Generators Overview for non- ν BSM at ν Facilities

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New Opportunities at the Next Generation ν Experiments

BSM Targets at ν Facilities



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

Backgrounds!

Neutrino backgrounds are quite uncertain



Data-driven or zero background when possible

Beam Production



BNB and NuMI beams have g4bnb and g4numi Caveat emptor: Cross-section uncertainties! Direct production of DM: Use MadGraph?

Batell, JB, Ismail: 1904.xxxx



Gauge Mediator: Broad Class of Models

$$egin{aligned} J^{\mu}_{Z',\psi} &= \overline{\psi} \, \gamma^{\mu} (Q^{\psi}_L \, P_L + Q^{\psi}_R \, P_R) \, \psi \ \mathcal{L}_{ ext{int}} &= g_{Z'} \, Z'_{\mu} J^{\mu}_{Z',\psi} \ \psi &= \{\chi, u, d, s, c, e\} \end{aligned}$$

Model completely specified by charges $Q_{L,R}^{\psi}$ plus

- ► Gauge coupling <u>g</u>_{Z'}
- **DM** and mediator Z' masses

Scalar DM interactions analogous (only one charge)

A New Tool



Similar, adapt from GENIE

Based on GENIE neutrino Monte Carlo!

JB: 1812.05616

Anatomy of Event Generation

- I. 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

$$rac{\sigma}{dQ^2 \, dW^2} \propto rac{g_{Z'}^4 \, \mathcal{M}_N^2}{4 \, \pi \left(E^2 - \mathcal{M}_\chi^2
ight)} \, \Delta_{\mu
ho} \, \Delta_{
u\sigma} \, L^{\mu
u} \, W_{
ho\sigma}$$

 $L^{\mu\nu}$: 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!

Fixed Target Kinematics Primer



$$p = (\mathcal{M}_N, \mathbf{o}, \mathbf{o}, \mathbf{o})$$

X: N for elastic, mess of hadrons for inelastic

$$q^2 = -Q^2 = (p'-p)^2$$
 & $W^2 = p'^2$
o $\leq Q^2 \leq 4p_{1,CM}^2$ & $M_N \leq W \leq \sqrt{s} - M_\chi$
Inelastic can begin at $\gamma \gtrsim 1 + M_\pi/M_N$

Three Different Processes



All processes could be important



Elastic Scattering Cross-section

▶ Four form factors required to describe elastic

$$\langle J_{Z',q}^{\mu} \rangle \propto F_{\scriptscriptstyle \rm I}(q^2) \, \gamma^{\mu} + rac{{\scriptscriptstyle \rm I}}{2\,\mathcal{M}_N} \, F_{\scriptscriptstyle 2}(q^2) \, \sigma^{\mu\nu} \, iq_{\nu} + F_{\mathcal{A}}(q^2) \, \gamma^{\mu} \, \gamma^5 + F_P(q^2) \, rac{q^{\mu}}{2\,\mathcal{M}_N} \, \gamma^5$$

Assume the standard dipole form

 $F \propto \mathrm{I}/(\mathrm{I} + Q^2/M_{V,\mathcal{A}}^2)^2$

- $F_{I}(o)$ constrained by charge conservation
- \triangleright $F_2(o)$ given by anomalous magnetic moments
- $F_A(o)$ fit from data or lattice (spin form factors)
- \blacktriangleright F_P related to F_A by Partially Conserved Axial Current

DIS: Cross-section

$W^{\mu u} \propto ext{Parton distribution functions}$

• W^2 traded for conventional $x = \frac{Q^2}{Q^2 + W^2 - M_N^2}$

▶ 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
 - \blacktriangleright Radiation not handled correctly-relevant at high W

Resonant Scattering: General Considerations

 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

$$d\sigma \propto |\langle N',\lambda'|V^{\mu}-\mathcal{A}^{\mu}|N,\lambda
angle|^{2}$$

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

Nuclear Effects: Kinematics

Approximate nucleus as Fermi gas with $p_F \sim$ 250 MeV



Pauli Blocking

 $d\sigma \propto \theta(p-p_F)$

Nuclear Effects: FSI

Interaction of hadronic FS with nuclear remnant

2 Charge exchange

3 Elastic

4 Inelastic







5 Absorption



8 Pion Production



Sample Event

ENIE	GHEP Event Recor	rd [pr:	int level: 3																
Idx	Name	Ist	I PDG		Moti	ner	Di	augh	ter	I	Px		₽у		Pz		E		
	chi_dm		2000010000		-1		1			I	0.000		0.000		17.321		20.000		10.000
	Ar40	0	1000180400		-1			2		I.	0.000		0.000		0.000		37.216		37.216
	neutron		2112					5			0.020		-0.071		-0.205		0.929		**0.940
	Ar39	2	1000180390		1			16	16	I .	0.020		0.071		0.205		36.286		36.286
	chi_dm		2000010000		0			-1		I -	0.614		0.353		15.958		18.846		10.000
5	HadrSyst	12	20000000001		2			6	8		0.594		-0.424		1.158		2.083		**0.000
	neutron	14	2112		5			9			0.273		-0.296		0.574		1.172		0.940
	pi+	14	211		5			13	14		0.148		0.053		-0.049		0.216		0.140
	pi-	14	-211		5			15			0.172		-0.181		0.633		0.695		0.140
	HadrClus	16	2000000300					10			0.273		-0.296		0.574		1.172		**0.000
	proton		2212								0.182		-0.362		0.153		1.033		0.938
	proton		2212								0.353		-0.071		0.109		1.011		0.938
	neutron		2112								0.102		0.137		0.312		1.005		0.940
	pi+		211								0.038		-0.107		0.039		0.184		0.140
	neutron		2112								0.080		0.228		-0.019		0.970		0.940
	pi-		-211		8					1	0.172		-0.181		0.633		0.695		0.140
	HadrBlob		2000000002								0.210		0.004		0.136		33.472		**0.000
	Fin-Init:									I	0.000		-0.000		0.000		0.000		
	Vertex:	chi_	dm @ (x =		00000) m, j	y =		0.00	000	m, z =	=	0.000	000			0.0000	00e	a+00 s)
Err	flag [bits:15->0]	: 000	000000000000000000000000000000000000000			1st :	set												none
Err	mask [bits:15->0]	: 11	1111111 1111111			Is u	nph	ysic	al:	NC	1 2	Aco	cepted:	Y	ES				
sig(Ev) = 5.685	527e-3	5 cm^2 d2si	.g (:	x,y;E	E)/dx	dy :			. 665	46e-3	3 (cm^2		Weigh	t =			1.00000

Recoil Kinematic Features



Resulting Distributions

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



Courtesy of Yun-Tse Tsai!

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?