Boosted Dark Matter at Large Volume Neutrino Detectors

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Cui, JB, Zhao: JCAP 1502 (2015) no.02, 005
Cui, JB, Necib, Petrillo, Tsai, Zhao: In progress

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Outline

Motivation

Benchmark Models

Dark Matter Flux

Detetion Phenomenology and Results

Conclusions

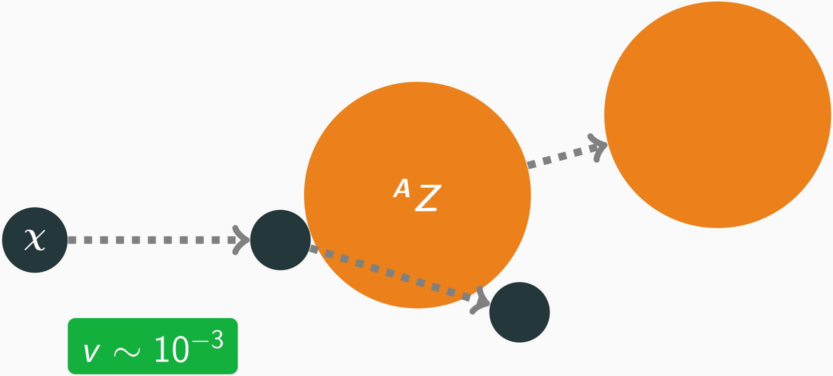
Motivation

Beyond a minimal WIMP

- Spin dependent interactions only
- Velocity suppression at low v
- Non-SM annihilation modes
- Non-minimal stabilization symmetry
- Multi-component DM sector
- High(er) velocity flux (i.e. boosted)

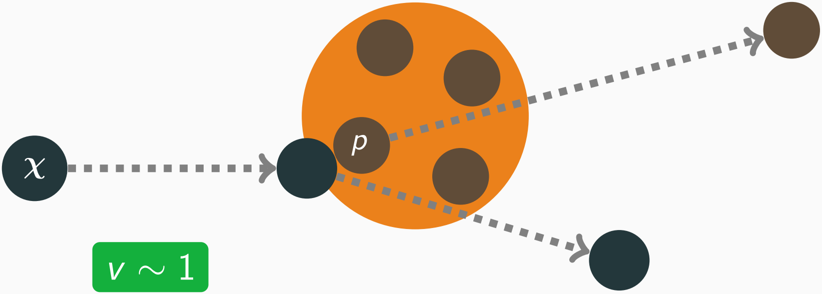
Thermal relic dark matter is slow

Nucleus Kinetic Energy $\mathcal{O}$**(10 KeV)**



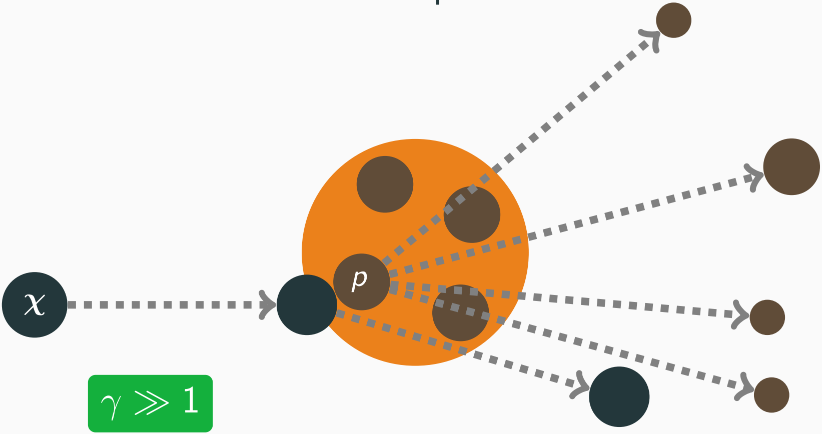
Boosted DM: "Elastic" scattering

Nucleon Kinetic Energy **$\mathcal{O}$(100 MeV)**



Boosted DM: Inelastic scattering

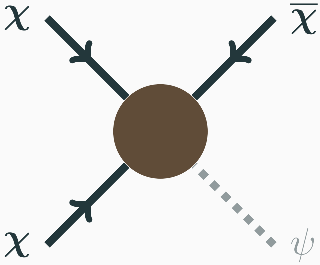
Multihadron production



Benchmark Models

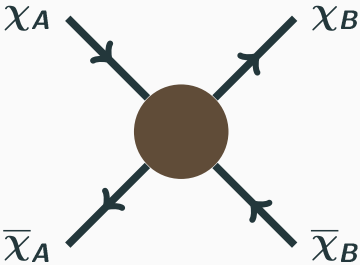
Simple BDM models exist

Z_3 Dark Matter with semi-annihilation



$v \approx 0.6$

Two component Dark Matter



$v = \sqrt{1 - m_B^2/m_A^2}$

First benchmark: Axial Z'

- In addition to annihilation, there is a scattering process that allows for detection

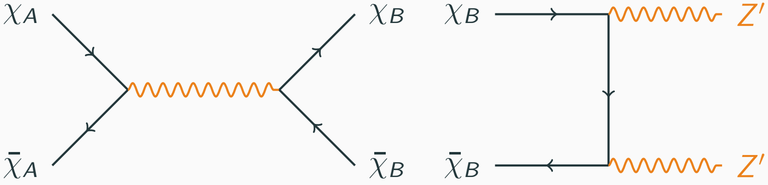
$$\begin{aligned}\mathcal{L} \;\supset\; & -Q_\chi^{V,(A)}\, g_{Z'}\, Z'_\mu\, \bar{\chi}\gamma^\mu(\gamma^5)\chi \\ & -\sum_f Q_f^{V,(A)}\, g_{Z'}\, Z'_\mu\, \bar{q}_f\gamma^\mu(\gamma^5)q_f\end{aligned}$$

- As a first benchmark, take

$$Q_i^V = 0, \quad Q_\chi^A = 1, \quad Q_{p,\text{eff}}^A = 1$$

Note on two component case

- Two component: annihilation with Z' with $Q_A^{\text{eff}} \ll Q_B$



- Abundance of B much less than A
- Charge of A floats the thermal relic abundance

Simple parametrization for elastic case

Direct detection cross-section: $\sigma_{\mathrm{DD}} \equiv \sigma_{\chi,p}^{v\to 10^{-3}}$

- Semi-annihilation has just 2 dominant parameters:

$$m_\chi, \sigma_{\mathrm{DD}}, (m_{Z'})$$

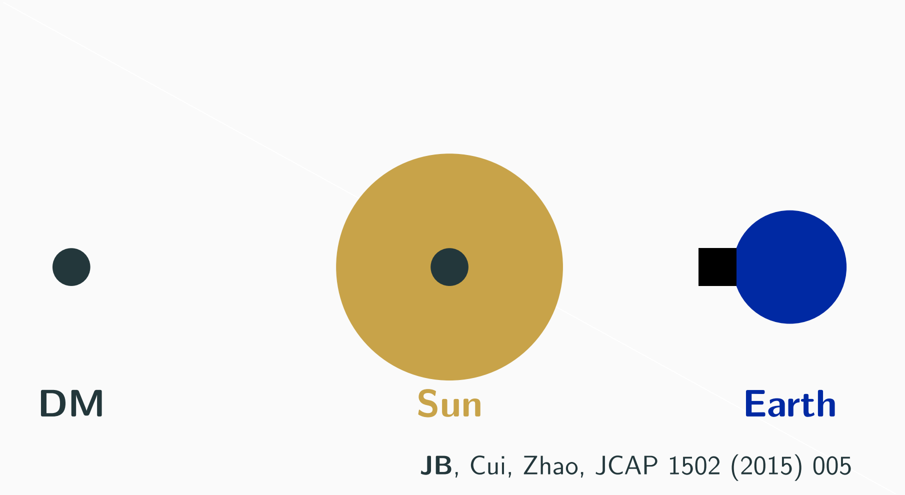
- Two component more complex, flexible:

$$m_A, m_B/m_A, \sigma_A, \sigma_B/\sigma_A, (m_{Z'}/m_A)$$

- Fermionic DM: $\sigma_{\chi,p} \propto v^0$ Scalar DM: $\sigma_{\chi,p} \propto v^2$

Dark Matter Flux

Solar capture & detection

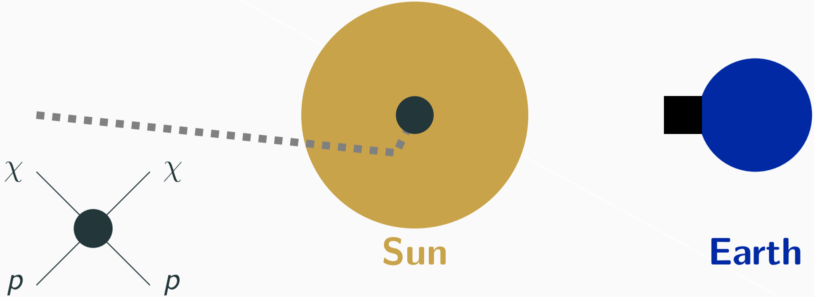


JB, Cui, Zhao, JCAP 1502 (2015) 005

Solar capture & detection

Capture

Hadron scattering



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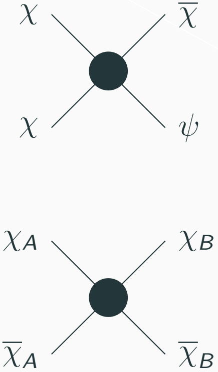
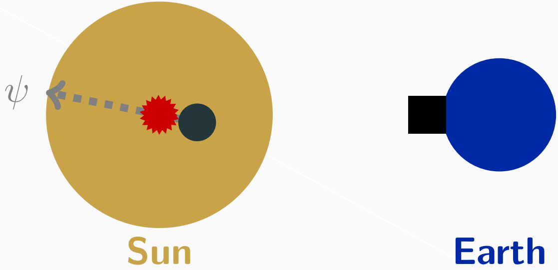
Solar capture & detection

Annihilation





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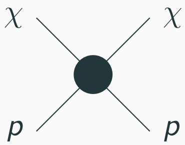
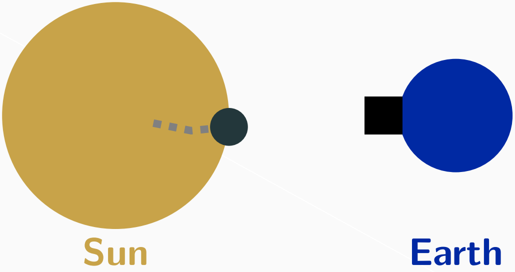
Solar capture & detection

Rescattering

Hadron scattering





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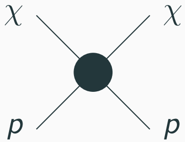
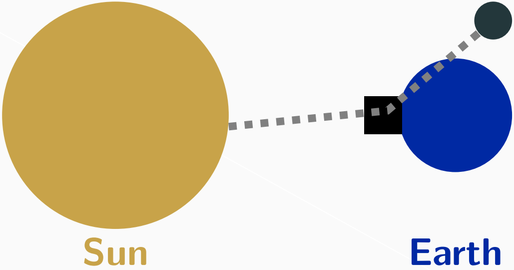
Solar capture & detection

Detection

Hadron scattering





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DM capture: Framework

$$C = \int dV\, du\, \underline{\sigma_{\chi,p}(w \to v)\big|_{v<v_{\mathrm{esc}}}}\; \underline{\frac{w^2}{u}}\; \underline{n_\chi}\; \underline{n_H}\; \underline{f(u)}$$

- $\sigma_{\chi,p} \sim \sigma_{\mathrm{DD}}$
- w/u: Velocity enhancement
- n_χ: Halo DM density
- n_H: Solor hydrogen density (from model AGSS-09)
- $f(u)$: DM (Boltzmann) velocity distribution at $r = \infty$

DM capture: Results

- Fermionic DM:

$$C = 8.7 \times 10^{22}\ \mathrm{sec}^{-1} \left(\frac{\sigma_{\mathrm{DD}}}{10^{-41}\ \mathrm{cm}^2}\right) \left(\frac{10\ \mathrm{GeV}}{m_\chi}\right)^2$$

- Scalar DM:

$$C = 2.0 \times 10^{24}\ \mathrm{sec}^{-1} \left(\frac{\sigma_{\mathrm{DD}}}{10^{-41}\ \mathrm{cm}^2}\right) \left(\frac{10\ \mathrm{GeV}}{m_\chi}\right)^2$$

- Enhanced scalar capture: larger v in the Sun

DM annihilation

- DM annihilation determined by equilibrium

$$A\,N^2 = C - E\,N$$

- Assuming annilation $\sigma \sim \mathrm{pb}$, $t_\odot \gg \tau_{\mathrm{eq}}$

- DM evaporation: DM upscattering by tail of H thermal distribution

- Evaporation negligible for $m_\chi > 5\ \mathrm{Gev}$

DM rescattering

- DM can lose energy escaping the Sun

$$\ell = \frac{1}{\sigma_{\chi,p}\, n_H}$$

- Higher v during escape → enhanced rescattering for scalar DM

- Calculate detection rate using $\langle E_\chi \rangle$

- Conservative estimate: fluctuations are important

DM detection rate

- Flux at Earth is given by

$$\Phi = \frac{C}{4\,\pi\,\mathrm{AU}^2}$$

- Combining to determine the detection rate

$$R = \Phi\,\sigma_{\chi,p}(p_{p,f} > p_{\mathrm{thresh}})\,N_p$$

- Detection rates accessible to kton detectors

$$R \sim 0.5\ \mathrm{yr}^{-1}\mathrm{kton}^{-1}\ \left(\frac{\sigma_{\mathrm{DD}}}{1\times 10^{-41}\ \mathrm{cm}^2}\right)^2$$

$$p_{\mathrm{thresh}} = 1.07\ \mathrm{GeV},\ \ m_\chi = 10\ \mathrm{GeV},\ \ \mathrm{scalar\ DM}$$

Other sources

- Earth capture when SI interactions have coherent enhancement
- Galactic center is generally subdominant

$$\begin{aligned}\Phi_{\mathrm{GC}} &\sim 10^{-7}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}\left(\frac{10\ \mathrm{GeV}}{m_\chi}\right)^2 \\ &\ll \Phi_\odot \sim 10^{-2}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}\end{aligned}$$

- DM produced in beam: possible with lighter DM

Detetion Phenomenology and Results

Looking with water Čerenkov

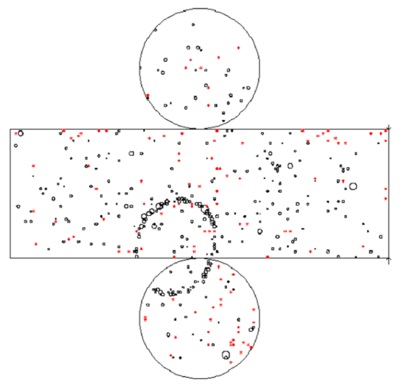
Physical energy threshold:

$$E_{\mathrm{K,recoil}} = 480\ \mathrm{MeV}$$

Hard to reconstruct inelastic

Experiments:

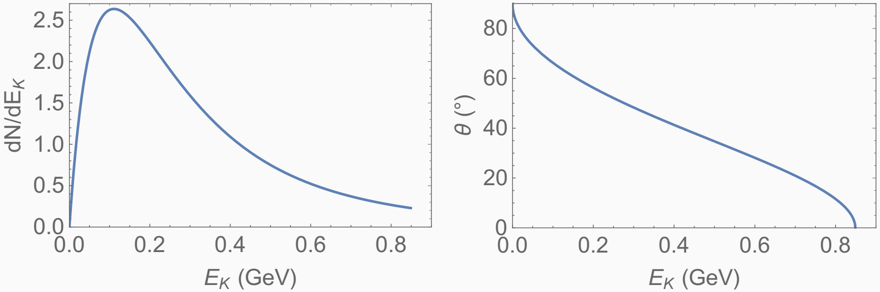
- Super-Kamiokande
- Hyper-Kamiokande



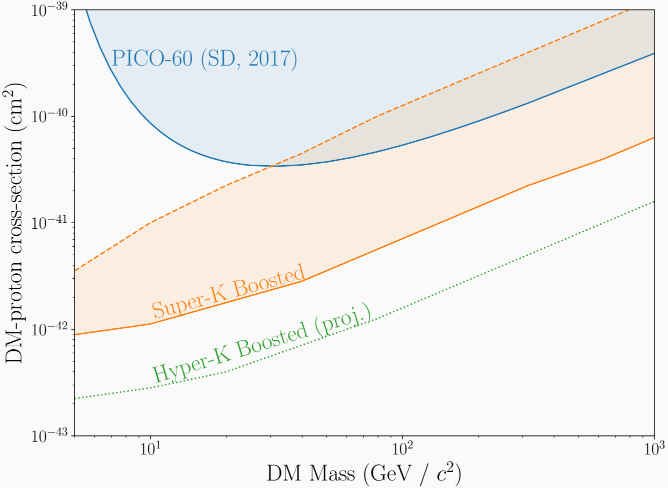
Super-Kamiokande: PRD79 (2009) 112010

Backround reduction

- Protons recoil within $\theta \sim 40^\circ$ of the sun
- Background dominated by near-isotropic atmospheric ν
- Large sideband to control systematics



Water Čerenkov results



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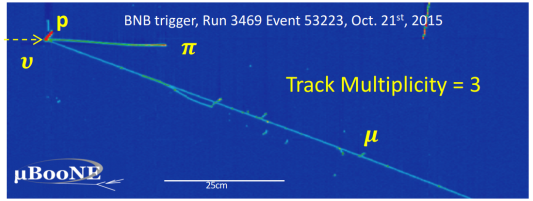
A future in liquid argon TPCs

Threshold:
$E_{\mathrm{K,recoil}} \lesssim 50\ \mathrm{MeV}$

Inelastic reconstruction possible

Experiments

- LArIAT
- ICARUS
- MicroBooNE
- DUNE



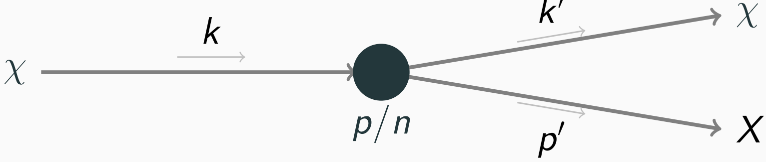
Yellow captions from talk by Luo

Checklist for DUNE

- ✓ Develop a Monte Carlo
  - Based on GENIE neutrino MC
  - Includes DIS and nuclear effects
  - Merged into GENIE v3
- ✓ Simulate dark matter flux from sun
- ✓ Integrate into LArSoft detector simulation
- Develop an analysis strategy & make projections

Theory: JB, Cui, Necib, Zhao
Experiment: Petrillo, Tsai, MicroBooNE BSM group
GENIE: Andreopoulos, Hatcher

Fixed target kinematics primer



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

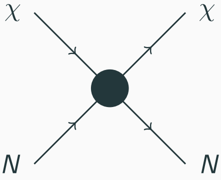
X: p/n for elastic, mess of hadrons for inelastic

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

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

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

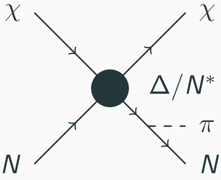
Three different processes



Elastic

Relatively easy

Needs form factor



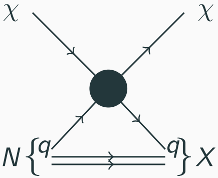
Resonant

Dominated by Δ, N^*

$W \in [1, 2]\ \mathrm{GeV}$

Needs a model

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

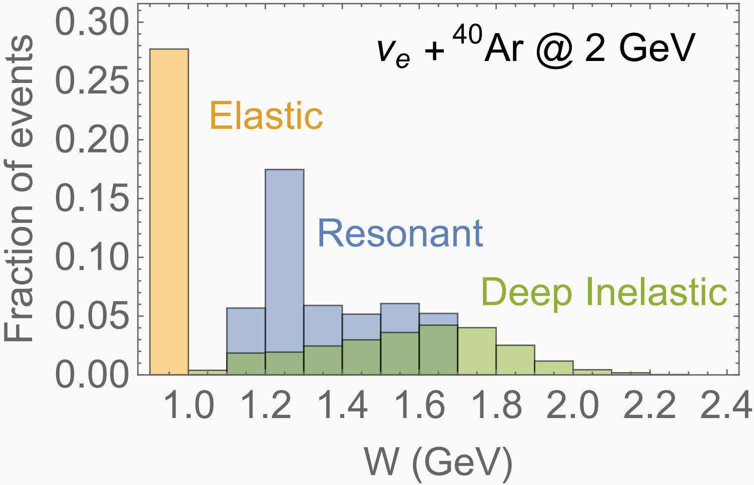


Deep Inelastic

Use standard parton model

DM beam?

All processes could be important



Elastic scattering

- Three form factors required to describe elastic

$$\Gamma^\mu = F_1(q^2)\,\gamma^\mu + \frac{1}{2\,M_N}\,F_2(q^2)\,\sigma^{\mu\nu}\,iq_\nu + F_A(q^2)\,\gamma^\mu\,\gamma^5$$

- Assume the standard dipole form

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

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

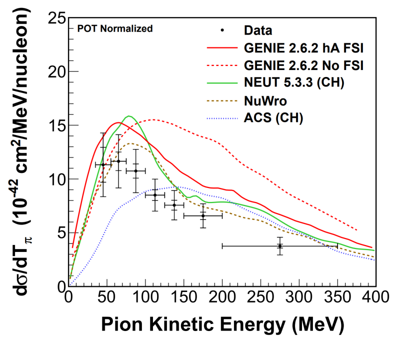
Deep inelastic scattering

- Low W: semi-empirical Koba-Nielsen-Olesen model
    - Imported from νN data, so inaccurate

- High W: simplified Pythia model
    - Treats beam remnant as a diquark
    - Fragments and hadronizes final state quark-diquark pair
    - Radiation not be handled correctly–relevant at high W

Resonant scattering, briefly

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

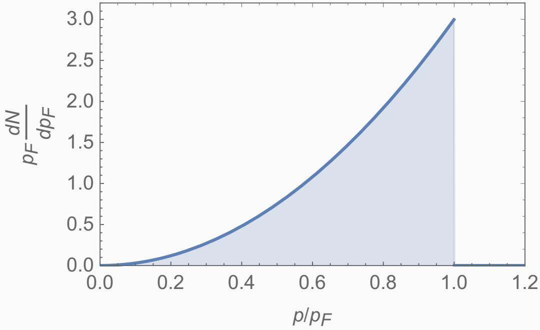


MINERvA:PRD92 (2015) 092008

Nuclear effects are important

Model large nucleus as Fermi gas with $p_F \sim 250\ \mathrm{MeV}$

Fermi motion



Pauli blocking

Final state interactions

$$\frac{d\sigma}{dp'} \to \frac{d\sigma}{dp'}\theta(p' - p_F)$$

Current Status of BDM in GENIE

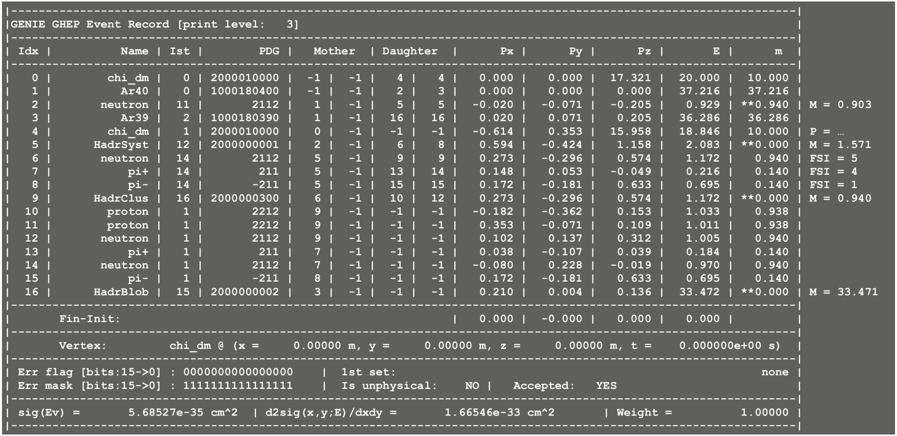
✓ 2 models: fermion or scalar DM, axial Z' coupling

✓ Elastic and Deep Inelastic scattering implemented

✓ Framework mostly set for further models

✓ Integrated into GENIE v3

Sample DIS event



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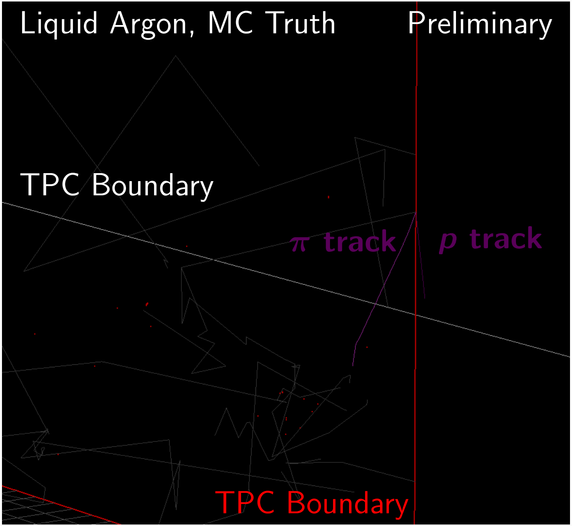
|------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                        |
|------------------------------------------------------------------------------------------------------------------|
| 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 |
|------------------------------------------------------------------------------------------------------------------|
```

Next steps: Detector simulation



Courtesy of

Yun-Tse Tsai

Conclusions

Next steps in theory

- Include additional interaction models: more general quark charges and interaction structures
- Include resonant production of excited baryons
- Improve modeling of nuclear and hadronic physics

Conclusions

- Traditional direct detection continues to put pressure on minimal WIMP scenarios
- Boosted dark matter models are an alternative with signals at large volume neutrino detectors
- New Monte Carlo tools required to determine sensitivity to BSM at fixed target experiments