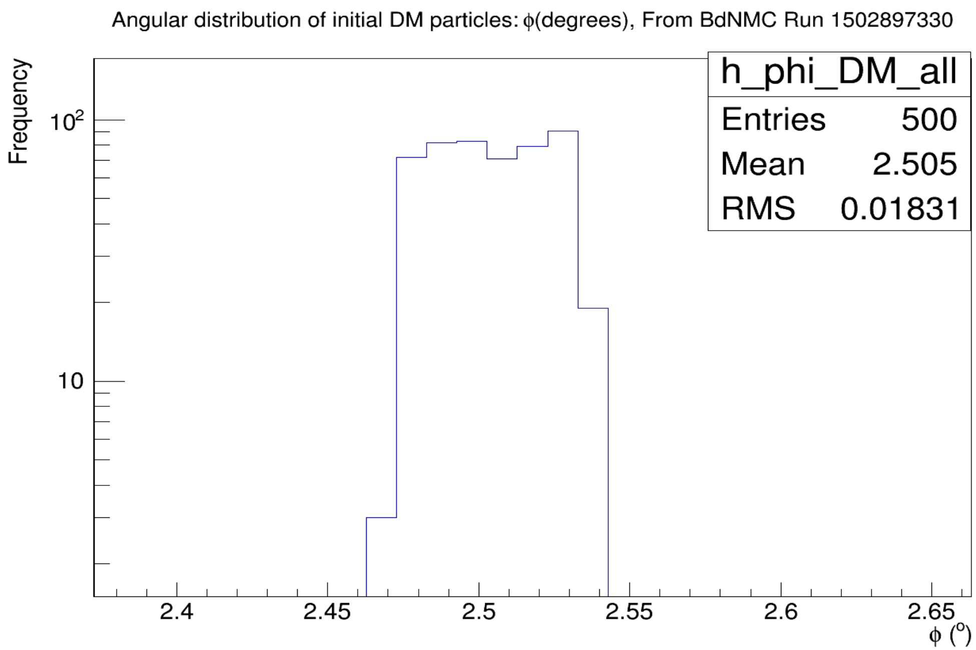


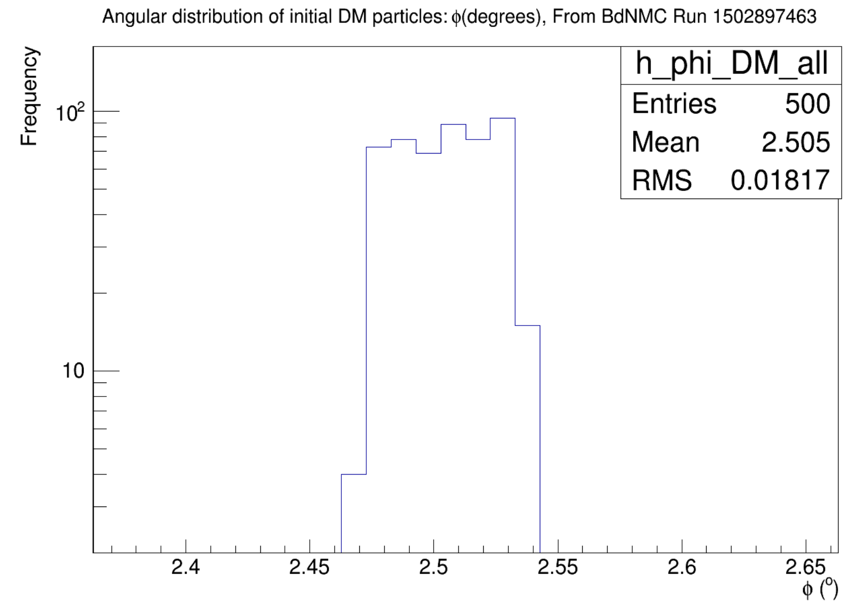
Run 1502895571: all three production channels

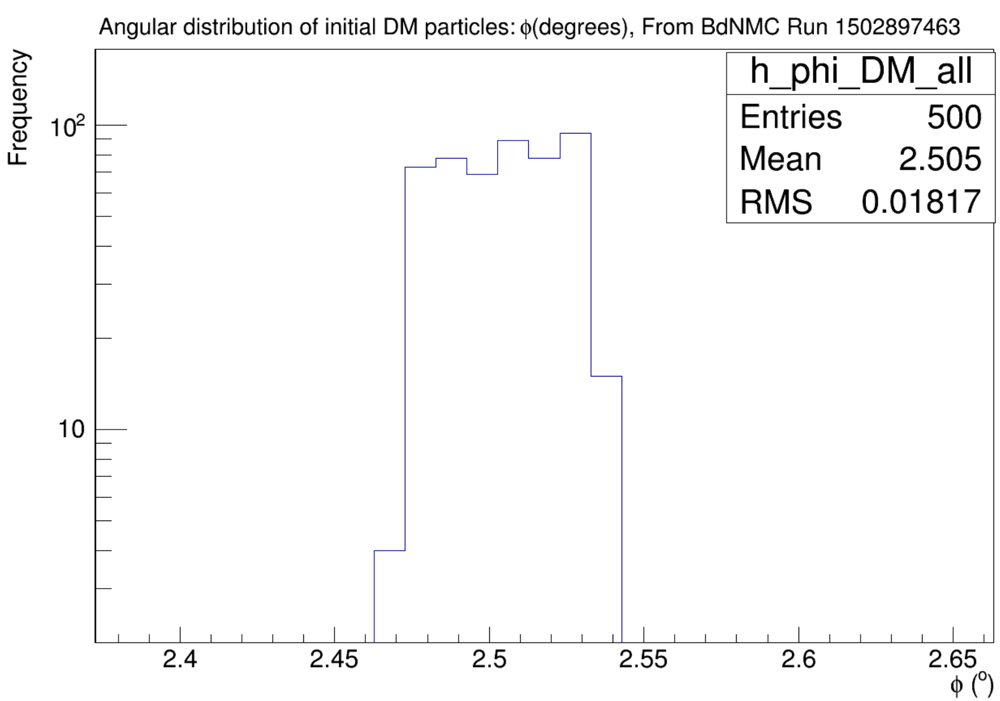
Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only

Run 1502897552 : proton Bremsstrahlung channel only





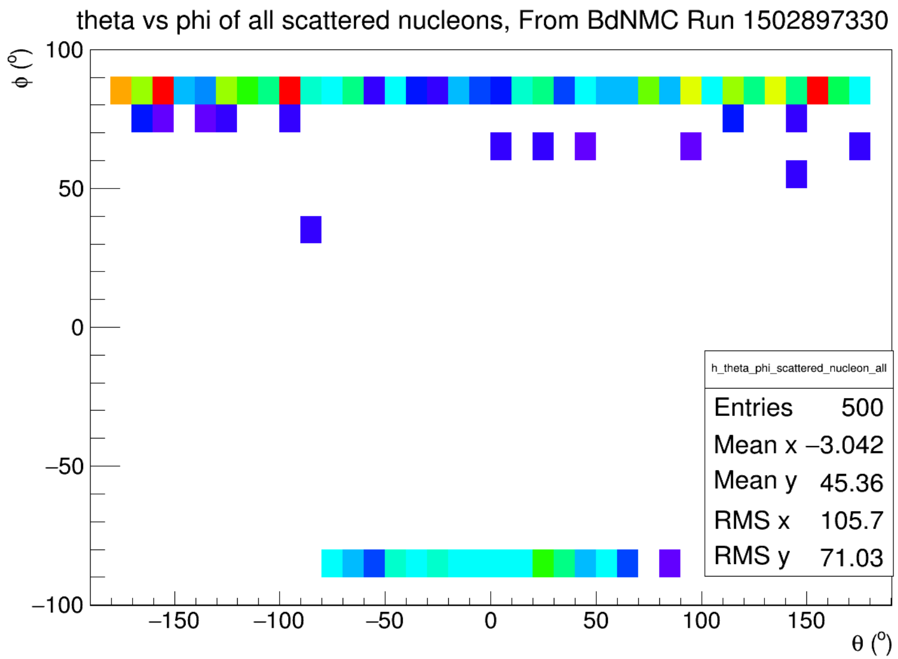


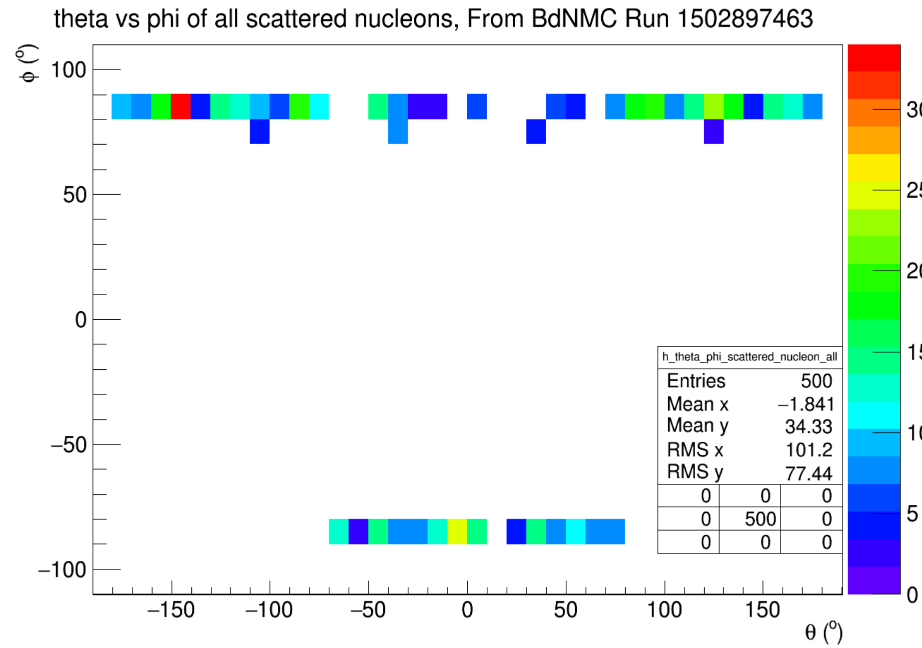
Run 1502895571: all three production channels

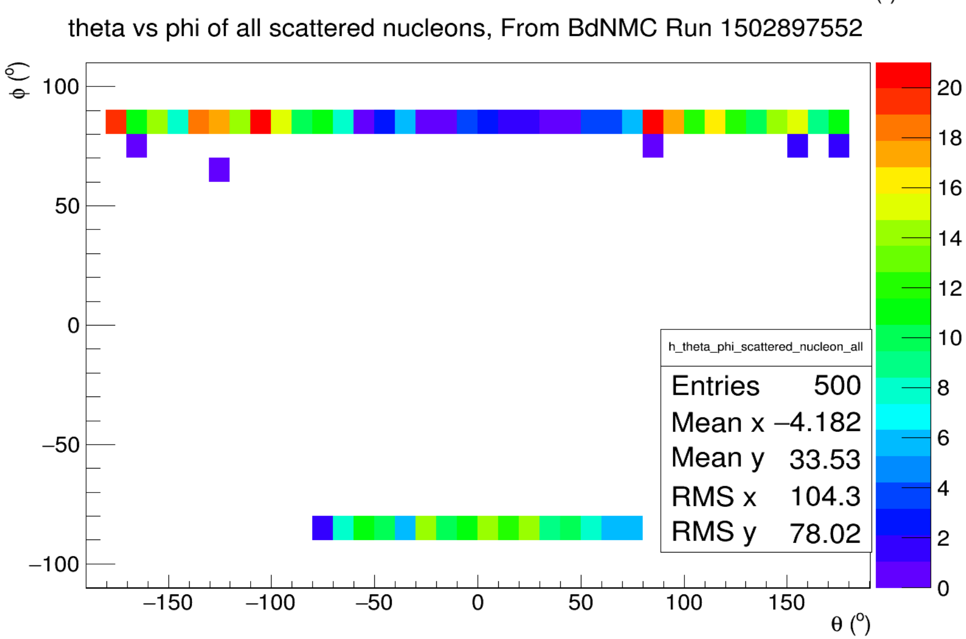
Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only

Run 1502897552 : proton Bremsstrahlung channel only

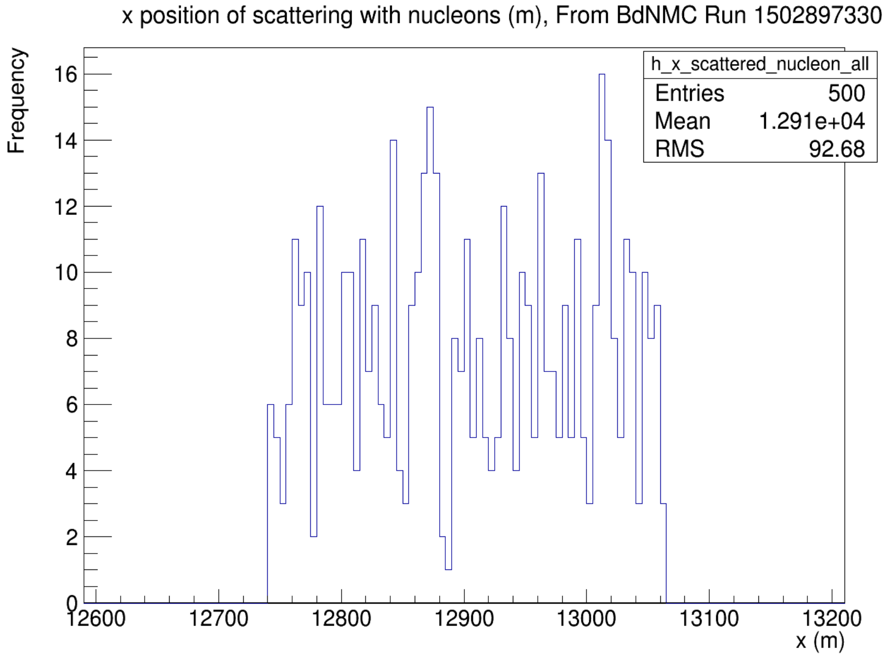


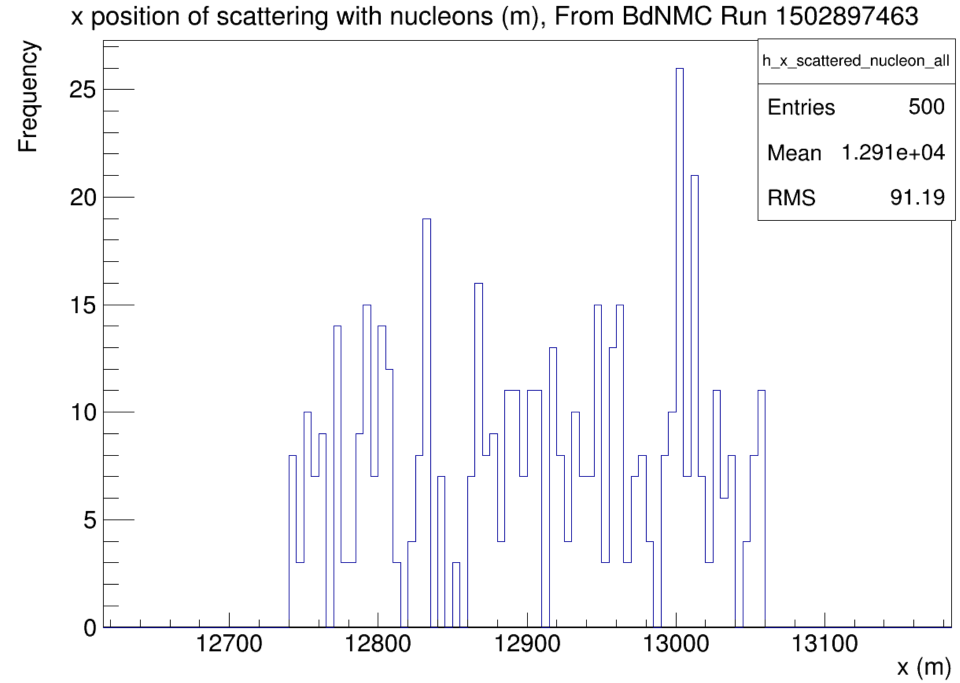


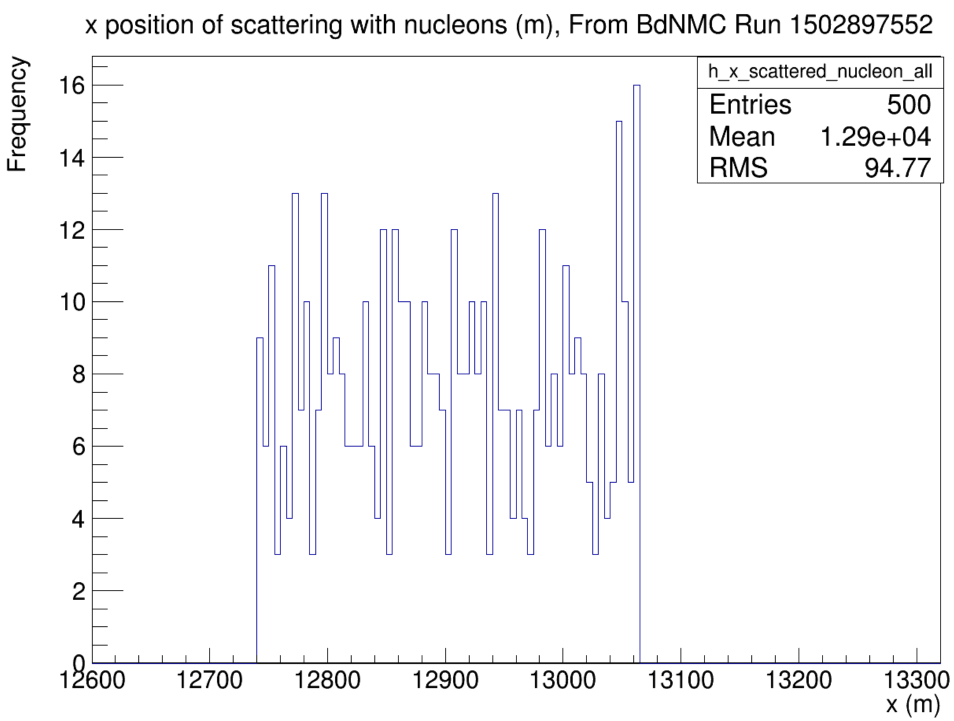


Run 1502895571: all three production channels | Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only | Run 1502897552 : proton Bremsstrahlung channel only



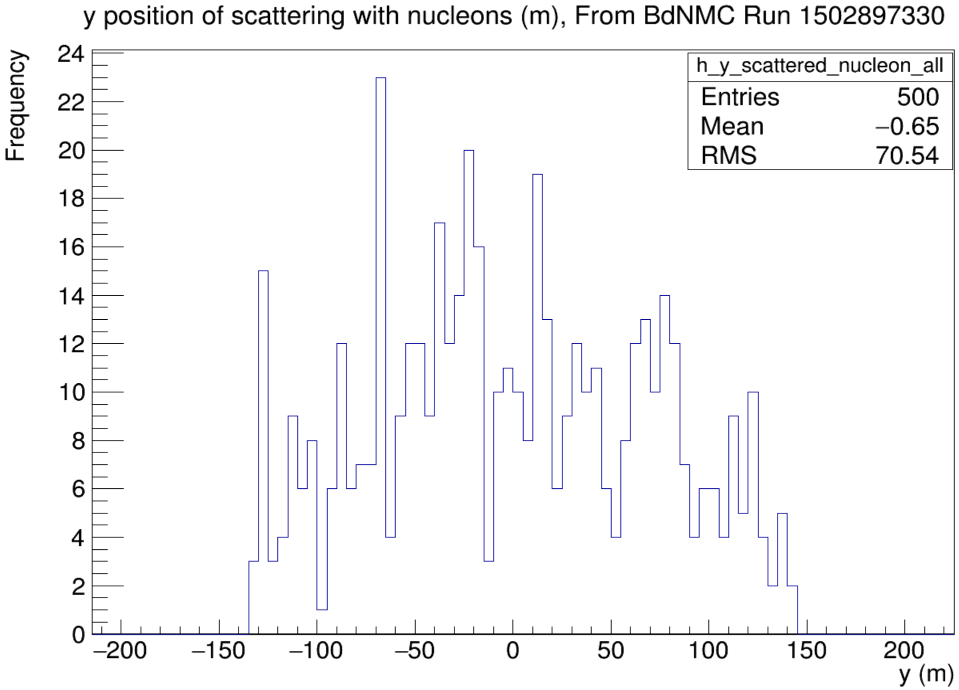


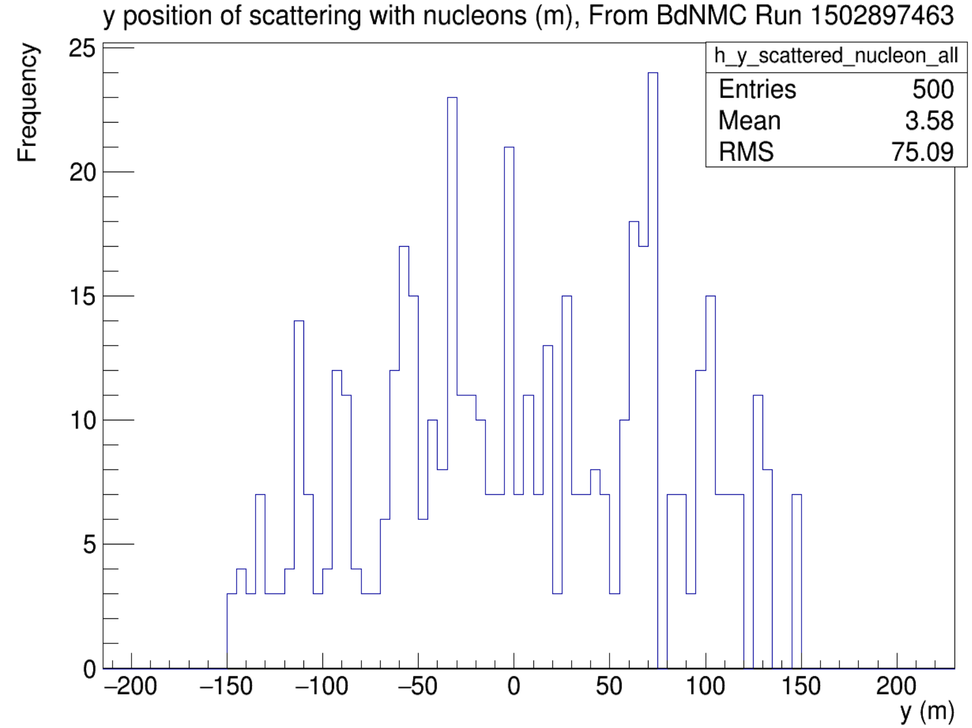


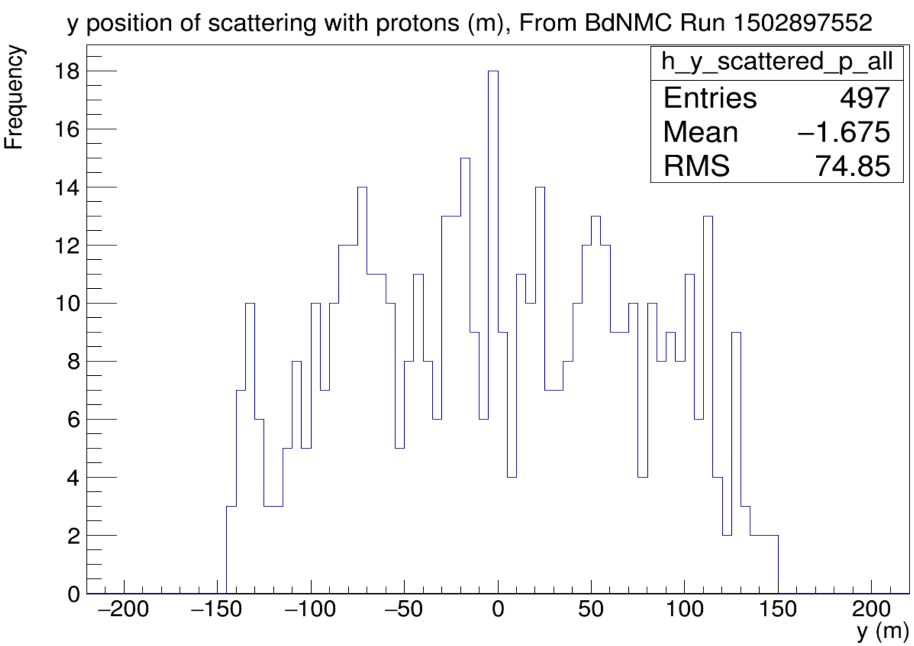
i0 production channel only

Run 1502897463: eta production channel only | Run 1502897552 : proton Bremsstrahlung channel only

Title



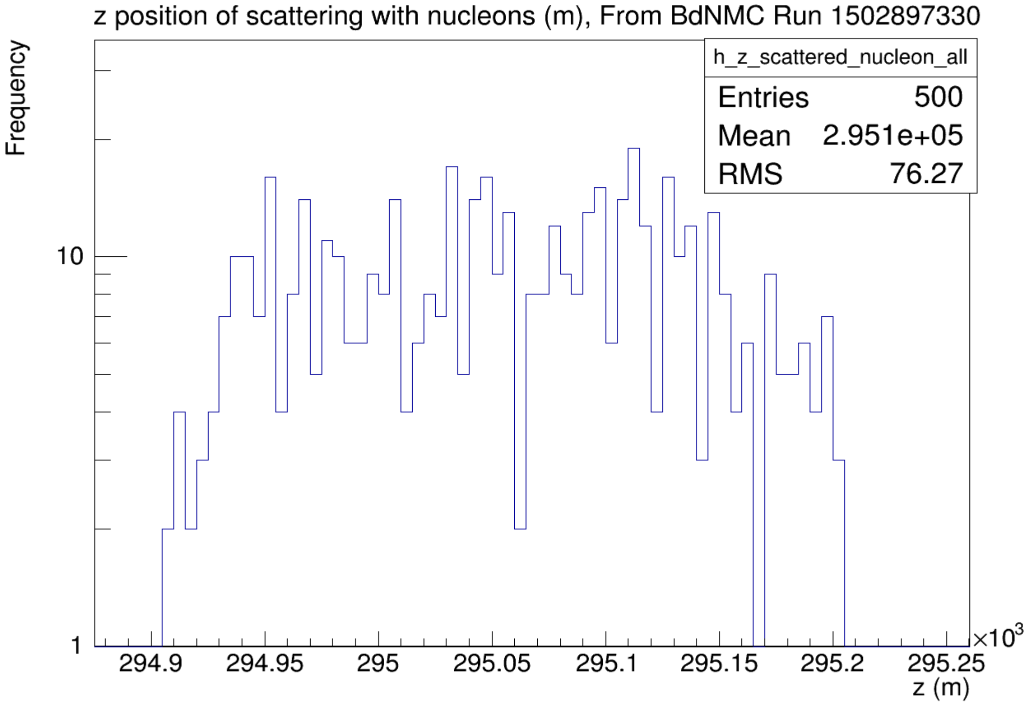


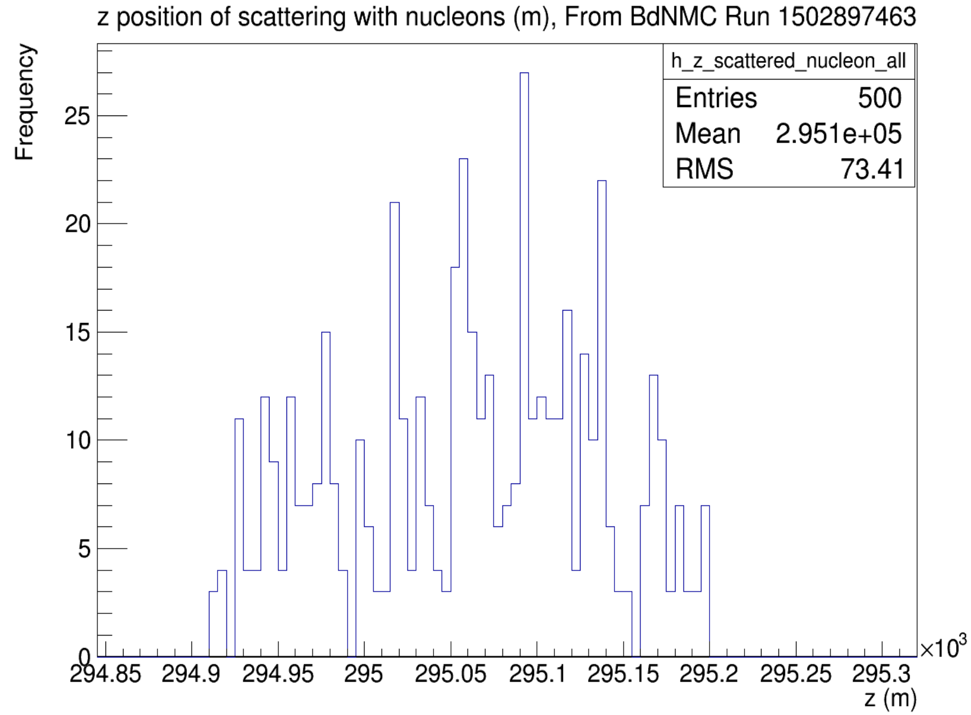


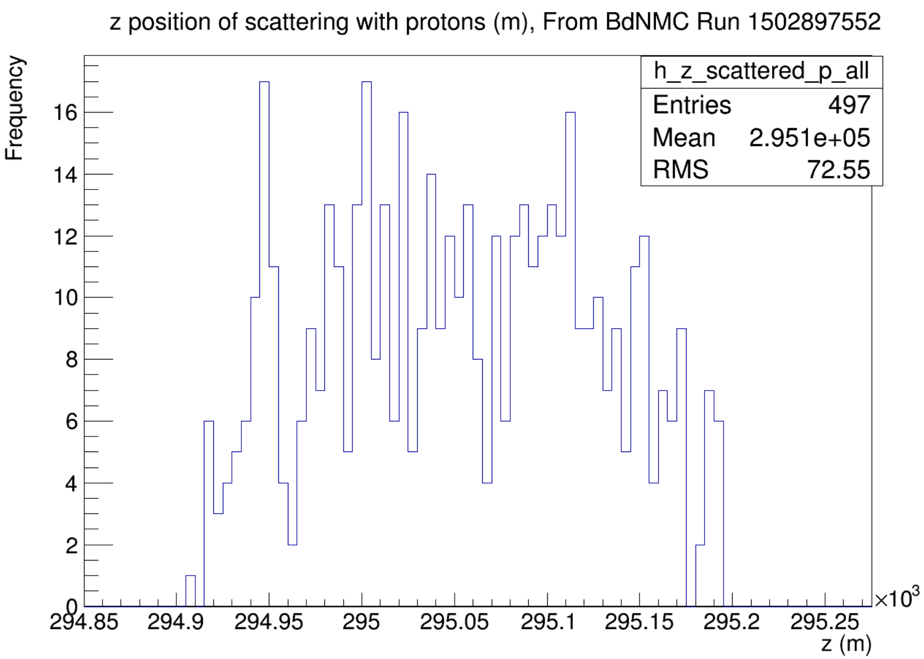
Run 1502895571: all three production channels | Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only | Run 1502897552 : proton Bremsstrahlung channel only

Title



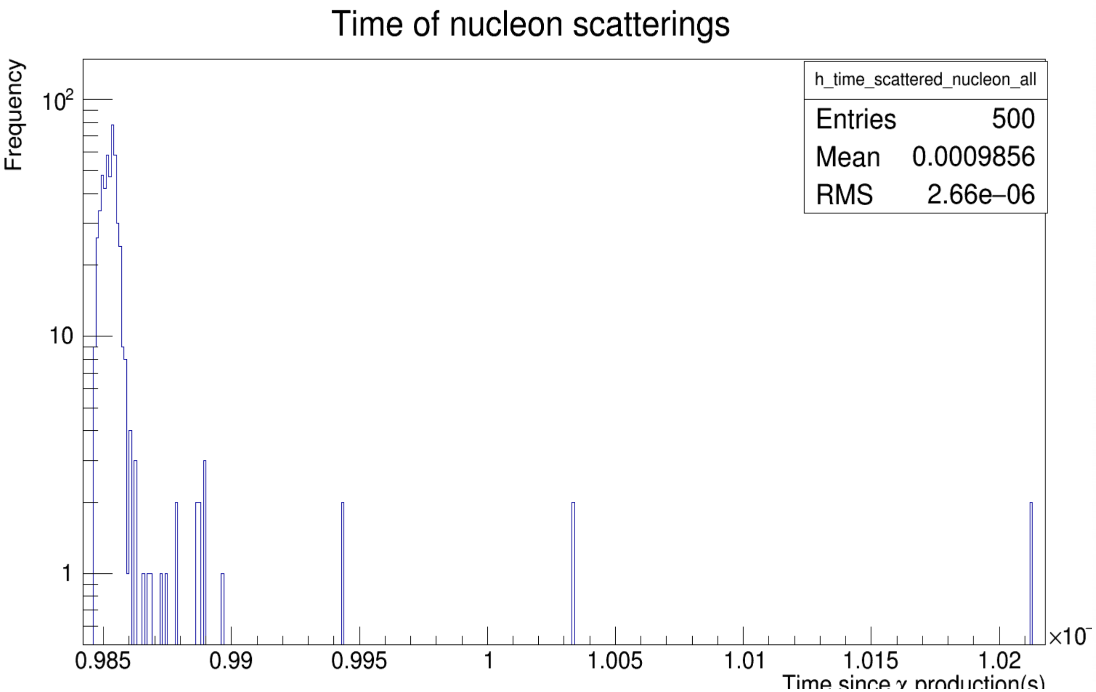


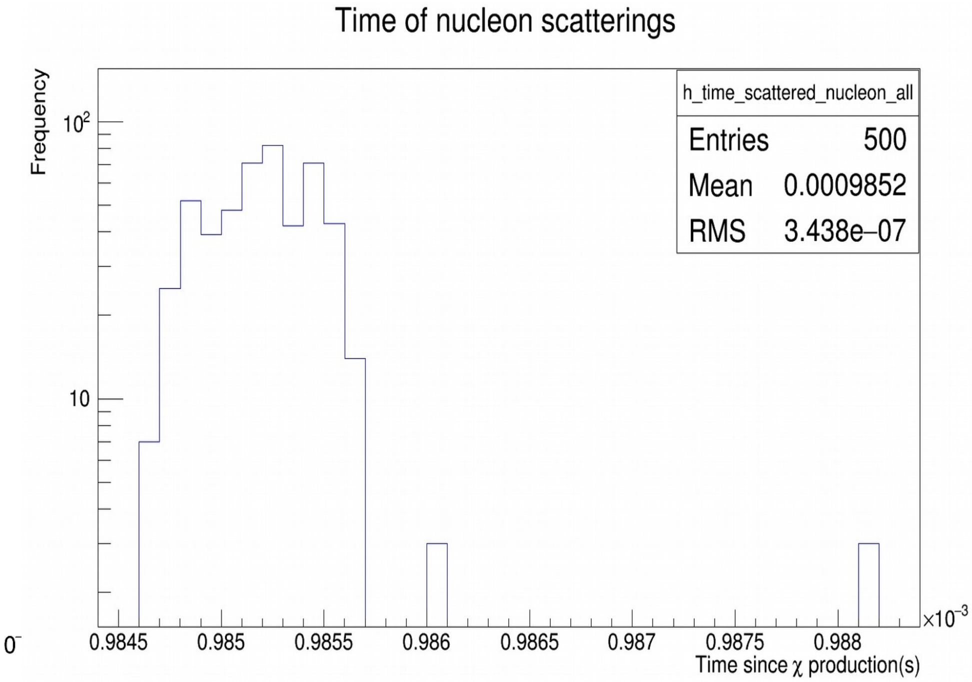


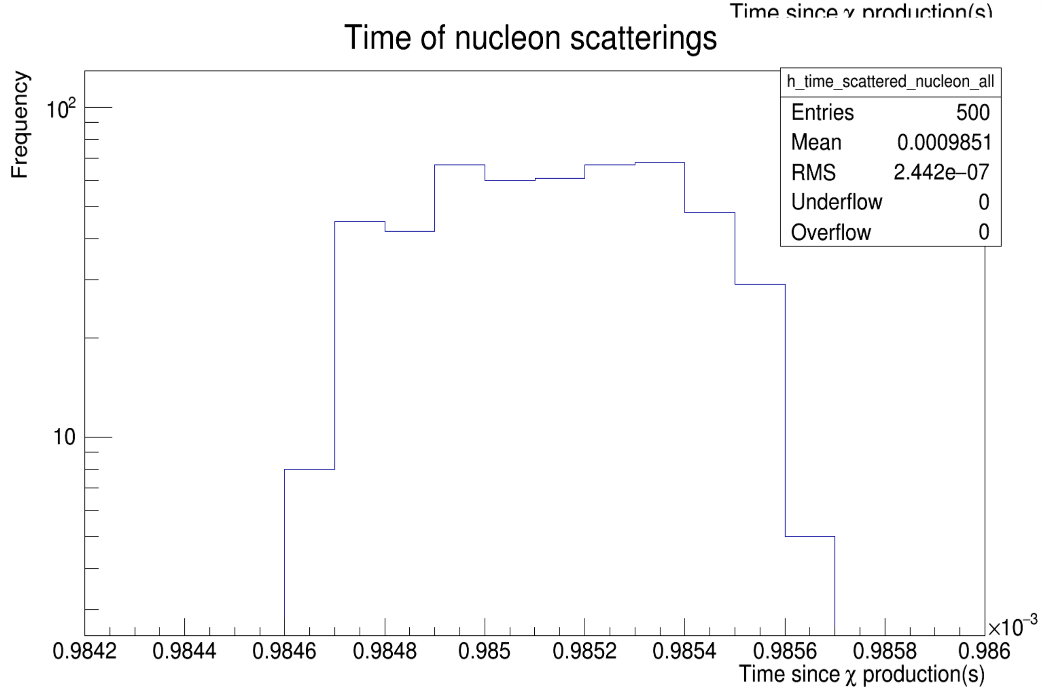
pi0 production channel only

Run 1502897463: eta production channel only | Run 1502897552 : proton Bremsstrahlung channel only

Title







Run 1502895571: all three production channels | Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only | Run 1502897552 : proton Bremsstrahlung channel only

Next steps:
- Q^2
- normalized histograms
- why the sinusoidal pattern
- write up a report

Run 1502895571: all three production channels | Run 1502897330: pi0 production channel only
Run 1502897463: eta production channel only | Run 1502897552 : proton Bremsstrahlung channel only

Back up :

Proton_target_cross_section

- Patrick has 1.5e-30 (I'm assuming this is in meters ^ 2)
- Paper below: (2.59 +/- 0.12) e-30 m²
  (https://journals.aps.org/pr/pdf/10.1103/PhysRev.125.2078)

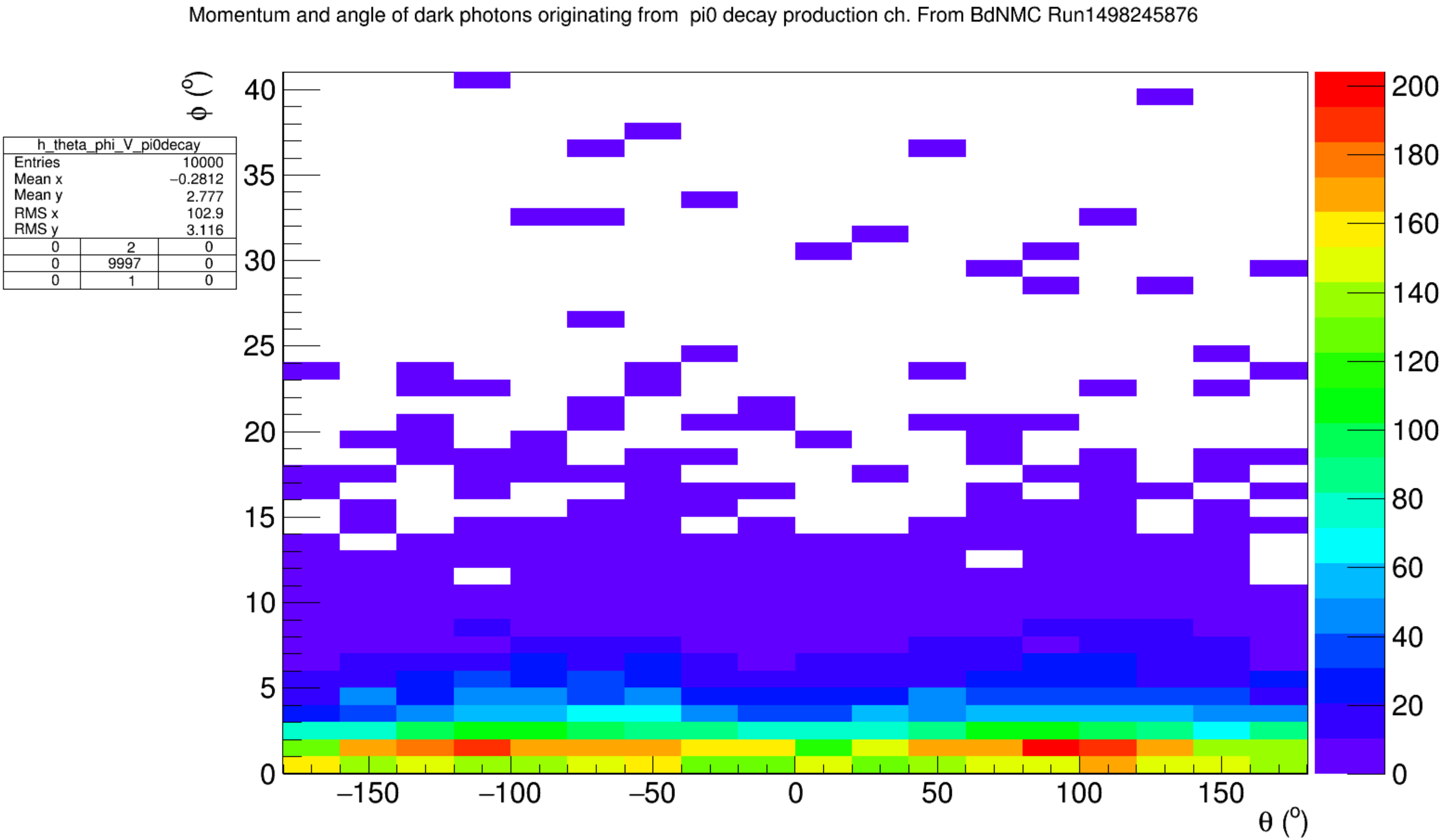
PHYSICAL REVIEW VOLUME 125, NUMBER 6 MARCH 15, 1962

$C^{12}(p,pn)C^{11}$ Cross Section at 28 Gev*

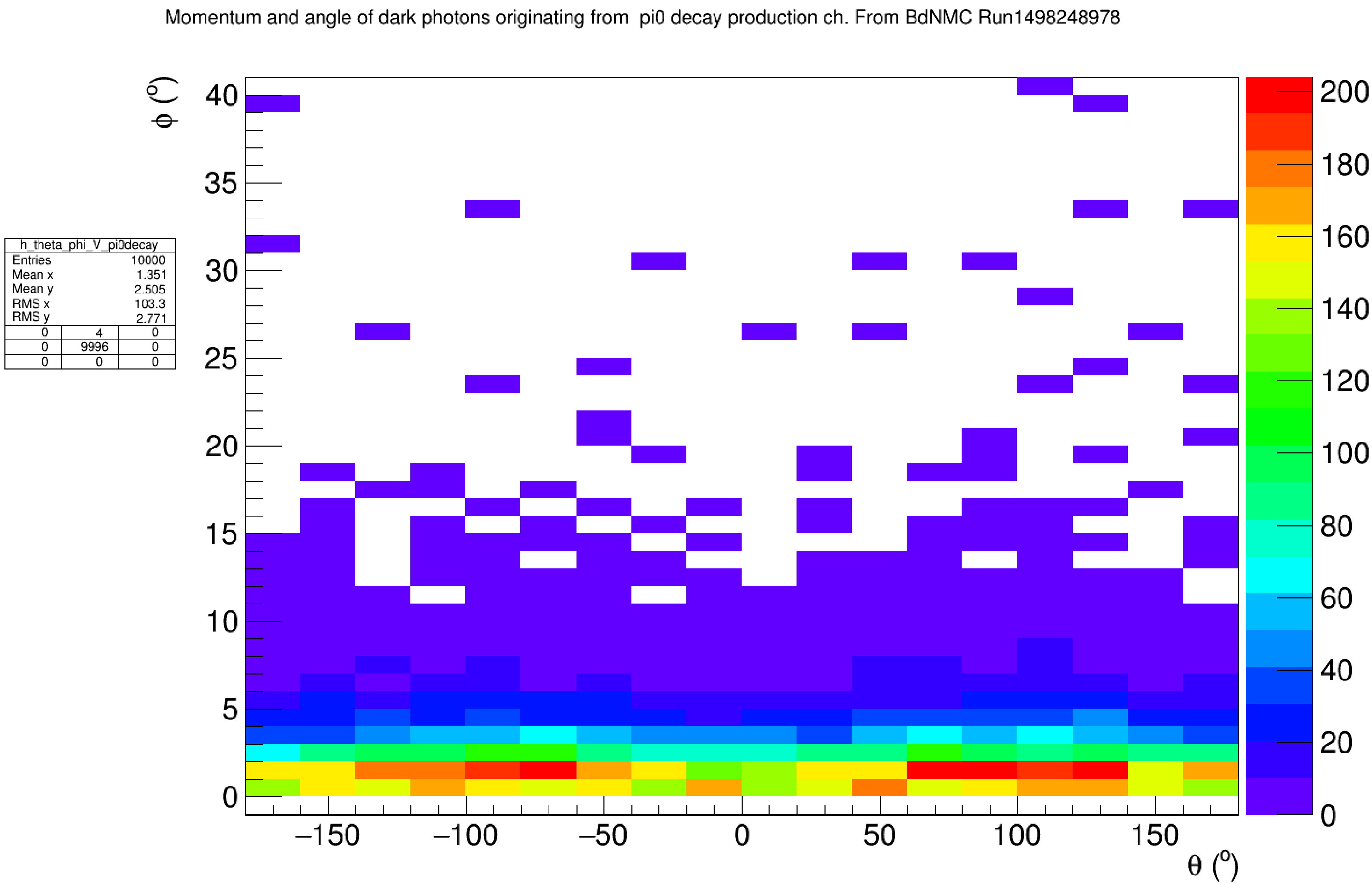
J. B. CUMMING, G. FRIEDLANDER, AND S. KATCOFF
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received November 7, 1961)

The $C^{12}(p,pn)C^{11}$ cross section has been measured in the 28-Gev diffraction scattered proton beam of the Brookhaven AGS. Proton fluxes were determined using nuclear emulsions and the C^{11} activity induced in plastic scintillators was measured by internal scintillation counting. The cross section at 28 Gev is 25.9 ± 1.2 mb, not significantly different from the values at 2 and 3 Gev.

Some angular distributions for the sample miniboone example from slides 7-12:

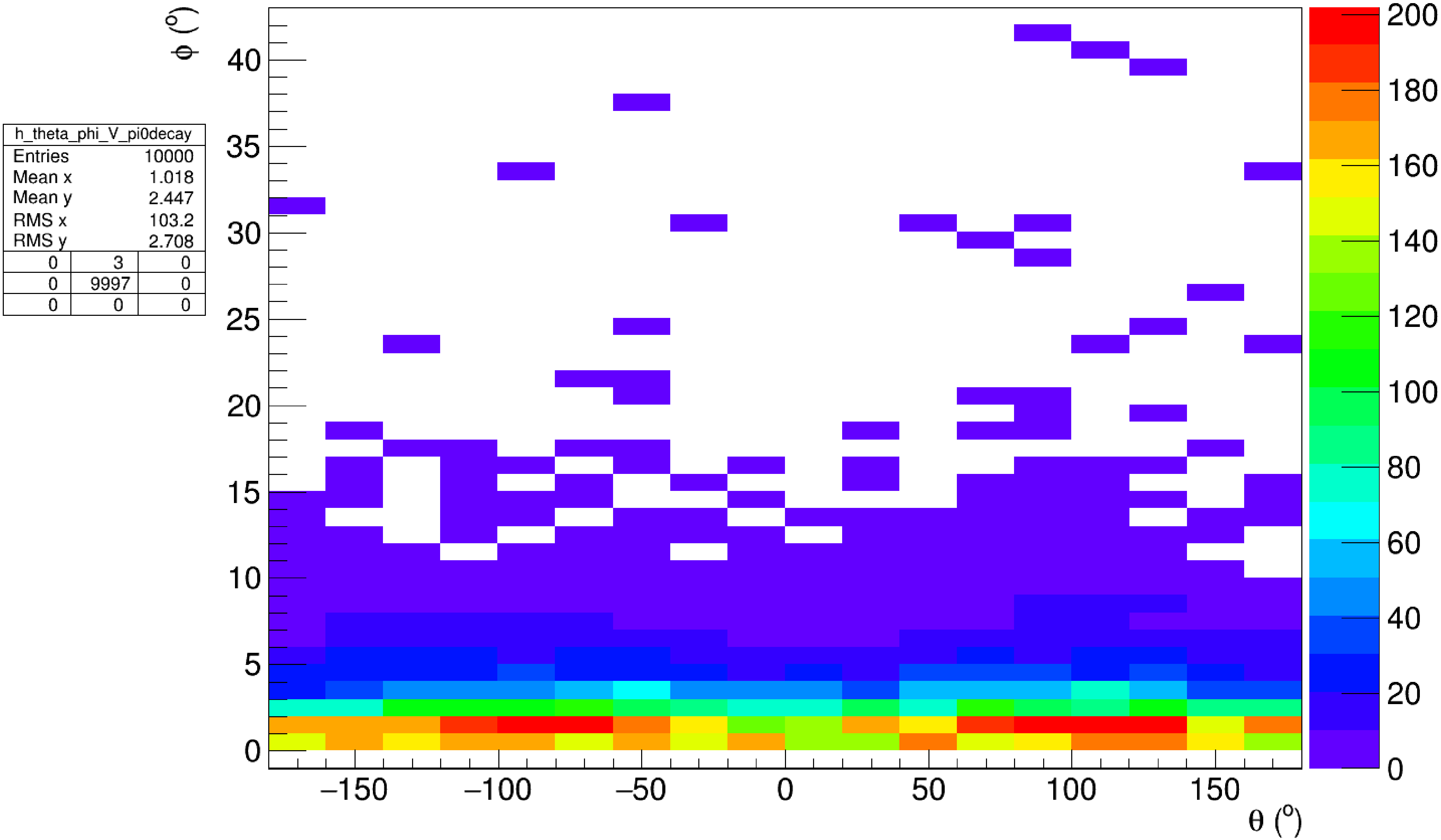


Run1498246615, mass_V=0.02 GeV
Run1498247168, mass_V=0.03 GeV
Run1498247730 mass_V=0.05 GeV
Run1498500989, mass_V= 0.1 GeV
Run 1498241455, mass_V= 0.2 GeV
Run1498244748 , mass_V = 0.3 GeV
Run1498245876, mass_V = 0.4 GeV
Run1498248978, mass_V = 0.8 GeV
Run1498251170, mass_V = 0.95 GeV

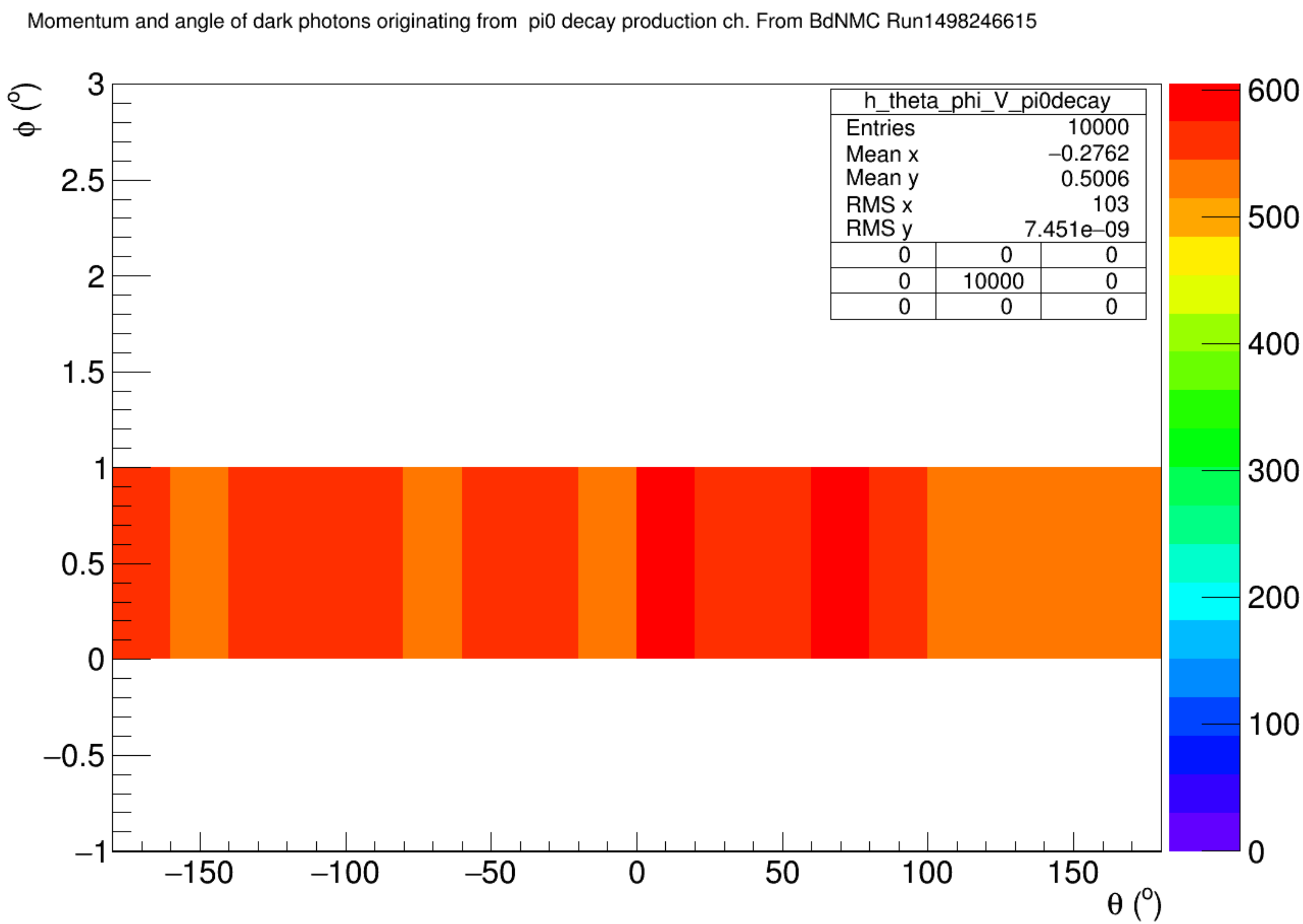


Run1498247730 mass_V=0.05 GeV
Run1498500989, mass_V= 0.1 GeV
Run 1498241455, mass_V= 0.2 GeV
Run1498244748 , mass_V = 0.3 GeV
Run1498245876, mass_V = 0.4 GeV
Run1498248978, mass_V = 0.8 GeV
Run1498251170, mass_V = 0.95 GeV

Momentum and angle of dark photons originating from pi0 decay production ch. From BdNMC Run1498251170



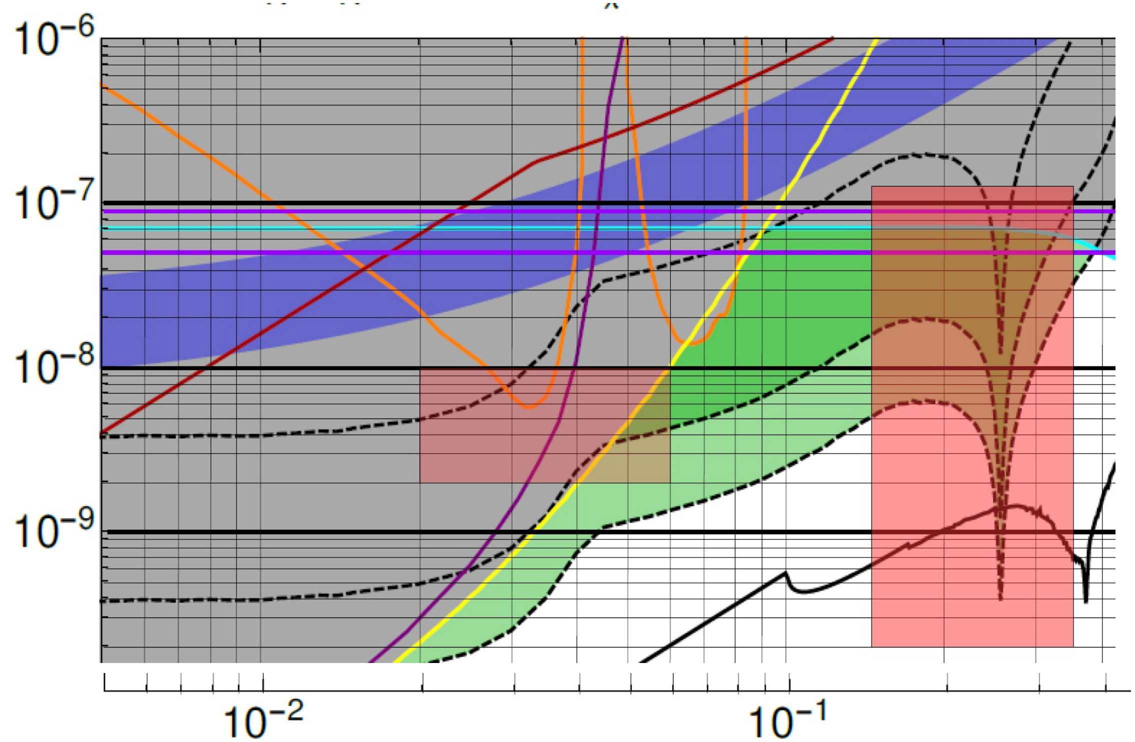
Run1498500989, mass_V= 0.1 GeV
Run 1498241455, mass_V= 0.2 GeV
Run1498244748 , mass_V = 0.3 GeV
Run1498245876, mass_V = 0.4 GeV
Run1498248978, mass_V = 0.8 GeV
Run1498251170, mass_V = 0.95 GeV



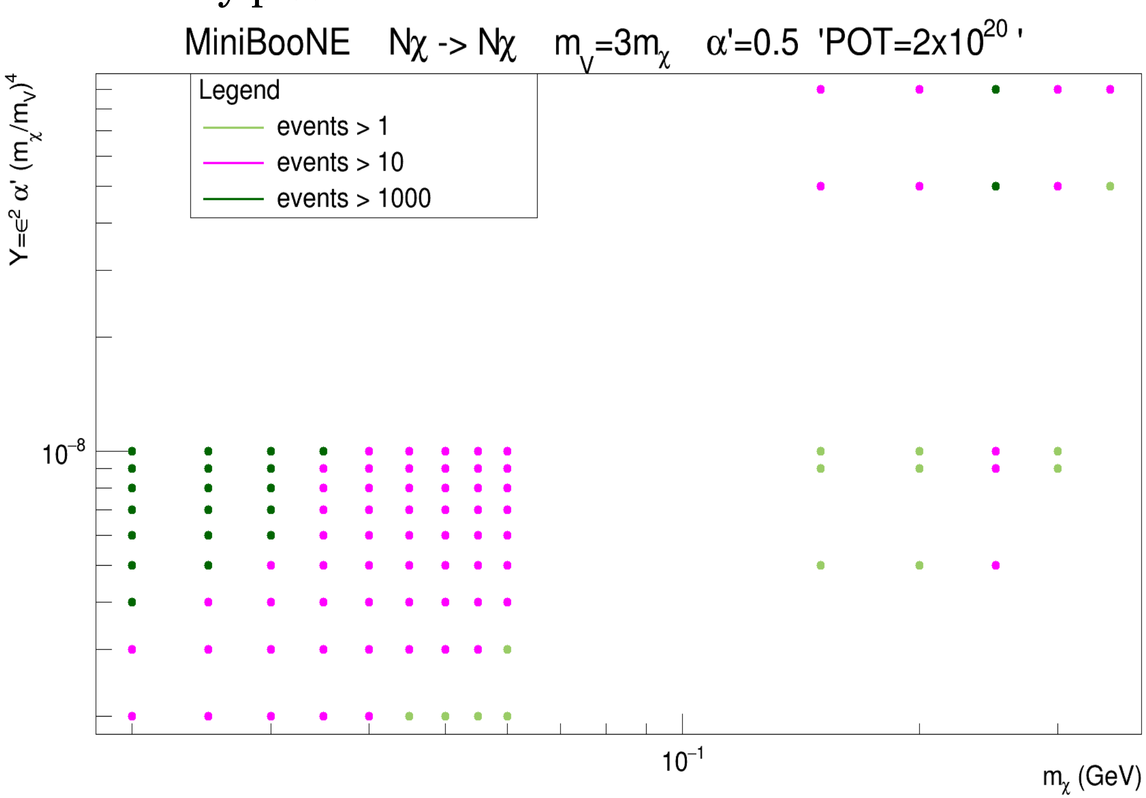
Run1498246615, mass_V=0.02 GeV
Run1498247168, mass_V=0.03 GeV
Run1498247730 mass_V=0.05 GeV
Run1498500989, mass_V= 0.1 GeV
Run 1498241455, mass_V= 0.2 GeV
Run1498244748 , mass_V = 0.3 GeV
Run1498245876, mass_V = 0.4 GeV
Run1498248978, mass_V = 0.8 GeV
Run1498251170, mass_V = 0.95 GeV

Pther stuff

Zoomed in section of figure 8 from last slide



My plot:

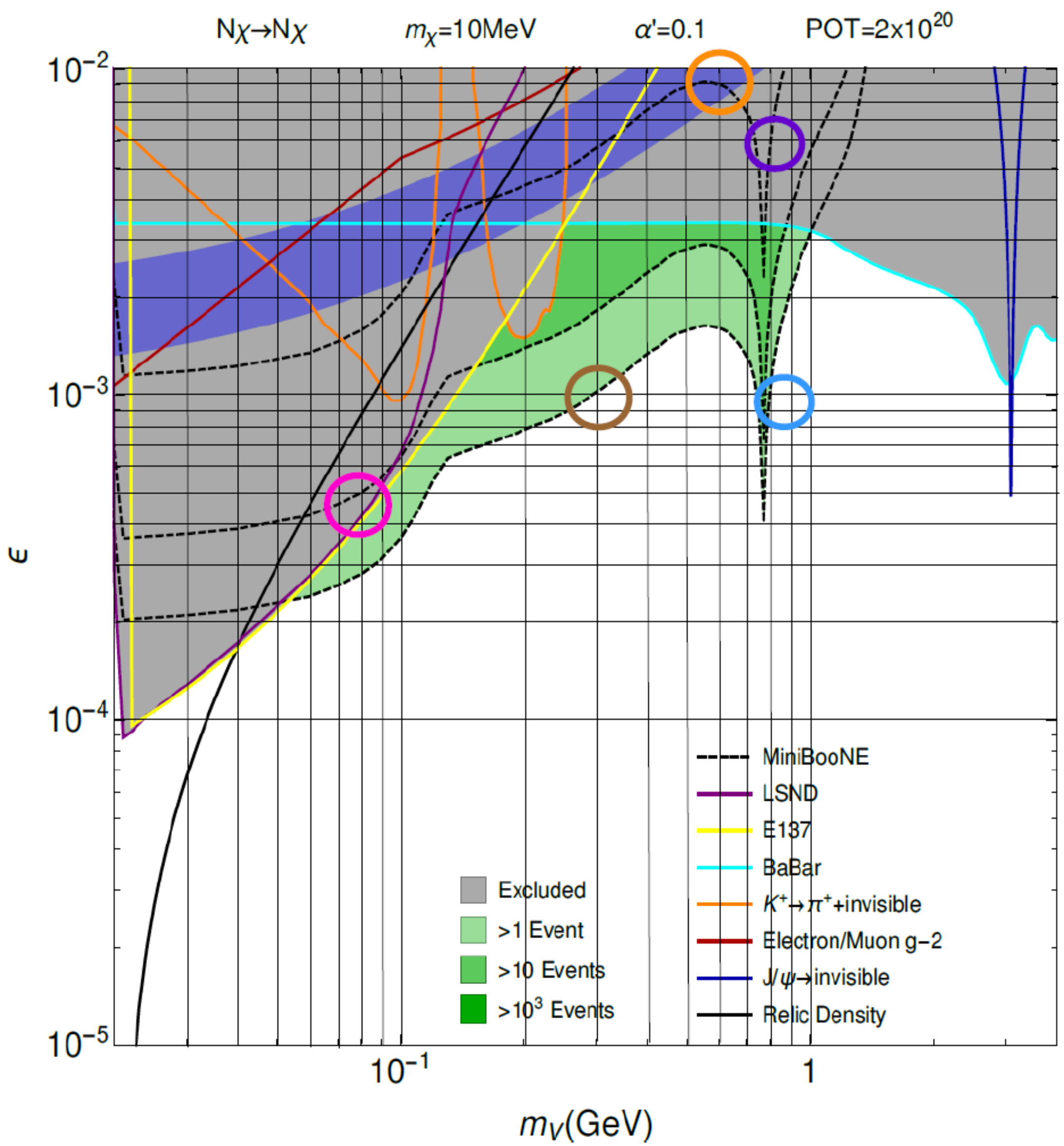


On-Shell/Off-shell

On-shell: $m_V > 2m$ and $m_V < m_X$ [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)

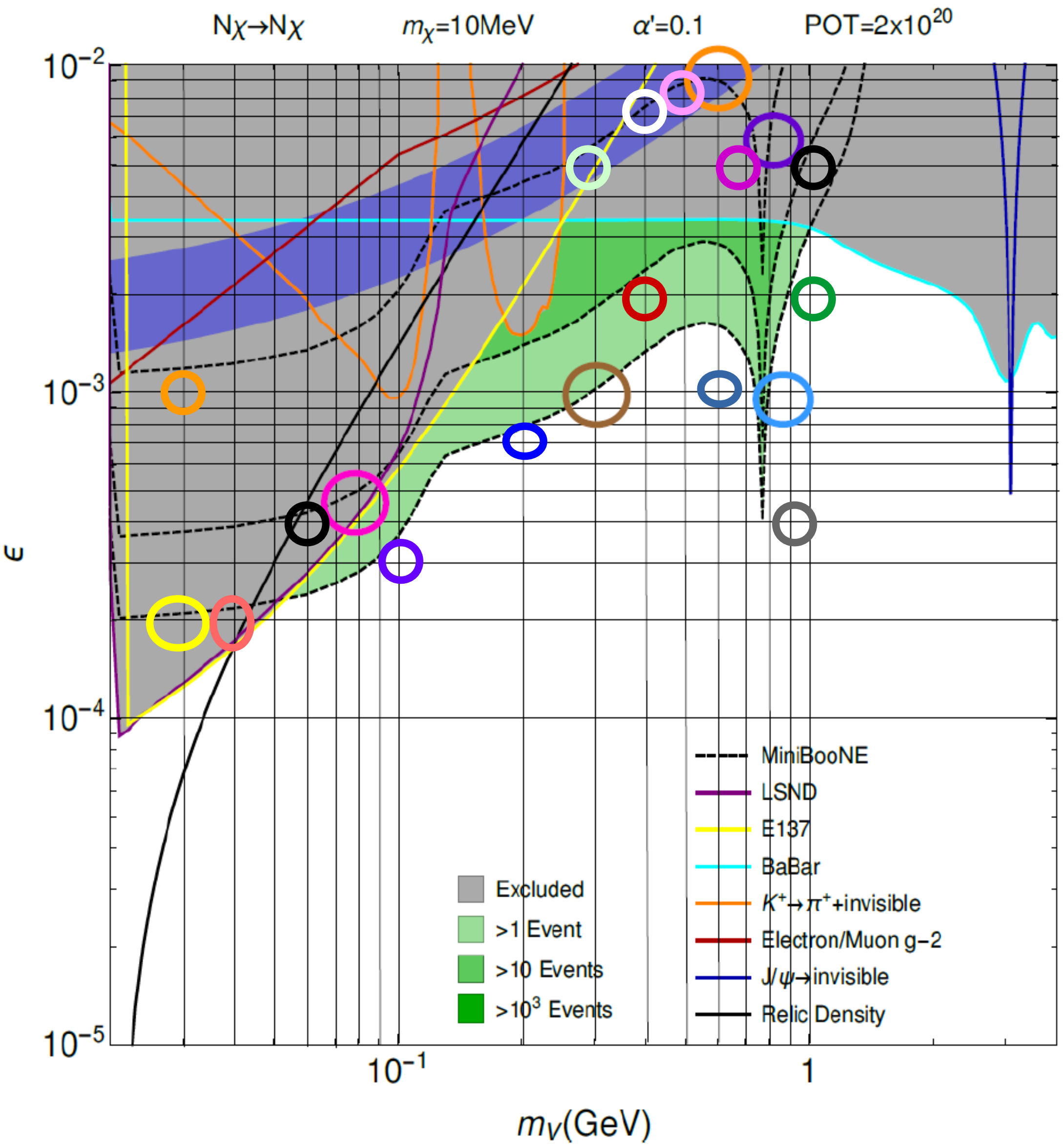
- Did what hiro suggested, ran BdNMC with POT=2×10^{25}, then divided #signal events by 10^5
  Did this for some points on the curves corresponding to events>1, events>10, events>1000



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

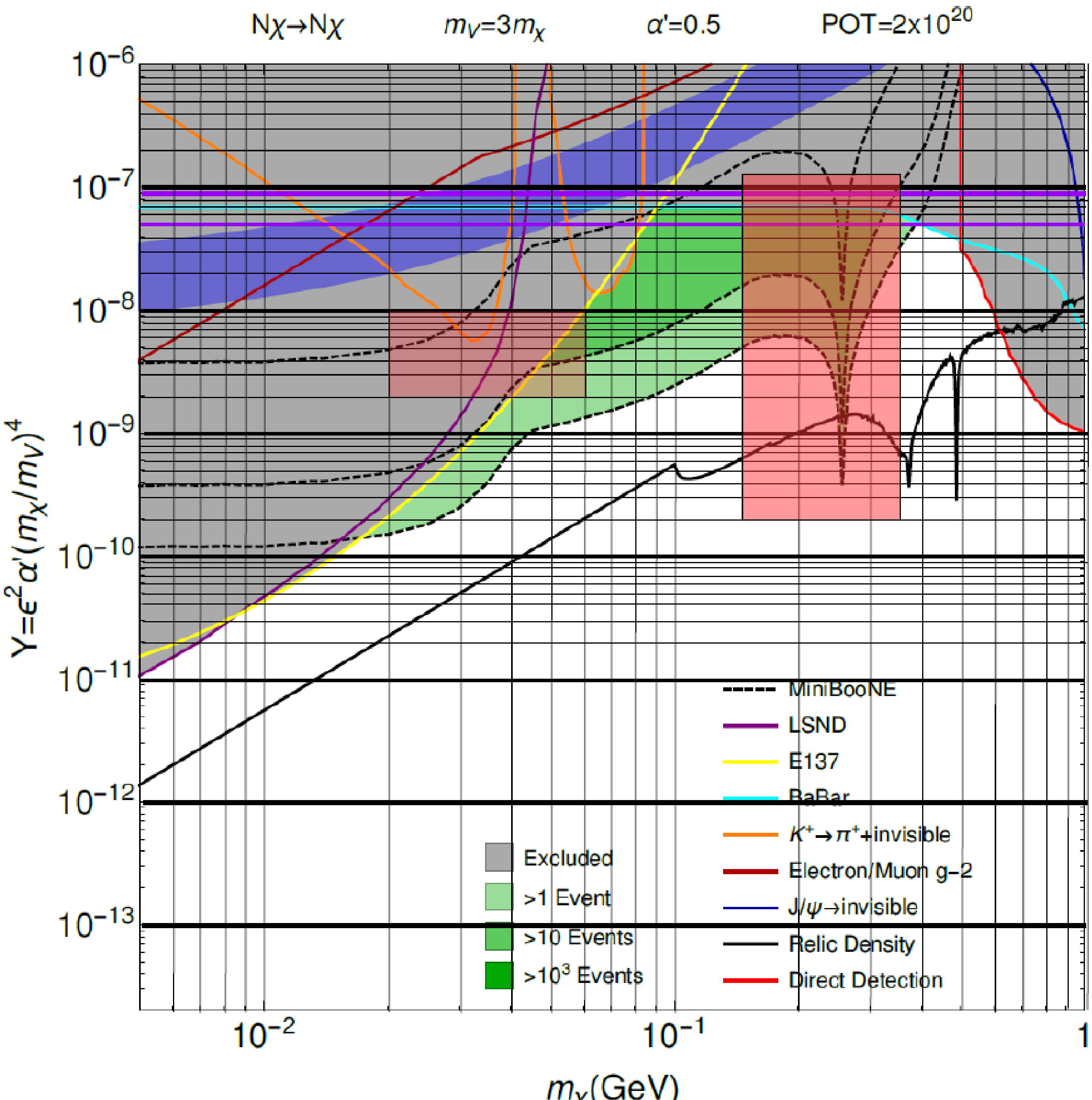
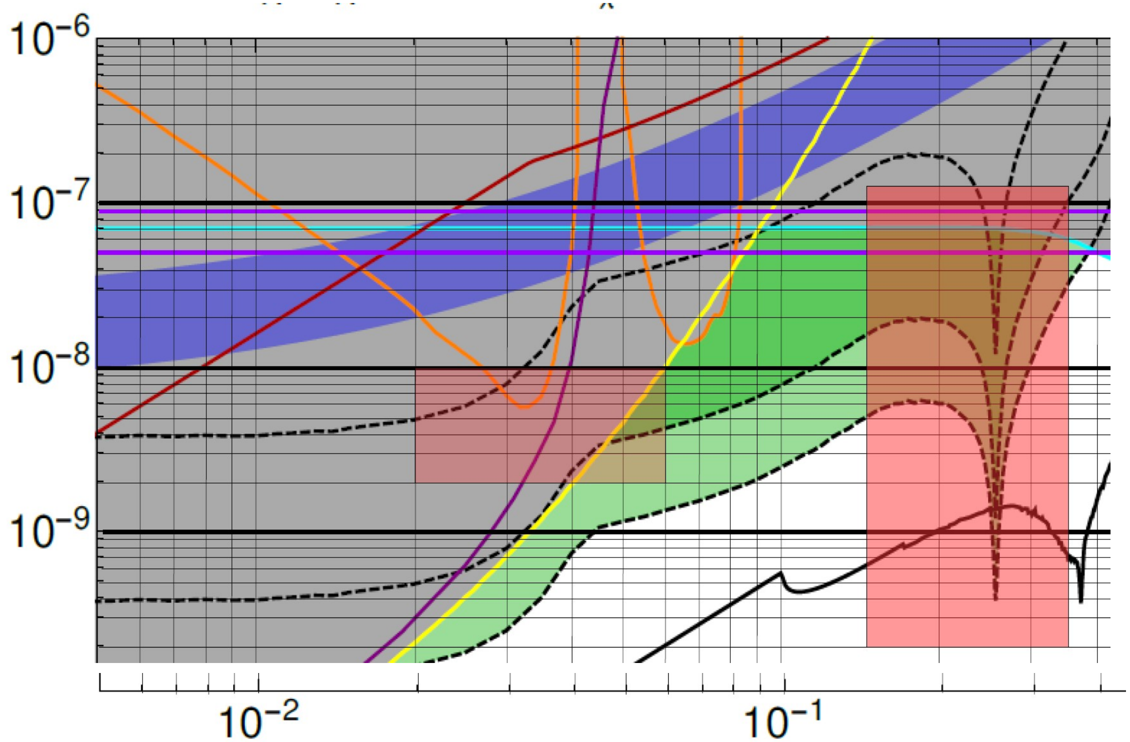


Fig 8.0 of arXiv:1609.01770v3: Further plots showing the MiniBooNE yield of light dark matter scattering events in various channels, now using mV = 3mX with alpha' = 0.5, and using the variable Y for the vertical scale. In these plots and below the black dotted line shows the parameters required to achieve the dark matter relic density, so smaller values of Y are excluded due to over-production of dark matter.

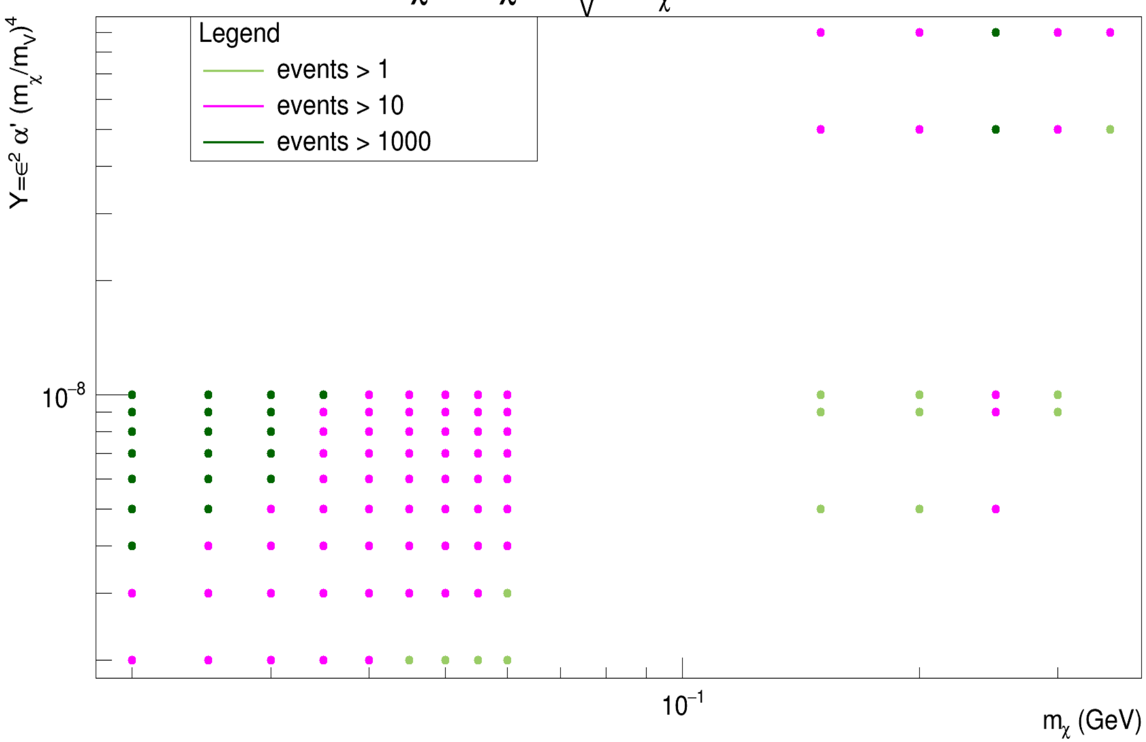
- Next: replicated some points (in red) in this plot
. Checked the number of signal events for each point: same 'issue' as figure 7: # signal events agree, but I get (a few) more signal for some points

Zoomed in section of figure 8 from last slide



My plot:

MiniBooNE Nχ -> Nχ $m_V=3m_\chi$ α'=0.5 'POT=2x10^{20} '



Resonant Vector Meson Mixing

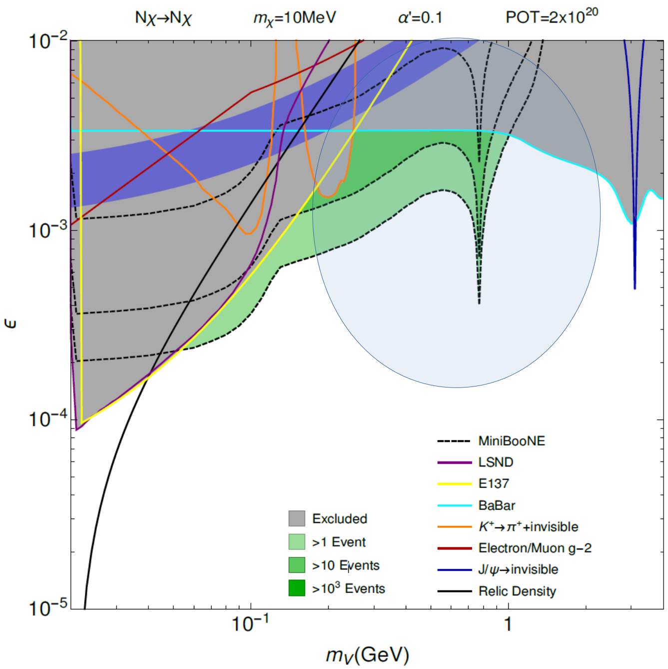


FIG. 7. Plots showing the MiniBooNE yield of light dark matter scattering events in nucleon elastic scattering. In this plot and the others to follow, the gray regions are excluded by existing constraints, while the green

← Causes this peak

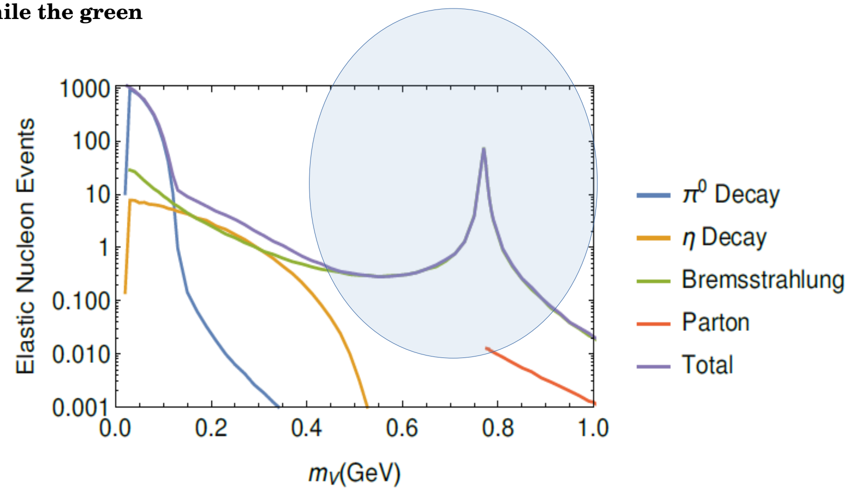
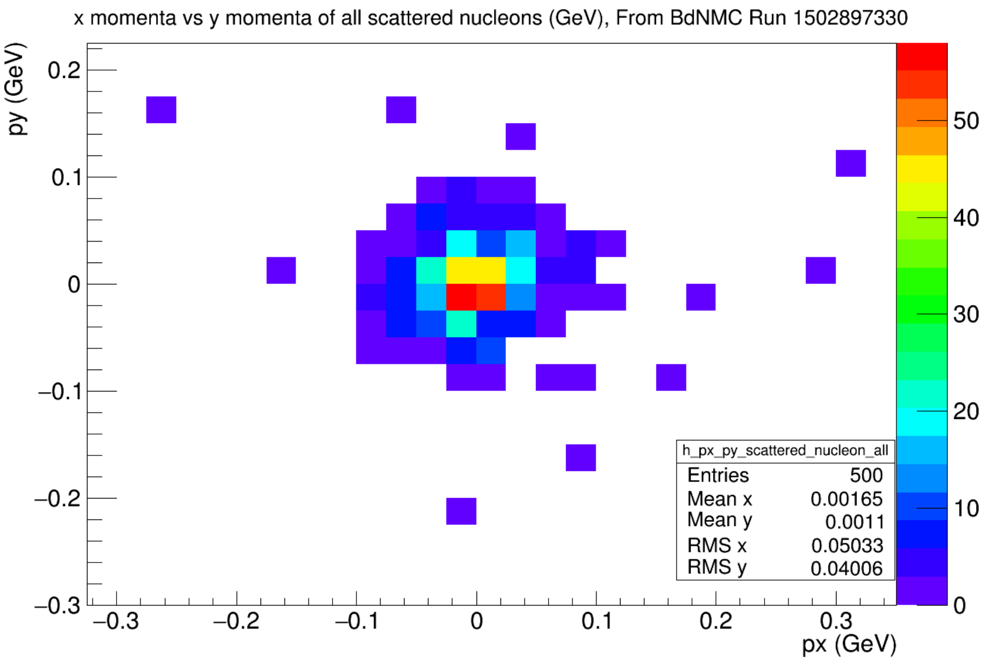
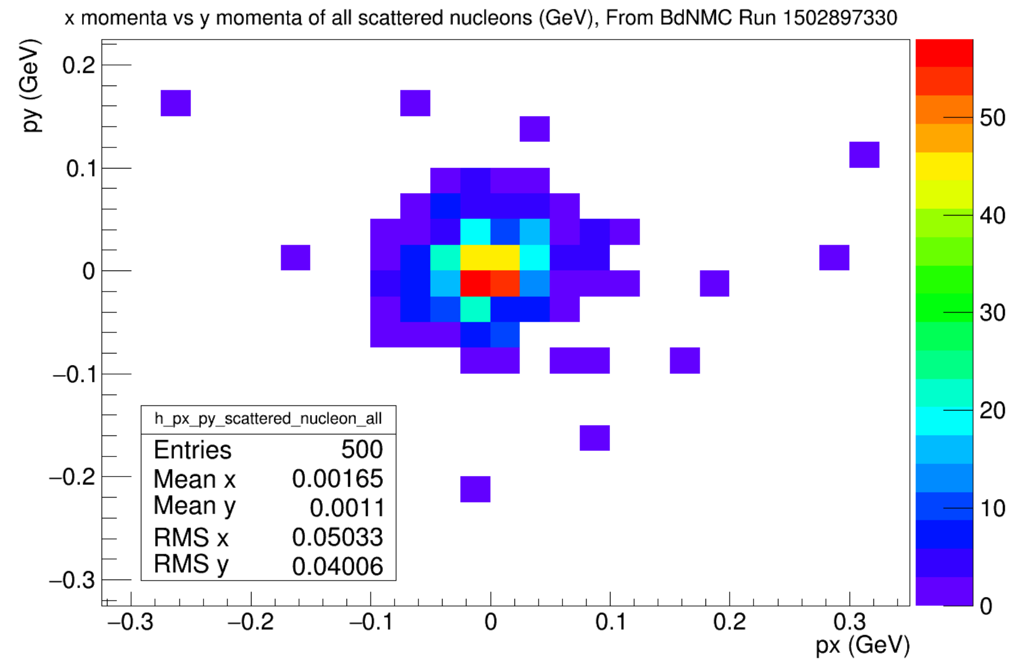


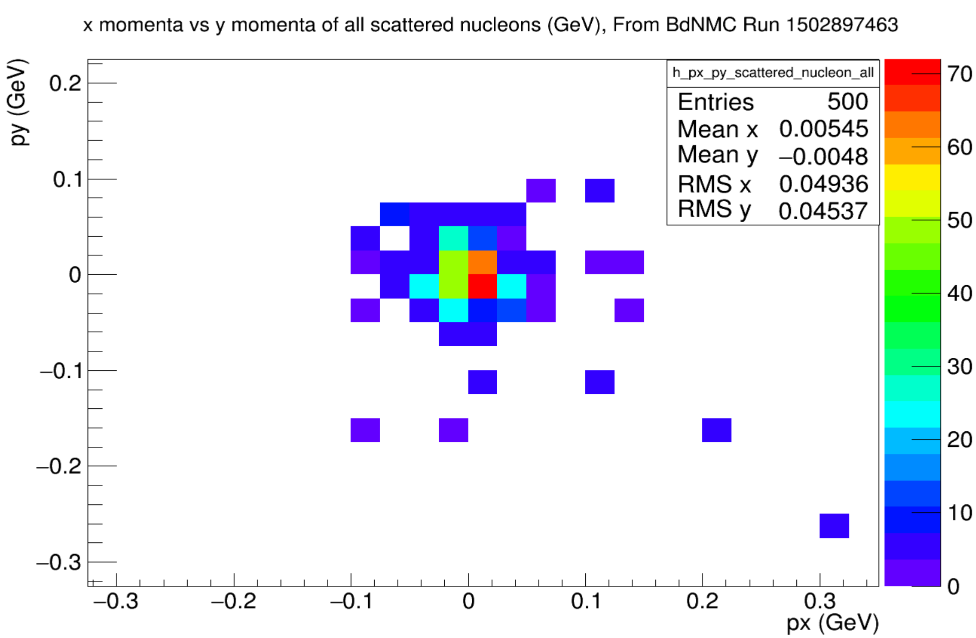
FIG. 1. A plot illustrating the distinct contributions to DM production (coupled through the vector portal), as discussed in the text, using the 9 GeV proton beam at MiniBooNE as an example. The rate of elastic scattering events on nucleons is plotted versus the vector mediator mass. From smaller to 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 $\alpha' = 0.1$.

Some extra nucleon distributions

Title





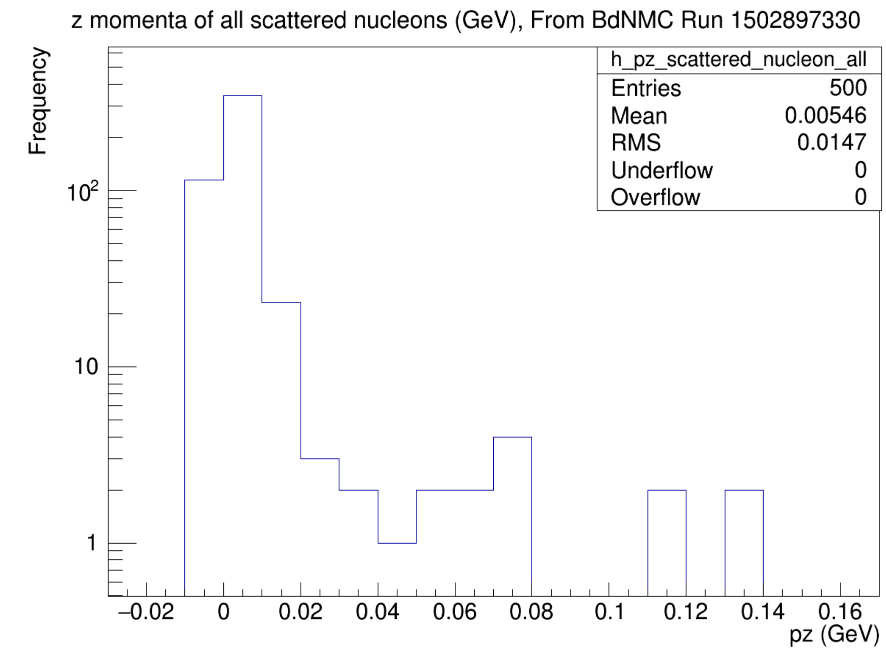


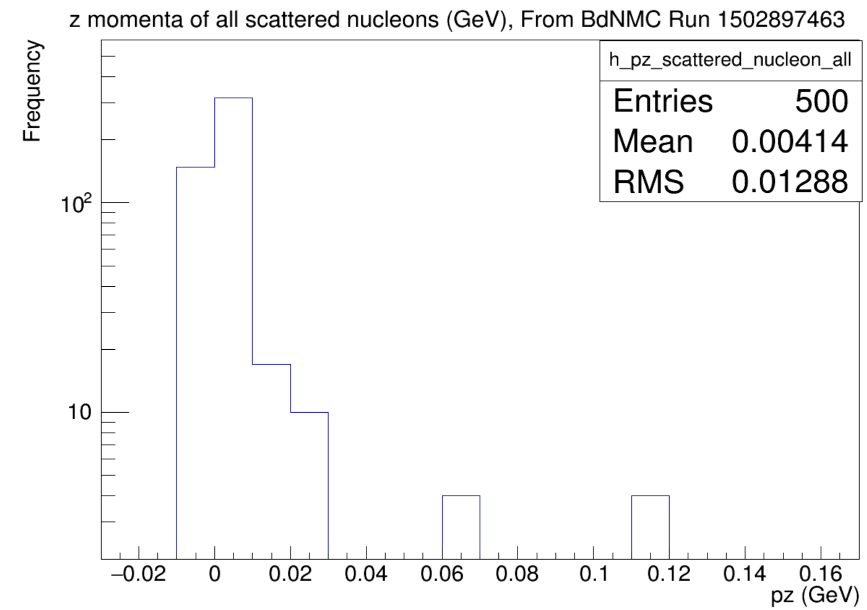
Notes: only 2 neutron scattering, 498 proton scattering

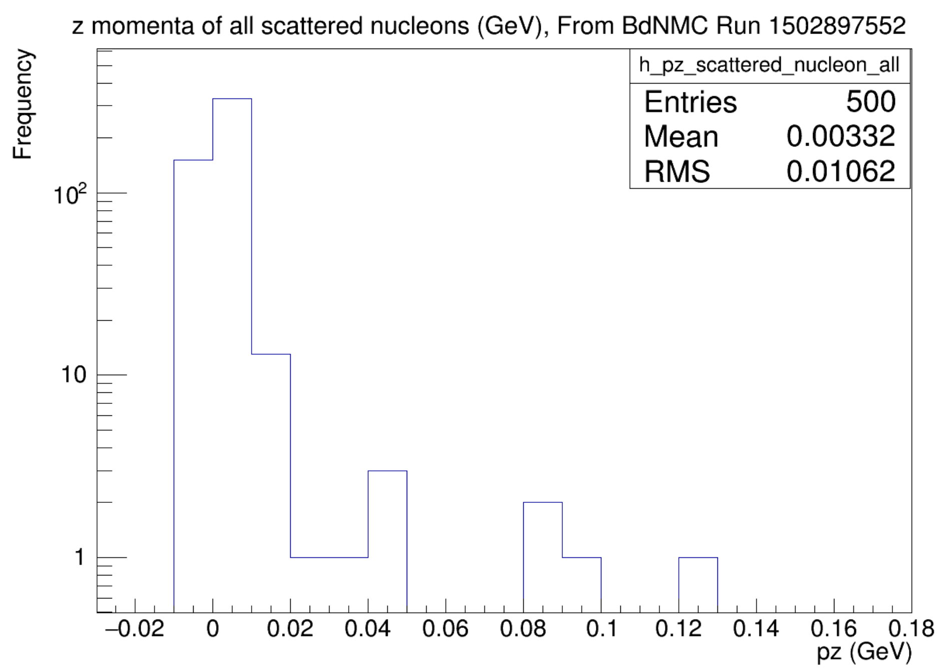
Run 1502895571: all three production channels | Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only | Run 1502897552 : proton Bremsstrahlung channel only

Title







Notes: only 2 neutron scattering, 498 proton scattering

Run 1502895571: all three production channels | Run 1502897330: pi0 production channel only

Run 1502897463: eta production channel only | Run 1502897552 : proton Bremsstrahlung channel only