The Higgs Nexus is Adams' 42

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The Post-Higgs Era

On July 4, 2012, at the CERN auditorium, two people met for the first time.

The occasion was the announcement of the discovery of a 125 GeV particle which behaves very much like the one long-sought missing link of the Standard Model (SM). It was broadcast all over the world.

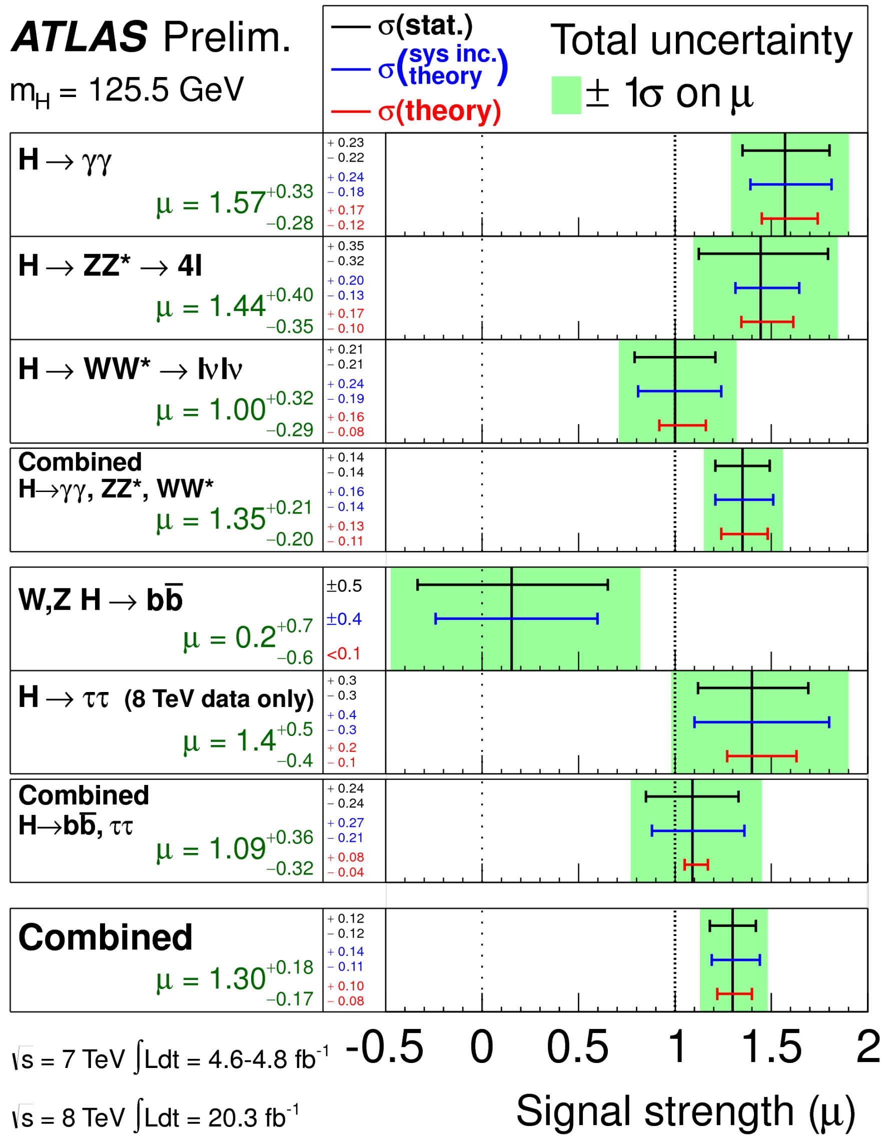
The two people were seen talking excitedly to each other.

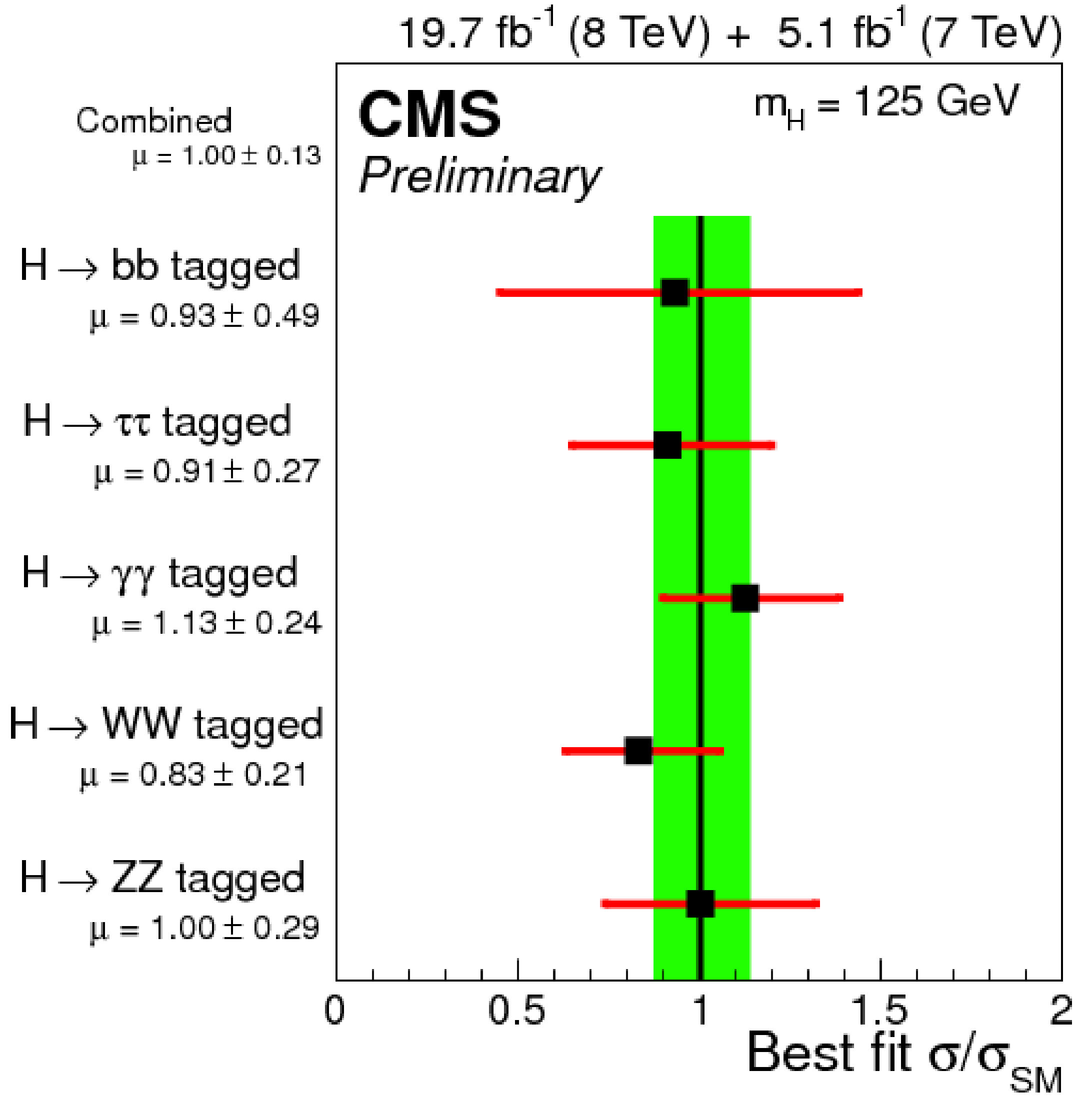

VED

Subsequent further data confirmed that the 125 GeV particle is indeed consistent with being the one predicted Higgs boson of the SM.

This means that the SM is potentially complete, and there is nothing else fundamental to discover, excepting of course the origins of neutrino mass and dark matter.

As a result, in the post-Higgs era, an important theoretical precept is the requirement that any natural extension of the SM should include an understanding of why there appears to be just one Higgs boson and that it resembles that of the SM in all ways.

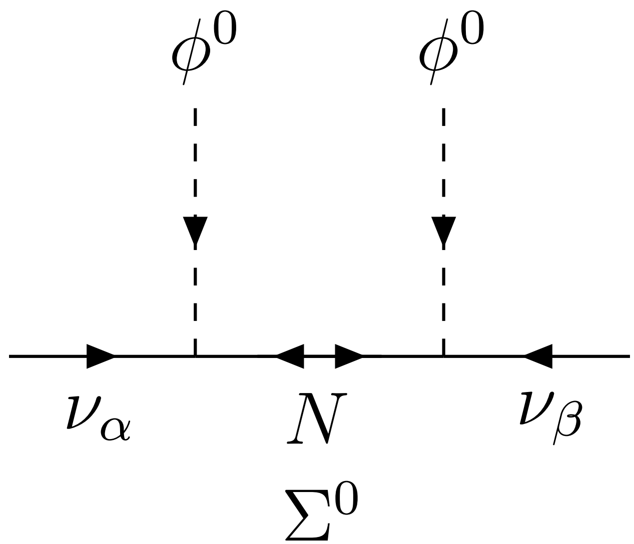

ATLAS Prelim.
m_H = 125.5 GeV
σ(stat.)
σ(sys inc. theory)
σ(theory)
Total uncertainty
± 1σ on μ
H → γγ
μ = 1.57 +0.33 −0.28
+0.23 −0.22 +0.24 −0.18 +0.17 −0.12
H → ZZ* → 4l
μ = 1.44 +0.40 −0.35
+0.35 −0.32 +0.20 −0.13 +0.17 −0.10
H → WW* → lνlν
μ = 1.00 +0.32 −0.29
+0.21 −0.21 +0.24 −0.19 +0.16 −0.08
Combined H→γγ, ZZ*, WW*
μ = 1.35 +0.21 −0.20
+0.14 −0.14 +0.16 −0.14 +0.13 −0.11
W,Z H → bb̄
μ = 0.2 +0.7 −0.6
±0.5 ±0.4 <0.1
H → ττ (8 TeV data only)
μ = 1.4 +0.5 −0.4
+0.3 −0.3 +0.4 −0.3 +0.2 −0.1
Combined H→bb̄, ττ
μ = 1.09 +0.36 −0.32
+0.24 −0.24 +0.27 −0.21 +0.08 −0.04
Combined
μ = 1.30 +0.18 −0.17
+0.12 −0.12 +0.14 −0.11 +0.10 −0.08
√s = 7 TeV ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
-0.5 0 0.5 1 1.5 2
Signal strength (μ)



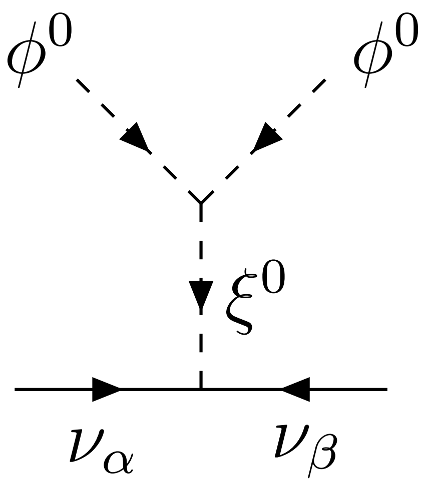
19.7 fb-1 (8 TeV) + 5.1 fb-1 (7 TeV)
CMS
Preliminary
mH = 125 GeV
Combined
μ = 1.00 ± 0.13
H → bb tagged
μ = 0.93 ± 0.49
H → ττ tagged
μ = 0.91 ± 0.27
H → γγ tagged
μ = 1.13 ± 0.24
H → WW tagged
μ = 0.83 ± 0.21
H → ZZ tagged
μ = 1.00 ± 0.29
0
0.5
1
1.5
2
Best fit σ/σSM

Scales of New Physics

Let $\Lambda_\nu =$ new physics scale for the origin of neutrino mass. Assume further that $\Lambda_\nu > \Lambda_{EW} \sim 10^2$ GeV. Then the seesaw mechanisms (I, II, III, inverse, radiative, etc.) are natural explanations of $m_\nu < 1$ eV, but Λ_ν remains unknown, say between 1 TeV and 10^{13} GeV, depending on the specific model and mechanism. There is no compelling reason for any particular choice.



ϕ^0
ϕ^0
ν_α
N
Σ^0
ν_β

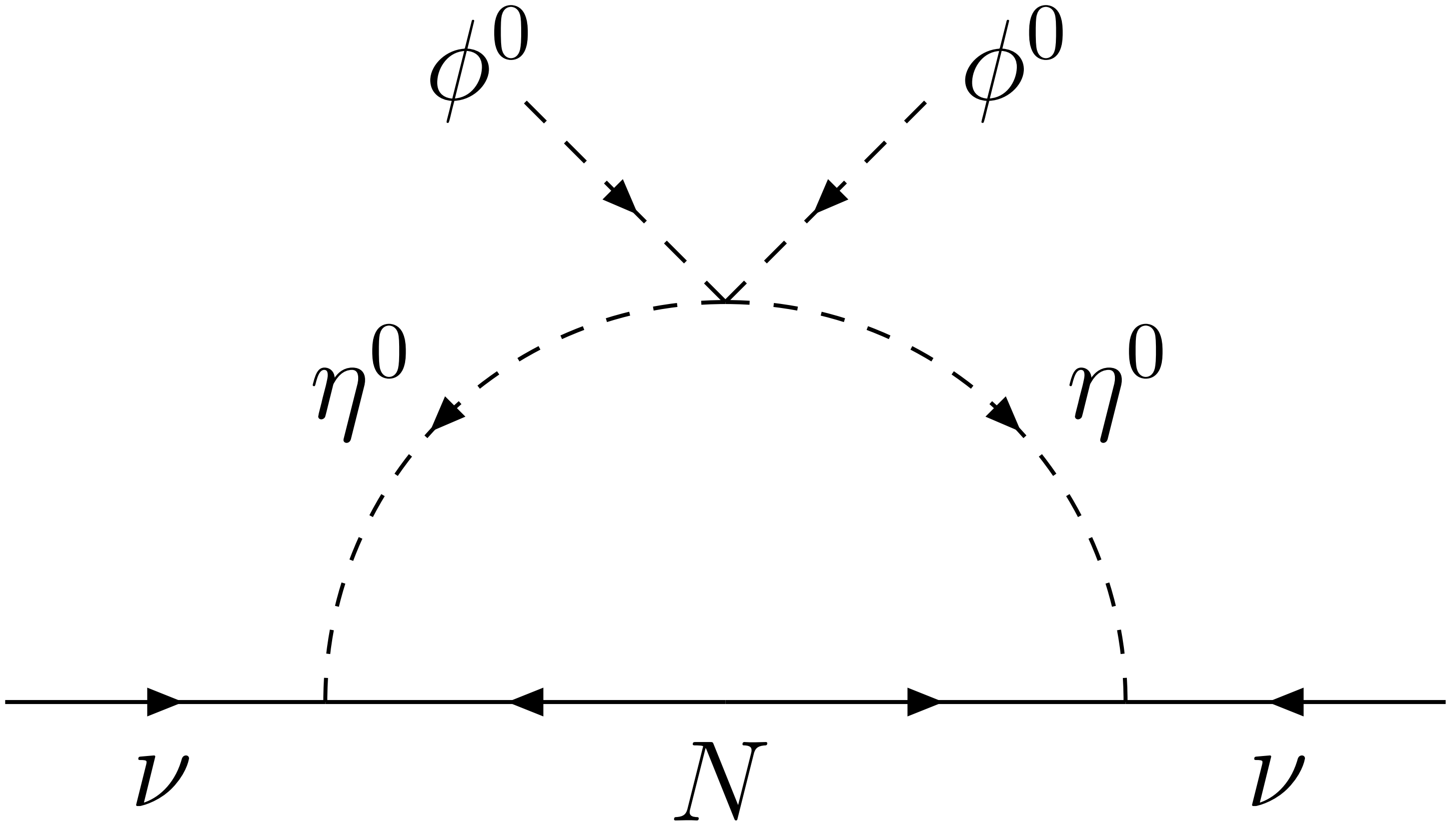


ϕ^0
ϕ^0
ξ^0
ν_α
ν_β

As for dark matter (DM), its possible mass also has a very wide range, from extremely small to very large. However, there is a common consensus that it is likely to be about 10^2 to 10^3 GeV, i.e. the WIMP (Weakly Interacting Massive Particle) Hypothesis.

In 2006, a connection was proposed linking the two, i.e.

$$\Lambda_\nu \sim \mathrm{WIMP\ mass.}$$



ϕ^0
ϕ^0
η^0
η^0
ν
N
ν

The idea is to invoke a symmetry (Z_2 in this case) which forbids a tree-level neutrino mass and enforces at the same time the stability of DM.

Hence (η^+, η^0) and $N_{1,2,3}$ are odd under Z_2, whereas all other (i.e. SM) particles are even.

The complex scalar $\eta^0 = (\eta_R + i\eta_I)/\sqrt{2}$ is split so that $m_R \neq m_I$. Let $m_R < m_I$, then η_R is a dark-matter candidate.

The model is known as 'scotogenic' from the Greek 'scotos' meaning darkness.

The Higgs Connection to Life, the Universe, and Everything

Douglas Adams (1952-2001):

42 is the answer to Life, the Universe, and Everything.

I make the following analogies:

(1) Life = quarks and leptons;

(2) Universe = dark matter and neutrinos;

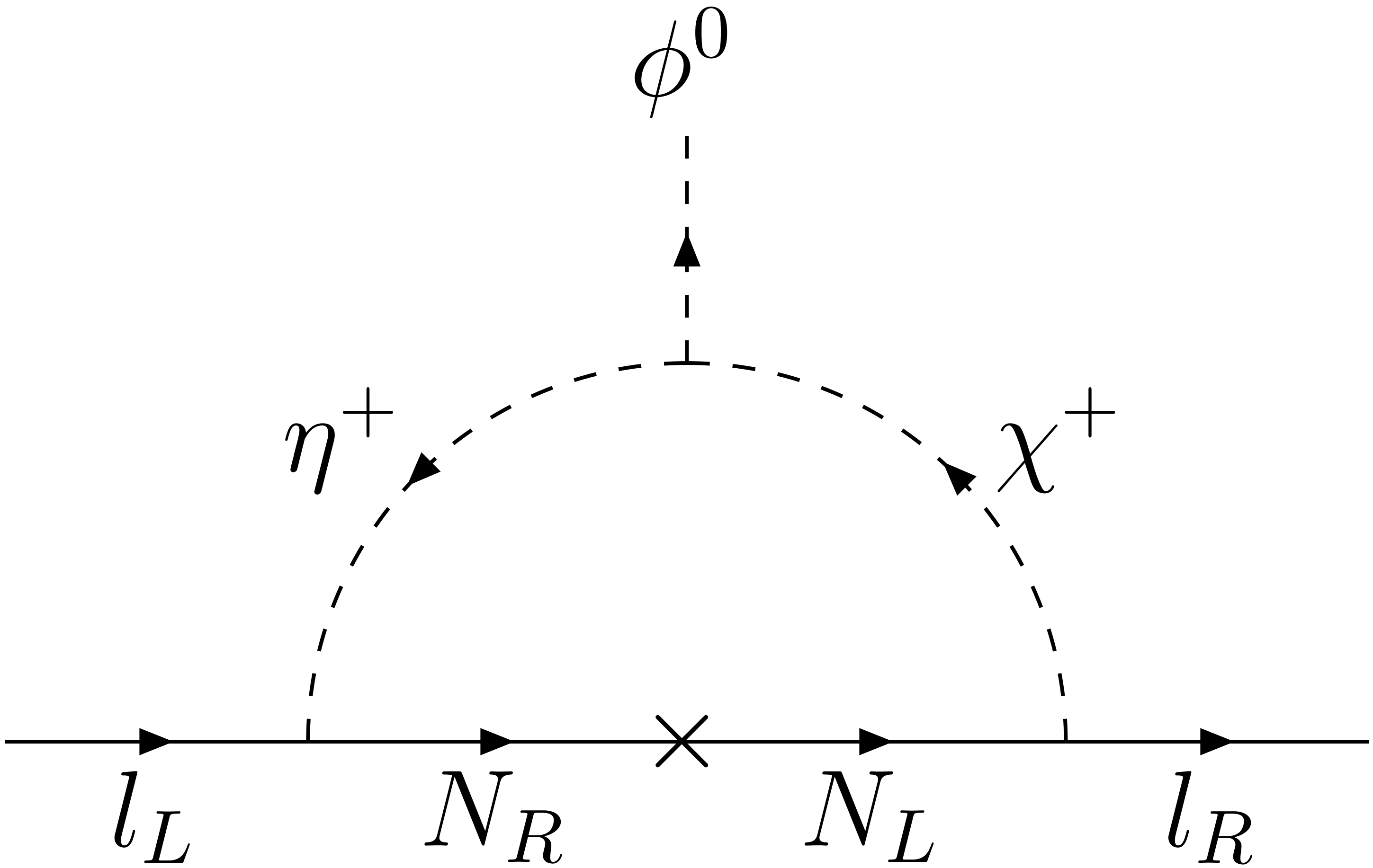
(3) Everything = physics beyond the SM;

(4) 42 = Higgs Nexus.

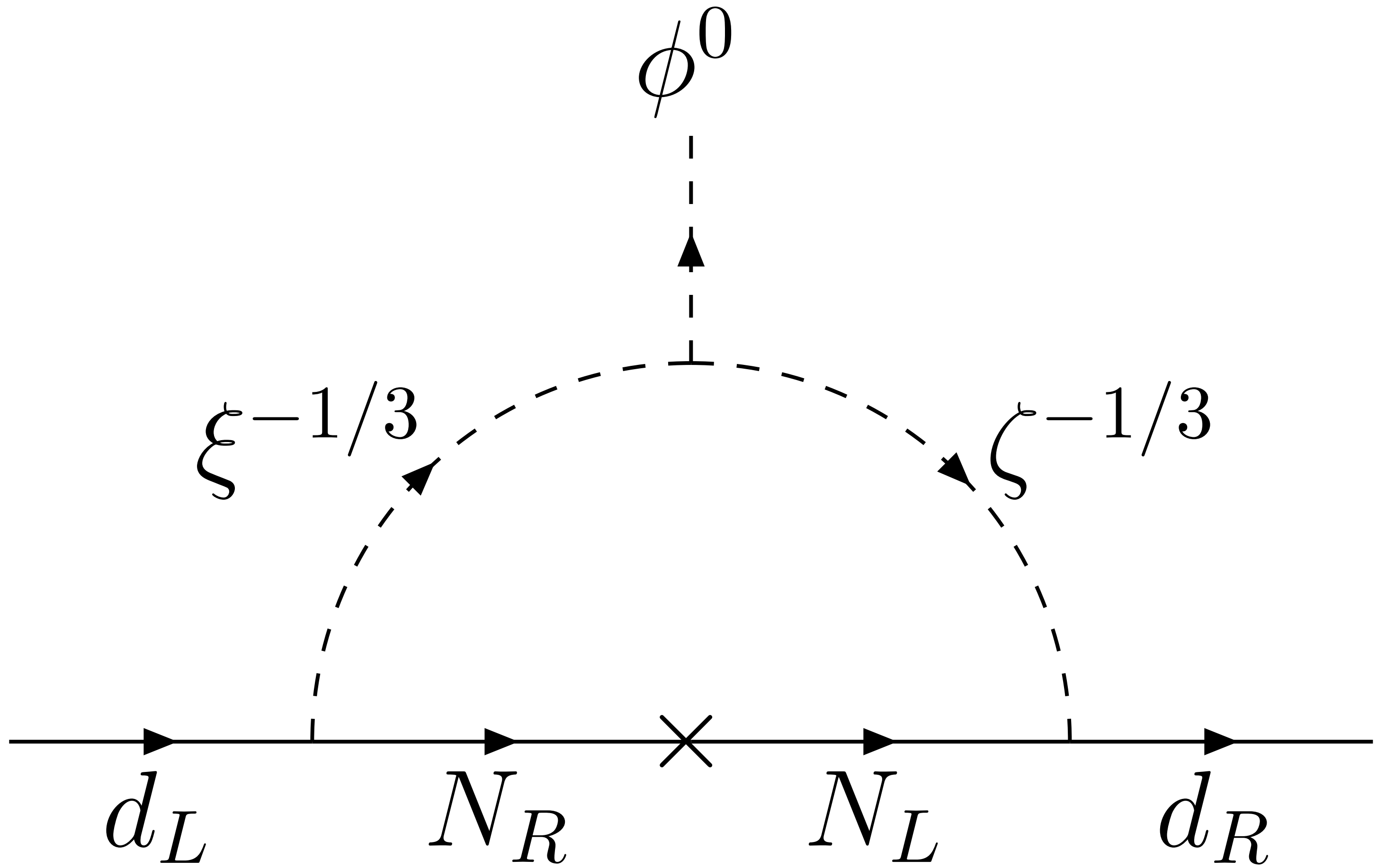
The Higgs connection to W, Z bosons is fundamental to the SM and should not be changed.

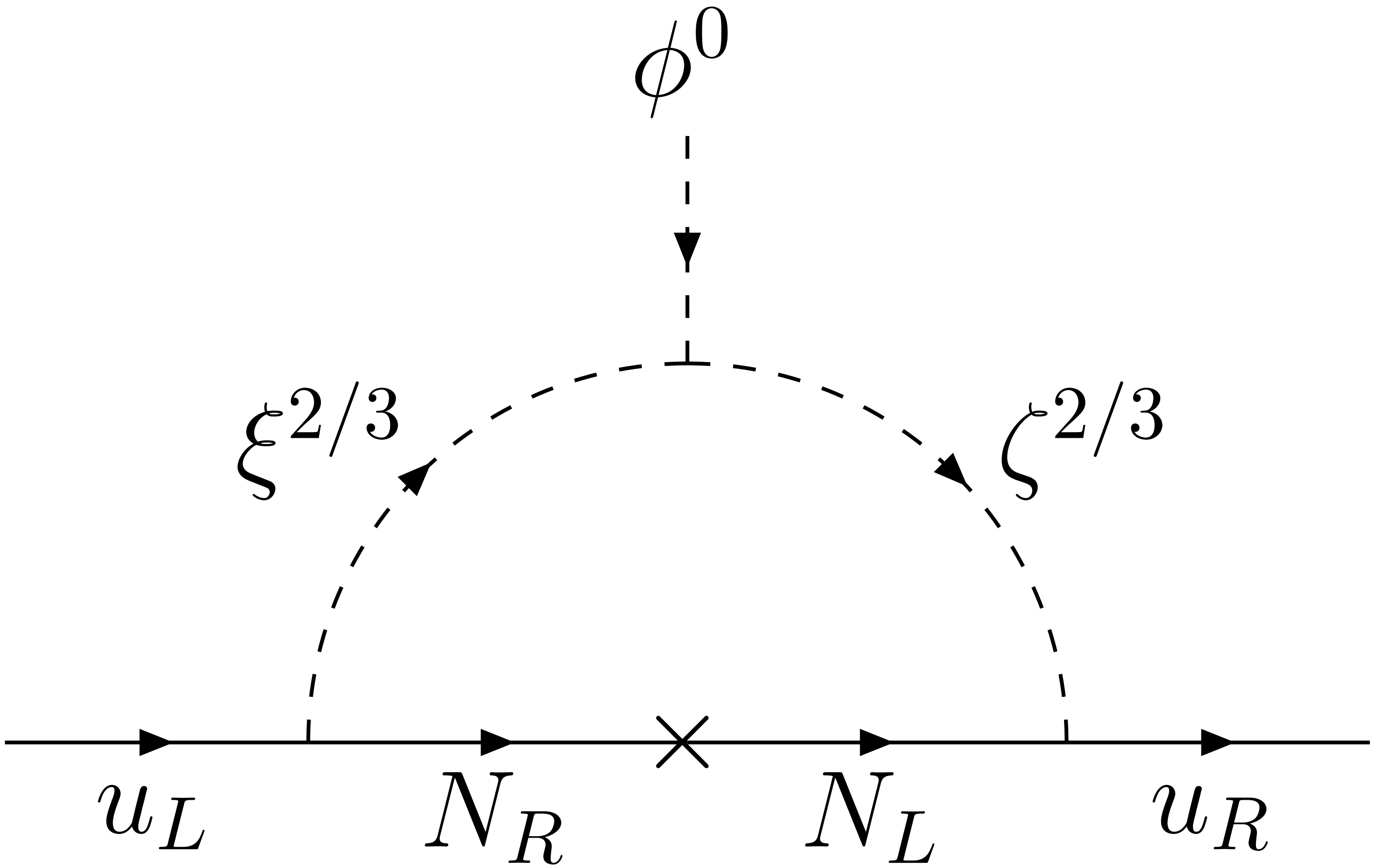
Question: What about its other connections? It has already been conjectured that it connects to neutrinos only through DM. Why not to (some) quarks and leptons? Ma, PRL 112, 091801 (2014):

Instead of the Higgs boson coupling directly to fermions, a (flavor) symmetry is imposed to forbid certain Yukawa couplings. However, a connection through dark matter is allowed. This symmetry is then broken softly and the fermion gets a radiative mass in one loop.



ϕ^0
η^+
χ^+
l_L
N_R
N_L
l_R


ϕ^0
$\xi^{-1/3}$
$\zeta^{-1/3}$
d_L
N_R
N_L
d_R



ϕ^0
$\xi^{2/3}$
$\zeta^{2/3}$
u_L
N_R
N_L
u_R

An immediate consequence of this scenario is a possible observable deviation of the Higgs Yukawa coupling of $h\bar{\psi}\psi$ which is well-known to be given by m_ψ/v in the SM where $v = 246$ GeV.

Fraser/Ma(2014):

In the radiative mechanism for leptons, the doublet (η^+, η^0) and singlet χ^+ mix through the term $\mu(\eta^+\phi^0 - \eta^0\phi^+)\chi^-$, where $\langle\phi^0\rangle = v/\sqrt{2}$. Let the mass eigenstates be $\zeta_1 = \eta\cos\theta + \chi\sin\theta$, and $\zeta_2 = \chi\cos\theta - \eta\sin\theta$ with masses m_1 and m_2, then $\mu v/\sqrt{2} = \sin\theta\cos\theta(m_1^2 - m_2^2)$.

Let $x_{1,2} = m_{1,2}^2/m_N^2$, the one-loop mass is

$$m_l = \frac{f_\eta f_\chi \sin\theta \cos\theta m_N}{16\pi^2} \left(\frac{x_1 \ln x_1}{x_1 - 1} - \frac{x_2 \ln x_2}{x_2 - 1} \right).$$

The Yukawa coupling of h to $\bar{l}l$ is now not exactly equal to m_l/v. It has three contributions, through $\eta^+\eta^-$, $\chi^+\chi^-$, and $\eta^\pm\chi^\mp$. Let $r_{\eta,\chi} = \lambda_{\eta,\chi}(m_N/\mu)^2$, then

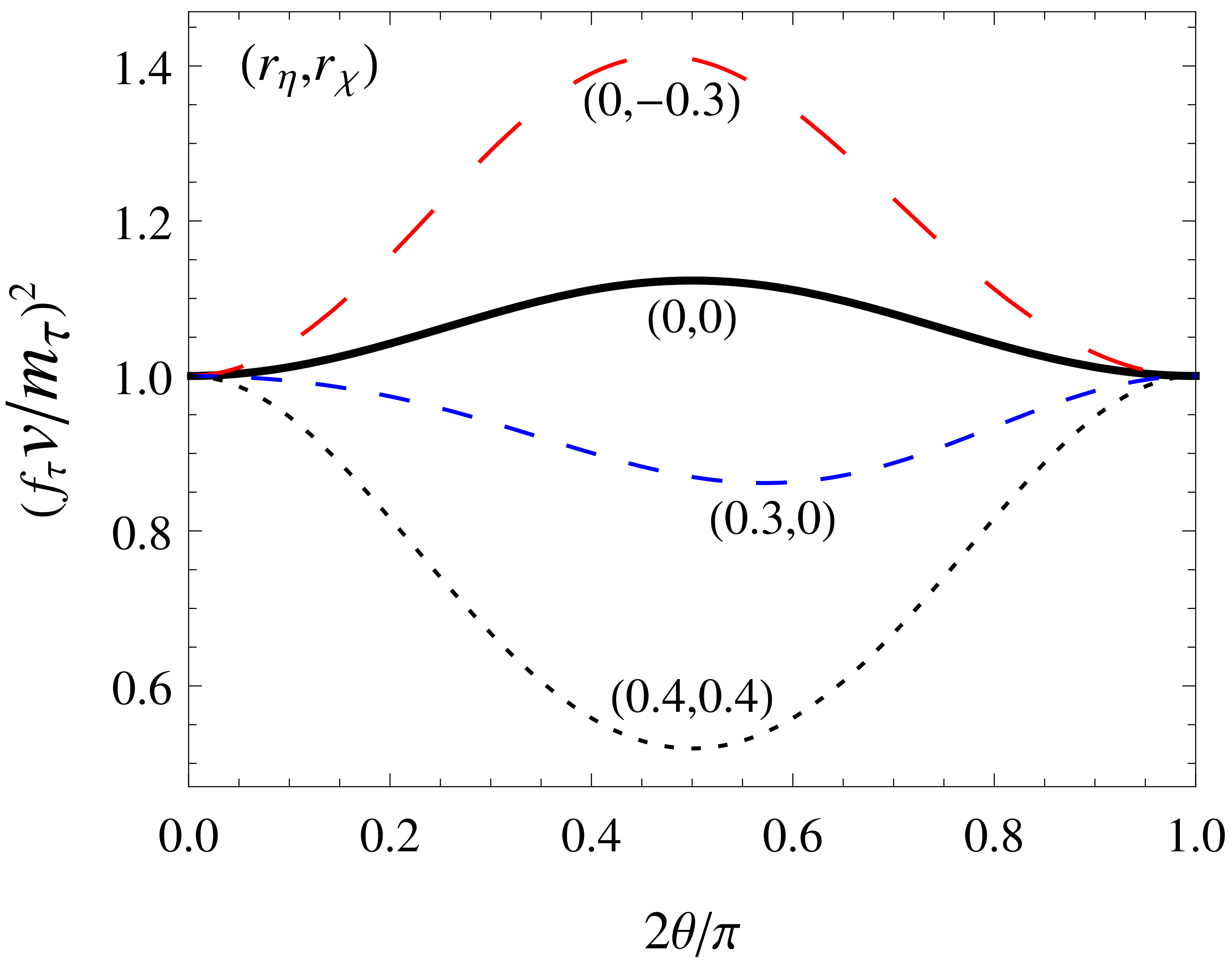
$$\frac{f_l v}{m_l} = 1 + \frac{1}{2}(\sin 2\theta)^2 (a_+ F_+ + a_- F_-),$$

where $a_+ = 1 + (x_1 - x_2)\cos 2\theta (r_\eta - r_\chi)$,

$a_- = (x_1 - x_2)(r_\eta + r_\chi)$, and
$F_+ = [F(x_1, x_1) + F(x_2, x_2)]/2F(x_1, x_2) - 1$,
$F_- = [F(x_1, x_1) - F(x_2, x_2)]/2F(x_1, x_2)$, with

$$F(x_1, x_2) = \frac{1}{x_1 - x_2}\left(\frac{x_1 \ln x_1}{x_1 - 1} - \frac{x_2 \ln x_2}{x_2 - 1}\right).$$

Take for example $x_1 = 3$ and $x_2 = 1$, then $F(3, 1) = 0.324$. For m_τ, this yields $f_\eta f_\chi/4\pi = 0.4(m_N/\mu)$ and $\sin 2\theta = \mu v/\sqrt{2}m_N^2$. Hence $m_N > 174$ GeV for $m_N/\mu < 1$. The effect on $(f_\tau v/m_\tau)^2$ is plotted for various values of (r_η, r_χ).



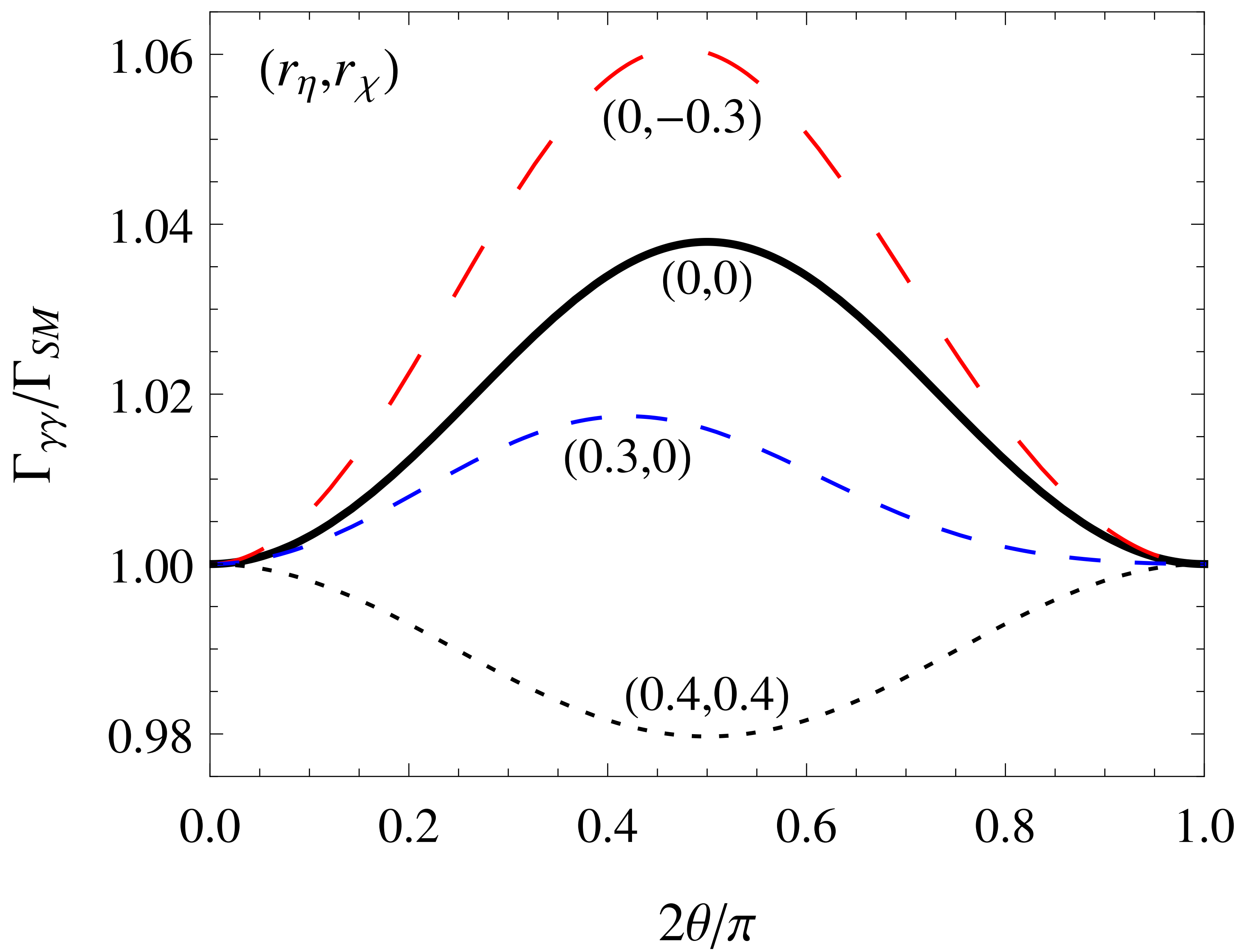
(r_η, r_χ)
(0,−0.3)
(0,0)
(0.3,0)
(0.4,0.4)
1.4
1.2
1.0
0.8
0.6
$(f_\tau v/m_\tau)^2$
0.0
0.2
0.4
0.6
0.8
1.0
$2\theta/\pi$

The charged scalars $\zeta_{1,2}$ also contribute to $h \to \gamma\gamma$. Assuming again $x_1 = 3$ and $x_2 = 1$, and also $\mu/m_N = 1$, $\Gamma_{\gamma\gamma}/\Gamma_{SM}$ is plotted against θ.

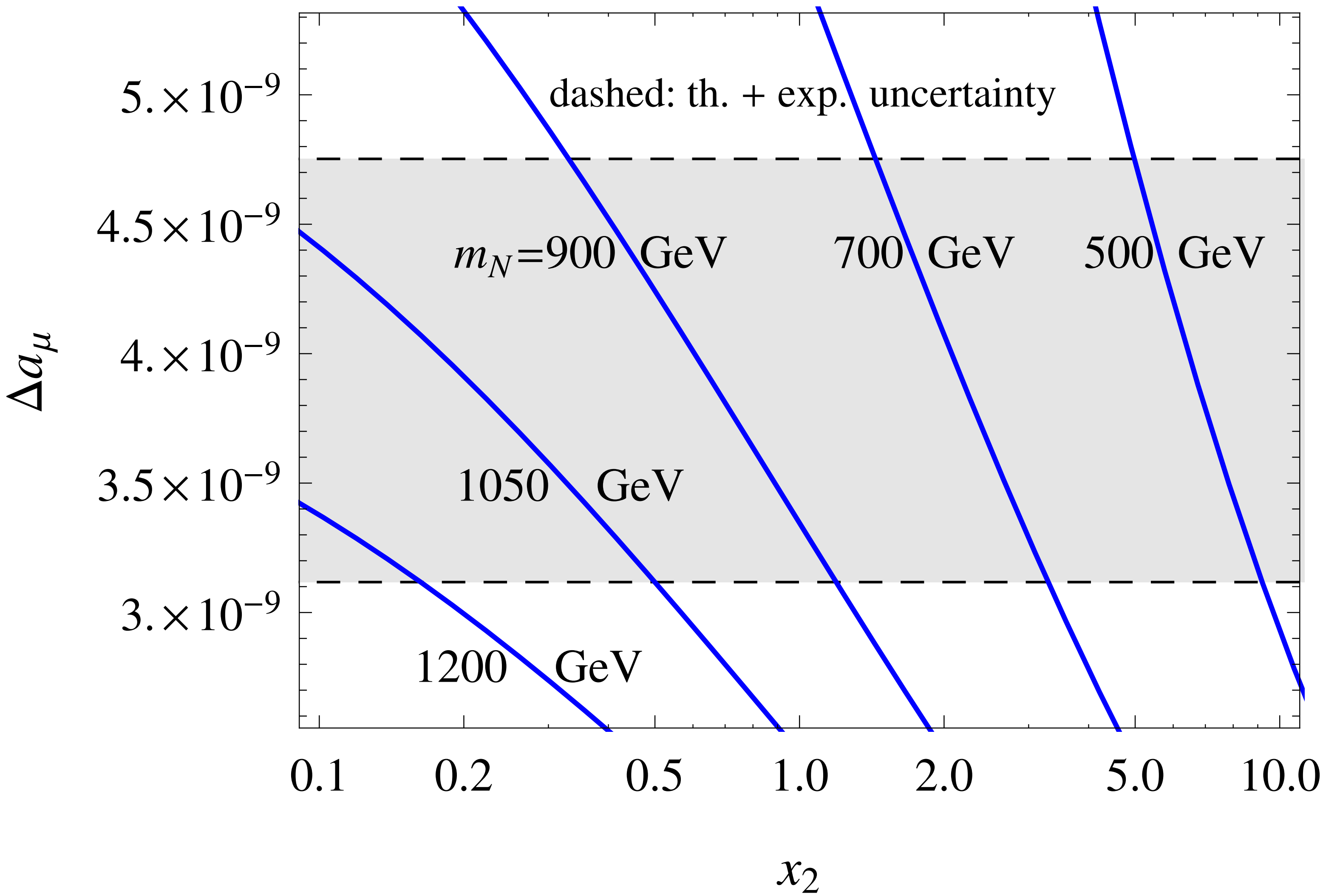
If we apply the same procedure to the muon, then

$$\Delta a_\mu = \frac{(g-2)_\mu}{2} = \frac{m_\mu^2}{m_N^2}\left[\frac{G(x_1)-G(x_2)}{H(x_1)-H(x_2)}\right],$$

where $G(x) = 2x\ln x/(x-1)^3 - (x+1)/(x-1)^2$, and $H(x) = x\ln x/(x-1)$. This is plotted against x_2 with $x_1 = x_2 + 2$ for various m_N.



1.06
1.04
1.02
1.00
0.98
(r_η, r_χ)
(0,−0.3)
(0,0)
(0.3,0)
(0.4,0.4)
$\Gamma_{\gamma\gamma}/\Gamma_{SM}$
0.0
0.2
0.4
0.6
0.8
1.0
$2\theta/\pi$



dashed: th. + exp. uncertainty
m_N=900 GeV
700 GeV
500 GeV
1050 GeV
1200 GeV
$5.\times10^{-9}$
4.5×10^{-9}
$4.\times10^{-9}$
3.5×10^{-9}
$3.\times10^{-9}$
Δa_μ
0.1
0.2
0.5
1.0
2.0
5.0
10.0
x_2

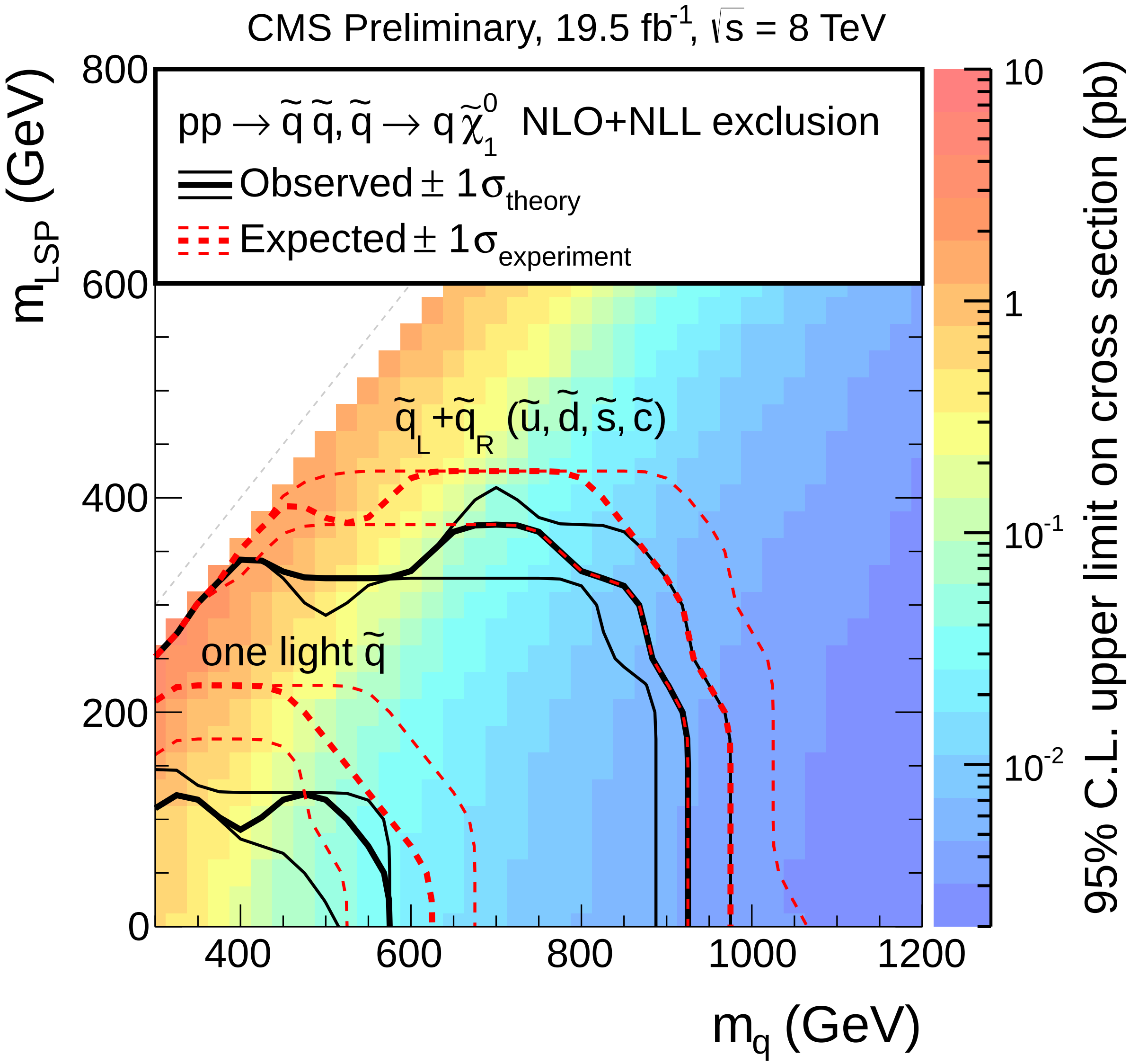
Flavored Dark Matter

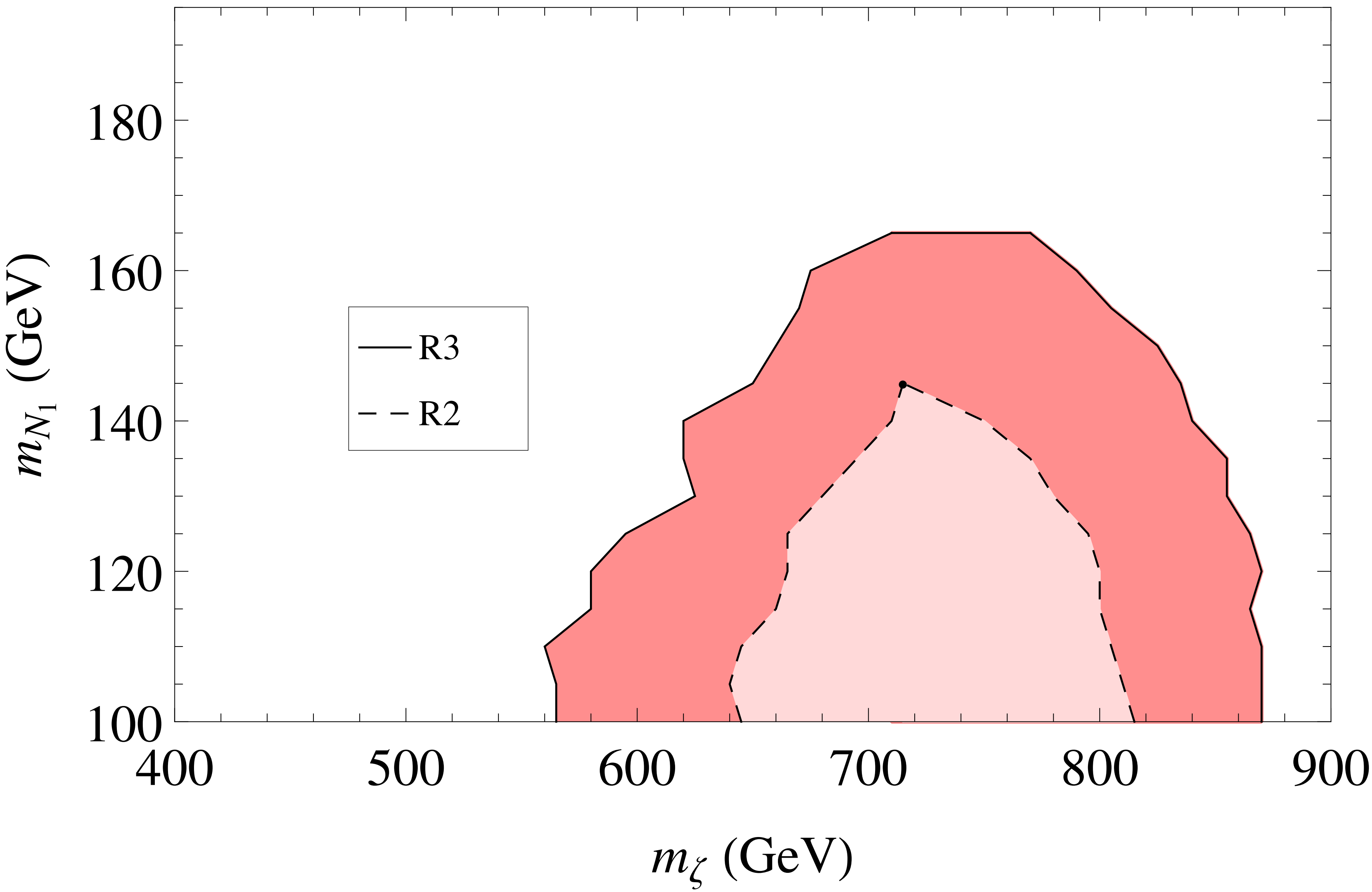
The dark-matter singlet neutral fermions $N_{1,2,3}$ carry flavor and their mixing pattern gets transmitted to the quarks, leptons, and neutrinos. Since flavor is organized through them, the production of scalar quarks, then $\tilde{q} \to q_{1,2} N_{1,2}$ with $N_2 \to \eta/\chi + \mu^\pm$ and $\eta/\chi \to N_1 e^\mp$ will result in 2 jets + $\mu^\pm$ + $e^\mp$ + missing energy at the LHC.

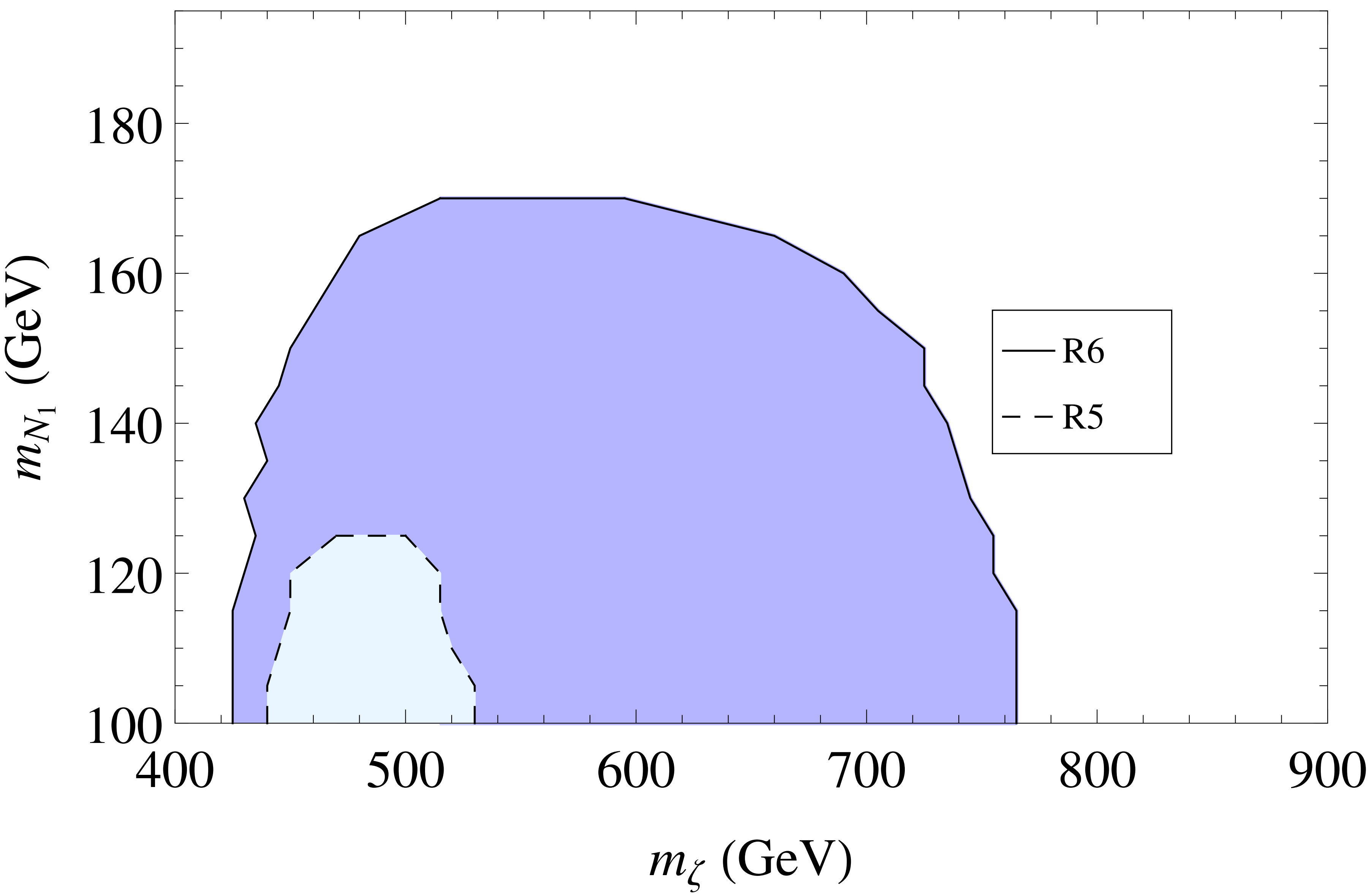
In contrast, in the Minimal Supersymmetric Standard Model, the neutral gauginos do not carry flavor, so the decays of squarks to dark matter will mostly result in 2 jets + $\mu^+\mu^-$ (or e^+e^-) + missing energy instead.

Ma/Natale(2014):

Consider the expected 13 TeV run at the LHC. This signature is observable with $S/N > 5$ where the SM background is mainly $t\bar{t}$ production. Applying the cuts: $|\eta_j| < 3$, $|\eta_e| < 2.4$, and $|\eta_\mu| < 2.5$, we consider four cut regions: R2: missing $E_T > 200$ GeV, $H_T > 600$ GeV, $p_T^j > 30$ GeV, $p_T^l > 20$ GeV; R3: missing $E_T > 275$ GeV, $H_T > 600$ GeV, $p_T^j > 30$ GeV, $p_T^l > 20$ GeV; R5: missing $E_T > 200$ GeV, $H_T > 350$ GeV, $p_T^j > 30$ GeV, $p_T^l > 20$ GeV; R6: missing $E_T > 200$ GeV, $H_T > 350$ GeV, $p_T^j > 150$ GeV, $p_T^l > 25$ GeV.


CMS Preliminary, 19.5 fb^{-1}, $\sqrt{s}$ = 8 TeV
$pp \to \tilde{q}\tilde{q}, \tilde{q} \to q\tilde{\chi}^0_1$ NLO+NLL exclusion
Observed ± 1σ_{theory}
Expected ± 1$\sigma_{experiment}$
$\tilde{q}_L + \tilde{q}_R$ ($\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$)
one light $\tilde{q}$
m_{LSP} (GeV)
m_q (GeV)
95% C.L. upper limit on cross section (pb)
800
600
400
200
0
1200
1000
10
1
10^{-1}
10^{-2}

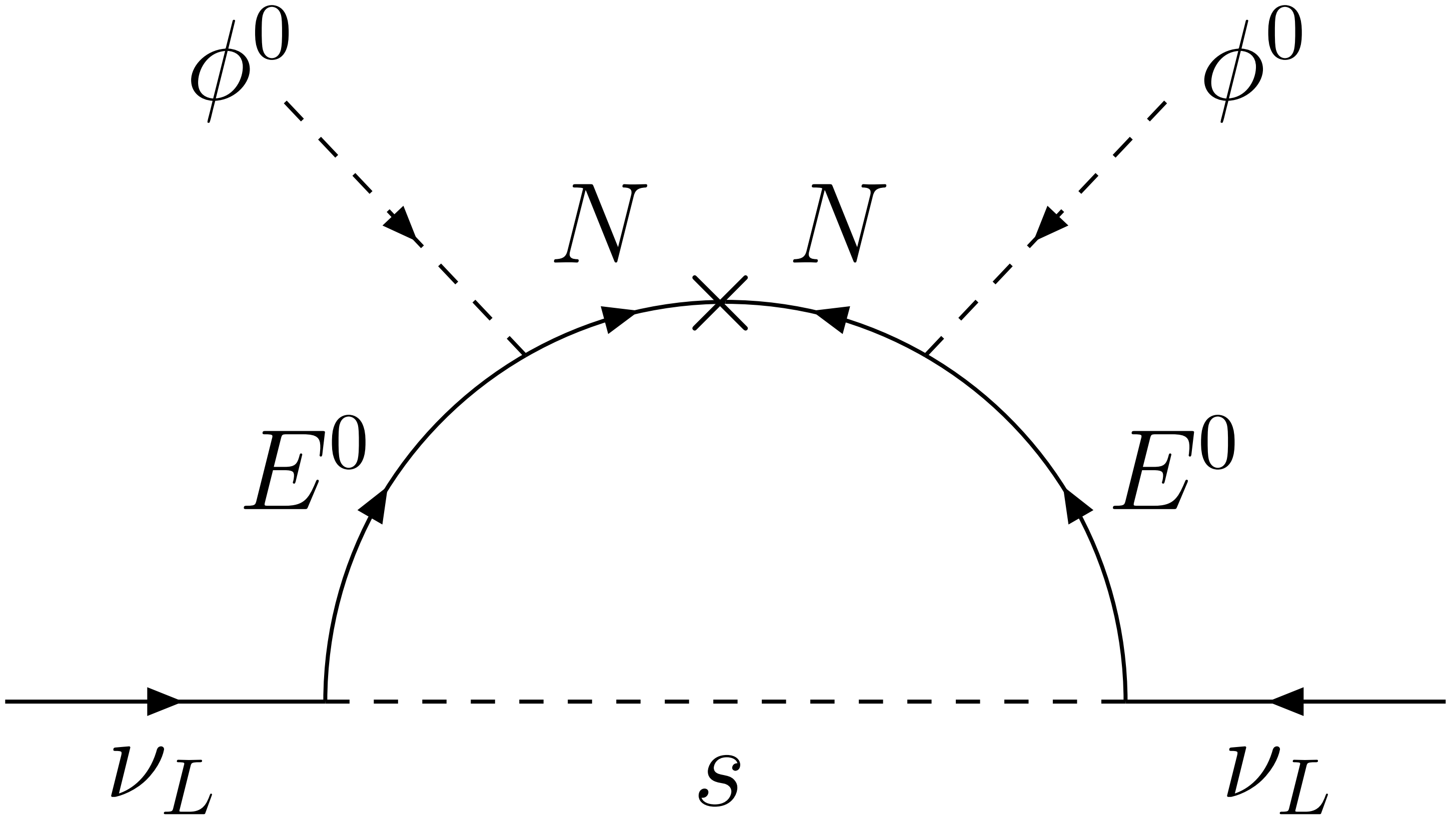

180
160
140
120
100
400
500
600
700
800
900
R3
R2
m_{N_1} (GeV)
m_ζ (GeV)



180
160
140
120
100
400
500
600
700
800
900
m_{N_1} (GeV)
m_ζ (GeV)
R6
R5

Flavored dark matter in the form of three real scalar particles $s_{1,2,3}$ is another possibility. This scenario is realized naturally in a scotogenic inverse seesaw model of neutrino mass. Fraser/Ma/Popov(2014):

The extra particles are a Dirac fermion doublet $(E^0, E^-)_{L,R}$ and a Dirac fermion singlet $N_{L,R}$. They and $s_{1,2,3}$ are all odd under a dark Z_2 symmetry. In addition, E^0, E^-, N have lepton number, which is only softly broken by the $N_L N_L$ and $N_R N_R$ Majorana mass terms. Neutrino masses are obtained in one loop using the third radiative mechanism first pointed out in 1998.


ϕ^0
ϕ^0
N
N
E^0
E^0
ν_L
s
ν_L

Consider the discrete symmetry Z_3, under which $(\nu_i, l_i)_L \sim \underline{1}, \underline{1}', \underline{1}''$, $l_{iR} \sim \underline{1}, \underline{1}', \underline{1}''$, $s_1 \sim \underline{1}$, $(s_2 + is_3)/\sqrt{2} \sim \underline{1}'$, $(s_2 - is_3)/\sqrt{2} \sim \underline{1}''$. Allow Z_3 to be broken softly by the $s_i s_j$ mass-squared matrix. Then the charged-lepton mass matrix is diagonal, and the neutrino mass matrix is of the form

$$\begin{pmatrix} f_e & 0 & 0 \\ 0 & f_\mu/\sqrt{2} & if_\mu/\sqrt{2} \\ 0 & f_\tau/\sqrt{2} & -if_\tau/\sqrt{2} \end{pmatrix} \mathcal{O}^T \mathcal{I} \mathcal{O} \begin{pmatrix} 1 & 0 & 0 \\ 0 & f_\mu/\sqrt{2} & f_\tau/\sqrt{2} \\ 0 & if_\mu/\sqrt{2} & -if_\tau/\sqrt{2} \end{pmatrix},$$

where $\mathcal{O}$ is an orthogonal matrix and each entry of the diagonal $\mathcal{I}$ is a loop integral over the three different scalar mass eigenvalues $m_{1,2,3}$.

The couplings $f_{e,\mu,\tau}$ may be chosen real by absorbing their phases into the charged leptons. If $f_\mu = f_\tau$ as well, then

$$\mathcal{M}_\nu = \begin{pmatrix} A & C & C^* \\ C & D^* & B \\ C^* & B & D \end{pmatrix},$$

which guarantees $\theta_{23} = \pi/4$, $\theta_{13} \neq 0$, and $\exp(-i\delta_{CP}) = \pm i$, i.e. maximal CP violation. Grimus/Lavoura(2004)

If $f_\mu \neq f_\tau$, then a correlation between θ_{23} and δ_{CP} will be obtained.

The dark matter of this model is the lightest of the three scalars $s_{1,2,3}$, call it S. Then it interacts with the SM Higgs boson h according to

$$-\mathcal{L}_{int} = \frac{\lambda_{hS}}{2} v h S^2 + \frac{\lambda_{hS}}{4} h^2 S^2.$$

Detailed studies have been made assuming that these dominate its relic-abundance as well as direct-detection cross sections. After the 2012 discovery, and using the recent LUX data, m_S is allowed to be just a few GeV below $m_h/2$ or greater than about 150 GeV.

Conclusion

Question: What does the one Higgs really tell us?

The answer may be that flavor and dark matter are also connected and they do so through the one Higgs. This new notion extends the scotogenic neutrino mass to all (or most) quark and lepton masses, with flavored dark matter.

In this framework, the new physics scales responsible for DM and neutrino mass are the same, say 1 TeV. If so, its impact is verifiable in the near future at the LHC.