Dark matter complementarity: Energy Frontier Perspective

Suchita Kulkarni (she/her) (University of Graz) @suchi_kulkarni
Input from:
Caterina Doglioni (she/her) (University of Manchester and Lund University) @CatDogLUofM

2022/07/19 - DM Complementarity Session, Snowmass Community Summer Study

Energy Frontier: overall goals and vision

From [M. Narain's talk at last Energy Frontier Community meeting](#)

Goal: study fundamental physics in two interrelated directions:
- Precise measurements of **known phenomena**
  - Includes measurements of the Higgs boson (10 year discovery anniversary this month)
- Search for evidence of **Beyond the Standard Model Physics**
  - Dark matter as a motivation

Tools: high energy colliders and related experiments (very simplified view below)
- Electron-positron colliders: best for precision measurements, "indirect" searches for BSM
- Hadron colliders: best for physics processes needing highest energy reach
- Muon collider (new studies for Snowmass): ambitious / challenging mix of the two

Community:
- Large number of scientists working in collaborations, many different expertises needed
  - Early career component numerical majority in current experiments
- Benefits from investments on technology and theoretical innovations

Energy Frontier: general priorities

From [M. Narain's talk at last Energy Frontier Community meeting](#)

Immediate future: **High Luminosity LHC**
- Deliver on P5 priority from last Snowmass
- Fully realize the LHC scientific potential in terms of Higgs boson couplings, searches for new particles (including DM), precision measurements as a stepping stone to future colliders

Intermediate future: **An electron-positron collider**
- Explore the Higgs in depth (couplings, BSM decays…)
- Search for deviations in SM predictions pointing to new physics

Longer term: **A multi-TeV discovery machine (hadron or muon collider)**
- Explore BSM physics at the highest possible energy scales
- Produce new fundamental particles responsible for e.g. electroweak symmetry breaking

Large scale of projects → international labs/collaborations necessary
but ambition to host future collider(s) in the US following strong involvement in LHC program

Dark matter at colliders (EF10)
The DM case studies that contributed to EF vision and priorities

1. What colliders and detectors do we need to test the **WIMP** paradigm?
   - Through the simplest/minimal **WIMP models** (EW multiplets) and their extensions
   - Using **simple BSM 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. What colliders and detectors do we need to explore **beyond-WIMP** scenarios?
   - Using portals that privilege **light 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 EF10 & other TGs and Frontiers
   - In terms of different experiments / observations to understand the nature of DM
   - In terms of detector, data acquisition and trigger design

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We received 14 contributed whitepapers from the community
Link to EF BSM report draft , comments can be added here

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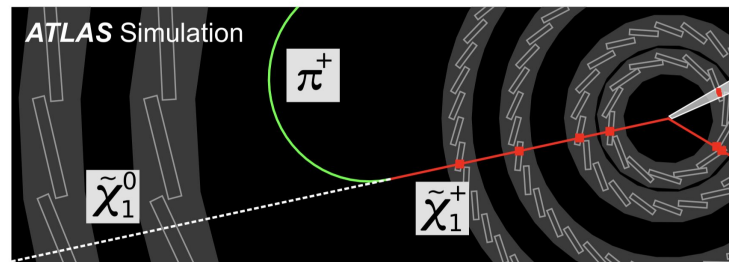# Simple WIMP: electroweak multiplet

Viable **thermal relic WIMP candidate**:
pure Wino/Higgsino in SUSY models <small>and other minimal models of DM</small>

Example of Higgsino - grey lines represent thermal relic
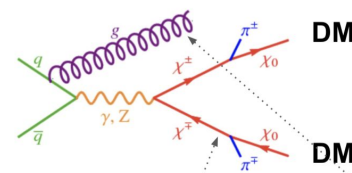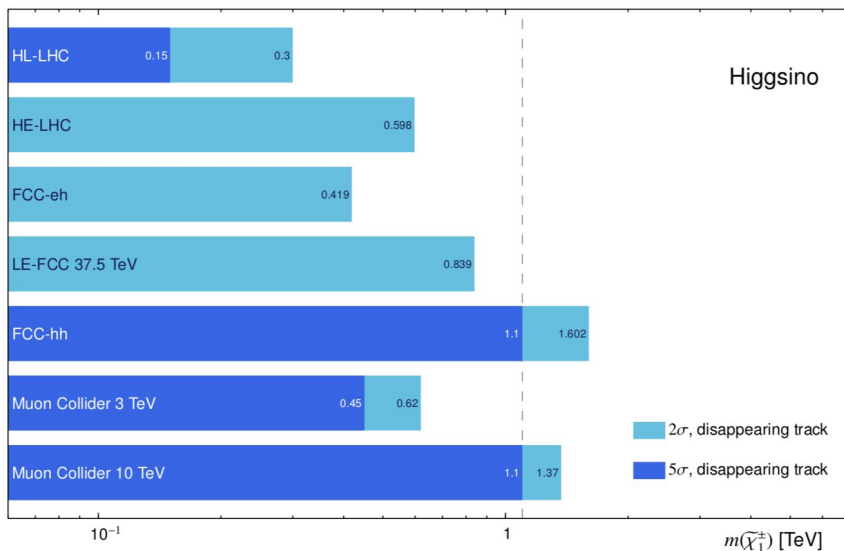
Signatures: **disappearing track, X+MET**

FCC-hh and muon colliders can probe the full thermal parameter space for these models, also using **disappearing tracks**
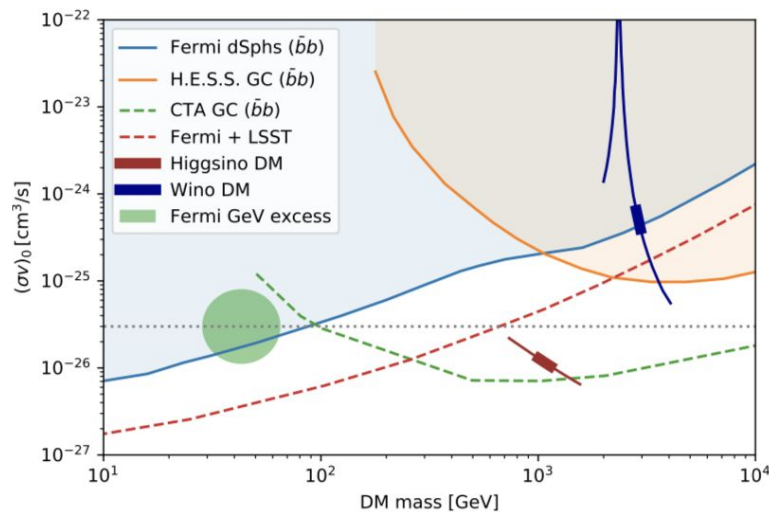

→ important to design detectors that are able to detect **unusual signatures**

Complementarity for electroweak multiplets

Example of Higgsino - red lines represent thermal relic, orange is current direct/indirect detection reach
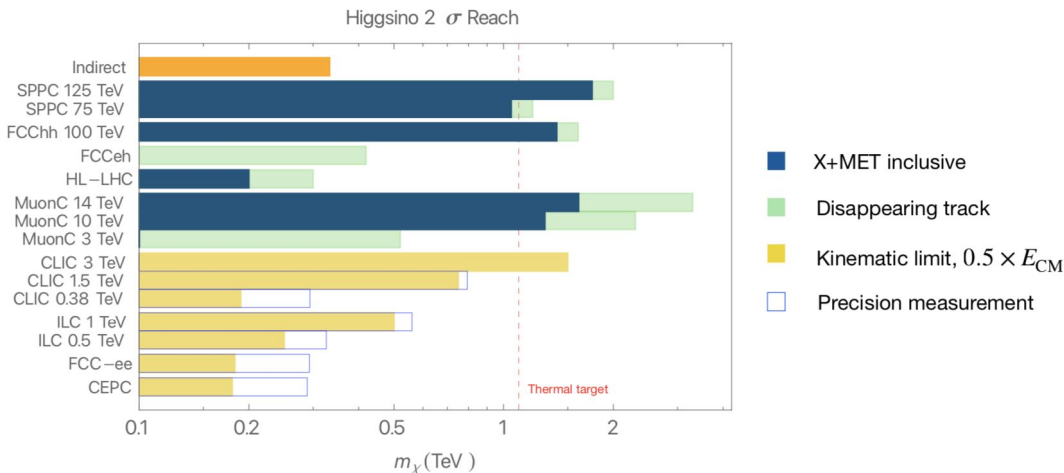
From European Strategy Briefing Book

Future hadron and muon colliders can probe the thermal WIMP
In a way that would **complement a discovery in future indirect detection experiments**

Dark matter mediated by new (BSM) particles

- At collider energy scales, we can resolve the (new) particles that mediate the SM-DM interactions
    - Mediator can decay into DM → excess in missing energy
    - Mediator can also decay into SM particles → resonance searches
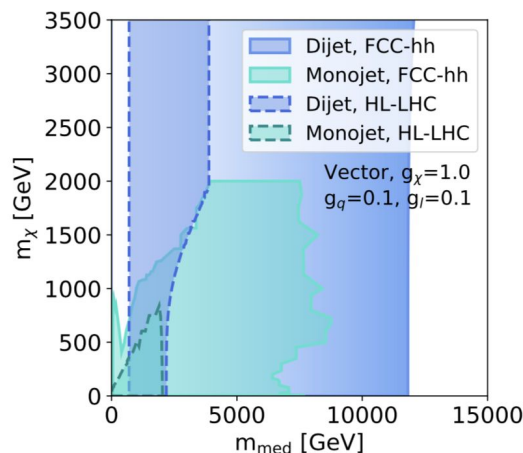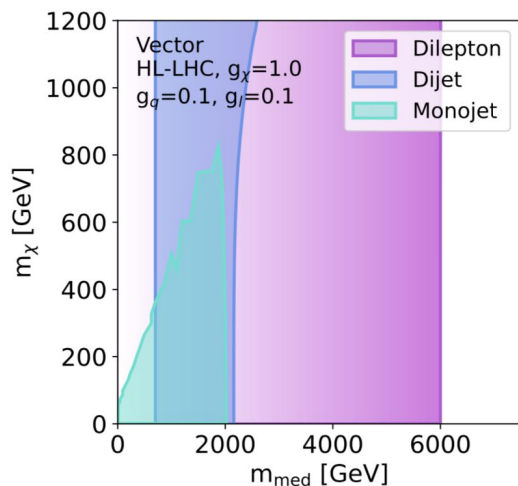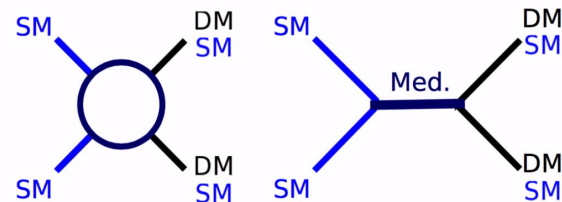
Example scenarios for reach of future colliders for s-channel vector mediator:

- ***Dilepton, dijet:** searches for **visible** decays of the mediator*
- ***Monojet:** searches for **invisible** (DM) mediator decays*
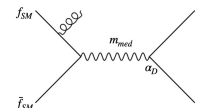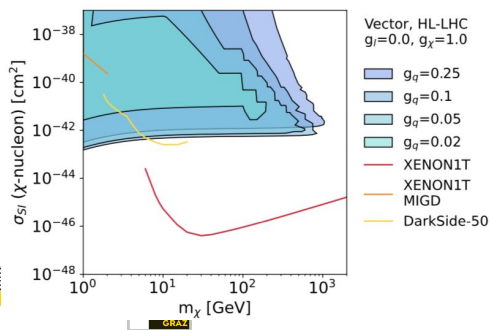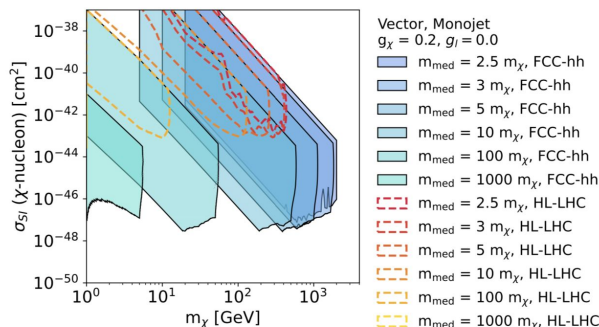
Complementarity in BSM mediated DM models

One can (in a model-dependent way) overlay results from collider simplified models searches to DD results in DM-nucleon plane

- New for Snowmass: scan parameters to understand extent to which statements are model-dependent

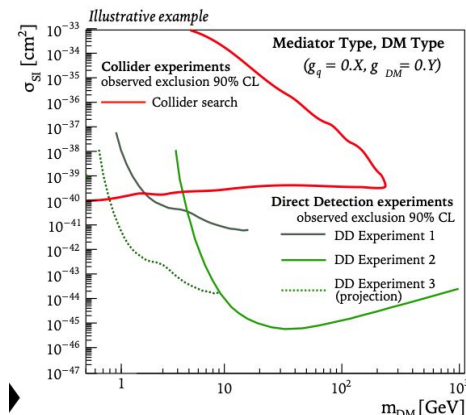**Overall message** does not change (from European Strategy): best region to discover DM is where **both** colliders and DD have coverage

- This allows us to determine both **cosmological origin** of discoveries as well as **nature of interaction**

Scanning couplings

Scanning DM/mediator mass ratios

Potential common sketch
(lines can be made more realistic)

Light(er) dark matter at colliders

- **Dark photon**: simple and minimal portal to dark sectors, focus on light dark matter
- Using the same benchmark parameters between EF and RPF, colliders and accelerator experiments have **complementary sensitivity** to **broad range of DM masses**
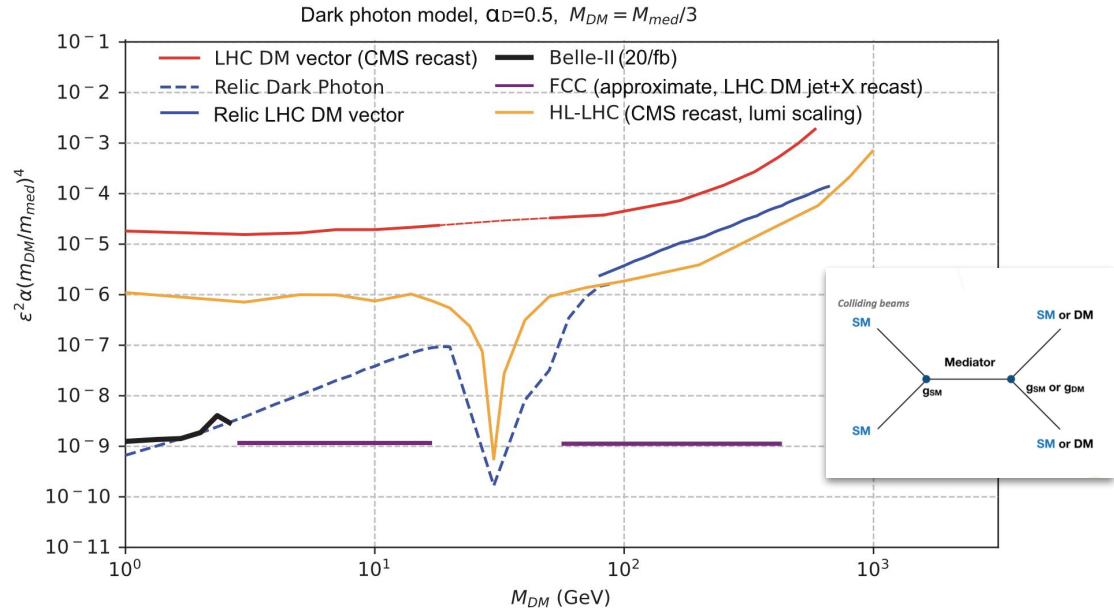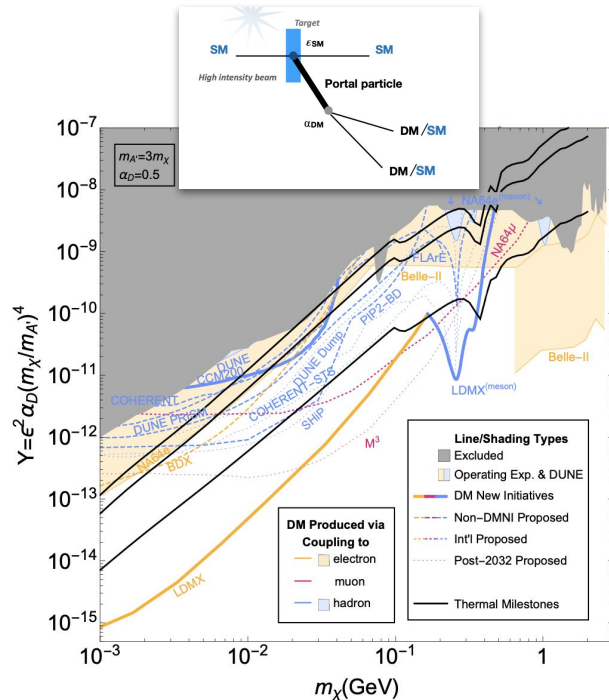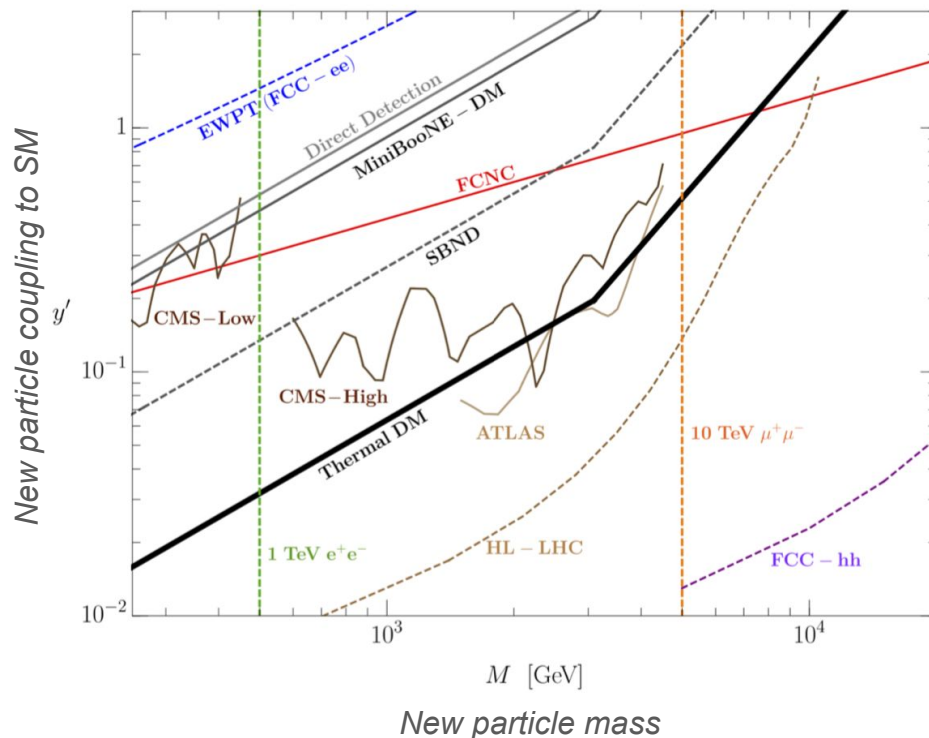
# Light(er) dark matter at colliders: completions

Example of dark scalar mediator model preferentially coupling to up-type quarks: thermal DM target can be reached with HL-LHC

Some "portal" models of light dark matter (dark photon, dark Higgs) require **new high mass particles** to be **theoretically self-consistent**

Colliders can **discover** directly the **high-mass particles**, complementing light DM discoveries at e.g. accelerator experiments


New particle mass

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Dark Matter Complementarity, Energy Frontier perspective - Suchita Kulkarni, Caterina Doglioni

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Dark sectors and dark showers (developments within Snowmass)

Dark QCD scenarios predict dark matter as a bound state emerging due to confinement

- Early [ATLAS](#) and [CMS](#) results exist

- First steps towards consistent collider analysis taken during Snowmass ([Dark showers project and meetings](#))

- Overlap between energy and **cosmic frontier** not yet clear → more work needed

- Excellent opportunity to exploit synergy with **accelerator searches**

- Some understanding via **lattice QCD calculations** for properties of SU(N) theories exists


Thermal Dark Matter, $\Omega_\pi = \Omega_{DM}$
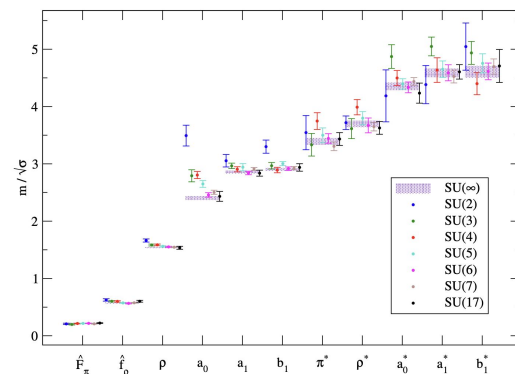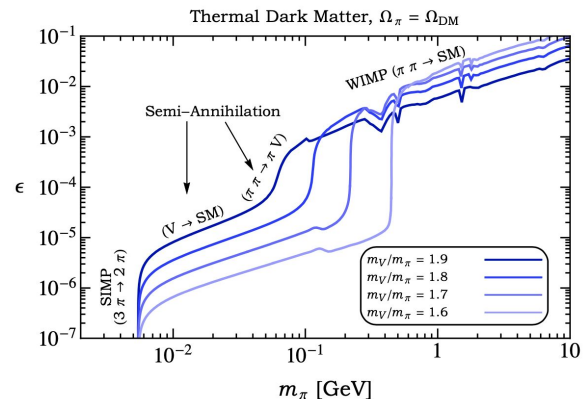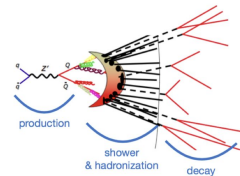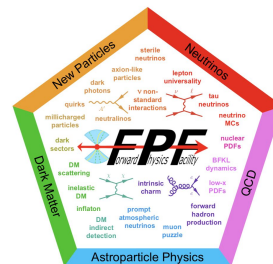
DM experiments co-located at colliders

Facilities with smaller experiments **built near / exploiting collider beams** → **spatial complementarity**

*example: the **Forward Physics Facility** for HL-LHC*

- Make the most of civil engineering at future colliders
- **Maximise the physics potential** e.g. with "dark matter beams" in the forward region
  - Many different dark matter models within reach

Complementary coverage for central / forward / transverse in long-lived particles for e.g. dark sector
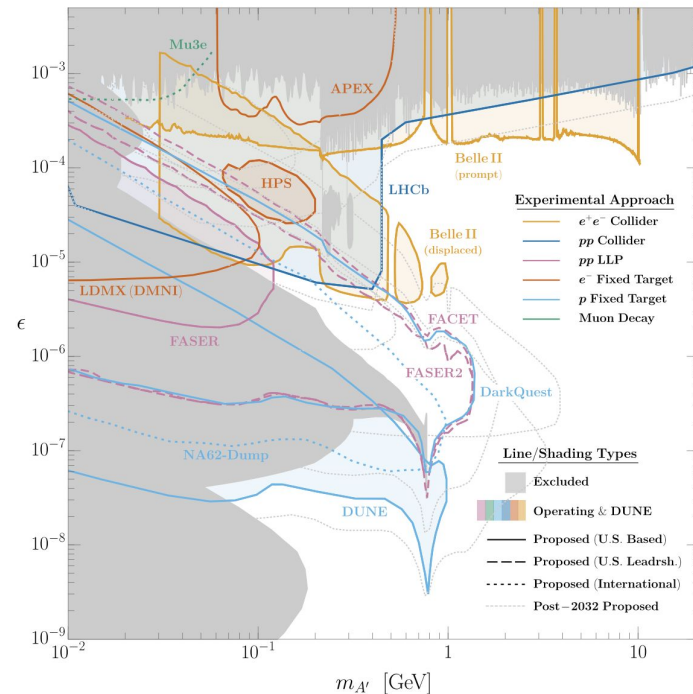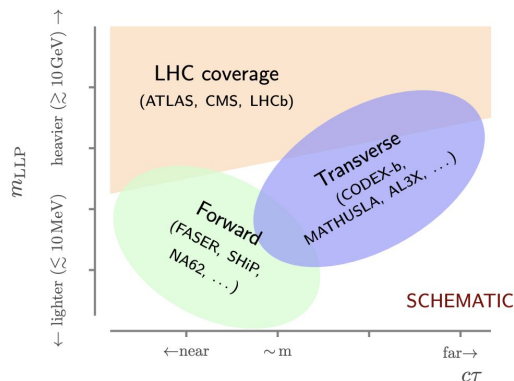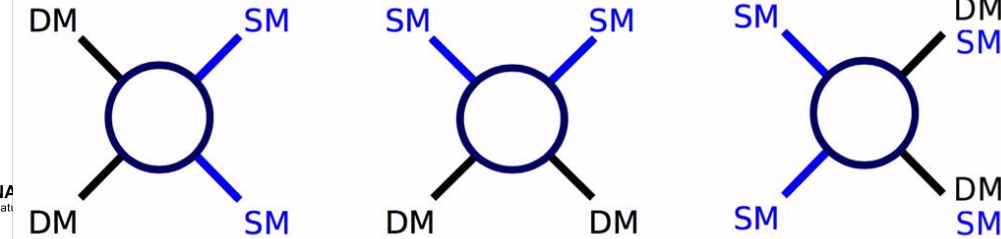

Visible dark photon decays

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How EF can advance DM discoveries, together with other Frontiers

Multiple observations, experiments and theories all needed for DM discovery

- Observations motivating/locating DM come from astrophysics & cosmic probes
- Theoretical frameworks are necessary to put different observations in context
- Direct Detection can discover DM with cosmological origin
- Indirect Detection can probe decays of cosmological DM into SM particles

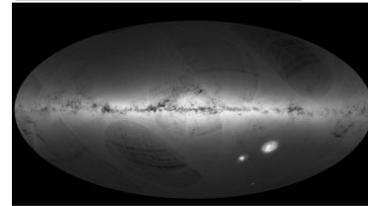- **Colliders / accelerators can produce DM and probe its dark interactions**
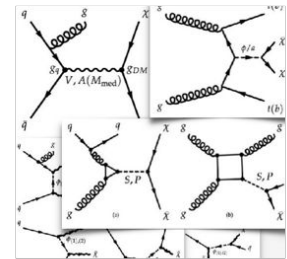
How EF can advance DM discoveries, together with other Frontiers

- By developing **search program across energy scales**, as unbiased as possible
- By extending searches for **DM particles** with the **highest possible masses** that can be **produced in the lab**
- By **constraining properties of SM - DM mediators** and **portal** interactions
- By defining **common working points and benchmarks**
  - such that it is easier to translate messages from one frontier to another and cross-correlate signatures
- By encouraging **topical cross-frontier activities beyond Snowmass**
  (example of iDMEu in Europe, supported by ECFA/APPEC/NuPECC)
  - This could include keeping the discussions on infrastructure/detectors/computing going beyond Snowmass