CATERINA DOGLIONI - LUND UNIVERSITY
6TH LLP COMMUNITY WORKSHOP, GHENT

Long Lived Particles and Dark Matter

@CatDogLund
http://www.hep.lu.se/staff/doglioni/
Disclaimers: I am rather new to this community && an experimentalist (&& it’s term time && I only have 15’ for this contribution)

Consequence: This is a limited, personal view of the matter, restricted to models that are themselves limited wrt the wealth of literature… …but this discussion should continue, here and in other fora!
Outline

• LHC DM benchmarks and searches: where we started and where to go
  • EFTs, simplified models, more complete models
• Interlude: when can we call a model a dark matter model?
  • [personal note: we shouldn’t stop searching for models w/o DM]
• Beyond WIMPs
  • Dark sectors as an example
  • Dark hidden photon boson models and complementarity
• Closing remarks
The WIMP miracle of complementarity

Complementary experiments tackling DM problem

Why we need complementarity:
DD/ID can discover DM with cosmological origin
Colliders can produce DM and probe the dark interaction

Indirect Detection  Direct Detection  Particle Colliders

Also: complementarity of colliders with direct / indirect detection
needs a theoretical framework (+ WIMP miracle)

This complementarity, in context of a predictive yet simple theory
facilitated wide adoption of WIMP models as LHC benchmarks
**Complementarity example**

- **Collider constraints** on simple models of DM can be compared to **direct detection** ones

\[
\sigma_{SI} \approx 6.9 \times 10^{-43} \text{ cm}^2 \cdot \left( \frac{\theta_{g_D M}}{1} \right)^2 \left( \frac{125 \text{ GeV}}{M_{\text{med}}/1 \text{ GeV}} \right)^4 \left( \frac{\mu_{\text{DM}}}{1 \text{ GeV}} \right)^2.
\]

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

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**Keep in mind:** these plots are only valid for the couplings specified, in the limited space of a benchmark model!
LHC experiment can probe Dark Matter mediators

If there’s a force there’s a mediator:

Can **probe the dark interaction** even if DM is inaccessible
Can look for both **invisible and visible decays** of the mediator
Now: LHC Dark Matter Working Group

http://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc

extending the menu of LHC benchmarks to less simplified models / dark sectors
Dark Matter mediators at the LHC

If there’s a force there’s a mediator:

Can **probe the dark interaction** even if DM is inaccessible
Can look for both **invisible and visible decays** of the mediator

Look for an inevitable LHC physics process:
**di-jet (and di-X) resonances**

See W. Kalderon’s talk
Illustrative example

Axial Vector mediator, Dirac DM
\( (g_q = 0.25, g_{DM} = 1) \)

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**

<table>
<thead>
<tr>
<th>Project acronym</th>
<th>Project</th>
<th>Researcher (PI)</th>
<th>Host Institution (HI)</th>
<th>Call Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>DARCJETS</td>
<td>Discovery strategies for Dark Matter and new phenomena in hadronic signatures with the ATLAS detector at the Large Hadron Collider</td>
<td>C. Doglioni</td>
<td>LUNDS UNIVERSITET</td>
<td>Sterling Grant (SG), PEZ, ERC-2015-STG</td>
</tr>
</tbody>
</table>

LHC Dark Matter Working Group

Tired of WIMPs? Go forth and UV-complete, or…

Effective field theories | Simplified models | UV-complete theories
---|---|---
model-independent, limited validity | model-dependent, rich phenomenology | 

Winner of the Twitter competition at DM@LHC 2018, Heidelberg
Credits to K. Hoberg for spotting the picture

K. Behr

S. Sevova

G. Polesello

Pre-LHC | LHC
---|---
(Extended from a slide by U. Haisch)
...go look for DM motivations in other models!

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

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

\[ p, \pi, \ldots \rightarrow \text{jets} \]

\[ \nu, W, Z \rightarrow \text{leptons, jets} \ldots \]

→ the way we think of benchmark models influences collider searches

**Simple models**

**More complex/complete models**

where do LLP stand?

some answers in e.g.
- arXiv:1903.04497
- arXiv:1810.12602
How does (particle) dark matter look like?

- Almost non-interacting
- Stable / very long lived
- (mostly) collisionless
- Cold / non-relativistic

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

Ordinary Matter: 68%
Dark Matter: 27%
Dark Energy: 5%

https://arxiv.org/abs/1308.0338
arXiv: 1308.0338
Another approach: take one small step further…

Take a 2HDM, add a pseudoscalar particle mediating DM

Take WIMP simplified models for production, add LLP in decay

- Start with WIMP simplified models (including DM candidate), add LLP in final state
  - Adds displaced vertex signature
  - Need to keep limitations in mind!

- Reasoning behind this approach:
  - Can be used systematically
  - Can map to more complete/realistic models

- Question (to CMS?): which searches use such an approach?

### Simplified DM Models

<table>
<thead>
<tr>
<th>Variables</th>
<th>DM candidate</th>
<th>Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\phi}$</td>
<td>Dirac</td>
<td>Vector</td>
</tr>
<tr>
<td>$m_{\chi}$</td>
<td>Majorana</td>
<td>Axial-Vector</td>
</tr>
<tr>
<td>$g_{\chi}$</td>
<td>Scalar-real</td>
<td>Scalar</td>
</tr>
<tr>
<td>$g_{\phi}$</td>
<td>Scalar-complex</td>
<td>Pseudoscalar</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Displaced Signature Extension</th>
<th>Decay of $\chi_2 \rightarrow \chi_1 X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$, $m_2$</td>
<td></td>
</tr>
</tbody>
</table>

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Scalar Projection $3ab^{-1}$

Example: comparison of CMS and dedicated search (blue) Mathusla (red) for one of these models with varying lifetimes arXiv:1806.07396
**Dark sectors: semi-visible jets**

Take WIMP simplified models, add a LLP

Take WIMP simplified models, add a dark sector

![Diagram of dark sectors and semi-visible jets](image)

**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 $r_{\text{inv}}$ spectrum
- some signal caught by monojet and dijet, but **not optimized**
Dark sectors: semi-visible jets & co

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]

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

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arXiv:1907.04346, see also: E. Bernreuther's talk @ DMLHC2019
Many other theory possibilities...

<table>
<thead>
<tr>
<th>Motivation</th>
<th>Top-down Theory</th>
<th>IR LLP Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naturalness</td>
<td>RPV SUSY, GMSB, mini-split SUSY, Stealth SUSY, Axinos, Sgoldstinos.</td>
<td>UV theory, BSM=\rightarrow LLP (direct production of BSM state at LHC that is or decays to LLP).</td>
</tr>
<tr>
<td>Baryogenesis</td>
<td>WIMP Baryogenesis, Exotic Baryon Oscillations, Leptogenesis.</td>
<td>exotic Z decays, exotic Higgs decays, exotic Hadron decays.</td>
</tr>
<tr>
<td>Neutrino Masses</td>
<td>Minimal RH Neutrino with (U(1)_{B-L}) (Z'), with (SU(2)_R) (W_R), long-lived scalars with Higgs portal from ERS, Discrete Symmetries.</td>
<td></td>
</tr>
</tbody>
</table>

arXiv:1806.07396
For more insight: go local!

Feebly coupled Dark Matter and long-lived particles at the LHC

Alberto Mariotti

Based on:
JHEP 1809 037 with Lorenzo Calibbi, Laura Lopez Honorez, Steven Lowette
arXiv:1904.07513 with Sam Juniuss and Laura Lopez Honorez

DESY Theory Seminar
6 May 2019

https://indico.desy.de(indico/event/22458/material/slides/0.pdf)
LLP complementarity is behind the corner!

- Physics Beyond Colliders (&& LLP community): non-WIMP benchmark models for **dark sector** searches with dark matter interpretation:
  - e.g. Dark photon, Axion(-like particles)

- Benchmark with thermal dark matter interpretation: dark photon $\rightarrow$ **complementarity of collider, non-collider and astrophysics**

- Axions/Axion-Like Particles (ALPs): inter-field connections, solve more than the DM problem
  - haloscopes starting to become **sensitive to QCD axion / DM regime**!

A change of paradigm from "DM == invisible particles"

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

- interact with detectors
  - need to take this into account for collider searches (WIMP and not)

- interact with atmosphere & earth
  - use/send detectors higher up!

- be detectable using astrophysical signals
  - Supernova, BBN, CMB...

Note also: “Looking up” is a necessary consequence of “looking at low mass DM”
Conclusions
Take-home points/conclusions

• Why connecting DM and LLP? The big picture is important:
  • good to look everywhere and leave no stone unturned...
  • …but models & big picture (e.g. complementarity) inevitably influence motivation for searches
    → use model dependence (in moderation) to our advantage

• Much work to be done, in synergy with DM community
  • one possible approach: build from current simplified models
    • …without forgetting their limitations!
  • always work alongside signature-based LLP community
    • can use LLPs as an extra handle to uncover/characterize DM

• Complementarity: many upcoming beyond colliders experiments!

Thank you for your attention!
...and to Oleg Brandt, Eva Brottmann, Deepak Kar, Suchita Kulkarni, Jannik Geisen, Gaia Lanfranchi, Christian Ohm, Sukanya Sinha, the Lund University Theory division for input&discussions
Do we have time for one more discussion point?
Putting different benchmarks on the same plot

…it is possible, but there may be disagreements

Comparing apples and oranges: a randomised prospective study
James E Barone

For many years the comparison of apples and oranges was thought to be impossible. Many authors use the analogy of the putative inability to compare apples and oranges as a means of scornfully reviewing the work of others. The titles of some recent publications¹ ² suggest an actual comparison of apples and oranges, but the authors do not, in fact, compare these two fruits. Our laboratory has been interested in this problem for many years. We attempted numerous pilot studies (unpublished data) but had not accomplished a true comparison until now. At last, successful comparison of apples and oranges has been achieved and is the subject of this report.

Table 1 Non-parametric background fructological information

<table>
<thead>
<tr>
<th></th>
<th>Apples</th>
<th>Oranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grown in orchards</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Flowering trees</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Considered a fruit</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>May be eaten</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>May be made into juice</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Subject to damage by disease</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Subject to damage by insects</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Involvement of Johnny Appleseed*</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

*P<0.01.

https://www.bmj.com/content/bmj/321/7276/1569.full.pdf
A point for discussion (brought up by Gaia Lanfranchi)

Potential issue: putting visible decays of **minimal** and **non-minimal** dark photon on the same plot

- cannot produce a Higgs not at colliders
- the Lagrangian of e.g. LHCb results does not have the extra terms for Higgs couplings

**Suggestion:** coherently with e.g. WIMP simplified models, use only minimal dark photon model, or perform specific reinterpretation

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Figure 3.2: Comparison of the lepton-jet searches at ATLAS [265] and CMS [264] with respect to a dark photon scenario [148] vis-a-vis dark photon limits coming from low-energy experiments. Figure taken from Ref. [264].
Physics Beyond Colliders visible dark photon

Visible dark photon decays

**Note:** HL-LHC and FCC projections assume 8 TeV trigger thresholds...essential to think of future collider detectors, trigger & DAQ together with physics (and do Turbo/Scouting/trigger-Level Analysis!)
Backup slides
Where do we go from here? Up to everyone

Dark Matter Working Group within LHC Physics Centre (LPCC) including ATLAS, CMS, LHCb and theory

• Mandate:

  • Define guidelines and recommendations for the benchmark models, interpretation and characterisation for broad and systematic DM searches at the LHC

  • Example: agree on classes of benchmark models used for experimental searches

  • Example: improve tools available to the experiments, such as higher-precision calculations of signals/backgrounds

  • Connect with broader DM community towards comprehensive understanding of viable dark matter models

Organizers:
Oleg Brandt, Francesca Ungaro (ATLAS)
Phil Harris (CMS)
Xabier Cid Vidal (LHCb)
Tim Tait, Uli Haisch (theory)

You’re welcome to join and help define DM searches at the LHC!
mailing lists lhc-dmwg@cern.ch / lhc-dmwg-contributors@cern.ch at https://e-groups.cern.ch
Dark Matter Working Group

2015
https://arxiv.org/abs/1507.00966

[Dark Matter Forum] Reach consensus on a common set of benchmark models for ATLAS and CMS early Run-2 searches

2016
https://arxiv.org/abs/1603.04156

Within the framework of the DMF simplified models, present results and compare Direct Detection (DD) / Indirect Detection

2017
http://arxiv.org/abs/1703.05703

Agree on how to present searches for mediators of DM interactions in visible decays together with searches for invisible DM particles

2017
https://arxiv.org/abs/1705.04664

Provide a procedure for estimation of theory uncertainties for precision backgrounds of mono-jet DM search at colliders

2018
https://arxiv.org/abs/1810.09420

Develop scalar sector and colored scalar benchmark models: 2HDM+a

Current topics

2017
https://arxiv.org/abs/1705.04664

Define recommendations for t-channel models

? your ideas here!

C. Doglioni - 09/04/2018 - Dark Matter Workshop Heidelberg
The dark matter landscape

- Identification strategies are necessarily (more or less) model dependent

- The **theoretical prejudice in dark matter searches** is also set by what we can probe with available data

- You always need some sort of signature of your model!

Direct detection

\[ \sigma_{SI} \propto \frac{e_d^2 g_q^2}{m_Z^4} \]

Combination of CRESST-III, CDMSLite, PICO-60, PandaX and XENON1T
Complementarity of DM experiments

Comparisons are possible only in the context of a model

Essential to **fully specify model/parameters**

and *be aware of limitations*

[Diagram showing $g_q$, $g_{DM}$, and SM particles]

LHC Dark Matter Working Group
[Link to arXiv.org/abs/1603.04156]

CMS Dark Matter Summary Plots for ICHEP 2018

For more thought on upper bounds to collider sensitivity:
G. Landsberg's contribution, DMWG meeting June 2017
[Link to arXiv.org/abs/1810.07705]

See S. Sevova's talk
What about complementarity with astrophysics?

Dark Matter in the Coming Decade: Complementary Paths to Discovery and Beyond + many more

Possible inputs to LHC DM searches: constraints on DM particle candidates from impact on astrophysical observables
Aside: the importance of triggering

Many different theories can explain DM, none favored by data yet
Very different detector signatures
- signals can be buried in high-rate backgrounds or rare but unusual

Look everywhere effect: we need to make sure we record the events first
→ software/hardware innovations needed

Making the most of LHC data: enabling discoveries by ensuring events are selected and recorded in the most efficient way

Crucial at HL-LHC: full exploitation of dataset will require innovation
Real-time* analysis across the ring

W. Kalderon’s talk

• Current paradigm: first record data, then analyze it
• Data Scouting (CMS) / Turbo Stream (LHCb) / Trigger-Level Analysis (ATLAS): do object reconstruction in real-time (* definitions vary)
  • Only save refined information
  • much smaller in size than full information → can record more

Can either store large amount of data for a small number of events....

... or small amount of data for many, many events

Enormous amount of data delivered by LHC

Graphics by K. Pachal

Cannot record all data (fixed storage space)

See W. Kalderon’s talk
Constraints on the DM-nucleon scattering cross-section

![Graph showing constraints on DM-nucleon scattering cross-section with various experimental data points and theoretical predictions.](image-url)
Colored scalar (t-channel) models

Colored scalar mediators: **less popular yet viable** simplified models

**No dijet resonance** signatures, sensitivity to jet+MET searches

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**Relic density:**
- “Compatible” region depends on coupling/mass of DM mediator, but still viable in many parameter scenarios

See S. Sevova's talk

See also references from [A. DiFranzo's talk in DMWG meeting Sep 2016](#)
More complex models: pseudo/scalars

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

Search for MET + two b-quarks
ATLAS / CMS
No excess observed yet

LHC dataset starting to be sensitive to this class of processes

See A. Cortes Gonzalez’s talk
Dark bosons decaying to dimuons: same principle as dijets
very large background but good mass resolution online
→ use trigger objects to discover new resonances with large SM backgrounds

LHCb in the future (Run-3)

“Triggerless” readout

\[ D^{*0} \rightarrow D^0 A', \quad A' \rightarrow e^+e^- \]

See T. Ferber's talk
Colliders can still do more (with Run-2 data)

Take advantage of a (relatively) low pile-up dataset
- Number of simultaneous p-p interactions will only increase in the future
  - So will trigger thresholds for recording events
  - Many interesting models have low pT/MET -> will we lose sensitivity?

L. Thomas, CMS HLT, ICHEP 2018

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- 1) In addition to searches in VBF, object + (other) ISR, make the most of current data
  - e.g. trigger-level-type analysis (trigger objects used for analysis)
  - new physics could still be buried in delayed / parked streams (not processed promptly)
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![ATLAS Trigger Operation Public Results](image)

L. Thomas, CMS HLT, ICHEP 2018
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     - e.g. trigger-level-type analysis (trigger objects used for analysis)
     - new physics could still be buried in delayed / parked streams (not processed promptly)
  2) Make analyses reproducible and easy to run so lower-pileup-datasets can be used later
     - Effort on containerization (e.g. Docker)
     - Use standard candles (Z boson) to search for non-SM production, unfold detector effects

\[ R_{\text{miss}} = \frac{\sigma_{\text{fid}}(p_T^{\text{miss}} + \text{jets})}{\sigma_{\text{fid}}(\ell^+ \ell^- + \text{jets})} \]
The future of the LHC

The exploration of the energy frontier has just started

LHC is highest-E, highest-L operational collider → full exploitation (√s ~ 14 TeV, 3000 fb⁻¹) is mandatory:

S. Bertolucci, LHC status, LHCP 2015 St Petersburg

C. Doglioni - 09/04/2018 - Dark Matter Workshop Heidelberg
Collider experiments with upgraded hardware

Examples of upgrades expected for Run-3
- ATLAS: Fast TracKer (FTK)
- LHCb: 40 MHz data taking (new tracking) + software trigger

Run-4 (HL-LHC) will bring new, more performant detector components (to sustain performance in high pile-up), as well as 10x recording rates.
- New tracking detectors for ATLAS, CMS
- Hardware track triggers for ATLAS, CMS
- Timing detectors
  - CMS: full barrel, ATLAS: endcap
  - Examples of improvements in the following slides
Example of improvements with timing upgrades

Improvements to hard scatter efficiency in forward region:

- ATLAS HGTD Technical Proposal

Relevant for **VBF Higgs to invisible searches**

Additionally: HGTD can be used as a luminometer

Luminosity uncertainty mostly relevant for measurements, but also not negligible for searches
Prospects for SUSY EW searches

Barrel timing information restores sensitivity equivalent to 140 PU
What can be done with timing detector (barrel)

Measurement of **decay time** becomes possible
More LLP acceptance can translate into sensitivity to different models

Known example: range of masses and lifetimes of SM particles

The LHC LLP Community,
*Searches for long-lived particles beyond the Standard Model at the Large Hadron Collider*

CMS Timing Detector (MTD) technical proposal

C. Doglioni - 30/10/2018 - Puzzle of DM, DESY