A Sub-GeV DM model

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Based on: Dutta, Ghosh, Kumar, 1905.02692
• \( \nu \) sector of SM (SU(3) x SU(2) x U(1)) requires new physics for understanding the experimental results on masses and mixing angles.

\[
\text{tiny } \nu \text{ mass: } \frac{m_{\nu_D}^2}{m_{\text{Maj}}}
\]

• Similarly, DM explanation (with \( M_{DM} \) anywhere between 1 KeV to 100 TeV) requires new physics.

・The new physics: new mass scales and new couplings.

\[
\alpha_x = \frac{g_x^2}{4\pi}
\]

\[
\log \alpha_x \quad \log \sigma_{\nu}
\]

\[
Y = \text{DM abundance}
\]

\[
H = n\langle\sigma v\rangle, \quad \sigma \sim 1\,\text{pb}
\]

\[
Y_{\text{eq}}
\]

\[
\text{Mass of DM/Temp.}
\]
New physics: new symmetry breaking scale

Existence of new scales above or below the SM in many theories
Intermediate scale, GUT scale etc.

String theory: Many U(1) symmetry with the symmetry breaking scale can be anywhere

Cicoli, Goodsell, Jaeckel, Ringwald, 2011
Harnik, Kopp, Machado, 2012
Various light mediators scenarios proposed:

- Dark Matter scenarios based on hidden sectors:
  e.g., models of asymmetric DM,
  Sommerfeld enhancements motivated by SIMP,
  Decay of the observable sector DM into hidden sector

- g-2 of electron: 2.4 σ discrepancy (recent)

- Neutrino sector physics.
  New Neutrino interactions to satisfy MiniBooNE excess

- Solutions of Yukawa couplings hierarchies problem
Model for a sub GeV DM

E.g., there may be a new symmetry breaking scale around GeV
\( \Rightarrow 2^{nd} \) and \( 1^{st} \) generation fermion masses (~MeV to few GeV)

Anomaly free

<table>
<thead>
<tr>
<th>field</th>
<th>( q_{T3R} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q^u_R )</td>
<td>-2</td>
</tr>
<tr>
<td>( q^d_R )</td>
<td>2</td>
</tr>
<tr>
<td>( \ell_R )</td>
<td>2</td>
</tr>
<tr>
<td>( \nu_R )</td>
<td>-2</td>
</tr>
<tr>
<td>( \eta_L )</td>
<td>1</td>
</tr>
<tr>
<td>( \eta_R )</td>
<td>-1</td>
</tr>
<tr>
<td>( \phi )</td>
<td>-2</td>
</tr>
</tbody>
</table>

\( SU(2)_L \times U(1)_Y \times U(1)_{T3R} \)

\( U(1)_{T3R} \) is broken at 1-10 GeV down to \( Z_2 \)

Low mass dark matter, gauge Boson, scalar

Predictions are testable at various low energy experiments

Dutta, Ghosh, Kumar, 2019

Similar model for with 3\(^{rd}\) generation: Dutta, Kumar, 2011
Scalar $\phi$ vev $V=(-\mu_\phi^2/2\lambda_\phi)^{1/2}$ breaks $U(1)_{T3R}$ to $Z_2$, vev is around 1-10 GeV with $m_{\phi'}=2\lambda_\phi^{1/2}V$.

Larger Yukawa couplings for first two generations are possible

$$\mathcal{L}_{Yuk} = -\frac{\lambda_u}{\Lambda} \bar{\tilde{H}} \phi \tilde{Q}_L q^u_R - \frac{\lambda_d}{\Lambda} H \phi \bar{Q}_L q^d_R - \frac{\lambda_{\nu}}{\Lambda} \bar{\tilde{H}} \phi \tilde{L}_L \nu_R - \frac{\lambda_{l}}{\Lambda} H \phi \bar{L}_L \ell_R$$

$$- \lambda \phi \bar{\eta}_R \eta_L - \frac{1}{2} \lambda_L \phi \bar{\eta}^c_L \eta_L - \frac{1}{2} \lambda_R \phi^* \bar{\eta}^c_R \eta_R - \mu_\phi^2 \phi^* \phi - \lambda_\phi (\phi^* \phi)^2 + H.c.,$$

Vector-like quarks with mass 1 TeV or higher can generate this Lagrangian

Dark Matter (parity odd): $\eta_{1,2}$
\[ \mathcal{L}_{\text{gauge}} = \frac{i}{4} g_{T3R} A'_{\mu} (\eta_1 \gamma^\mu \eta_2 - \bar{\eta}_2 \gamma^\mu \eta_1) + \frac{m_{A'}^2}{V} \phi' A'_{\mu} A'^{\mu} + i g_{T3R} A'_{\mu} (\phi' \partial^\mu \phi' - \phi' \partial^\mu \phi) - \frac{1}{2} g_{T3R} j_{A'}^{\mu} A'_{\mu}, \]

\[ j_{A'}^{\mu} = \sum_{f} Q_{T3R}^f \bar{f} \gamma^\mu f. \]

\[ m_{A'}^2 = 2 g_{T3R}^2 V \]

\[ i \Pi_2^{A' A'} (k^2) = A'_{\mu} \]

\[ i \Pi_2^{A' Z} (k^2) = A'_{\mu} \]
\( \phi' : \phi' \rightarrow \bar{\nu}_L \nu_s \nu_A, \pi \pi, A' A' : \) dominate, if kinematically allowed. Otherwise, \( \phi' \rightarrow \gamma \gamma \) (one loop diagram) dominates

\( A' : A' \rightarrow \bar{\nu}_L \nu_s, \pi \pi, \phi' \phi' : \) dominate, if kinematically allowed. Otherwise, \( A' \rightarrow \nu_L \nu_L \) (one loop diagram) dominates

\( \nu_s : \nu_s \rightarrow \nu_A \gamma \gamma : \) mediated by an offshell \( \phi' \) dominate
Parameter Space

Various scenarios: Gauge boson ($A'$)-scalar ($\phi'$) mediators parameter space

- **Muon model**: $u_R, d_R, \nu_R, \mu_R$

- **Electron model**: $u_R, d_R, \nu_R, e_R$

- **Similarly, models with second generation quarks**
Various ways of probing Sub-GeV DM:

**Cosmic ray scattered**

Low mass DM (up to 10 GeV) becomes energetic → detection becomes easier
Production of DM(χ₁) at COHERENT

Deniverville, Pospelov, Ritz,'15

There is also another process: Charge exchange

- $\pi^- + p \to n + A', \ A' \to \chi\chi$

$\pi^0 \to \gamma + A'$  \[\text{JSNS}^2\ TDR\]

**Probe Dark Photon (A') decay into DM utilizing: timing measurements**

- DM mass needs to be less than 70 MeV

Dutta, Kim, Liao, Park, Shin, Strigari: 1906.10745
direct detection

Constraints from CRESST, Xenon1T (cosmic ray scattered, Dent Dutta, Newstead, Shoemaker, 2019)

Inelastic scattering:
\[ \mathcal{A} \mathcal{A}' \, m_{\mathcal{A}} \, \alpha \beta \mathcal{Q} \mathcal{Q} \mathcal{R} \]

Elastic scattering:
\[ \bar{\eta} \eta \bar{q}_L \eta q_R \]

\[ m_{\phi'} = 200 \text{ MeV}, \quad V = 10 \text{ GeV} \]

\[ m_\eta (\text{GeV}) \]

\[ \sigma_{\text{SI}} \text{ scalar} (p,n) = \frac{\mu_\eta^2 m_\eta^2}{\pi V^4 m_{\phi'}^4} f_{p,n} \]

\[ \sigma_{\text{SI}} \text{ vector} (p,n) = \frac{\mu_\eta^2}{16\pi V^4} \]

\[ m_\eta (\text{GeV}) \]

\[ \sigma_{\text{SI}} \text{ scalar} (cm^2) \]

\[ \sigma_{\text{SI}} \text{ vector} (cm^2) \]
The allowed cross-section $\leq 10^{-40} \text{ cm}^2$

*Ema, Sala, Sato, 2018*

*Xenon 1T, 1906.04717*
direct detection

Dark Matter-nucleon

Dark Matter-electron
Thermal Relic Abundance

Dominant two body final states:

\[ \ell \ell, \bar{\nu} \nu, \pi \pi, \pi^0(\phi', A', \gamma) \]

\[ + \]

\[ A'A', \phi'\phi' \text{ and } \phi'A' \]

\[ + \ldots \]

\textbf{P-wave}

\textbf{S-wave}

Resonance/non-resonance:

<table>
<thead>
<tr>
<th>Case</th>
<th>( m_{A'} ) (MeV)</th>
<th>( m_{\phi'} ) (MeV)</th>
<th>( m_\eta ) (MeV)</th>
<th>( m_{\nu_s} ) (MeV)</th>
<th>( m_{\nu_D} ) (MeV)</th>
<th>( \langle \sigma v \rangle ) (cm(^3)/sec)</th>
<th>( \sigma_{SI}^{scalar} ) (pb)</th>
<th>( \sigma_{SI}^{vector} ) (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon case</td>
<td>55</td>
<td>200</td>
<td>100</td>
<td>10</td>
<td>( 10^{-3} )</td>
<td>( 3 \times 10^{-26} )</td>
<td>2.05</td>
<td>6.50</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>( 10^4 )</td>
<td>50</td>
<td>( 10^{16} )</td>
<td>( 10^4 )</td>
<td>( 3 \times 10^{-26} )</td>
<td>3.29 ( \times 10^{-7} )</td>
<td>1.80</td>
</tr>
<tr>
<td>Electron case</td>
<td>( 5 \times 10^{-6} )</td>
<td>200</td>
<td>100</td>
<td>10</td>
<td>( 10^{-3} )</td>
<td>( 3 \times 10^{-26} )</td>
<td>2.05</td>
<td>6.50</td>
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Outlook

• What is the scale of new physics?

• Models with light mediators are very interesting: Dark Matter, g-2 of electron, neutrino masses, Yukawa coupling hierarchy, MiniBooNE excess

• We constructed a model, where DM mass \( \sim 100 \) MeV, two light mediators: scalar and gauge boson

• The model has sufficient allowed parameter space after satisfying various experimental constraints

• DM relic abundance can occur thermally