Leptophilic Dark Portals

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Voyage into the dark sector

(from *Symmetry* Magazine)
Portals to the Dark Sector

This report summarizes the scientific importance of and motivations for searches for dark-sector particles below the EW scale, the current status and recent progress made in these endeavors, the landscape and major milestones motivating future exploration, and the most promising and exciting opportunities to reach these milestones over the next decade. We summarize the different experimental approaches and we discuss proposed experiments and their accelerator facilities. In addition, as part of the Snowmass process, we defined three primary research areas, each with associated ambitious—but achievable—goals for the next decade. This categorization is motivated, in part, by how we search for DM in different scenarios. When DM is light, portals to the dark sector allow its production and detection at accelerators (e.g., in mediator decay if the DM is lighter than half of the mediator mass, or coupled through an o-shell mediator). In fact, accelerators can probe DM interaction strengths motivated by thermal freeze-out explanations for the cosmological abundance of DM. If DM is heavier, the mediator decays into visible SM particles. In addition to thermal DM models, visible mediators also arise in theories that address various open problems in particle physics (e.g., the strong-CP problem, neutrino masses, and the hierarchy problem). A third scenario is where the dark sector is richer, which can lead to decays of the mediator to both DM and SM particles, or to other final states not considered in the standard minimal benchmark models. Each of these research areas is discussed in detail in this report.

Theoretical Framework

The leading possible interactions between ordinary and dark-sector particles, classified below, are known as portals. The strength of portal interactions can be naturally suppressed by symmetry reasons, and can arise only at higher orders in perturbation theory. Figure 1 shows a schematic representation of the dark-sector paradigm. This simple scenario where dark-sector particles only couple indirectly to ordinary matter naturally leads to feeble interactions, and opens the door to the possibility that BSM physics may exist below the EW scale. In fact, the mass of dark-sector particles might be naturally light if protected by some symmetry (this is the case, e.g., for ALPs). In addition, the inherently feeble interactions of dark-sector matter with ordinary matter provides a natural thermal-production origin for DM for the case where DM is light, extending the well-known WIMP miracle to lower mass scales. Due to the Lee-Weinberg bound, light mediators are generically needed if DM is at or below the GeV scale. Therefore, testing the dark-sector hypothesis requires innovative high-intensity experiments, not necessarily high energies.

The landscape of potentially viable dark sectors is broad with many regions largely untested experimentally and unexplored theoretically. Even so, the physics of dark sectors can be systematically studied using the few allowed portal interactions as a guide. The gauge and Lorentz symmetries of the SM greatly restrict how

[Snowmass reports: 2207.06898, 2207.06905, 2209.04671]
Portals to the Dark Sector

In this talk,

- **Leptophilic** Higgs and vector portals.
- Possibility of interesting LFV signals.
- Complementarity between low and high-energy LFV searches.
- Connection to neutrino mass, gravitational waves, and more.

[Snowmass reports: 2207.06898, 2207.06905, 2209.04671]
LFV is guaranteed!

- LFV is forbidden in the SM due to an accidental global symmetry: $U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$.
- Observed neutrino oscillations already imply LFV.
- But we haven’t seen LFV in the charged lepton sector.

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- Negligible in the SM(+neutrino mass) [Petcov ’76]:

\[
\ell^- \beta \rightarrow \ell^- \alpha \gamma : \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\beta i} U_{\alpha i} \frac{m^2_{\nu_i}}{m^2_W} \right|^2 \lesssim \mathcal{O}(10^{-54})
\]

- Opportunity for probing new physics: $m^2_\nu/m^2_W \rightarrow m^2_F/\Lambda^2$.
- Could be enhanced by orders of magnitude over the SM.
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Low-energy experiments are doing a great job.

High-energy colliders provide a powerful complementary probe of LFV (e.g. via exotic decays of Higgs, Z and top).

see talk by W. Altmannshofer
LFV decays of $h(125) \rightarrow \mu^\pm \tau^\mp$

[Barman, BD, Thapa 2210.16287 (PRD '23)]

see also [Harnik, Kopp, Zupan 1209.1397; Davidson, Verdier 1211.1248; Altmannshofer, Caillol, Dam, Xella, Zhang 2205.10576]
BSM Higgs $H \rightarrow \mu^{\pm} \tau^{\mp}$

Type-I: $m_H = 400$ GeV, $\tan \beta = 6.0$, $\cos(\beta - \alpha) = 0.1$

$|Y_{\mu\tau}|$

$|Y_{\tau\mu}|$

$\tau \rightarrow 3\mu$ @ Belle II

$\tau \rightarrow 3\mu$ @ Belle II

$\text{HL-LHC}$

$\text{PSI}\mu\text{SR}$

$\text{LH-}$

$(g - 2)_\mu$ (2σ)

$(g - 2)_\mu$ (1σ)

[Barman, BD, Thapa 2210.16287 (PRD '23)]
Leptophilic Higgs@LHC?

3.8σ (2.8σ) local (global) excess 😊

\[ \sigma(pp \to H(146) \to e\mu)_{\text{CMS}} = 3.89^{+1.25}_{-1.13} \text{ fb} \]

**Hint of LFV?** [2305.18106]
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**Hint of LFV?** [2305.18106]

**ATLAS**

\[ t\bar{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1} \]

Data

- Background model
- Signal \( B(H \rightarrow e\mu) = 0.05\% \)

\[ \text{Data - fit} \]

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

0

100

200

300

400

500

600

700

Entries / GeV

-1

no excess 😞

\[ \sigma(pp \rightarrow H(146) \rightarrow e\mu)_{ATLAS} \lesssim 3 \text{ fb} \]

(ballpark estimate only, not conclusive)

[1909.10235 and EW Moriond ’23 talk by K. Leney]
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- **If survives, simplest explanation:** Leptophilic (pseudo)scalar resonance, e.g. in a leptophilic 2HDM.
- **Use lepton PDF of the proton.** [Bertone, Carrazza, Pagani, Zaro (JHEP ’15); Buonocore, Nason, Tramontano, Zanderighi (JHEP ’20, ’21)]

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**CMS**

138 fb$^{-1}$ (13 TeV)

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Explaining the CMS $e\mu$ excess in a leptophilic 2HDM

$m_{H/A}=146$ GeV

$\sigma(pp\rightarrow H/A\rightarrow e\mu)$ [fb]

$|Y_{e\mu}|$

[Afik, BD, Thapa, 2305.19314]
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$m_{H/A} = 146$ GeV

$\sigma(pp \rightarrow e\mu)$

approx. ATLAS excl.

CMS-excess (1σ)
CMS-excess (2σ)

$|Y_{e\mu}|$

$\sigma(pp \rightarrow H/A \rightarrow e\mu)$ [fb]

$|Y_{e\mu}| = 146$ GeV

[Afik, BD, Thapa, 2305.19314]
How about muon $g - 2$?

$m_{H/A} = 146$ GeV

$\sigma(pp \rightarrow e\mu)$

approx. ATLAS excl.

$|Y_{e\mu}|$

CMS-excess (1σ)
CMS-excess (2σ)
$(g-2)_\mu^{WP}$ (1σ)

$\sigma(pp \rightarrow e\mu)$ [fb]

$0.01$
$0.10$
$1$
$10$
$100$

$|Y_{e\mu}|$

$0.5$
$1.0$
$1.5$
$2.0$

$|Y_{e\mu}|$

$0.01$
$0.10$
$1$
$10$
$100$

$\sigma(pp \rightarrow H/A \rightarrow e\mu)$

[mH/A=146 GeV]

[Afik, BD, Thapa, 2305.19314]
BMW fits better than WP

$m_{H/A} = 146$ GeV

$\sigma(pp \rightarrow e\mu)$

approx. ATLAS excl.

$|Y_{e\mu}|$

$\sigma(pp \rightarrow H/A \rightarrow e\mu)$ [fb]

CMS-excess (1σ)

CMS-excess (2σ)

$(g-2)_{\mu}^{WP}$ (1σ)

$(g-2)_{\mu}^{BMW}$ (1σ)

[Afik, BD, Thapa, 2305.19314]
LEP dimuon constraint

$m_{H/A} = 146$ GeV

$\sigma(pp \rightarrow e\mu)$

approx. ATLAS excl.

ATLAS excl.

CMS-excess (1σ)

CMS-excess (2σ)

$(g-2)_\mu^{WP}$ (1σ)

$(g-2)_\mu^{BMW}$ (1σ)

$|Y_{e\mu}|$

[Afik, BD, Thapa, 2305.19314]
Muonium-antimuonium oscillation is the killer

$m_{H/A} = 146$ GeV

![Graph showing various measurements and limits, including CMS, ATLAS, MACS, and LEP exclusions.](Afik BD Thapa, 2305.19314)
Can be evaded for a degenerate scalar spectrum

\( m_H \approx m_A = 146 \text{ GeV} \)

- CMS excess (1σ)
- CMS excess (2σ)
- \((g-2)_\mu\) WP (1σ)
- \((g-2)_\mu\) BMW (1σ)
- \(\sigma(pp \rightarrow e\mu)\)
- approx. ATLAS excl.
- MACS excl.
- \(\sigma(pp \rightarrow H/A \rightarrow e\mu) \approx \text{fb}\)
- Not applicable for \(m_H \approx m_A\)
- LEP excl.

[Afik, BD, Thapa, 2305.19314]
LFV in the Higgs sector, but no cLFV at tree level

\( m_H \approx m_A = 146 \text{ GeV} \)

[Afik, BD, Thapa, 2305.19314]
Future lepton collider prospects of leptophilic Higgs

Zee model

\[ Y_{e\mu} \]

\[ m_H \text{ [GeV]} \]

\[ \sigma(\mu^+e^- \rightarrow \mu^-e^+) \]

\[ \sigma(\mu^+e^- \rightarrow H\gamma) \]

\[ \sigma(\mu^+e^- \rightarrow HZ) \]

\[ \sigma(\mu^+\mu^+ \rightarrow e^+e^+) \]

\[ (g-2)_\mu \text{ excluded} \]

\[ \tau \rightarrow e^-\mu^+ (B_4) \]

\[ \tau \rightarrow e^-\mu^+ (A_1) \]

\[ \tau \rightarrow \mu^-\mu^+ (B_3) \]

[BD, Heeck, Thapa, 2309.06463]

\[ \mu \text{TRISTAN} \] [Hamada, Kitano, Matsudo, Takaara, Yoshida 2201.06664; ]
LFV $Z'$ in $U(1)_{L_{\alpha}-L_{\beta}}$: Current constraints

$$\mathcal{L} \supset g' Z'_\mu (\bar{L}_\alpha \gamma^\mu L_{\alpha} + \bar{e}_{R,\alpha} \gamma^\mu e_{R,\alpha} - \bar{L}_{\beta} \gamma^\mu L_{\beta} - \bar{e}_{R,\beta} \gamma^\mu e_{R,\beta}).$$
$\mathcal{L} \supset g' Z'_\mu (\bar{L}_\alpha \gamma^\mu L_\alpha + \bar{e}_{R,\alpha} \gamma^\mu e_{R,\alpha} - \bar{L}_\beta \gamma^\mu L_\beta - \bar{e}_{R,\beta} \gamma^\mu e_{R,\beta})$. 

Dasgupta, BD, Han, Padhan, Wang, Xie, 2308.12804 (JHEP '23)
Gravitational wave signal

First-order phase transition if scalar sector is conformally invariant:

\[ V_{\text{tree}} = \lambda_H (H^\dagger H)^2 + \lambda (\Phi^\dagger \Phi)^2 - \lambda' (\Phi^\dagger \Phi)(H^\dagger H). \]
Conclusions

- LFV is a ‘smoking gun’ signal of BSM physics.

- High-energy colliders provide a powerful probe of LFV (from heavy BSM physics), complementary to the low-energy cLFV searches.

- We covered the possibility of LFV originating from the Higgs and vector portal scenarios.
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- High-energy colliders provide a powerful probe of LFV (from heavy BSM physics), complementary to the low-energy cLFV searches.

- We covered the possibility of LFV originating from the Higgs and vector portal scenarios.

- The recent CMS $e\mu$ excess is an intriguing hint of LFV. [Update at Moriond ’24?]

- A flavorful way to BSM physics?