Boosted Dark Matter Resonant Scattering Theory

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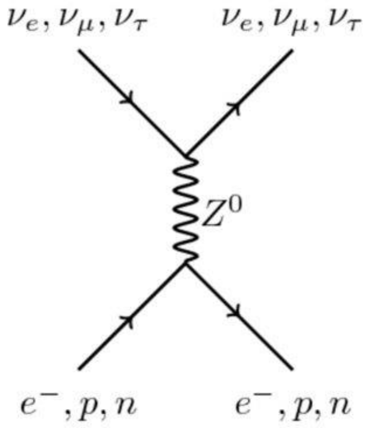
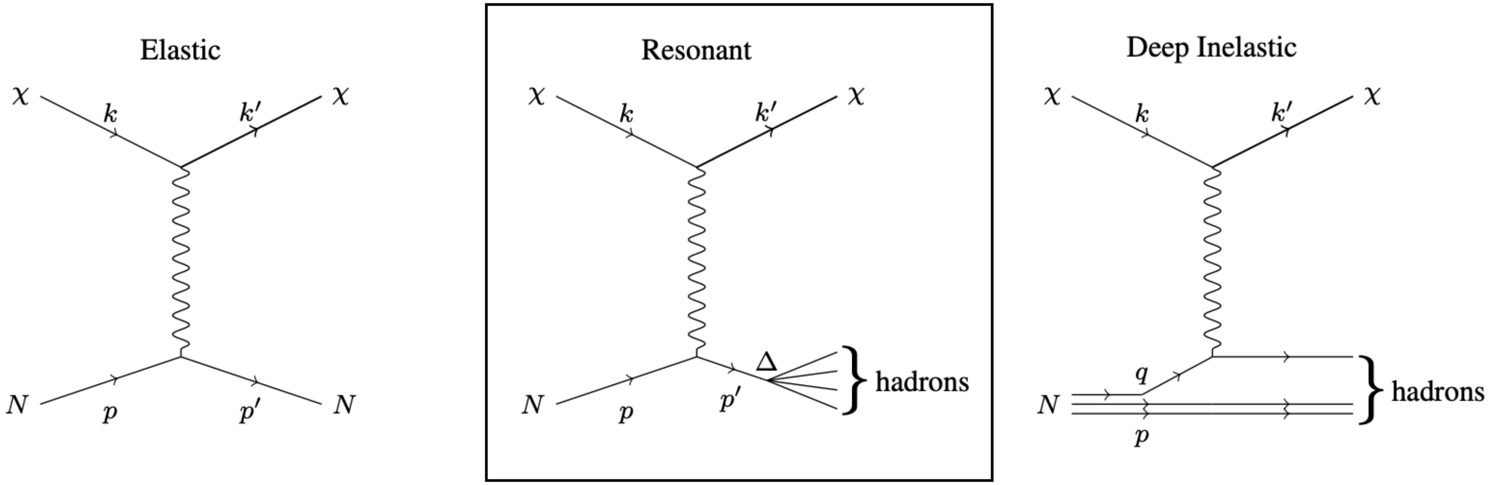
Background

- LArTPC at DUNE uses GENIE code event generator to search for neutrino scattering events.
- Our goal is to modify the GENIE code for Dark Matter scattering events.





Hagebout, Robert-Jan. "Beyond the Standard Model with neutrino physics." (2014).

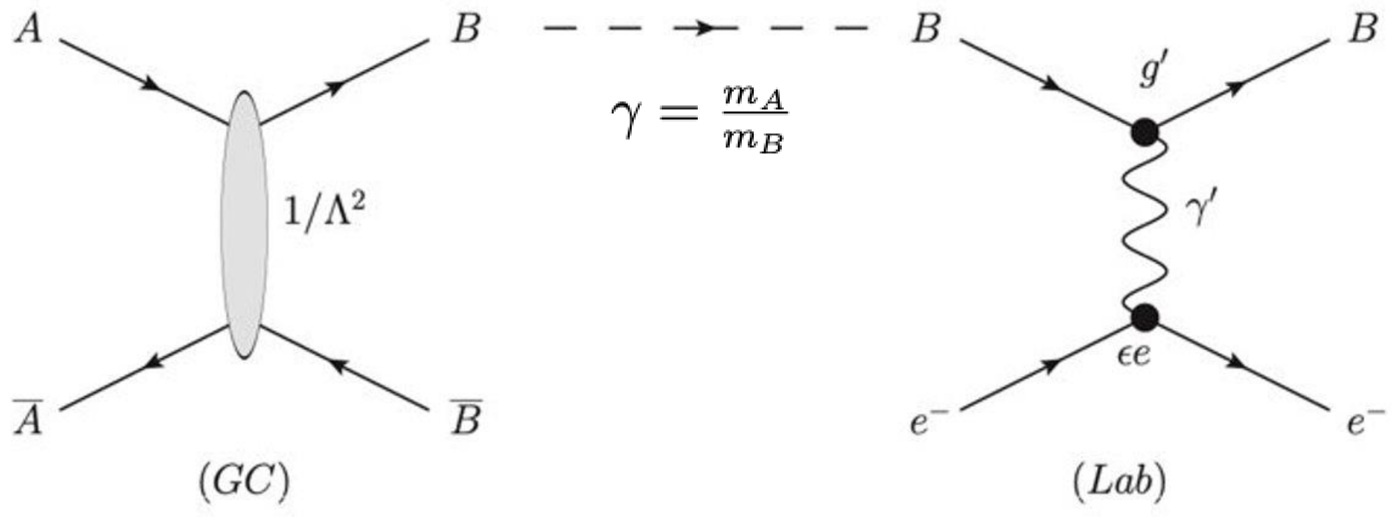
arXiv: 1912.05558v2 10/6/20

The Trouble With Dark Matter

- Present day DM is moving slow, 10^-3, which presents an issue for detectors.
- Neutrino experiments are not sensitive to the nuclear recoil of this kind of DM.
- However, many DM models exist.
  - Some predict that part of the DM may be moving at relativistic speeds after receiving a Lorentz boost.

Boosted Dark Matter (BDM)

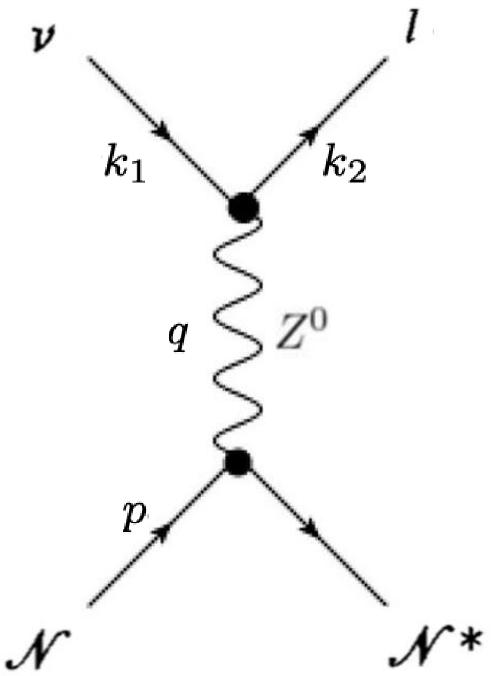
- Inclusive of many DM models and compatible with neutrino experiments.
- Example:
  - 2-species DM Fermions $\mathcal{L} = \frac{1}{\Lambda^2}\bar{\psi}_A\psi_B\bar{\psi}_B\psi_A$
    - Dominant species (No SM Coupling) $A\bar{A} \rightarrow B\bar{B}\ where, m_A > m_B$
    - Light sub-dominant boosted species (SM coupling) $\psi_B X \rightarrow \psi_B X'$



arXiv: 1405.7370v4 12/31/14

Neutrino Cross-Section

$$\nu + \mathcal{N} \rightarrow l + \mathcal{N}^*$$



- Production Amplitude from current-current formulation of weak interaction:

$$T(\nu\mathcal{N}^0 \rightarrow \ell\mathcal{N}^{*+}) = \frac{G_c}{\sqrt{2}}[\bar{u}_\ell\gamma^\beta(1-\gamma_5)\,u_\nu]\langle\mathcal{N}^{*+}|J^+_\beta(0)|\mathcal{N}^0\rangle$$

- The cross-section for Neutrinos:

$$\frac{d^2\sigma}{d\nu dq^2} = \frac{1}{32\pi m_{\mathcal{N}}E^2}\frac{G_c^2}{2}L^{\mu\nu}W_{\mu\nu}$$

$$L^{\mu\nu} = |\bar{u}_l\gamma^\mu[1-\gamma_5]u_\nu|^2$$
$$= 8(-g^{\mu\nu}(k_1\cdot k_2) + k_1^\nu k_2^\mu + k_1^\mu k_2^\nu + i\epsilon^{\mu\nu k_1 k_2})$$

$$W_{\mu\nu} = 2m_{\mathcal{N}}(-g_{\mu\nu}W_1 + p_\mu p_\nu\frac{W_2}{m_{\mathcal{N}}^2} - i\epsilon_{\mu\nu pq}\frac{W_3}{m_{\mathcal{N}}^2})$$

DIETER REIN AND LALIT M. SEHGAL "Neutrino-Excitation of Baryon Resonances and Single Pion Production"

ANNALS OF PHYSICS 133, 79-153 (1981)

F . RAVNDAL

"Weak Production of Nuclear Resonances in a Relativistic Quark Model"

Partial Cross-Section Structure: Neutrinos

- Contraction: $L^{\mu\nu}W_{\mu\nu}$
- Using conservation of the leptonic current: $e \cdot q = 0$
- There are three linearly independent solutions: The three polarization vectors of the intermediate vector boson.

$$\begin{cases} e_S^\mu = \sqrt{\frac{1}{-q^2}}(Q;\,0,\,0,\,\nu)\,, \\ e_R^\mu = \sqrt{\frac{1}{2}}(0;\,-1,\,-i,\,0)\,, \\ e_L^\mu = \sqrt{\frac{1}{2}}(0;\,+1,\,-i,\,0)\,, \end{cases}$$

$$\frac{d^2\sigma}{d\nu dq^2} = \frac{G_c^2}{4\pi^2}\frac{-q^2}{Q^2}K[u^2\sigma_L + v^2\sigma_R + 2uv\sigma_S]$$

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Helicity Amplitude Calculation: Neutrinos

$$W_{\mu\nu} = \frac{1}{2}\Sigma_{S_z} < \mathcal{N}|J_\mu^-|\mathcal{N}^* >< \mathcal{N}^*|J_\nu^+|\mathcal{N} > \delta(W^2 - M^2)$$

- Contributing current components: $J_\mu = 2MF_\mu$

$$\sigma_i = \frac{\pi}{K^*}\frac{1}{2}\Sigma_{S_z}| < \mathcal{N}|e_i^\mu F_\mu|\mathcal{N}^* > |^2\delta(W - M)$$

- The 3 Helicty Current Operators relate to the vector and axial-vector current operators:

$$2MF_\mu = V_\mu - A_\mu$$

Helicity Amplitudes

- "Current Matrix Elements from a Relativistic Quark Model" - Feynman, Kislinger, Ravndal (FKR)
  - V and A operators have been determined in this model and related to the Helicity Current Operators:

$$\begin{cases} F_0^V = +9\tau_a^+ S \exp[-\lambda a^z], \\ F_+^V = -9\tau_a^+[R^V\sigma_a^+ + T^V a^-]\exp[-\lambda a^z], \\ F_-^V = -9\tau_a^+[R^V\sigma_a^- + T^V a^+]\exp[-\lambda a^z], \end{cases}$$

$$\begin{cases} F_0^A = \left(\frac{-q^2}{Q^{*2}}\right) F_t^A + \frac{\nu^*}{Q^{*2}} D = -9\tau_a^+[C\sigma_a^z + B(\boldsymbol{\sigma}_a \cdot \boldsymbol{a})]\exp[-\lambda a^z], \\ F_+^A = +9\tau_a^+[R^A\sigma_a^+ + T^A a^-]\exp[-\lambda a^z], \\ F_-^A = -9\tau_a^+[R^A\sigma_a^- + T^A a^+]\exp[-\lambda a^z]. \end{cases}$$

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"Weak Production of Nuclear Resonances in a Relativistic Quark Model"

DOI:https://doi.org/10.1103/PhysRevD.3.2706

Helicity Amplitude Tables

- Calculated and tabulated results depend entirely on kinematic

Resonance (Multiplet)	Helicity ampl.	Electromagnetic P	Electromagnetic N	Weak CC N	Weak NC (Salam–Weinberg, $x = \sin^2\theta_w$) P	Weak NC (Salam–Weinberg, $x = \sin^2\theta_w$) N
$P_{33}(1234)$	f_{-3}	$-\sqrt{6}\,R$	$N = P$	$+\sqrt{6}\,R^-$	$-\sqrt{6}\,(R^- + 2xR)$	$N = P$
${}^4(10)_{3/2}[56, 0^+]_0$	f_{-1}	$-\sqrt{2}\,R$		$+\sqrt{2}\,R^-$	$-\sqrt{2}\,(R^- + 2xR)$	
	f_{+1}	$+\sqrt{2}\,R$		$-\sqrt{2}\,R^+$	$-\sqrt{2}\,(R^+ + 2xR)$	
	f_{+3}	$+\sqrt{6}\,R$		$-\sqrt{6}\,R^+$	$-\sqrt{6}\,(R^+ + 2xR)$	
	f_{0+}	0		$-2\sqrt{2}\,C$	$-2\sqrt{2}\,C$	
	f_{0-}	0		$-2\sqrt{2}\,C$	$-2\sqrt{2}\,C$	

$$f_{-3} = \langle \mathcal{N}, \tfrac{1}{2} \mid F_- \mid \mathcal{N}^*, \tfrac{3}{2} \rangle,$$
$$f_{-1} = \langle \mathcal{N}, -\tfrac{1}{2} \mid F_- \mid \mathcal{N}^*, \tfrac{1}{2} \rangle,$$
$$f_{+1} = \langle \mathcal{N}, \tfrac{1}{2} \mid F_+ \mid \mathcal{N}^*, -\tfrac{1}{2} \rangle,$$
$$f_{+3} = \langle \mathcal{N}, -\tfrac{1}{2} \mid F_+ \mid \mathcal{N}^*, -\tfrac{3}{2} \rangle,$$
$$f_{0\pm} = \langle \mathcal{N}, \pm\tfrac{1}{2} \mid F_0 \mid \mathcal{N}^*, \pm\tfrac{1}{2} \rangle,$$

$$\frac{d\sigma}{dq^2} = \frac{G_c^2}{4\pi}\left[2uv|f_0|^2 + \left(\frac{-q^2}{Q^{*2}}\right)\left(u^2|f_+|^2 + v^2|f_-|^2\right)\right]$$

DIETER REIN AND LALIT M. SEHGAL "Neutrino-Excitation of Baryon Resonances and Single Pion Production" ANNALS OF PHYSICS 133, 79-153 (1981)

F . RAVNDAL "Weak Production of Nuclear Resonances in a Relativistic Quark Model"

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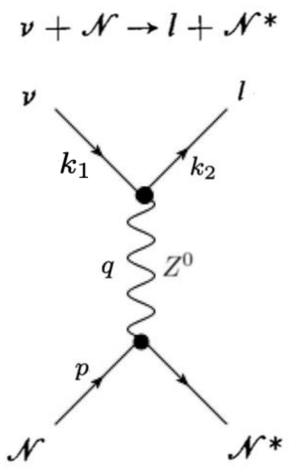
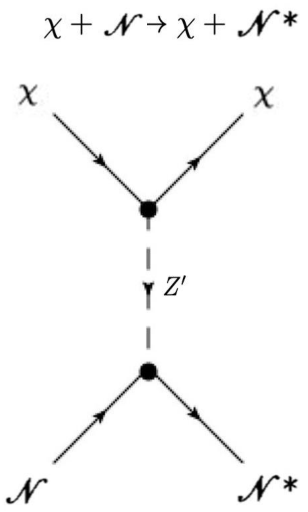
Boosted Dark Matter Scattering

- Similarity to Neutrino event generation:





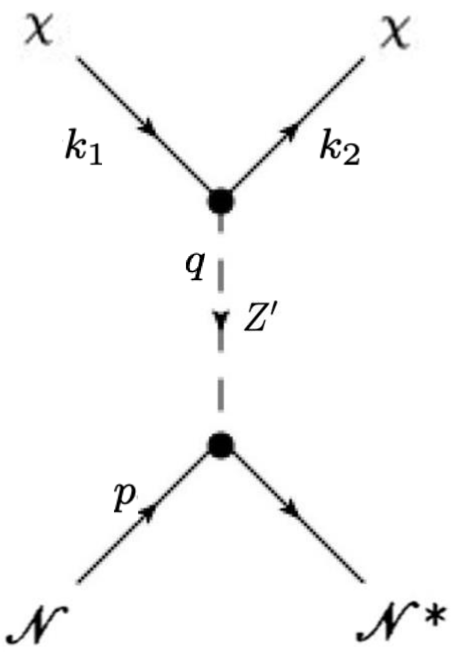
$$\mathcal{L}_{\chi,\text{int}} = g_{Z'}\, Z'_\mu \overline{\chi}\, \gamma^\mu \left(Q^\chi_L P_L + Q^\chi_R P_R\right) \chi$$

- Adjustments:
  - Massive fermionic DM
  - New Couplings

arXiv: 1812.05616v1 12/13/18

BDM Cross-Section

$$\chi + \mathcal{N} \rightarrow \chi + \mathcal{N}^*$$



The partial cross-section adjustment for BDM:

$$\frac{d^2\sigma}{d\nu dq^2} = \frac{1}{32\pi m_{\mathcal{N}}(E^2-m_\chi^2)} \frac{g_Z^4}{m_Z^4(m_Z^2+Q^2)^2} L^{\mu\nu}(m_Z^2 g_{\alpha\mu} - q_\alpha q_\mu)(m_Z^2 g_{\beta\nu} - q_\beta q_\nu) W_{\alpha\beta}$$

$$L^{\mu\nu} = \frac{1}{2}|\bar{u_\chi}\gamma^\mu[Q_V + \gamma_5 Q_A]u_\chi|^2$$
$$= 2(-g^{\mu\nu}((Q_A^2+Q_V^2)(k_1 \cdot k_2)+m_\chi^2(Q_A^2-Q_V^2))+(Q_A^2+Q_V^2)(k_1^\nu k_2^\mu+k_1^\mu k_2^\nu)-2iQ_A Q_V \epsilon^{\mu\nu k_1 k_2})$$

$$W_{\alpha\beta} = 2m_{\mathcal{N}}([-g_{\alpha\beta}W_1 + p_\alpha p_\beta \frac{W_2}{m_{\mathcal{N}}^2} - i\epsilon_{\alpha\beta pq}\frac{W_3}{m_{\mathcal{N}}^2}] + q_\alpha q_\beta \frac{W_4}{m_{\mathcal{N}}^2} + (p_\beta q_\alpha + p_\alpha q_\beta)\frac{W_5}{m_{\mathcal{N}}^2})$$

arXiv: 1812.05616v1 12/13/18

Resonance Production Amplitudes: BDM

- Contraction: $L^{\mu\nu}(m_Z^2 g_{\alpha\mu} - q_\alpha q_\mu)(m_Z^2 g_{\beta\nu} - q_\beta q_\nu)W_{\alpha\beta}$
- Leptonic current is not conserved: $e \cdot q \neq 0$ $\quad e_Z^\mu = \sqrt{\frac{1}{-q^2}}(-\nu; 0, 0, -Q)$

$$\frac{d^2\sigma}{d\nu dq^2} = \frac{g_Z^4}{(m_Z^2+Q^2)^2}\frac{K}{8\pi^2}[U^2\sigma_L + V^2\sigma_R + 2UV\sigma_S + (-\frac{(m_Z^2-q^2)^2}{m_Z^4})X\sigma_Z]$$

$$\sigma_Z(W,q^2) = \frac{\pi}{K^*}(\frac{1}{-q^2})\frac{1}{2}\Sigma_{S_Z}| < \mathcal{N}, S_Z|D|\mathcal{N}^*, S_Z > |^2\delta(W-M)$$

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Helicity Amplitudes: DM

- Relation to Helicity Amplitudes in FKR model: $D = \frac{q^\mu A_\mu}{2M}$

$$Z^{-1} q^\mu A_\mu = -9 G e_a e^{-\left(\frac{2}{\Omega}\right)^{\frac{1}{2}} q \cdot a^\dagger} \{(\vec{\sigma_a} \cdot \vec{Q^*})[\tfrac{2}{3} M + \tfrac{q^2}{2mg^2} - \tfrac{2}{3}\sqrt{\tfrac{\Omega}{2}} \tfrac{\vec{Q^*} \cdot (\vec{a} + \vec{a^\dagger})}{2mg^2} - \tfrac{2}{3}\sqrt{\tfrac{\Omega}{2}}(a_t + a_t^\dagger)] + \tfrac{2}{3}\sqrt{\tfrac{\Omega}{2}} \vec{\sigma_a} \cdot (\vec{a} + \vec{a^\dagger})(\nu^* + \tfrac{Q^{*2}}{2mg^2})\} e^{\left(\frac{2}{\Omega}\right)^{\frac{1}{2}} q \cdot a}$$

$$D = -9 \frac{ZG}{2M} e_a \{(\sigma_a^z Q^*)[\tfrac{2}{3} M + \tfrac{q^2}{2mg^2} - \tfrac{2}{3} \tfrac{\Omega}{2} \tfrac{NQ^*}{2mg^2}] + \tfrac{2}{3}\sqrt{\tfrac{\Omega}{2}} (\vec{\sigma_a} \cdot \vec{a})(\nu^* + \tfrac{Q^{*2}}{2mg^2})\} e^{-\left(\frac{2}{\Omega}\right)^{\frac{1}{2}} Q^* a_z}$$

$$D = -9 \tau_a^+ [C_D \sigma_a^z + B_D (\vec{\sigma_a} \cdot \vec{a})] e^{-\lambda a_z}$$

Conclusion

- BDM is a phenomenon which can manifest in multiple DM models
- LArTPC at DUNE has potential to search for BDM interactions
- By minimally adjusting kinematic factors for neutrino resonant scattering, we can explore the resonant scattering regime for BDM.
- What's next?: Incorporate this work in GENIE code

Thank You