Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

INSERT TITLE HERE

Antonio Boveia[1], Caterina Doglioni[2, 3], and Liantao Wang[4]

[1]The Ohio State University
[2]University of Manchester
[3]Lund University
[4]University of Chicago

Abstract

Abstract.

1 Introduction and executive summary

This topical group focuses on Dark Matter and Dark Sector searches at high energy colliders. We will also address the complementarity between the collider searches and other probes of dark matter.

2 How can we best test the WIMP paradigm?

2.1 Testing the simplest/minimal WIMP models (EW multiplets) and their extensions

Simplest/minimal WIMP models. This is the case in which dark matter is part of a electroweak multiplet. Extension of the minimal scenario can include nearby states and more coannihilation channels. It is very predictive, and the thermal relic abundance typically requires the dark matter particle to be up to the TeV range. The LHC will explore the hundreds of GeV range. To fully explore this scenario, a 100 TeV proton proton collider or a high energy lepton collider would be necessary. This is a clear physics argument for the parameters of the future colliders.

The main results to be summarized in this section.

1. Minimal DM and thermal targets [a table].
2. With doublet (Higgsino) and triplet (wino) as examples, summary plot including the following reaches
   (a) Reach at HL-LHC, CLIC, ILC, FCC-hh/SppC. This is basically taken from the briefing book [1] [need more references].
   (b) Reaches at muon collider, including results from new studies [2–7]

2.2 Testing the Higgs portal

Higgs portal. This scenario take advantage of the unique property of the Higgs boson to form the most relevant portal operator between the SM and the dark sector. It also offers a connection between dark matter and the weak scale. At the same time, the models in this scenario are not limited to WIMPs. There are many connections surrounding this scenario with EF02 and EF09. Precision measurement such as Higgs coupling and Higgs decay both at the LHC and future colliders can offers interesting probes in this scenario.

The results summarized here

1. Higgs invisible decay and DM reach. [8]
2. Singlet extension with flavorful coupling. [9–12]. [perhaps check with Homiller again for contribution]

2.3 Testing simple mediator models (s-channels/t-channels)

Content of section and whitepapers included (as references):

Most of the text will be summarized/come from this whitepaper in preparation, main reference for this section: `https://www.overleaf.com/read/zjjwrpqxncnw`

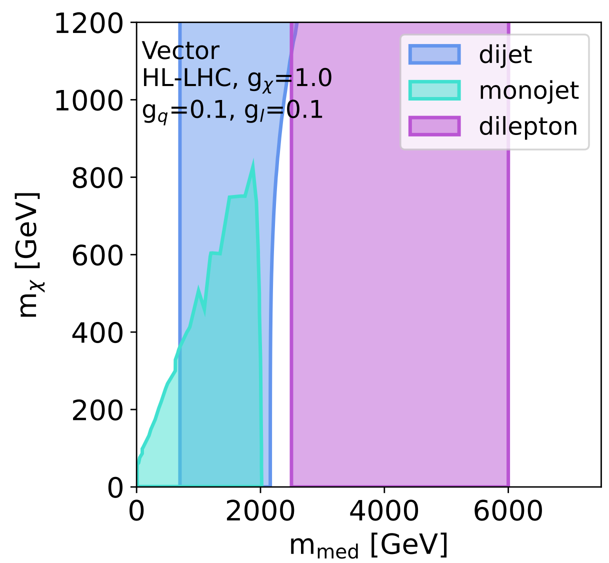
- Motivations for simplified models at the LHC
- Brief description of models with simple mediators (includes $s-$and $t-$channel models, introduce $t-$channel for connection to dark showers). Also mention similar submitted models from [13, 14].
- Status at the time of the European Strategy (models with fixed couplings)
- Updates from the European Strategy: varying model couplings analytically [15]
- Collider complementarity between DM (MET) search and mediator searches [16–18]. Connect to results in terms of resonances from EF09. Summary plots similar to those in Figs. 1.
- Complementarity with other experiments: Cosmic and Rare and Precision Frontiers
  - Vector and scalar mediator with ID/DD (Figs. 5, 4, 3)
  - Mention invisible decays of dark photon (goes in the non-WIMP section)
  - Connection to Gravitational Waves [13]

Main messages for this section:

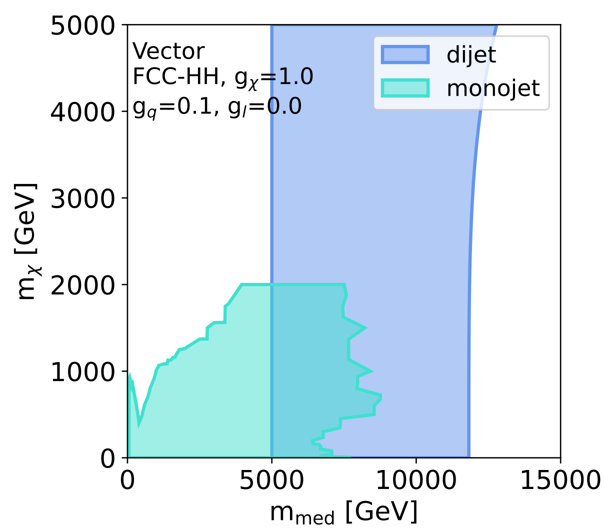
- A future hadron collider has the best reach for simple mediator models with quark couplings
- The sensitivity of colliders depends on simplified model couplings and masses; after having tested a number of scenarios it appears that collider bounds are strongest in cases of TeV-scale mediator masses (no matter what the other parameters are)

- Electron collider results strongest for models with lepton couplings and with mixing to Z/Higgs/photon (*CD: we don't have much of a statement for muon colliders, maybe work with EF09 to include a statement from resonant searches*)
- We need cosmological confirmation that what we discover (resonance/invisible particle) is dark matter, so complementary experiments are essential
- Strenghts of colliders: probing DM mass scales between DD and ID (depends on the model but part of the overall strategy), probing the dark interaction even when one cannot produce the DM particle

Summary plots to be included in this section:

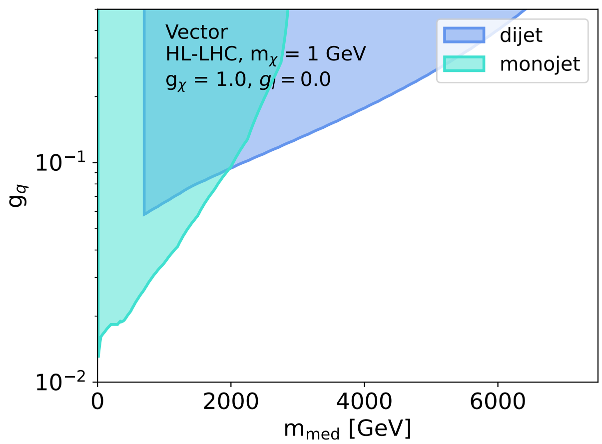


(a) New scenario with varied SM couplings: $g_q = 0.1$, $g_\chi = 1.0$, $g_l = 0.1$

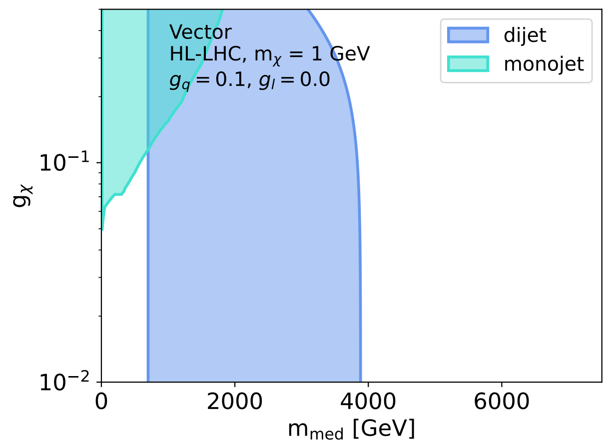


(b) $g_q = 0.1$, $g_\chi = 1.0$, $g_l = 0.0$

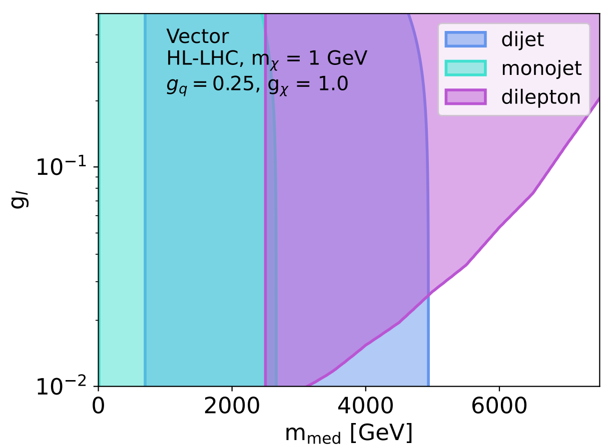
Figure 1: HL-LHC and FCC-hh projected limits for individual analyses in the vector model and with a range of couplings.



(a)

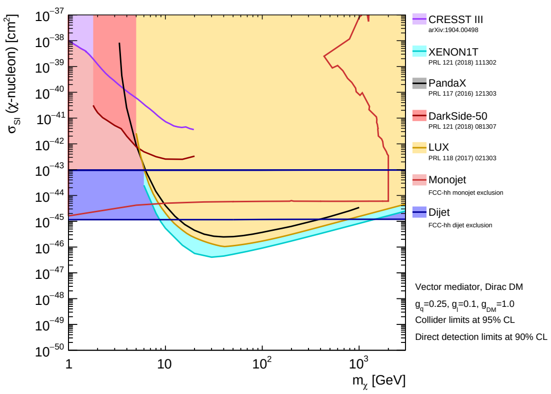


(b)

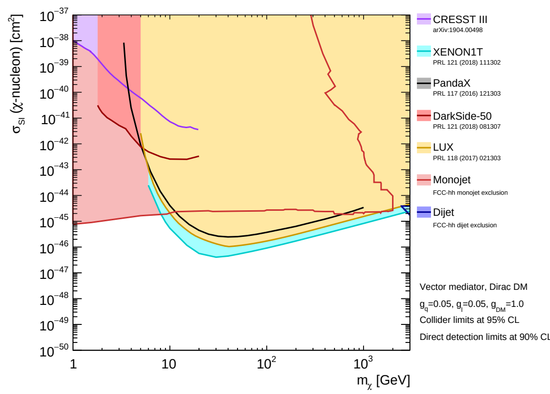


(c)

Figure 2: Projected exclusion limits on the couplings g_q (a), g_χ (b), and g_l (c) for a vector mediator at the HL-LHC. The result is shown as a function of the mediator mass m_{med}; the mass of the DM candidate is fixed to 1 GeV in all cases. The coupling on the y axis is varied while the other two couplings are fixed: in (a), g_χ=1.0 and g_l=0.0; in (b), g_q=0.1 and g_l=0.0; and in c, g_q=0.25 and g_χ=1.0. This will also contain FCC-hh limits on couplings, overlaid.

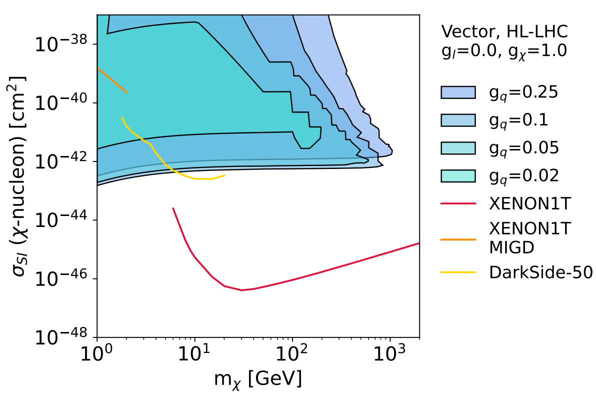


(a) $g_q = 0.25$, $g_\chi = 1.0$, $g_l = 0.1$

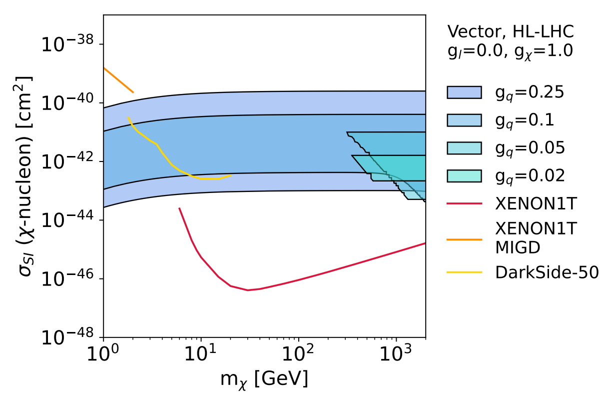


(b) $g_q = 0.05$, $g_\chi = 1.0$, $g_l = 0.05$

Figure 3: Comparison of projected limits from FCC-hh with constraints from current DD experiments on the spin-independent DM–nucleon scattering cross section in the context of the vector simplified model. This figure will also contain HL-LHC bounds, and there will be another one for scalar models.

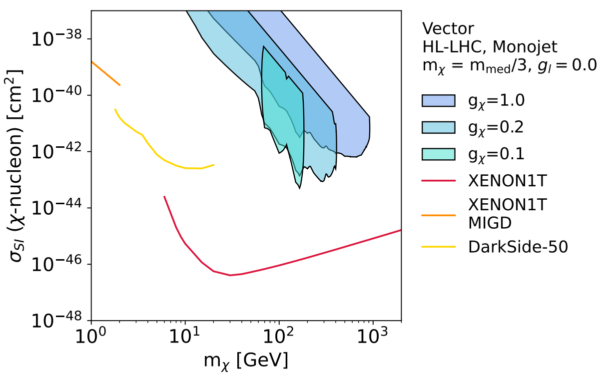


(a) Monojet analysis

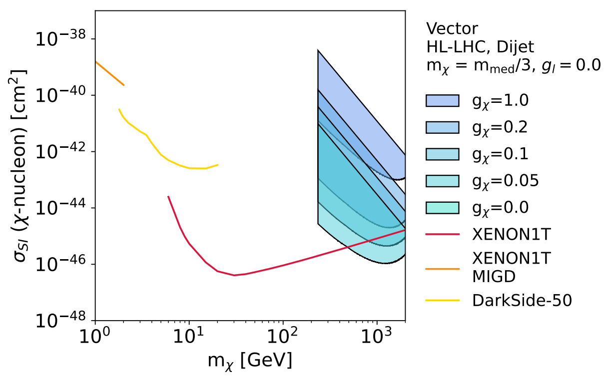


(b) Dijet analysis

Figure 4: Effects on the HL-LHC exclusion limits in $\sigma_{\rm SI}$ for the monojet (a) and dijet (b) signatures when varying the g_q coupling. The dark matter coupling is held fixed to $g_{\rm DM} = 1$; there is no coupling to leptons. Limits from existing direct detection experiments are shown for context.



(a) Monojet analysis



(b) Dijet analysis

Figure 5: Effects on the HL-LHC exclusion limits in $\sigma_{\rm SI}$ for the monojet (a) and dijet (b) signatures when varying the g_χ coupling. The mass of the mediator is fixed to $m_{\rm med} = 3m_\chi$; there is no coupling to leptons. Limits from existing direct detection experiments are shown for context. These curves will be merged into the previous figure.

3 Beyond WIMP

CD: Since this will be part of the overall BSM report, we need to think about how to integrate the topics below in what EF09 has written. I am happy if the big questions go at the start of the overall merged whitepaper and the DM considerations follow each of the model description and results.

Content of section and whitepapers included (as references):

1. Recasting simplified models results in terms of dark photon and PBC benchmarks (HL-LHC), see Figs.6, 7, 8. `https://www.overleaf.com/read/zjjwrpqxncnw`. Also lepton collider results [19]
2. High mass particles as completion of dark sector models [20]
3. Models of dark showers, perspectives on dark matter [21, 22]
4. Potential of the Forward Physics Facility for beyond-WIMP DM scenarios [23]
5. Discussion of non-minimal dark sectors [24].

Main messages for this section:

1. Even though DM at colliders mainly focused on WIMP so far, there are non-WIMP DM models and rich dark sectors accessible to colliders. Examples of vector (dark photon), scalar and axion portal. It is possible to determine what coupling is needed to make up the entirety of the relic using these models, but there are caveats to doing so (e.g. other processes that modify early universe abundances), so we shouldn't restrict/stop our searches even when the model is overproducing DM.
2. Models and results from "generic WIMP" searches often apply to non-WIMP with some reinterpretation (important to make material available for doing so)
3. Many models can have DM interpretation (Pedro Schwaller's "dark showers story": *Analogy with QCD, you have a dark interaction, this basically gives you candidates because things (like the proton) don't decay. This is a strong story that can be told. Also you don't need the mass from the Higgs, you have a theory that makes massive, stable, neutral states. . . this can be emphasized. DM doesn't necessarily mean we have MET, maybe there's a dark baryon that isn't in the shower. Once you find it, you scrutinize what kind of DM we get..*
4. Colliders can share infrastructure for beyond-WIMP experimental facilities (see forward physics facilities list of points).

Summary plots to be included in this section:

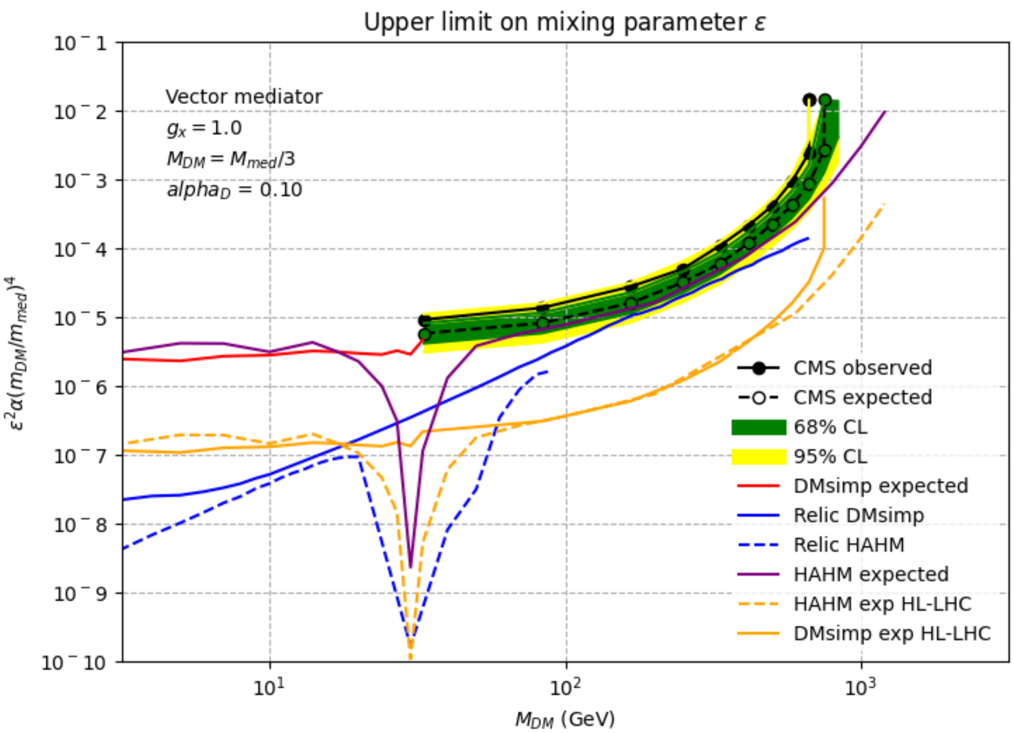


Figure 6: Comparison of two vector-mediated models, *DMsimp* and *HAHM*, corresponding to simplified vector mediated and dark photon mediated models respectively. The mass ratio between mediator and DM mass is fixed to $\frac{1}{3}$, allowing the mediator to decay to DM. The conventional dark coupling constant $\alpha = \frac{g_{DM}^2}{4\pi}$, with coupling $g_{DM} = 1.0$. The models have been generated with quark couplings $g_q = 0.01$ for DMsimp and mixing $\epsilon = 0.01$ for HAHM. Expected and observed limits at 95% CL are plotted using the data from the CMS analysis [CMS_EXO_20_004] [**?**] for the monojet final state, at 13 TeV using 137 fb^{-1} of data. The blue relic lines represent the minimum parameter combinations which reproduce the observed thermal relic density for each model, with the expected deviation for the dark photon model around the Z resonance. Orange lines forecast the increased sensitivity of this search for these two models at the HL-LHC, estimated by the effect on the cross section of scaling up the luminosity. [**?**]

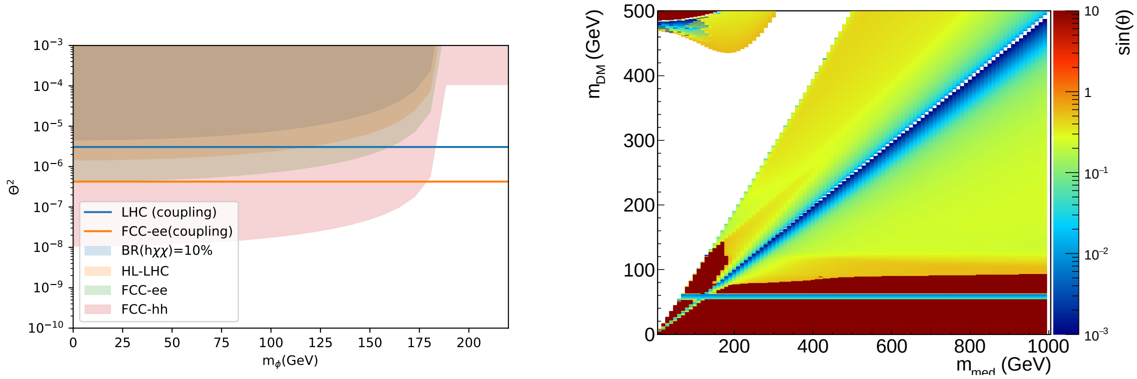


Figure 7: (Left) minimium mixing angle for the Higgs to invisible search when directly applying this search to the singlet mixing model. The solid lines indicate the constraints coming from indirecrt bounds on the Higgs couplings. (Right) minimum allowed mixing angle for a model containing a Dark Higgs that mixes with the standard model Higgs boson.

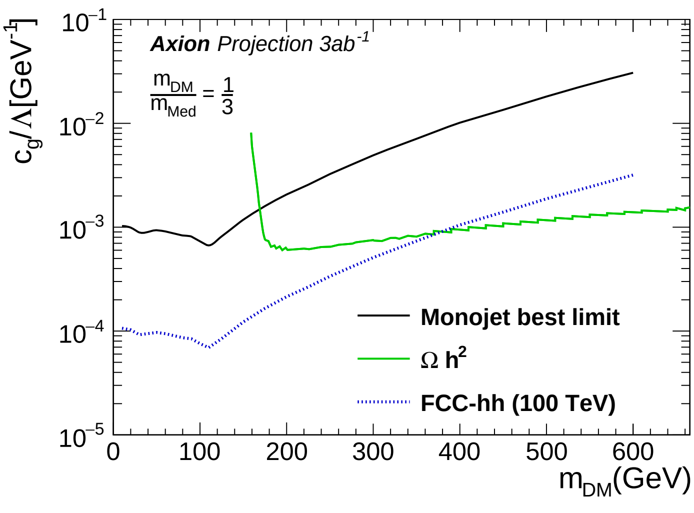


Figure 8: Recast of Pseudoscalar simplified model bounds to the axion portal using the gluon effective coupling.

4 Conclusion

References

[1] Richard Keith Ellis et al. Physics Briefing Book: Input for the European Strategy for Particle Physics Update 2020. 10 2019.

[2] Tao Han, Zhen Liu, Lian-Tao Wang, and Xing Wang. WIMPs at High Energy Muon Colliders. 9 2020.

[3] Tao Han, Zhen Liu, Lian-Tao Wang, and Xing Wang. WIMP Dark Matter at High Energy Muon Colliders –A White Paper for Snowmass 2021. In *2022 Snowmass Summer Study*, 3 2022.

[4] Rodolfo Capdevilla, Federico Meloni, Rosa Simoniello, and Jose Zurita. Hunting wino and higgsino dark matter at the muon collider with disappearing tracks. 2 2021.

[5] Salvatore Bottaro, Alessandro Strumia, and Natascia Vignaroli. Minimal Dark Matter bound states at future colliders. *JHEP*, 06:143, 2021.

[6] Salvatore Bottaro, Dario Buttazzo, Marco Costa, Roberto Franceschini, Paolo Panci, Diego Redigolo, and Ludovico Vittorio. Closing the window on WIMP Dark Matter. *Eur. Phys. J. C*, 82(1):31, 2022.

[7] Salvatore Bottaro, Dario Buttazzo, Marco Costa, Roberto Franceschini, Paolo Panci, Diego Redigolo, and Ludovico Vittorio. The last Complex WIMPs standing. 5 2022.

[8] Mohamed Zaazoua, Loan Truong, Kétévi A. Assamagan, and Farida Fassi. Higgs portal vector dark matter interpretation: review of Effective Field Theory approach and ultraviolet complete models. 7 2021.

[9] Brian Batell, Ayres Freitas, Ahmed Ismail, and David Mckeen. Probing Light Dark Matter with a Hadrophilic Scalar Mediator. *Phys. Rev. D*, 100(9):095020, 2019.

[10] Brian Batell, Ayres Freitas, Ahmed Ismail, David McKeen, and Mudit Rai. Renormalizable models of flavor-specific scalars. *Phys. Rev. D*, 104(11):115032, 2021.

[11] Daniel Egana-Ugrinovic, Samuel Homiller, and Patrick Meade. Aligned and Spontaneous Flavor Violation. *Phys. Rev. Lett.*, 123(3):031802, 2019.

[12] Simon Knapen and Dean J. Robinson. Disentangling Mass and Mixing Hierarchies. *Phys. Rev. Lett.*, 115(16):161803, 2015.

[13] Jia Liu, Xiao-Ping Wang, and Ke-Pan Xie. Scalar-mediated dark matter model at colliders and gravitational wave detectors - A White paper for Snowmass 2021. In *2022 Snowmass Summer Study*, 3 2022.

[14] Tathagata Ghosh, Chris Kelso, Jason Kumar, Pearl Sandick, and Patrick Stengel. Simplified dark matter models with charged mediators. In *2022 Snowmass Summer Study*, 3 2022.

[15] Andreas Albert et al. Displaying dark matter constraints from colliders with varying simplified model parameters. 3 2022. Submitted to proceedings of Snowmass 2021.

[16] Jan Kalinowski, Wojciech Kotlarski, Krzysztof Mekala, Kamil Zembaczynski, and Aleksander Filip Zarnecki. New approach to DM searches with mono-photon signature. In *2022 Snowmass Summer Study*, 3 2022.

[17] Jan Kalinowski, Tania Robens, and Aleksander Filip Zarnecki. New Physics with missing energy at future lepton colliders - Snowmass White Paper. In *2022 Snowmass Summer Study*, 3 2022.

[18] Robert M. Harris, Emine Gurpinar Guler, and Yalcin Guler. Sensitivity to dijet resonances at proton-proton colliders. 2022. Submitted to proceedings of Snowmass 2021.

[19] Scott Snyder, Christian Weber, and Danyi Zhang. Prospects for searches for Higgs boson decays to dark photons at the ILC. In *2022 Snowmass Summer Study*, 3 2022.

[20] Thomas G. Rizzo. Portal Matter and Dark Sector Phenomenology at Colliders. In *2022 Snowmass Summer Study*, 2 2022.

[21] Guillaume Albouy et al. Theory, phenomenology, and experimental avenues for dark showers: a Snowmass 2021 report. 3 2022.

[22] Hugues Beauchesne and Giovanni Grilli di Cortona. Event-level variables for semivisible jets using anomalous jet tagging. In *2022 Snowmass Summer Study*, 11 2021.

[23] Jonathan L. Feng et al. The Forward Physics Facility at the High-Luminosity LHC. 3 2022.

[24] Keith R. Dienes and Brooks Thomas. More is Different: Non-Minimal Dark Sectors and their Implications for Particle Physics, Astrophysics, and Cosmology - 13 Take-Away Lessons for Snowmass 2021. In *2022 Snowmass Summer Study*, 3 2022.