Snowmass 2021: Dark matter at colliders

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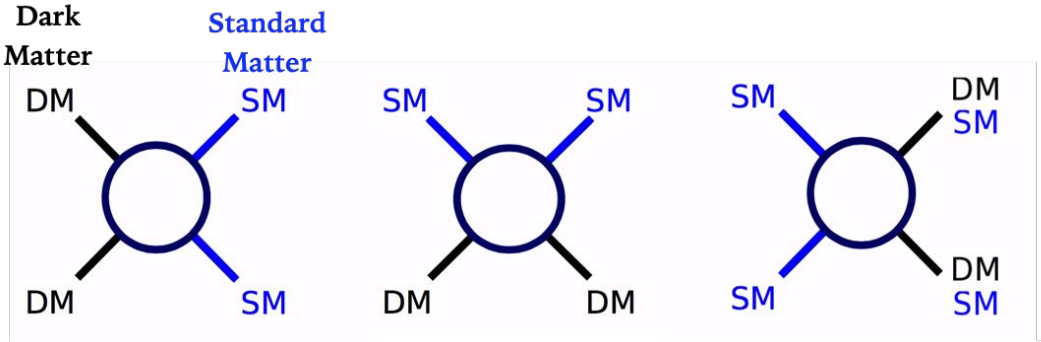
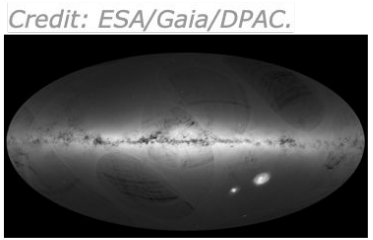
DM@colliders in the broader Snowmass context

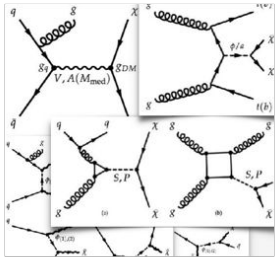
Observations, experiments and theories all needed for DM discovery

- 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





Astrophysics



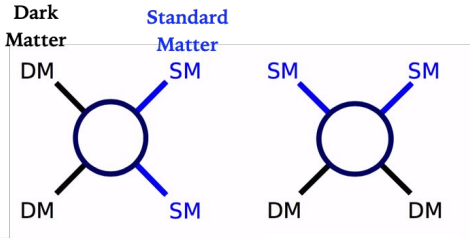
Theory

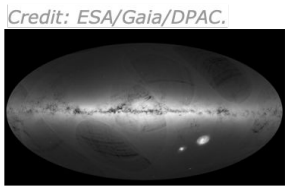
DM @ Colliders: continued exploration of *different experimental signatures of DM* at *different energy scales* (MeV -- TeV), motivated by many *different DM models* (WIMP-like, SUSY, dark sectors…)

PM

DM@colliders in the broader Snowmass context

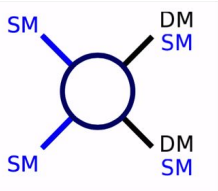
Observations, experiments and theories all needed for DM discovery





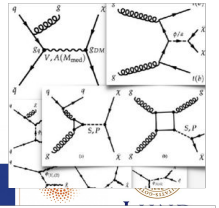
Astrophysics

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)



Theory

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

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

How we started our work: discussion of benchmarks

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

- Necessary to coordinate the work in practice, given the breadth of DM explanations
  - At colliders, different benchmark models give different signatures → different searches
- Necessary 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):**

- 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
→ we want to be as inclusive as possible while keeping an eye on big picture

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
- We are working towards providing **technical help** to the collaborations/interested parties
  - e.g. model repository, common code pipelines (with CompF07?)
    - Interest within EF10, see e.g. this talk at the Preparatory Meeting and this LOI

See **Simplified Models discussion** (& intro by Suchita Kulkarni) at EF08-10 parallel sessions at the EF Workshop [notes here]

Studies that **highlight potential differences wrt common benchmarks**

- Not necessarily comprehensive in terms of experimental coverage
- E.g. highlight different complementarity or different signatures

Studies that **point out novel / less-explored DM models**

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 between DM@colliders & others
   - 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]

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 ~ 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 ~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!)

Ongoing work on DM simplified models

DM Simplified models at colliders

EF/SNOWMASS21-EF10_EF0_Peiwen_WU-103.pdf - **Search for t + j + 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!)

Ongoing work on complementarity

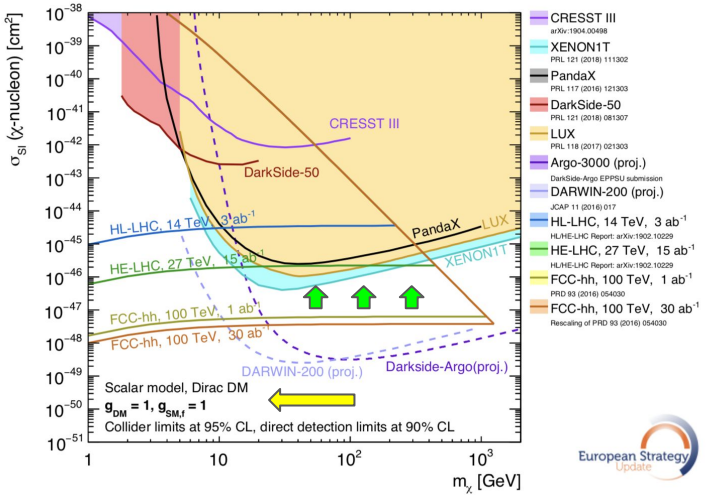
From European Strategy BSM and DM working groups:

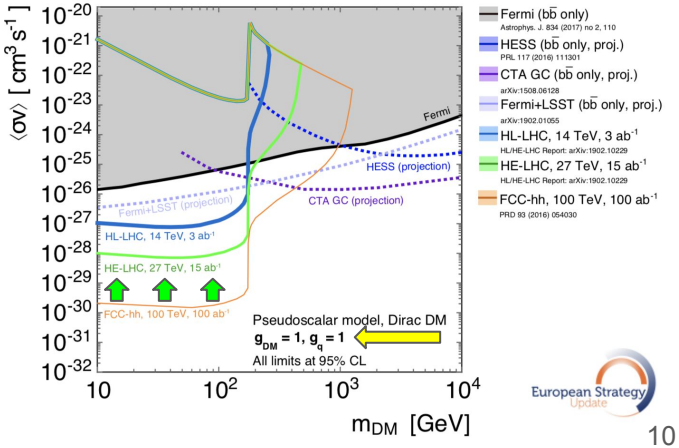
- Plots including collider / direct / indirect detection results, using a simple WIMP-like model scenario (pseudo/scalar SM-DM mediator with fixed o(1) couplings)
- After discussions with other communities, will be updating plots to lower coupling hypotheses to better connect to other DM searches e.g. 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))

http://cds.cern.ch/record/2691414/files/Briefing_Book_Final.pdf





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

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

Slack channel: #ef10-dark_matter under https://snowmass2021.slack.com

Email list: 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)

Beyond WIMPs: two main directions

[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 (< GeV)

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