THE HIGGS PORTAL TO DARK MATTER AT THE LHC

Susanne Westhoff

Universität Heidelberg

Carl Zeiss Stiftung

Seminar — July 21, 2016 — Humboldt University Berlin
DARK MATTER!

Gravitational Lens in Abell 2218
PF95-14 · ST ScI OPO · April 5, 1995 · W. Couch (UNSW), NASA
DARK MATTER?

[ATLAS experiment, event n. 55091306, recorded on July 14, 2012]
Relic dark matter abundance after thermal freeze-out:

\[ \Omega_{\text{DM}} h^2 \approx \frac{3 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma_A v \rangle} = 0.1199 \pm 0.0022 \quad \text{[Planck coll. 2015, arXiv:1502.01589]} \]

Thermally averaged annihilation cross section:

\[ \langle \sigma_A v \rangle = 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1} \approx 1 \text{ pb} \]

Weakly Interacting Massive Particle around \( \Lambda_{\text{EW}} \approx 100 \text{ GeV} \)?
PARTICLE DARK MATTER

Weak interactions with standard model suggest **heavy mediator**:

Example: **fermion dark matter**

\[
M_{\eta}^2 \gg q^2 : \mathcal{L}_{\text{eff}}^{(6)} = \mathcal{C} (\bar{\chi} \Gamma \chi)(\bar{\psi} \Gamma \psi) + \ldots
\]

\[
\mathcal{C} = \frac{g^2}{M_{\eta}^2} \ll \frac{1}{q^2}
\]
(H†H) is a standard-model singlet. $H = \frac{1}{\sqrt{2}} \left( \sqrt{2} G^+ + v + h + iG^0 \right)$

$\chi$ is part of a dark sector.

$Z_2$ symmetry → DM candidate stable.

**Renormalizable portal** interactions:

Scalar DM $\chi = S$:

$$\mathcal{L} = (S^\dagger S)(H^\dagger H)$$

Vector DM $\chi = V_\mu$:

$$\mathcal{L} = (V_\mu V^\mu)(H^\dagger H)$$

**Effective portal** interaction through mediator(s):

Fermion DM:

$$\mathcal{L}_{\text{eff}} = \frac{g_S}{\Lambda} (\bar{\chi}\chi)(H^\dagger H) + i\frac{g_P}{\Lambda} (\bar{\chi}\gamma_5\chi)(H^\dagger H)$$
HIGGS PORTAL AT THE LHC

invisible Higgs decay
very strong bounds
[e.g. Djouadi et al., arXiv:1310.8214]

off-shell Higgs processes
very weak bounds
[Endo, Takaesu, arXiv:1407.6882] [Craig et al., arXiv:1412.0258]
UV-COMPLETE FERMION HIGGS PORTALS

\[ g_S = \frac{y^2}{2m_D} \]

\[ m_D \gg m_S \]

\[ m_D \lesssim \text{few 100 GeV} \]

**singlet-singlet**

**singlet-doublet**

**doublet-triplet**

[Lee et al., 2008, …]

[Mahbubani, Senatore, 2005, …]

[Dedes, Karamitros, 2014]

[triplet-quadruplet: Tait, Yu, 2016]

Higgs portal at the LHC is “open” for mediator searches.
**SINGLET-DOUBLET MODEL**

Dark fermions mix through Yukawa interaction:

\[
\mathcal{L} = -m_D \bar{\psi}_D \psi_D - m_S \bar{\psi}_S \psi_S - (y \bar{\psi}_D H \psi_S + \text{h.c.})
\]

\[
\langle H \rangle = \frac{v}{\sqrt{2}}
\]

\[
\begin{align*}
\chi^0_l &= \cos \theta \psi^0_D - \sin \theta \psi_S \\
\chi^0_h &= \sin \theta \psi^0_D + \cos \theta \psi_S
\end{align*}
\]

Mixing controls coupling to Higgs and gauge bosons:

\[
\begin{align*}
\chi^0_l &\rightarrow \frac{y}{\sqrt{2}} \sin(2\theta) \\
\chi^0_l &\rightarrow -\frac{g}{2c_W} \cos^2 \theta
\end{align*}
\]

Three parameters: \( m_{\chi^0_l}, m_{\chi^0_h}, y \)
SEARCH FOR (HIGGS-PORTAL) DARK MATTER

- relic abundance (annihilation)
- high-energy colliders (production)
- direct detection (scattering)

Bounds from indirect detection are weak. [Beniwal et al., 1512.06458]
DIRECT DETECTION
Measure recoil of atomic nuclei in shielded place.

e.g. at the Large Underground Xenon experiment LUX

Spin-independent DM-nucleus scattering:

\[ \sqrt{k^2} \approx 10 - 50 \text{ MeV} \ll M_\chi \]

\[ \sigma_0 = \frac{\mu_A^2}{\pi} |Z f_p + (A - Z) f_n|^2 \]

[picture taken at the Homestake Mine in Lead, SD]
Currently strongest bound on weak-scale DM scattering: 

\[ \sigma_0(m_\chi \approx 100 \text{ GeV}) \lesssim 10^{-45} \text{ cm}^2 \]  

DARK FERMION-NUCLEON SCATTERING

\[ \mathcal{O}_V = (\bar{\chi} \gamma_\mu \chi)(\bar{q} \gamma^\mu q) \]

\[ \mathcal{O}_S = (\bar{\chi} \chi)(\bar{q} q) \]

Effective interactions:

\[ f_{p,n} \sim \frac{g_Z^Z g_q^Z}{M^2_Z} \]

Dirac singlet:

\[ g_Z^Z = -\frac{g}{2c_W} \cos^2 \theta \]

Majorana singlet:

\[ g_Z^Z = 0 \]

Direct detection bounds \( \rightarrow \) \( \text{DM must be singlet-like, } \theta \approx \pi/2. \)
RELIC ABUNDANCE

**Dirac** dark matter annihilation: \( \chi \bar{\chi} \rightarrow Z \rightarrow q \bar{q}, \ell^+ \ell^- \)

**Majorana** dark matter:

**Observed abundance:** \( \Omega \chi h^2 = 0.1199 \pm 0.0022 \)  

Direct detection strongly constrains DM annihilation rate.

**Co-annihilation** prevents over-abundance: small DM-mediator mass splitting
COLLIDER SEARCHES

Look for missing energy or production of mediators.

e.g. at the Large Hadron Collider

Dark-matter production in proton-proton collisions:

$$\sigma(pp \rightarrow \chi\chi + X) = \int ds L_{ij}(s) \hat{\sigma}_{ij}(s)$$

Mono-jet searches

Mediator searches
DARK FERMION SEARCHES AT COLLIDERS

Soft leptons: \( m_0^0 - m_1^0, m^+ - m_1^0 \lesssim 30 \text{ GeV} \)

Similar to SUSY electroweakino searches: [Giudice, Han, Wang, Wang, arXiv:1004.4902]
[Schwaller, Zurita, arXiv:1312.7350]

Vector boson fusion might be complementary.
Mono-jet signal is too small for LHC energies.

LHC Run II
\( \mathcal{E}_T > 300 \text{ GeV} \)
\( p_T(j_1) > 300 \text{ GeV} \)
\( p_T(\ell) < 20 \text{ GeV} \)

[Schwaller, Zurita, arXiv:1312.7350]
[Dutta et al., arXiv:1411.6043]
[Berlin et al., arXiv:1502.05044]
EWK-INO SEARCH WITH SOFT LEPTONS

Di-leptons + ISR jet + missing energy:

Interpret these signatures in fermion Higgs portal context.

$E_T^{\text{miss}} > 200$ GeV

$p_T^j > 150$ GeV

$p_T^{\ell_1} : 5 - 15, 15 - 25$ GeV

$p_T^{\ell_2} < 15$ GeV
SUMMARY DARK DIRAC FERMIONS

\[ \delta_m = 0.1 \]

\[ \Omega_{\chi^0_i} = \Omega_{\text{Planck}} \]

\[ \delta_m \equiv \left( m^0_h + m^0_l \right) / m^0_l \]

\[ m_l \text{ [GeV]} \]

[Freitas, SW, Zupan, arXiv:1506.04149]
Future direct detection experiments and/or a high-energy collider can test this model.

[Freitas, SW, Zupan, arXiv:1506.04149]
FERMION DARK MATTER AT FUTURE COLLIDERS

**electron-positron** (ILC): $\sqrt{s} = 500 - 1000$ GeV
  - clean environment, less background
  - fermion mediators: soft leptons (+ISR)
  - sensitivity to mediator masses $m_\eta \lesssim \sqrt{s}/2$

**proton-proton** (FCC): $\sqrt{s} = 100$ TeV
  - enhanced cross section allows for sharper cuts
  - fermion mediators: soft leptons and jet(s)
  - boson mediators: jet(s)+missing energy
  - extended mass reach $m_{\text{max}}^{\text{FCC}} \approx 5 \times m_{\text{max}}^{\text{LHC}}$

[Berggren et al., arXiv:1309.7342]
[Bramante et al., arXiv:1412.4789]
[Harris et al., arXiv:1509.02904]
TAKE HOME

Higgs-portal fermion dark matter

- Opportunity at **LHC Run II**: Search for resonant production of mediators with soft leptons and missing transverse energy.

- **Direct detection** experiments provide complementary information.

- **Future** lepton and high-energy hadron **colliders** are helpful to test such models conclusively.
BACKUP
VECTOR BOSON FUSION

Sensitivity to fermion Higgs portal at 13-TeV LHC:

CMS: $\mathcal{B}(h \rightarrow \text{inv}) < 0.57$ [95\% CL]
DIRECT DETECTION BOUNDS

fermion dark matter with scalar Higgs-portal coupling:

FIG. 10: Direct search limits on the Majorana model parameter space. The grey shaded region is ruled out by the relic density constraint. The regions excluded by LUX (XENON1T) experiment are delineated with dashed blue (dotted blue) lines and dark (light) shadings.

Left: A close-up of the resonant annihilation region, $m_\chi \approx m_h/2$. The pink shaded region is excluded by an upper limit of 19% on $\text{BR}(h \rightarrow \chi\chi)$.

Right: The full mass range of $m_\chi$. [Beniwal et al., 1512.06458]
FIG. 6: Allowed parameter space for the Majorana singlet-doublet model in the Higgs resonance region, with the constraint $\rho = \rho_{\text{DM}}$. The solid lines indicate the correct DM density for different values of the Yukawa coupling $y$. The red-shaded region is excluded by direct detection limits from LUX. Also shown are projected 95% C.L. limits from LHC14 with 3000 fb$^1$ (dotted horizontal lines and shading) and FCC-hh with 3000 fb$^1$ (dot-dashed horizontal line and shading). The vertical lines depict the projected limits from invisible measurements at LHC14 with 300 fb$^1$ (short dashed) and 3000 fb$^1$ (dotted), and at ILC with $p_s = 250$ GeV (long dashed), as well as from direct detection searches at XENON1T (red dotted). See text for details.