Progress of BdNMC work

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Outline

- Some issues fixed

- Been working on outlining the possible events that BdNMC can generate and how they would look in events.dat (the data file that BdNMC outputs)

- Making a TTree that stores all the information in events.dat

  - > Working on a better way to organize the data (it would be hard to deal with all the different types of events with the code I had created before)

- Reading stuff on leptophobic model of DM

Solved: Repeated pion info line in events.dat

- Previously, I talked about:
  - Pion information lines in events.dat were repeated
- → I asked Patrick: it was a bug in the code, fixed in the newer releases of BdNMC
- → I am now running the newest release of BdNMC
  - > Problem solved

Newest version of BdNMC: BdNMC 3.2.0

- **Main features:**

- "Coherent scattering has been added to the code for NCE_nucleon and NCE_nucleon_baryonic signal channels, along with the piminus capture signal channel. The coherent scattering mode can be invoked by adding coherent true to the parameter file... Coherent scattering iterates over all of the materials listed in the detector, and sums the resulting event rates together. The materials are differentiated in the comprehensive output."

  – I've been running BdNMC without the coherent scattering option for now (the previous release didn't have coherent scattering).

  – coherent scattering: refers to the wave nature of the particles, coherently scattered particles remain in phase (same wavelength+phase), elastic collisions are usually coherent

  – I'll run BdNMC later with coherent scattering once I figure out if I *should* be running it with coherent scattering

- Piminus scattering simulates the isotropic emission of dark photons from the pi-minus absorption process

  P+ pi minus → N* -> N + dark gamma   , where N is a nucleon

  This production channel can be invoked with production_channel piminus_capture.

- "Added signal_channel Pion_Inelastic_Charged. This is very similar to the Pion_Inelastic channel, but includes Δ decays into charged pion states in addition to pi0 mesons. This occurs approximately 1/3 of the time, increasing the event rate over Pion_Inelastic by 50%"

  – Haven't looked at these yet

- Some bug fixes

Outlining the possible interactions generated by BdNMC

- Outlined in the separate PDF possible_events

- Motivation: understand the interactions I'm expecting

A bit more info on the proton Bremsstrahlung production channel:

- User needs to state the values of these parameters when using the proton brem. channel:

```
#This invokes the bremsstrahlung production channel. This works, but may be
#unreliable around the rho resonance. The zmin/zmax values seem reasonable
#for MiniBooNE energies. ptmax could be as large as the proton mass, but
#probably would not change signal much.
production_channel V_decay
production_distribution proton_brem
ptmax 0.2
zmin 0 3
zmax 0.7
```

ptmax: The maximum transverse momentum which a produced V mediator may possess. The minimum is assumed to be 0.

zmin: The minimum value of $z = \frac{p_{V,z}}{P}$, where $p_{V,z}$ 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.

zmax: The maximum value of z, defined as in the zmin.

Calculating the total number of V bosons (N_V) produced by the proton bremsstrahlung production channel: (V mediators decay to dark matter isotropically)

$$N_V = \text{POT} \int_0^{\text{ptmax}^2} dp_\perp^2 \int_{\text{zmin}}^{\text{zmax}} dz \frac{d^2 N_V}{dz \, dp_\perp^2}, \tag{11}$$

Where the differential V production rate is:

$$\frac{d^2 N_V}{dz \, dp_\perp^2} = \frac{\sigma_{pA}(s')}{\sigma_{pA}(s)} F_{1,N}^2(q^2) w_{ba}(z, p_\perp^2), \tag{6}$$

where $s' = 2m_p(E_p - E_V)$, $s = 2m_p E_p$ and the photon splitting function is [54]

$$w_{ba}(z, p_\perp^2) = \frac{k_{V,B}^{(0)}}{2\pi H} \left[\frac{1 + (1-z)^2}{z} - 2z(1-z) \left(\frac{2m_p^2 + m_V^2}{H} - z^2 \frac{2m_p^4}{H^2} \right) \right.$$
$$\left. + 2z(1-z)(z + (1-z)^2) \frac{m_p^2 m_V^2}{H^2} + 2z(1-z)^2 \frac{m_V^4}{H^2} \right],$$

with $H = p_\perp^2 + (1-z)m_V^2 + z^2 m_p^2$, and $k_{V,B}^{(n)}$ was defined above in (5). $\longrightarrow k_{V,B}^{(n)} = \begin{cases} \epsilon^2 \alpha (\alpha')^n & \text{for } U(1)' \\ \alpha_B^{n+1} & \text{for } U(1)_B \end{cases}$

Proton Bremsstrahlung Production Channel cont.

. The paper goes into detail about the "timelike form factor $F_{1,N}(q^2)$

(page 5 of "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and ShiP")

→ not really sure what they mean, but basically: the equation that the paper uses for the differential V production rate requires the following kinematic conditions:

$E_P >> m_P$

$E_V >> m_V$

$E_P - E_V >> |P_\perp|$

- So the range of values of z and $|P_\perp|$ over which the integral for N_V is calculated must be such that the conditions are met.
- Paper says these conditions are met if $z \in [0.1, 0.9]$ and
   $|P_\perp| < 1$ GeV for high energy experiments like SHiP, but not for lower energy experiments.
- eg for MiniBooNE (much lower energy than SHiP), the paper uses $z \in [0.3, 0.7]$ and $|P_\perp| < 0.2$ GeV (as in the parameter cards for the MiniBooNE-like experiments)
- When I start running BdNMC with SK geometry, I have to figure out what values to use.

Previously, I was wondering why some events in events.dat have 2 DM particles and 1 scattering particle:

- I saw events like:

```
event 946
pion        -0.0154112    0.00305755    5.47189    5.47357
V           -0.01901      0.00302043    5.46847    5.46861
DM          0.00244228    0.0109462     3.12955    3.12957
proton      0.112974      0.10087       0.0155096  0.950543    0.388669    1.742     498.042   1.6613e-06
DM          -0.0214522    -0.00792579   2.33892    2.33904
```

```
event 2385
pion        0.0592345     -0.00187014   4.20713    4.20971
V           -0.0040877    -0.00149819   3.41142    3.41149
DM          -0.00362855   0.00784093    1.23582    1.23586
DM          -0.00045915   -0.00933912   2.1756     2.17562
proton      0.233897      0.0672624     0.0463667  0.970431   -0.104796   -2.13154   496.555   1.65635e-06
```

From: 2nd MiniBooNE ex parameters but only pion_decay production channel

- Follow up on Hiro's comment: You're right, it's not that χ and χ† scatter off the same particle in the detector, I asked Patrick, and here's why:

- For each event, a dark matter particle is appended to a list to be recorded in the output data file if it intersects the detector, but the event itself only gets recorded if at least 1 DM particle scatters. So:

- If both DM particles (χ and χ†) get scattered, they will both be recorded (I've seen this before in the events)

- If one DM particle scatters and the other intersects the detector but doesn't scatter, then the event get recorded and shows only 1 DM scattering (like event 946 and 2385 above)

An example of both DM particles scattering in the detector:

This is an event generated by BdNMc (3.2.0) using the same parameters as the 2nd MiniBooNE example in "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and SHiP" but with only pion_decay production channel activated. In particular:

epsilon = 1e-3   dark_matter_mass= 0.005 GeV   dark_photon_mass = 0.4 GeV   alpha_D = 0.1

```
event 2793
pion        0.0290155      0.00213912     5.5879       5.58961
V           0.0221793      0.00210953     5.57373      5.57387
DM          0.0196613      0.015394       3.5326       3.53269
proton     -0.201581       0.240188       0.067551     0.991586      2.77987     2.17653      499.469      1.66609e-06
DM          0.00251806    -0.0132844      2.04113      2.04118
proton      0.241008       0.0232979      0.0463406    0.970118      0.617443   -3.25742      500.497      1.66952e-06
```

->Both χ and χ† interact within the detector

- The following slides present some info about the leptophobic dark matter model, taken from the paper "Leptophobic dark matter at neutrino factories" by Brian Batell et al.

- I've been looking at Griffith's chapter on gauge theories to understand what they mean

The model: dark matter coupling to hadronic states via a dark photon *or* baryonic vector mediator

From the paper, we have

- DM couples to the Standard Model through a dark photon: a new massive gauge boson that kinetically mixes with the ordinary photon
  - Couples primarily to the electromagnetic current
- We don't know the structure of the dark matter couplings to ordinary matter, so it's important to also consider other models.
  - Eg the mediator can be leptophobic (coupling dominantly to quarks) or leptophilic.
- Paper describes a leptophobic model
  - "based on a local $U(1)_B$ baryon number symmetry, which (like the kinetic mixing portal) is phenomenologically safe since the corresponding current conserves all approximate symmetries of the Standard Model.
  - The DM is charged under $U(1)_B$ and the baryonic gauge boson serves as the mediator coupling the DM to the SM."
  - **Corina and I are deciding if we should consider this (the baryonic production channels and baryonic NCE nucleon scattering channel)**

Progress on putting BdNMC's output information into a Ttree

- Mainly been trying to make the code work properly ..

Trouble with putting BdNMC's output information into a TTree:

- Reminder:
  BdNMC outputs a data file containing info about the particles involved in the interactions. For example, some events from a data file outputted by BdNMC is shown here. The format is:

particle name	px	py	pz	E	x	y	z	t

```
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
```

- x,y,z, and t are only shown for the signal particle (particle that the DM scatters off)

Ttree that stores all the information in events.dat

- Better way to organize the data: branches that are arrays of variable length (as Hiro suggested)

- The branches:

  event_num: event number

  n: number of particles in each interaction; varies for each event

  eg **n=3 for event 1**

  n=4 for event 2 in the events.dat file below

```
event 1
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 1

event 2
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
```

Ttree that stores all the information in events.dat

- The other branches (they are all arrays of size n):

- nth_part: an integer that stores the order of the particle in the interaction (eg 1 for the first particle in the interaction, 2 for the second, etc)

   → useful later when I want to know which particles participated in each interaction for a given event

- particle_type (a Char_t now, will store this as an integer using the PDG particle numbering convention)

- px: x momentum (GeV)

- py: y momentum (GeV)

- Pz: z momentum (GeV)

- E: energy (GeV)

- x: x position of interaction (m)

- y: y position of interaction (m)

- z: z position of interaction (m)

- time: time of interaction (since production of dark matter particles, in seconds)

- Later: can make cuts on the data that enters the histograms by calling MakeClass() on the tree etc

Maybe it's better if I show you (Hiro & Corina) my code instead of trying to explain it here, so I'll just give a brief intro of the issue I'm having:

I need to read the data file ad store the info into different branches

I read each line of the data file and store it into an array of chars (declared as char line[200]; line is the name of my array)

Then I have something like:

sscanf(&line, "%s %f %f %f %f %s %s %s %s ", &particle_type[i], &px[i], &py[i], &pz[i], &E[i],&x[i], &y[i], &z[i], &time[i]);

A 'line' looks like:

```
event 4
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
neutron       0.179911      -0.149193      0.206807      0.988812      0.854665      1.14009       498.657       1.66357e-06
DM            0.0520242      0.000893986   0.4303537     0.230358
neutron       0.479911      -0.249193      0.4206807     0.198881      0.3854665     1.514009      198.657       2.66357e-06

endevent 4
```

So the sscanf(...) is supposed to store the info into the corresponding branches, eg:

particle_type	px	py	pz	E	x	y	z	time
proton	-0.297628	-0.242418	0.186791	1.03082	1.10585	-0.810828	496.231	1.65528e-06

And when the particle is not a signal particle, I don't want to fill x,y,z,time. Eg:

particle_type	px	py	pz	E	x	y	z	time
V	-0.447128	-0.203878	2.29495	2.38081	_____ x, y,z, time shouldn't get filled_____

→ The px, py, pz, E arrays get filled properly, but I'm having trouble filling the x,y,z,time arrays because x,y,z,time are not always printed in the data file...

The TTree cont.

- I store x, y, z, time as a Char_t (I want to be able to store "none" when x, y, z, time are not there

- I've been having issues filling an array of type Char_t …

  – Would be great if someone referred me to some documentation regarding using Char_t

  – I've looked at some ROOT examples where some branches of the tree are type Char_t (cernbuild.C) or when the branches are arrays of variable length (tree3.C)

    – > no luck

- The problem: x, y, z, time don't get filled when they should

(Immediate) next steps

- BdNMC data output file → Ttree

- Store the particle name as an integer (using the PDG particle numbering convention

- The leptophobic DM model and its significance to SK @ T2K

Backup

Follow up on Corina's question: how often does a DM scatter off a proton vs a neutron

- Elastic NC-like nucleon scattering:

  The paper says for incoherent scattering, the leading term of the cross section is

  $$\frac{d\sigma_{\chi N}}{dE_\chi} = 4\pi k_{V,B}^{(1)} Q_N^2 G_D(Q^2) \frac{2m_N EE_\chi - m_\chi^2(E - E_\chi)}{(E^2 - m_\chi^2)(m_V^2 + Q^2)^2} + \cdots \tag{13}$$

  where again Q_N is the nucleon electric charge (or unity in the baryonic case), E_χ the energy of the recoiling DM particle, $Q^2 = 2m_N(E - E_\chi)$ is the momentum transfer, and $G_D(Q^2)$ is the Sachs form-factor, $G_D(Q^2) = 1/(1 + Q^2/M^2)^2$ with $M = 0.843\,\text{GeV}$. Further dipole form factor terms, which are generally subleading (for protons), are suppressed to simplify the presentation, although they are included in the final results (see [2, 43] for full details). The resulting nuclear scattering cross section will be discussed later in Section 5.

  - > leading term couples to electric charge so more proton scatterings than neutron scatterings
  - Leading term is dependent on mass of chi and dark photon.

- I'm trying to see how the other terms in the cross section create an asymmetry between proton and neutron scatterings and the ratio of proton vs neutron scattering