BDNMC progress

Rose Atashi
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outline

- **Reminder**
- **Creating a TTree from the information in the output of BDNMC- progress**
- **Goals**

Reminder: BDNMC

. simulates the production, propagation, and scattering of light dark matter particles inside a detector (user inputs the properties of the detector, model parameters, etc)

. The setup is currently MiniBooNE like (can be changed)

Example

- Ran BDNMC with parameters from the “2nd MiniBooNE example” from the paper “Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and ShiP” by Patrick deNiverville etc

  (except with less statistics: only 5 events → easy to show you what is going on)

- Key parameters are described below:

  alpha_D = 0.1 epsilon = 10^{-3} dark_matter_mass = 0.005 GeV dark_photon_mass = 0.4 GeV

- POT = 2e20 beam_energy = 8.9 GeV

  Reminder:

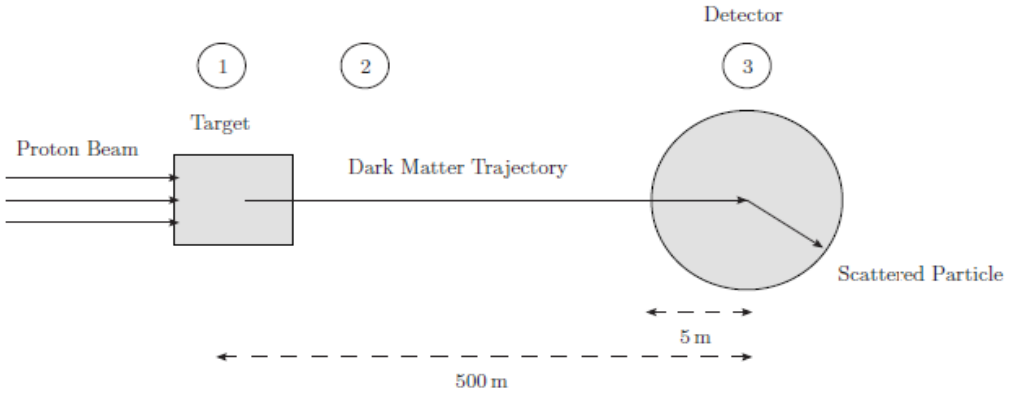
alpha_D: The dark sector coupling strength $\alpha' = \frac{\epsilon'^2}{4\pi}$, or in a baryonic model, α_B.

dark_matter_mass: The mass of the dark matter candidate χ

dark_photon_mass: The mass of the V mediator.

epsilon: The mixing constant ϵ between the V mediator and the photon.

- pi0_decay and eta_decay production channels and NCE_nucleon scattering signal channel
- Experiment setup: MinoBooNE like:
  - Spherical detector, filled with CH_2



- Generates an “events.dat” file
- For the example we had (has 5 events):

“[particle name px py pz E x y z t]
where x y z t are the optional position and time coordinates only shown for the signal particle”

```
Run 1495052956
event 1
eta             0.259824        -0.198728       3.08678         3.15205
V               0.267948        -0.0747792      2.75542         2.79816
DM              -0.00796544     0.00861999      1.8036          1.80364
proton          -0.342382       -0.192742       0.132485        1.02581         -2.1939         2.37418         496.759         1.65705e-06

endevent 1

event 2
eta             -0.512015       -0.241737       2.33848         2.46764
V               -0.447128       -0.203878       2.29495         2.38081
DM              0.00205929      -0.0015099      0.924071        0.924088
proton          -0.297628       -0.242418       0.186791        1.03082         1.10585         -0.810828       496.231         1.65528e-06

endevent 2

event 3
eta             -0.293065       0.34329         0.469601        0.851124
V               -0.309001       0.180154        0.415015        0.678362
DM              0.000520242     0.000693986     0.303537        0.30358
proton          0.179911        -0.149193       0.206807        0.988812        0.854665        1.14009         498.657         1.66357e-06

endevent 3

event 4
eta             0.201343        0.0308145       1.48316         1.59418
V               0.0900625       -0.0459892      1.31611         1.37927
DM              -0.00937164     -0.00410258     1.25522         1.25527
proton          -0.163164       0.489317        0.307398        1.11396         -3.73169        -1.63361        499.817         1.66728e-06

endevent 4

event 5
eta             0.218842        0.0638994       2.53861         2.60704
V               0.167578        0.174846        2.11992         2.17088
DM              0.000325398     0.0106658       1.60572         1.60577
proton          -0.0390258      -0.0817933      0.00751692      0.942669        0.101427        3.32456         500.509         1.66956e-06

endevent 5
```

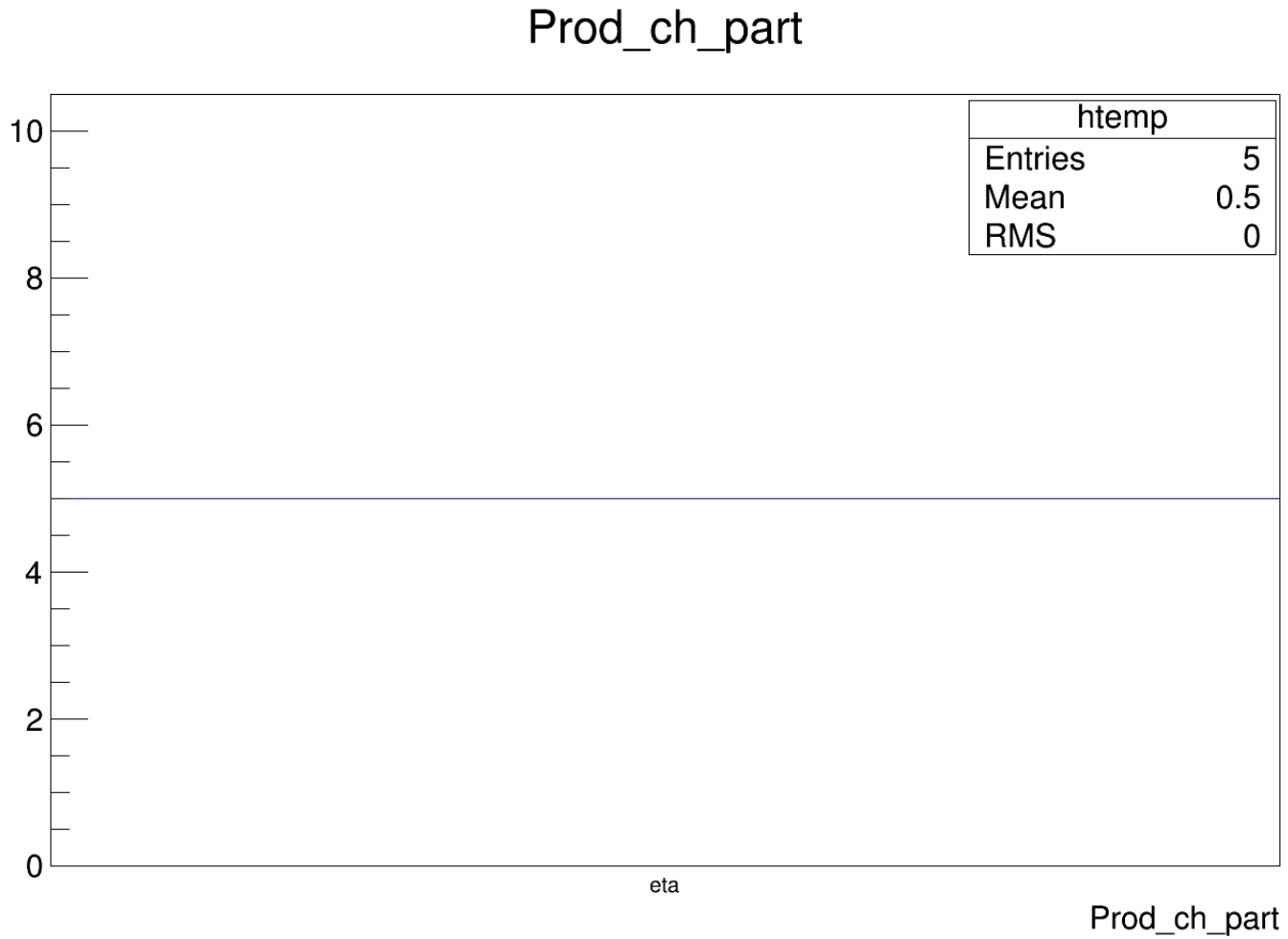

→ By chance: all are eta decays

My code

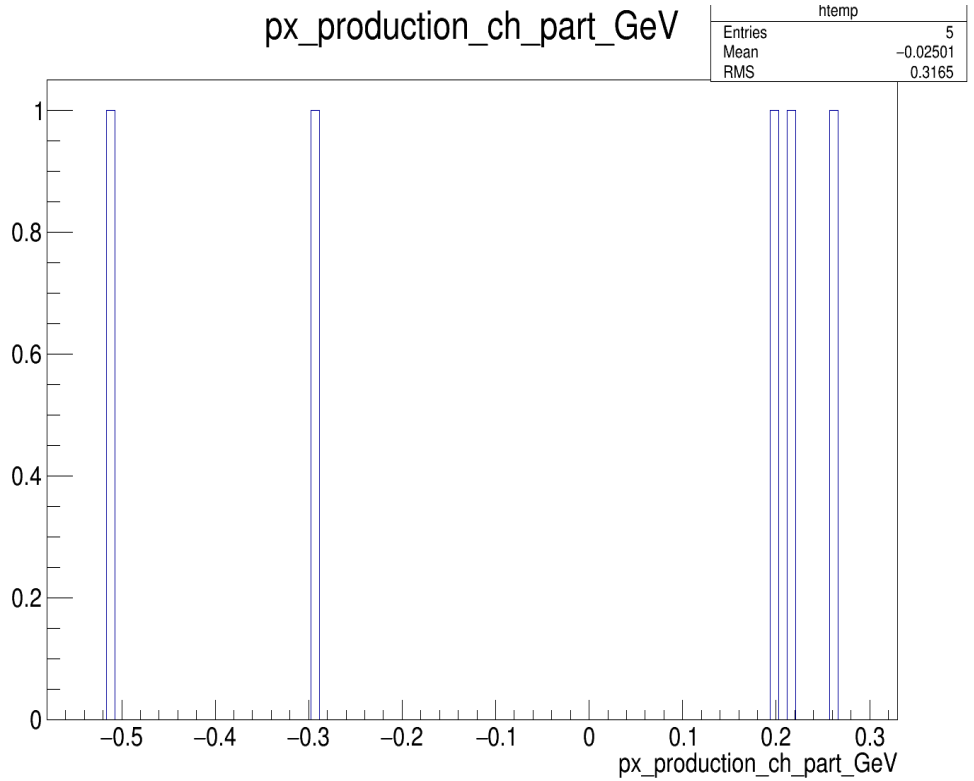
- Takes an events.dat file and outputs a ROOT tree containing the information (+saves it in a .root file)
- Tree stores each piece of info in a branch with 1 leaf
- The branches:
  - Event_num: event number
  - Prod_ch_part: type of production channel particle (eg eta, pion, etc)
  - Scatt_ch_part: the particle that the DM scatters off of (eg proton, neutron, etc)
  - px_production_ch_part_GeV: x momentum of the production ch particle
  - py_production_ch_part_GeV: y momentum of the production ch particle
  - pz_production_ch_part_GeV: z momentum of the production ch particle
  - E_production_ch_part_GeV: energy of production channel particle
  - px_V_GeV: x momentum of dark photon that generates the χ particles
  - py_V_GeV: y momentum _____//_____
  - pz_V_GeV: z momentum _____//_____
  - E_V_GeV: energy of dark photon that generates the χ particles
  - px_scatt_part_GeV: x momentum of particle that χ scatters off of in the detector
  - py_scatt_part_GeV: y momentum _____//_____
  - pz_scatt_part_GeV: z momentum _____//_____
  - E_scatt_part_GeV: energy of particle that χ scatters off of in the detector
  - x_pos_scatt_part_meters: x position of the interaction of χ in the detector
  - y_pos_scatt_part_meters: y position _____//_____
  - z_pos_scatt_part_meters: z position _____//_____
  - time_scatt_seconds: time of the interaction of χ in the detector (time since production of χ? will look into this)

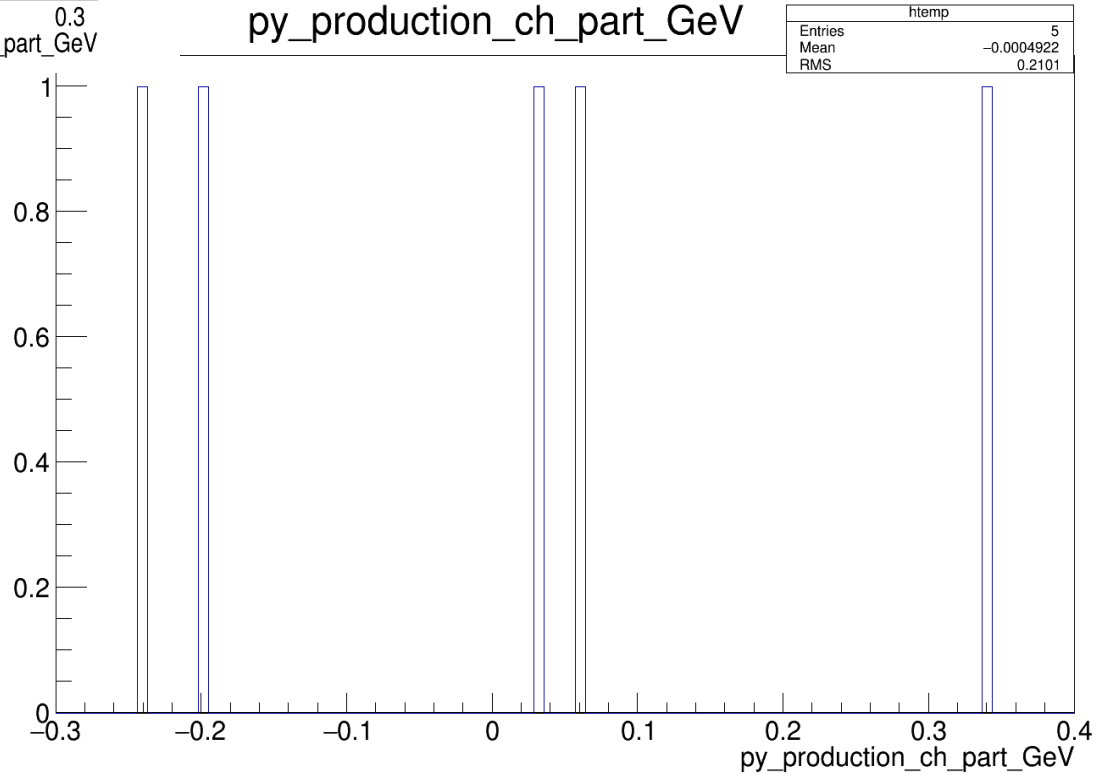
My code

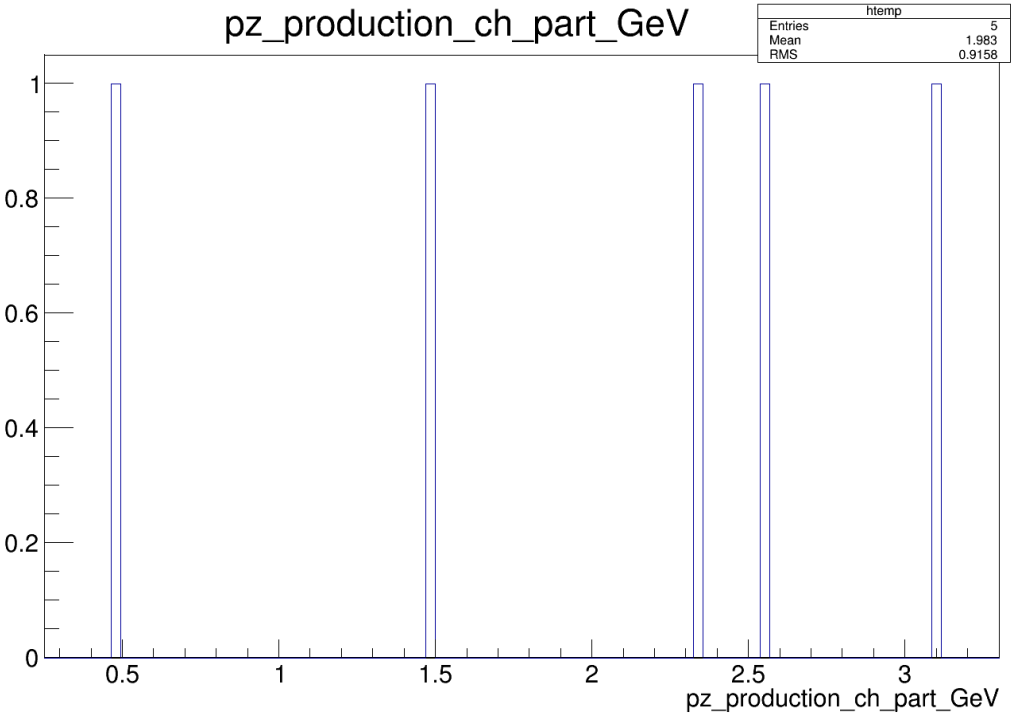
- The following tree branches were generated by the code using the events.dat file I described\
- Only 5 events → easy to show you what is going on
- I got the histograms from ROOT's TBrowser

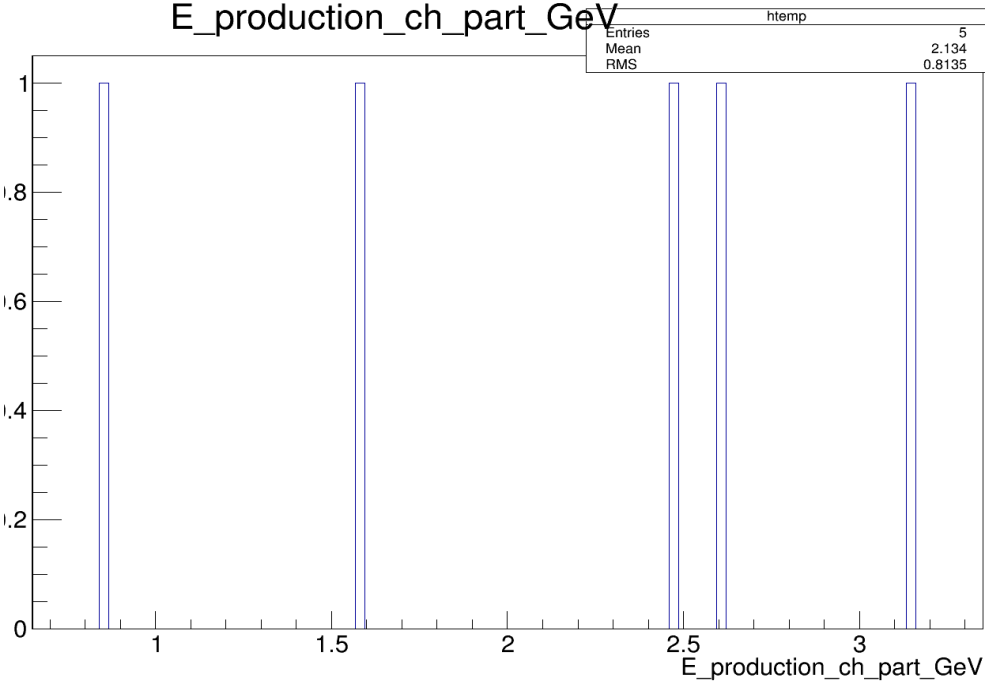


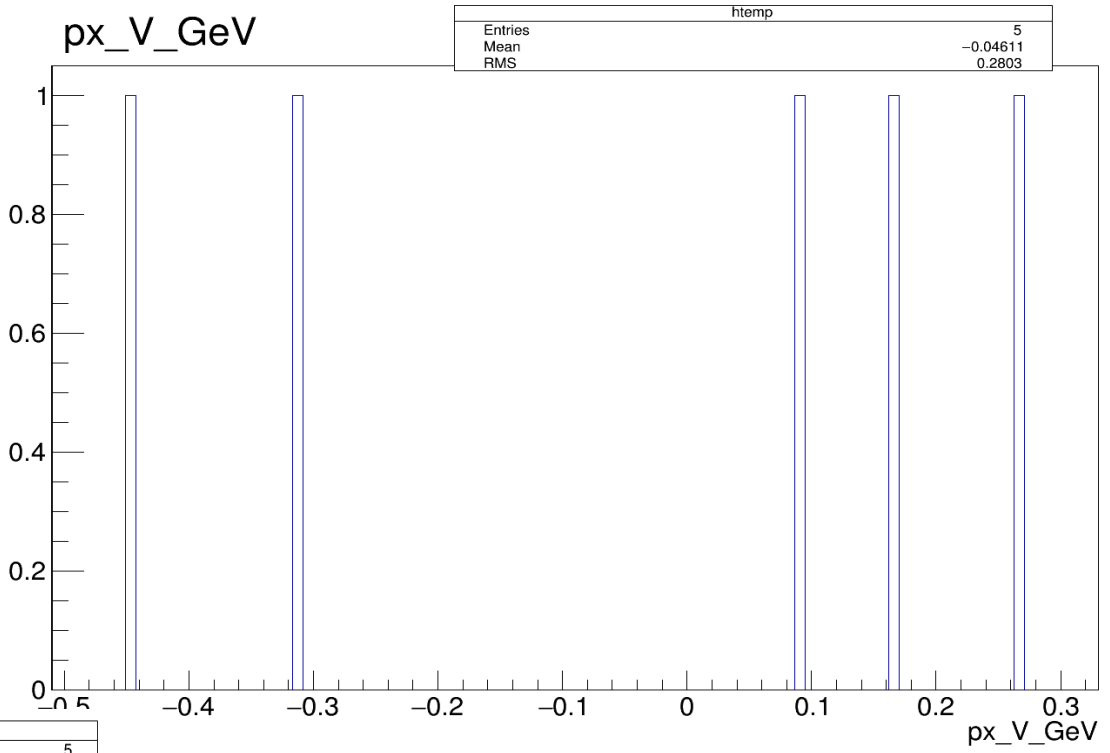

Scatt_ch_part
htemp
Entries 5
Mean 0.5
RMS 0
10
8
6
4
2
0
proton
Scatt_ch_part

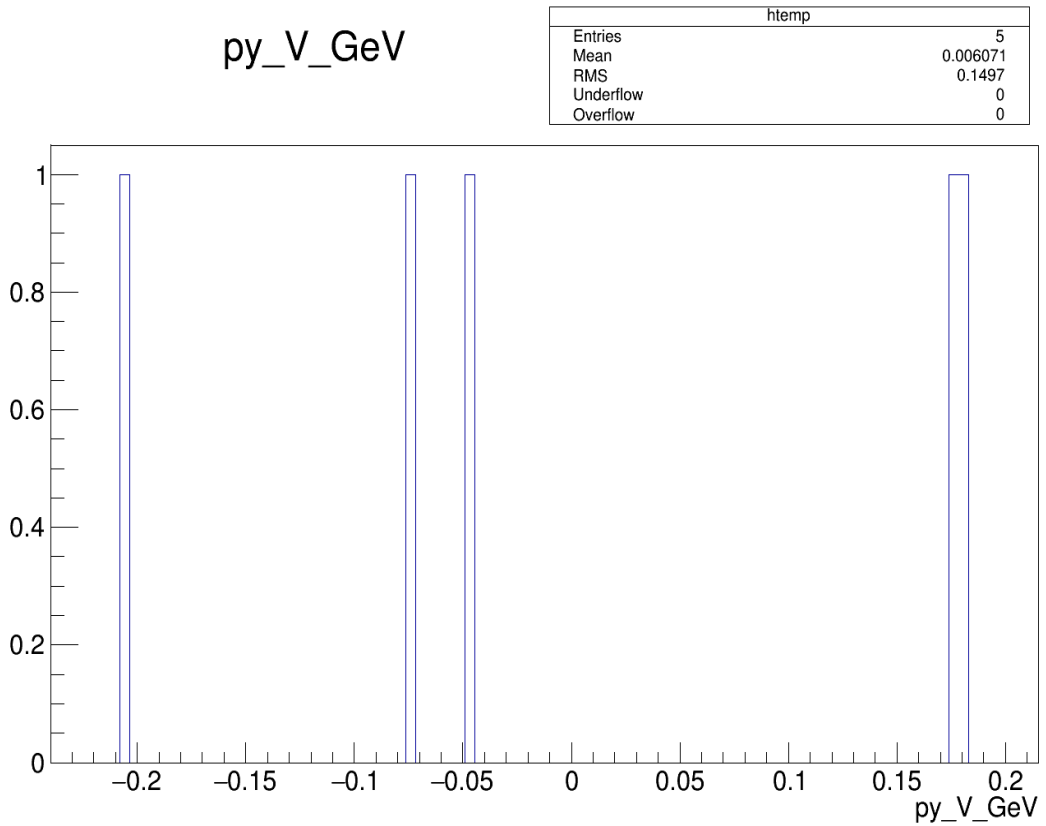

px_production_ch_part_GeV
htemp
Entries 5
Mean −0.02501
RMS 0.3165
1
0.8
0.6
0.4
0.2
0
−0.5
−0.4
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
px_production_ch_part_GeV

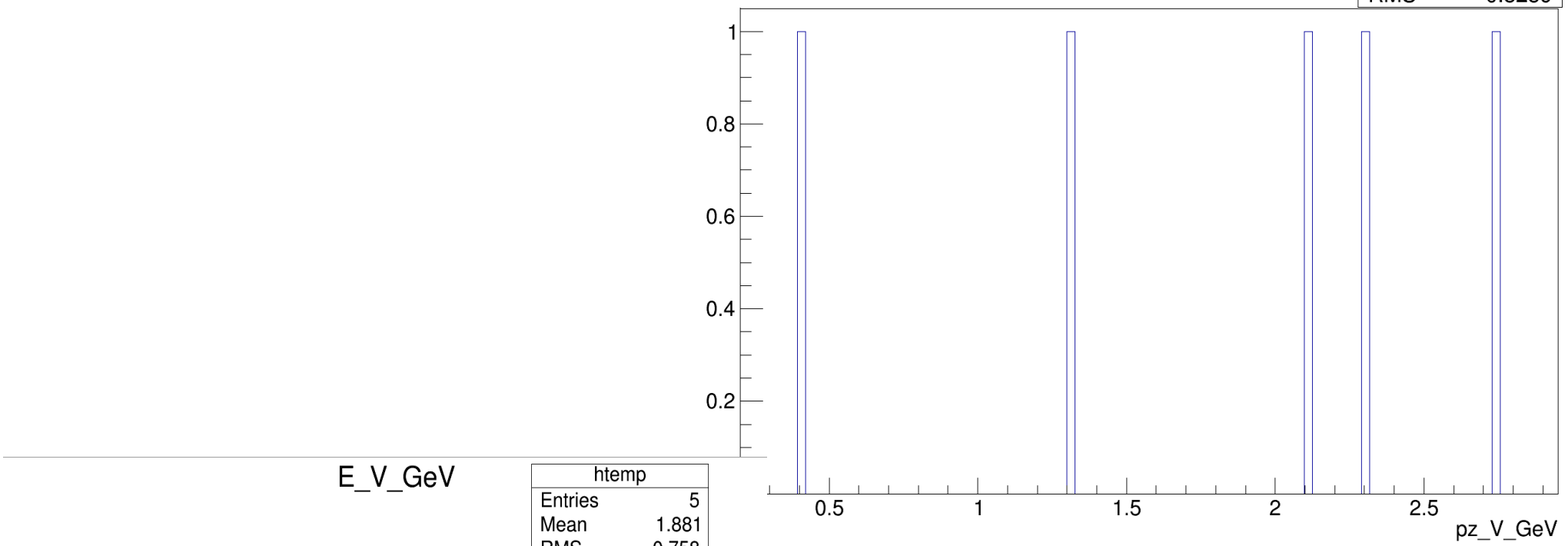

py_production_ch_part_GeV
htemp
Entries 5
Mean −0.0004922
RMS 0.2101
1
0.8
0.6
0.4
0.2
0
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
0.4
py_production_ch_part_GeV

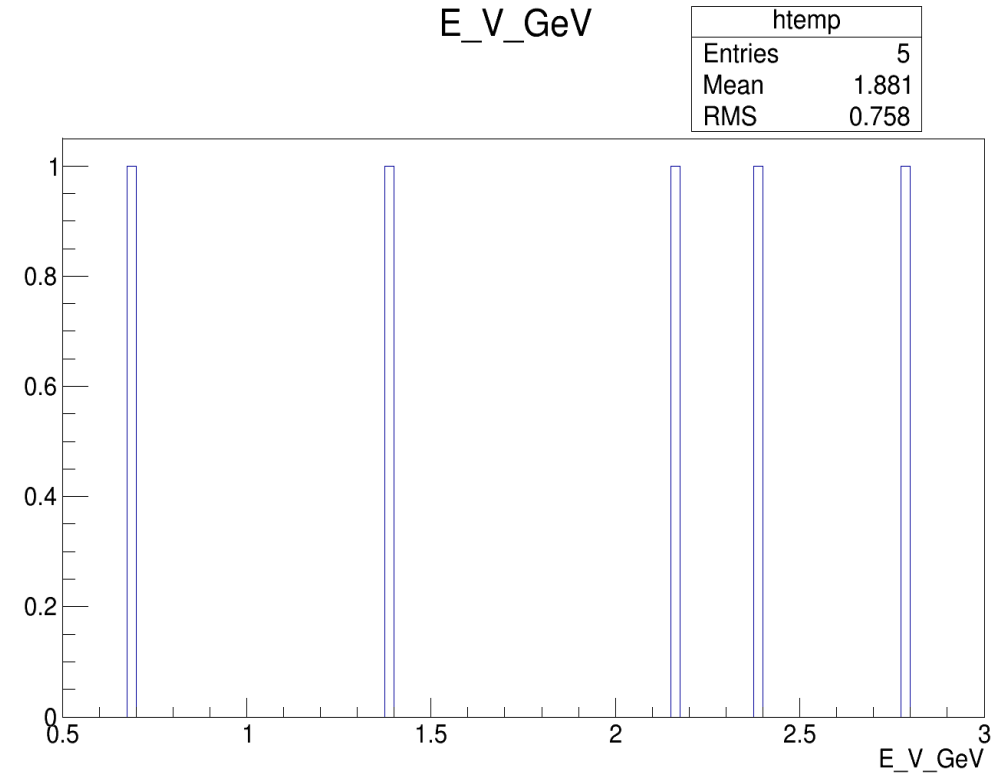

pz_production_ch_part_GeV
htemp
Entries 5
Mean 1.983
RMS 0.9158
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
pz_production_ch_part_GeV

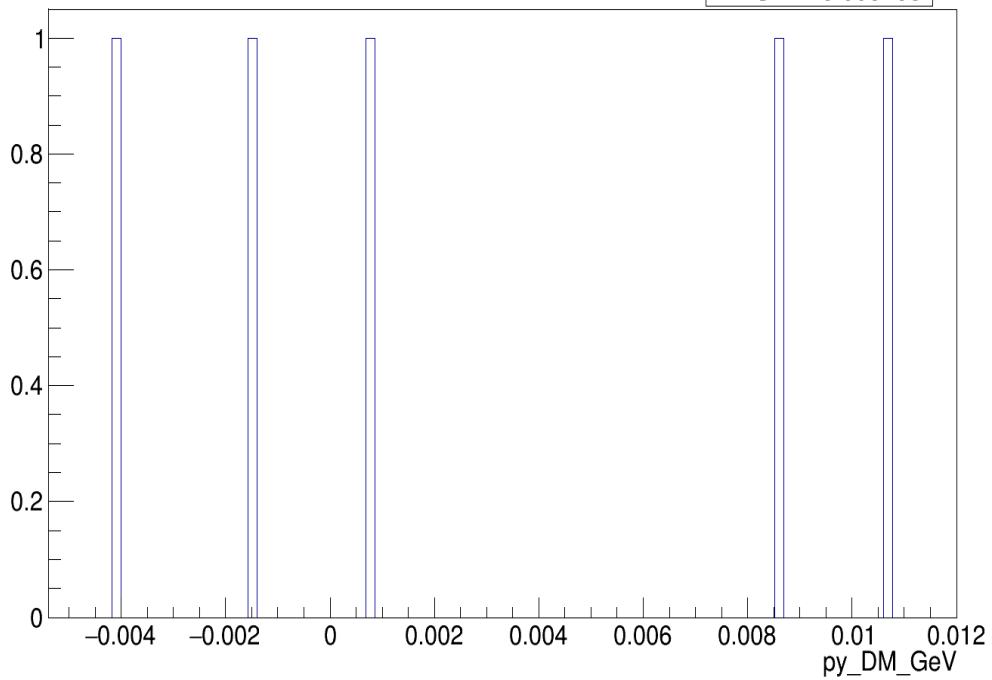

E_production_ch_part_GeV
htemp
Entries 5
Mean 2.134
RMS 0.8135
1
0
1
1.5
2
2.5
3
E_production_ch_part_GeV

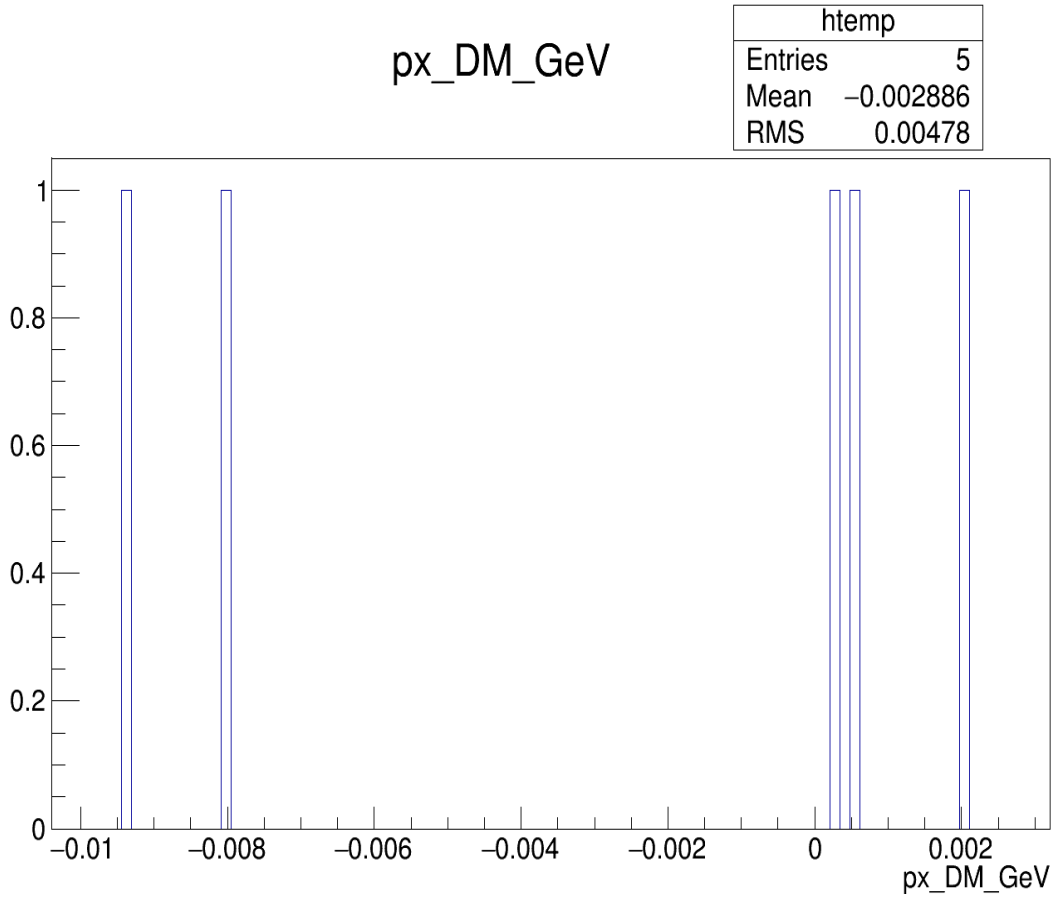

px_V_GeV
htemp
Entries 5
Mean −0.04611
RMS 0.2803
1
0.8
0.6
0.4
0.2
0
−0.4
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
px_V_GeV

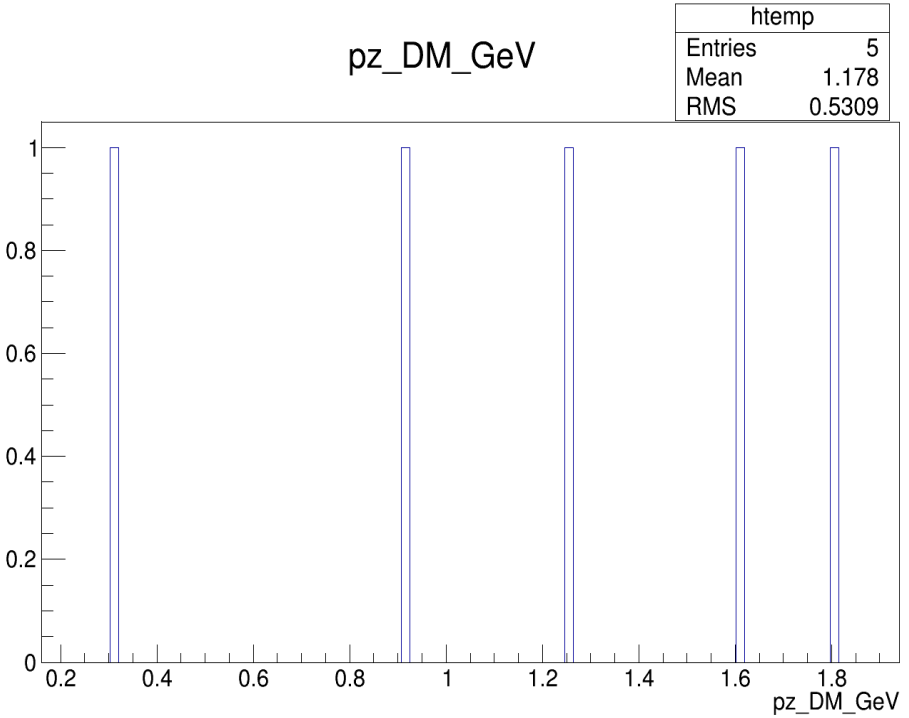

py_V_GeV
htemp
Entries 5
Mean 0.006071
RMS 0.1497
Underflow 0
Overflow 0
1
0.8
0.6
0.4
0.2
0
−0.2
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
0.2
py_V_GeV

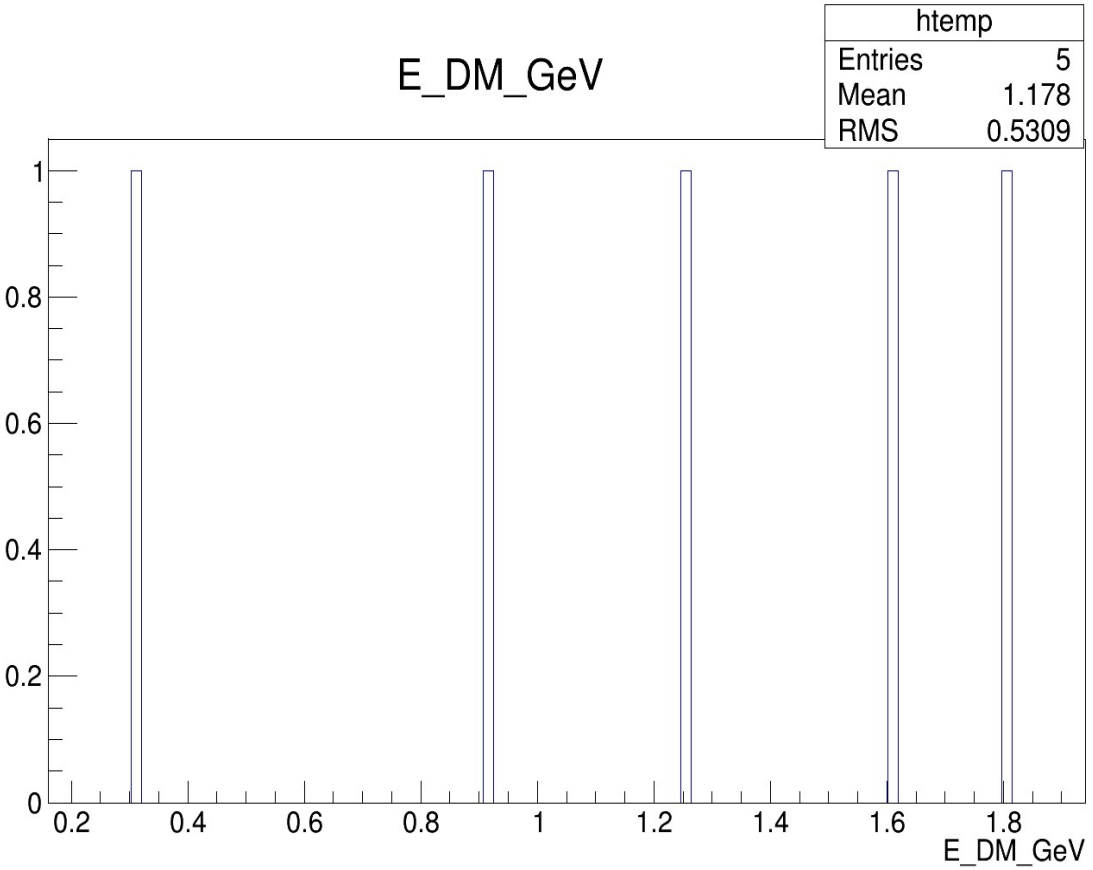

pz_V_GeV
htemp
Entries 5
Mean 1.78
RMS 0.8259
1
0.8
0.6
0.4
0.2
0.5
1
1.5
2
2.5
pz_V_GeV

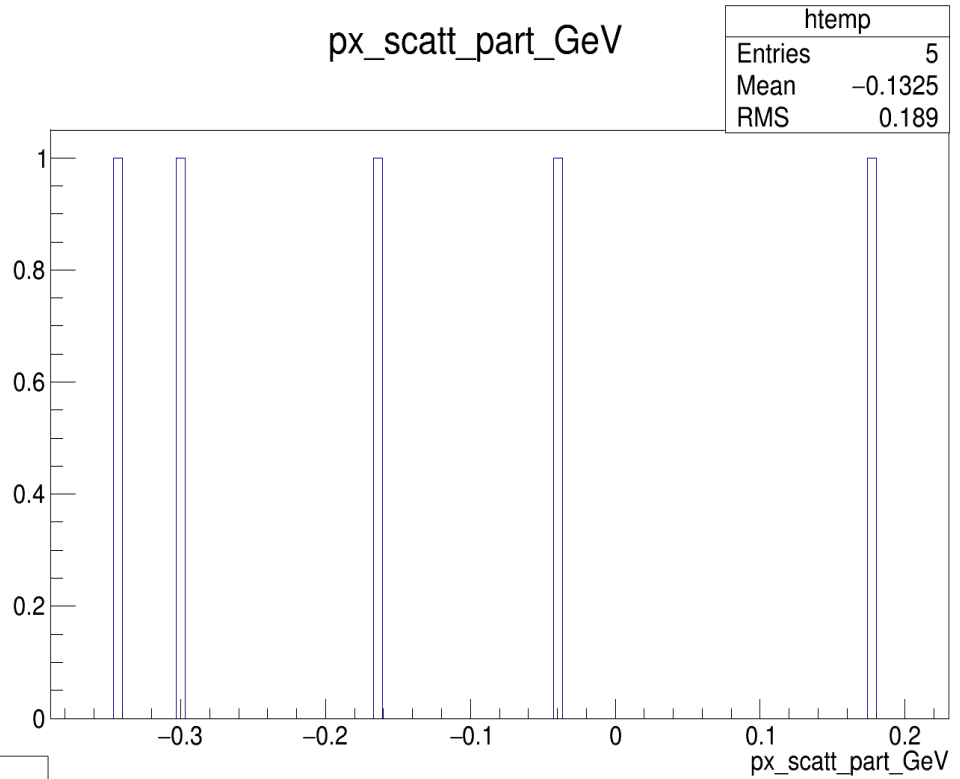

E_V_GeV
htemp
Entries 5
Mean 1.881
RMS 0.758
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
E_V_GeV

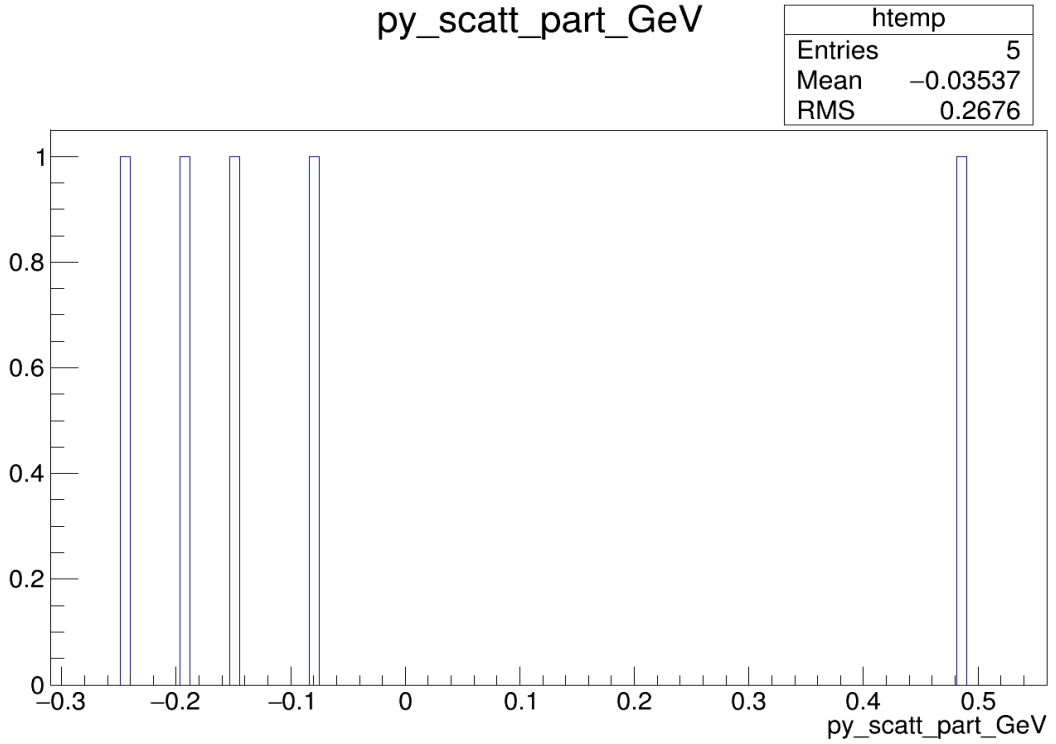

py_DM_GeV
htemp
Entries 5
Mean 0.002873
RMS 0.005768
1
0.8
0.6
0.4
0.2
0
−0.004
−0.002
0
0.002
0.004
0.006
0.008
0.01
0.012
py_DM_GeV

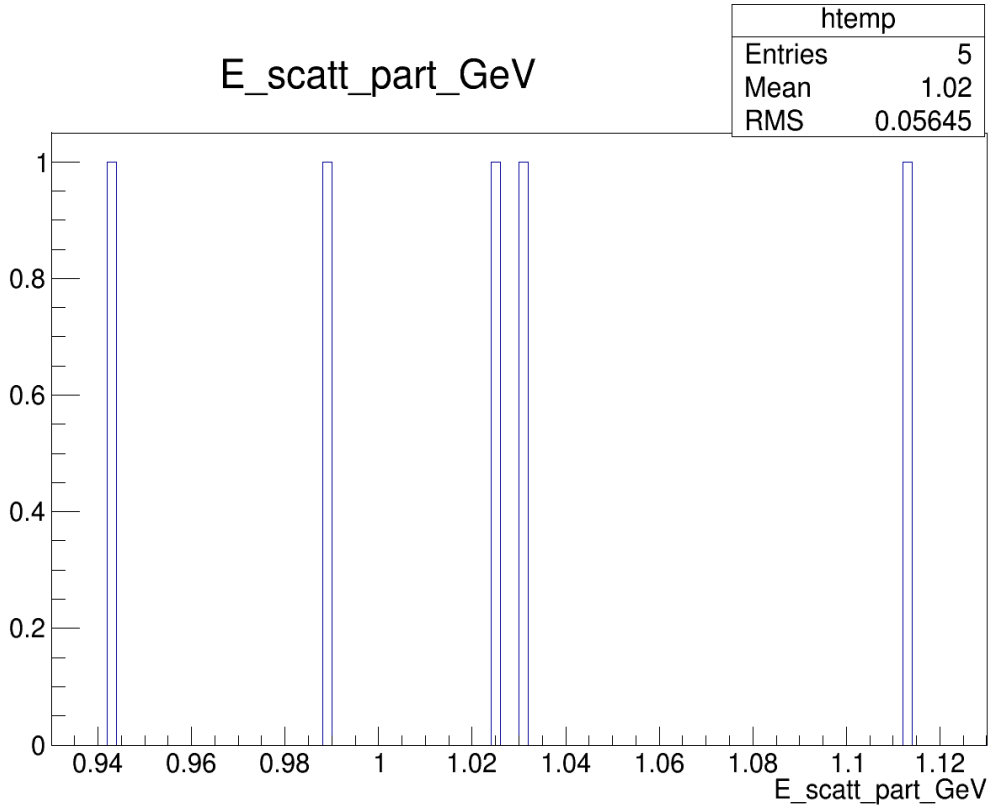

px_DM_GeV
htemp
Entries 5
Mean −0.002886
RMS 0.00478
1
0.8
0.6
0.4
0.2
0
−0.01
−0.008
−0.006
−0.004
−0.002
0
0.002
px_DM_GeV

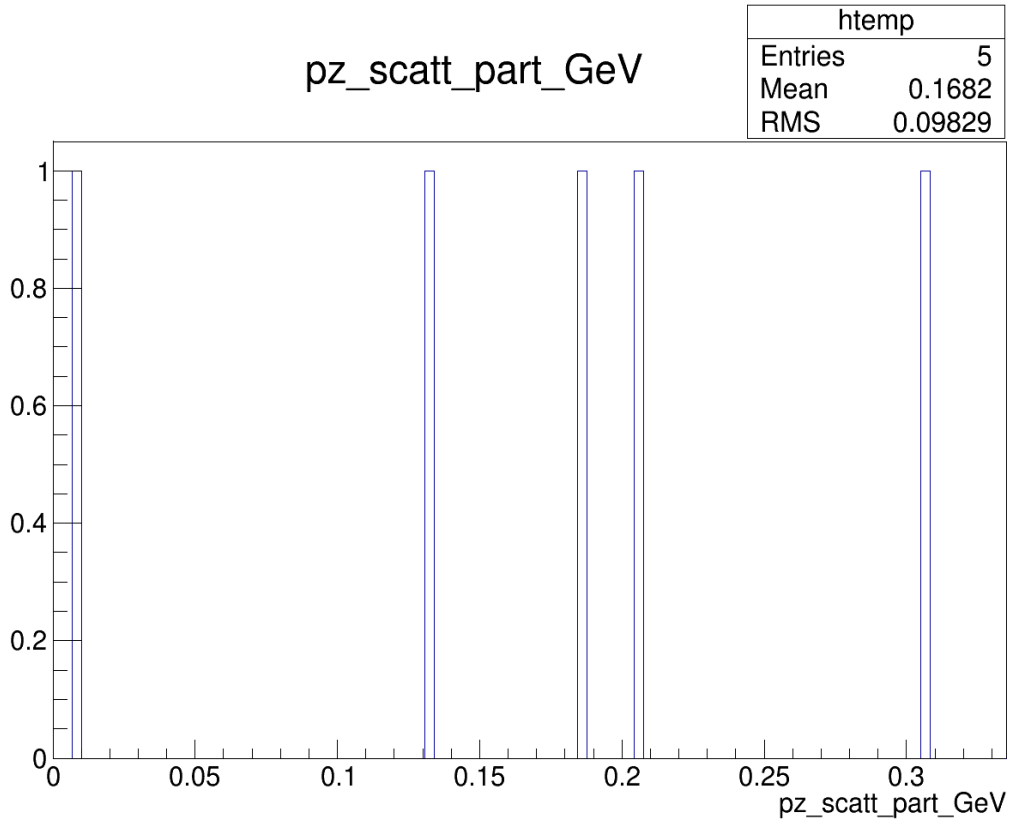

pz_DM_GeV
htemp
Entries 5
Mean 1.178
RMS 0.5309
1
0.8
0.6
0.4
0.2
0
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
pz_DM_GeV

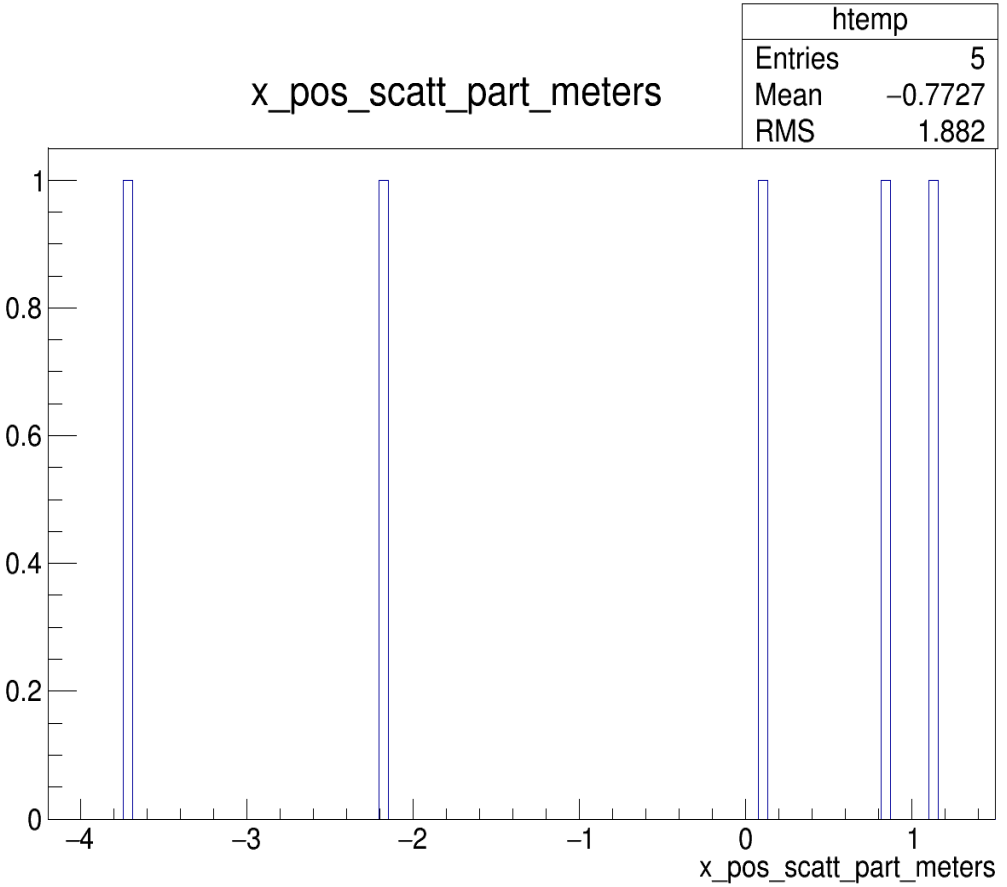

E_DM_GeV
htemp
Entries 5
Mean 1.178
RMS 0.5309
1
0.8
0.6
0.4
0.2
0
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
E_DM_GeV

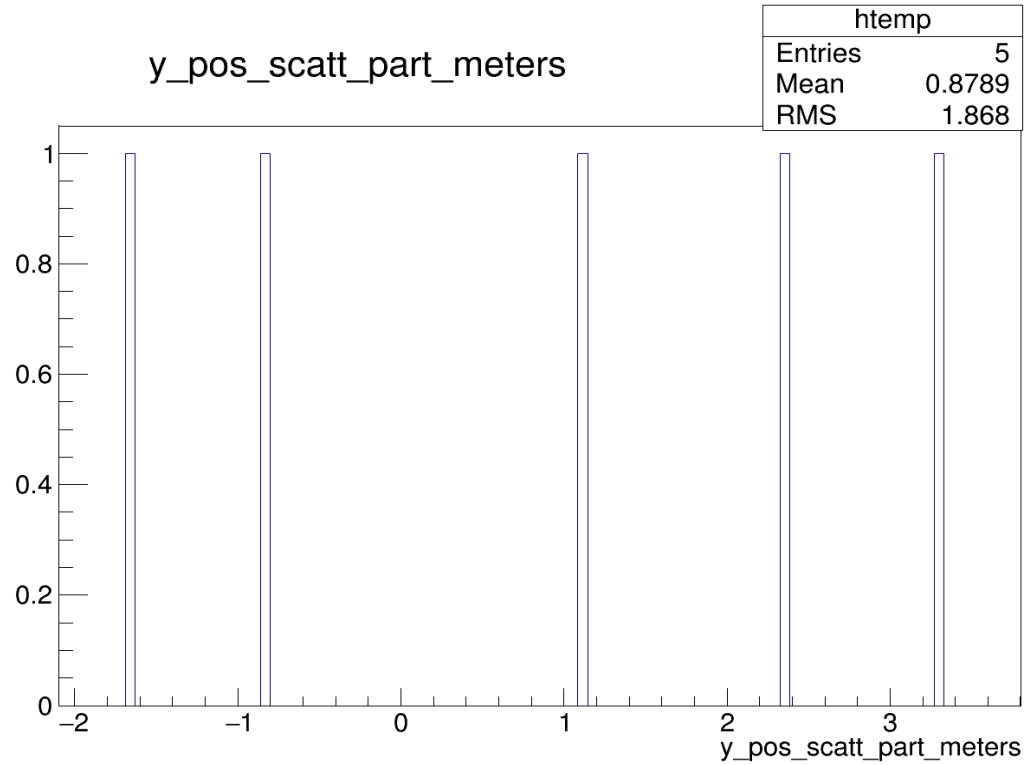

px_scatt_part_GeV
htemp
Entries 5
Mean −0.1325
RMS 0.189
1
0.8
0.6
0.4
0.2
0
−0.3
−0.2
−0.1
0
0.1
0.2
px_scatt_part_GeV

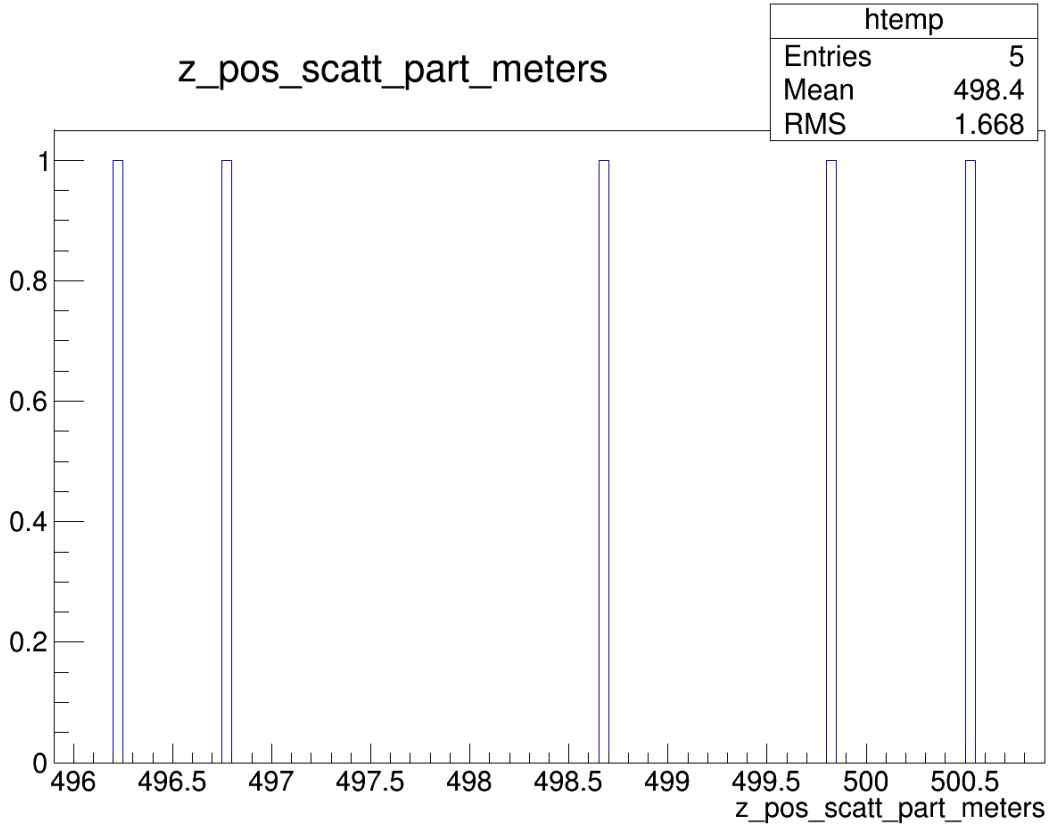

py_scatt_part_GeV
htemp
Entries 5
Mean −0.03537
RMS 0.2676
1
0.8
0.6
0.4
0.2
0
−0.3
−0.2
−0.1
0
0.1
0.2
0.3
0.4
0.5
py_scatt_part_GeV

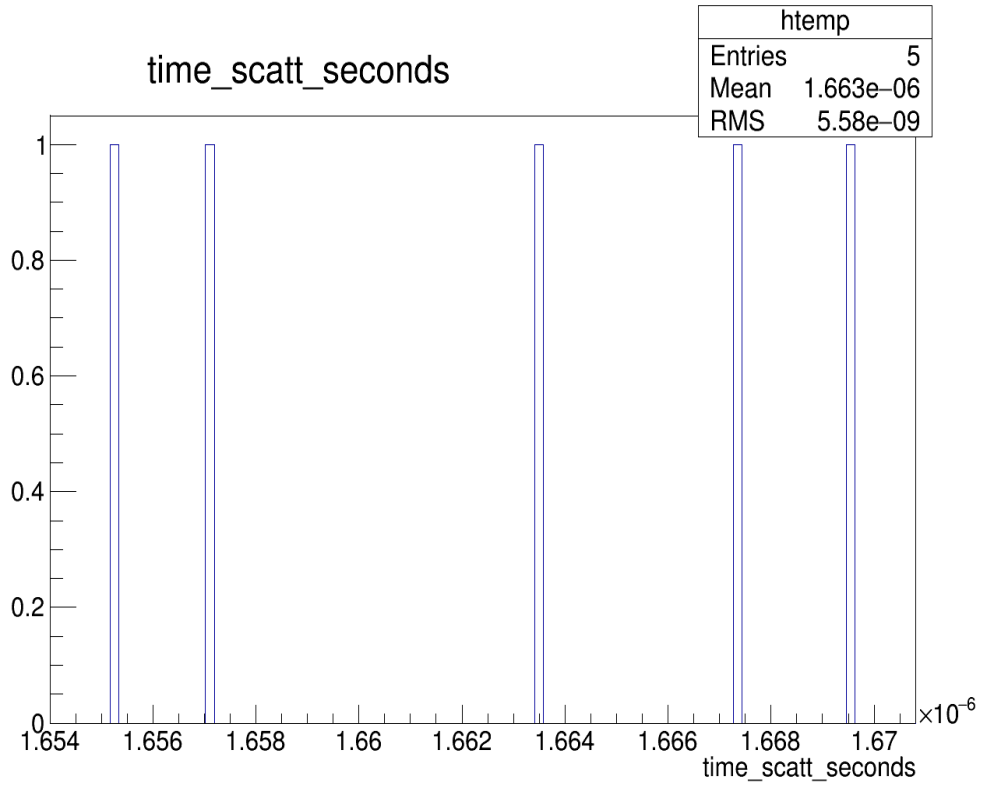

E_scatt_part_GeV
htemp
Entries 5
Mean 1.02
RMS 0.05645
0 0.2 0.4 0.6 0.8 1
0.94 0.96 0.98 1 1.02 1.04 1.06 1.08 1.1 1.12
E_scatt_part_GeV


pz_scatt_part_GeV
htemp
Entries 5
Mean 0.1682
RMS 0.09829
0 0.2 0.4 0.6 0.8 1
0 0.05 0.1 0.15 0.2 0.25 0.3
pz_scatt_part_GeV


x_pos_scatt_part_meters
htemp
Entries 5
Mean −0.7727
RMS 1.882
1
0.8
0.6
0.4
0.2
0
−4
−3
−2
−1
0
1
x_pos_scatt_part_meters


y_pos_scatt_part_meters
htemp
Entries 5
Mean 0.8789
RMS 1.868
1
0.8
0.6
0.4
0.2
0
−2
−1
0
1
2
3
y_pos_scatt_part_meters


z_pos_scatt_part_meters
htemp
Entries 5
Mean 498.4
RMS 1.668
1
0.8
0.6
0.4
0.2
0
496
496.5
497
497.5
498
498.5
499
499.5
500
500.5
z_pos_scatt_part_meters


time_scatt_seconds
htemp
Entries 5
Mean 1.663e−06
RMS 5.58e−09
1
0.8
0.6
0.4
0.2
0
1.654
1.656
1.658
1.66
1.662
1.664
1.666
1.668
1.67
×10^−6
time_scatt_seconds

My code: in progress

- Code reads the data file line by line since I know the (rough) format of the file:

  production channel particle info

  dark photon info

  dark matter info

  scattering particle info

- BUT not all events have the same format (eg # of lines), so I'm modifying it to handle all possible formats of an event in events.dat:

Eg: when production channel = eta decay:

```
event 1
eta          -0.0259158     0.210498       1.42688        1.54308
V            -0.0440264     0.171757       0.776362       0.891166
DM           0.00511908     -0.00272575    0.690469       0.690511
proton       -0.0129762     0.201052       0.055063       0.961237       3.71272        -1.97691       500.777        1.67051e-06
```

-

vs production channel = proton bremm

```
event 1
V             -0.0138055     -0.0105523     3.7683         3.9038
DM            -0.0269147     0.0119419      3.8334         3.83351
proton        0.0662269      -0.165411      0.0221731      0.955297       -3.5126        1.55852        500.292        1.66884e-06
```

---> different number of lines in the event

----> Need some if statements to ensure the information gets stored in the right branch when reading line by line (eg if the particle in the line == V, etc)

- (the 2 events above are from 2 different runs of BDNMC with 2 different parameter cards, but events like these do occur in the same events.dat file)

Another example: both X and anti-X scatter within the detector in event 106:

```
event 103
pion            0.142531        0.0323313       4.37345         4.37797
pion            0.142531        0.0323313       4.37345         4.37797
V               0.0114986       0.0115383       1.52641         1.52784
DM              0.00812916      0.00505364      1.49899         1.49903
proton          0.0170654       0.142133        0.0173402       0.949288        2.7311          1.69784         503.605         1.67989e-06

endevent 103

event 104
pion            -0.102206       0.117306        0.711593        0.740804
pion            -0.102206       0.117306        0.711593        0.740804
V               -0.083451       0.0594319       0.329003        0.353407
DM              0.000981155     -0.000292196    0.120521        0.120629
proton          -0.100136       -0.0338289      0.0931251       0.948788        4.05392         -1.20729        497.969         1.66253e-06

endevent 104

event 105
pion            -0.0915958      -0.0365178      3.89371         3.8973
pion            -0.0915958      -0.0365178      3.89371         3.8973
V               -0.105115       -0.0354361      3.82411         3.82639
DM              -0.00459679     -0.0103343      1.40518         1.40524
proton          -0.0419061      -0.436779       0.187333        1.05261         -1.62949        -3.66337        498.117         1.6616e-06

endevent 105

event 106
pion            -0.0276628      0.0114309       4.79049         4.79248
pion            -0.0276628      0.0114309       4.79049         4.79248
V               0.0074556       0.0105287       4.46888         4.46897
DM              0.0101267       -0.00308872     1.54118         1.54123
proton          0.197749        0.0821299       0.0389422       0.963183        3.27227         -0.998063       498.004         1.66121e-06
DM              -0.00267114     0.0136174       2.9277          2.92774
proton          -0.0929863      0.248199        0.0488611       0.976213        -0.453602       2.31245         497.17          1.6584e-06

endevent 106

event 107
pion            0.0386193       0.104689        1.26152         1.27361
pion            0.0386193       0.104689        1.26152         1.27361
V               0.0112252       0.0950418       1.17262         1.18009
DM              -0.00474502     -0.00031398     0.545634        0.545677
proton          0.242948        -0.0512756      0.105463        0.976284        -4.33013        -0.286526       497.925         1.66103e-06
```


From: 2nd miniboone ex parametes but only pion_decay porduction channel

Also observed events that look like these:

- in progress: trying to understand them, will modify code to handle them

```
event 326
pion          0.0264024      0.0028714      6.67239        6.67381
pion          0.0264024      0.0028714      6.67239        6.67381
V             -0.0268431     0.00235709     5.51638        5.51657
DM            0.00444216     0.0106228      2.01677        2.01681
proton        -0.15981       0.114951       0.0303853      0.959182       1.09548        2.61969        497.353        1.65902e-06
DM            -0.0312852     -0.00826576    3.49961        3.49976

endevent 326
```

```
event 4648
pion           -0.0781262     -0.0319178     6.25642        6.25844
pion           -0.0781262     -0.0319178     6.25642        6.25844
V              -0.0338324     -0.028847      5.70819        5.70842
DM             -0.015353      -0.0275361     3.74953        3.74966
proton         0.28434        0.257986       0.104141       1.01912        -2.04499       -3.66775       499.43         1.66598e-06
DM             -0.0184794     -0.00131094    1.95867        1.95876
```

```
event 4267
pion           0.064185       0.015637       5.86896        5.87088
pion           0.064185       0.015637       5.86896        5.87088
V              0.0106357      0.0133365      5.0492         5.04937
DM             0.0236581      0.00684457     2.48449        2.48462
DM             -0.0130224     0.00649193     2.56471        2.56476
proton         -0.0446074     0.179991       0.0245366      0.956736       -2.53336       1.26293        498.935        1.6643e-06
```

From: 2nd miniboone ex parametes but only pion_decay porduction channel

Also: in a lot of the events, the line for the pion's information is repeated

→ my code can handle this right now

→ will investigate why the simulation does this...

Goals

- Go through each of the 12 production channels, look at how the events.dat file looks like in each case, and make sure the code can read the events properly.
- The production channels:

pi0_decay, pi0_decay_baryonic, eta_decay, eta_decay_baryonic, omega_decay, omega_decay_baryonic, rho_decay, phi_decay, phi_decay_baryonic, pi-minus_capture, parton_production, parton_production_baryonic, V_decay, V_decay_baryonic

  - Understand the proton bremmstruhlung production channel better:
    - BDNMC says that the bremm production channel " works but may be unreliable around the rho resonance" , has parameters ptmax, zmin, zmax

- Investigate the baryonic production channels
  - Important for T2K/SK?
  - Will look at "Leptophobic dark matter at neutrino factories" by Brian Batell, Patrick deNiverville, …

- Make separate histograms for the momenta and energy of the production channel particle based on the type of the particle (eta/pion in meson decay)
  - Reminder: BDNMC can have multiple production channels activated at the same time
  - Currently: the momentum of the particles from all production channels fall into one branch (i.e. x momentum of pions and etas fall in one branch)
  - Will make cuts on these histograms
- Same thing for scattering particle (neutron/proton, electron in NCE electron)

Goals cont.

- Look more into how BDNMC creates scattering events:
  - trials and pmax
- figure out why BdNMC makes duplicate pion info in events.dat

```
event 103
pion            0.142531        0.0323313       4.37345         4.37797
pion            0.142531        0.0323313       4.37345         4.37797
V               0.0114986       0.0115383       1.52641         1.52784
DM              0.00812916      0.00505364      1.49899         1.49903
proton          0.0170654       0.142133        0.0173402       0.949288        2.7311          1.69784         503.605         1.67989e-06

endevent 103

event 104
pion            -0.102206       0.117306        0.711593        0.740804
pion            -0.102206       0.117306        0.711593        0.740804
V               -0.083451       0.0594319       0.329003        0.353407
DM              0.000981155     -0.000292196    0.120521        0.120629
proton          -0.100136       -0.0338289      0.0931251       0.948788        4.05392         -1.20729        497.969         1.66253e-06

endevent 104
event 105
pion            -0.0915958      -0.0365178      3.89371         3.8973
pion            -0.0915958      -0.0365178      3.89371         3.8973
V               -0.105115       -0.0354361      3.82411         3.82639
DM              -0.00459679     -0.0103343      1.40518         1.40524
proton          -0.0419061      -0.436779       0.187333        1.05261         -1.62949        -3.66337        498.117         1.6616e-06

endevent 105

event 106
pion            -0.0276628      0.0114309       4.79049         4.79248
pion            -0.0276628      0.0114309       4.79049         4.79248
V               0.0074556       0.0105287       4.46888         4.46897
DM              0.0101267       -0.00308872     1.54118         1.54123
proton          0.197749        0.0821299       0.0389422       0.963183        3.27227         -0.998063       498.004         1.66121e-06
DM              -0.00267114     0.0136174       2.9277          2.92774
proton          -0.0929863      0.248199        0.0488611       0.976213        -0.453602       2.31245         497.17          1.6584e-06

endevent 106

event 107
pion            0.0386193       0.104689        1.26152         1.27361
pion            0.0386193       0.104689        1.26152         1.27361
V               0.0112252       0.0950418       1.17262         1.18009
DM              -0.00474502     -0.00031398     0.545634        0.545677
proton          0.242948        -0.0512756      0.105463        0.976284        -4.33013        -0.286526       497.925         1.66103e-06
```

Goals cont.

- Replicate sensitivity plots in the paper
- Eg:

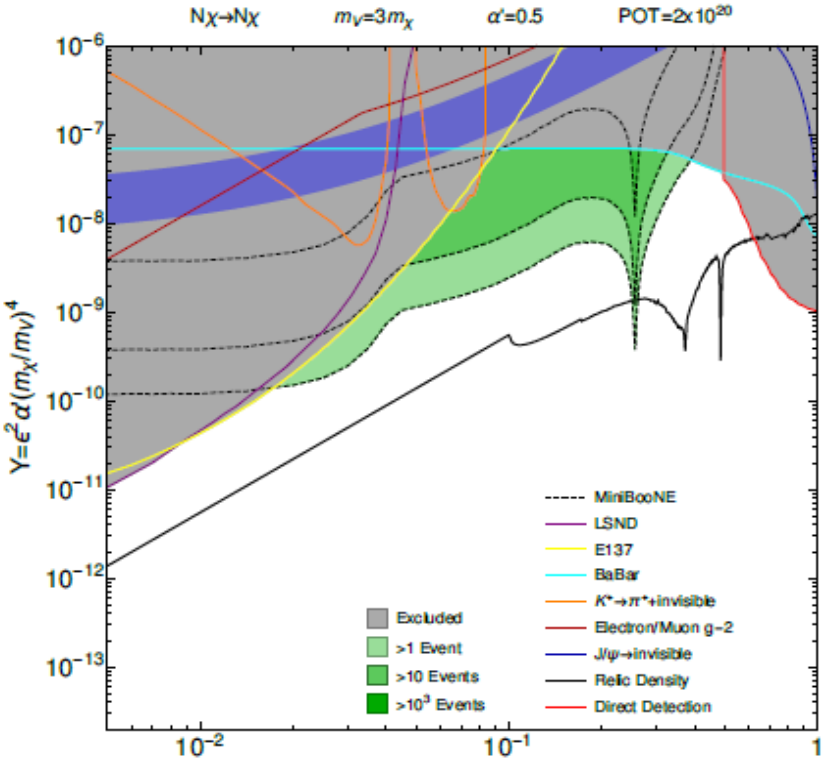


FIG. 8. Further plots showing the MiniBooNE yield of light dark matter scattering events in various channels, now fixing $m_V = 3m_\chi$ with $\alpha' = 0.5$, and using the variable Y for the vertical scale (see Eq. (20)). The strongest low-mass direct detection constraint is from CRESST-II [44], shown as the red contour. 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.

- pick a point on the plot, put the corresponding parameters in BDNMC and check how many events I get.
  - Find out how Patrick et al. made the sensitivity plots