Boosted Dark Matter Event Generation at SBN

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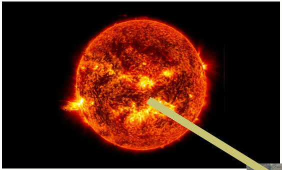
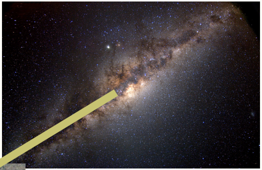
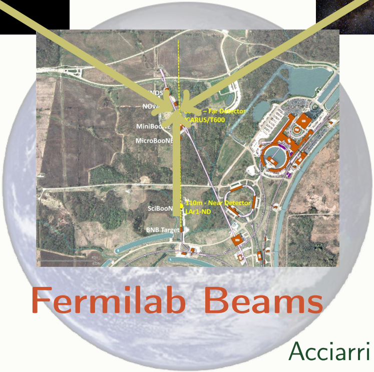
SBN-Theory Mini-workshop

BSM Targets at ν Facilities

Astrophysical Sources







Fermilab Beams

NASA
Acciarri et. al.: 1503.01520

What Are We Generating?

Astrophysical Sources:

DM Distribution
Annihilation Rate
Flux

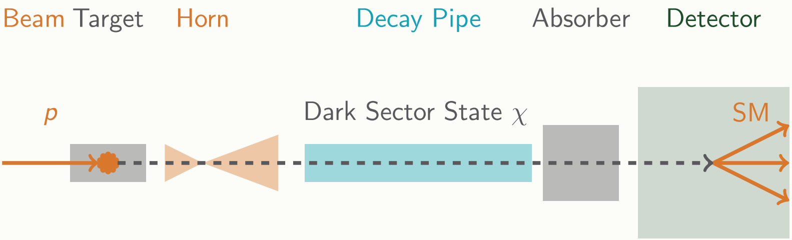
Beam Sources:

Direct Production
Meson-based Production
Flux

Interactions in Detector:

DM-Nucleus scattering at scale $Q \in [0.1, 10]$ GeV
At low end: Nuclear effects very important
At high end: Inelastic nucleon scattering

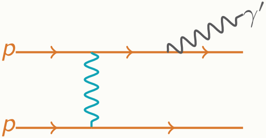
Beam Production



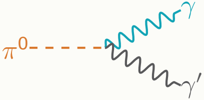
- SBN experiments sensitive to neutral, long-lived particles produced in the beam
- Several targets of opportunity to complement the neutrino program

Beam Production Tools

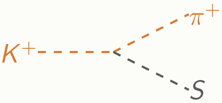
- Direct Production:
  BdNMC and MadDump



- Short-lived meson decay:
  BdNMC and MadDump



- Long-lived meson decay:
  Modify g4 beam simulation



deNiverville et. al.: PRD95 (2017), 035006
Buonocore et. al.: JHEP05(2019)028
Batell et. al.: PRD104 (2021), 075026
Batell, JB, Ismail: PRD100 (2019), 115039

Gauge Mediator: Broad Class of Models

$$J^{\mu}_{Z',\psi} = \overline{\psi}\,\gamma^{\mu}(Q^{\psi}_{L}\,P_L + Q^{\psi}_{R}\,P_R)\,\psi$$

$$\mathcal{L}_{\text{int}} = g_{Z'}\,Z'_{\mu}\,J^{\mu}_{Z',\psi}$$

$$\psi = \{\chi, u, d, s, c, e\}$$

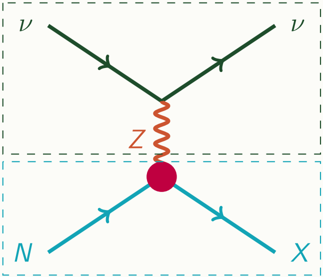
Parameters: charges $Q^{\psi}_{L,R}$, $g_{Z'}$, Z' mass, DM mass

Scalar DM interactions analogous (only one charge)

Includes models such as vector portal mediator and axial coupling DM

A New Tool

Different, but simple



Similar, adapt from `GENIE`

Based on `GENIE` neutrino Monte Carlo!

JB: 1812.05616

Anatomy of Event Generation

1. Add the DM-nucleus initial state
2. Add a selected nucleon, vertex in nucleus
3. Give nucleon nuclear kick
4. Generate interaction kinematics
5. Add the outgoing DM
6. Figure out the hadronic final state
7. Pauli blocking
8. Hadron transport through nuclear remnant

Structure of Cross-section

$$\frac{\sigma}{dQ^2\, dW^2} \propto \frac{g_{Z'}^4\, M_N^2}{4\,\pi\,(E^2 - M_\chi^2)}\, \Delta_{\mu\rho}\, \Delta_{\nu\sigma}\, L^{\mu\nu}\, W_{\rho\sigma}$$

$L^{\mu\nu}$: DM squared matrix element with Z' current

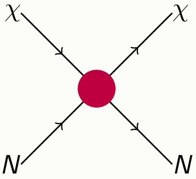
$\Delta_{\mu\nu}$: Z' mediator propagator

$W^{\mu\nu}$: Hadronic squared matrix element with Z' current

Summed over all hadronic final states

Challenging to model!

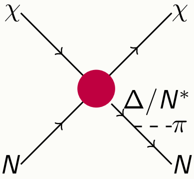
Three Different Processes



Elastic

Relatively easy

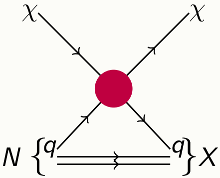
Needs form factor



Resonant

Dominated by Δ, N^*
$W \in [1, 2]$ GeV

Needs a model



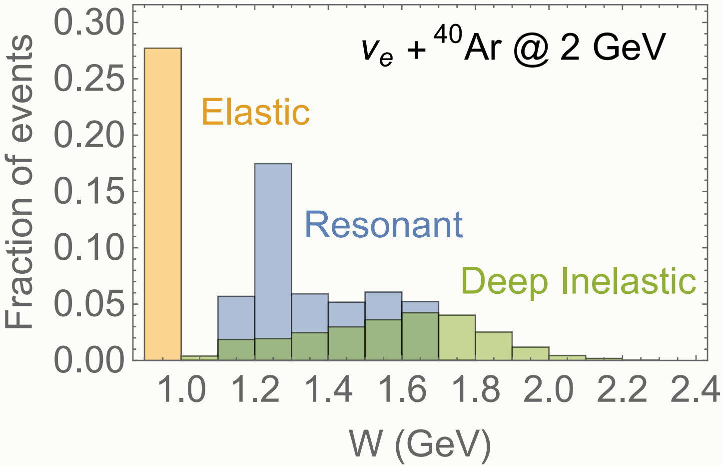
Deep Inelastic

Use standard
parton model

DM beam? Low Q?

Rein & Sehgal: Ann.Phys.133, 79 (1981)

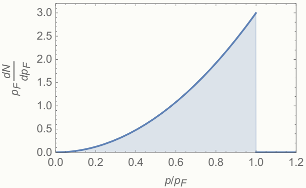
All processes could be important

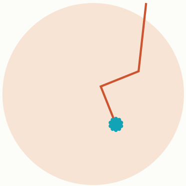


Nuclear Effects: Distortion of Signal

Initial state:

- Nucleons are not at rest ($p \sim 240$ MeV)
- Nuclei are dense with fermions: Pauli blocking



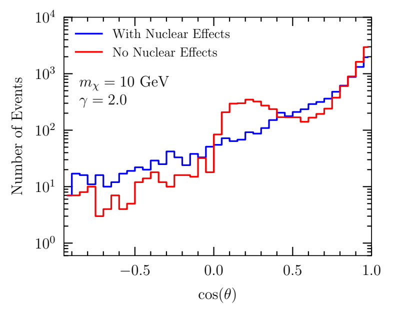


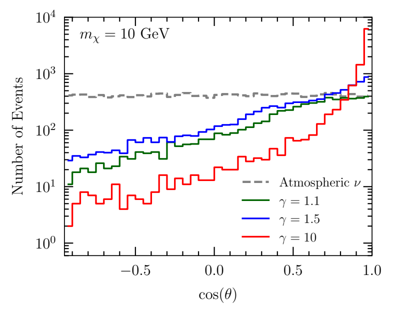
Final state:

- Hadrons can scatter off nuclear remnant

Resulting Distributions

$m_\chi = 10$ GeV





Berger et. al.: PRD 103, 095012 (2021)

Sample Event

```
|---------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                      |
|---------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |       Px |       Py |       Pz |        E |      m  |
|---------------------------------------------------------------------------------------------------------------|
|   0 |        chi_dm |   0 | 2000010000 |  -1 |  -1 |   4 |   4 |    0.000 |    0.000 |   17.321 |   20.000 |   10.000 |
|   1 |          Ar40 |   0 | 1000180400 |  -1 |  -1 |   2 |   3 |    0.000 |    0.000 |    0.000 |   37.216 |   37.216 |
|   2 |       neutron |  11 |       2112 |   1 |  -1 |   5 |   5 |   -0.020 |   -0.071 |   -0.205 |    0.929 | **0.940 | M = 0.903
|   3 |          Ar39 |   2 | 1000180390 |   1 |  -1 |  16 |  16 |    0.020 |    0.071 |    0.205 |   36.286 |   36.286 |
|   4 |        chi_dm |   1 | 2000010000 |   0 |  -1 |  -1 |  -1 |   -0.614 |    0.353 |   15.958 |   18.846 |   10.000 | P = …
|   5 |      HadrSyst |  12 | 2000000001 |   2 |  -1 |   6 |   8 |    0.594 |   -0.424 |    1.158 |    2.083 | **0.000 | M = 1.571
|   6 |       neutron |  14 |       2112 |   5 |  -1 |   9 |   9 |    0.273 |   -0.296 |    0.574 |    1.172 |    0.940 | FSI = 5
|   7 |           pi+ |  14 |        211 |   5 |  -1 |  13 |  14 |    0.148 |    0.053 |   -0.049 |    0.216 |    0.140 | FSI = 4
|   8 |           pi- |  14 |       -211 |   5 |  -1 |  15 |  15 |    0.172 |   -0.181 |    0.633 |    0.695 |    0.140 | FSI = 1
|   9 |      HadrClus |  16 | 2000000300 |   6 |  -1 |  10 |  12 |    0.273 |   -0.296 |    0.574 |    1.172 | **0.000 | M = 0.940
|  10 |        proton |   1 |       2212 |   9 |  -1 |  -1 |  -1 |   -0.182 |   -0.362 |    0.153 |    1.033 |    0.938 |
|  11 |        proton |   1 |       2212 |   9 |  -1 |  -1 |  -1 |    0.353 |   -0.071 |    0.109 |    1.011 |    0.938 |
|  12 |       neutron |   1 |       2112 |   9 |  -1 |  -1 |  -1 |    0.102 |    0.137 |    0.312 |    1.005 |    0.940 |
|  13 |           pi+ |   1 |        211 |   7 |  -1 |  -1 |  -1 |    0.038 |   -0.107 |    0.039 |    0.184 |    0.140 |
|  14 |       neutron |   1 |       2112 |   7 |  -1 |  -1 |  -1 |   -0.080 |    0.228 |   -0.019 |    0.970 |    0.940 |
|  15 |           pi- |   1 |       -211 |   8 |  -1 |  -1 |  -1 |    0.172 |   -0.181 |    0.633 |    0.695 |    0.140 |
|  16 |      HadrBlob |  15 | 2000000002 |   3 |  -1 |  -1 |  -1 |    0.210 |    0.004 |    0.136 |   33.472 | **0.000 | M = 33.471
|---------------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                                |    0.000 |   -0.000 |    0.000 |    0.000 |          |
|---------------------------------------------------------------------------------------------------------------|
|       Vertex:         chi_dm @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =    0.000000e+00 s)  |
|---------------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000    |  1st set:                                                 none |
| Err mask [bits:15->0] : 1111111111111111    |  Is unphysical:    NO |   Accepted:   YES                       |
|---------------------------------------------------------------------------------------------------------------|
| sig(Ev) =       5.68527e-35 cm^2  | d2sig(x,y;E)/dxdy =      1.66546e-33 cm^2       | Weight =         1.00000 |
|---------------------------------------------------------------------------------------------------------------|
```

Current Status

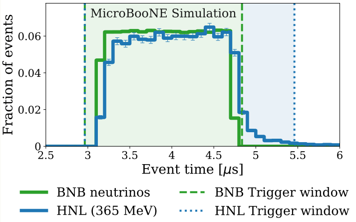
- Arbitrary flavor-dependent Z' charges
- Scalar and fermionic dark matter
- Elastic, Deep Inelastic, & Electron scattering
- Preliminary version in official `GENIE v3`
- Update with remaining features soon!

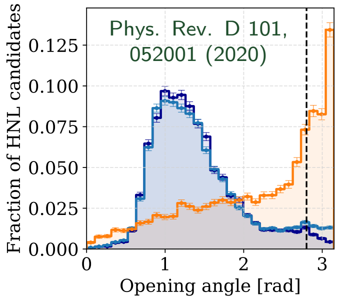
Further Directions

- Resonant scattering: implementation & validation
- More models: inelastic DM, your favorite model?
- Can we better treat nuclear unknowns?
- BSM models with other simulation needs?

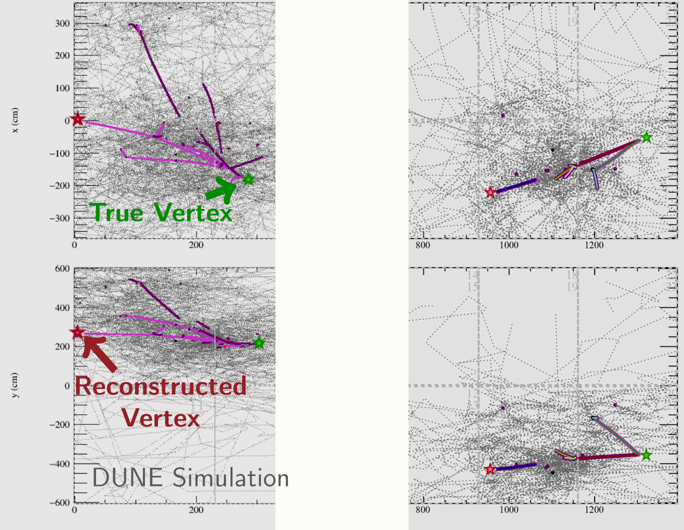
BSM Analysis Strategy

- Time of flight (for heavy particles)
- Selection of neutral-current (NC) interaction (for NC-like signal)
  - μ-π separation
- Efficient reconstruction of particles not along the standard beam line
- Correct vertex location (reducing cosmic rays or atmospheric ν, etc.)
- 4-momentum reconstruction





BDM Search Example



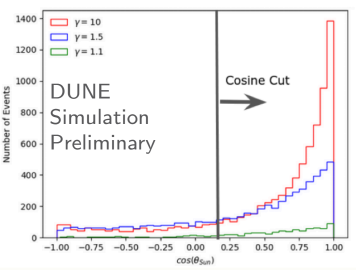
DUNE Studies by L. Peres

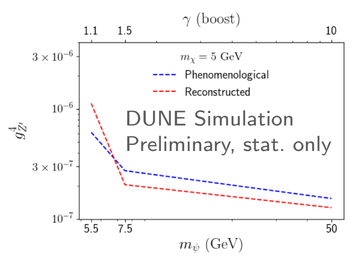
BDM Search in DUNE

- Phenomenological studies: Smearing the final state visible particles according to DUNE CDR

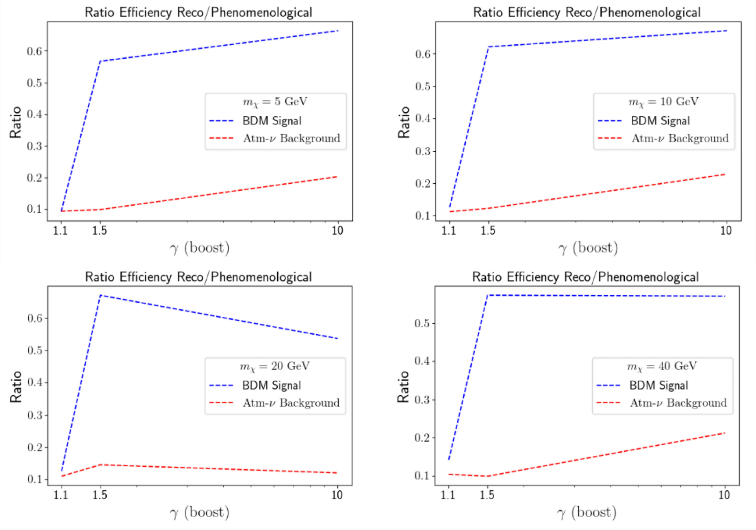
  Berger et. al.: PRD103, 095012 (2021)

- Reconstructed studies:
  - Assume 100% separation of charged-current and NC events
  - Assume vertices are reconstructed correctly, but not necessarily precisely
  - Only reconstruct contained tracks
- Similar sensitivities





Detection Threshold



Outlook

- ν experiments use proton beams so hadronic signals of great interest
- Hadronic scattering is challenging to model due to resonant baryon production & nuclear effects
- Hadronic (& electronic) scattering are now simulated in `GENIE`
- Reconstruction strategies are dependent on the specific signals and require further study
- Plenty more models to consider at SBN and beyond

Backup

Detection: Range of Scales

E (GeV)

10

Pion production threshold

1 — Cherenkov proton threshold

Nuclear Fermi motion

0.1

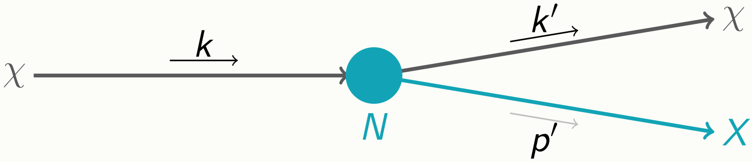
LArTPC KE thresholds

0.01 — Nuclear binding per nucleon

Inelastic

Elastic

Fixed Target Kinematics Primer



$$p = (M_N, 0, 0, 0)$$

X: N for elastic, mess of hadrons for inelastic

$$q^2 = -Q^2 = (p' - p)^2 \quad \& \quad W^2 = p'^2$$

$$0 \leq Q^2 \leq 4p_{1,\mathrm{CM}}^2 \quad \& \quad M_N \leq W \leq \sqrt{s} - M_\chi$$

Inelastic can begin at $\gamma \gtrsim 1 + M_\pi / M_N$

Elastic Scattering Cross-section

- Four form factors required to describe elastic

$$\langle J^{\mu}_{Z',q} \rangle \propto F_1(q^2)\,\gamma^{\mu} + \frac{1}{2\,M_N}\,F_2(q^2)\,\sigma^{\mu\nu}\,iq_{\nu} + F_A(q^2)\,\gamma^{\mu}\,\gamma^5 + F_P(q^2)\,\frac{q^{\mu}}{2\,M_N}\,\gamma^5$$

- Assume the standard dipole form

$$F \propto 1/(1 + Q^2/M^2_{V,A})^2$$

  - $F_1(0)$ constrained by charge conservation
  - $F_2(0)$ given by anomalous magnetic moments
  - $F_A(0)$ fit from data or lattice (spin form factors)
  - F_P related to F_A by PCAC

DIS: Cross-section

$$W^{\mu\nu} \propto \text{Parton distribution functions}$$

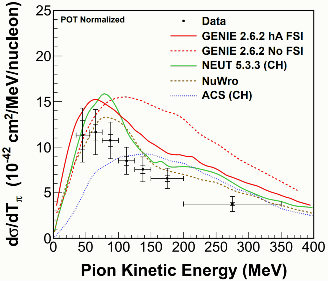
- W^2 traded for conventional $x = \dfrac{Q^2}{Q^2 + W^2 - M_N^2}$
- Use GRV98LO PDFs tuned to low E scattering
- Calculation is inclusive (but we need exclusive)

DIS: Specifying Final State

- Low W: empirical Koba-Nielsen-Olesen model
  - Imported from νN data, so inaccurate
- High W: simplified Pythia model
  - Treats beam remnant as a diquark
  - Fragments & hadronizes FS quark-diquark pair
  - Radiation not handled correctly–relevant at high W

Resonant Scattering: General Consideration

- Most models based on Feynman-Kislinger-Ravndal
- Baryons as a harmonic oscillator
- Amplitudes calculated for each baryon resonance



MINERvA:PRD92 (2015) 092008

Resonant Scattering for DM

- Amplitude for each resonance in terms of up to 6 helicity amplitudes for V,A currents

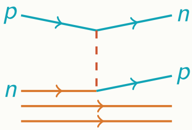
$$d\sigma \propto |\langle N', \lambda' | V^\mu - A^\mu | N, \lambda \rangle|^2$$

- Dominated by spin 3/2 baryon Δ, but 17 other excited baryons included!
- Challenging to validate and test
- Amplitudes implemented, but not validated

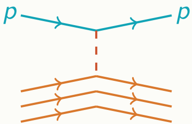
Nuclear Effects: FSI

Interaction of hadronic FS with nuclear remnant

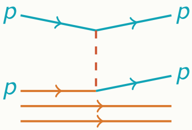
2 Charge exchange



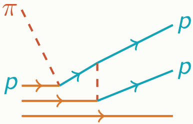
3 Elastic



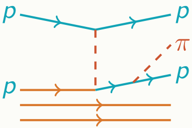
4 Inelastic



5 Absorption

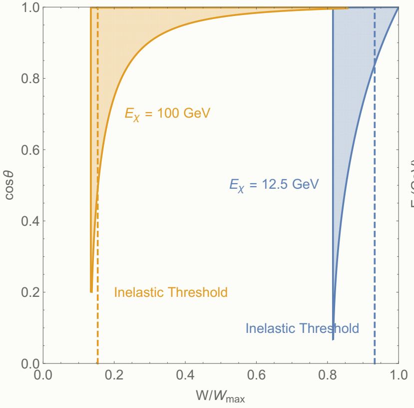


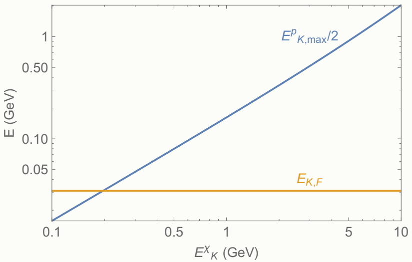
8 Pion Production



Recoil Kinematic Features

$$M_\chi = 10\ \text{GeV}$$





Different Nuclear Models