Light in the Dark
Opening a new window to the Dark Sector

UVA HEP Seminar
14 November 2019

Ruth Pöttgen, Lund University
How do we know Dark Matter is there?
Rotation Curves

stars in the outer parts of many galaxies rotate much faster than expected based on gravitation from visible matter

shown by Vera Rubin in the 1970s for hundreds of galaxies

first observation of “dunkle Materie” (dark matter) in 1930(s) (often attributed to F. Zwicky, 1933, studied Coma Cluster)

but actually first mentioned by Knut Lundmark in 1930 (see L. Bergström's presentation in April 2015)
Dark Matter, a known unknown

ample evidence for existence of non-luminous form of matter

• all based on gravitational effects
• observed on vastly different scales (single galaxies up to entire Universe)
Dark Matter, a known unknown

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Cosmic Microwave Background

radiation from shortly after the big bang
- density fluctuations in early Universe encoded in temperature fluctuations of CMB
- measured most recently by ESA PLANCK satellite

This is how we know how much Dark Matter there is in the Universe.

Nobel Prize 2019 for J. Peebles
What Particles could Dark Matter be made of?
What Particles?

Some basic requirements

• electrically neutral (dark!)
• stable on cosmological timescales
• massive
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Given astronomical observations, what are allowed masses of dark matter particles?
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Anything from $10^{-20}$ eV up to several solar masses.
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Once interaction rate < expansion rate of Universe: amount of dark matter remains constant (thermal relic)
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Constrains viable mass range to MeV - TeV region!
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Constraints viable mass range to MeV - TeV region!

below: problems with BBN, structure formation, $\Delta N_{\text{eff}}$
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Constrains viable mass range to MeV - TeV region!
below: problems with BBN, structure formation, $\Delta N_{\text{eff}}$
above: too much DM
Searches for Thermal Relic DM

- SM
- DM

Dark Matter Particle Mass
- MeV
- GeV
- TeV

Thermal Relic
Searches for Thermal Relic DM

Some non-gravitational interaction!
(i.e. we might detect it in experiments)
 Searches for Thermal Relic DM

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Searches for Thermal Relic DM

**WIMP:** Weakly Interacting Massive Particle

![Diagram of SM and DM interactions](image)

**Dark Matter Particle Mass**

- MeV
- GeV
- TeV

**Thermal Relic**

- Some **non-gravitational** interaction!
  (i.e. we might detect it in experiments)

**Eng. Run**

- 1st Physics Run

**Prelim Design**

- FY21

**Build**

- FY17

**HiLum Physics Run**

- FY22

**Final Design**

- FY23

**Upgrade**

- FY24
Searches for Thermal Relic DM

WIMP: Weakly Interacting Massive Particle

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~known weak interaction of Standard Model
Searches for Thermal Relic DM

indirect detection (annihilation)

SM

DM

SM

DM

Thermal Relic

WIMPs

Dark Matter Particle Mass

MeV

GeV

TeV

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- Indirect detection (annihilation)

SM → DM → SM

Thermal Relic

Dark Matter Particle Mass

MeV → GeV → TeV

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- **indirect detection** (annihilation)
  - production at collider

- **direct detection** (scattering)

- **Thermal Relic**
  - **WIMPs**
  - Dark Matter Particle Mass
    - MeV
    - GeV
    - TeV

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Searches for Thermal Relic DM

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Indirect detection (annihilation)

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No observation so far.

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- **direct detection (scattering)**
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- **indirect detection (annihilation)**

**Thermal Relic**

- **Light Dark Matter**
- **WIMPs**

**Dark Matter Particle Mass**

- MeV
- GeV
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- Thermal Relic
  - Light Dark Matter
  - WIMPs

Dark Matter Particle Mass
- MeV
- GeV
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- SM
- DM

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~known weak interaction of Standard Model
Searches for Thermal Relic DM

Anticipate 2 years to complete design + 2 years for construction
Phase I Run beginning in late 2021. Phase 2 two years later.
Details depend upon accelerator schedules.

LDMX Phase I+II costs are <$10M.
Funding in FY18 is critical to support engineering and technical design.

SM

DM

Some non-gravitational interaction!
i.e. we might detect it in experiments

new feeble interaction

~known weak interaction of Standard Model
 Searches for Thermal Relic DM

Some non-gravitational interaction!
(i.e. we might detect it in experiments)

production mechanism at accelerators

new feeble interaction

~known weak interaction of Standard Model
How to realise LDM

starting point: thermal relic assumption
  • restricts viable mass range
  • minimum annihilation cross section
  • otherwise overproduction of DM

if WIMPs ‘too light’ (\( m_\chi < \text{ few GeV} \))
  • annihilation into SM inefficient
  • overproduction of DM
  • Lee-Weinberg-bound

introduce new, light mediator
  • additional annihilation channel
  • correct relic abundance

representative benchmark model: Dark Photon (A’)
  • vector mediator
  • kinetically mixes with photon (\( \epsilon \))
  • annihilation cross section

\[
\sigma v \sim \alpha_D \epsilon^2 \frac{m_\chi^2}{m_{A'}^4} \sim \alpha_D \epsilon^2 \frac{m_\chi^2}{m_{A'}^4} \frac{1}{m_\chi^2} \sim y \frac{1}{m_\chi^2}
\]

\[
y = \alpha_D \epsilon^2 \frac{m_\chi^4}{m_{A'}^4}
\]

clear experimental thermal targets

conservative:

\[
\alpha_D = 0.5 \quad \frac{m_\chi}{m_{A'}} = \frac{1}{3}
\]

Ruth Pöttgen  
UVA HEP Seminar  
12  
14 Nov 2019
Sub-GeV Dark Matter Detection
Direct Detection

Direct detection: **nuclear** recoil due to WIMP scattering
- sensitivity drops quickly below few GeV

Many new ideas in recent years to get to lower masses
- needs lower energy threshold
  - examples:
    - electron-DM scattering
    - semiconductors
Why not only direct detection?

direct detection:
strong spin/velocity dependency

![Graph showing Thermal and Asymmetric Targets for DM–e Scattering](Image)

**FIG. 17:** Direct annihilation thermal freeze-out targets and asymmetric DM target for (left) non-relativistic e-DM scattering probed by direct-detection experiments and (right) relativistic accelerator-based probes. The thermal targets include scalar, Majorana, inelastic, and pseudo-Dirac DM annihilating through the vector portal. Current constraints are displayed as shaded areas. Both panels assume $m_{MED} = 3m_{DM}$ and the dark fine structure constant $\frac{g^2}{4\pi} = 0.5$. These choices correspond to a conservative presentation of the parameter space for accelerator-based experiments (see section VI G).
Why not only direct detection?

direct detection:

strong spin/velocity dependency

at accelerators: relativistic production

—> spin/velocity dependency reduced

all thermal targets in reach!
The aim of the workshop is to explore the opportunities offered by the CERN accelerator complex and infrastructure to get new insights into some of today’s outstanding questions in particle physics through projects complementary to high-energy colliders and other initiatives in the world. The focus is on fundamental physics questions that are

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Maturity</th>
<th>Type</th>
<th>&amp;mass[GeV]</th>
<th>Detection</th>
<th>Mass Range [GeV]</th>
<th>Sensitivity</th>
<th>First beam</th>
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<td>BNB</td>
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</tr>
<tr>
<td>NeQuad</td>
<td>MI</td>
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<td>vis. prompt</td>
<td>$0.22 &lt; m_{ee} &lt; 0.9$</td>
<td>$g &gt; 10^{-14}$</td>
<td>2019+</td>
</tr>
</tbody>
</table>

Future international initiatives

| Belle II    | SuperKeKB & KEK | e+e− collider | 0.9 | MMass (k vis.) | $0 < m_{ee} < 10$ | $g > 10^{-10}$ | 2018 |
| MAGIX       | MESA & Mani   | electron FT   | 0.105 | vis. | $0.01 < m_{ee} < 0.060$ | $g > 10^{-10}$ | 2021-2022 |
| PADME       | DAFNE & Frascati | proton FT | 0.550 | MMass | $m_e < 0.824$ | $g > 10^{-7}$ | 2018 |
| SHIP        | SPSCERN       | proton BD     | 400 | DM scatter | $m_e < 0.4$ | $g > 10^{-12}$ | 2026+ |
| VEPP3       | VEPP3@BINP   | proton FT     | 0.500 | MMass | $0.005 < m_{ee} < 0.022$ | $g > 10^{-8}$ | 2019-2020 |

Current and completed initiatives

| APEX        | CEA     | CD   | 1.1-4.5    | vis. | $0.06 < m_{ee} < 0.55$ | $g > 10^{-7}$ | 2018-2019 |
| RABAR       | PEP-II  | CD   | 1.1-4.5    | vis. | $0.02 < m_{ee} < 10$ | $g > 10^{-7}$ | done |
| Belle       | KEKB    | CD   | 1.1-4.5    | vis. | $0.1 < m_{ee} < 10.5$ | $g > 10^{-7}$ | done |
| BPS         | CEA     | CD   | 1.1-4.5    | vis. | $0.015 < m_{ee} < 0.5$ | $g > 10^{-7}$ | done |
| NA64        | SPSCERN | CD   | 100        | MEnergy | $m_e < 1$ | $g > 10^{-10}$ | started |
| Milumine    | BNB     | PB   | 8          | DM scatter | $m_e < 0.4$ | $g > 10^{-9}$ | done |
| TREK        | K beam  | CD   | 0.240      | vis. | N/A | N/A | done |
Signatures

\[ \sigma v \propto \alpha_D^2 \]

\[ A' \]

\[ \bar{\chi} \]

\[ \chi \]

\[ f^+ \]

\[ f^- \]

\[ m_{\chi} \]

\[ 2m_{\chi} \]

\[ m_{A'} \]
Signatures

![Diagram of DM annihilation and mediator decay channels]

**secluded**

\[ \sigma v \propto \alpha_D^2 \]

\[ \tilde{\chi} \rightarrow A' \rightarrow f^+ f^- \]

\[ \chi \rightarrow A' \rightarrow f^+ f^- \]

**direct annihilation**

\[ \sigma v \propto \epsilon^2 \alpha_D \]

\[ \tilde{\chi} \rightarrow A' \rightarrow f^- f^+ \]

\[ \chi \rightarrow A' \rightarrow f^- f^+ \]

\[ m_{A'} \]

\[ m_{\chi} \]

\[ 2m_{\chi} \]

2.1 Important Variations

2.1.1 Inelastic Dark Matter (iDM)

If the mediator couples to a DM fermion with both Dirac and Majorana masses, the leading interaction is generically off-diagonal, with:

\[ A_0 \mu J_{\mu}^{DM} \]

This scenario is well-motivated by

\[ \frac{v^2}{\langle \epsilon \rangle^2} \]
Signatures

**secluded**

\[ \sigma v \propto \alpha_D^2 \]

\[ \chi \to A' \]

\[ \tilde{\chi} \to A' \]

\[ m_\chi \]

\[ \frac{\sigma v}{e^2} \]

\[ f^+ \]

\[ f^- \]

\[ m_{A'} \]

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\[ f^+ \]

\[ f^- \]

\[ \tilde{\chi} \to A' \]

\[ \tilde{\chi} \to A' \]

\[ 2m_\chi \]

**invisible**

**visible**
Figure 1: Classification of dominant DM annihilation and mediator decay channels in the benchmark dark photon ($A_0$) mediated scenario of different $m_{A_0}/m_{f}$ ratios.

- **secluded**
  \[ \sigma v \propto \alpha_D^2 \]

- **direct annihilation**
  \[ \sigma v \propto \epsilon^2 \alpha_D \]

**Signature Categories**

- **Visible**
  - prompt decay (resonance feature)
  - long-lived (displaced decay)

- **Invisible**

**Important Variations**

2.1. Inelastic Dark Matter (iDM)

If the $A_0$ couples to a DM fermion with both Dirac and Majorana masses, the leading interaction is generically off-diagonal and $A_0 \mu J_\mu \mu I $, where the usual Dirac fermion decomposes into two Majorana ("pseudo-Dirac") states $1, 2$ with masses $m_1, 2$ split by an amount $T$. This kind of scenario is well-motivated...
2.1 Important Variations

2.1.1 Inelastic Dark Matter (iDM)

If the $A_0$ couples to a DM fermion with both Dirac and Majorana masses, the leading interaction is generically off-diagonal and $A_0 \mu J_{\mu}^{\text{DM}} \neq A_0 \mu \bar{J}_{\mu} \equiv 0$, (6) where the usual Dirac fermion decomposes into two Majorana (“pseudo-Dirac”) states $1, 2$ with masses $m_1, 2$ split by an amount $\Delta m$. This kind of scenario is well motivated.

Figure 1: Classification of dominant DM annihilation and mediator decay channels in the benchmark dark photon ($A_0$ mediated) scenario of different $m_{A_0}/m_{A'}$ ratios.

Also, the same classification holds for Majorana-DM, with the substitution $(1, 2)$. (a) In the left column, the mediator is lighter than the DM, so for the dominant annihilation is in the “secluded” channel, which is independent of the mediator coupling to the SM. This scenario has no direct thermal target; every arbitrarily small values of $\alpha_D$ are compatible with a thermal annihilation rate.

(b) The middle column represents the $m_{A'} < m_{A_0} < 2m_\chi$ window in which the annihilation rate is sensitive to $\alpha_D$ but the mediator decays visibly. This regime has a predictive thermal relic target, which can be tested by probing sufficiently small values of $\alpha_D$ in searches for visibly decaying dark photos (e.g. HPS, APEX, Belle II).

(c) The right column where $m_{A_0} > 2m_\chi$ ample parameter space with a predictive thermal target and features mediators that decay invisibly to DM states. Since $v/\alpha_D^2 \gg \Delta m$ this scenario has a thermal target which can be probed by testing sufficiently small values of this combination at BDMX, whose signal yield scales as the same combination of input parameters.
Fixed-Target Missing Energy/Momentum
Accelerator Production

‘Dark bremsstrahlung’ in field of a nucleus

Main background: ‘ordinary’ bremsstrahlung of a SM photon
Complimentary Approaches

**collider**
\[ \sigma_{\text{coll}} \propto \frac{e^2}{E_{\text{cm}}^2} \]

**fixed target**
\[ \sigma_{\text{FT}} \propto \frac{Z^2e^2}{m_A^2} \]
\[ N \propto \varepsilon^2 (1 - \varepsilon^2) \approx \varepsilon^2 \]

**beam dump**
\[ N \propto \varepsilon^4 \]

but "direct DM detection"

**examples**
<table>
<thead>
<tr>
<th>collider</th>
<th>fixed target</th>
<th>beam dump</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>PADME MMAPS</td>
<td>E137 SBNepi</td>
</tr>
<tr>
<td>Belle II</td>
<td>NA64 VEPP3</td>
<td>LSND MiniBooNE</td>
</tr>
<tr>
<td>LHC</td>
<td>LDMX DarkLight (II)</td>
<td>BDX SHiP</td>
</tr>
</tbody>
</table>

**mass range**
- collider: 0.1 - 10 GeV
- fixed target: MeV - GeV
- beam dump: MeV - GeV
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\[ N \propto \varepsilon^4 \]

but “direct DM detection”

**beam dump**

**examples (existing or planned)**

- BaBar
- Belle II
- LHC
- PADME
- NA64
- VEPP3
- LDMX
- MMAPS
- DarkLight (II)
- E137
- SBNes/pi
- LSND
- MiniBooNE
- BDX
- SHiP

**mass range**

- 0.1 - 10 GeV
- MeV - GeV
Kinematics

very different from SM bremsstrahlung (main background)

Mediator carries most of the energy
$\rightarrow$ soft recoil electron, large missing energy
Kinematics

very different from SM bremsstrahlung (main background)

Mediator carries most of the energy

→ soft recoil electron, large missing energy

Recoil electron gets transverse 'kick'

→ large missing transverse momentum

measurement of $p_T$: strong discriminator
AND information about (missing) mass!
Light Dark Matter eXperiment (LDMX)
design paper [arxiv:1808.05219]

**Beam**
energy \( E_B \), 4-16 GeV

**Target**

**Tracking**

**Sampling Calorimeters**

\[ E < E_B \]

- DM
- DM

- DM

**individually measure up to \( 10^{16} \) electrons on target (EoT), missing energy & **missing (transverse) momentum**

small-scale experiment
The Beam
A special beam…

beam energy ideally 4 GeV < E_B < 20 GeV

looking for extremely rare signal
—> need very large statistics

goal: \(10^{14} - 10^{16}\) electrons in few years

—> beam with high duty-cycle

resolve individual particles
—> low number of electrons per bunch (≤10)
—> large beam spot

options (still an open question):

**SLAC** *(default, first stage)*
dedicated transfer line from LCLS-II
*(Linac Coherent Light Source)*

**CERN** *(later stage)*
new Linac injecting electrons into SPS
*(Super Proton Synchrotron)*
S30XL @ LCLS-II @ SLAC

(Sector 30 Transfer Line)

Goal: Parasitically extract low-current, high-rate electron beam from LCLS-II linac

Physics program spans dark matter physics (LDMX), neutrino physics (electro-nuclear scattering as reference), test beam program...

energy: 4 (8) GeV
bunch frequency: 46 MHz (186 MHz)

4x10^{14} EoT year 1
parasitic
S30XL @ LCLS-II @ SLAC

(Sector 30 Transfer Line)

Laser system to fill unused buckets with electrons for S30XL

S30XL beamline to Endstation A

LCLS-II SCRF Linac

Beam Kickers

Endstation A

BSY dump

Soft X-Ray FEL

Hard X-Ray FEL

S30XL kicker/septum system downstream of FEL kickers (min. interference)
Staged approach:

• first: S30 Accelerator Improvement Project (kicker & ~100m beamline – ending in beam switchyard)
  • Design underway following funding in FY19; release of construction funding expected after successful review (~early January)
  • Installation timeframe: depends on LCLS-II downtime schedule
  • Enable characterization of dark current, long-pulse kicker demonstration, single-electron QED tests, and high-rate single electron test beam
• second: additional ~100m beamline to connect to existing End Station A line, potentially laser system
**eSPS at CERN**

Get e- back in CERN accelerators, next step for X-band linac developed for CLIC, accelerator R&D

Idea ~2 years ago, quickly picked up momentum

Expression of interest to SPSC in October 2018  [https://cds.cern.ch/record/2640784](https://cds.cern.ch/record/2640784)  Input to Strategy Update (#36)

- 3.5 GeV Linac as injector to SPS
- large number of electrons can be filled within 2s
- slow extraction over 10s
- can run in parallel with other SPS programme

flexible parameters:
- energy: 3.5 - 16 GeV
- electrons per bunch: 1 - 40
- bunch spacing: multiples of 5 ns
- adjustable beam size

optimal catering for LDMX-like experiment
Backgrounds and Detectors
Backgrounds

```
relative rate

10^0  10^-1  10^-2  10^-3  10^-4  10^-5  10^-6  10^-7  10^-8  10^-9  10^-10  10^-11  10^-12  10^-13  10^-14  10^-15  10^-16  ...
```

```
incoming

e^-

bremsstrahlung

trident

EN

+hadrons

+μ^+ μ^-

γ → hadrons

γ → μ^+ μ^-
```

```
outgoing

γ

+e^+ e^-
```

```
Veto Handles
```

```
increasingly rare

photo-nuclear
```

```
“visible” backgrounds ≪ 10^-16
```

```
“invisible” backgrounds ≪ 10^-16
```

```
ν (Møller + CCQE)
```

essentially only instrumental backgrounds
Background Challenges

main background:
SM photon bremsstrahlung

particularly challenging:
photo-nuclear reactions producing neutral final states (relative rate: \( \sim 10^{-9} \))

\[ E < E_B \]

\[ nn, \ldots \]

\[ \text{Sampling Calorimeters} \]

Beam

energy \( E_B \), 4-16 GeV

Target

Tracking

-> most design work (with UVA!) recently on HCal to optimise rejection power
Tracking

simplified copy of Silicon Vertex Tracker (SVT) of HPS experiment@JLab (visible Dark Photon search)

- fast (2ns hit time resolution)
- radiation hard
- technology well understood

FIG. 16: An overview of the tracking systems and target inside the LDMX magnet.

- tagging tracker
  - in 1.5T dipole field
  - measure incoming electron
  - momentum filter
  - impact point on target
- recoil tracker
  - in fringe field
  - measure recoil electron
- target
  - ~0.1 - 0.3 $X_0$ tungsten
  - balance signal rate & momentum smearing
Electromagnetic Calorimeter

ECal
- draw on design of CMS@LHC forward SiW calorimeter upgrade
  - fast, radiation hard, dense
  - 40 radiation lengths (>30 layers)
  - high granularity (‘tracking’ of minimum ionising particles, MIP)
  - potentially increase granularity in central module
**Hadronic Calorimeter**

**HCal**
- highly efficient *veto* of low- and high-energy neutrons
- surround ECal as much as possible (back and side)
- plastic scintillator with steel absorber (inspiration from Minos/Mu2e/CMS)

**Testbeam**
- obtained first funding from Swedish sources for R&D/prototype
- planned for fall 2020
- prototype layout coming together
Hadronic Calorimeter

Scintillator bars: based on Mu2e cosmic ray veto that UVA group is building
- great to have this first-hand expertise for LDMX!
- bars extruded at FNAL with one hole in the middle for fiber (Mu2e uses two holes)
- LDMX probably going to use quad-bar units instead of di-bars
Hadronic Calorimeter

Benchmark example:
veto inefficiency of at most $10^{-6}$ for single neutrons (~15λ)

Absorber thickness?
- too thick: neutrons ‘get stuck’
  —> no signal in scintillator
- too thin: detector needs to be very large

Currently assuming 25mm, 4m deep, transverse size 2-3m

“Side HCal” around the ECal: Similar configuration, few λ deep

Finalisation of design parameters ongoing
Analysis Strategy

trigger on missing energy
+ combine ECal features into a BDT
+ veto on activity in HCal
+ MIP tracking in ECAL (new!)

at 4 GeV: close to 0-background for 4e14 EoT
based on simulation studies
Analysis Strategy

trigger on missing energy
+ combine ECal features into a BDT
+ veto on activity in HCal
+ MIP tracking in ECAl (new!)

at 4 GeV: close to 0-background for 4e14 EoT
based on simulation studies

important:
several handles not exploited yet, in particular $p_T$!
HCal optimisation ongoing
things get easier at higher energy!

[Image: Analysis Strategy Diagram]

arxiv:1808.05219
Analysis Strategy

trigger on missing energy
+ combine ECal features into a BDT
+ veto on activity in HCal
+ MIP tracking in ECal (new!)

at 4 GeV: close to 0-background for 4e14 EoT
based on simulation studies

important:
several handles not exploited yet, in particular p_T!
HCal optimisation ongoing
things get easier at higher energy!

with data:
  redundancy in vetoes —> data control samples, verify rejection
  comprehensive kinematic information —> establish signal-likeness
Funding

**US:** Awaiting outcome of application for R&D funding submitted in spring

**Europe:** Some funding awarded during summer/fall

- support for HCal prototype/testbam
- Crafoord Foundation + Royal Physiographic Society Lund
- project grant for research programme on LDMX from Knut and Alice Wallenberg Foundation
- individual support from Swedish Research Council

--> Things are moving along!
Going Beyond
Why higher energy?

increased signal yield

![Graph showing yield enhancement vs. A' mass (MeV) for different beam energies (4, 8, 16 GeV) and target materials (W, Al). The graph illustrates how increasing the LDMX beam energy to 8 or 16 GeV, and/or switching from Tungsten to Aluminum targets, impacts the signal production cross-section for different dark photon masses.]
Why higher energy?

improved background rejection possibilities

particularly critical
Projected Sensitivity

LDMX can explore a lot of new parameter space

sensitive to various thermal targets already with "pilot run"

ultimately potential to probe all thermal targets up to O(100) GeV

timescale: few years
Further Potential

also sensitive to

- DM with quasi-thermal origin (asymmetric, SIMP/ELDER scenarios)
- new invisibly decaying mediators in general (A’ one example)
- displaced vertex signatures (e.g. co-annihilation, SIMP)
- milli-charged particles

(more in Berlin, Blinov, Krnjaic, Schuster, Toro arxiv:1807.01730)

in addition: measurement of photo- and electro-nuclear processes (for neutrino experiments)
Summary

- More than 5 times as much Dark Matter as normal matter
- Light, thermal relic Dark Matter well motivated
- Broad interest in Dark Sector physics, many new initiatives
- LDMX can achieve outstanding sensitivity (within a few years)
- Potential to probe thermal targets in MeV - GeV range
- First funding coming in

The next few years will be exciting!
Thank you!
Additional Material
Two Approaches

**missing energy**

- Higher signal yield/EoT (thicker target)
- Greater signal acceptance
- No e-γ particle ID

**missing momentum**

- Includes missing energy
- $p_T$ as discriminator & signal identifier
- E-γ particle ID
Parameter Dependence

\[ \alpha_D \text{ variation, } m_{A'} = 3m_\chi \]

\[ y = \epsilon^2 \alpha_D (m_\chi/m_{A'})^4 \]

\[ m_\chi [\text{GeV}] \]

\[ \alpha_D = 0.5 \]

\[ \alpha_D = 10^{-3} \]

\[ m_{A'} [\text{GeV}] \]

Dark Photon, Majorana DM, \( \alpha_D = 0.5 \)

BaBar

beam dumps

scalar

Majorana

pseudo-Dirac

Missing Momentum

\[ y = \epsilon^2 \alpha_D (m_\chi/m_{A'})^4 \]

\[ m_\chi [\text{GeV}] \]

\[ \alpha_D = 0.5 \]

\[ \alpha_D = 10^{-3} \]

\[ m_{A'} [\text{GeV}] \]

LDMX

Extended LDMX

BaBar

\[ m_{A'}/m_\chi = 5.0 \]

\[ m_{A'}/m_\chi = 3.0 \]

\[ m_{A'}/m_\chi = 2.5 \]

\[ m_{A'}/m_\chi = 2.3 \]
Various Future Projections

- **Scalar Elastic Dark Matter:** In this scenario, is a complex scalar particle with \( U(1)_D \) breaking mass terms (by analogy to the \( SU(2)_W \) breaking mass terms of particles in the Standard Model). Therefore, \( \alpha_D \) couples to \( A_0 \) elastically and must transition to a slightly heavier state in order to scatter through the current escape, \( J_\mu D = i(\cancel{\alpha}_1 \partial_\mu \cancel{\alpha}_2 - \cancel{\alpha}_2 \partial_\mu \cancel{\alpha}_1) \), which typically suppresses direct detection signals even for small mass differences between

- **Scalar Inelastic Dark Matter:** Model also yields elastic signatures at direct detection experiments, so it can be probed with multiple complementary techniques. The thermal target and parameter space for this model are presented in the lower left panel of Fig. 5.