Dark Matter:
Indirect Detection & LHC searches

Nicole Bell
The University of Melbourne, Australia

in collaboration with

Ahmad Galea, Amelia Brennan (Melbourne)
Thomas Jacques, James Dent, Lawrence Krauss (Arizona)
Tom Weiler (Vanderbilt)
production (collider searches)

\[ q \rightarrow \chi \]

scattering (direct detection)

\[ \bar{q} \rightarrow \chi \]

annihilation (indirect detection)
production (collider searches) →

annihilation (indirect detection) →

2→3 modes are important!
Indirect detection

~

dark matter annihilation
Annihilation cross section

Parameterize the annihilation cross section as:

$$\langle \sigma v \rangle = a + b v^2 + \ldots$$

- $a$ -- from s-wave ($L=0$) annihilation
- $b$ -- both s-wave and p-wave ($L=1$) contributions

The $L^{th}$ partial wave contribution is suppressed as $v^{2L}$

In galactic halos, $v \sim 10^{-3}c$, so only the s-wave contribution will be significant.

However, in many models, s-wave annihilation to a fermion pair is helicity suppressed by a factor of $\left( m_f / m_{DM} \right)^2$
Example: SUSY

Majorana neutralinos annihilate to a fermion pair via:

- **t- and u-channel exchange of sfermions** → helicity suppressed

- **s-channel exchange of Z** → helicity suppressed

- **s-channel exchange of higgs** → suppressed by yukawa couplings
  \[ \left( \frac{m_f}{\text{vev}} \right)^2 \]
Example of suppressed annihilation

- Cao, Ma, Shaughnessy, PLB 2009.
- Dark matter = gauge-singlet Majorana fermion = $\chi$

$\mathcal{L} = f (\nu_L \eta^0 - \ell_L \eta^+) \chi + h.c.$

$\nu \sigma = \frac{f^4 v^2}{24\pi m^2_\chi} \frac{1 + \mu^2}{(1 + \mu)^4}$

$\mu = \frac{m^2_\eta}{m^2_\chi}$

SUSY analogue

Annihilation of bino dark matter to fermions via exchange of sfermions
Lifting the suppression (photons)

Emission of a photon can lift this suppression:

Bergstrom, PLB 225, 372, 1989;
Flores, Olive, Rudaz, PLB 232, 377, 1989;
Bringmann, Bergstrom, Edsjo, 2008;
Barger, Gao, Keung, Marfatia, 2009,
...

The photon carries away a unit of angular momentum
→ no longer helicity suppressed.

$$\chi \chi \rightarrow f \bar{f} \gamma \gg \chi \chi \rightarrow f \bar{f}$$
Lifting the suppression (photons)

Bringmann, Bergstrom, Edsjo, 2008

Final state radiation (FSR)  “Virtual internal bremsstrahlung” (VIB)

- Effect most pronounced for near-degenerate $\chi$ and $\eta$
  (i.e. coincides with the co-annihilation region)
Bremsstrahlung signals

Gamma rays

Positrons

Supposed FERMI gamma ray line at ~130GeV fit by bremsstrahlung signal with m~150GeV, arXiv:1203.1312

Bergstrom, Bringmann, Edsjo, PRD 2008
Lifting the suppression: electroweak (W,Z) bremsstrahlung

- Radiating a W or Z boson can also lift the suppression
- Both VIB and FSR are present
- similar to $\gamma$ brem, except for W/Z mass effects.
- distinct phenomenology: W and Z bosons decay to charged leptons, neutrinos, gammas, and hadrons
  $\rightarrow$ hadron production even for “leptophillic” models

Bell, Dent, Jacques & Weiler, PRD 2010.
Ciafaloni, Cirelli, Comelli, De Simone, Riotto & Urbano, JCAP 2011
**W brem rate larger than photon brem rate, except near threshold**

Adding all the bremsstrahlung processes:

$$\sigma_{\text{brem, total}} = \sigma_{e^+\nu W^-} + \sigma_{\bar{\nu}e^- W^+} + \sigma_{\bar{\nu}\nu Z} + \sigma_{e^+e^- Z} + \sigma_{e^+e^- \gamma} = 7.16 \sigma_{e^+e^- \gamma}.$$  

(in the limit where the W/Z mass is negligible)

Bell, Dent, Galea, Jacques, Krauss and Weiler, arXiv:1104.3823
Ratio of $e\nu W$ and $e^+e^-$ cross sections

- Annihilation to $e^+e^-\gamma$, $e^+e^-Z$ & $e\nu W$ dominates over $e^+e^-$
- Enhancement by up to three orders of magnitude!

$R = \frac{(\sigma v)(\chi\chi \rightarrow W\nu)}{(\sigma v)(\chi\chi \rightarrow e^+e^-)}$

$\mu = \frac{m_\eta^2}{m_\chi^2}$

$m_\chi = 300 \text{ [GeV]}$

$(v \sim 10^{-3}c, \text{ Galactic halo})$

Bell, Dent, Galea, Jacques, Krauss and Weiler, arXiv:1104.3823
Annihilation spectra: $\gamma / W / Z$ brem

Bell, Dent, Jacques & Weiler, arXiv:1101.3357
Bremsstrahlung can’t make significant contribution to e+ flux, without overproducing pbar.
Models with no helicity suppression

→ EW-brem still occurs, but is subdominant

→ W/Z decays ensures there is at least a minimal yield of hadrons, photons, charged leptons and neutrinos.

Kachelriess, Serpico and Solberg
PRD 2009.

Neutrinos-only
\( \chi\chi \rightarrow \nu\bar{\nu} \) (+ W/Z brem)

Electrons-only
\( \chi\chi \rightarrow e^+e^- \) (+ W/Z brem)
Neutrinos from the Sun

- Dark matter accumulates in the centre of Sun
- Capture rate and (if in equilibrium) the annihilation rate controlled by WIMP-nucleon scattering cross section
- Neutrinos are the only annihilation products able to escape
- Hard spectra (WW) more detectable than soft spectra (bb)
- EW brem annihilation mode → distinctive hard spectra

(D. Hooper)
Solar WIMP limits
- limits depend on the assumed annihilation spectrum
Neutrinos from the Sun - EW brem

EW brem relative muon track rates - IceCube

<table>
<thead>
<tr>
<th></th>
<th>200 GeV</th>
<th>500 GeV</th>
<th>1000 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>normalised to $\tau^+\tau^-$</td>
<td>1.8</td>
<td>1.2</td>
<td>0.6</td>
</tr>
<tr>
<td>normalised to $W^+W^-$</td>
<td>3.8</td>
<td>2.4</td>
<td>1.9</td>
</tr>
</tbody>
</table>
LHC dark matter searches with electroweak bremsstrahlung
Dark matter at the LHC

The dominant DM production process at the LHC may be:

\[ \overline{q} q \rightarrow \chi \chi \]

But this process is invisible to the detectors (DM stable, weakly interacting)

We need a visible particle in the final state, to recoil against some missing transverse energy,

e.g. \[ \overline{q} q \rightarrow \chi \chi + \text{gauge boson} \]

Dark matter visible as high pT state + missing ET
Dark matter at the LHC

- gauge boson is a gluon or photon → monojet or monophoton searches

  Fox, Harnik, Koop, Tsai, 1109.4398, 1103.0240
  Beltran, Hooper, Kolb, Krusberg, Tait, 1002.4137
  Frandsen, et al, 1204.3839
  CMS collaboration, 1204.0821, 1206.5663
  ATLAS collaboration, 1106.5327
  ...

- gluon radiation
  - high cross section & large backgrounds
- monophoton
  - complementary to (but less constraining than) monojets

- electroweak channels?
  - relatively low backgrounds
Consider the Z decay to muons:

→ Signature: pair of high pT muons which reconstruct to a Z, recoiling against missing ET.

\[ \bar{q} q \to \chi \chi Z \to \chi \chi \mu^+ \mu^- \]
**Backgrounds**

- **Signal**: pair of muons + missing $E_T$
  \[ \bar{q} q \rightarrow \chi \chi Z \rightarrow \chi \chi \mu^+ \mu^- \]

- **EW backgrounds**:
  - $ZZ \rightarrow \bar{\nu} \nu \mu^+ \mu^-$
  - $W^+ Z \rightarrow \nu l^+ \mu^+ \mu^-$
  - $W^- Z \rightarrow \bar{\nu} l^- \mu^+ \mu^-$
  - $W^+ W^- \rightarrow \nu \mu^+ \bar{\nu} \mu^-$

- **QCD backgrounds**:
  - $t \bar{t} \rightarrow b \bar{b} W^+ W^-$
  - $Z + jets$

**ZZ background** has large missing $E_T$ & is kinematically most similar to our signal.

**Z+jets** is a large background, but can be removed with kinematic cuts.
similar model as before, but now we take the scalar to be charged under SU(3), \( \eta^c \sim (3,2,1/3) \),

(i.e. \( \chi \) and \( \eta \) are analogous to the neutralino and squark. But, importantly, note we don’t have a gluon.)
Signal and Backgrounds - before cuts

(Includes a cut on invariant mass of the muon pair, and an inclusive muon $p_T$ cut of 50 GeV)

Bell, Dent, Galea, Jacques, Krauss & Weiler, in preparation

Nicole Bell, CoEPP, The University of Melbourne

The LHC, Particle Physics and the Cosmos, 13 July 2012
signal/background – as function of $\Delta R$ cut

$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$, where $\phi$ is the azimuthal angle and $\eta$ is the pseudo-rapidity of a particle in the detector.

$Z$ boosted $\rightarrow$ muons co-linear $\rightarrow$ signal has small $\Delta R$
Signal and Backgrounds - after cuts

Cuts: - missing $E_T > 100$ GeV
- $\Delta R < 1$

$m_{\chi} = 300$ GeV, $\sqrt{s} = 2$.

- $W^- W^+ \rightarrow \mu^- \bar{\nu} \mu^+ \nu$
- $W^- Z \rightarrow l^- \bar{\nu} Z$
- $W^+ Z \rightarrow l^+ \nu Z$
- $\bar{\nu} \nu Z$
- $\chi \chi Z$
- $\forall Z \rightarrow \mu^+ \mu^-$. 

Bell, Dent, Galea, Jacques, Krauss & Weiler, in preparation
Signal falls away for large dark matter mass
(note: couplings chosen to be consistent with relic density)
Comparison with monojet searches

At 7 TeV, 1fb⁻¹, and same model parameters → similar sensitivity

Monojet analysis
Fox et al.
arXiv:1109.4398

Z brem analysis
Bell, Dent, Galea, Jacques, Krauss, Weiler, in preparation
Conclusions

3-body final states are important for dark matter searches

Electroweak bremsstrahlung - indirect detection
- Annihilation to a fermion pair is often helicity suppressed
- Internal bremsstrahlung of $\gamma$, $W$ & $Z$ removes the suppression; Allows indirect detection of otherwise unobservable physics
- Interesting multimessenger signals. Antiproton limits important.
- Distinctive neutrino signal for solar WIMP searches

Electroweak bremsstrahlung - colliders
- Signal is a gauge boson plus missing transverse energy
- Large signal/background
- Complementary to monojet and monophoton searches