Multilepton Decays of the 126 GeV Higgs Boson

Ernest Ma
Physics and Astronomy Department
University of California
Riverside, CA 92521, USA

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$U(1)$ Gauge Model Revisited

The Lagrangian of an $U(1)$ gauge model with scalar interactions is given by

$$\mathcal{L} = -\frac{1}{4}(\partial_\mu C_\nu - \partial_\nu C_\mu)^2 + |(\partial_\mu - igC_\mu)\chi|^2 - V(\chi),$$

where $V = \mu^2\chi^\dagger\chi + (\lambda/2)(\chi^\dagger\chi)^2$. If $\mu^2 < 0$, then the famous phenomenon of spontaneous symmetry breaking occurs with $|\chi| = v_D$, where $v_D^2 = -\mu^2/\lambda$. This makes $C = \gamma_D$ massive with $m^2 = 2g^2v_D^2$ (BEH mechanism), and $\sqrt{2}Re\chi = h_D$ has $m^2 = 2\lambda v_D^2$ (Higgs mode).

Farzan/Akbarieh(2012):

This spontaneously broken $U(1)$ gauge model has a Z_2 residual symmetry, with γ_D odd and h_D even. So γ_D may be absolutely stable dark matter. If v_D is around the electroweak energy scale, then γ_D is cold dark matter.

Although γ_D only interacts through the $h_D\gamma_D\gamma_D$ and $h_Dh_D\gamma_D\gamma_D$ vertices, the interaction of h_D with the Standard-Model Higgs boson may enable γ_D to be in thermal equilibrium and freezes out with the correct relic abundance, but it will be very difficult to detect.

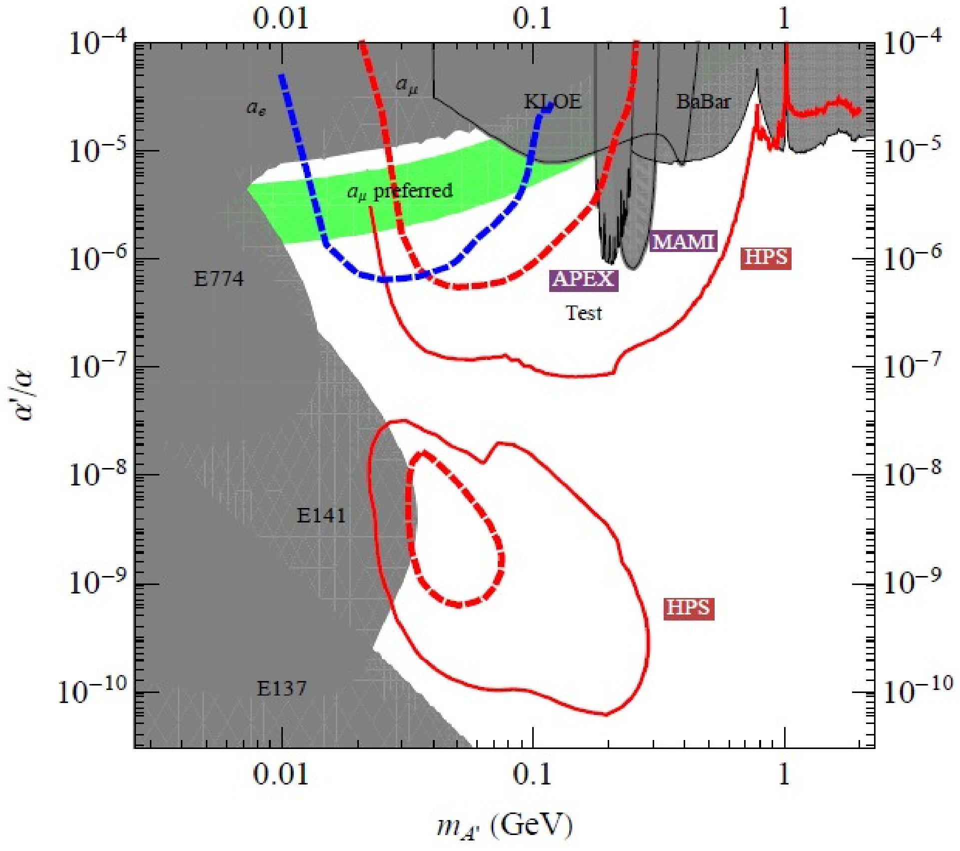
The Photon Portal

Holdom(1986), Pospelov/Ritz/Voloshin(2008), Jaekel/Redondo/Ringwald(2008), Arkani-Hamed/Finkbeiner/Slatyer/Weiner(2009):

In general, C_μ may have an explicit (Stuckelberg) mass and mixes kinetically: $(\partial_\mu C_\nu - \partial_\nu C_\mu)(\partial^\mu A^\nu - \partial^\nu A^\mu)$. This breaks the Z_2 symmetry, but the mixing may be very small.

Now γ_D will decay through its mixing with γ. Such a heavy or hidden or dark photon will be searched for at the HPS experiment (2014) at JLab.

HPS Reach ≈ ”Full HPS” Reach



1 week 1.1 GeV

1 week 2.2 GeV

3 months 2.2 GeV

3 months 6.6 GeV

HPS Dark2012 27

If the mass of C_μ comes from the BEH Mechanism, then the dark Higgs boson h_D also exists. The process

$$e^+e^- \to \gamma_D h_D, \quad \text{then } h_D \to \gamma_D\gamma_D$$

with $\gamma_D \to e^+e^-, \mu^+\mu^-$ may be searched for.

BaBar (2012): For $m(\gamma_D)$ in the range 0.3 to 2.5 GeV, and $m(h_D)$ in the range 0.5 to 10 GeV, the $\gamma_D - \gamma$ mixing is less than 10^{-3} to 10^{-4}.

BELLE (2013): Similar results are expected.

$\gamma_D - \gamma$ oscillations may allow light shining through wall.

The Higgs Portal

With the addition of the $U(1)_D$ scalar χ, the SM Higgs potential V becomes

$$\mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \mu_\chi^2 \chi^* \chi + \lambda_\chi (\chi^* \chi)^2 + \lambda_{\Phi\chi} (\Phi^\dagger \Phi)(\chi^* \chi).$$

From this, $v_{SM} = 256$ GeV and v_D are obtained with $h_{SM} - h_D$ mixing to form $h_{1,2}$. Setting $m_1 = 126$ GeV, there are then only three independent parameters: m_2, v_D, and the $h_{SM} - h_D$ mixing angle α. They determine the 4 trilinear and 5 quadrilinear couplings of $h_{1,2}$.

Chang/Ma/Yuan(2013):

The $h_1 h_2^2$ trilinear coupling is given by

$$3v\lambda_\Phi \sin^2\alpha\cos\alpha + 3v_D\lambda_\chi\cos^2\alpha\sin\alpha$$
$$+\frac{1}{8}(v\cos\alpha + v_D\sin\alpha + 3v\cos 3\alpha - 3v_D\sin 3\alpha).$$

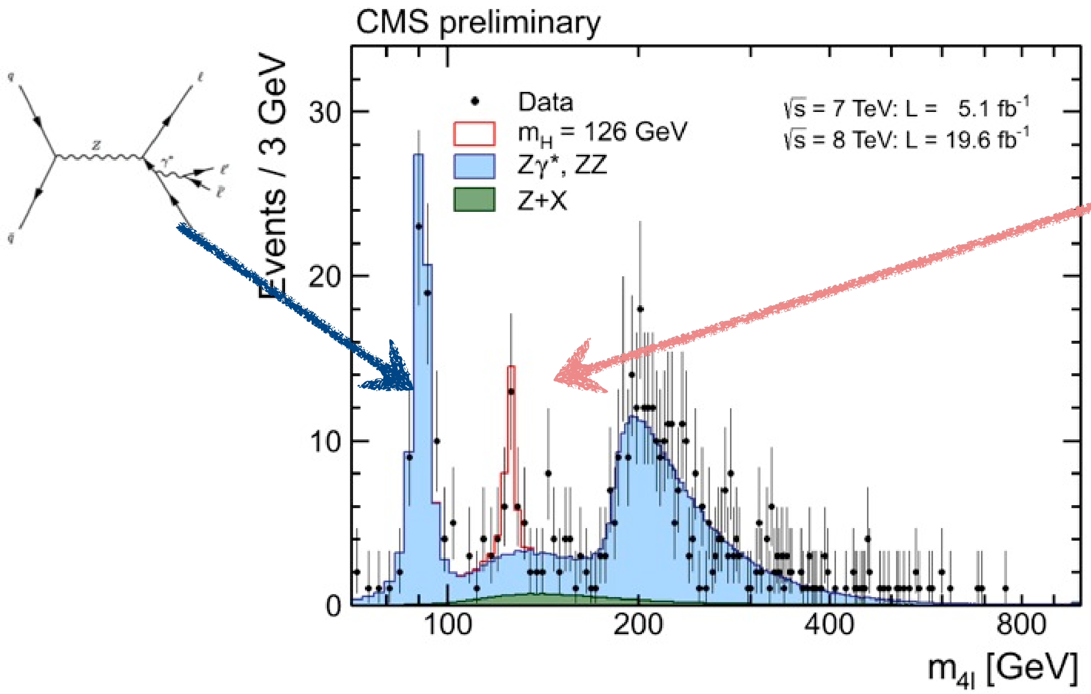
The $h_1 h_2^3$ quadrilinear coupling is given by

$$-\frac{1}{4}\sin 2\alpha(-2\lambda_\chi\cos^2\alpha + 2\lambda_\Phi\sin^2\alpha + \lambda_{\Phi\chi}\cos 2\alpha),$$

$$\text{where}\;\; \sin 2\alpha = \frac{2\lambda_{\Phi\chi} v v_D}{2\lambda_\Phi v^2 - 2\lambda_\chi v_D^2}.$$

Assuming that h_2 and γ_D are lighter than h_1, there are thus the possible decays $h_1 \to \gamma_D\gamma_D$, h_2h_2, $h_2\gamma_D\gamma_D$, $h_2h_2h_2$, etc. Once h_2 is produced, it can either decay into $\gamma_D\gamma_D$ through its h_D component if kinematically allowed, or decay into SM particles through its h_{SM} component. Once γ_D is produced, it can decay into lepton pairs through its photon component. Hence h_1 may have final states of 4, 8, or more charged leptons. These exotic final states are not excluded at the LHC at present. [At Scalar 2011, I talked about Higgs decaying into lighter scalars, but in the context of lepton flavor triality.]

m_{4l} spectrum with data



Clean signal peak @ mass around 126 GeV/c^2 golden channel !

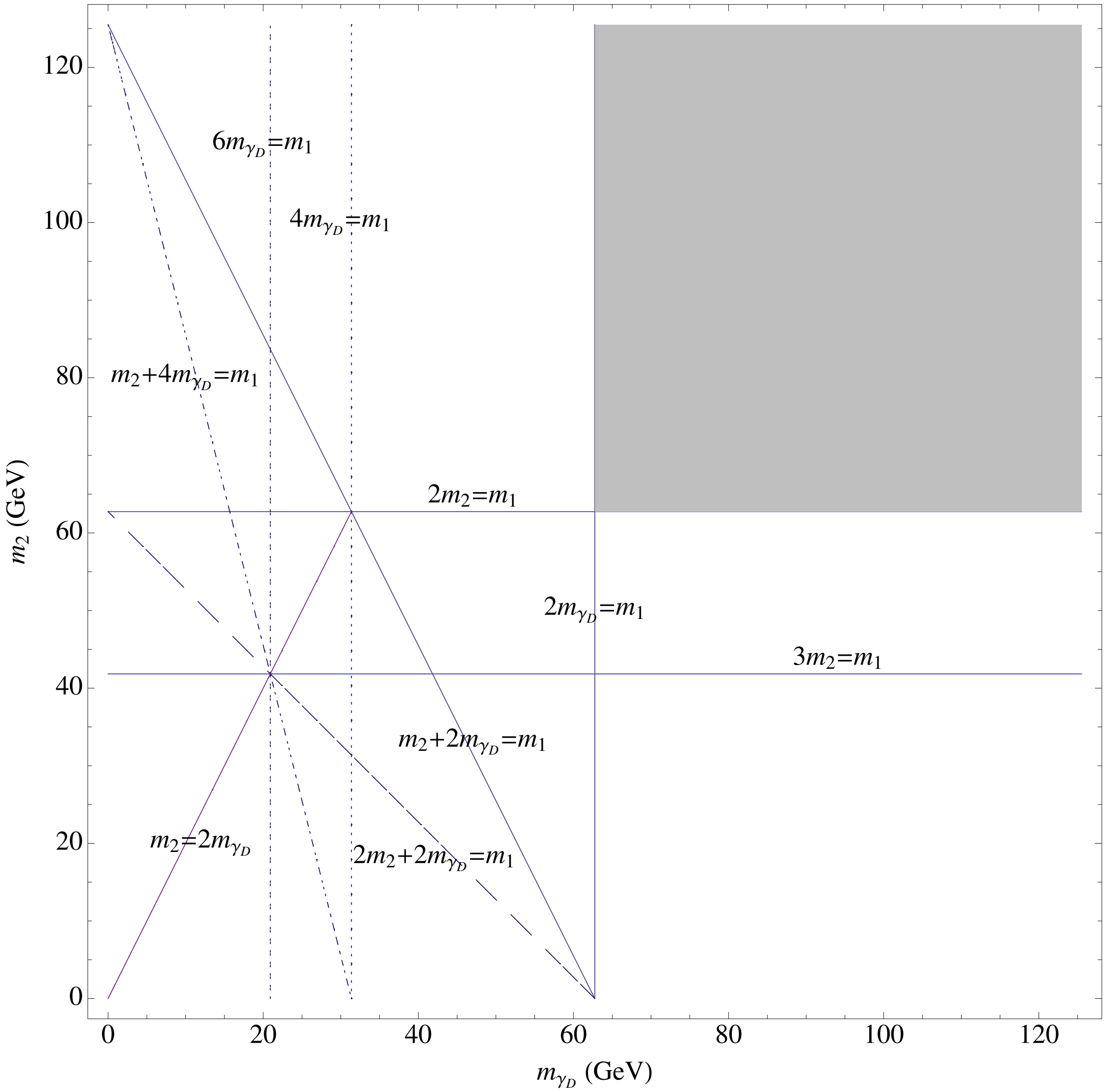
<u>Good control of the background :</u>

$M_{4l} > 160$ GeV/c^2

Data = 380 evts

Predicted = 364.7 evts

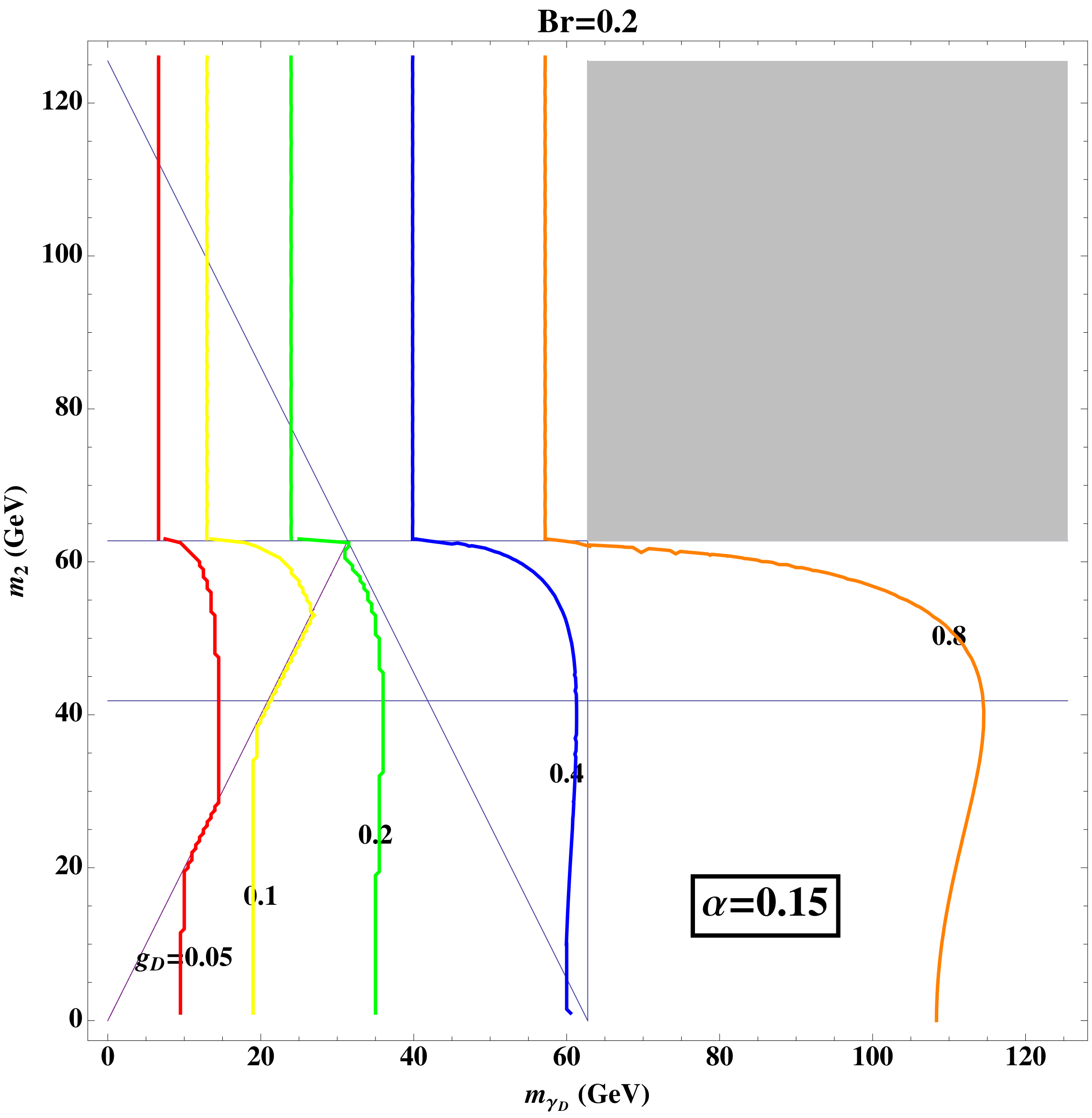
use of a multivariate method taking the Higgs kinematic as input to increase sensitivity

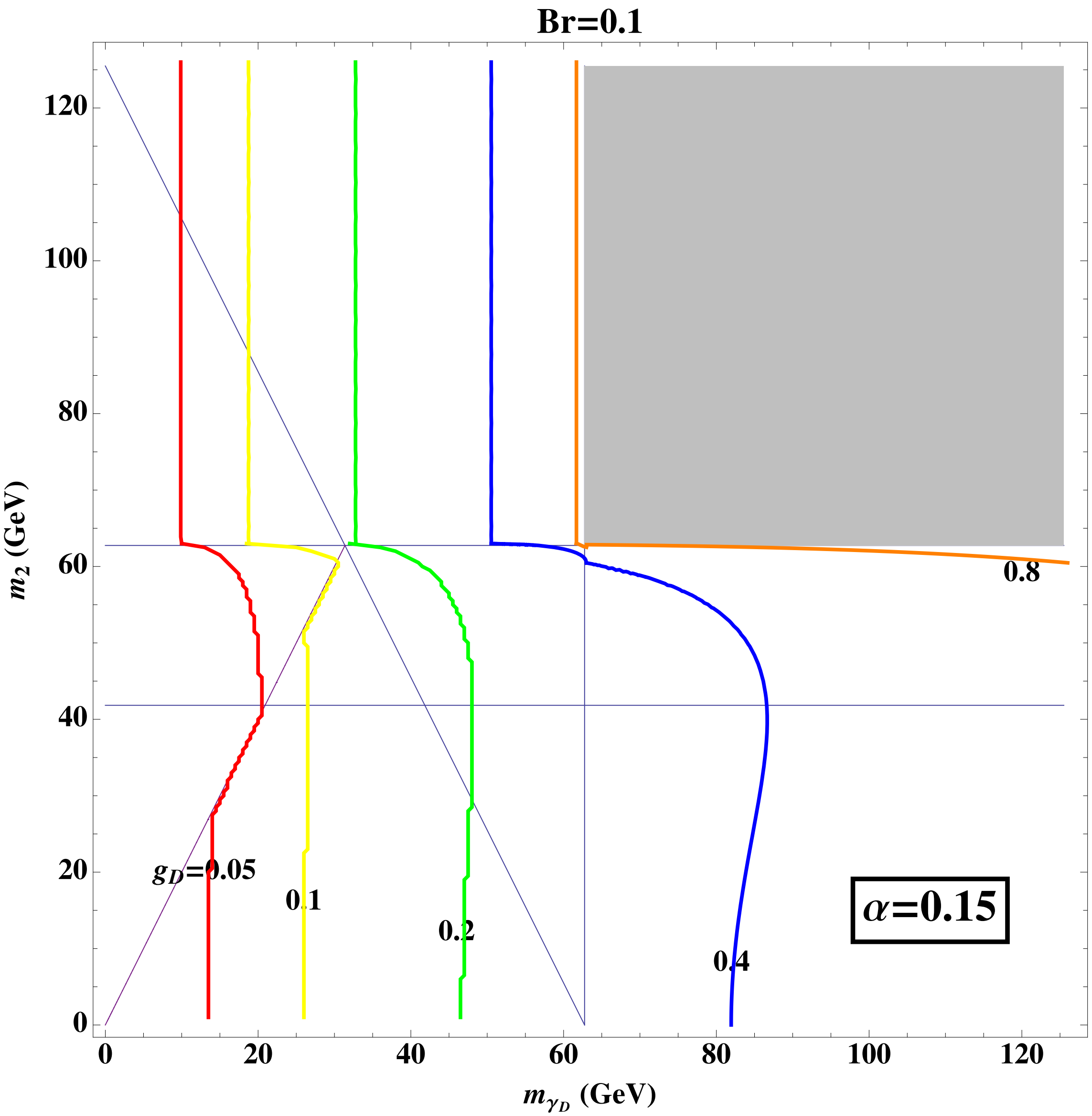


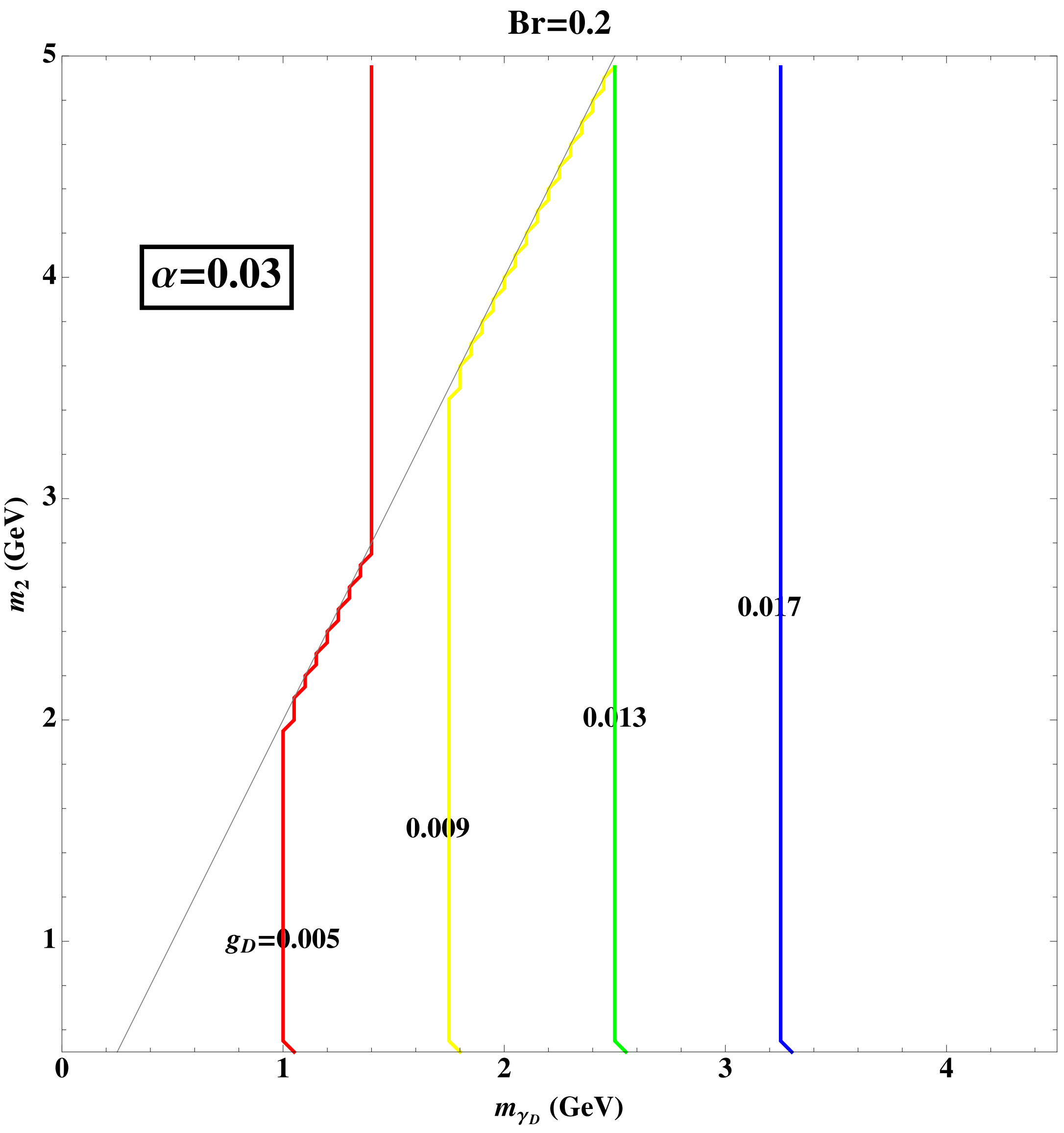
$6m_{\gamma_D}=m_1$
$4m_{\gamma_D}=m_1$
$m_2+4m_{\gamma_D}=m_1$
$2m_2=m_1$
$2m_{\gamma_D}=m_1$
$3m_2=m_1$
$m_2+2m_{\gamma_D}=m_1$
$m_2=2m_{\gamma_D}$
$2m_2+2m_{\gamma_D}=m_1$
m_2 (GeV)
m_{γ_D} (GeV)
0
20
40
60
80
100
120

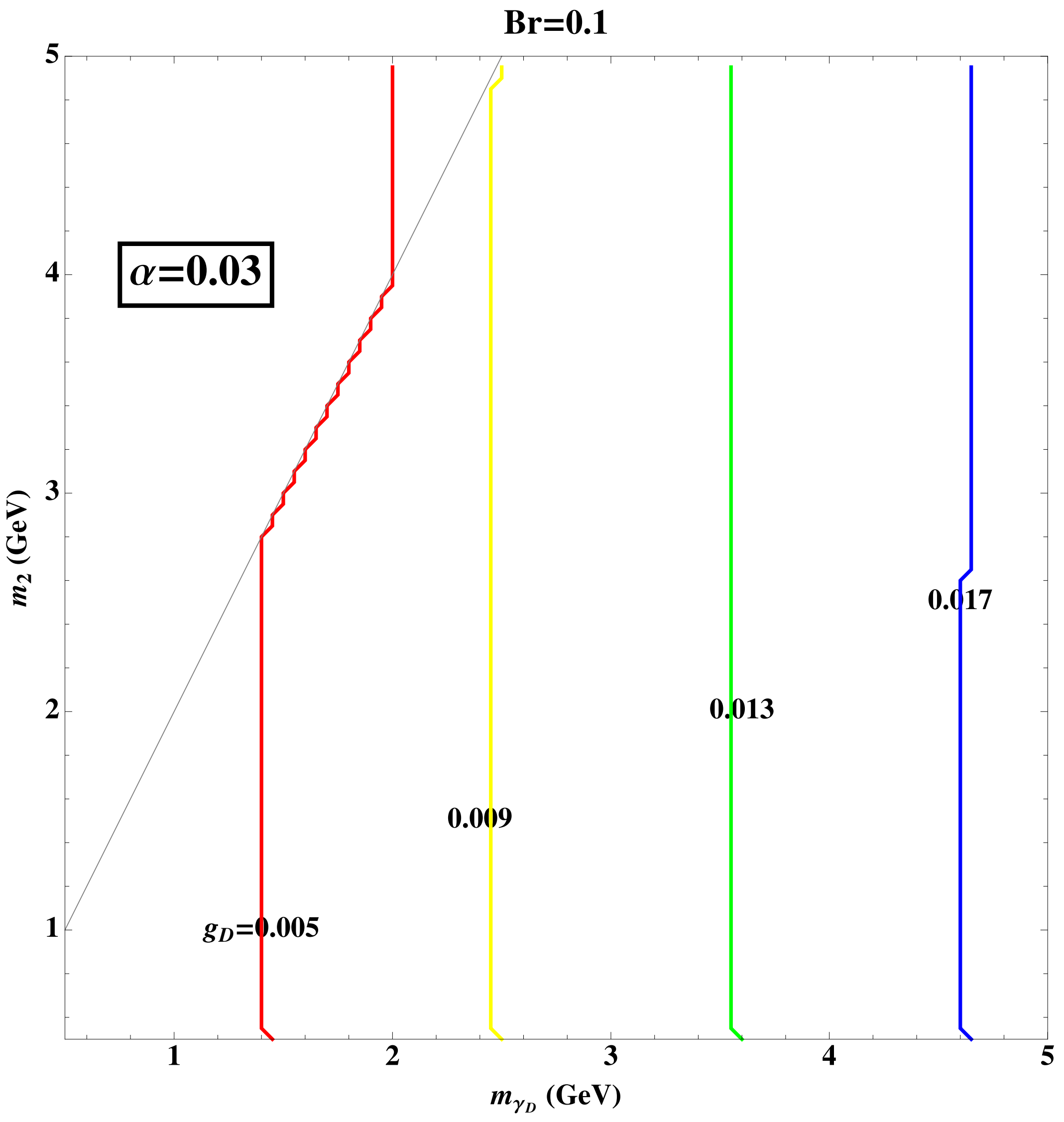
Present LHC data are consistent with the SM Higgs production and decay, but a 20% branching fraction into final states not predicted by the SM is still allowed. The following figures assume either 20% or 10% total branching fraction to final states containing h_2 and γ_D. Fixing $\alpha = 0.15$ with $g_D = 0.05, 0.1, 0.2, 0.4, 0.8$, the allowed regions in the entire (m_2, m_{γ_D}) plane are shown.

Similar plots are made for the small mass region with $\alpha = 0.03$ and $g_D = 0.005, 0.009, 0.013, 0.017$.
In this region, $\lambda_\Phi = 0.13$, $\lambda_\chi < 0.001$, $\lambda_{\Phi\chi} < 0.02$, $\lambda_3^{(3)}/v < 0.02$, and $-\lambda_4^{(3)} < 0.003$.


Br=0.2
m_2 (GeV)
m_{γ_D} (GeV)
0
20
40
60
80
100
120
0
20
40
60
80
100
120
g_D=0.05
0.1
0.2
0.4
0.8
α=0.15

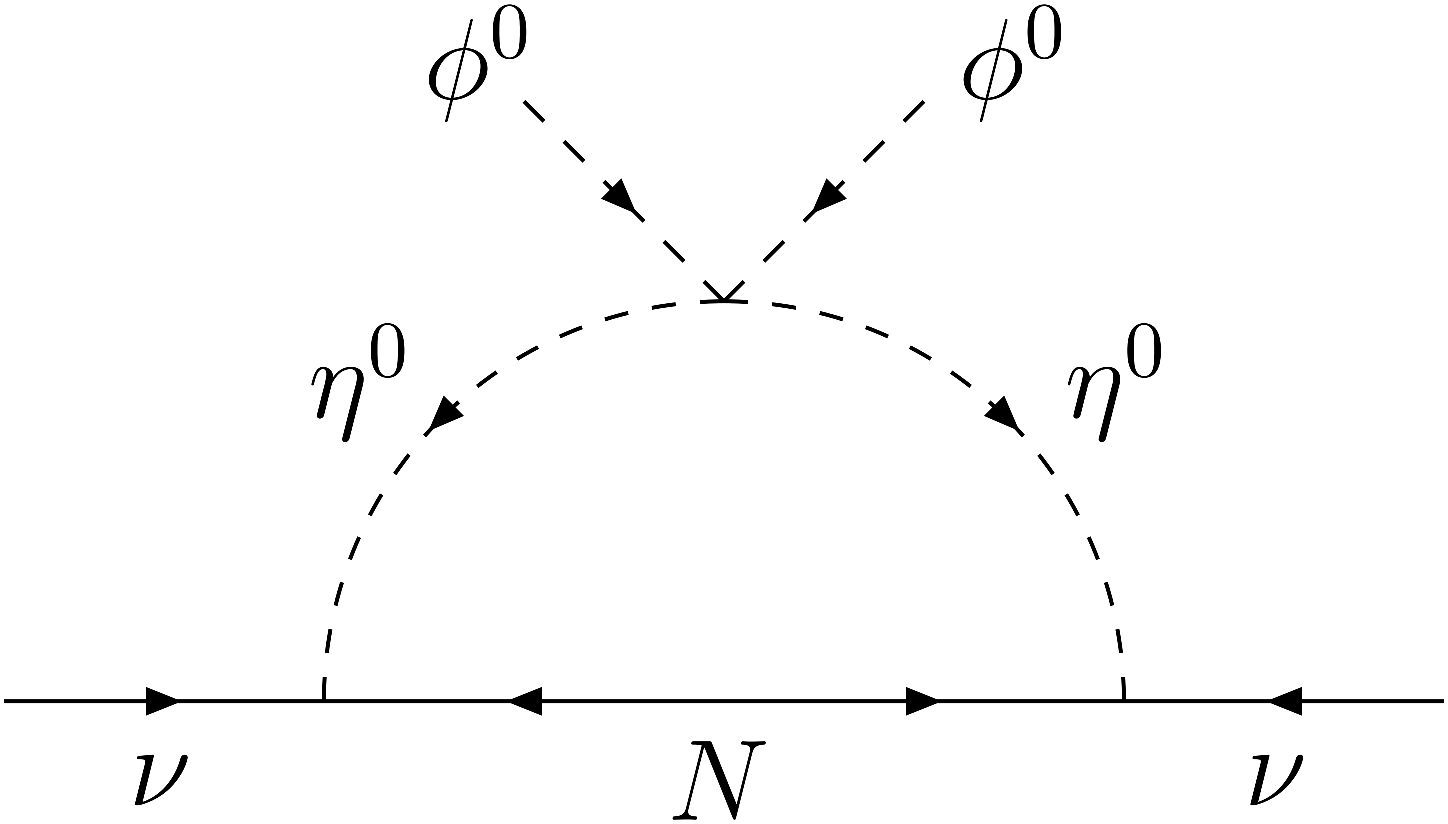

Br=0.1
120
100
80
60
40
20
0
m_2 (GeV)
0
20
40
60
80
100
120
m_{γ_D} (GeV)
g_D=0.05
0.1
0.2
0.4
0.8
α=0.15

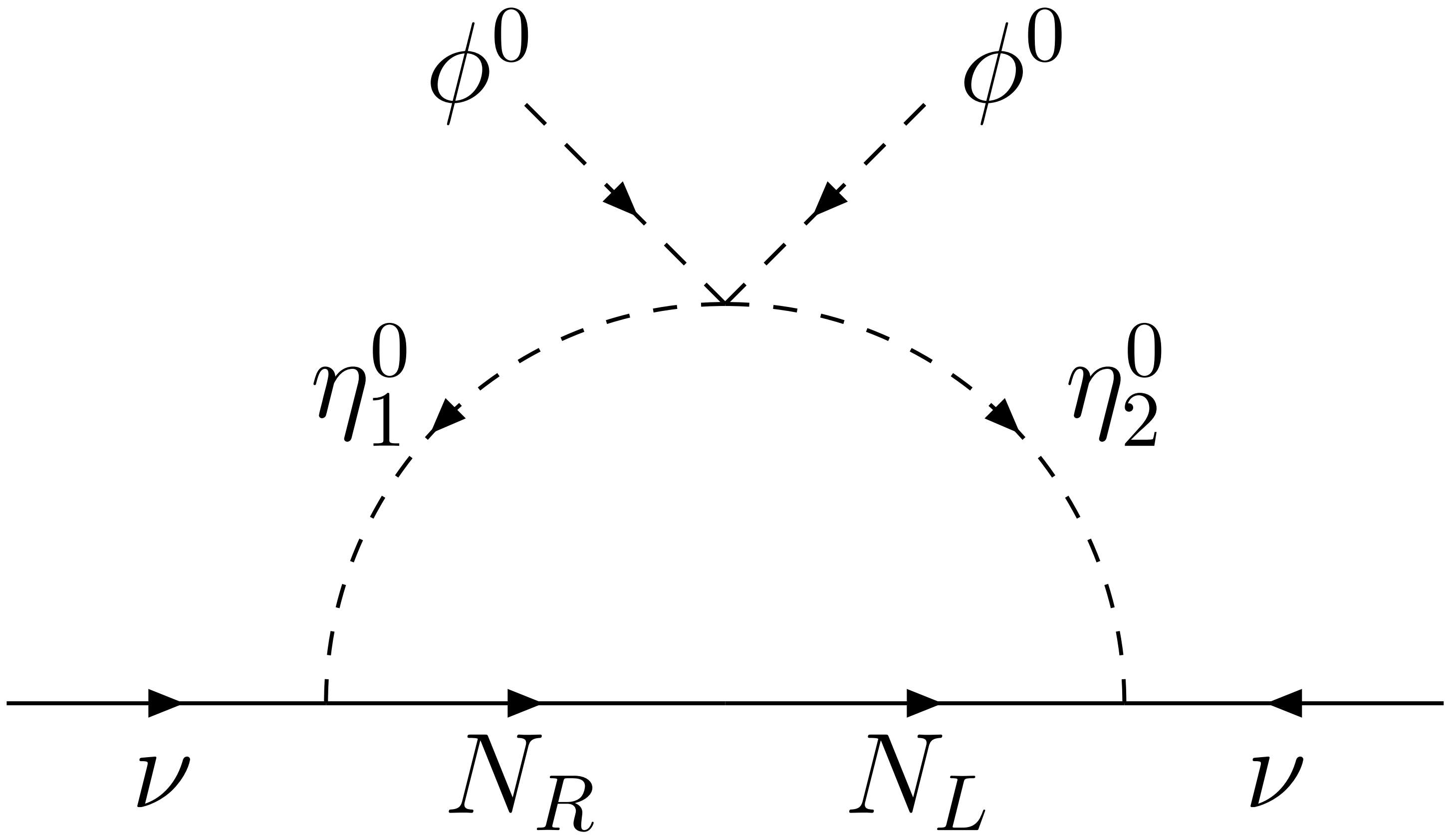

Br=0.2
α=0.03
g_D=0.005
0.009
0.013
0.017
m_2 (GeV)
m_{γ_D} (GeV)
0
1
2
3
4
5


Br=0.1
α=0.03
g_D=0.005
0.009
0.013
0.017
m_2 (GeV)
m_{γ_D} (GeV)
1
2
3
4
5
1
2
3
4
5

$U(1)_D$ for Radiative Neutrino Mass

The minimum stabilizing symmetry for dark matter is Z_2, but it may well be $U(1)_D$. Whereas Z_2 has been used in the well-studied scotogenic model of one-loop radiative neutrino mass, where a second (inert) scalar doublet (η^+, η^0) is added together with three neutral singlet Majorana fermions $N_{1,2,3}$, a new realization has recently been proposed [Ma/Picek/Radovcic(2013)] with two extra scalar doublets $(\eta^+_{1,2}, \eta^0_{1,2})$ transforming as ± 1 under $U(1)_D$ and three neutral singlet Dirac fermions $N_{1,2,3}$ transforming as 1 under $U(1)_D$.


ϕ^0
ϕ^0
η^0
η^0
ν
N
ν


ϕ^0
ϕ^0
η_1^0
η_2^0
ν
N_R
N_L
ν

The allowed couplings completing the loop are $h_1 \bar{N}_R \nu_L \eta_1^0$, $h_2 N_L \nu_L \eta_2^0$, and $(\Phi^\dagger \eta_1)(\Phi^\dagger \eta_2)$ which mixes η_1^0 and $\bar{\eta}_2^0$ with angle θ and mass eigenvalues $m_{1,2}$. The Majorana neutrino mass matrix is then

$$(\mathcal{M}_\nu)_{ij} = \sin\theta\cos\theta \sum_k \frac{[(h_1)_{ki}(h_2)_{kj} + (h_2)_{ki}(h_1)_{kj}]M_k}{8\pi^2}$$

$$\times \left[\frac{m_1^2}{m_1^2 - M_k^2} \ln \frac{m_1^2}{M_k^2} - \frac{m_2^2}{m_2^2 - M_k^2} \ln \frac{m_2^2}{M_k^2} \right].$$

Note that $U(1)_D$ is not broken in the loop.

Breaking $U(1)_D$ results in h_D and γ_D. Suppose N_1 is the dark-matter candidate, then it must interact with γ_D. It may or may not interact with h_D, depending on the $U(1)_D$ charge assignments of χ relative to N. In either case, the annihilation of $N_1 \bar{N}_1 \to \gamma_D \gamma_D$ is not suppressed by fermion masses. Since N_1 is a Dirac fermion, it is also not p-wave suppressed as with a Majorana fermion.

The thermally averaged cross section × relative velocity is $\pi \alpha_D^2 / M_1^2$, where $\alpha_D = g_D^2 / 4\pi$.
The proper relic density $\Omega_{DM} h^2 = 0.1187$ is obtained for $M_1 = 1$ TeV and $\alpha_D = 0.04$.

If γ_D is light enough, its multiple exchange between the annihilating $N_1\bar{N}_1$ may result in a Sommerfeld enhancement of its present cross section relative to what it was at the time of freeze-out. Together with the fact that γ_D may decay into charged leptons, this will help explain PAMELA and AMS-02.

Another effect is the change of the dark-matter density profile from the usual cold collisionless WIMP scenario. For example, if $M_1 = 1$ TeV and $m_{h_{D,\gamma_D}} \sim 4$ MeV, it is sufficient to explain the discrepancy in the observation of the dark matter distribution in dwarf galactic halos.

Conclusion

The original Abelian Higgs Model, i.e. a complex scalar field χ interacting with a vector gauge boson C, is remarkably versatile. It provides the simplest example of the BEH Mechanism, which is manifested in the electroweak $SU(2) \times U(1)_Y$ model, culminating in the discovery of the 126 GeV particle (presumably the Higgs boson) at the LHC. However $C = \gamma_D$ may itself be the dark photon, and $\sqrt{2}Re(\chi)$ the dark Higgs scalar h_D, providing long-range interactions which could save the cold dark matter paradigm.

In general, h_D mixes with h_{SM} to form $h_{1,2}$ with angle α. Assuming that h_1 is the 126 GeV particle discovered at the LHC, and that h_2 and γ_D are lighter than h_1, the decays $h_1 \to h_2 h_2, \gamma_D \gamma_D, h_2 \gamma_D \gamma_D, h_2 h_2 h_2$ should be explored. Once h_2 is produced, it may decay into $\gamma_D \gamma_D$ if kinematically allowed.

Once γ_D is produced, it may decay into a charged lepton pair through its mixing with the photon. Thus the 126 GeV Higgs boson may have final states of 4, 8, or 12 charged leptons.

The original Abelian Higgs model may yet be realized!