Cosmic Constraints on Gauge-Higgs Dark Matter

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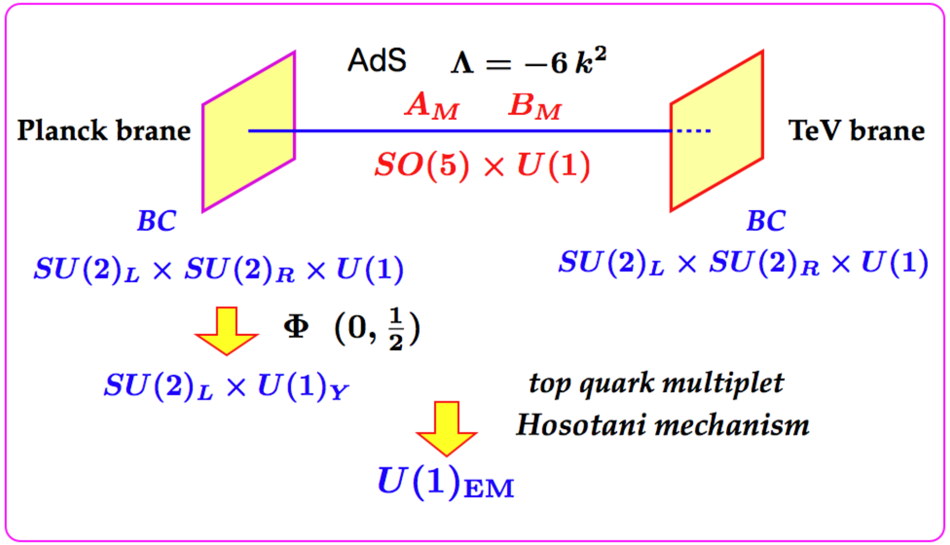
Outline

- The Gauge-Higgs Unification Model and the Higgs boson as the DM candidate.
- Cosmic positron and antiproton constraints
- Collider implications
- Conclusions.

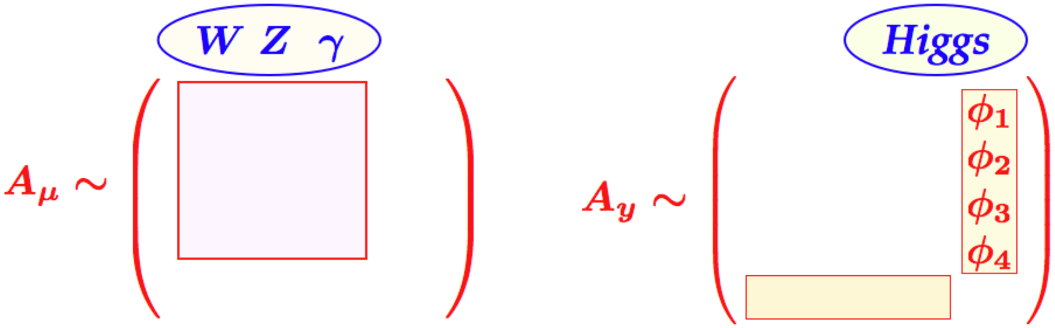
Gauge-Higgs Unification Model

Hosotani, Ko, Tanaka (0908.0212), Hosotani et al. (0806.0480), Hosotani (1003.3129)

1. The 4D Higgs boson is identified as a part of the extra-dim component of the gauge field, and couplings with other particles are given by gauge principle.
2. The setup is the $SO(5) \times U(1)$ gauge-Higgs unification model in the RS warped space.



3. The 4×4 part of the zeroth mode of A_y field is the SM gauge bosons, while the off-diagonal part is the SM Higgs field:



Effective Interactions for the Higgs DM

The Higgs boson is the fluctuation mode of the Aharonov-Bohm phase $\hat{\theta}_H$ along the fifth dimension

$$\hat{\theta}_H = \theta_H + H(x)/f_H$$

The Lagrangian is

$$\mathcal{L} = V_{\rm eff}(\hat{\theta}_H) - m_W^2(\hat{\theta}_H) W_\mu^+ W^{-\mu} - \frac{1}{2} m_Z^2(\hat{\theta}_H) Z_\mu Z^\mu - \sum_f m_f(\hat{\theta}_H) \bar{\psi}_f \psi_f \ ,$$

where the mass functions are

$$m_W(\hat{\theta}_H) = \frac{1}{2} g f_H \sin\hat{\theta}_H, \quad m_Z(\hat{\theta}_H) = \frac{1}{2} g_Z f_H \sin\hat{\theta}_H,, \quad m_f(\hat{\theta}_H) = y_f f_H \sin\hat{\theta}_H \ .$$

- $V_{\rm eff}(\hat{\theta}_H)$ is the effective potential at 1 loop, and has a periodic structure, invariant under

$$\theta_H \longrightarrow \theta_H + 2\pi$$

- The EW symmetry $SU(2)_L \times U_Y$ is unbroken at $\theta_H = 0, \pi$.

- Bulk fermions and gauge bosons contribute to $V_{\text{eff}}(\hat{\theta}_H)$. Especially, the top multiplet dominates and gives a negative contribution to V_{eff}, triggering EW symmetry breaking dynamically.
- The global minimum of V_{eff} occurs at $\theta_H = \pm\pi/2$. The W, Z, and f acquire their masses.
- We can expand the Higgs field around $\pi/2$, $\hat{\theta}_H = \theta_H + H(x)/f_H$.

  $$m_W(\hat{\theta}_H) = \frac{1}{2} g f_H [1 - (H/f)^2/2! + (H/f)^4/4! - ...]$$

  The first term gives the W boson mass. We feed this back into the Lagrangian.
- There is no triple vertices: HW^+W^-, HZZ, and $H\bar{f}f$. Only quartic vertices exist: HHW^+W^-, $HHZZ$, and $HH\bar{f}f$.
- A new parity, called H-parity emerges such that the Higgs has odd parity while all the SM particles have even parity.
- Decays of H into SM particles are forbidden by the new H parity. The Higgs boson is then a dark matter candidate.

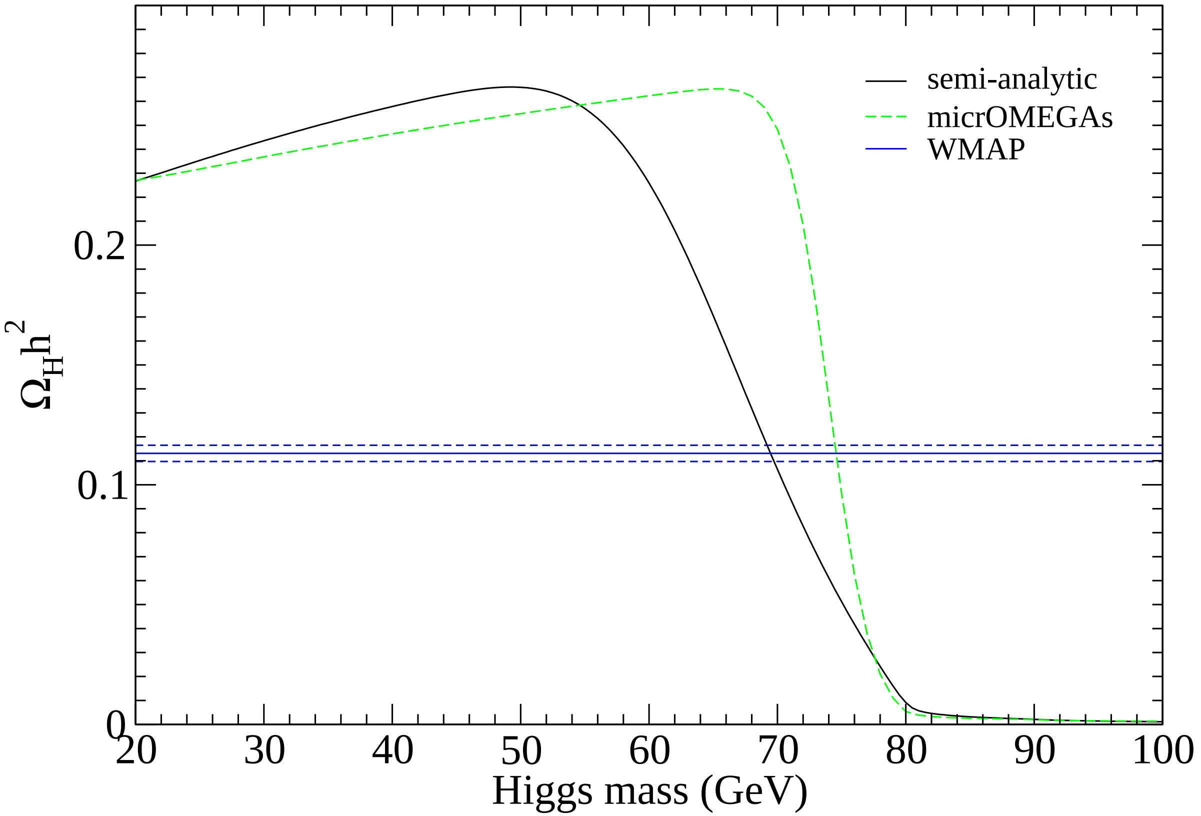
- This Higgs boson can be produced thermally in early Universe history via

$$W^+W^-, ZZ, \bar{f}f \to HH$$

- Once we fix the W and Z boson masses, $f_H = 246$ GeV. So the m_H is the only free parameter of the model at low energy.

Relic Density

Hosotani, Ko, Tanaka



Calculation of Positron Spectrum

- Here we take the assumption that this Higgs DM constitutes all the dark matter of the Universe. Requiring the Higgs DM not overclosing the Universe, the mass can be larger than 70 GeV.
- When the thermal source is not dominant, we assume that there are other sources of this Higgs DM, e.g., Kaluza-Klein states, or other GUT relics.
- The dominant process for cosmic ray positron from DM annihilation is
$$HH \to W^+W^- \to e^+\nu_e + X, \qquad HH \to ZZ \to e^+ + X$$
- e^+ could come from the hadrons, which are fragmentation products in $W \to q\bar{q}'$. And also from the hadrons in $HH \to b\bar{b},\ c\bar{c}$. But these positron sources are much softer and smaller.

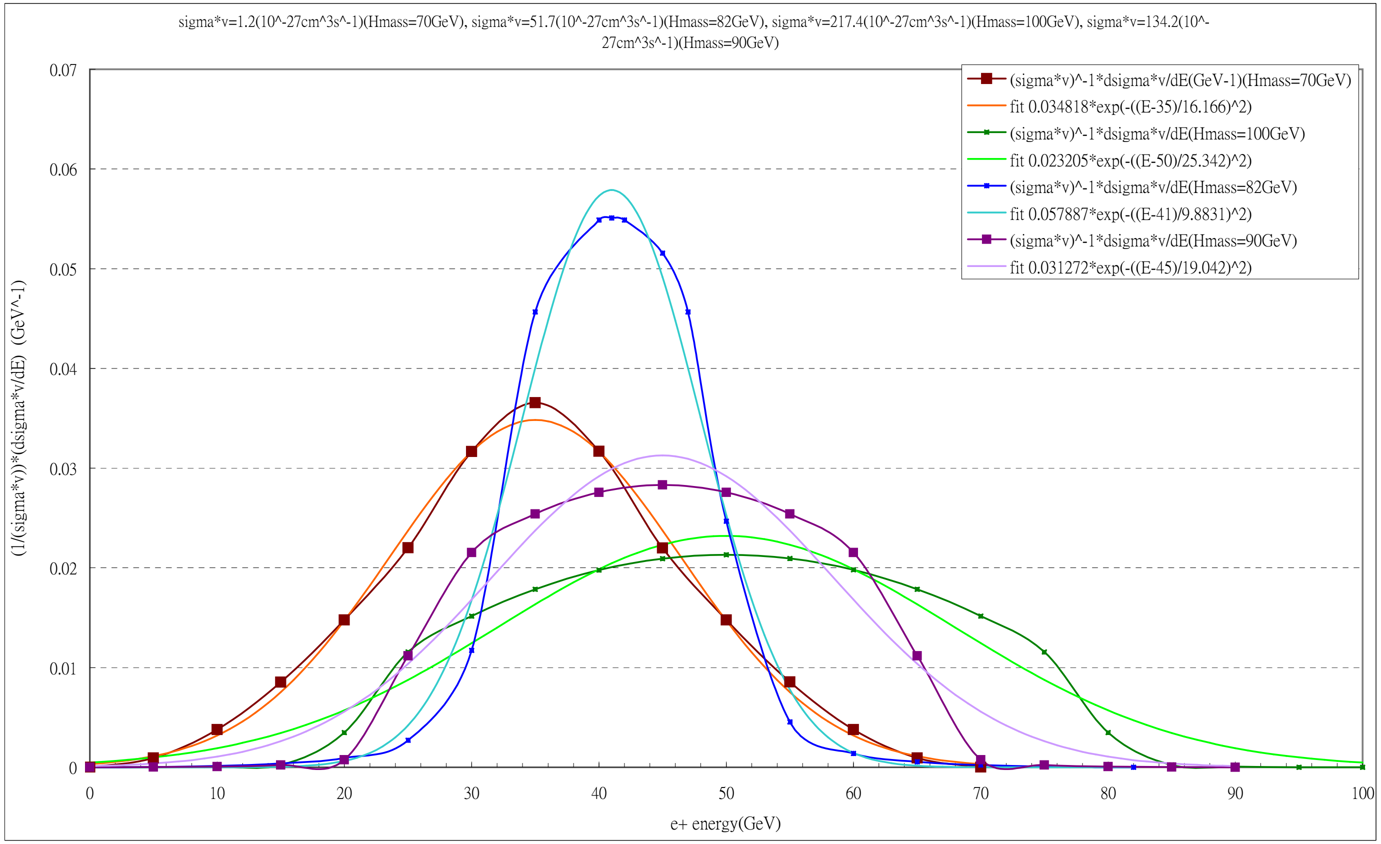
The annihilation rate is given by

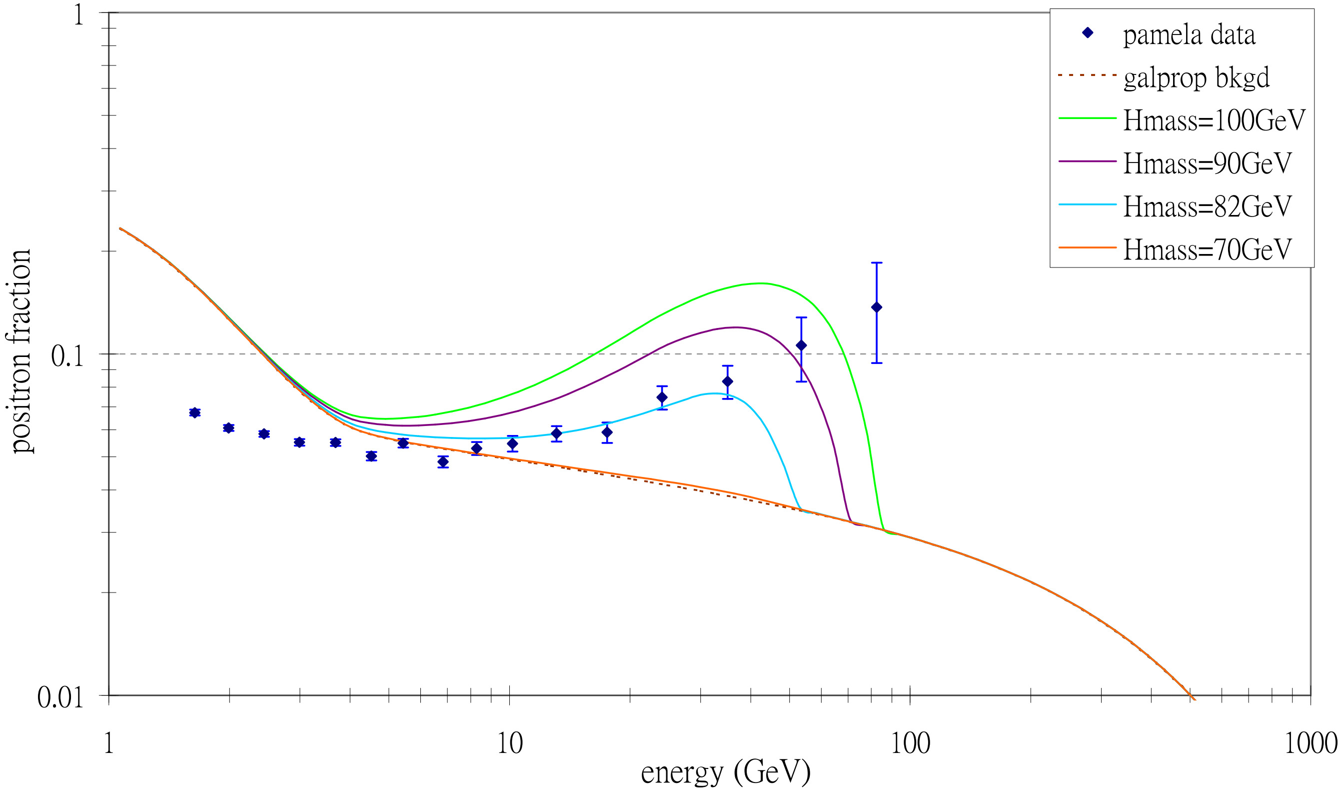
$$\begin{aligned}
\langle \sigma v \rangle_{HH\to WW} &\equiv \sigma(HH \to W^+W^-)\,(2\beta_H) = \frac{g^4 \beta_W}{32\pi s}\left(3 - \frac{s}{m_W^2} + \frac{s^2}{4m_W^4}\right) \\
\langle \sigma v \rangle_{HH\to ZZ} &\equiv \sigma(HH \to ZZ)\,(2\beta_H) = \frac{g_z^4 \beta_Z}{64\pi s}\left(3 - \frac{s}{m_Z^2} + \frac{s^2}{4m_Z^4}\right)
\end{aligned}$$

where $2\beta_H = 2\sqrt{1 - 4m_H^2/s}$

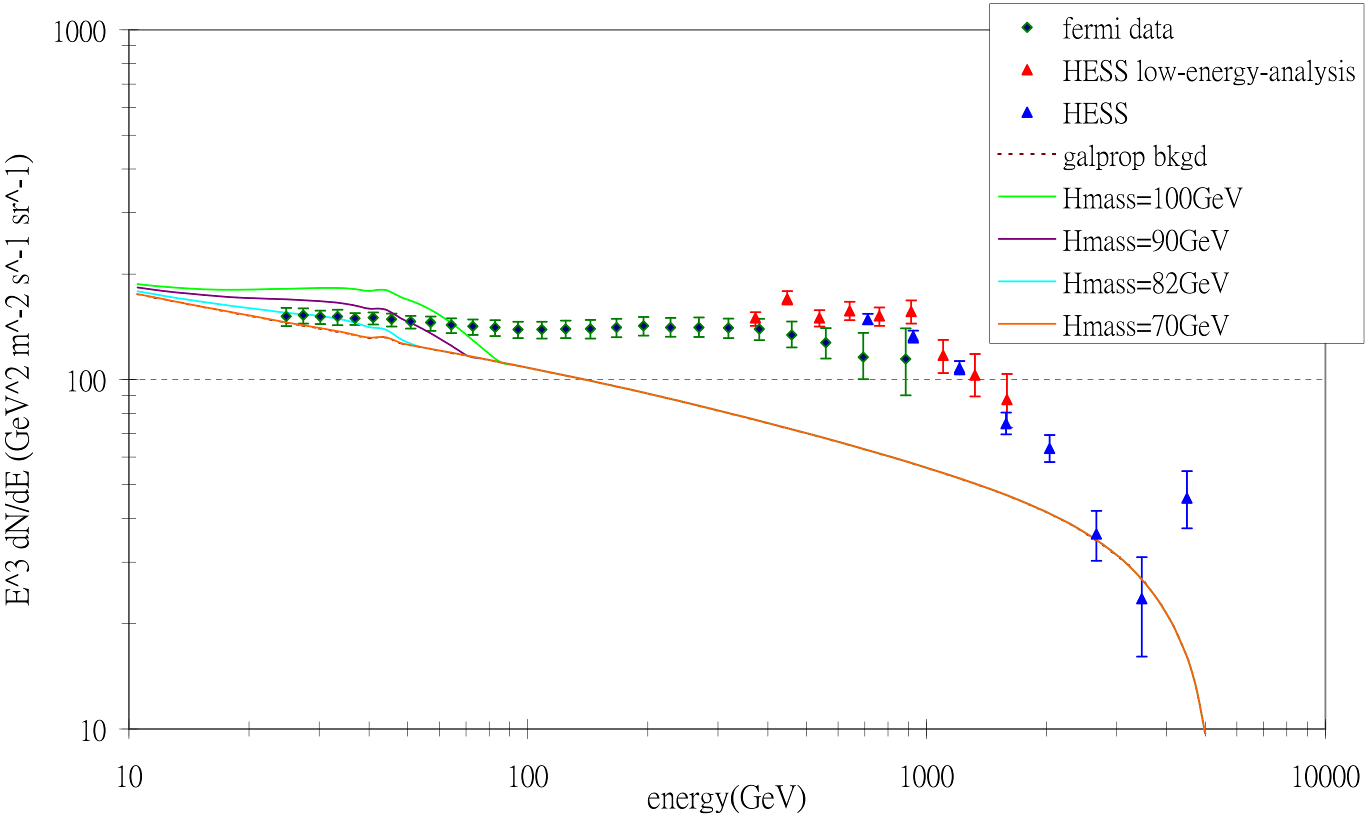
The diffusion equation is solved with the following source term:

$$Q_{\mathrm{ann}} = \frac{1}{2}\left(\frac{\rho_{\mathrm{CDM}}}{M_{\mathrm{CDM}}}\right)^2 \left[\langle \sigma v \rangle_{HH\to WW}\,\frac{dN_{e^+}^{WW}}{dE_{e^+}} + \langle \sigma v \rangle_{HH\to ZZ}\,\frac{dN_{e^+}^{ZZ}}{dE_{e^+}}\right] ,$$


sigma*v=1.2(10^-27cm^3s^-1)(Hmass=70GeV), sigma*v=51.7(10^-27cm^3s^-1)(Hmass=82GeV), sigma*v=217.4(10^-27cm^3s^-1)(Hmass=100GeV), sigma*v=134.2(10^-27cm^3s^-1)(Hmass=90GeV)
(sigma*v)^-1*dsigma*v/dE(GeV-1)(Hmass=70GeV)
fit 0.034818*exp(-((E-35)/16.166)^2)
(sigma*v)^-1*dsigma*v/dE(Hmass=100GeV)
fit 0.023205*exp(-((E-50)/25.342)^2)
(sigma*v)^-1*dsigma*v/dE(Hmass=82GeV)
fit 0.057887*exp(-((E-41)/9.8831)^2)
(sigma*v)^-1*dsigma*v/dE(Hmass=90GeV)
fit 0.031272*exp(-((E-45)/19.042)^2)
(1/(sigma*v))*(dsigma*v/dE) (GeV^-1)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
60
70
80
90
100
e+ energy(GeV)



1
0.1
0.01
positron fraction
1
10
100
1000
energy (GeV)
pamela data
galprop bkgd
Hmass=100GeV
Hmass=90GeV
Hmass=82GeV
Hmass=70GeV


1000
100
10
10
100
1000
10000
energy(GeV)
E^3 dN/dE (GeV^2 m^-2 s^-1 sr^-1)
fermi data
HESS low-energy-analysis
HESS
galprop bkgd
Hmass=100GeV
Hmass=90GeV
Hmass=82GeV
Hmass=70GeV

Implications of the e^+ spectrum

1. When $m_H \gtrsim m_W$ the annihilation rate increases rapidly and explains part of the rising spectrum. But the Higgs is not heavy enough to explain the whole spectrum.
2. When $m_H = 90 - 100$ GeV it can pass through one more point, but the annihilation rate increases far more than the lower part can allow.
3. The e^+ fraction spectrum disfavors $m_H > 90$ GeV.
4. This model cannot explain at all the wide bump in the the total $e^- + e^+$ flux measured by FERMI-LAT.

Antiproton Spectrum

The corresponding diffusion equation is solved with the following source term:

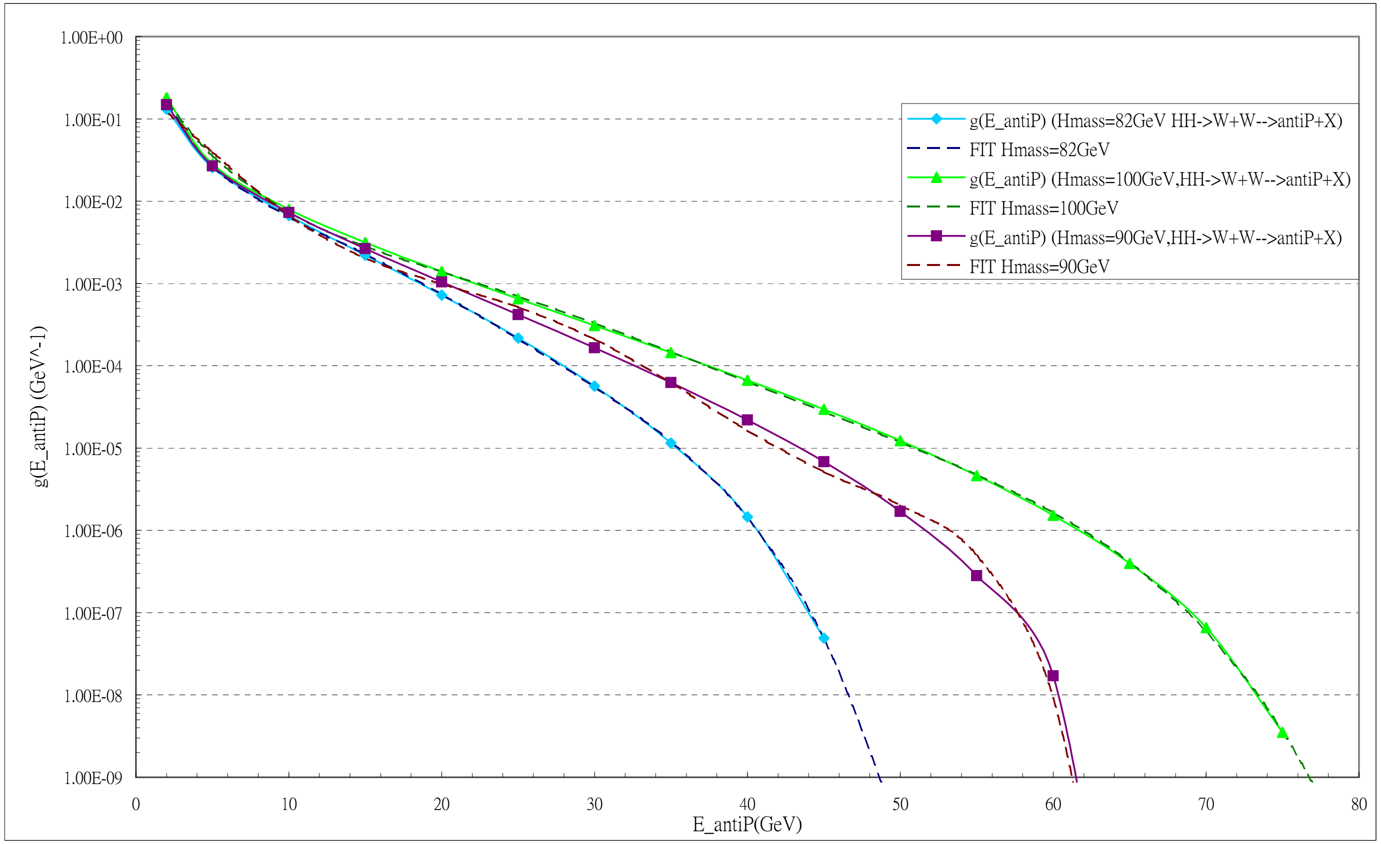
$$Q_{\rm ann} = \eta \left(\frac{\rho_{\rm dm}}{M_{\rm dm}} \right)^2 \sum \langle \sigma v \rangle_{\bar{p}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}}$$

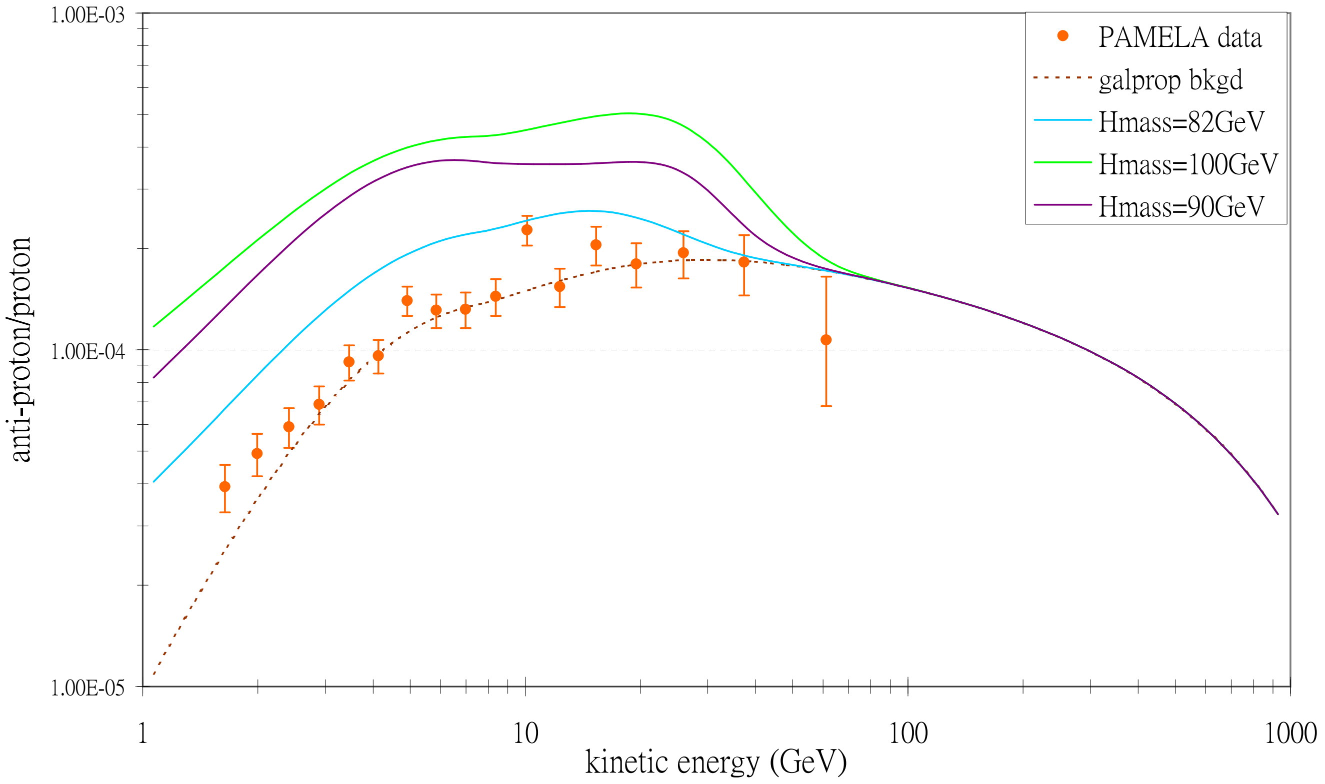
The dominant contribution comes from

$$HH \to W^+W^-, ZZ \to (q\bar{q}')(q\bar{q}') \to \bar{p} + X$$

We use (Albino, Kniehl, Kramer, NPB 725, 181) the fragmentation function $D_{q \to h}(z)$ for any quark q into hadrons h, e.g., $p, \bar{p}, \pi$.

We do not take into the sub-leading contributions:
$HH \to b\bar{b} \to \bar{p} + X$.


1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
g(E_antiP) (GeV^-1)
0
10
20
30
40
50
60
70
80
E_antiP(GeV)
g(E_antiP) (Hmass=82GeV HH->W+W-->antiP+X)
FIT Hmass=82GeV
g(E_antiP) (Hmass=100GeV,HH->W+W-->antiP+X)
FIT Hmass=100GeV
g(E_antiP) (Hmass=90GeV,HH->W+W-->antiP+X)
FIT Hmass=90GeV


1.00E-03
1.00E-04
1.00E-05
anti-proton/proton
1
10
100
1000
kinetic energy (GeV)
● PAMELA data
galprop bkgd
Hmass=82GeV
Hmass=100GeV
Hmass=90GeV

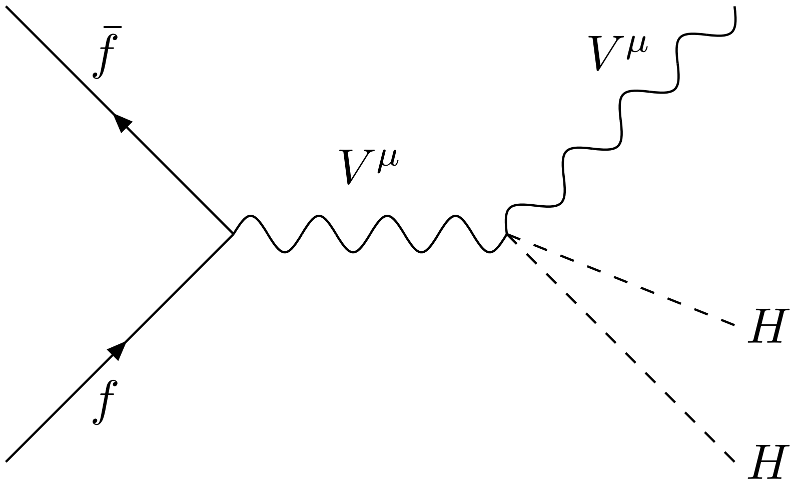
Implications from $\bar{p}$ fraction spectrum

1. The $m_H = 82$ GeV spectrum is barely consistent with the data.
2. The $m_H = 90$ GeV spectrum is obviously ruled out by the data.

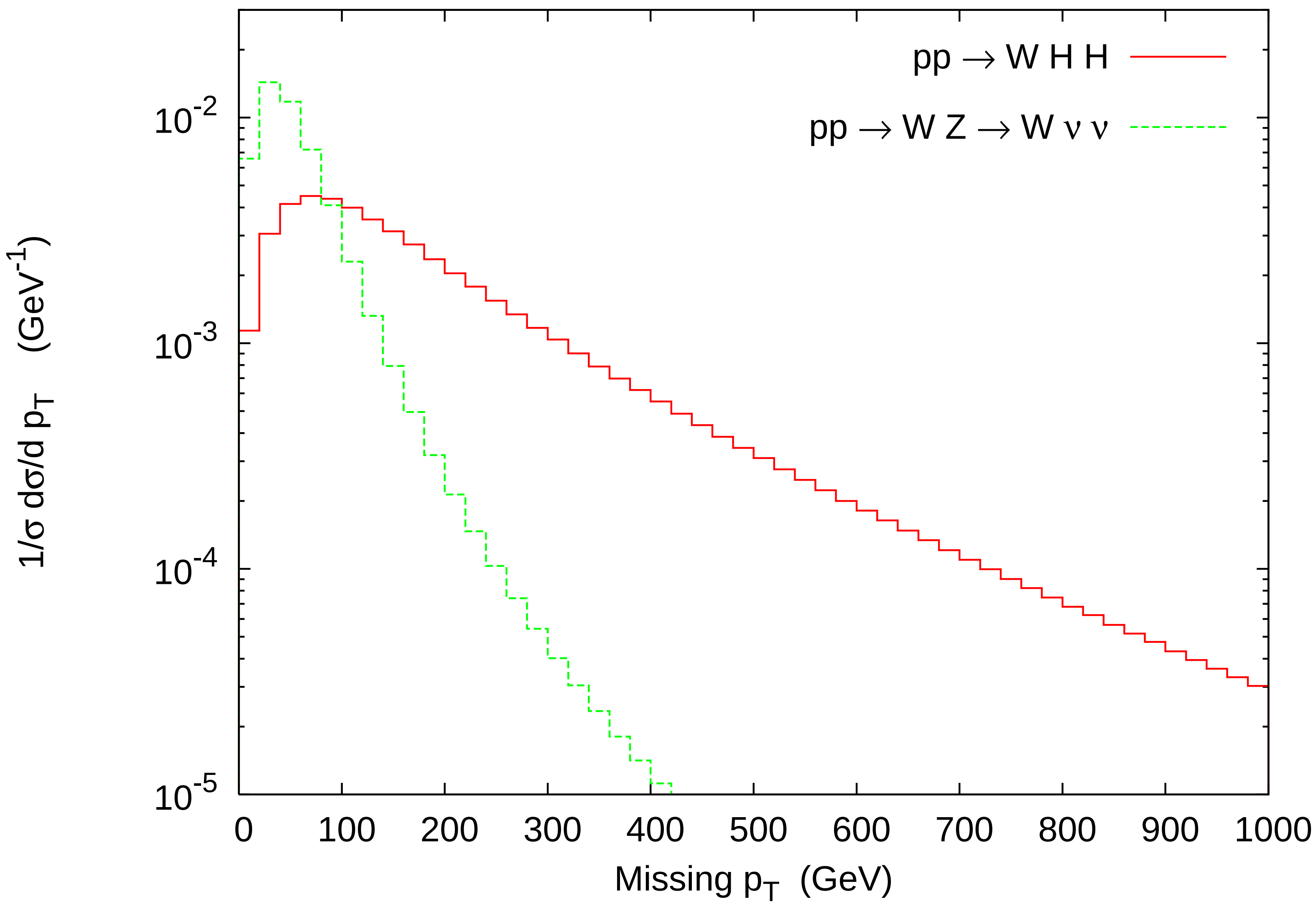
Collider Signatures at the LHC

Associated production with a W or Z boson:

$$q\bar{q}^{(\prime)} \to Z(W^{\pm})HH$$



Background: $q\bar{q}^{(\prime)} \to Z(W^{\pm})\nu\bar{\nu}$.


pp → W H H
pp → W Z → W ν ν
1/σ dσ/d p$_T$ (GeV^{-1})
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
100
200
300
400
500
600
700
800
900
1000
Missing p$_T$ (GeV)

The cross section in fb for the signals ZHH and $W^{\pm}HH$ and the corresponding backgrounds $ZZ \rightarrow Z\nu\bar{\nu}$ and $WZ \rightarrow W\nu\bar{\nu}$ at the LHC. The applied cuts include $|y(Z/W)| < 2$ and $\not{p}_T > 100$ GeV.

ZHH	$ZZ \rightarrow Z\nu\bar{\nu}$	$W^{\pm}HH$	$WZ \rightarrow W\nu\bar{\nu}$
0.2 fb	370 fb	0.4 fb	390 fb

Collider Signatures at the ILC

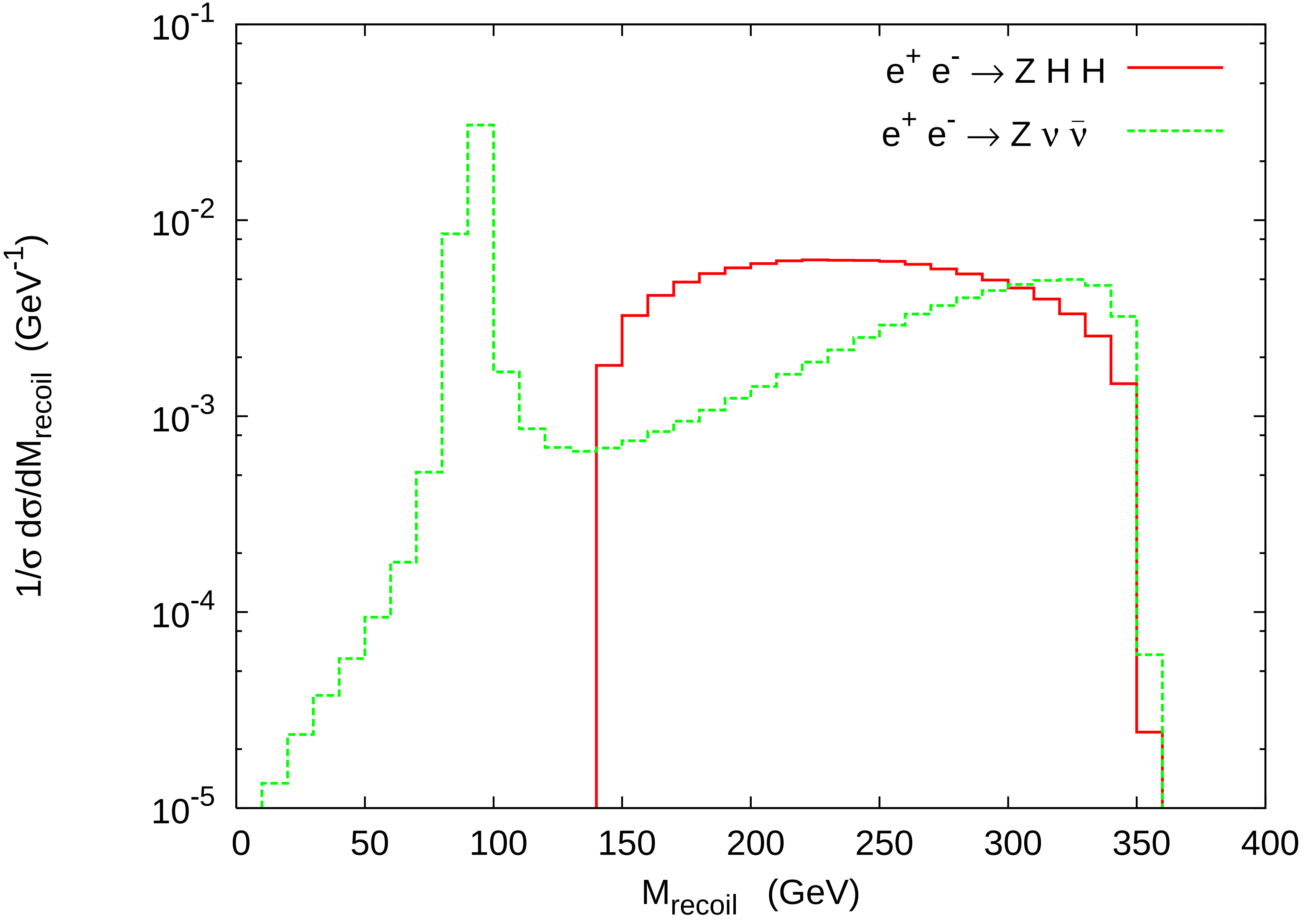
Associated production with a Z boson: $e^+e^- \rightarrow ZHH$

Background: $e^+e^- \rightarrow Z\nu\bar{\nu}$ (both ZZ and t channel W exchange).

Advantages of ILC:

- Polarization of the beams. The e^- can be polarized right-handed to remove the W diagrams (similarly left-handed e^+ beam).
- Known initial beam energy. One can reconstruct the missing particle by measuring the visible one:

$$m^2_{\text{recoil}} = m^2_{HH} = s + m^2_Z - 2\sqrt{s}E_Z$$



It is clear a cut $m_{\rm recoil} > 140$ GeV can remove the Z peak background.

P_{e^-}	P_{e^+}	$\sigma(e^-e^+ \to Z^{(\mathrm{vis})}\nu\bar{\nu})$	$\sigma(e^-e^+ \to Z^{(\mathrm{vis})}HH)$	$S/\sqrt{B}$
$+1$	-1	3.8 fb	0.14 fb	2.2
-1	$+1$	200 fb	0.18 fb	0.4
0	0	52 fb	0.08 fb	0.3
0.8	-0.6	6.8 fb	0.10 fb	1.2

Conclusions

1. An H parity emerges as the EW symmetry is spontaneously broken at 1 loop. The triple vertices $HWW, HZZ, H\bar{f}f$ vanish and ensure the Higgs boson is stable.
2. The 4-point vertices $HHWW, HHZZ, HH\bar{f}f$ enables the annihilation/creation of the Higgs boson in the early Universe. If all the existing dark matter density is due to thermal production, m_H is confined to be around 70 GeV.
3. In this work, we take conservative approach that the Higgs DM does not overclose the Universe and there could be other nonthermal sources.
4. The present PAMELA e^+ and $\bar{p}$ fraction spectra put a strong constraint on the model: $m_H \gtrsim 90$ GeV is obviously not allowed.

5. Compared to other constraints, like unitarity requires $m_H < 1$ TeV, the e^+ and $\bar{p}$ are much stronger.
6. Collider signatures at the LHC are W, Z, or $t\bar{t}$ plus missing energy. The signatures themselves are very interesting, but the event rate is too low. Further studies that involves KK states are possible.
7. The search at the ILC is better with polarized e^+ and e^- beams.