The Leptonic Higgs as a Messenger of Dark Matter

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Hock-seng Goh, Lawrence Hall and P. K.
We believe that Dark matter exists

What is it??
Note the presence of electrons and positrons and absence of antiprotons.
Fermi 0905.0025

Possible estimated Background

Excess of $e^+$, $e^-$ flux persists, but not as sharp as that in ATIC.

These observation could mean the following:

• We need a new understanding of the background
• We have observed a near astrophysical source, such as pulsars.
• We have observed dark matter
If it is Dark matter, things become more interesting. (At least for us)

What do we learn from the data?

• Dark Matter mass ~ multi TeV
• Annihilating DM – Large cross-section
• Decaying DM – Very long lifetime.
• Preferably annihilate/decay to leptons.
• Sommerfeld enhancement
• Non-thermal production.
• Other changes in cosmological history.

• Hadrons heavier than leptons --- kinematics.
• Lepto-philic Dark sector --- symmetry.
In fact, idea has been around

If DM is an SM singlet:
- Silveira & Zee (PLB 1985)
- Higgs portal

(March-Russell et al 0801.3440)

Hints from data imply:

Leptonic Higgs
Leptonic Higgs: A simple 2-Higgs Doublet Model

\[ L \supset Q_i H_q u_j + Q_i H_q d_j + l_i H_l e_j + f(H_l) \]  
\[ \text{dark} \]

-- Has a chiral leptonic symmetry (parity) where

\[ l_i H_l = \text{odd}; \quad e_j, Q_p d_j H_q = \text{even} \]

\[ H_q^0 = v_q + h_q + i a_q \quad H_l^0 = v_l + h_l + i a_l \]

\[ A = a_l \cos \beta - a_q \sin \beta \quad Z_p = a_l \sin \beta + a_q \cos \beta \]

\[ H = h_l \cos \alpha - h_q \sin \alpha \quad h = h_l \sin \alpha + h_q \cos \alpha \]

-- Want \( v_l, v_q \) such that \( v_l \ll v_q \) \( \tan \beta = v_l/v_q \ll 1 \). (technically natural)

-- Would also like \( \sin \alpha \ll 1 \)

-- Have to satisfy constraints on parameters. Come back to it later.
A simple example: (annihilation to 4 $\tau$)

Other topologies and different leptonic final states possible depending on Dark Matter model.

In general, can have annihilation or decays within this framework.
Dark matter particle

Dark matter halo

Supernovae remnants

Nuclear physics

Interstellar medium

$f_D(E)$

$f_0(E)$

Diffusion

Signal

Background

Data

(peak, cut off at ~ DM mass)

(power law expected)
For the annihilation mode:

\[ \chi \chi \rightarrow H A \rightarrow 4\tau \]

\[ m_\chi = 4 \text{ TeV}, \quad B^e_{tot} = 10000 \]

\[ B^e_{tot} = B_\sigma \cdot B_{\text{clump}} \cdot B_\epsilon \]

--- Note, cannot fit ATIC peak.

--- However, fits FERMI data quite well.

--- Precise shape depends on particular channel.

\( M_\chi \) and \( B \) also change with choice of parameters.
Results of $\chi^2$ analysis after FERMI Data

Best fit: $2\tau$, $4\mu$ and $4\tau$ final states.
DM with $M = 3$ TeV that annihilates into $\tau^+\tau^-$ with $\sigma v = 2.0 \times 10^{-22}$ cm$^3$/s

P. Meade, M. Papucci, A Strumia, T. Volansky 0905.0480
Best fit decay channel in our framework

Can be obtained if DM mixes a little with the leptonic Higgs, such as via the operator: $\mu^2 H_D^\dagger H_l$

(with $\mu = \nu^2 / M_{\text{GUT}}$)
Implications for Other Observables

• In order to test approach, can look for correlated signals.

  -- Diffuse Gamma Ray emission from Galactic Center and nearby dwarf galaxies.

  -- Neutrinos from the Galactic Center.

  -- Exciting Signals for Higgs Physics at the LHC.

Although DM quite heavy, and not produced at the LHC, higgs signals could readily distinguish this framework with others.
Astrophysics Signals - Photons and Neutrinos

Strongly constrain DM annihilating to $\tau$ (but also very good chances of observation in the near future)

Dominated by $\pi^0$ decays from $\tau$s.

Other subdominant channels

(for $E \gtrsim 100$ GeV):

- final state radiation
- inverse compton scattering
- synchrotron radiation

(Lots of neutrinos) (BR = 100%)
Gamma-ray Constraints from Dwarf Galaxies (Annihilation)

- $B_{\gamma\text{tot}} < \sim 5000$ (Large core)
- $B_{\gamma\text{tot}} < \sim 700$ (NFW)

Since need $B_{e\text{tot}} \sim 10000$, so annihilation mode seems disfavored.

However, $B_{e\text{tot}} \neq B_{\gamma\text{tot}}$ in general. This, and a shallow profile, may resolve tension.

\[ B_{e\text{tot}} = B_0 \cdot B_{\text{clump}} \cdot B_e \]
Astrophysics Summary

Annihilating DM

- Need $B_{\text{tot}}^e \sim 10,000$
  
  For eg. ($B_\sigma = B_{\text{sommer}}$, $B_0 \sim 1000$; $B_{\text{clump}}^e = \text{few}$; $B_\varrho = \text{?}$)

- DM mass $M\chi \sim 5$ TeV

- Tension from gamma rays and neutrinos. (if correct, then should soon have signals.)

- Non-thermal production of Dark Matter natural within this framework.

Some explicit models in our paper

Decaying DM

- Life-time $\sim 10^{26}$ s (can be understood by spontaneously broken parity at dim 6).

- DM mass is $\sim 8$-10 TeV (depends on the model).

- Safe from gamma ray and neutrino constraints but constraints from neutrinos remain strong.

- Thermal production consistent with relic abundance.
The Leptonic Higgs
at the LHC

SM like (as far as couplings to quarks are concerned)

Other groups have looked at similar models from only particle physics motivation

-- Su, Thomas (0903.0667), Logan, McLennan (0903.2246), Barger, Logan, Shaughnessy (0902.0170), Arhrib et al (0906.0387), ...

New kinds of scalars

We have connected this in a natural way to Dark Matter

Won't discuss Charged Higgs, but also important.
**Constraints on Masses**

\[ m_H + m_A > 185 \text{ GeV} \]

| \[ |m_H - m_A| < m_Z \] | Prevents H from decaying to Z |
| --- | --- |
| \[ m_H < 2m_W \] | Prevents H from decaying to W |
| \[ m_H < 2m_A \] | Prevents H from decaying to AA (spectrum too soft) |

60 \sim \frac{2m_Z}{3} < m_A < 2m_W + m_Z \sim 250

45 \sim \frac{m_Z}{2} < m_H < 2m_W \sim 160

\[ \text{No decoupling at the LHC} \]
**Potential LHC signals**

- “SM” Higgs searches can change significantly (2 tau and 4 tau channels):

  ![Diagram of h to tau and BR ~ (sin α) / (sin β) so can be enhanced. Production same as that in SM. Good for mh < ~ 150 GeV.](image)

- New states A, H (predominantly leptonic):

  ![Diagram of h to A and BR ~ 1. (Good for mh < ~ 130 GeV)](image)

  If the quartic coupling is large

  Similar analysis to that for the NMSSM needed.

- New states A, H (predominantly leptonic)

  ![Diagram of p to Z* to H and BR ~ 1.](image)

  Dependent only on the mass of A, H.

  (No dependence on α, β)!

  For eg. ~ 350 fb for 100 GeV H, A

  May be seen with moderate luminosity.

  (More study required).
-- Can also have $2\tau$ signals from leptonic higgs H

only H couples to W

\[ H \rightarrow \tau \tau \]

BR ~ 1, Production suppressed by $\sin^2(\alpha - \beta)$ for VBF, but ($\sigma \times \text{BR}$) can be enhanced. Good for mH <~ 150 GeV

-- $8\tau$ channel also possible!

\[ p p \rightarrow h A A A A \rightarrow 8\tau \]

~ 35 fb for 120 GeV h

Findings consistent with other authors.

Tau physics determine the fate of the Higgs searches!

Need: efficient $\tau$-tagging --- challenging

Trading a tau-pair with a $\mu$-pair helps due to much smaller backgrounds.
Conclusions

• Recent astrophysical observations may have already provided the first non-gravitational evidence for DM. However, even if true, nature of DM likely different from “standard paradigm”.

• The Leptonic Higgs can serve as a messenger of DM and explain the observed PAMELA/Fermi/HESS data. Has very interesting implications for related astrophysics observations of photons and neutrinos.

• Favored DM heavy, so not produced at the LHC. However, have *correlated* Higgs signals at the LHC which could effectively probe this framework.

\[ \tau \] may be the key to Higgs physics.
BACKUP SLIDES
Astrophysical source for high energy cosmic rays

Primary (mostly particle, no antiparticle), flux \( \sim E^\alpha \)

Secondary (both particle and antiparticle)

\[ \gamma \rightarrow e^+e^- \]
Models of dark matter

**LLN model**

\[ L_{dark} = \lambda L H_1 N + m_L L L^c + m_N N N \]

Need \( \lambda \sim (3-4) \)

**Annihilation**

\[ \delta L_{dark} = \delta m^i L_i L_i^c + \ldots \]

**Decay**

\[ \chi \rightarrow (A, H) + \nu_l \rightarrow \tau^+ \tau^- \nu_l \]

or

\[ \chi \rightarrow H^\pm + l^\mp \rightarrow \tau^\pm l^\mp \nu_\tau \]
Innert doublet model

\[ L_{dark} = \lambda \left| H_l \right|^2 \left| H_{D} \right|^2 + \ldots \]

\[ \delta L_{dark} = \delta m H_l^\dagger H_l + \ldots \]

Singlet scalar model

\[ L_{dark} = \lambda \left| H_l \right|^2 (\Phi)^2 + \ldots \]

\[ \delta L_{dark} = \delta m \left| H_l \right|^2 \Phi + \ldots \]
**Summary of models**

<table>
<thead>
<tr>
<th></th>
<th>annihilation</th>
<th>decay</th>
<th>symmetry</th>
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</thead>
<tbody>
<tr>
<td><strong>LLN</strong></td>
<td>L, large coupling</td>
<td>N, have both direct lepton and cascade τ, less Boost factor, DM mass</td>
<td>Chiral parity for both lepton and quark, $Z_2$ Dark parity</td>
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<tr>
<td></td>
<td>Little hierarchy</td>
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<tr>
<td><strong>singlet</strong></td>
<td>No symmetry suppression on Hq mode</td>
<td>~8-10 TeV DM</td>
<td>$Z_6$ Dark parity</td>
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<tr>
<td></td>
<td></td>
<td>No suppression of Hq mode</td>
<td></td>
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<tr>
<td><strong>Inert D</strong></td>
<td>No symmetry suppression on Hq mode</td>
<td>Hq mode suppressed, decay to ZZ open but suppressed</td>
<td>Chiral parity for both lepton and quark, $Z_4$ Dark parity</td>
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Neutrinos

Constraints from Super-K very stringent:

Study by Liu, Yin, Zhu shows:

- 2 TeV dark matter annihilating to 2 $\tau$ that fits Pamela/Atic has muon flux (induced by neutrino) 3 times bigger than the bound

- We have 4 TeV dark matter annihilate to 2 H to 4 $\tau$

  e are softer $\rightarrow$ boost factor larger

  $\nu$ are softer too

[Typically these effects compensate and give same muon flux]

\[ B_{total}^e = 10000 \quad \text{need} \quad B_{total}^e = \# B_{total}^\nu \]

# = a few is reasonable
CMS, ATLAS are studying the reach of this signal (from Higgs working group)

No existing study available except a similar one for the NMSSM with \( m_A = 7 \) GeV, \( m_h = 120 \)

The claim is

\[ h \rightarrow AA \rightarrow 4\tau \]

- 20 \( \sigma \) discovery with 300 fb\(^{-1} \) \( \sim \) 5 \( \sigma \) with 30 fb\(^{-1} \)
- \( h \) heavier than 130 GeV become hard as \( tt \) background rise
- we expect heavier \( A \) will not reduce the efficiency, but Br suppressed by the small phase space if \( h \) is light.

Need more study
Review of existing studies

$h \rightarrow 2\tau$ and $H \rightarrow 2\tau$ (mass $\sim 115 - 145$ GeV)

$$\sigma_{VBF}(h) \times BR(h \rightarrow \bar{\tau}\tau) \approx \left[ \sigma_{VBF}^{SM} \times BR(h_{SM} \rightarrow \bar{\tau}\tau) \right] \frac{\left( \frac{\sin^2 \alpha}{\sin^2 \beta} \right)}{[1 + \left( \frac{\sin^2 \alpha}{\sin^2 \beta} - 1 \right) BR(h_{SM} \rightarrow \bar{\tau}\tau)]}$$

$$\sigma_{VBF}(H) \times BR(H \rightarrow \bar{\tau}\tau) \approx \left[ \sigma_{VBF}^{SM} \times BR(h_{SM} \rightarrow \bar{\tau}\tau) \right] \frac{\sin^2 (\alpha - \beta)}{BR(h_{SM} \rightarrow \bar{\tau}\tau)}.$$
H, A production $\rightarrow 4\tau$ (Drell - Yan)

mA = 80 GeV
mH = 100 GeV
$\sigma(Z^*) = 350$ fb

Further study needed!
5 \sigma \text{ curve}