Accelerator Searches for Dark Matter

Natalia Toro
SLAC

SSI Aug 24, 2017
Outline

- Motivation
  - Models & Parametrics
  - Complementarity – Why Accelerators?

- LHC Searches for Dark Matter
  - Techniques, Limitations, and Path Forward

- Intensity Frontier Searches for Dark Matter and Dark Forces
  - Techniques, Limitations, and Path Forward
Motivation: Thermal Dark Matter

As Universe cools below DM mass, thermal abundance decreases as $e^{-m/T}$

Dark Matter interactions with SM maintain chemical equilibrium until $\Gamma_{\text{annihilation}} \sim \Gamma_{\text{cooling}}$, then $Y_{DM} = n/s$ fixed

$$T^3 Y_{DM} \sigma_{\text{ann}} v \sim H \sim T^2/M_{Pl}$$

non-relativistic freeze-out at $T \sim m$ $\Rightarrow$ $Y_{DM} \sim (\sigma_{\text{ann}} v M_{Pl} m)^{-1}$

$$\rho_{DM} \sim Y_{DM} s_0 m \sim s_0/(\sigma_{\text{ann}} v M_{Pl})$$

DM Abundance Today $\leftrightarrow$ Strength of Interactions with SM
Motivation: Thermal Dark Matter

DM can easily fit in to Standard Model (TeV-scale, weakly interacting particle)

Or...maybe instead we need to understand how the SM fits into the dark sector? (See J. Feng & P. Schuster)

WIMP miracle:
\[ \sigma_{\text{ann}} \sim \alpha_2^2 \frac{m_{DM}^2}{m_W^4} \]

Lighter DM, weaker coupling → Intensity frontier

Heavier DM, strong coupling → LHC [Z' & E_T]
Light Thermal Dark Matter

For DM lighter than a few GeV, \( \sigma_{\text{ann}} \sim \alpha_2^2 \frac{m_{\text{DM}}^2}{m_W^4} \rightarrow \) insufficient annihilation – too much DM (Lee-Weinberg)

This simply means there \textbf{must} be another force, with effective 4-fermi coupling \( \alpha_D \alpha_{\text{SM}} / m_{\text{MED}}^4 > G_F \),

i.e. larger coupling or lighter mediator

The most experimentally viable direction is a \textbf{much} lighter mediator with \textbf{much} weaker coupling.
A New Force Carrier?

Can simply posit a new, massive force-mediator with arbitrary couplings to SM and dark matter:

\[ \mathcal{L} \supset V^\mu (g_D \bar{\chi} \gamma_\mu \chi + g_e \bar{\bar{e}} \gamma_\mu e + \ldots) \]
\[ \mathcal{L} \supset \phi (g_D \bar{\chi} \chi + g_e \bar{\bar{e}} e + \ldots) \]

For 10 MeV–GeV-scale mediators, decay-independent constraints on \( g_e \sim 10^{-3} \) to 1/30.

Simple origin for such a small coupling: Kinetic mixing

\[ \mathcal{L} \supset \frac{\epsilon}{2 \cos \theta_W} \partial^\mu [V^\nu F_{\mu\nu}^Y] \]
\[ \rightarrow \epsilon e V^\mu \left( \sum_i q_i \bar{\psi}_i \gamma_\mu \psi_i \right) \]

conventionally \( V \rightarrow U \) or \( A' \)

In basis where kinetic terms & mass diagonal, dark force carrier has small coupling to EM-charged matter
Sources and Sizes of Kinetic Mixing

- 0(1) in fundamental theory? [not phenomenologically viable]

- Perturbative sources of kinetic mixing
  - One-loop effect from heavy particle charged under both U(1)’s

\[ \gamma A' \sim \frac{e g D}{16\pi^2} \sim 10^{-2} - 10^{-4} \]

- GUT symmetry forbids tree and loop couplings; leading mixing is two-loop

\[ \gamma A' \sim 10^{-5} - 10^{-3} \]

- Non-perturbative physics can generate much smaller \( \epsilon \)
What do we learn about Light Dark Matter from its Abundance?

Abundance set by small $g_D$ - independent of $\varphi$-SM coupling

Abundance set by $g_D\epsilon/m_{A'}^2$ ⇒ sharp target $\epsilon$!

Visible mediator $\varphi$ (CMB constraints → can’t be vector)

Invisible mediator

I’ll focus on this case but experiments are also sensitive to the other
Light Thermal Dark Matter

Consistent with expectation for perturbative kin. mixing 
$(10^{-2} - 10^{-3}) \times \epsilon_{1-2}$ loop$^2$

$\sigma V \sim \epsilon \alpha \alpha_D m_{DM}^2 / m_W^4$

$X$ (velocity-factors) 
precise coupling depends on DM spin

Elastic & Inelastic Scalar Relic Targets
Majorana Relic Target
Pseudo-Dirac Fermion Relic Target

$y = \epsilon^2 \alpha_D (m_\chi / m_A)^4$

$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-16}$

$m_\chi$ [MeV]
Why Accelerators?

- Relativistic kinematics comparable to thermal freeze-out
- Avoid non-relativistic kinematic suppression

Classify Viable Models by DD Scattering?

 Scalar DM  Majorana DM  Pseudo-Dirac DM inelastic

\[ A'_{\mu} \chi^* \partial_{\mu} \chi \]  \[ A'_{\mu} \tilde{\chi} \gamma^\mu \gamma^5 \chi \]  \[ A'_{\mu} \tilde{\chi}_1 \gamma^\mu \chi_2 \]

\[ \sigma_e \sim 10^{-39} \text{ cm}^2 \]  \[ \sigma_e \sim 10^{-39} v^2 \text{ cm}^2 \]  \[ \sigma_e \sim 10^{-48} \text{ cm}^2 \]

Very different cross sections despite similarity @ high energy
Each \( \bullet \) interaction can realize \( \chi \), thermal annihilation at \( T \sim M \)

G. Krnjaic
CV DM Workshop
Inelastic/Coannihilating DM

- Mediator mass $\Rightarrow$ dark gauge group $U(1)_D$ is broken
  - Very plausible that DM mass terms break $U(1)_D$ as well
  - This leads to DM mass splitting
    - complex scalar DM $\rightarrow$ two real states, or
    - Dirac fermion DM $\rightarrow$ two Majorana fermions

- The leading (only, for scalar) vector interaction is mass-off-diagonal.

\[ X \rightarrow e^+ + e^- + \gamma \]

\[ g_D \]
Why Accelerators?

- Relativistic kinematics comparable to thermal freeze-out
  - Avoid non-relativistic kinematic suppression
  - More robust yield predictions

[Diagram showing thermal and asymmetric targets for DM-e scattering and yield predictions compared to accelerator production targets.]
Why Accelerators?

- Relativistic kinematics comparable to thermal freeze-out
  - Avoid non-relativistic kinematic suppression
  - More robust yield predictions
- Probe couplings to heavy SM particles (quarks, leptons and gauge bosons)
Why Accelerators?

- Relativistic kinematics comparable to thermal freeze-out
  - Avoid non-relativistic kinematic suppression
  - More robust yield predictions
- Probe couplings to heavy SM particles (quarks, leptons and gauge bosons)
- Opportunities to measure the dark sector through multiple reactions
The flip-side

It goes without saying that other experiments have complementary strengths, e.g.

- Accelerators can’t tell us about DM candidate’s stability beyond ~μs timescales; direct and indirect detection do

- Accelerator searches have their own kinematic limit
  - just as direct detection can only explore elastic scattering, accelerators can only search for DM lighter than CM kinetic energy
  - Sensitivity often assumes accessibly light mediator too

- Some parameter regions have non-relativistic enhancement of direct detection signal (DM-spin-independent scattering with $m_{\text{Mediator}} \ll m_{\text{DM}}$); no corresponding enhancement in accelerator production
Beyond Thermal DM

- **Asymmetric** dark matter also needs to annihilate a symmetric component, with $\sigma \gtrsim \sigma_{\text{ann}}$ from last slide.
- **(Natural) co-annihilations** $\chi \chi^* > \text{SM SM}$ where $\chi$ and $\chi^*$ are related by symmetry (e.g. pseudo-Dirac).

- DM thermal abundance depleted by a process other than pair annihilation – e.g. **semi-annihilation** ($\chi A \rightarrow BC$) or **cannibalization** ($3\chi \rightarrow 2\chi$).
  - e.g. “pions” in confined hidden sector (SIMP).
  - Kinetic equilibrium between the two sectors can be maintained by scattering or decays.

- At even weaker coupling, DM with zero initial abundance **freezes in**.

"Thermal" for purpose of this talk.

If scattering controls decoupling, thermal-like mass-coupling target.

Generic parameter space is undetectable; can get lucky.
Thermal (and related) DM hypothesis motivates WIMP and hidden-sector models for DM production, with stronger coupling at high mass and weaker coupling at low mass.

- The small couplings needed for annihilation of light DM can naturally arise in hidden-sector models.
- “Direct” annihilation through dark-force-carrier implies a lower bound on mediator-SM coupling.

Accelerator searches have unique advantages:
- Relativistic kinematics gives access to models with velocity-suppressed or inelastic interactions.
- Explore a wide variety of couplings.
- Enable multiple complementary measurements of dark sector.
Motivation

- Models & Parametrics
- Complementarity – Why Accelerators?

LHC Searches for Dark Matter

- Techniques, Limitations, and Path Forward

Intensity Frontier Searches for Dark Matter and Dark Forces

- Techniques, Limitations, and Path Forward
LHC Dark Matter Searches: Inclusive MET + X

Sarah Eno’s talk nicely summarized the results & framework for interpretation in simplified models.

We don’t know what the mediator is. So why not just use a contact interaction? This worked well for Fermi, before it was known that the W mediated the weak interaction. This works well for direct detection experiments.

Please remember that this is just for one parameter set for one model.
LHC Dark Matter Searches: Inclusive MET + X

Viable models of TeV-scale DM have large mediator couplings to quarks and/or leptons → no hiding from resonance searches

(resonance constraints depend significantly on q vs. l couplings)
LHC Dark Matter Searches: Inclusive MET + X

Large backgrounds & their systematics limit detection of lower-mass, weaker-coupled mediators

Please remember that this is just for one parameter set for one model
Inelastic models motivate searches for mono-\(X\) + soft leptons/photons

- Can be visibly displaced

\(\gamma, \ell^+\ell^- \ldots \)
LHC Dark Matter Searches: Higgs \( \rightarrow \) (Partly) invisible

\[ h \rightarrow \not{E}_T \]

competitive with direct detection in searching for DM coupled directly to 125 GeV Higgs
Summary: LHC

- **MET+X** searches explore many different types of interaction between SM & DM
  - In consistent models, resonance searches also important
  - Main opportunities for improvement: broadening final states covered and increasing mass reach at large coupling

- Other LHC searches motivated by dark matter:
  - MET+X + soft searches for inelastic dark sectors
    - Significant territory not yet explored
  - Invisible Higgs decays
    - Further analysis will continue to improve BR upper limit
  - Semi-invisible Higgs decays
    - Many channels not yet well explored
Outline

□ Motivation
   – Models & Parametrics
   – Complementarity – Why Accelerators?

□ LHC Searches for Dark Matter
   – Techniques, Limitations, and Path Forward

□ Intensity Frontier Searches for Dark Matter and Dark Forces
   – Techniques, Limitations, and Path Forward
### Detection Strategies

<table>
<thead>
<tr>
<th>Colliding Beams</th>
<th>Fixed Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detect DM scattering</td>
<td>beam dump (p or e beam)</td>
</tr>
<tr>
<td>Infer from kinematics</td>
<td></td>
</tr>
<tr>
<td>Dark-force searches</td>
<td></td>
</tr>
</tbody>
</table>

- **Colliding Beams**
  - Missing E
  - Missing Mass (e)
  - Lepton jets
  - Displaced vtx & resonance (e)

- **Fixed Target**
  - Missing Mass (e)
  - Missing E/p (e)
  - Displaced vtx & resonance (e beam, meson decays)

**Different strategies for multi-GeV → O(GeV) → sub-GeV detection**

- Trade energy [kinematic reach] for luminosity [coupling reach] –
Missing Mass at Colliders

Motivating process

- Look for single $\gamma$ recoiling against “nothing”
- Reconstruct invisible mass from $(p_{e^-}+p_{e^+}-p_{\gamma})^2$
- Bump signal if $A'$ on-shell

Experimental considerations

- Requires single-$\gamma$ trigger – implemented late in BaBar run, will be developed for Belle II
- Background from $e^+e^-\rightarrow 2\gamma, 3\gamma, e^+e^-\gamma$ with 1 or more undetected particles (e.g. from cracks or outside acceptance) must be rejected.
- $2\gamma$ component looks just like low-mass signal – low-mass reach relies on measuring veto inefficiency

Assumes we can quantitatively predict background levels.
- Photon efficiency over barrel/endcap gaps.

Better calorimeter hermeticity to suppress $e^+e^-\rightarrow \gamma\gamma$

Reach masses of 9.1–9.5 GeV/c$^2$ with lower trigger threshold (vs 8 GeV/c$^2$ for BaBar)
Missing Mass at Colliders Confronts Thermal Targets

Belle II luminosity insufficient to reach thermal target for MeV-scale DM
**Sensitivity vs. Target**

**Scenario: Scalar DM**

For smaller $\alpha_D$ or bigger mass hierarchy, accelerator limits get *better* in this param. space (because they just depend on $\epsilon$)
**Sensitivity vs. Target**

Scenario: Fermion inelastic (pseudo-Dirac) DM

![Graph showing sensitivity vs. target for Fermion inelastic (pseudo-Dirac) DM with various experiments and models.](image)

- **LHC**
- **LEP**
- **BaBar**
- **E787**
- **E949**
- **Super CDMS SNOLAB (1-loop)**

**Equation:**

\[ y = e^2 \alpha_D \left( \frac{m_\chi}{m_A^*} \right)^4 \]

**Relic Density**

- **N_{eff}, model dependent**

**m_\chi** (MeV):

10^{-16} to 10^{-1}

**Graph**:

- **y**-axis: \( 10^{-16} \) to \( 10^{-1} \)
- **x**-axis: \( 1 \) to \( 10^3 \)
Missing Mass at Colliders
Confronts Thermal Targets
– another perspective –

BaBar constrains $\epsilon^2$; thermal freeze-out fixes $y \equiv \epsilon^2 \alpha_D (m_\chi/m_{A'})^4$

- Physical limits: $\alpha_D < 0.5$ and $m_\chi/m_{A'} < 0.5$
- Previous plot: saturating the physical limits $\rightarrow$ conservative (worst case) constraint on $y^*$
- Alternately, fix $y$ to thermal relic and $m_\chi/m_{A'}$ near minimum
  - Experimental constraint on $\epsilon$ implies maximum $\alpha_D$
  - For scalar models, Belle-II largely closes off strong coupling

![Graph showing the relationship between $\alpha_D$ and $m_{DM}$]
Sensitivity vs. Target

Scenario: Scalar DM

For smaller $\alpha_D$ or bigger mass hierarchy, accelerator limits get better in this param. space (because they just depend on $\epsilon$)
Sensitivity vs. Target
Scenario: Fermion inelastic (pseudo-Dirac) DM

Pseudo–Dirac Thermal Relic DM

\[ y = \frac{e^2 \alpha_D}{N_{\text{eff}}} \left( \frac{m_\chi}{m_N} \right)^4 \]

\[ m_\chi \text{ (MeV)} \]

\[ N_{\text{eff}}, \text{ model dependent} \]

Relic Density

LHC

LEP

Super CDMS
SNOLAB (1–loop)

BaBar

E787

E949

33
Missing Mass at Colliders Confronts Thermal Targets
– another perspective –

- BaBar constrains $\epsilon^2$; thermal freeze-out fixes $y \equiv \epsilon^2 \alpha_D (m_\chi/m_{A'})^4$
  - Physical limits: $\alpha_D < 0.5$ and $m_\chi/m_{A'} < 0.5$
  - Previous plot: saturating the physical limits → conservative (worst case) constraint on $y^*$
  - Alternately, fix $y$ to thermal relic and $m_\chi/m_{A'}$ near minimum
    - Experimental constraint on $\epsilon$ implies maximum $\alpha_D$
    - For pseudo-Dirac, Belle-II (and more) needed to explore SM-like range of $\alpha_D$
Scenario: Scalar DM

For smaller $\alpha_D$ or bigger mass hierarchy, accelerator limits get better in this param. space (because they just depend on $\epsilon$)
**Sensitivity vs. Target**

Scenario: Fermion inelastic (pseudo-Dirac) DM

---

**Pseudo–Dirac Thermal Relic DM**

- LHC
- LEP
- BaBar
- E787
- E949
- Super CDMS
- SNOLAB (1-loop)

**Formula:**

\[ y = e^2 a_D (m_\chi / m_A)^4 \]

**Graph axes:**

- Y-axis: \( y = e^2 a_D (m_\chi / m_A)^4 \)
- X-axis: \( m_\chi \) (MeV)

**Logarithmic scale:**

- 10^{-16} to 10^{-1}

---

**Parameters:**

- \( N_{eff} \), model dependent
- \( m_\chi, m_A \)
Going Further With Fixed Targets

**Luminosity**

- $e^+e^-$ (or pp)
  - $10^{11}$ e$^-$
  - $10^{11}$ e$^+$

- **Fixed-Target**
  - $10^{11}$ e$^-$
  - $\sim 10^{23}$ atoms in target

**Cross-Section**

- N(hard scatter) $\sim 1$
  - per crossing

- $\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10 \text{ fb})$

- N(hard scatter) $\sim 0.01 - 1$
  - per electron

- $\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10 \text{ pb})$

Diagram showing electron, gamma, muons, and nucleus interactions with energy $E_1$, $A'$, $x$, and $1 - x$.
Fixed-Target Missing Mass

- Same signal from positron beam on atomic electron
  - Optimized for lower-energy kinematics
  - Requires small, dedicated experiment
    - Yield not competitive with Belle-II ultimate sensitivity (with assumed veto performance)

- VEPP3 and MMAPS don’t need veto – sensitive to arbitrary $A'$ decay
Beam Dump Experiments

FIG. 1: Schematic experimental setup. A high-intensity multi-GeV electron beam impinging on a beam dump produces a secondary beam of dark sector states. In the basic setup, a small detector is placed downstream so that muons and energetic neutrons are entirely ranged out. In the concrete example we consider, a scintillator detector is used to study quasi-elastic $-n$ucleon scattering at momentum transfers $\sim 140$ MeV, well above radiological backgrounds, slow neutrons, and noise. To improve sensitivity, additional shielding or vetoes can be used to actively reduce cosmogenic and other environmental backgrounds.

FIG. 2: a) $\bar{p}$ pair production in electron-nucleus collisions via the Cabibbo-Parisi radiative process (with $A_0$ on- or off-shell) and b) $\bar{\chi}$ scattering off a detector nucleus and liberating a constituent nucleon. For the momentum transfers of interest, the incoming $p$ resolves the nuclear substructure, so the typical reaction is quasi-elastic and nucleons will be ejected.

nuclear dissociation; nucleon, nucleus, or electron recoil

0906.5614, 1107.4580, 1205.3499
Batell, DeNiverville, McKeen, Pospelov, Ritz

Izaguirre, Krnjaic, Schuster & NT
PRD.88.114015 and 1403.6826
Uniquely achievable at fixed target experiments – **collimated forward DM production** needed for efficient detection

Very high luminosity – e.g. LSND: $10^{23}$ protons on target, 1 barn$^{-1}$ per proton $\rightarrow 10^5$ ab$^{-1}$

Many experiments can be done (mostly) parasitically
- dedicated analysis/run at accelerator neutrino experiment [already done]
- downstream of beam-dump for other e– beam experiments [several proposals]

On-shell mediator enhances yield, but **not** essential to signal definition
Beam Dump Sensitivity

Bounds from mining 1980s data – both p (LSND) and e\(^-\) (E137) beam – are world-leading below 100 MeV!

Recent dedicated MiniBoone run sets best limit on hadronic couplings at higher masses

Several ideas to go further with both electrons and protons
Rate scales as $\epsilon^4$ ($\epsilon^2$ for production and $\epsilon^2$ for detection) – so a factor of 100 in luminosity or detector size only increases $\epsilon^2$ sensitivity by 10, if yield-limited.

Backgrounds can be non-negligible as well

- neutrino elastic scattering, especially at proton beams
- cosmic rays in e- beam experiments (existing high-intensity beams aren’t pulsed)

In this case, a factor of 100 in lumi may only buy a factor of 3 in sensitivity
Use distinctive kinematics of $A' / DM$ pair production in $e^-$ beam, without trying to reconstruct its mass:

- When DM pair is produced, it carries away most of the incident $e^-$ energy.
- Look for low energy deposition (no hadronic energy) from a high-energy $e^-$.

A detector with tracking can measure $e^- p_T$ for a second hint of heavy-particle production.
Use distinctive kinematics of $A'/\text{DM}$ pair production in $e^-$ beam, without trying to reconstruct its mass

- When DM pair is produced, it carries away most of the incident $e^-$ energy
- Look for low energy deposition (no hadronic energy) from a high-energy $e^-$

Such a search requires firing one electron at a time, measuring detector response, and vetoing other final state particles with exquisite efficiency.

A relatively new technique, but the only one capable of scaling well below current beam-dump sensitivity
NA64: A calorimetric search with $\sim 3 \times 10^9$ electrons @ 100 GeV (~pC) on the cusp of competing with best current constraints (background free runs with 100-1000x more charge anticipated)

FIG. 2: The left panel shows the measured distribution of events in the $(E_{ECAL};E_{HCAL})$ plane from the combined BGO and PbSc run data at the earlier phase of the analysis. Another plot shows the same distribution after applying all selection criteria. The dashed area is the signal box region which is open. The side bands A and C are the one used for the background estimate inside the signal box. For illustration purposes the size of the signal box along $E_{HCAL}$-axis is increased by a factor five.
Missing Energy/Momentum

For the ultimate missing energy/momentum search

- Want $10^{14} - 10^{16}$ $e^-$ – need $O(\text{ns})$ bunch spacing & fast detector
  - Detector must contend with lower beam energy of high-rate accelerators
  - Need exceptionally pure veto
- Exploit tracking and recoil $e^- p_T$ as additional handles for bkg rejection
- These motivate key design parameters for LDMX
FIG. 20: Combined constraints (shaded regions) and sensitivity estimates (dashed/solid lines) on the parameter $y$ for scalar elastic, scalar inelastic, Majorana and pseudo-Dirac DM. The prescription $m_A^0 = 3 m$ and $\alpha_D = 0.5$ is adopted where applicable. For larger ratios or smaller values of $\alpha_D$, the accelerator-based experimental curves shift downward, but the thermal relic target remains invariant. See section V for sensitivity estimates for direct detection experiments. Courtesy G. Krnjaic.
Summary: Intensity Frontier

☐ Low-mass DM expected to be quite weakly coupled → high-luminosity techniques required to search for it

☐ A variety of complementary strategies
  - Missing mass at (super) B-factories → best $O$(GeV)-mass coverage
  - Missing mass at fixed-target → most inclusive sensitivity
  - Beam-dump experiments → unique coupling measurement, best measurement of hadronic couplings
  - Missing energy/momentum → greatest low-coupling sensitivity for sub-GeV models

☐ Taken together, excellent prospects to fully explore the most predictive models of light thermal DM!
Conclusions

- We don’t know what DM is made of, but thermal production defines a broad and important lamp-post
- Accelerator searches are well matched to the challenge of exploring this possibility – multiple experiments are needed in different parameter regions
- A very exciting field!
  - Rich search opportunities at the LHC
  - New ideas in theory are informing completely new experiments, at accessible cost and timescales
- Dark matter is ours to find!