# Progress

Rose Atashi, May 11

Outline

- Background
- Overview of the light dark matter search
- My project/ goals for the summer
- Some background on the production and scattering of light dark matter
- Details of the Monte Carlo simulation BdNMC
- What I'm currently working on
- Next steps

Background on light dark matter search at T2K

- T2K is a long baseline neutrino oscillation experiment

  - \> Fixed target proton-proton collisions at J-PARC produce neutrino beams (through a chain of reactions)

  - BUT the proton-proton collisions also produce DM particles

  - DM particles travel from J-PARC to the T2K near detector (280 m from J-PARC) and continue to the far detector (Super-Kamiokande: 295 km from J-PARC).

  - We can also detect the DM particles through their interactions inside the detectors.

Super-Kamiokande   J-PARC   Near Detector   280 m   1000 m   **Dark Matter also travels from J-PARC to SK**   Neutrino Beam   295 km
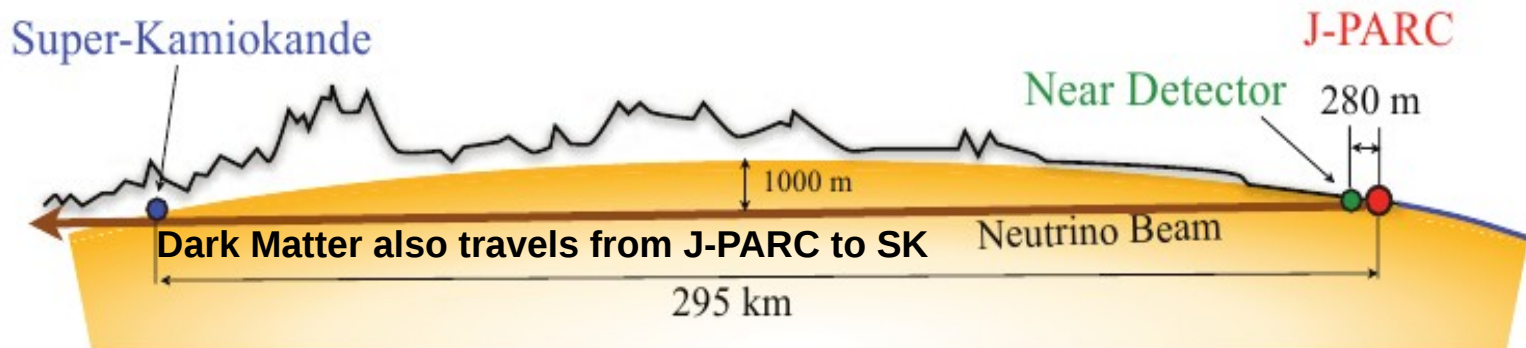
Overview of the light dark matter search

- Want to understand:

- how many χ particles are (eventually) produced from the fixed target proton-proton collisions at T2K

- how many propagate to the near detector and the far detector

- how many χ particles interact inside the detector

- what an interaction would "look like" in the detector (i.e. how the PMT's react to the de-excitation gammas from the scattering of the χ particles off nucleons inside SK)

My project

-Study the detection signatures of the dark matter particles at Super-K

- BdNMC: Monte Carlo simulation code from Patrick deNiverville et al. from Uvictoria

→ simulates the production, propagation, and scattering of these light dark matter particles inside a detector (user inputs the properties of the detector and other parameters)

→ details of BdNMC on the following slides

- I will put in the particles involved in the scattering of DM into the Super-K detector simulation SkdetSIM to study how the Super-K detector responds to a DM particle

BdNMC overview

- The following is mainly from the paper "Light dark matter in neutrino beams: production modelling and scattering signatures at MiniBooNE, T2K and ShiP" by Patrick deNiverville et al.

- → Paper introduces the model, analyzes some of the light DM production channels, scattering signals etc + appendix for BdNMC

- Reminder: BdNMC models light dark matter production and downstream scattering for fixed target experiments

- can be used for various proton beam energies, production targets, detector geometries, fixed target geometries

- Supports many production channels (more on this later) and four possible scattering interactions between hidden sector dark matter and the material in fixed target neutrino detectors.

Quick overview of BdNMC

- Takes in a parameter card (a .dat file) which specifies the parameters of the model, detector properties, etc

  1) Generates DM particles (the numbers on the diagram below are the physical locations where this process would occur)

- 2) Propagates DM particles

- 3) generates DM particle interactions within the detector

- Records information about each scattering event in a file called events.dat
- Records a summary of the run (including the total number of interactions given the POT) in a file called summary.dat
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BdNMC: the parameter card

- All outlined starting on pg.21 of the paper.

- Some important ones:

- POT

- Samplesize: The number of scattering events to generate before terminating the run.

- beam_energy: The total energy of the proton beam. Defaults to 8 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. Defaults to 1.0.

- pi0_per_POT: The number of $\pi 0$'s expected per proton on target.

- Which scattering signal to use: NCE_nucleon,NCE_nucleon_baryonic,NCE_electron and pion_inelastic.

- Different 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

  $\rightarrow$ can use more than one production channel

- Timing and energy cuts

- χ and V (dark photon) mass, dark sector coupling strength α' , the mixing constant epsilon between the V mediator and the photon

- Detector parameters: spherical or cylinderical, geometry, material

- A lot of parameters relating to the MCMC process that generates the DM particle and scattering interactions.

Summary of what BdNMC does

(learning ongoing)

- When you run BdNMC, it:

- Reads the parameter cards and sets up the necessary variables (eg the model parameters, detector geometry etc)

- Creates a list of production channels based on the parameter card).

- Calculates the total number of dark matter particles that is expected to be produced for the POT (from the parameter card)

- "The simulation loop begins": it selects a production channel from the list produced earlier. Each channel has a probability of being chosen equal to fraction of the total number of dark matter particles that would be produced through the channel.

- Generates the 4 momenta of a meson or V produced form the P-P collision.

- Decays this initial particle and outputs a pair of dark matter particle 4 momenta.

- Checks to see if the dark matter 4 momenta intersect with the detector

- When it does:

- Code checks to see if the particle scatters (still working on understanding the details of this process)

- Code repeats this process until the requested number of sample signal events (samplesize) has been generated. Then it calculates the total # of signal events (more on this coming up) and appends it to summary.dat along with some other information.

- For each successful interaction, the four-momentum of the recoil particle is recorded in an events file (events.dat)

Calculating the number of signal events

- From the paper:

  for each production channel i:

-
- $$\text{signal\_events}[i] = \frac{\text{ninteractions}[i]}{\text{trials}} \times \text{vnumtot} \times \text{pmax} \times \textbf{efficiency},$$

- ninteractions is the samplesize that the user inputs in the parameter card

  (basically the code does x trials until samplesize scattering events are generated)

- total_signal_events: sum of signal events for all production channels

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- $$\text{total\_signal\_events} = \sum_{i}^{\text{chan\_count}-1} \text{signal\_events}[i].$$

- Note: efficiency is the efficiency of the detector

- Vnumtot is the total dark photons produced that decay into dark matter particles (outputted when you run BdNMC)

- Ran BdNMC using the given parameters for a Miniboone-like example in the paper and got a similar numbers for signal_events.

- Manually calculated signal_events using samplesize as ninteractions, trials, vnumtot and pmax as given in the BdNMC output, and efficiency from the given parameter card (using the formula below):

- $$\text{signal\_events}[i] = \frac{\text{ninteractions}[i]}{\text{trials}} \times \text{vnumtot} \times \text{pmax} \times \text{efficiency},$$

- Got the same number

Events.dat and Summary.dat files

channel_name dark_photon_mass dark_matter_mass signal_events[i] epsilon alpha_D signal_channel POT Efficiency samplesize vnum[i]

The summary output terminates with one final line with the format:

Total dark_photon_mass dark_matter_mass total_signal_events epsilon alpha_D signal_channel POT Efficiency samplesize vnumtot

The output expected for our example experiment from App. A 1 is provided here:

```
Run  1470677009
pi0_decay  0.1  0.01  4137.09  0.001  0.1  NCE_nucleon  2e+20  1  2000
Total  0.1  0.01  4137.09  0.001  0.1  NCE_nucleon  2e+20  1  2000
```

Events.dat and Summary.dat files

```
Run  1462311643
event  1
pion              0.285398        −0.0544237       5.54369          5.55294
V                 0.204215        −0.0118137       4.14206          4.14832
DM                −0.00377294     −0.00148947      0.658276         0.658307
proton            −0.185011       0.235048         0.134491         0.993941
−2.82029          −1.11338        492.064          1.64143e−06

endevent  1

event  2
pion              0.0252685       0.113951         1.771            1.77997
V                 0.039564        0.105479         1.71365          1.72026
DM                −0.00213871     −0.000317347     0.733531         0.733551
proton            0.205311        −0.208192        0.118041         0.989841
−1.42464          −0.21139        488.618          1.6299e−06

endevent  2

event  3
pion              −0.0597918      −0.0244405       5.17368          5.17585
V                 −0.0199172      −0.0266187       4.24083          4.24214
DM                −0.0127331      −0.0416011       4.10137          4.1016
neutron           −0.305361       −0.15944         0.0761656        1.00362
−1.53362          −5.01059        493.984          1.64785e−06

endevent  3
```

[particle_name px py pz E x y z t] where x y z t

Goal

- Write code that inputs the events.dat file and outputs a ROOT tree containing the information

    → currently working on this

- Continue investigating how BdNMC generates the DM scattering events

    -> Probably will need to learn more about MCMC's

- Want to better understand how BdNMC calcualtes signla_events

    → find out what pmax is, how the trials are done?
    - Investigate why Trials < vnumtot

- Later: put the particles that the DM scatters off of into SkdetSIM

- At some point: due the health and safety training course for summer students