Going Beyond the SM

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Snowmass’22 Community Summer Study, Seattle (July 19th, 2022)
Why BSM?

**Experimental evidence:**
- Dark matter
- Neutrino masses
- Matter-antimatter asymmetry
- Gravitational interaction

**Theoretical indications:**
- Strong CP problem
- Hierarchy problem
- Flavor puzzle
- Cosmological constant
ok, so...where is it??
ok, so...where is it??

Visible sector \[?\] Hidden sector
Why neutrino experiments?

- Powerful beam
- Near detectors (ND) available
- Large underground far detector (FD)
  - new physics in neutrino oscillations
  - new particles produced in the beam
  - new particles produced in the atmosphere
Why DUNE?

- The DUNE design has specific advantages:
  - High luminosity
  - Long baseline (matter effects)
  - High neutrino energy
    - D-mesons and $\tau$ at the target
    - $\nu_{\tau}$ detection?
  - FD/ND: LAr TPC offers great PID, energy and angular resolution
  - Other near detectors or configurations:
    - DUNE Prism! Gas TPC!
This talk

- What can we search for at DUNE?
  - New fermions
  - New vector bosons
  - New (pseudo)scalars

→ Apologies if your favorite model is not included

→ For DUNE prospects, see talks by A. Sousa and J. Yu
(I) New fermions

→ Heavy neutral leptons, sterile neutrinos, right-handed neutrinos, neutrino portal, ...
Sterile neutrino searches

eV  keV  MeV  GeV  TeV  GUT
Sterile neutrino searches

- eV
- keV
- MeV
- GeV
- TeV
- GUT

- Warm dark matter
- Oscillations
- Beta decay
- Colliders
- Leptogenesis
- Tau and meson decays
- Neutrinoless double beta decay
- Charged lepton flavor violation
eV-scale sterile neutrinos

A sterile may leave multiple imprints through oscillations:

- Anomalous appearance
- $\nu_e$ disappearance
- $\nu_\mu$ disappearance
- NC measurements

Both ND and FD could be used for this:

- sensitive to different ranges in mass-squared splitting
- solar neutrinos also provide useful input → See Goldhagen et al, 2109.14898

All of them available at DUNE!

\[
\sin^2 2\theta_{ee} = 4(1 - |U_{e4}|^2)|U_{e4}|^2; \\
\sin^2 2\theta_{\mu\mu} = 4(1 - |U_{\mu4}|^2)|U_{\mu4}|^2; \\
\sin^2 2\theta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2.
\]
Heavier steriles and Non-Unitarity

- Heavier steriles can still be produced, but oscillations will be averaged out; at ND, zero-distance effect.

- General (model-independent) parametrization:

\[
N = (I - T)U
\]

\[
T = \begin{pmatrix}
\alpha_{ee} & 0 & 0 \\
\alpha_{\mu e} & \alpha_{\mu \mu} & 0 \\
\alpha_{\tau e} & \alpha_{\tau \mu} & \alpha_{\tau \tau}
\end{pmatrix}
\]

Escrihuela, Forero, Miranda, Tortola 2015
Heavier steriles and Non-Unitarity

<table>
<thead>
<tr>
<th></th>
<th>“flavor+electroweak” $m &gt; EW$ (2σ limit)</th>
<th>“Averaged-out oscillations” $\Delta m^2 \gtrsim 0.1$ eV$^2$ (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_{ee}$</td>
<td>$1.3 \cdot 10^{-3}$ [36]</td>
<td>$8.4 \cdot 10^{-3}$ [55]</td>
</tr>
<tr>
<td>$\alpha_{\mu\mu}$</td>
<td>$2.2 \cdot 10^{-4}$ [36]</td>
<td>$5.0 \cdot 10^{-3}$ [15]</td>
</tr>
<tr>
<td>$\alpha_{\tau\tau}$</td>
<td>$2.8 \cdot 10^{-3}$ [36]</td>
<td>$6.5 \cdot 10^{-2}$ [56]</td>
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<tr>
<td>$</td>
<td>\alpha_{\mu\tau}</td>
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<td>$</td>
<td>\alpha_{\tau e}</td>
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<td>$</td>
<td>\alpha_{\tau\mu}</td>
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</tr>
</tbody>
</table>

Snowmass’21 White Paper “BSM effects on Neutrino Flavor”, 2203.10811
(see also Blennow et al, 1609.08637)

→ Interesting possibility: use the DUNE ND to test for anomalous tau neutrino appearance?
Heavier steriles and Non-Unitarity

Coloma, Lopez-Pavon, Rosauro-Alcaraz, Urrea, 2105.11466
(see also Miranda, Pasquini, Tortola, Valle, 1802.02133)
Heavy Neutral Leptons

- Minimal scenario: production and decay through mixing

Figure from Snowmass’21 WP “Dark sector searches with neutrino beams”, 2207.06898

See e.g., Krasnov, 1902.06099; Ballett et al, 1905.00284; Berryman et al, 1912.07622; Coloma et al, 2007.03701; Breitbach et al, 2102.03383; ...
Heavy Neutral Leptons

- Minimal scenario: production and decay through mixing

Caputo, Hernandez, Lopez-Pavon, Salvado, 1704.08721
Heavy Neutral Leptons

- Minimal scenario: production and decay through mixing

\[ \delta = -\pi/2 \]
\[ s_{23}^2 = 0.42, 0.58 \]

Drewes, Klaric, Lopez-Pavon, 2207.02742
Heavy Neutral Leptons

- Minimal scenario: production and decay through mixing
- Non-minimal extensions could lead to new signatures @ FD:

See e.g. Batell et al, 1604.06099; Magill et al, 1803.03262; Atkinson et al, 2105.09357; Schwetz et al, 2203.02309; ...

Figure from Snowmass’21 WP “Dark sector searches with neutrino beams”, 2207.06898
(II) New vector bosons

→ Vector portal to DM, dark photons, flavored $Z'$, ...
Light flavored $Z'$

\[
\mathcal{L}_{Z'} \supset \sum_f g_{Z'} Q'_f Z'_\mu \bar{f} \gamma^\mu f + \frac{1}{2} M_{Z'}^2 Z'_\mu Z'_\mu
\]

Anomaly free within SM particle content: Foot '91; He, Joshi, Lew, Volkas, '91; Foot, He, Lew, Volkas, hep-ph/9401250

\[\mathcal{G} = G_{SM} \times U(1){L_\alpha - L_\beta}\]

See eg, Ma, Roy, Roy, hep-ph/0110146; Baek, Deshpande, He, Ko, hep-ph/0104141; Heeck, Rodejohann, 1107.5238; Choubey, Rodejohann, hep-ph/0411190

Fig from Greljo, Stangl, Thomsen, Zupan, 2203.13731
Light flavored $Z'$: present bounds

Coloma, Gonzalez-Garcia and Maltoni, 2009.14220
**Light flavored Z’**

\[ \mathcal{L}_{Z'} \supset \sum_f g_{Z'} Q'_f Z'_\mu \bar{f} \gamma'^{\mu} f + \frac{1}{2} M_{Z'}^2 Z'_\mu Z'_\mu \]

**NSI, long-range forces**

**Tridents**

**ν-e scattering**

**Decays**

NSI: many references!
LRF: Chatterjee et al, 1509.03517

Altmannshofer et al, 1902.06765; Ballett et al, 1902.08579

Ballett et al, 1902.08579; Chakraborty et al, 2111.08767

Berryman et al, 1912.07622; Capozzi et al, 2108.03262

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Vector portal

\[ \mathcal{L} \supset -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} M_V^2 V_\mu V^\mu + \frac{\varepsilon}{2} V_{\mu\nu} F^{\mu\nu} + \]

Vector coupling to dark sector:

- Scalar/vector DM
- Pseudo-Dirac fermions (iDM)
- Subset of states (BDM)
Vector portal

\[ \mathcal{L} \supset -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} M_V^2 V_\mu V^\mu + \frac{\epsilon}{2} V_{\mu\nu} F^{\mu\nu} + \]

{Scalar/vector DM pseudo-Dirac fermions (iDM)
Subset of states (BDM)}
Vector portal

- **MiniBooNE: clear example of prior success**
  Batell, Pospelov, Ritz, 0906.5614; deNiverville, Pospelov, Ritz,1107.4580; deNiverville, McKeen, Ritz, 1205.3499, ...

- **Careful with backgrounds:**
  - go off-axis  Coloma, Dobrescu, Frugiuele, Harnik, 1512.03852
  - beam-dump  Bhattarai, Brdar, Dutta, et al, 2206.06380
  - use electron scattering  de Romeri, Kelly, Machado, 1903.10505
Vector portal

Scalar DM;
e⁻ scattering on LArTPC

\( \alpha_D = 0.1, \; M_\phi = 20 \text{ MeV} \)

(de Romeri, Kelly, Machado, 1903.10505
(see also e.g. Coloma et al, 1512.03852; Breitbach et al, 2102.05383, Berryman et al, 1912.07622)
(III) New (pseudo)scalars

→ axions, axion-like particles, dark pions, dark Higgs, ...
Light (pseudo)scalars

• Is the Higgs the only fundamental scalar?

• Light scalars arise as pseudo-Nambu Goldstone bosons in BSM models with global symmetry breaking
  - The axion solves the strong CP problem and provides a viable DM candidate
  - However, it is not the only possibility → ALPs
**ALPs**

\[ \mathcal{L} \supset -\frac{1}{4} g_{a\gamma a} F_{\mu\nu} \tilde{F}^{\mu\nu} \]

ALPs

\[ \mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \]

\[ g_{ae} \partial_\mu a \bar{e} \gamma^\mu \gamma^5 e \]

\[ e^- N \rightarrow e^- a \ N \]
\[ e^- e^+ \rightarrow \gamma a \]

\[ a \rightarrow e^+ e^- \]

ALPs

\[ \mathcal{L} \supset -\frac{1}{4} g_a \gamma a F_{\mu \nu} \tilde{F}^{\mu \nu} \]

\[ g_a e \partial_\mu a \bar{\epsilon} \gamma^\mu \gamma^5 e \]

\[ \frac{a}{8\pi f_a} \left( c_3 \alpha_3 G_G + c_2 \alpha_2 WW + c_1 \alpha_1 B \tilde{B} \right) \]

\[ \begin{align*}
\gamma e^- & \to e^- a \\
e^- N & \to e^- a N \\
e^- e^+ & \to \gamma a 
\end{align*} \]

\[ a \to e^+ e^- \]

\[ a \to \gamma \gamma \\
a \to \pi \pi \pi, \pi \pi \gamma, \ldots \]

ALPs

→ See Salvador Urrea’s talk on Saturday!
Summary

- We have good reasons to believe that BSM physics is out there.
- A new Era of precision neutrino experiments is well positioned to search for deviations from the standard picture.
- DUNE offers an appealing design, with key features that define it as a BSM facility.
Thanks!
Backup
Heavier steriles and Non-Unitarity

Averaged-out oscillations

Fig from Bolton, Deppisch, Dev, 1912.03058
www.sterile-neutrino.org
Solar neutrinos

Goldhagen, Maltoni, Reichard, Schwetz, 2109.14898
(solar analysis as in Esteban et al, 2007.14792)
eV-scale sterile neutrinos @ ND

Great potential, but we have to be careful with systematics:

\[
\sin^2(\vartheta_{24}) = |U_{\mu 4}|^2
\]

Coloma, Lopez-Pavon, Rosauro-Alcaraz, Urrea, 2105.11466
eV-scale sterile neutrinos @ ND

DUNE offers the possibility to combine multiple samples in the same experiment:

Coloma, Lopez-Pavon, Rosauro-Alcaraz, Urrea, 2105.11466