Dark Matter at colliders

and synergies with other experiments

CATERINA DOGLIONI - LUND UNIVERSITY

WITH RESULTS FROM ATLAS, CMS, LHCB

Inputs and discussion:

European Strategy PPG BSM/DM/Higgs, ATLAS Collaboration, Jean-Jacques Blaising, Antonio Boveia, Oleg Brandt, Linda Carpenter, Boyu Gao, Ulrich Haisch, Phil C. Harris, Isabelle John, Matt McCullough, Jocelyn Monroe, Hideki Okawa, Marco Rimoldi, Ulrike Schnoor, Emma Tolley, Francesca Ungaro, Andrea Wulzer, Christoph Weniger

Outline

Introduction: why searching for Dark Matter at accelerators

Dark matter at colliders: present and future for chosen **WIMP** benchmarks

- Present and future collider **results in context** of direct and indirect detection

Non-WIMP (examples): ideas and prospects at colliders and accelerators

Synergies between particle and astroparticle physics strategies for DM

Introduction

Outline

What do we know about **dark matter**?

[quite a lot, judging from the research in the Manchester particle physics group]

it is dark

it is dark

it has mass

Images: NASA/ESA

it has mass

Images: NASA/ESA

it is dark

it is needed to describe galaxy structure formation

simulations were performed at the National Center for Supercomputer Applications by A. Kravtsov and A. Klypin.

The Nobel Prize in Physics 2019

Ill. Niklas Elmehed. © Nobel Media.

James Peebles

Prize share: 1/2

"for theoretical discoveries in physical cosmology"

https://sci.esa.int/s/Wnqq4bw

Images: NASA/ESA

it constitutes most of the matter in the universe

many are writing about it

https://benty-fields.com/trending
Papers on the arXiv with the words in the title or abstract
Credits for finding it: Xenon1T, Twitter
Disclaimer: website not to be used as input by funding agencies

it may be a new particle not yet in the Standard Model...

...but the only hints we have about it are from astrophysics → synergies needed

Thermal relic WIMP at colliders

Motivation for DM@colliders & assumptions

- Generally characterise the DM particle as follows:
  - **interacts with SM** particles → we can **produce and detect it** at

Particle colliders (a subset of accelerators) { **LHC**, KEK, ILC, CLIC, CEPC, FCC… } **ATLAS**, **CMS**, **LHCb**, Belle-2, Future } Collider experiments

known particle collision

production of DM particles

Caveat: very simplified diagram

Motivation for DM@colliders & assumptions

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Particle colliders (a subset of accelerators) { **LHC**, KEK, ILC, CLIC, CEPC, FCC… } **ATLAS**, **CMS**, **LHCb**, Belle-2, Future } Collider experiments

- is dark, stable → **invisible to detectors**

- *[may be a matter of preference]* is a thermal relic → **W**eakly**I**nteracting**M**assive**P**articles
  - a number of other relic hypotheses exist!
  - many other particle models as well
    (can easily change: WI→Feebly Interacting, M → Lighter, P → Quasi-particle)

Searches for ~~DM~~ invisible particles at colliders

Signature of invisible particles
(like Dark Matter):
missing transverse momentum (E_T^{miss})

Good performance of missing transverse momentum crucial for DM searches
e.g. reject fake E_T^{miss}

- Why calling DM "new invisible particle"?
  - production & discovery of new invisible particle needs **confirmation of cosmological origin** (see later slides)
- We can then interpret the results according to DM models

Categories of collider searches & models

Generic searches ⟷ More specialised searches

- Good for **simple models** with **sizable cross-sections**
- **Fewer assumptions** on specific model characteristics

- More sensitive to **specific models**
- More reliant on **model assumptions**

→ the way we think of benchmark models **influences collider searches**

Simple models ⟷ More complex/complete models

Broad categories of collider searches

Generic searches ⟵ ⟶ More specialised searches

- Good for **simple models** with **sizable cross-sections**
- **Fewer assumptions** on specific model characteristics

- More sensitive to **specific models**
- More reliant on **model assumptions**

In this talk
I will focus on **generic searches** for **simplified WIMP models**
(more options in backup)

→ the way we think of benchmark models **influences collider searches**

Simple models ⟵ ⟶ More complex/complete models

Choice of benchmarks

https://abstrusegoose.com/406

"Why should we choose/believe the simplest models?"
"Do we think DM is all made of a single WIMP model?"

(not really…see **dark sectors**!)

- **Lesson from SM:** most common particles discovered first

from DM ATLAS feature

- Even simple models can encapsulate **relevant experimental characteristics** representing wider classes of theories

as long as we are aware that they can be more rare than what we choose as example

Generic production of invisible particles at LHC

Production of invisible particles is common in the SM

Eur. Phys. J. C 77 (2017) 765

Generic production of invisible particles at LHC

Production of invisible particles can be common in the SM
use **standard candles** (Z boson) to search for non-SM production

$$R^{\text{miss}} = \frac{\sigma_{\text{fid}}\left(p_{\text{T}}^{\text{miss}} + \text{jets}\right)}{\sigma_{\text{fid}}\left(\ell^+\ell^- + \text{jets}\right)}$$

Eur. Phys. J. C 77 (2017) 765

Generic searches for DM: "*X+MET*"

ISR (jet, photon, V boson...) + MET signature
- Background normalized using data
- Background shapes need precise theory predictions EPJC 2017 77:829
- Results can be interpreted in a variety of models - here: vector mediator

Phys. Rev. D 97, 092005 (2018)

arXiv:1807.11471

Dark Matter mediators at the LHC

If there's a force other than gravity, there's a **mediator**,
and the LHC could **detect** it:
simplified models are popular Run-2 LHC search benchmarks

Phys. Dark Univ. 26 (2019) 100371
https://lpcc.web.cern.ch/content/dark-matter-wg-documents
Annual Review of Nuclear and Particle Science, Vol. 68:429-459, 2018

Bread & butter of high-energy colliders: di-object searches

di-jet

http://arxiv.org/abs/1911.03947

di-electron

Phys. Lett. B 796 (2019) 68

di-muon

Phys. Rev. Lett. 120, 061801 (2018)

diboson

JHEP 09 (2019) 091

Also: di-photon, weird jets....

Future: simplified models w/mediators

Axial vector

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma_5 q \,.$$

Scalar/(pseudoscalar)

Yukawa couplings

$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}q \,,$$

M. McCullough's talk at EPPSU Granada

Note: strong constraints from visible searches depend on the coupling between SM and DM

Complementarity of visible/invisible searches

Illustrative example

LHC Dark Matter Working Group
https://arxiv.org/abs/arXiv:1703.05703

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Keep in mind: different couplings —> different picture

Motivation for innovating trigger system

Illustrative example

s-channel simplified models motivated **further use of innovative data taking techniques**

doing **a lot of work** to get to this data **needed a good motivation**

Project acronym	DARKJETS
Project	Discovery strategies for Dark Matter and new phenomena in hadronic signatures with the ATLAS detector at the Large Hadron Collider
Researcher (PI)	Caterina Doglioni
Host Institution (HI)	LUNDS UNIVERSITET
Call Details	Starting Grant (StG), PE2, ERC-2015-STG

Searches for DM particles
Dijet searches for DM mediators
Low-mass dijet searches for DM mediators

LHC Dark Matter Working Group
https://arxiv.org/abs/arXiv:1703.05703

Motivation for innovating trigger system

LHC Dark Matter Working Group
https://arxiv.org/abs/arXiv:1703.05703

Interlude: a look at the Standard Model

Online | Offline

Event selection (trigger) → Object reconstruction and calibration → Data analysis

Data I like

Data I would have used to like if I had been a data hipster

Data you like

What we can record in full after the trigger

Data ~nobody likes

Data produced by the LHC

(multiplied by large number)

Online ◀ ▶ Offline

Event selection (trigger) ▶ Object reconstruction and calibration ▶ Data analysis

Data produced by the LHC

(multiplied by large number)

Data I like

including DM mediators decaying to dijets

Data I would have used to like if I had been a data hipster

Data you like

What we can record in full after the trigger

Data ~nobody likes

How LHC collaborations make the most of the data

Interesting time for high energy accelerator physics:
we don't know what to expect from DM/new physics
(but we have a prior: it should be *somewhere*)
we have the **LHC running now**,
and the data we discard is **gone forever**

Trigger-level Analysis (ATLAS),
Turbo stream (LHCb),
Data Scouting (CMS)

1. Analyze as much data as possible, **as fast as possible**
2. Save data for **further reconstruction, later**
3. Implement more refined algorithms to **look for the unexpected**
   - Including unsupervised searches / novelty detection

Visible/invisible searches for DM (mediators)

http://cds.cern.ch/record/2684864?ln=en

Keep in mind: these plots are only valid for the couplings specified, in the **limited case of a benchmark model**!

Sensitivity possible thanks to non-standard analysis workflows

Complementarity in WIMP searches

Complementarity for ~~invisible particle~~ WIMP searches

WIMP solution, guided by **thermal relic density**:

Weakly Interacting Massive Particles

=

Dark Matter particles invisible to detectors,

with masses at the **TeV scale**

Indirect Detection

Direct Detection

Colliders

Credit: ESA/Gaia/DPAC.

Astrophysics

Theory

Complementarity for ~~invisible particle~~ WIMP searches

WIMP solution, guided by **thermal relic density**:

Weakly Interacting Massive Particles

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Indirect Detection

Direct Detection

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Credit: ESA/Gaia/DPAC.

Astrophysics

Theory

Complementary experimental strategies & inputs

All needed, given what we don't know about DM!

Colliders, direct and indirect detection

- Why DM discoveries need complementary experiments:
  - DD/ID can discover DM with **cosmological origin**

Indirect Detection Direct Detection Particle Colliders

Colliders, direct and indirect detection

- Why DM discoveries need complementary experiments:
  - DD/ID can discover DM with **cosmological origin**
  - Colliders can produce DM and **probe the dark interaction**

Indirect Detection Direct Detection Particle Colliders

Colliders, direct and indirect detection

- Why DM discoveries need complementary experiments:
  - DD/ID can discover DM with **cosmological origin**
  - Colliders can produce DM and **probe the dark interaction**

Indirect Detection Direct Detection Particle Colliders

Complementarity needs a theoretical framework!

Complementarity of DM experiments

How do we compare results of different experiments
~~in the most model independent way possible?~~

Comparisons are possible only in the context of a model
Essential to **fully specify model/parameters** and **be aware of limitations**

For more thoughts on upper bounds to collider sensitivity:
arXiv:1810.07705 and DMWG meeting June 2017

Complementarity of colliders with direct (indirect) detection performed **within the chosen benchmark models & parameters**

(work started in ATLAS together with Manchester colleagues: how to visualize different assumptions?)

Scalar mediator, hadron colliders and direct detection

- Limits on scalar mediator mass/scale can be translated to limits in the DM-nucleon plane

$$\sigma_{\rm SI} \simeq 6.9 \times 10^{-43}\ {\rm cm}^2 \cdot \left(\frac{g_q g_{\rm DM}}{1}\right)^2 \left(\frac{125\ {\rm GeV}}{M_{\rm med}}\right)^4 \left(\frac{\mu_{n\chi}}{1\ {\rm GeV}}\right)^2 .$$

arXiv:1603.04156

Inputs and code from: M. Rimoldi, F. Ungaro, I. John, E. Tolley

ttbar+MET

V/jet+MET

Keep in mind: these plots are only valid for the couplings specified, in the limited space of a benchmark model!

Scalar mediator, hadron colliders and direct detection

Synergy: complementary reach for future colliders and direct detection

- **Collider discovery** of invisible particle needs **confirmation of cosmological origin** from DD/ID
- **DD/ID discovery** needs collider **understanding of nature of interaction**
- A **future collider program** that increases sensitivity to invisible particles **coherently with DD/ID** serves these purposes
- Synergies with also in **non-WIMP DM**, for DD and beam dump experiments: [Physics Beyond Colliders]

Scalar mediator, hadron colliders and direct detection

Synergy: complementary reach for future colliders and direct detection

Inputs and code from: M. Rimoldi, F. Ungaro, I. John, E. Tolley

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- Synergies also in non-WIMP DM, for DD and beam dump experiments: see later slides for discussion on **Physics Beyond Colliders WG**

Increasing understanding between communities

Often said about Direct (Indirect) Detection results: "DD experiment subject to astrophysical uncertainties, how much do they matter when comparing to collider searches?" Note: collider searches (not displayed) have uncertainties too

Isabelle John, Lund University Master's thesis, with M. Benito's help and inputs, updates in M. Benito's talk @ GGI 2019

Figure 5.1: Exclusion plot with direct detection searches, including all deviations and uncertainty bands for direct detection limits.

"complementarity" message does not change even with uncertainties, but **interplay and discussion on astro theory & observations with DD/ID needed**

Direct detection: looking *down* (to rarer WIMPs)

- Major updates to direct detection experiments planned
  - in terms of **detectors** F. Petricca's talk @ GGI 2019
  - in terms of **reduction of challenging backgrounds** E. Baracchini's talk @ GGI 2019

J. Phys. G43 (2016) 1, 013001& arXiv:1509.08767

Image from F. Petricca's talk @ GGI 2019

European Strategy Update Briefing Book

Wish: A common **detector technology forum / test beams** within CERN platform can **benefit the DD community**

[implementation needs agreement & discussion, as we heard yesterday in the Q&A]

Indirect detection: looking *down* (to rarer WIMPs)

- Major updates to indirect detection searches planned
  - in terms of **survey of DM-rich objects** A. Schneider's talk @ GGI 2019
  - in terms of **reduction of challenging backgrounds** F. Calore's talk @ GGI 2019, M. Cirelli's talk @ GGI 2019

European Strategy Update Briefing Book

Are we looking everywhere?

What might we learn from lines of research that are off the beaten track? They check accepted ideas, always a Good Thing, and there is the chance Nature has prepared yet another surprise for us.

J. Peebles

Are we looking everywhere?

up: stronger interactions

What might we learn from lines of research that are off the beaten track? They check accepted ideas, always a Good Thing, and there is the chance Nature has prepared yet another surprise for us.

J. Peebles

left: lower masses

right: more massive objects

Looking *left* (to lower DM masses)

"Traditional" DM-SM recoil direct detection searches lose sensitivity to low-DM masses, but...

- detectors can be **more sensitive** to lower thresholds (e.g. phonon-based calorimeters) F. Petricca's talk @ GGI 2019
- **subdominant effects** can enhance "kick" from DM E.g. arXiv:1702.04730, 1707.07258, 1905.00046, 1810.07705, 1810.10543...
- can explore **new materials & detectors** → collaboration of **astrophysics** & **solid state physicists** E.g. arXiv:1709.07882

Image from F. Petricca's talk @ GGI 2019

Other light DM benchmarks & prospects

- Non-WIMP benchmark models for **dark sector** searches:
  - e.g. Dark photon, Heavy Neutral Lepton, Heavy Higgs, Axion-like particles
- Benchmark with thermal dark matter interpretation: dark photon
  → **complementarity of collider, non-collider and astro experiments**

mixing between SM and dark sector

Invisible dark photon decays

Physics Beyond Colliders Working Group
arXiv:1901.09966

Even lighter DM: axions

Axions/Axion-Like Particles (ALPs):
example of new particle
with inter-field connections,
solving more than the DM problem

I. Irastorza's talk @ EPS-HEP 2019

also using nuclear physics experiments (EDM rings)
or novel dielectric materials

New: sensitivity of haloscopes
to **"dark matter" axions**

Wish: beneficial to connect many **smaller experiments,**
in terms of **joint expertise** and **common discussion platforms**

Looking *up* (to hints from astrophysics & more)

"Looking up" as a consequence of "looking left":

change of paradigm from "DM == invisible particles"

https://arxiv.org/abs/1905.06348

very low-mass but "strongly interacting" DM particles will

- interact with **detectors**
  - need to take this into account for WIMPs@colliders
- interact with **atmosphere & earth**
  - use/send detectors higher up!
- be detectable using **astrophysical signals**
  - SN (supernova), BBN, CMB...

Example of "dark shower" search @ LHC

Theory:
a variety of models for "*dark QCD*"
stable *dark hadron* = DM candidate
example: emerging jets

https://arxiv.org/pdf/1502.05409.pdf

Experiment: select events
with regular & displaced jets

https://arxiv.org/abs/1810.10069

Regular jets

Emerging jets

Displaced jet

Regular jet

Regular jet

Displaced jet

(no evidence for new phenomena)

Looking *right* (to much more massive objects)

G. Losurdo's talk @ JENAS 2019

Gravitational wave experiments / **multimessenger** astronomy:

- Revolutionary combination of information on the cosmos
- experiments can shed light on **DM with a wide range of masses**

arXiv:1907.10610

Ongoing synergistic initiatives

Support for synergistic initiatives

Astroparticle (APPEC)

Particle (ECFA)

Nuclear physics (NuPECC)

Astroparticle, particle and nuclear physics in Europe have **strategies and plans** that **recognize the importance of synergies** between the different fields

US: ***Snowmass*** effort starting soon, (for *DM at Colliders* WG:

)

More synergies: ”foundations” for common challenges

Astroparticle

Particle

Nuclear

Common theory ground

instrumentation
(accelerators, beams, detectors, vacuum & cryogenics, control & automation...)

data acquisition, software, computing, data sharing & open science

Approaching synergies from different perspectives

searches & interpretation

JENAS EoI: Initiative for Dark Matter in Europe and beyond: Towards facilitating communication and result sharing in the Dark Matter community (iDMEu)

https://indico.cern.ch/event/869195/
ESCAPE newsletter APPEC newsletter

build a discussion platform to facilitate collaboration of existing groups/efforts on **dark matter searches** and **interpretation**

Approaching synergies from different perspectives

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ESCAPE
European Science Cluster of Astronomy & Particle physics ESFRI research Infrastructures

HSF
HEP Software Foundation

Towards a Dark Matter Test Science Project

ESCAPE Progress Meeting, 2020

software & data

compare **end-to-end analysis workflows** for WIMP searches, towards their implementation in a common **Software Catalogue** and as input to the design of the **European Open Science Cloud**

More initiatives and links in backup slides

European Research Council
Established by the European Commission

ATLAS EXPERIMENT

Conclusions and take-home points

The search for DM@colliders, even of WIMPs alone, is **not yet over…**

…now it's the time to **look for the rare & unusual**

larger datasets, "precision searches"

improved detectors, triggers & analysis tools

Now and future: essential **physics complementarity** across different experiments

cosmological origin
DD/ID/astrophysics

and

nature of the DM-SM interaction
colliders(/beam dumps)

but also on **tools**, given **shared theory, experimental & computing challenges**

Much room to contribute as new initiatives are starting: **get in touch** if interested!

JENAS EoI: Initiative for Dark Matter in Europe and beyond: Towards facilitating communication and result sharing in the Dark Matter community (iDMEu)

Thanks for your attention (and thanks to the junior physicists who worked with me on many of these results)!

ATLAS DM results: the DARKJETS Team (Lund)

William Kalderon, Eric Corrigan, Eva Hansen, Per Alexander Ekman (not pictured: Jannik Geisen)

Direct Detection plots: Isabelle John (Lund)

with Emma Tolley, Antonio Boveia, Jocelyn Monroe, Maria Benito

Scalar mediator plots: Marco Rimoldi (DESY)

with Francesca Ungaro, Hideki Yukawa, Oleg Brandt

Indirect Detection plots: Boyu Gao (OSU)

with Emma Tolley, Linda Carpenter, Antonio Boveia, Christoph Weniger

Backup slides

Motivation for DM@accelerators & assumptions

- Generally characterise the DM particle as follows:
  - **interacts with SM** particles → we can **produce and detect it** at

Particle accelerators { SPS, LHC, Future } SHIP, LDMX, NA62/4, FASER, MATHUSLA, CODEX-b, Other ideas… } Planned/proposed experiments

mixing between SM and dark sector

Common benchmarks for collider WIMP searches

Simple models ⟷ More complex/complete models

Simple DM mediation

SM mediator

Z/Higgs portals

Beyond-SM mediator

Vector-like mediator

Scalar-like mediator
and Two Higgs Doublet Models

Supersymmetry

(*Simplified model* diagram)

JHEP 03 (2018) 160

Also: DM models with **long-lived particles / dark sectors**

Benchmarks of choice (for heavy WIMP DM)

"Big question" for the update of the European Strategy of Particle Physics

What cases of thermal relic WIMPs are still unprobed and can be covered by collider searches?

Problem: unable to cover all cases!

- Large number of model possibilities for WIMPs, even limiting to the simplest models (see e.g. LHC Dark Matter Forum/WG documents)

Ann.Rev.Nucl.Part.Sci. 68 (2018) 429-459

- Any benchmarks chosen will be **only examples -** what to choose and why?
  - **Wino/Higgsino DM:** simple extension of SM portals, within SUSY framework
  - **Higgs portal DM:** newly discovered Higgs, simple interaction
  - **Simplified models of vector/scalar-mediated DM:**
    - Vector/axial vector: visible and invisible signatures
    - Scalar: cross-sections are small → good collider probes

BSM mediators, Dirac DM

Vector/axial vector mediators

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q\,,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu\gamma_5\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu\gamma_5 q\,.$$

Scalar/pseudoscalar mediators

Yukawa couplings

$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}q\,,$$

$$\mathcal{L}_{\text{pseudo-scalar}} = -i g_{\text{DM}}\phi\bar{\chi}\gamma_5\chi - i g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}\gamma_5 q\,,$$

arXiv:1603.04156 & references

- How to detect new scalar mediators of DM:
  - **invisible decays** (MET searches)

Vector & scalar: mono-jet or mono-photon searches

Scalar: also in association with heavy flavor quarks
(also: single top, Wt signatures)

  - **visible decays of mediators back to SM**
    - especially relevant in case of dijet/dilepton decays
    - also 2HDM+pseudoscalar (HL-LHC benchmark)

4-top signatures

arXiv:1902.10229 and ATL-PHYS-PUB-2018-036

More complex models: pseudo/scalars in 2HDM

Compelling searches with increase of LHC dataset involve **new particles interacting with DM**, alongside **Higgs boson**

Example: pseudoscalar interacting with DM in a Two (2)-Higgs Doublet Model

LHC Dark Matter Working Group
https://arxiv.org/abs/1810.09420

E.g. search for MET + two b-quarks
ATLAS / CMS
No excess observed yet

LHC dataset sufficient to start being sensitive to this kind of processes, **Run-3 dataset needed** for more

Higgs portal model

arXiv:1903.03616

$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi\bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi\ .$$

$$\Delta\mathcal{L}_S = -\frac{1}{2}M_S^2S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{HSS}\Phi^\dagger\Phi S^2\ ,$$

Lambda for fermion EFT: assumed 1 TeV

- Different kinds of dark matter
  - Majorana fermion DM
  - Scalar DM
  - Vector DM: would need more advanced UV completion, not covered here, see e.g. arXiv: 1512.06853

- How to detect invisibly decaying Higgs:
  - **directly** (MET searches)

VBF signature

Higgs-strahlung signature

  - **indirectly** (deviation of SM coupling through fits, using κ-framework)
    - including only σ x Branching Ratio (BR) measurements/ratios, no high-pT Higgs keeping SM BR fixed, only allow invisible BR to float in the fit (subtracting SM)
- Drawing from work by Higgs Physics Planning Group (PPG), arXiv:1905.03764

Higgs portal DM results with partial Run-2 data

- Only add the DM particle to SM, Higgs = mediator
- Search directly for invisible decays, or indirectly (fits)
- Interpret in terms of different kinds of dark matter

https://arxiv.org/abs/1809.05937

Collider	95% CL upper bound on BR_{inv} [%]	
	Direct searches	Fit to BR_{inv} only
HL-LHC	2.6	1.9
HL-LHC & HE-LHC		1.5
FCC-hh	0.025	0.024
HL-LHC & LHeC	2.3	1.1
CEPC	0.3	0.26
$FCC\text{-}ee_{240}$	0.3	0.22
$FCC\text{-}ee_{365}$		0.19
ILC_{250}	0.3	0.25
ILC_{500}		0.22
$CLIC_{380}$	0.69	0.60
$CLIC_{1500}$		0.41
$CLIC_{3000}$		0.30

arXiv:1903.03616

LHC sensitive to a **Higgs to invisible BR of ~0.2**

SM value: invisible BR ~ 10^{-3}, reachable by **future colliders**

Higgs portal, plot for direct searches

- Limits on BR can be translated to limits in the DM-nucleon plane

$$\sigma_{\chi N} = \Gamma_{\rm inv} \frac{8 m_N^4 f_N^2}{v^2 \beta m_h^3 (m_\chi + m_N)^2} g_\chi\left(\frac{m_h}{m_\chi}\right), \qquad (15)$$

arXiv:1708.02245

where $g_S(x) = 1$,
$g_f(x) = 2/(x^2-4)$, $\beta = \sqrt{1 - 4m_\chi^2/m_h^2}$, $v = 246\,\mathrm{GeV}$

Collider reach and relic density

European Strategy "big question"

What cases of thermal relic WIMPs are still unprobed and can be covered by collider searches?

- Very simple model, so careful with taking relic density at face value
- If Higgs portal is to make up 100% of DM, can exclude using DD and colliders

arXiv:1903.03616

Wino/Higgsino models

arXiv:1802.04097, arXiv:0706.4071, arXiv:1705.04843

- Viable thermal relic WIMP candidate, in SUSY terms: lightest neutralino - pure Wino/Higgsino
  - Also standalone model of "minimal DM" with simple SM mediation

ATLAS Supersymmetry summary plots

M. McCullough's talk at EPPSU Granada

Future: Wino/Higgsino models

arXiv:1802.04097, arXiv:0706.4071, arXiv:1705.04843

- Viable thermal relic WIMP candidate in SUSY terms: lightest neutralino - pure Wino/Higgsino
  - Also standalone model of "minimal DM"

M. McCullough's talk at EPPSU Granada

SUSY examples in DM context: scans & fits

Parameter scans of SUSY model (e.g. electroweak) where LSP = DM candidate

JHEP09 (2016) 175

Global fits including a variety of constraints (e.g. GAMBIT)

$$\mathcal{L} = \mathcal{L}_{\text{collider}}\mathcal{L}_{\text{DM}}\mathcal{L}_{\text{flavor}}\mathcal{L}_{\text{EWPO}}\cdots$$

https://gambit.hepforge.org + Eur. Phys. J. C (2019) 79:395

Example: combined collider constraints on neutralinos and charginos

Many other SUSY searches @ LHC!

ATLAS SUSY results CMS SUSY results

Reinterpretation of collider results

Given the many incarnations of DM @ colliders, very important to **allow theorists to reinterpret search results** in terms of different models

Available on the CMS information server **CMS NOTE-2017/001**

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

2017/11/07

https://cds.cern.ch/record/2242860

Simplified likelihood for the re-interpretation of public CMS results

The CMS Collaboration

ATL-PHYS-PUB-2019-032

ATLAS PUB Note

ATL-PHYS-PUB-2019-032

11th August 2019

RECAST framework reinterpretation of an ATLAS Dark Matter Search constraining a model of a dark Higgs boson decaying to two *b*-quarks

ATL-PHYS-PUB-2019-029

ATLAS PUB Note

ATL-PHYS-PUB-2019-029

5th August 2019

Reproducing searches for new physics with the ATLAS experiment through publication of full statistical likelihoods

Auxiliary material

ATLAS SUSY public results

As part of ATLAS SUSY journal publications auxiliary material is made available in digital format via the HEPData project. This can be accessed via the "Documents" and then "Data points" links. The information in HEPData includes:

- the observed and expected exclusion contour lines,
- the observed upper limits on the signal model cross-section,
- the acceptance and the efficiency (encapsulating detector effects) numbers for selected signal models,
- detailed cut-flows for selected signal models (sometimes only in the "Auxiliary figures and tables" section of the public results webpage),
- with the corresponding SLHA files (new HEPData: click on "Resources"-"Common Resources"),
- [starting in 2017] code snippet with the implementation of the analysis selection at truth-level, as used to produce the acceptance numbers (new HEPData: click on "Resources"-"Common Resources").

Higgsino exclusion summary (Dec 2017). Stop exclusion summary (Dec 2017). High jet multiplicity event from SUSY-2016-13.

The acceptance is calculated using objects at truth-level following the definitions in ATL-PHYS-PUB-2015-013 with the following choices / minor modifications:

- using `undressed' leptons,
- jets: excluding muons and neutrinos,
- missing transverse momentum: include neutrinos from hadrons (e.g. from semi-leptonic b decays).

All experimental effects are absorbed in the so-called "efficiency", which is defined such that the product of acceptance and efficiency is the full selection efficiency calculated using reconstructed objects i.e. including all detector effects.

How does (particle) dark matter look like?

Do we need a particle like this in our LLP models?

- It would be nice...
- ...but it is not needed to justify searching for the model, especially in broad-range searches
  - T. Sjöstrand: "[Hidden Valley] models don't have a direct connection to cosmology, they just "could happen" @ *Lund Dark Sector mini-workshop, last week*

Do we need to make up *all* the DM relic density with this particle?

- Some like Occam's razors...
- This has never been a strict requirement in WIMP models
  - Some reasons: see this talk
- Also: different ways to get at the relic (freeze in/out/...) lead to different (interesting) properties
  - see e.g. asymmetric DM arXiv: 1308.0338

Why DM in long lived particles @ LHC?

Why long-lived particles? (LLP)

Long lifetimes arise from a hierarchy of scales or a small coupling*

Three mechanisms:

- Off-shell decay
- Small splitting (phase space)
- Small coupling

Lessons from the SM:

- generic if there is more than one scale
- Often 3 body decays
- Weak theory prior on lifetime

(e.g. proton decay!)

small coupling

$$\Gamma \sim y^2 \left(\frac{m}{M}\right)^n m$$

Set by symmetry structure, typically n ≥ 4

hierarchy of scales

http://arxiv.org/abs/1903.04497
https://arxiv.org/abs/1810.12602

* could either be a hierarchy or loop suppression

Why are LLPs so interesting at this point?

- many theories predict these mechanisms
- some SM particles have a long lifetime, why shouldn't be BSM ones?
- because they are harder to find!

Dark sectors: semi-visible jets

arXiv:1707.05326
arXiv:1503.00009

~~Take WIMP simplified models, add a LLP~~

Take WIMP simplified models, add a dark sector

both s- and t-channel models studied

- **Reasoning:** DM is part of a more complex dark sector with strong couplings
  - we may have missed it so far because:
    - it could look *QCD-like*: dark fragmentation (may have different substructure)
    - it could look *QCD-background-like* (to MET searches): MET behind jet
  - solution: design searches targeting benchmarks on the r_{inv} spectrum
    - some signal caught by monojet and dijet, but **not optimized**

Dark sectors: semi-visible jets & co

Inspired by C. Fallon's talk @ DMLHC2019 and by this twitter thread

A family of signatures, with DM particles (& more) in the dark shower

Generate using Madgraph WIMP simplified models + Pythia Hidden Valley

Can be searched for in ATLAS and CMS [arXiv:1810.10069]

arXiv:1907.04346, see also: E. Bernreuther's talk @ DMLHC2019

Dark sectors: thermal relic in semi-visible jets

~~Take WIMP simplified models, add a LLP~~

Take WIMP simplified models, add a dark sector with a thermal relic

- **Reasoning**: let's build a model with a suitable DM candidate, avoiding too much dependence on the model
  - Ingredients:
    - A dark QCD with 2 flavors:
      - Stable pions (for DM candidate), unstable rhos (for thermal relic)
    - A TeV-scale Z' coupling to regular and dark quarks
- Still plenty of parameter space for dedicated LHC searches

Signature: semi-visible jets

potential for dedicated LLP searches

Different kinds of (WIMP) communities

C. Tunnell, HSF/WLCG/OSG workshop 2019

From C. Tunnell: Area corresponds to number of people based on most recent publication from any experiment that has published scientific papers in the last two years. This relied on Inspire-HEP. See gist for calculation notes. 16/March/2019

Diagram only representing **collider and direct detection**

- Differences in collaboration variety and size
- Differences in data volumes:
  - Colliders: "Big Data" volumes (>> PB)
  - DD: smaller data volumes (~TB/PB)
- Synergies in statistical analysis and interpretation of results

Different modus operandi for **indirect detection**

- Collaborations e.g. Fermi release data for general use ("observatory mode"), but also perform high-profile analyses themselves

Keep differences in mind when looking for synergies

Recent dark matter activities and initiatives

APPEC news,
after Granada '19:
wish to **enhance collaboration and discussion between LHC DMWG and DD/ID**

Direct Detection collaborations input to EPPSU:
strenghten common efforts

Astroparticle **Particle** **Nuclear**

APPEC input to EPPSU:
EuCAPT starting in 2019
with CERN as first 5-year host

European Center for Astroparticle Theory (EuCAPT)

Common theory ground

instrumentation
(accelerators, beams, detectors, vacuum & cryogenics, control & automation...)

data acquisition, computing, data sharing & open science

HSF
HEP Software Foundation

How to connect different activities?

- Discussions, from **Granada** to the **APPEC-ECFA-NuPECC JENAS meeting** held in Orsay this October

- New initiative centered around **dark matter, prompted by JENAS**
  - https://indico.cern.ch/e/iDMEu
- **Summary of the aims** in N bullet points (for full list: see link above):
  - offer a permanent platform where different communities discuss
    - make new connections e.g. with nuclear physics/gravitational waves
  - build on the work of existing working groups in terms of e.g. benchmarks
    - WIMP and beyond, "how to put different experiments on the same plot"
  - connect repositories for sharing of results with software experts
  - gather list of experiments/tools/conferences/outreach material
    - connect to ongoing work in ESCAPE project including particle&astroparticle

A (tentative) timeline of future colliders

V. Shiltsev's talk @ Granada
https://arxiv.org/abs/1905.03764

- Technology for lepton colliders ready earlier than for high-energy hadron colliders
- Example: magnets & accelerators

From **C. Biscari**'s talk @ EPSHEP'19

A. Yamamoto

Figure 13. Sketch of timeline of various collider projects starting at the "earliest start time" stated in the respective documents. For FCC-eh/hh this figure assumes that it is not preceeded by FCC-ee. If it comes after FCC-ee it would start in the early 2060s.

Input scenarios for colliders, from Higgs PPG

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] [e^-/e^+]	N(Det.)	$\mathscr{L}_{\text{inst}}$ [10^{34}] cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)	(1y SD before $2m_{top}$ run)	
ILC	ee	250 GeV	$\pm80/\pm30$	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	$\pm80/\pm30$	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	$\pm80/\pm30$	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)	(1y SD after 250 GeV run)	
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	$\pm80/0$	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	$\pm80/0$	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	$\pm80/0$	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)	(2y SDs between energy stages)	
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	2.6 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

https://arxiv.org/abs/1905.03764

Full programs include earlier versions / CoM energies

Future colliders timeline

V. Shiltsev's talk @ Granada

https://arxiv.org/abs/1905.03764

Figure 1. Time line of various collider projects starting at time T_0. Given are the luminosity values and energies, also shown in Table 1. For the clarification of the meaning of a year of running, see the caption to Table 1. Figure 13 in the appendix reworks this figure using the earliest possible start date (i.e. the calendar date of T_0) given by the proponents.

Changing couplings in dijet search constraints

- Not necessarily a "changing one thing at a time" comparison
  - proton vs neutron xsec, so DD changes too
  - left plot has larger quark couplings than right plot

State of the art for s-channel A-V mediator

http://cds.cern.ch/record/2684864?ln=en

Keep in mind: these plots are only valid for the couplings specified, in the **limited case of a benchmark model**!