SEARCHES FOR
LEPTOPHILIC DARK MATTER
WITH ASTROPHYSICAL EXPERIMENTS

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Erice - June 20th, 2016

«Ettore Majorana» Foundation and Centre for Scientific Culture
International School for Subnuclear Physics
54th Course: THE NEW PHYSICS FRONTIERS IN THE LHC-2 ERA
Dark Matter - exciting challenge

Overwhelming evidence for the existence of non-luminous matter.
Exploration of nature of dark matter: one of the most exiting challenges of particle and astroparticle physics.

Properties, assuming DM is a (maybe more) new particle

According to the observations DM should be
- cold (non relativistic);
- massive (local density $= 0.3 \text{ GeV/cm}^3$);
- electrically neutral;
- weakly interacting (not observed);
- small self interaction cross section (Bullet cluster);

We consider WIMP dark matter ($M_{\text{WIMP}} \sim 10 \text{ GeV up to } \sim \text{ TeV}$)

N.B. There are more exotic scenarios, but we stick to this one.
Huge experimental effort in DM searches.

In principle there are three ways of discovering Dark Matter:

Assumption: a type of non-gravitational interaction with SM particles exists

- production at colliders (LHC);
- direct detection;
- indirect detection, e.g. AMS-02
AMS-02: very precise measurements of CR fluxes

AMS-02 experiment measures fluxes and composition of charged CR with unprecedented precision

⇓

search for antimatter and DM studies

Positron flux

Electron flux
DM explanation for AMS data

To explain AMS excess:

1. only astrophysical sources (pulsar, supernovae, etc.)
DM explanation for AMS data

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1. only astrophysical sources (pulsar, supernovae, etc.)
2. only Dark Matter, with large annihilation cross section in light final states
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1. only astrophysical sources (pulsar, supernovae, etc.)
2. only Dark Matter, with large annihilation cross section in light final states
3. excess mostly due to astrophysical source/uncertainty in propagation models.

**DM contribution is subdominant:** additional structures in the data.
From a theoretical perspective, many possibilities...
Various theoretical models provide dark matter candidate(s) ⇒ Exclusion of models ⇒ or regions of ⇒ parameter space!

No clear signal from experiments so far (but many anomalies...)

We consider leptophilic DM models, place limits on the annihilation cross section. (Actually our procedure is rather model independent!)

Two ingredients:
1 prediction for signal due to Dark Matter annihilation in the galactic halo (electroweak corrections);
2 description of astrophysical background.
Theoretical predictions for the signal

**Secondary fluxes of antimatter from DM annihilation:**

1. **Flux at production** ⇔ **primary flux**
   (DM + DM annihilation is parametrized by the cross section \( \langle \sigma v \rangle = a + bv^2 + O(v^4) \))
   (FeynArt + FormCalc, MadGraph, CalcHEP)

2. **Parton shower and hadronisation**
   (PYTHIA 8)
   ⇔ **primary stable SM flux**

3. **Propagation through the Galaxy**
   ⇔ **secondary flux**
   (Galprop or Green functions)

4. **Solar modulation**
   ⇔ **flux measured by AMS-02**
   (force field approx.)
Theoretical predictions - EW corrections

Importance of inclusion of electroweak emission for calculation of energy spectra.

At the $\sim$ TeV scale EW corrections can be extremely relevant:

the DM mass $M$ is much larger than the EW scale
$\Rightarrow$ the emission is enhanced by factors $\ln \frac{M^2}{M_W^2}$ (Sudakov logs)

Decay and hadronisation of EW bosons
$\Rightarrow$ all stable SM particles in the final state, independent of initial state;
$\Rightarrow$ modification of low energy part of $e^\pm$ spectra.
Constraints dark matter models with AMS-02 data

Limits from colliders:
- Background model very well known: Standard Model
  - Theoretically very well motivated model
  - Parameters are known!
To place limits: 1 (few) free parameter(s), e.g. coupling or signal normalisation.

Limits from AMS-02:
- No reliable background description from first principles
  - Phenomenological model
  - Parameters are unknown!
To place limits: 1 (few) free parameter(s) + fit of the background to extract the parameters.
Background modelling

- Appropriate description of fluxes measured by AMS-02 needed;
- **MAIN ASSUMPTION**: fluxes of astrophysical origin are smooth (DM adds structures on top);
- Phenomenological model describes the $e^+$ and $e^-$ fluxes also at low energies;
- Electrons primary and secondary particles: spectral index energy dependent.
- Positrons only secondary particles: one spectral index gives good description.

\[
\Phi_{e^-} = \frac{E^2}{\tilde{E}^2} \left[ C_{e^-} \tilde{E}^{-\gamma_{e^-}} + C_{S} \tilde{E}^{-\gamma_{S} e^-} / \tilde{E} / E_S \right]
\]

\[
\Phi_{e^+} = \frac{E^2}{\tilde{E}^2} \left[ C_{e^+} \tilde{E}^{-\gamma_{e^+}} + C_{S} \tilde{E}^{-\gamma_{S} e^+} / \tilde{E} / E_S \right]
\]
Limits on the annihilation cross section

Setting limits

- Absence of signal ⇒ set limits on normalisation of the signal.
- Background parameters free to vary when scanning over possible normalisations.

![Graph showing AMS-02 positron flux, background + signal from 100 GeV DM annihilation, and signal from 100 GeV DM annihilation.](graph.png)
Results: upper limits on $<\sigma v>$

Upper limits on annihilation cross section for leptophilic models, $\text{DM DM} \rightarrow e^+ e^-$

- Checked impact of choice of astrophysical parameters/DM halo model.
Results: upper limits on $<\sigma v>$

Expected upper limits on $<\sigma v>$ for leptophilic models
EW radiation has negligible effect on upper limits, however it is relevant: we obtain predictions for the antiproton flux!

![Graph showing antiproton flux predictions under different DM masses compared to PAMELA and AMS-02 data.](image-url)
Results: inclusion of EW radiation

Uncertainties due to knowledge of the antiproton production cross section:

![Graph showing antiproton production cross section uncertainties with lines for PAMELA, AMS-02, background only, and DM masses of 425 GeV, 1000 GeV, and 5000 GeV. The graph plots the ratio of baryon density to proton density (\(\bar{\rho}/\rho\)) against kinetic energy (GeV).]
Results: inclusion of EW radiation

Uncertainties due to modelling of propagation through the Galaxy:

![Graph showing results]

- PAMELA
- AMS-02
- Background only
- DM Mass = 425 GeV
- DM Mass = 1000 GeV
- DM Mass = 5000 GeV

Kinetic energy (GeV)
Limits on DM annihilation cross section

- reliable description of the background is important;
- better understanding of astrophysical uncertainties needed;

EW corrections

- small impact on limits from $e^+$, $e^-$ fluxes;
- induce correlations between different signals;
- prediction for antiprotons even within a leptophilic model.
- however better measurements of antiproton production cross sections needed.

[L.A.C., H. Gast, M. Krämer, M. Pellen, S. Schael, in preparation]
WE'VE BEEN STUDYING MATTER FOR A COUPLE OF HUNDRED YEARS...

AND WE HAVE A FINE UNDERSTANDING OF CHEMICALS, ETC...

AND ALL OF A SUDDEN WE DISCOVER THAT ALL THAT WORK WE'VE BEEN DOING,

IS ONLY A TINY FRACTION OF WHAT THE UNIVERSE IS MADE OUT OF!

AND IT'S LIKE YOU'VE BEEN STUDYING AN ELEPHANT'S TAIL FOR TWO HUNDRED YEARS AND YOU DISCOVER...

IT'S ONLY THE TAIL!
Backup
Sudakov parametrisation for massive bosons

Implementation of the splitting function approach:

**Sudakov parametrisation**

- **Initial state:** \( S^\mu = (2E, 0, 0, 0) \), where \( E = \frac{M_{\text{DM}}}{\sqrt{1 - v_{\text{cm}}^2}} \);

- **Momentum of the electron that radiates the Z boson**
  \[
p_1 = \left( E \left( x + \frac{k_t^2}{4E^2 x} \right), -k_t, 0, E \left( x - \frac{k_t^2}{4E^2 x} \right) \right), \quad \text{with} \; k_t \ll 1, \; x = \frac{E_Z}{\sqrt{s}};
  \]

- **Four-momentum of the emitted Z boson:**
  \[
k_Z = \left( E \left( (1 - x) + \frac{k_t^2 + m_Z^2}{4E^2 (1-x)} \right), k_t, 0, E \left( (1 - x) - \frac{k_t^2 + m_Z^2}{4E^2 (1-x)} \right) \right).
  \]

- **Four-momentum of the electron which does not radiate**
  \[
p_2 = \left( E \left( 1 - R(k_t, x) \right), 0, 0, -E \left( 1 - R(k_t, x) \right) \right),
  \]
  with \( R(x, k_t) = \frac{k_t^2}{4E^2 x} + \frac{k_t^2 + m_Z^2}{4E^2 (1-x)} \).

**Perfect conservation of four-momentum ensured.**
Analytical calculation for 2 → 3 in UED

Differential cross section integrated over angles: \[ v d\sigma = \frac{|M|^2}{256\pi^3} dx_1 dx_2, \]
x_1 and x_2 parametrize the phase space:
\[ k^0 = (1 - x_2)\sqrt{s}/2 \quad , \quad p_1^0 = x_1\sqrt{s}/2 \quad , \quad p_2^0 = (1 - x_1 + x_2)\sqrt{s}/2, \]
Integration of the phase space for x_1: \[ x_- \leq x_1 \leq x_+, \]
\[ x_\pm = \frac{1 + x_2}{2} \pm \sqrt{\frac{(1-x_2)^2}{4} - \frac{m_Z^2}{s}}, \]
and for x_2: \[ -\frac{m_Z^2}{s} \leq x_2 \leq 1 - 2\frac{m_Z}{\sqrt{s}}. \]

Expansion in \( v \), integration over x_1, terms vanishing for \( m_Z \rightarrow 0 \) neglected:
\[
\frac{d\langle \sigma v \rangle}{dx_2} = \frac{\alpha}{2304M_{DM}^2\pi^2} \frac{(1 - 2\sin^2 \theta_w)^2}{\sin^2 \theta_w \cos^2 \theta_w} |g_L|^4 F(x_2), \quad \text{with} \quad g_L = Y_L g_1 \quad \text{and}
\]
\[
F(x_2) = \frac{1 + x_2^2}{1 - x_2^2} \log \left( \frac{x_+}{x_-} \right) + \frac{3(1-x_2)}{4(1+x_2)^2} \left( 5 + 8x_2 + 5x_2^2 \right) + \frac{(1+4x_2+9x_2^2+4x_2^3+x_2^4)}{(1+x_2)^3} \log(x_2),
\]
\[ \bar{x}_\pm = 1 - x_2 \pm \sqrt{(1 - x_2)^2 - m_Z^2/M_{DM}^2}. \]
Expanding Born cross section in \( v \), only lowest order contribution:
\[ \langle \sigma v \rangle_{\text{Born}} = \frac{|g_L|^4}{576M_{DM}^2\pi^2}. \]

We can recast it in the form:
\[
\frac{d\langle \sigma v \rangle}{dx_2} = 2\langle \sigma v \rangle_{\text{Born}} \frac{\alpha}{2\pi} \frac{g_f^2}{\sin^2 \theta_w \cos^2 \theta_w} F(x_2).
\]
Discrepancy

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<th>Mass [GeV]</th>
<th>$2 \to 2 \ [pb]$</th>
<th>$2 \to 3 \ [pb]$</th>
<th>splitting [pb]</th>
<th>discrepancy [%]</th>
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<td>3000</td>
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<td>$1.221 \times 10^{-4}$</td>
<td>$1.227 \times 10^{-4}$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Courtesy of M. Pellen
Propagation through the Galaxy - Green function’s method

Positrons and antiprotons

\[
\frac{d\Phi_{e^\pm}}{dE} (\epsilon, r_\odot) = \frac{1}{4\pi} \frac{\nu_{e^\pm}}{b_T(\epsilon)} \frac{1}{2} \left( \frac{\rho_\odot}{M_{DM}} \right)^2 \langle \sigma v \rangle \int_{\epsilon}^{M_{DM}} d\epsilon_s \frac{dN_{e^\pm}}{dE}(\epsilon_s) \mathcal{I} (\lambda_D(\epsilon, \epsilon_s))
\]

\[
\frac{d\Phi_{\bar{p}}}{dK} (\epsilon, r_\odot) = \frac{1}{2} \frac{\nu_p}{4\pi} \left( \frac{\rho_\odot}{M_{DM}} \right)^2 R(K) \langle \sigma v \rangle \frac{dN_{\bar{p}}}{dK}
\]

in both cases

\[
\frac{dN_{e^\pm, \bar{p}}}{dE} = \frac{1}{\langle \sigma v \rangle_{DM \rightarrow I}} \frac{d\langle \sigma v \rangle_{DM \rightarrow I \times BR_{I \rightarrow e^\pm, \bar{p}}}}{dE}
\]

Solar modulation

Approximated parametrisation used:

\[
\frac{d\Phi_{e^\pm}^{SolMod}}{dE} (E) = \frac{E^2}{(E + \Psi_{\pm})^2} \frac{d\Phi_{e^\pm}}{dE} (E + \Psi_{\pm})
\]

\(\Psi_{\pm}\) effective parameters, \(\hat{E}_{\pm} \equiv E_{\pm} + \Psi_{\pm}\)
Results: upper limits on $<\sigma v>$

Projected upper limits on $<\sigma v>$ for leptophilic models

![Graph showing projected upper limits on $<\sigma v>$ for leptophilic models.](image)
Results: inclusion of EW radiation

Impact of EW corrections on the upper limits is negligible.
UL all channels

Upper limits on annihilation cross section for different channels

\[
\langle \sigma v \rangle \text{(cm}^3/\text{s)}
\]

\[
10^{-22} \quad 10^{-23} \quad 10^{-24} \quad 10^{-25} \quad 10^{-26} \quad 10^{-27} \quad 10^{-28} \quad 10^{-29}
\]

\[
10 \quad 10^2
\]

DM Mass (GeV)

Graph showing upper limits on annihilation cross section for different channels:
- DM DM -> e^+ e^-
- DM DM -> b \bar{b}
- DM DM -> \tau^+ \tau^-
- DM DM -> \mu^+ \mu^-
- DM DM -> W W
- DM DM -> Z Z

Legend:
- Red: DM DM -> e^+ e^-
- Green: DM DM -> b \bar{b}
- Blue: DM DM -> \tau^+ \tau^-
- Orange: DM DM -> \mu^+ \mu^-
- Pink: DM DM -> W W
- Blue: DM DM -> Z Z