

# Snowmass 2021: Dark matter at colliders

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2021/09/02 - Snowmass EF restart workshop



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# Quick re-introduction to EF10



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# How we started our work: discussion of benchmarks

We needed **guiding principles** to organize DM @ Colliders studies for Snowmass

- to coordinate the work in practice, given the breadth of DM explanations
  - At colliders, different benchmark models give different signatures → different searches
- to put studies in a broader context and compare to other experiments

→ EF10 has categorized LOIs and community work in two categories:

- 1) Test the **WIMP paradigm** (including non-minimal WIMPs/simplified models) [this session]
- 2) Explore signatures of DM **beyond WIMPs** (including dark sectors) [session #108, #127]

Keeping in mind what **Brian Shuve & Raman Sundrum** presented at the [EF08-10 parallel sessions at EF Workshop \(July 2020\)](#):

- Need broad and comprehensive search strategies to counteract small probability that any individual scenario is correct

[notes [here](#)]

*What you think is plausible plays a big role in making superhuman (not just human) efforts to make discoveries, as that is what it might take. So I think there's nothing wrong with saying dark matter is a big mystery, and even that mystery may be informed by considerations of naturalness.*

# Organization of work around benchmarks

The DM @ Colliders community is quite broad and **shares work** with many other TGs and Frontiers  
→ we want to be as **inclusive** as possible while keeping an eye on **big picture**

1. Studies of **common DM benchmarks** agreed-upon with other groups/frontiers
  - Leads to “big picture” plots e.g. comparing other experiments
    - Similar to what was done for the European Strategy Briefing Book
  - Our contributors have been working towards providing **technical help** to the collaborations and interested parties
    - e.g. model repository, common code pipelines (potentially with CompF07?)
      - Interest within EF10, where some contributors work within [this project](#)
2. Studies that **highlight potential differences wrt common benchmarks**
  - Not necessarily comprehensive in terms of experimental coverage
  - E.g. highlight different complementarity or different signatures
3. Studies that **point out novel / less-explored DM models** (mostly joint with EF09)
  - E.g. highlighting uncovered phase space

# List of focused questions from EF10

## 1. How can we best test the **WIMP** paradigm?

- Through the simplest/minimal WIMP models (EW multiplets) and their extensions
- Using simple mediator models (s-channels/t-channels) already used for collider searches
- Through the Higgs portal, since the Higgs boson is the most relevant portal operator between SM and DM and there are connections to precision measurements

## 2. How can we best explore **beyond-WIMP** scenarios?

- Using portals that privilege light dark sectors / dark matter
- Focusing on less-explored signatures of dark sectors that can highlight present/future blind spots

## 3. How to best exploit **synergies & complementarity** between DM@colliders & other TGs and Frontiers

- In terms of different experiments / observations answering the same physics question on the nature of DM
- In terms of detector, data acquisition and trigger design [e.g. IF04 kick-off]

# EF10 goals recap: testing the WIMP paradigm

## 1. Electroweak multiplets [[meeting 04/06/20](#), [02/07/20](#)]

- Electroweak multiplet: higgsino/wino(minimal DM). Mediator: W/Z/h.
- Target: TeV(and above)-scale DM masses, motivated by relic density

Common benchmarks  
with EF08/CF

## 2. Simplified mediator models [[meeting 18/06/20](#)]

- S-channel and t-channel mediators.
- Well established benchmarks for LHC, simple benchmarks for comparisons
- Main target: DM masses  $< \frac{1}{2}$  mediator mass.

Common benchmarks  
with EF09/RF06/CF

## 3. Higgs portal [[upcoming meeting](#)]

- Well motivated coupling between SM to the dark world
- Main target: DM masses  $< \frac{1}{2}$  Higgs mass.

Common benchmark  
with Higgs EFs

# EF10 goals recap: beyond WIMPs

[joint [EF09-10/RF05/AF06 meeting 16-17/07](#)]

1. (Very) different DM masses and couplings with respect to the WIMP
  - a. Strongly interacting DM, light DM ( $< \text{GeV}$ )
    - i. E.g. dark QCD benchmarks LOI
2. Different portals with respect to LHC simplified models:
  - a. dark photon and generic dark scalar/pseudoscalar (including rare decays)
    - i. Develop connections between these portals and DM simplified models  
See [this talk by N. Toro](#) at the “LLP preparatory meeting” (EF8-10/RF05/AF06)
    - ii. Understand how to present them coherently - see [this talk by N. Toro](#) at EF10 meeting

Common benchmarks in discussion with EF09/RF05, also to be discussed with CF



# Before the break: work on LOIs

44 LOIs so far [EF10 LOIs: links and titles](#)

Mostly cross-listed with EF09/CF

Roughly grouped by topics:

- WIMP (9) Covered in September 10 biweekly meeting.
- Alternative models (2) Covered in September 10 biweekly meeting.
- Displaced, dark sector (17)
- Higgs portal (2)
- Directly related to a facility. (5) Covered in Sept 23rd meeting
- Computing. (4)
- Complementarity between different probes (4)  
Covered in Sept 23rd meeting

EF	COMPLEMENTARITY	EF/SNOWMASS21-EF10_EF9_Liu_W	29/08/2020	EPF	EF10 Lepton portal dark matter, gravitational waves and collider phenomenology
EF	COMPLEMENTARITY	EF/SNOWMASS21-EF10_EF9_Andre	30/08/2020	EPF	EF10 Displaying dark matter constraints from colliders with varying spin
EF	COMPLEMENTARITY	EF/SNOWMASS21-EF9_EF10-RFG_R	31/08/2020	EPF	EF9 Summarizing experimental sensitivities of colliders/experiments to LSPs
CompF	COMPUTING	CompF/SNOWMASS21-CompF4_Co	31/08/2020	EPF	EF10 Application of Quantum Machine Learning to High Energy Physics
CompF	COMPUTING	CompF/SNOWMASS21-CompF7_Co	31/08/2020	EPF	EF10 The ESCAPE Dark Matter Test Science Project
EF	COMPUTING	EF/SNOWMASS21-EF10_EF9-CompF	31/08/2020	EPF	EF10 Optimization of High Energy Physics Analysis Performance Using
EF	COMPUTING	EF/SNOWMASS21-EF9_EF10-CompF	31/08/2020	EPF	EF9 Anomaly Detection at Future Colliders
CF	DISPLACED/DARK	CF/SNOWMASS21-CF1_CFO-EF7_EE	31/08/2020	EPF	EF10 Accelerator Search for a Stable, Neutral, Long-Interaction-Length Dark Matter Particle
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF9_CFI_C	28/08/2020	EPF	EF10 Feebly interacting Dark Matter at colliders and Early Universe Cosmology
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF9_Meng	28/08/2020	EPF	EF10 Search for Asymmetric Dark Matter model at CEPC by displaced lepton
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10_Chh_L	28/08/2020	EPF	EPF9 Po-Jen Chung, Kingman Cheung, Yi-Lun Chung, Shih-Chieh Hsu et al.
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10_S01_Co	30/08/2020	EPF	EPF9 Probing Dark Matter Dynamics with Long-Lived Particle Searches
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10_Paul_J	30/08/2020	EPF	EPF9 Searches for Dark Photons and Doubly-Charged Higgs in 4-Layered
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF8_Rahm	31/08/2020	EPF	EPF9 Vector-Portal Search for Dark Matter Particles
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF9_Kulkar	31/08/2020	EPF	EF10 Studies of dark shower benchmarks
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10-L44_Co	31/08/2020	EPF	EPF9 Dark Sector and Dark Matter model searches from exotic Z decays
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10-NF3_N	31/08/2020	EPF	EPF9 Recent Progress and Next Steps for the MAHUSLA LLP Detector
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10-RFG_R	31/08/2020	EPF	EPF9 Long-lived particle signatures at the energy frontier
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10_EE	31/08/2020	EPF	EPF9 Forward Physics Facility
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF9-CFI_C	1/9/2020	EPF	EPF9 Collider Signals of FIMP Dark Matter with Heavy Mediators
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10-009.pdf	27/05/2020	EPF	EF10 Dark Photons, Kinetic Mixing and UV Scenarios
EF	DISPLACED/DARK	EF/SNOWMASS21-EF10_EF9-042.pdf	24/08/2020	EPF	EPF9 Disappearing Tracks at the High-Luminosity LHC and future hadron colliders
EF	SIMPLE WIMP	EF/SNOWMASS21-EF10_EF9_Kilic-D	26/08/2020	EPF	EPF9 Optimizing Tracked-Based Searches for Higgs-like DM
EF	DISPLACED/DARK	EF/SNOWMASS21-EF9_EF10-TF7_T	28/08/2020	EPF	EPF9 Double Displaced Vertices: A New Strategy for Unmasking Non-Minimal
IF	DISPLACED/DARK	IF/SNOWMASS21-IF-EF10-002.pdf	28/08/2020	EPF	EPF10 Triggering on charged particles using silicon pixel detectors
IF	EXPERIMENT/FACILITY	IF/SNOWMASS21-IF-EF10-RFG_R	30/08/2020	EPF	EPF10 The CMS Collaboration contribution to Snowmass 2021
EF	EXPERIMENT/FACILITY	EF/SNOWMASS21-EF10_EF9_Jayatil	31/08/2020	EPF	EPF9 Dark Matter Searches at Future Colliders: The Unique Reach of the
RF	EXPERIMENT/FACILITY	EF/SNOWMASS21-EF10_EF9_Armo	1/9/2020	EPF	EPF10 LHC and FCC-hh: Dark Matter (EF 10)
RF	EXPERIMENT/FACILITY	EF/SNOWMASS21-RF6_RFG-EF10_E	31/08/2020	EPF	EPF10 Letter of Interest for the Light Dark Matter eXperiment
RF	EXPERIMENT/FACILITY	EF/SNOWMASS21-RF6_RFG-EF10_E	1/9/2020	EPF	EPF10 Letter of Interest for the Muon Missing Momentum experiment
RF	EXPERIMENT/FACILITY	EF/SNOWMASS21-RF6_RFG-EF9_EE	1/9/2020	EPF	EPF9 Accelerator Probes of Millicharged Particles/Dark Matter
EF	HIGGS PORTAL	EF/SNOWMASS21-EF10_EF9_Xin_S	28/08/2020	EPF	EPF10 Dark Matter via Higgs portal at CEPC
EF	HIGGS PORTAL	EF/SNOWMASS21-EF10_EF9_Selme	31/08/2020	EPF	EPF10 LQ on $W \rightarrow \text{invisible}$
EF	OTHER MODEL	EF/SNOWMASS21-EF10_EF8-079.pdf	29/08/2020	EPF	EPF9 Sharing but not Caring at colliders
EF	OTHER MODEL	EF/SNOWMASS21-EF8_EF10-132.pdf	31/08/2020	EPF	EPF9 Feasibility study on probing the Seesaw Mechanism with full detector
EF	SIMPLE WIMP	EF/SNOWMASS21-EF10_EF9-069.pdf	28/08/2020	EPF	EPF10 Electroweak multiplets at the Muon Collider
EF	SIMPLE WIMP	EF/SNOWMASS21-EF10_EF9-071.pdf	28/08/2020	EPF	EPF9 Doublet Singlet Dark Matter
EF	SIMPLE WIMP	EF/SNOWMASS21-EF10_EF9_dh80	30/08/2020	EPF	EPF10 A final word on minimal dark matter at future lepton colliders
EF	SIMPLE WIMP	EF/SNOWMASS21-EF10_EF8-TF7_T	31/08/2020	EPF	EPF10 Long-lived charginos in the MSB and beyond
EF	SIMPLE WIMP	EF/SNOWMASS21-EF9_EF10-TF7_T	31/08/2020	EPF	EPF9 Searching for the Stop-Bottom Coannihilation Using CMS/Open Data
EF	SIMPLE WIMP	EF/SNOWMASS21-EF8_EF10-258.pdf	1/9/2020	EPF	EPF9 Future collider reach for light DM in the NMSM via light Higgs sea
EF	SIMPLE WIMP SEARCH	EF/SNOWMASS21-EF10_EF9_Filip_J	27/08/2020	EPF	EPF9 New approach to DM searches with mono-photon signature
EF	SIMPLE WIMP SEARCH	EF/SNOWMASS21-EF10_EF9_Pelaez	30/08/2020	EPF	EPF10 Search for $\nu\bar{\nu}$ MET signals from dark matter decays at future e+e-

We answered ~all LOIs individually

- Useful to build a discourse with the proponents, and to match-make with SEC members who contacted us

Recordings and notes available in the spreadsheet



# What happened during the break?

Our feeling: people (us included) really took a Snowmass break  
→ mostly worked on other things (still relevant for Snowmass)

We did not organize a conversation meeting - mostly because main EF10 contributors were busy/left

Parallel efforts were encouraged and followed, naming the most relevant/active:

- Snowmass *Dark Showers group* (joint with EF09) - Suchita Kulkarni [th], Marie-Helene Genest [exp]
  - Had a number of meetings on new publications / benchmark discussions (~ every 3 weeks)
  - Organized a tutorial/workshop with experts during the Long Lived Particles Community Workshop
  - [Talk by Suchita Kulkarni today](#)
- WIMPs at muon colliders
  - There have been several studies on the search for WIMP dark matter (focusing on the so called Minimal Dark Matter scenario) at muon collider (with various energy and luminosity options), as well as a few more on-going work.
  - While it may not be as complete as the study for the 100 TeV pp collider for the briefing book, a set of basic results are available now to paint a big picture on this topic.
  - [Talks by M. Costa and J. Zurita today](#)
- WIMPs and lighter DM at hadron/lepton colliders → see also next slide
  - Some of our main contributors graduated, some are back as PhD students starting in September, some are new
  - One of the postdoc leaders of whitepaper also moving on to new jobs (!colliders) but want to keep contributing once Snowmass restarts
  - [Talks by A. Albert today](#)



- New Wino/Higgsino studies with monojet signature ongoing - Andie Wall & Elliott Lipeles



# Summary of Parallel Session H

## *EF10 contributed talks*

[Link to live notes](#)



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<https://arxiv.org/abs/2107.09688>

# Wino & Higgsino at muon colliders

Speakers at EF10 Parallel Session H: Marco Costa, Jose Francisco Zurita [talk link](#)

Considering **pure WIMP scenarios** where the EW interaction sets the relic (mass as a free parameter) and DM is the neutral component of a multiplet

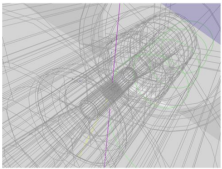
Many different signatures for WIMPs @ muon colliders in new literature / recent workshops:

- Recoil against visible objects
- Resonances from the DM particle bound states, which can be excited as a resonance and decay into visible particles
- Disappearing tracks (DT)

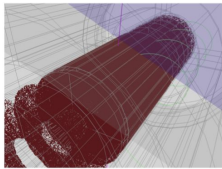
Results can be put into context of direct and indirect detection (esp. CTA projections)

“Lessons learned” from studies that can be brought back to AF:

- Beam background is significant at muon colliders

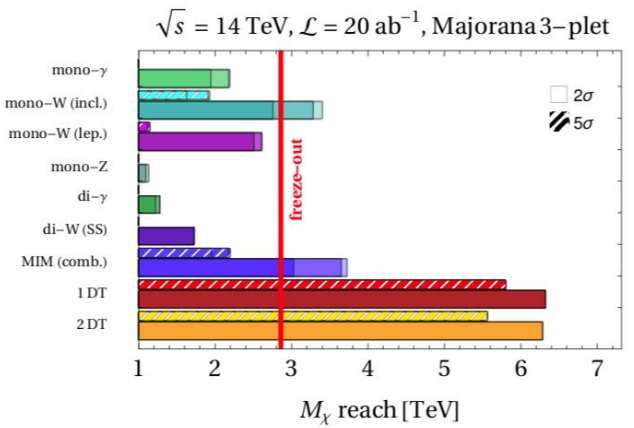


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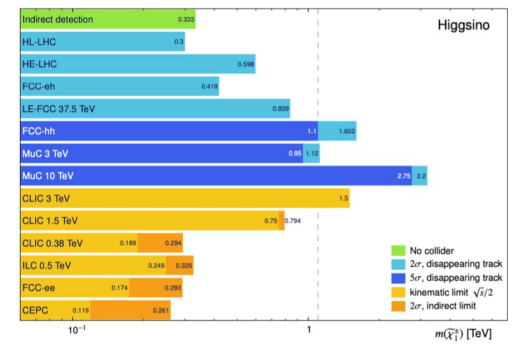


BIB on

Credit: F. Meloni



<https://arxiv.org/abs/2102.11292>



**Message for EF10 whitepaper:** a muon collider is competitive with FCC-hh for thermal WIMP scenarios

**Complementarity message:** muon collider results can lead to joint WIMP discoveries with DD and ID

# Dark Matter WG work on simplified model coupling scan

DMWG coupling LOI contacts and organizers: Katherine Pachal, Andreas Albert, [talk link](#)

EF10 Focus Topic #1.2:  
WIMP-like simplified  
models

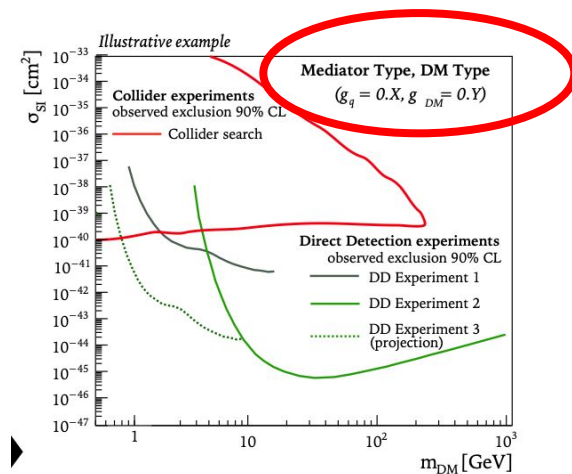
Coupling scan necessary to **extend current benchmarks** for DM simplified models used for e.g. European Strategy (& ATLAS+CMS), where DM simplified models have couplings  $o(1)$

**Goal:** explore coupling scenarios systematically and efficiently to connect to other experiments / show effect of varying couplings

- Efficiently: **analytical** rescaling of existing constraints rather than generate more MCs for different couplings

**Scope** of Snowmass whitepaper:

- Have a reference document defining the rescaling method for dijet / monojet + possible refinements (e.g. PDF weights, complex modelling of propagators...)
- Cover different topologies, monojet, dijet, dilepton searches
- Provide Python code for different users with summary plots as a final goal



**Message for EF10 whitepaper:** future colliders can probe lower couplings, not just  $o(1)$  couplings...

**Complementarity message:** ...enabling joint discoveries with other experiments in this phase space

# Dark showers project status and updates

Dark showers project LOI contacts and organizers: Suchita Kulkarni, Marie-Helene Genest, [talk link](#)

**Motivation for dark showers & DM:** non-abelian QCD-like theories with dark confinement → dark pions (e.g. one of which can be DM candidate) within dark showers

**Challenge:** many parameters (details of mediator, details of dark sector...) leading to different signature space

**Goals** of this working group / common whitepaper:

- Common work on phenomenological studies of existing benchmarks
- Strengthen connections with theory (e.g. [meeting on Sept 15th](#))

**Tools:** common code and model repository, shared meetings and presentations of different / related LOIs that will lead to different whitepapers within EF09/EF10.

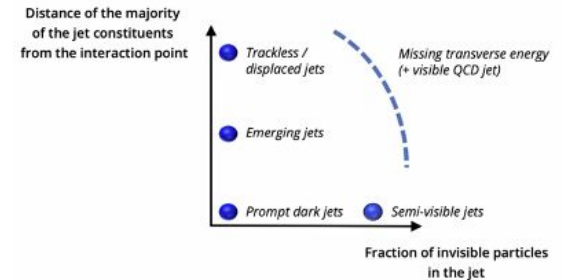
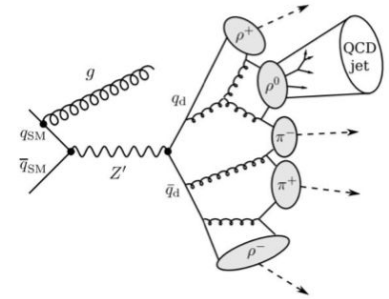
**Meetings since 2020:** literature survey, connection to broader community (e.g. participation in LLP WG joint sessions including discussions about astrophysics), well-attended tutorials.

**Ongoing project example:** how the distributions in the colliders vary depending on the parameters of the model (e.g. mediator mechanics).

**Message for EF10 whitepaper:** pointers to interesting signatures of models containing DM candidates [not sure if we will be able to have projections in time due to lack of people]

EF10 Focus Topic #2.1:  
beyond WIMP

arXiv:1907.04346



# Highlights from Parallel Session B

## *DM summary plots*

[Link to live notes](#)



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# DM summary plots joint with RF06 (rare&precision)

EF10 Focus Topic #3:  
synergies

Mike Williams's slides, diagram by Natalia Toro

## Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	$m_\chi$ vs. $y$ [ $m_\chi/m_\tau=3, a_D=5$ ] $m_\chi$ vs. $y$ [ $a_D=0.5, 3$ $m_\chi$ values] $m_\chi$ vs. $a_D$ [ $m_\chi/m_\tau=3, y=y_d$ ] $m_\chi$ vs. $m_\chi$ [ $a_D=0.5, y=y_d$ ] Millicharge $m$ vs. $q$	$m_\chi$ vs. $\epsilon$ [decay-mode agnostic] $m_\chi$ vs. $\epsilon$ [decays]	iDM $m_\chi$ vs. $y$ [ $m_\chi/m_\tau=3, a_D=5$ ] (anom connection) SIMP-motivated cascades [slices TBD] $U(1)_{B-L/\mu-t/B-3c}$ (DM or SM decays)
Scalar	$m_\chi$ vs. $\sin\theta$ [ $\lambda=0$ , fix $m_\chi/m_\tau, g_\beta$ ] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	$m_\chi$ vs. $\sin\theta$ [ $\lambda=0$ ] $m_\chi$ vs. $\sin\theta$ [ $\lambda=s.t. Br(H\rightarrow\phi\phi)=10^{-5}$ ]?	Dark Higgs-sstrahlung (w/vector) scalar SIMP models? Leptophilic/leptophobic dark Higgs?
Neutrino	$c/\mu/\tau$ a la 1709.07001?	$m_\chi$ vs. $U_c$ $m_\chi$ vs. $U_c$ $m_\chi$ vs. $U_\tau$ Think more about reasonable flavor structures	Sterile neutrinos with new forces?
ALP	$m_\chi$ vs. $f q/l$ [ $\lambda=0$ , fix $m_\chi/m_\tau, g_\beta$ ] (thermal target excluded) What about $f_r, f_c$ ?	$m_\chi$ vs. $f_f$ $m_\chi$ vs. $f_G$ $m_\chi$ vs. $f_q=f_l$ (separate?) Think more about reasonable coupling relations including $f_{W/Z}$	FV axion couplings

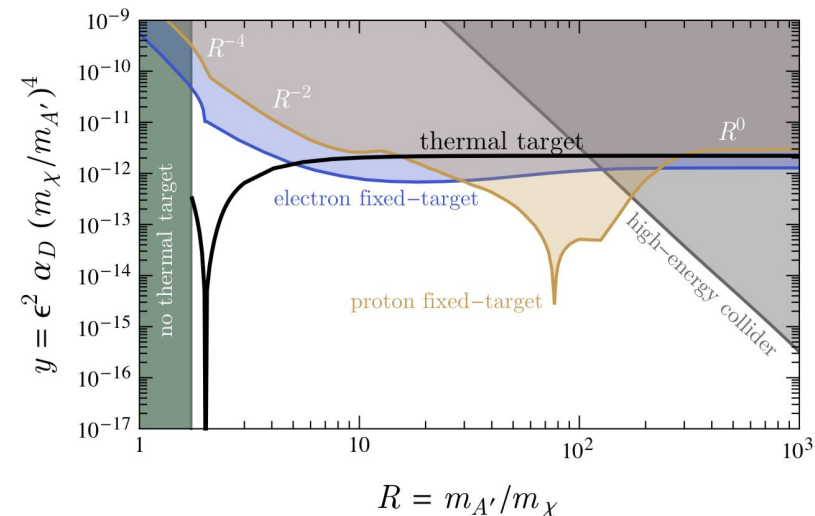
+ Neutron portal (See e.g. 2003.02270)? Hidden valleys (or are these out-of-scope)?

**Bold = BRN benchmark, italic = PBC benchmark, others are new suggestions.** Underline = CV benchmarks that were not used in BRN

**EF10 plans:** improve from European Strategy with benchmarks that leave the coupling (and mass) as a variable, following DMWG LOI

**Complementarity message:** different mass/coupling ranges reached by different kinds of experiments

Example of a joint EF10-RF06 plot, vector portal



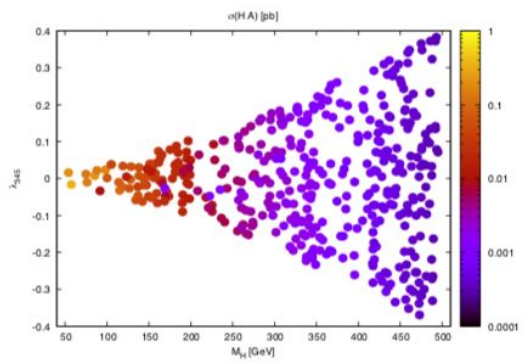
# DM complementarity in Higgs portal

Tania Robens et al.

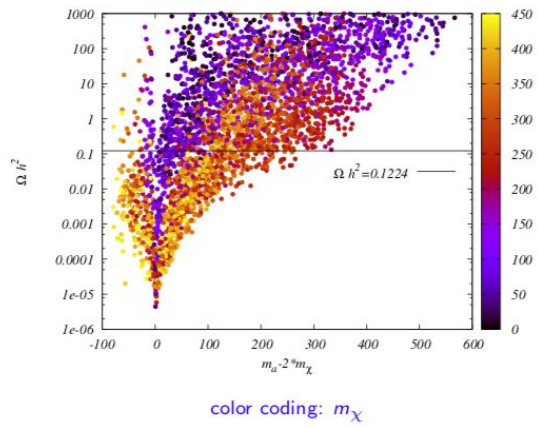
Previous work highlighting complementarity in Higgs context:

- Higgs portal models (focused on HL-LHC)
- Inert Doublet Model
- Two Higgs Doublet Model + pseudoscalar (from LHC dark matter working group)

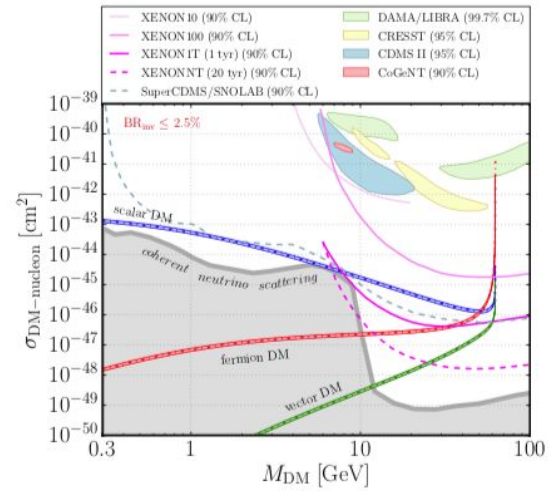
*Inert Doublet Model, example: ability of LUX to probe coupling while mass probed at colliders*  
[Phys.Rev.Lett. 121 (2018) no.11, 111302]



*Two Higgs Doublet Model, global fits*  
arXiv:2105.06231, arXiv:2106.02962



*Higgs portal (need discussion on vector DM)*



HL-LHC Yellow Report

Wish to organize a joint  
EF2+ EF10 meeting

**Complementarity message:** different experiments can probe different parameters of the same model



# Next steps



# Tentative plan for the future

- Resuming monthly meetings
  - Next meetings: **September 22, Oct 27, and Nov 17**
- To potential contributors: don't hesitate to bring updates to our attention (even though we will inquire for progress with LOI authors)
  - We can only include in final whitepapers what we know about!
- Discussions for DM complementarity plots also expected to resume once Cosmic Frontier restarts (September onwards)
- Discussion ongoing for a joint EF-8/9/10 workshop in early 2022



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# Backup slides



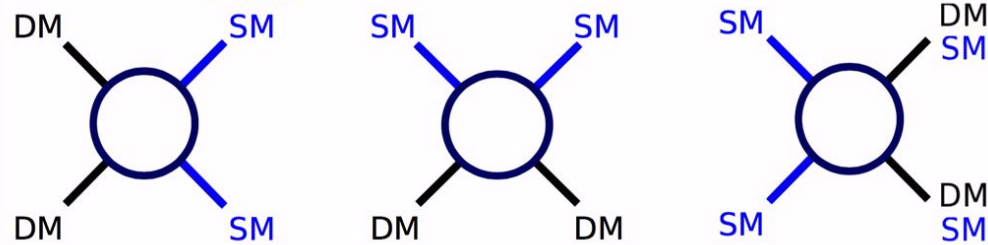
# DM@colliders in the broader Snowmass context

Observations, experiments and theories all needed for DM discovery

- DD/ID can discover DM with cosmological origin
- Colliders / accelerators can produce DM and probe the dark interaction
- Observations motivating DM come from astrophysics / gravitational interactions
- Theoretical frameworks are necessary to put different observations in context

Dark Matter

Standard Matter

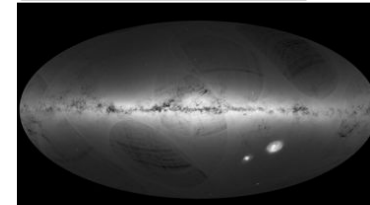


Indirect Detection

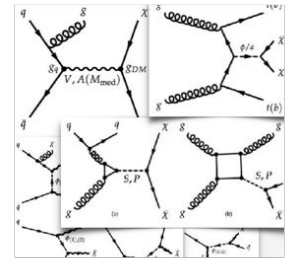
Direct Detection

Colliders & accelerators

Credit: ESA/Gaia/DPAC.



Astrophysics



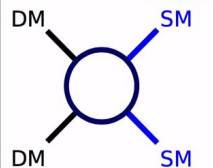
Theory

**DM @ Colliders:** continued exploration of *different experimental signatures of DM* at *different energy scales (MeV -- TeV)*, motivated by many *different DM models* (WIMP-like, SUSY, dark sectors...)

# DM@colliders in the broader Snowmass context

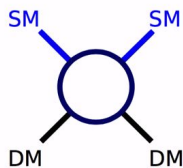
Observations, experiments and theories all needed for DM discovery

Dark Matter



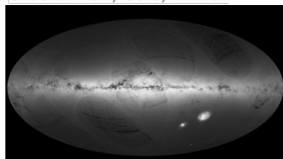
Indirect Detection

Standard Matter



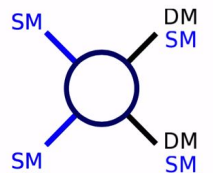
Direct Detection

Credit: ESA/Gaia/DPAC.



Astrophysics

Cosmic Frontier 01 (particle-like DM)  
CF02 (wave-like DM)  
CF03 (cosmic probes of DM)  
Underground Frontier  
Neutrino Frontier



Colliders & accelerators

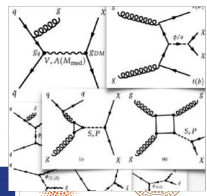
EF10 (this TG), EF02, EF03, EF08, EF09  
(+ others for backgrounds)

Rare & precision Frontier 06 (dark sectors at accelerators)

Accelerator Frontier 05 (accelerators for dark sectors)

Nearly all the physics in EF10 is **synergistic** with other groups / frontiers

→ keeping in sync & communicating often is part of our day-to-day work



Theory

Theory Frontier 07 (collider phenomenology)  
TF07 (BSM model building)  
TF09 (Astro-particle physics & cosmology)  
(+ others for backgrounds)

# Testing the WIMP paradigm: three main directions

## 1. Electroweak multiplets [[meeting 04/06, 02/07](#)]

- Electroweak multiplet: higgsino/wino(minimal DM). Mediator: W/Z/h.
- Target: TeV-scale DM masses, motivated by relic density

Common benchmarks  
to be discussed with  
EF08 (after LOIs)

## 2. Simplified mediator models [[meeting 18/06](#)]

- S-channel and t-channel mediators.
- Well established benchmarks for LHC, simple benchmarks for comparisons
- Target: DM masses  $\sim$  GeV-scale and above

Common benchmarks  
in discussion with  
EF09/RF05, to be  
discussed with CF

## 3. Higgs portal [[upcoming meeting](#)]

- Well motivated coupling between SM to the dark world
- Target: DM masses  $\sim$  GeV-scale and above

Common benchmark to  
be discussed with EF02

# Ongoing work on simple WIMP models

## Electroweak multiplet WIMP

[EF/SNOWMASS21-EF10\\_EF9-069.pdf](#) - Electroweak multiplets at the Muon Collider

[EF/SNOWMASS21-EF10\\_EF0\\_Armesto\\_LHeC\\_BSM10-180.pdf](#) LHeC and FCC-he: Dark Matter (EF 10)

[EF/SNOWMASS21-EF10\\_EF9-071.pdf](#), singlet + doublet WIMP simplified model

[EF/SNOWMASS21-EF10\\_EF9\\_diego\\_redigolo-104.pdf](#) - Electroweak multiplets at the Muon Collider

[EF/SNOWMASS21-EF10\\_EF8-TF7\\_TF0-CompF2\\_CompF0\\_Kulkarni\\_Suchita-139.pdf](#) - Long lived charginos

[EF/SNOWMASS21-EF9\\_EF10-TF7\\_TF0\\_Haipeng\\_An-237.pdf](#) - stop-bino coannihilation with open data

[EF/SNOWMASS21-EF8\\_EF10-258.pdf](#) - light dark matter in NMSSM via light higgs and electroweakino searches

[EF/SNOWMASS21-EF10\\_EF0\\_Peiwen\\_WU-103.pdf](#) - top+jet+MET at future e+e- colliders

[EF/SNOWMASS21-EF10\\_EF0\\_Kilic-051.pdf](#) - Optimizing Higgsino searches

## Higgs portals:

[EF/SNOWMASS21-EF10\\_EF2\\_Ketevi\\_Assamagan-035.pdf](#) *LOI on H → invisible*

[EF/SNOWMASS21-EF1\\_EF2\\_Patrick\\_Janot-172.pdf](#) - H → invisible at the FCC-ee

[EF/SNOWMASS21-EF10\\_EF0\\_Xin\\_Shi-080.pdf](#) - DM via Higgs portal at CEPC

Full list of LOIs and recording [here](#) (please contact us if we missed yours due to the cross-listing form limitations!)



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# Ongoing work on DM simplified models

## DM Simplified models at colliders

[EF/SNOWMASS21-EF10\\_EF0\\_Peiwen\\_WU-103.pdf](#) - Search for  $t + j + \text{MET}$  signals from dark matter models at future ee collider

[EF/SNOWMASS21-EF10\\_EF9\\_Filip\\_Zarnecki-054.pdf](#) - New approach to DM searches with mono-photon signature

[EF/SNOWMASS21-EF10\\_EF9\\_Andreas\\_Albert-094.pdf](#) - Displaying dark matter constraints from colliders with varying simplified model parameters

[EF/SNOWMASS21-EF9\\_EF10-RF6\\_RF0-CF1\\_CF3\\_Boyu\\_Gao-160.pdf](#) - Summarizing experimental sensitivities of collider experiments to Dark Matter models and comparison to other experiments

## Future collider and experiment (they group more than one search)

HL-LHC ATLAS: [EF/SNOWMASS21-EF0\\_EF0-RF0\\_RF0\\_ATLASCollaboration-195.pdf](#)

HL-LHC CMS: [EF/SNOWMASS21-EF1\\_EF10-RF5\\_RF7\\_CMSCollaboration-109.pdf](#)

Muon collider: [EF/SNOWMASS21-EF10\\_EF0\\_Jayatilaka-225.pdf](#)

LHeC: [EF/SNOWMASS21-EF10\\_EF0\\_Armesto\\_LHeC\\_BSM10-180.pdf](#)

CLIC: [EF/SNOWMASS21-EF0\\_EF0\\_CLICphysics-170.pdf](#)

Lepton colliders: [EF/SNOWMASS21-EF0\\_EF0-TF0\\_TF0-AF0\\_AF0-244.pdf](#)

## Also: theory (general BSM overviews)

[Energy Frontier BSM Wishlist](#)

Full list of LOIs and recording [here](#) (please contact us if we missed yours due to the cross-listing form limitations!)



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# Ongoing work on complementarity

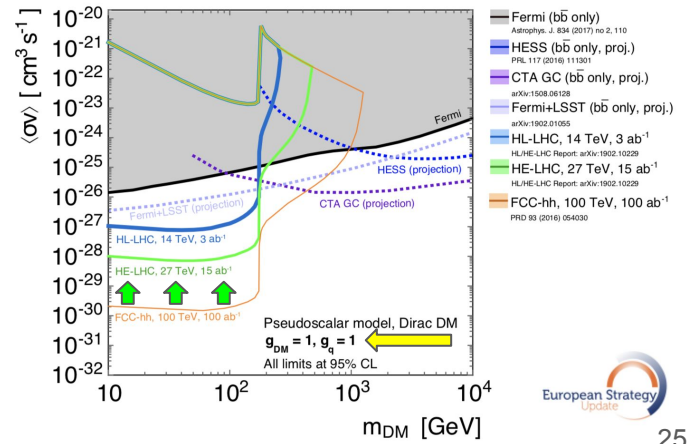
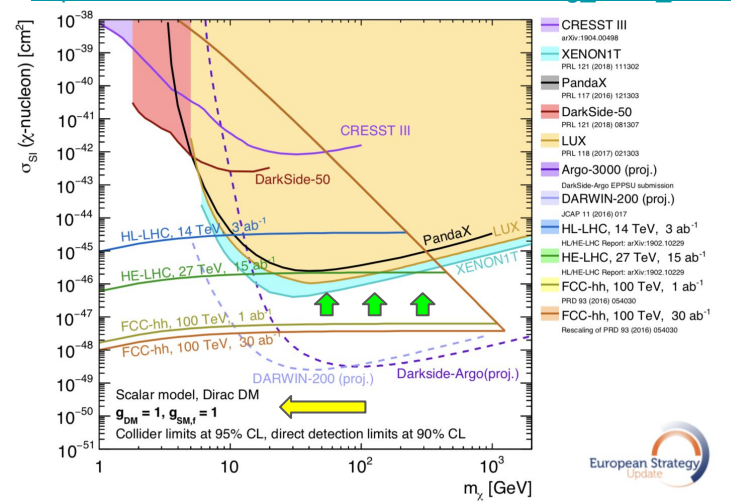
From European Strategy BSM and DM working groups:

- Plots including collider / direct / indirect detection results, using a simple WIMP-like model scenario (pseudo/scalar SM-DM mediator with fixed  $o(1)$  couplings)
- After discussions with other communities, will be updating plots to lower coupling hypotheses to better connect to other DM searches e.g. accelerator-based
  - See this LOI (w/Dark Matter Working Group) and this LOI (plots of heavier WIMPs by EF10)

## Other synergies emphasized by European Strategy

- What can we learn from:
  - Non-collider experiments (for dark sector searches)
  - Astrophysics and nuclear physics
- How can we work together towards the same physics goals:
  - In collaboration with theory, instrumentation & computing

(see also [ESCAPE project](#) / [HSF](#) / [IRIS-HEP](#) (US))



# Some initial questions on possible joint summary plots

Need discussion between EF/CF/RF/NF/TF (topical workshop(s)?)

- Are simple WIMP models / simplified models [[Dark Matter Working Group](#)] / portals [[Physics Beyond Colliders](#)] a framework we want to agree upon for summary plots? (Widely used by the collider community already)
- Exclusion areas plotted by colliders don't impose any relic density constraints on exclusion areas from simplified models → is this making the constraints incompatible?
- Is extending collider limits for thermal relics below 1 GeV in summary plots theoretically sound, and welcome by other communities?
- What is the best way to display uncertainties for the experiments involved?

# Conclusions and outlook from CPM

1. Lively community → broad program of DM@Collider studies within EF10
  - Work on common “big picture” benchmarks alongside unexplored models/signatures
2. Future discovery of / constraints on DM requires a broad physics perspective
  - Coordinate with other Topical Groups and frontiers
  - Would like to update the [DM Complementarity Snowmass 2013 whitepaper](#) with an even more global picture of DM (including accelerators and large astro surveys)
    - i. See [session #150, tomorrow at 12:15](#)
  - Willing to start this journey with CF/EF/RF with joint meetings for joint summary plots!
3. Important to consider *tools* to answer questions about physics of DM
  - Necessary to plan for reinterpretable / reusable searches & measurements (already at the LHC) [potential collaborations with CompF07]
  - Follow detector, data acquisition and trigger design [e.g. [IF04 kick-off](#)]

# Join us, give input

Webpage of EF 10: [https://snowmass21.org/energy/dark\\_matter](https://snowmass21.org/energy/dark_matter)

Slack channel: #ef10-dark\_matter under <https://snowmass2021.slack.com>

Email list: [SNOWMASS-EF-10-DARK\\_MATTER@FNAL.GOV](mailto:SNOWMASS-EF-10-DARK_MATTER@FNAL.GOV)

Instructions on how to join: <https://snowmass21.org/energy/start#communications>

List of all EF10 LOIs (title / authors): [Spreadsheet with presentation recordings \(more will be added\)](#)