Radiative Type II Seesaw Mechanism for Neutrino Mass with Dark Matter

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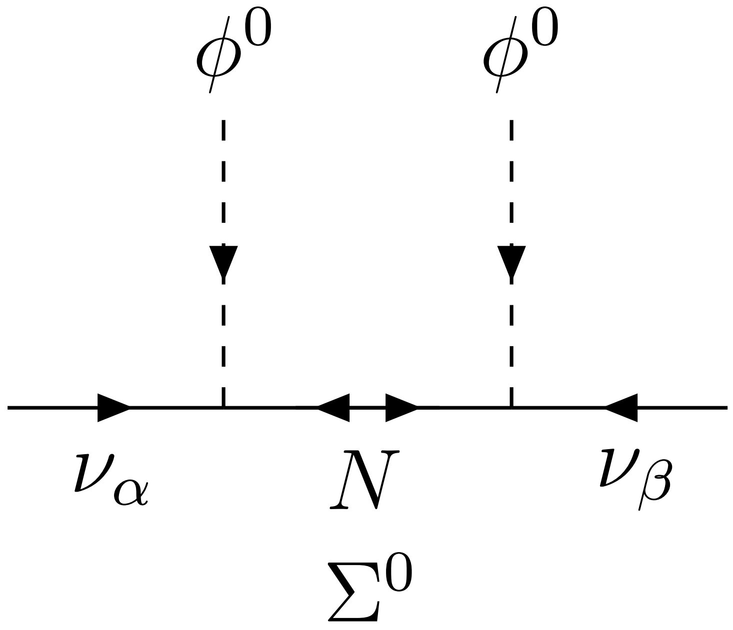
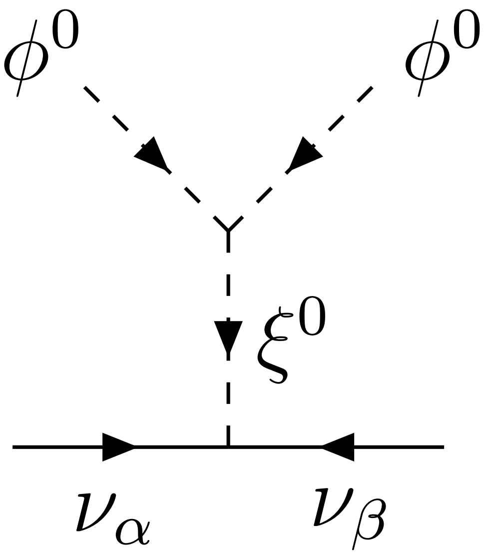
Seesaw Variants

Weinberg(1979): Assuming that the new physics (particles and interactions) responsible for neutrino mass is above the scale of electroweak symmetry breaking, there is an unique dimension-five operator in the standard model for Majorana neutrino mass:

$$\frac{f_{\alpha\beta}}{2\Lambda}(\nu_\alpha\phi^0 - l_\alpha\phi^+)(\nu_\beta\phi^0 - l_\beta\phi^+) \Rightarrow \mathcal{M}_\nu = \frac{f_{\alpha\beta}v^2}{\Lambda}.$$

Ma(1998): There are three and only three tree-level realizations (ultraviolet completions), namely


ϕ^0
ϕ^0
ν_α
N
Σ^0
ν_β


ϕ^0
ϕ^0
ξ^0
ν_α
ν_β

(I) fermion singlet N (1979),

(II) scalar triplet $(\xi^{++}, \xi^{+}, \xi^{0})$ (1980),

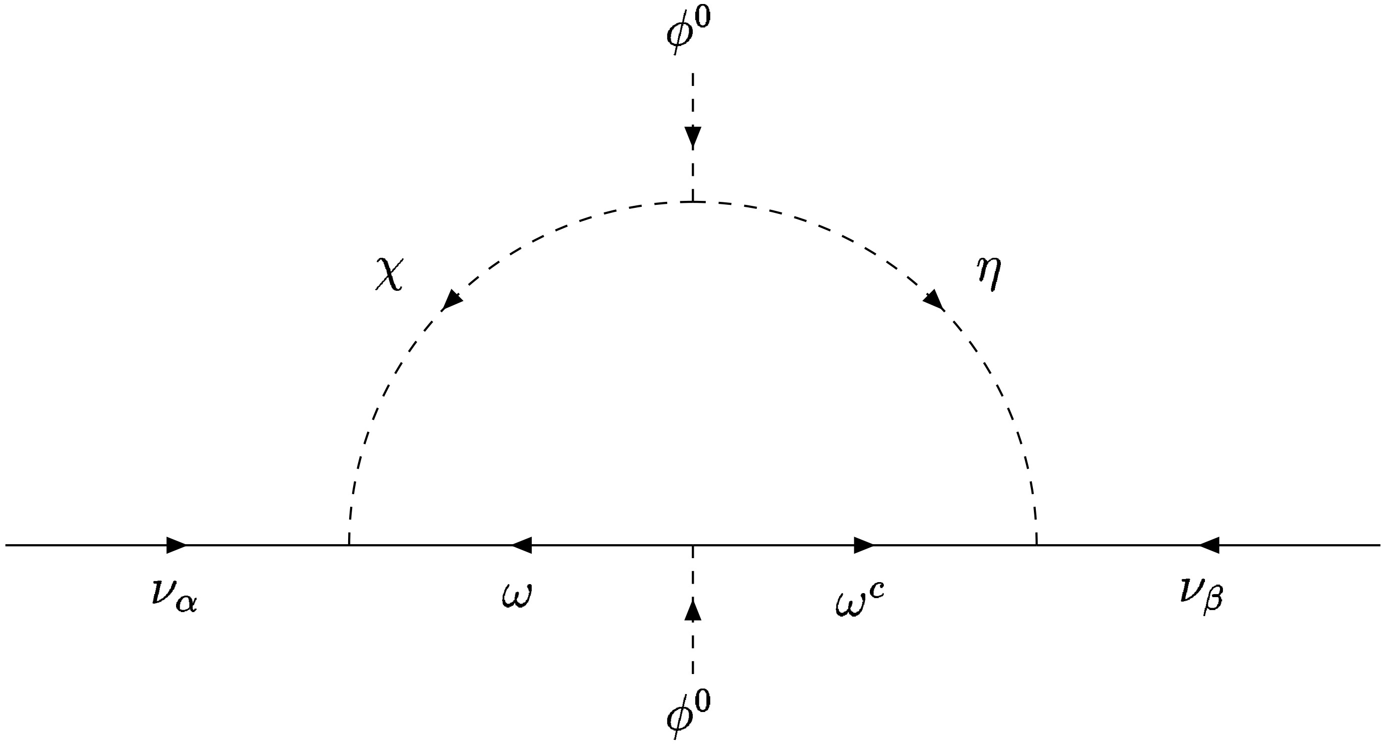
(III) fermion triplet $(\Sigma^{+}, \Sigma^{0}, \Sigma^{-})$ (1989);

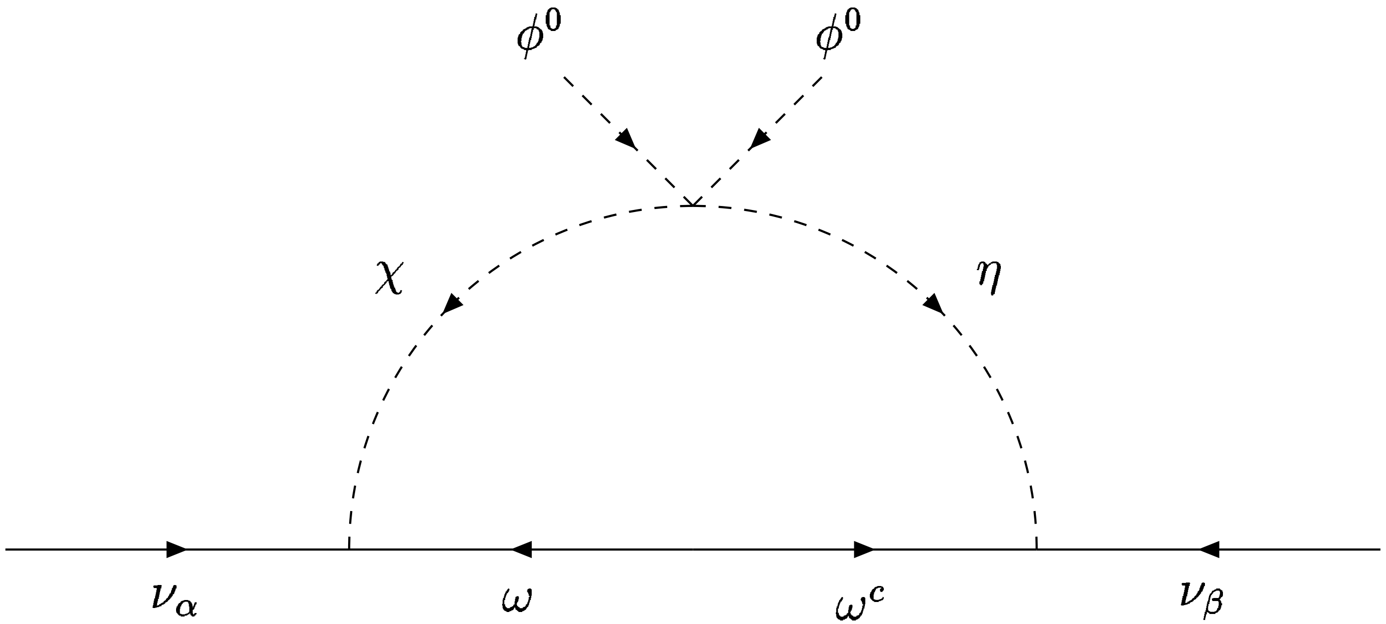
and three generic 1PI (one particle irreducible) one-loop realizations:

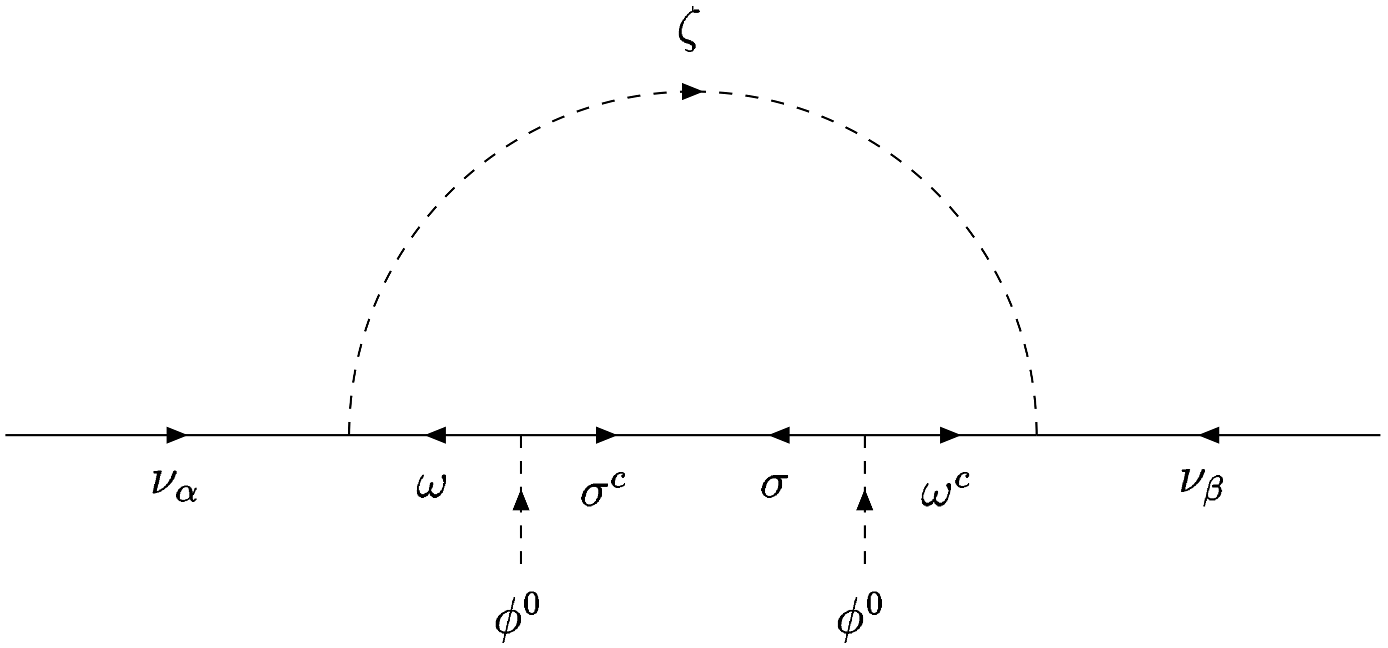
(IV) (Zee, 1980),

(V) (Ma, 2006),

(VI) (Fraser/Ma/Popov, 2014).


ϕ^0
χ
η
ν_α
ω
ω^c
ν_β
ϕ^0

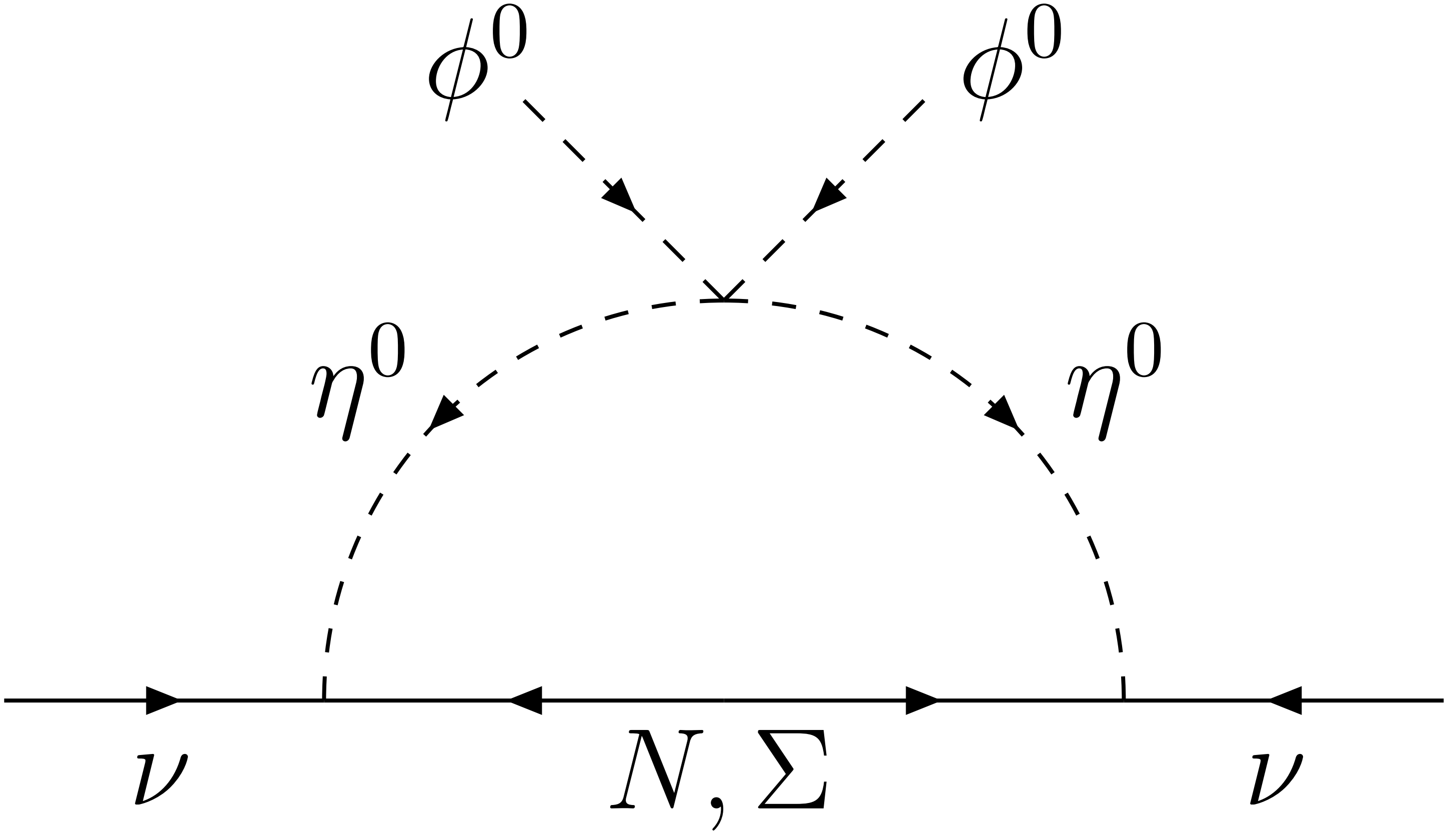

ϕ^0
ϕ^0
χ
η
ν_α
ω
ω^c
ν_β


ζ
ν_α
ω
σ^c
σ
ω^c
ν_β
ϕ^0
ϕ^0

Radiative Seesaw with Dark Matter

Ma(2006): Radiative Type I seesaw with dark matter ('scotogenic' from the Greek 'scotos' meaning darkness).
Ma/Suematsu(2009): Radiative Type III analog.
$\omega = \omega^c = N$ or Σ, $\chi = \eta = (\eta^+, \eta^0), \langle \eta^0 \rangle = 0$.
N or Σ interacts with ν, but they are not Dirac mass partners, because of the exactly conserved Z_2 symmetry, under which N or Σ and (η^+, η^0) are odd, and all SM particles are even. Using $f(x) = -\ln x/(1-x)$,

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_i \frac{h_{\alpha i} h_{\beta i} M_i}{16\pi^2} [f(M_i^2/m_R^2) - f(M_i^2/m_I^2)].$$


ϕ^0
ϕ^0
η^0
η^0
ν
N, Σ
ν

The linkage of neutrino mass to dark matter provides an important clue to the scale of new physics. It is a possible answer to the **Question**: Is the new physics responsible for neutrino mass also responsible for some other phenomenon in particle physics and astrophysics? Here the answer is yes, and it is dark matter. Since dark matter is mostly assumed to be a Weakly Interacting Massive Particle (WIMP), its mass scale is reasonably set at 1 TeV. This is the crucial missing piece of information which allows us to expect observable new physics related to both dark matter and neutrino mass at the LHC.

In radiative neutrino mass models, the tree-level mass is forbidden by a symmetry. In the canonical Type I seesaw model, the tree-level mass is actually also corrected by a finite one-loop contribution which may be important for large m_N.

Grimus/Lavoura(2002):
Aristizabal Sierra/Yaguna(2011):

$$\frac{\delta m_\nu}{m_\nu} = \frac{G_F}{8\pi^2\sqrt{2}}\left[m_h^2 \ln\frac{m_N^2}{m_h^2} + 3m_Z^2 \ln\frac{m_N^2}{m_Z^2}\right].$$

Type II Seesaw

Whereas the Higgs doublet (ϕ^+, ϕ^0) is used twice to implement Type I and Type III seesaws so that neutrino mass comes from the effective dimension-five Weinberg operator, a Higgs triplet (ξ^{++}, ξ^+, ξ^0) does the job with a renormalizable dimension-four term

$$\xi^0 \nu_i \nu_j - \xi^+ (\nu_i l_j + l_i \nu_j)/\sqrt{2} + \xi^{++} l_i l_j.$$

Therefore, a tree-level m_ν is always obtained for $\langle \xi^0 \rangle \neq 0$.

Gelmini/Roncadelli(1981):
Assign $L = -2$ to ξ, so that the scalar trilinear term

$$\mu(\xi^0\bar{\phi}^0\bar{\phi}^0 + \sqrt{2}\xi^+\bar{\phi}^0\phi^- + \xi^{++}\phi^-\phi^-)$$

is forbidden, then break L spontaneously with $\langle\xi^0\rangle = u \neq 0$. Since $u^2 << v^2$, this solution requires extreme fine tuning, and was considered rather unnatural.

In any case, it has a testable prediction because this results in a massless Goldstone boson (majoron) which contributes to the invisible decay of the Z. As such, this model has been ruled out by data for many years.

Ma/Sarkar(1998):
If $m_\xi^2 > 0$ and sufficiently large, then

$$u \simeq \frac{-\mu v^2}{m_\xi^2 + (\lambda_4 + \lambda_5) v^2}.$$

This means that u may be small if either μ is small or m_ξ^2 is large or both. Note that $\rho_0 = 1.00040 \pm 0.00024$ implies that $u < 1.1$ GeV.

If $m_\xi < 1$ TeV so that it may be produced at the LHC, μ has to be small, but how small? Let $m_\nu = f_\nu u$, then $f_\nu \sim 0.1$ implies $u \sim 1$ eV.

Ma/Raidal/Sarkar(2000):

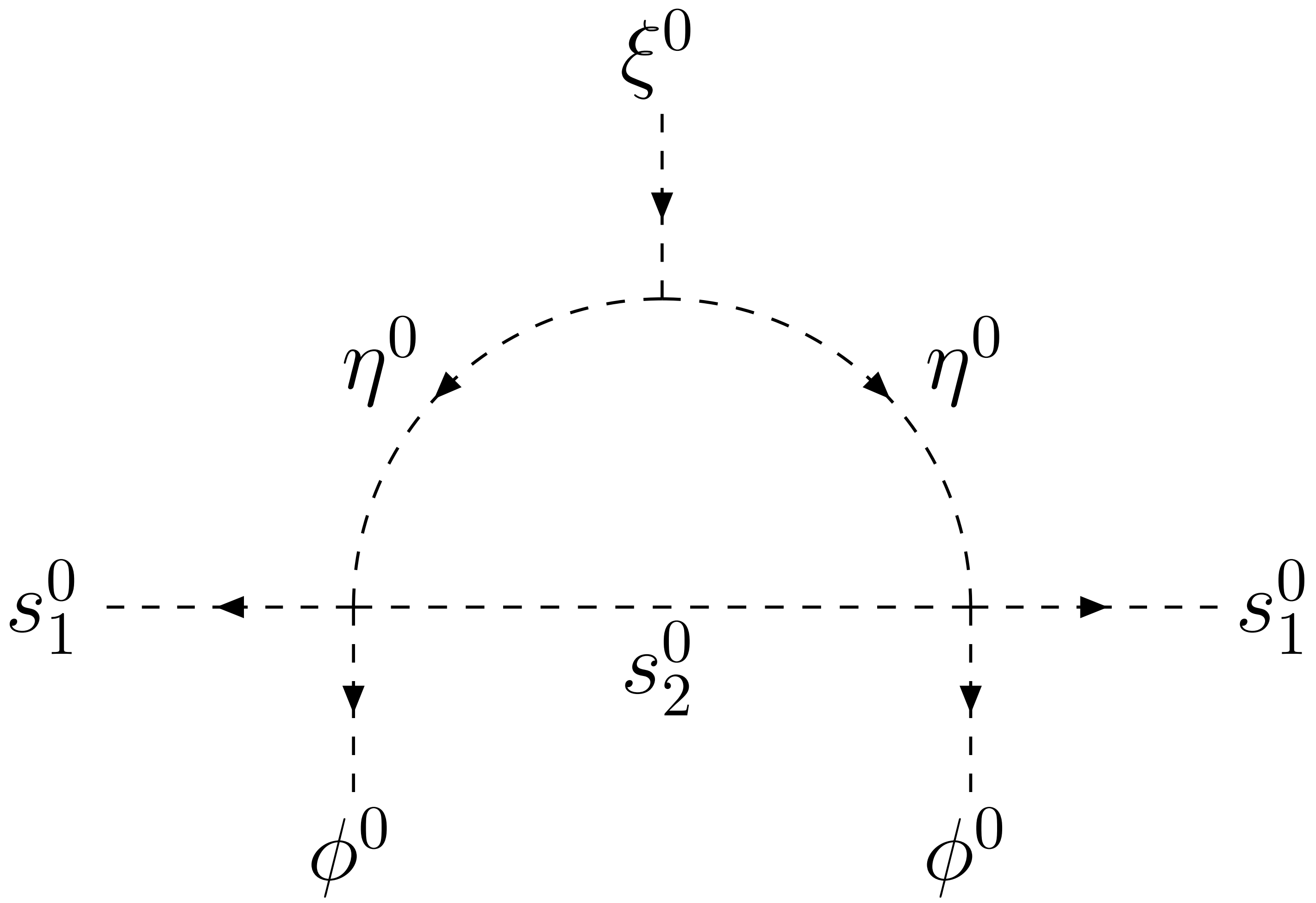
This may be achieved in a model of extra dimensions by promoting the parameter μ to a dynamical singlet scalar field which acts as a messenger field from a distant brane to our brane. It carries $L = 2$ and couples to a corresponding singlet in the distant brane, which is the source of the lepton number violation. Its effect on our brane is reduced by the volume of the bulk, so that the value of μ may be naturally small. This scenario leads to a possible observable ξ^{++} with dominant decays into $l_i^+ l_j^+$, and thus mapping out the neutrino mass matrix.

Kanemura/Sugiyama(2012):

Impose L conservation with $\xi \sim -2$, then $\xi^\dagger \Phi\Phi$ is forbidden. Impose also dark Z_2, with new scalar singlets $s_1^0(L=-1, Z_2 \text{ even})$, $s_2^0(L=0, Z_2 \text{ odd})$, and new scalar doublet $(\eta^+, \eta^0)(L=-1, Z_2 \text{ odd})$.

Break L spontaneously with $\langle s_1^0 \rangle \neq 0$, then μ is generated radiatively. Note that dark Z_2 circulates in the loop and is unbroken. Thus s_2^0 is a good dark matter candidate.

This model also predicts dominant $\xi^{++} \to l_i^+ l_j^+$ decay.
It also has a massless singlet majoron.


ξ^0
η^0
η^0
s_1^0
s_1^0
s_2^0
ϕ^0
ϕ^0

Radiative Type II Seesaw with Dark Matter

Just as the direct tree-level coupling $\bar{N}_R \nu_L \phi^0$ must be forbidden by a symmetry in radiative Type I and III seesaws, the analogous $\nu_L \nu_L \xi^0$ coupling must be forbidden if radiative Type II seesaw is desired. Whereas Z_2 odd for N_R works in the Type I and III cases, it will not work in Type II. What works is global lepton number symmetry (or $B - L$ gauge symmetry) as shown below.

Ma(2015):
Assign $L = 0$ to ξ, then the dimension-four term $\nu_L \nu_L \xi^0$ is forbidden. Add one Dirac fermion doublet $(N, E)_{L,R}$

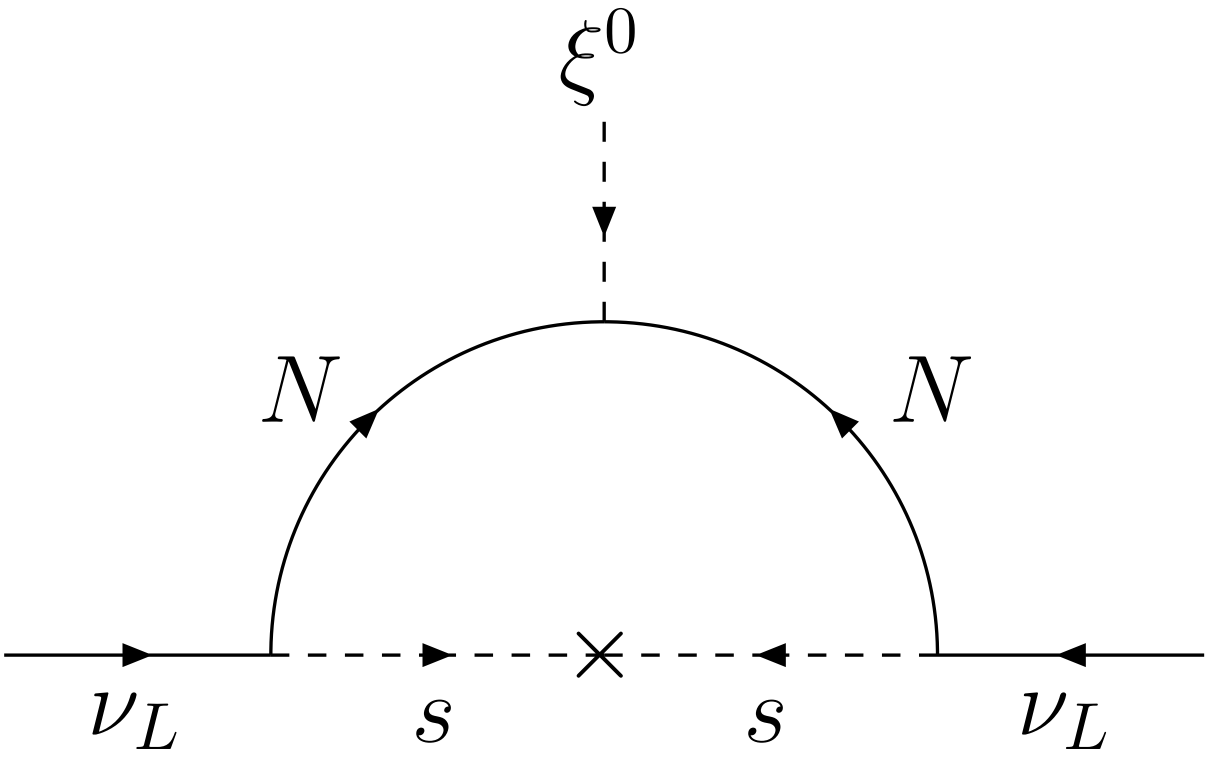
with $L = 0$, and three complex neutral scalar singlets s with $L = 1$. Break L softly with the $s_i s_j$ mass-squared matrix, then m_ν is radiatively generated.

$$m_\nu = \frac{f_s^2 urx}{16\pi^2}[f_R F_R(x) + f_L F_L(x)]$$

where $x = m_s^2/m_N^2$, $r = \Delta m_s^2/m_s^2$, and

$$F_R(x) = \frac{1+x}{(1-x)^2} + \frac{2x\ln x}{(1-x)^3},$$

$$F_L(x) = \frac{2}{(1-x)^2} + \frac{(1+x)\ln x}{(1-x)^3}.$$

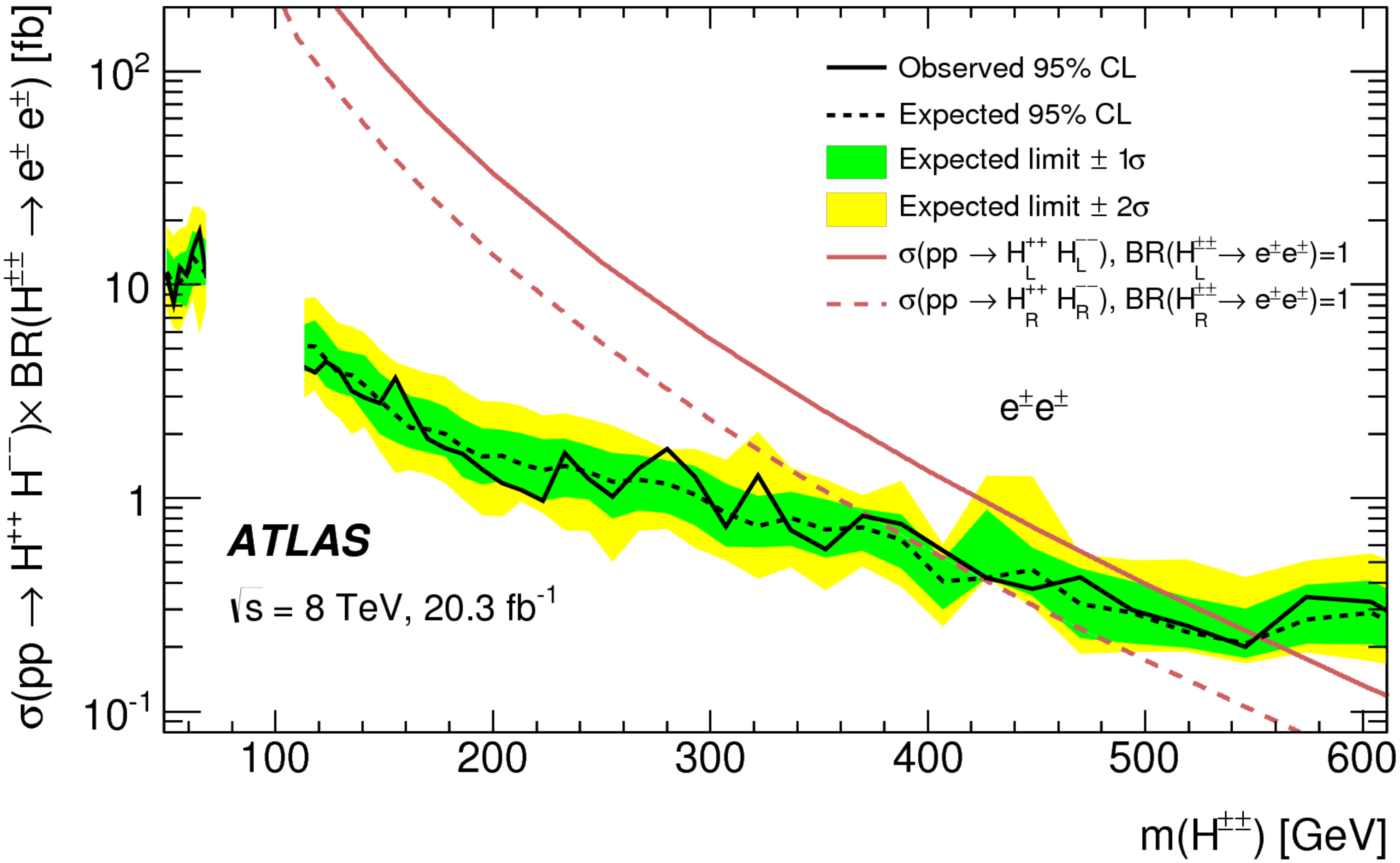

ξ^0
N
N
ν_L
s
s
ν_L

Important implication for the search of ξ^{++} at the LHC: Since f_ν is small, $\xi^{++} \to l_i^+ l_j^+$ is negligible relative to $\xi^{++} \to W^+ W^+$.

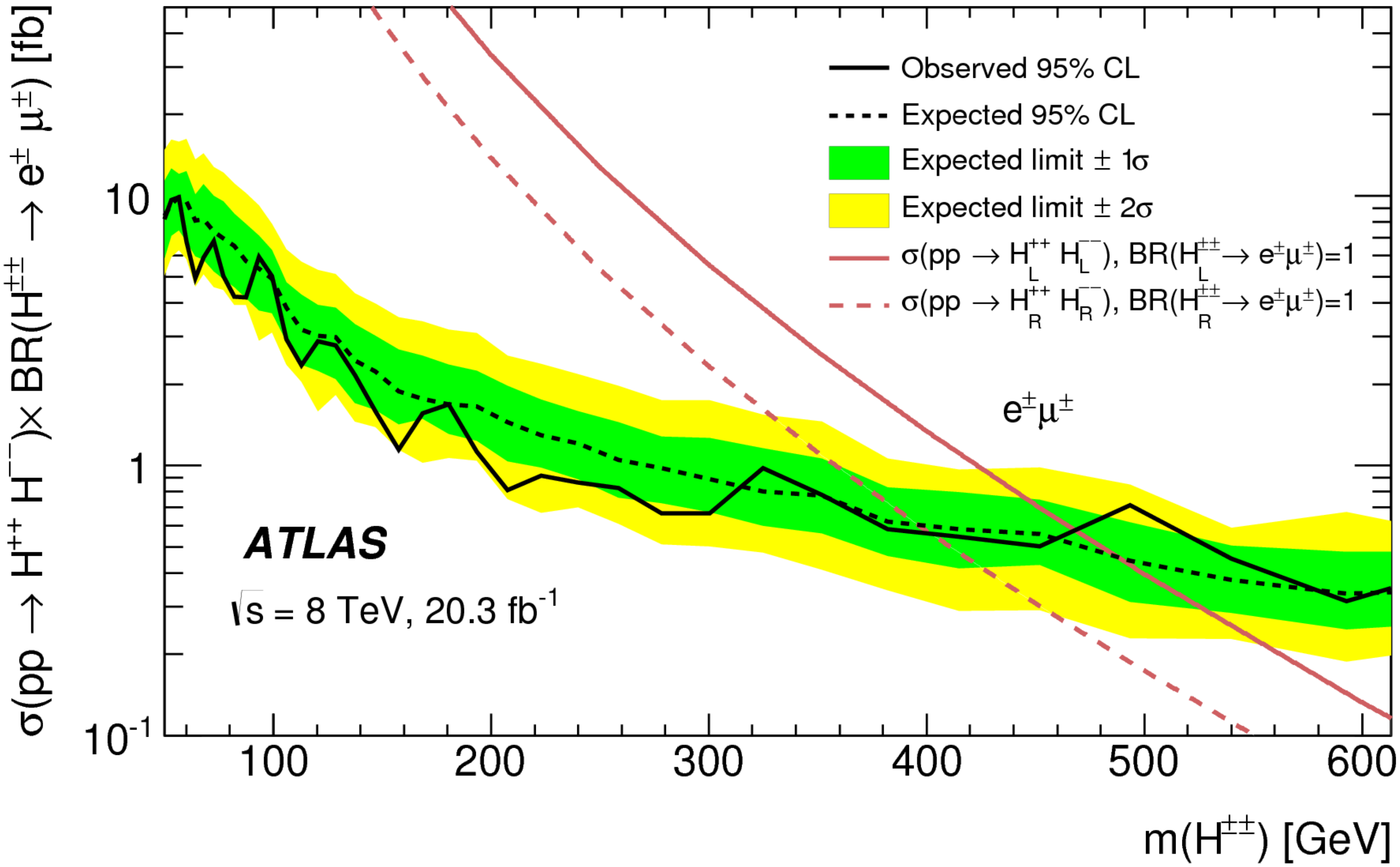
ATLAS(2014): Bounds on $m(\xi^{++})$ using $e\mu$, $\mu\mu$, and ee final states are about 490 to 550 GeV, assuming for each a 100% branching fraction.

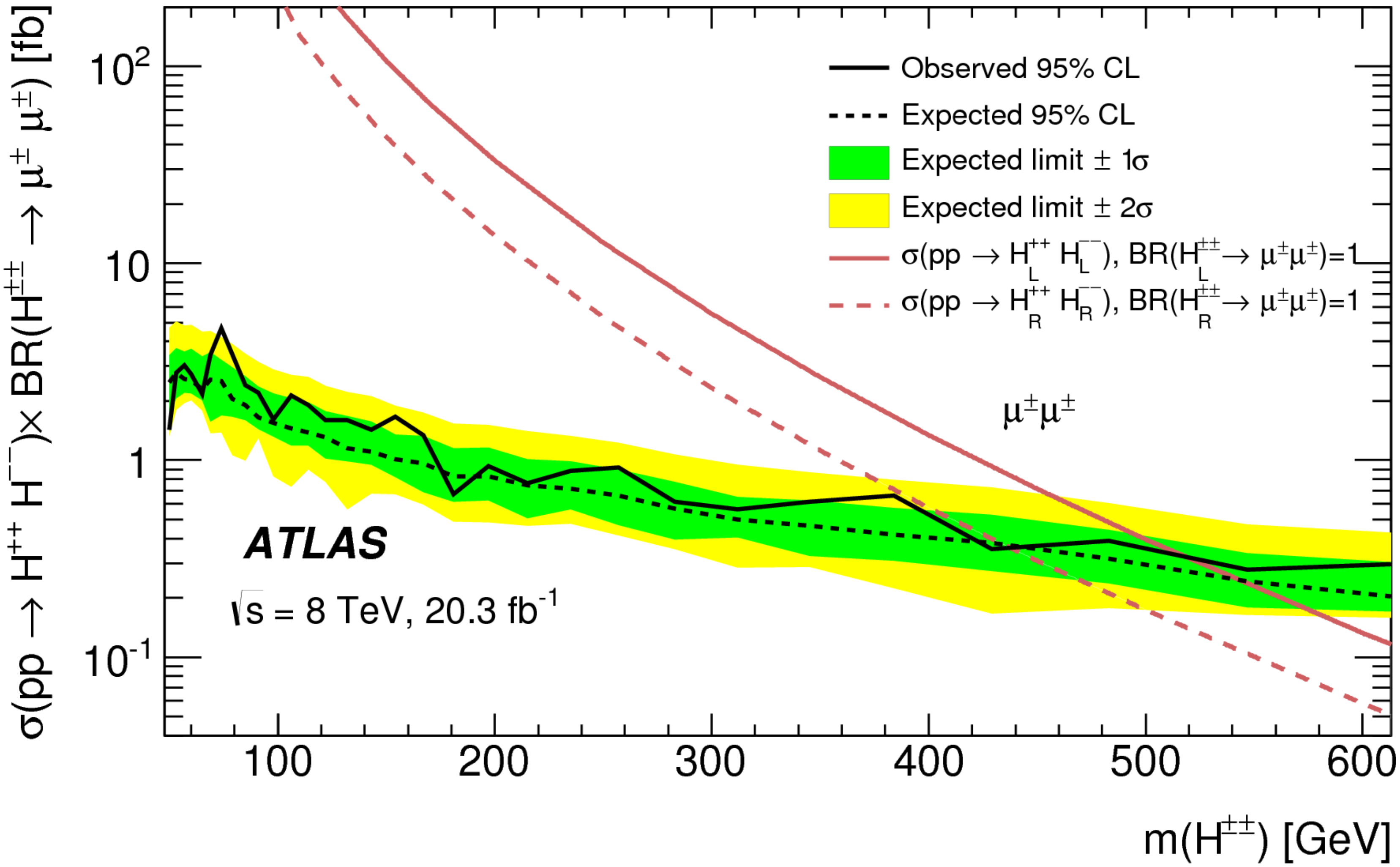
Kanemura/Kikuchi/Yagyu/Yokoya(2014):
If $\xi^{++} \to W^+ W^+$ is dominant, a bound may still be extracted from the ATLAS data, but it is only 84 GeV.

A dedicated search for the $W^+ W^+$ mode is recommended!



$\sigma(pp \to H^{++} H^{--}) \times BR(H^{\pm\pm} \to e^{\pm} e^{\pm})$ [fb]
10^2
10
1
10^{-1}
100
200
300
400
500
600
$m(H^{\pm\pm})$ [GeV]
Observed 95% CL
Expected 95% CL
Expected limit ± 1σ
Expected limit ± 2σ
$\sigma(pp \to H_L^{++} H_L^{--})$, $BR(H_L^{\pm\pm} \to e^{\pm}e^{\pm})=1$
$\sigma(pp \to H_R^{++} H_R^{--})$, $BR(H_R^{\pm\pm} \to e^{\pm}e^{\pm})=1$
$e^{\pm}e^{\pm}$
ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}


Observed 95% CL
Expected 95% CL
Expected limit ± 1σ
Expected limit ± 2σ
$\sigma(pp \to H_L^{++} H_L^{--})$, $BR(H_L^{\pm\pm} \to e^\pm\mu^\pm)=1$
$\sigma(pp \to H_R^{++} H_R^{--})$, $BR(H_R^{\pm\pm} \to e^\pm\mu^\pm)=1$
$e^\pm\mu^\pm$
ATLAS
$\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
$\sigma(pp \to H^{++} H^{--}) \times BR(H^{\pm\pm} \to e^\pm \mu^\pm)$ [fb]
10
1
10^{-1}
100
200
300
400
500
600
$m(H^{\pm\pm})$ [GeV]



Observed 95% CL
Expected 95% CL
Expected limit ± 1σ
Expected limit ± 2σ
σ(pp → H$_L^{++}$ H$_L^{--}$), BR(H$_L^{\pm\pm}$→ μ±μ±)=1
σ(pp → H$_R^{++}$ H$_R^{--}$), BR(H$_R^{\pm\pm}$→ μ±μ±)=1
μ±μ±
ATLAS
√s = 8 TeV, 20.3 fb^{-1}
σ(pp → H^{++} H^{--})× BR(H$^{\pm\pm}$ → μ± μ±) [fb]
10^2
10
1
10^{-1}
100
200
300
400
500
600
m(H$^{\pm\pm}$) [GeV]

As L is broken to $(-1)^L$, a conserved dark parity $(-1)^{L+2j}$ emerges, under which (N, E) and s are odd, whereas all other particles are even. Hence the lightest s with $m_s > 150$ GeV is a good dark matter candidate.

In fact, the three s scalars are the analogs of the three right-handed sneutrinos in supersymmetry, and $(N, E)_{L,R}$ are the analogs of the two higgsinos. However, their interactions are simpler here and less constrained.

From the $(s^* s)(\Phi^\dagger \Phi)$ interactions, electroweak baryogenesis is possible.

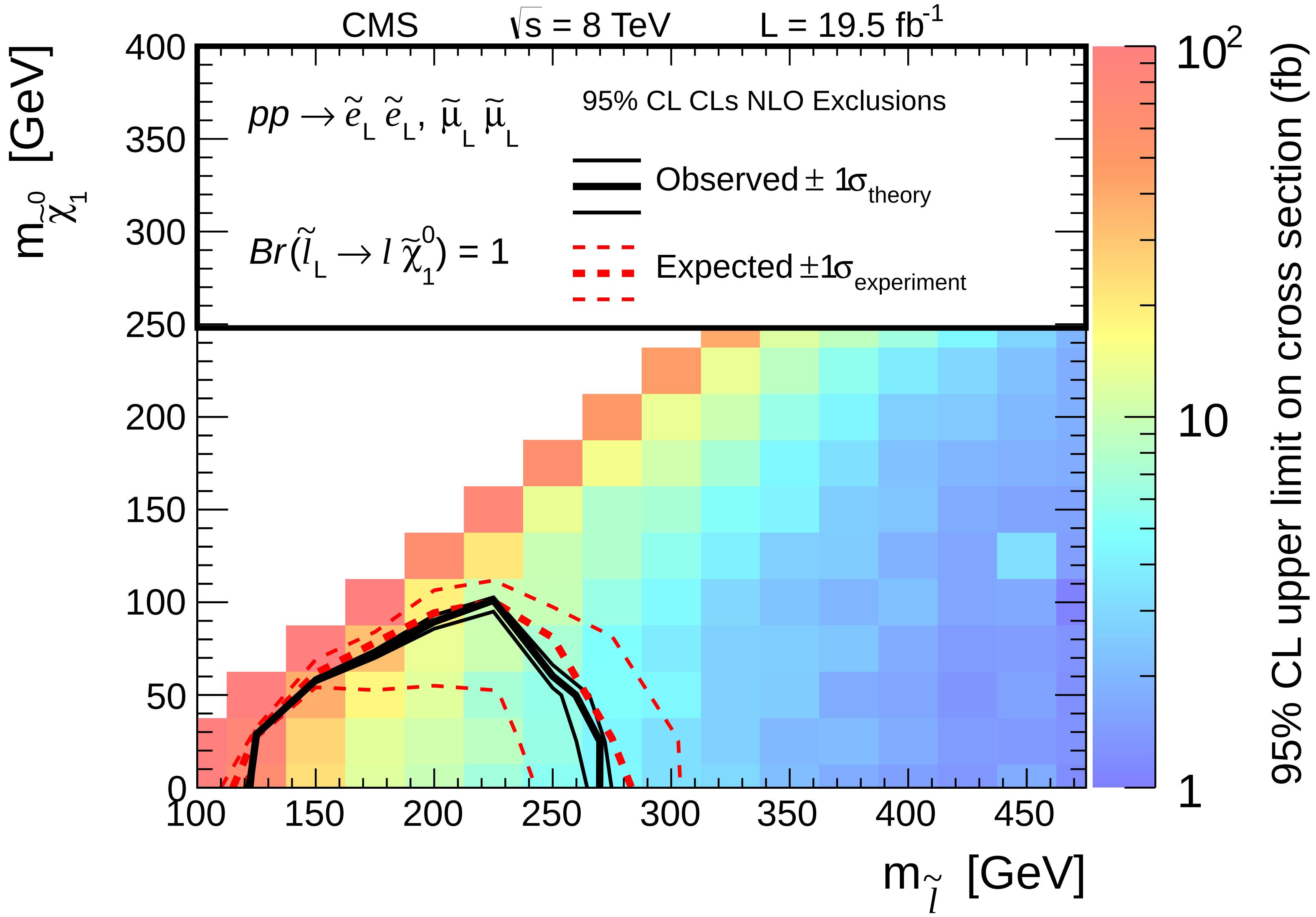
Whereas one s cannot be both dark matter and induce a first-order phase transition in the Higgs potential [Cline/Kainulainen(2013)], there are three complex singlets here with mass splitting between the real and imaginary parts.

The lightest one is dark matter. The others may have strong enough couplings with the Higgs boson to allow successful baryogenesis.

These large loop-induced deviations of the Higgs self couplings are important for diHiggs production at the LHC and a possible future Higgs factory.

If $m(\xi^{++}) > 2m_E$, then the decay channel $\xi^{++} \to E^+E^+$ opens up and will dominate. In that case, the subsequent decay $E^+ \to l^+s$, i.e. charged lepton plus missing energy, will be the signature. The present experimental limit on m_E, assuming electroweak pair production, is about 260 GeV, if $m_s < 100$ GeV for a 100% branching fraction to e or μ, and no limit if $m_s > 100$ GeV.

At a lower threshold, ξ^{++} may decay through a virtual E^+E^+ pair to ssl^+l^+, resulting in same-sign dileptons plus missing energy.



CMS
$\sqrt{s}$ = 8 TeV
L = 19.5 fb^{-1}
$pp \to \tilde{e}_L \tilde{e}_L, \tilde{\mu}_L \tilde{\mu}_L$
$Br(\tilde{l}_L \to l \tilde{\chi}^0_1) = 1$
95% CL CLs NLO Exclusions
Observed $\pm$ 1σ_{theory}
Expected $\pm$1$\sigma_{experiment}$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{l}}$ [GeV]
95% CL upper limit on cross section (fb)
0
50
100
150
200
250
300
350
400
100
150
200
250
300
350
400
450
1
10
10^2

The lepton number symmetry L may be promoted to the well-known $B-L$ gauge symmetry, but then three neutral singlet fermions N_R transforming as -1 under $U(1)_{B-L}$ are usually added to satisfy the anomaly-free conditions. This means that neutrinos obtain tree-level Dirac masses from the allowed term $\bar{\nu}_L N_R \bar{\phi}^0$, and Type II seesaw would not be necessary.

Montero/Pleitez(2009), Ma/Srivastava(2015):
Use instead $-4-4+5=-3$ and $-64-64+125=-3$ for anomaly cancellation, then $\bar{\nu}_L N_R \bar{\phi}^0$ is forbidden, and the radiative mechanism holds.

The Z_{B-L} boson couples to $s^*\partial s - s\partial s^*$, and through the subsequent decays of heavier s states to lighter ones, i.e. $s_i \to l_i^\pm E^\mp \to l_i^\pm l_j^\mp + s_j$ and eventually to the dark matter particle, there will be a variety of final states consisting of missing energy and n dileptons of different flavor. This would be a very distinctive signature at the LHC, as well as any future e^+e^- collider. Since Z_{B-L} has large gauge couplings to the neutral singlet fermions transforming as $(-4,-4,5)$, which may also be stable (realizing the notion of multipartite dark matter), it may have a very large invisible decay width.

Z_3 Flavor Symmetry

To obtain a desirable pattern for the neutrino mass matrix, a discrete symmetry is often employed. Ma(2002), Babu/Ma/Valle(2003), Grimus/Lavoura(2004):

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

where A, B are real, implies $\theta_{13} \neq 0$, $\theta_{23} = \pi/4$, and $\delta_{CP} = \pm\pi/2$. The symmetry is $\mu \leftrightarrow \tau$ exchange with CP

conjugation. Its predictions are consistent with present experimental data:

$$\sin^2(2\theta_{23}) = 0.999 \begin{pmatrix} +0.001 \\ -0.018 \end{pmatrix}, \quad \text{(normal ordering)},$$

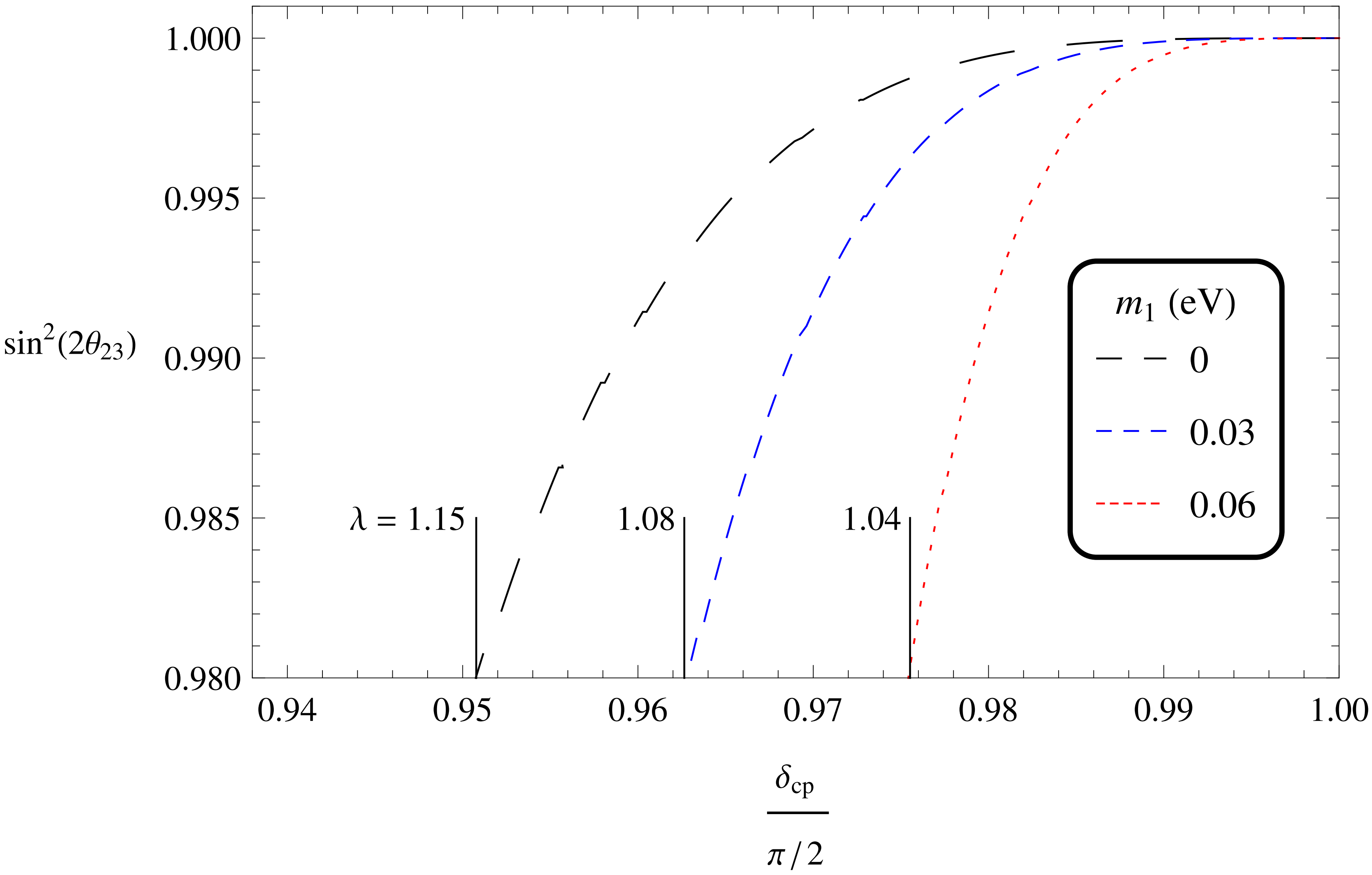
$$\sin^2(2\theta_{23}) = 1.000 \begin{pmatrix} +0.000 \\ -0.017 \end{pmatrix}, \quad \text{(inverted ordering)}.$$

Fraser/Ma/Popov(2014):
Impose Z_3 flavor symmetry where
$(\nu_i, l_i)_L \sim \underline{1}, \underline{1}', \underline{1}''$, $l_{iR} \sim \underline{1}, \underline{1}', \underline{1}''$, $s_1 \sim \underline{1}$,

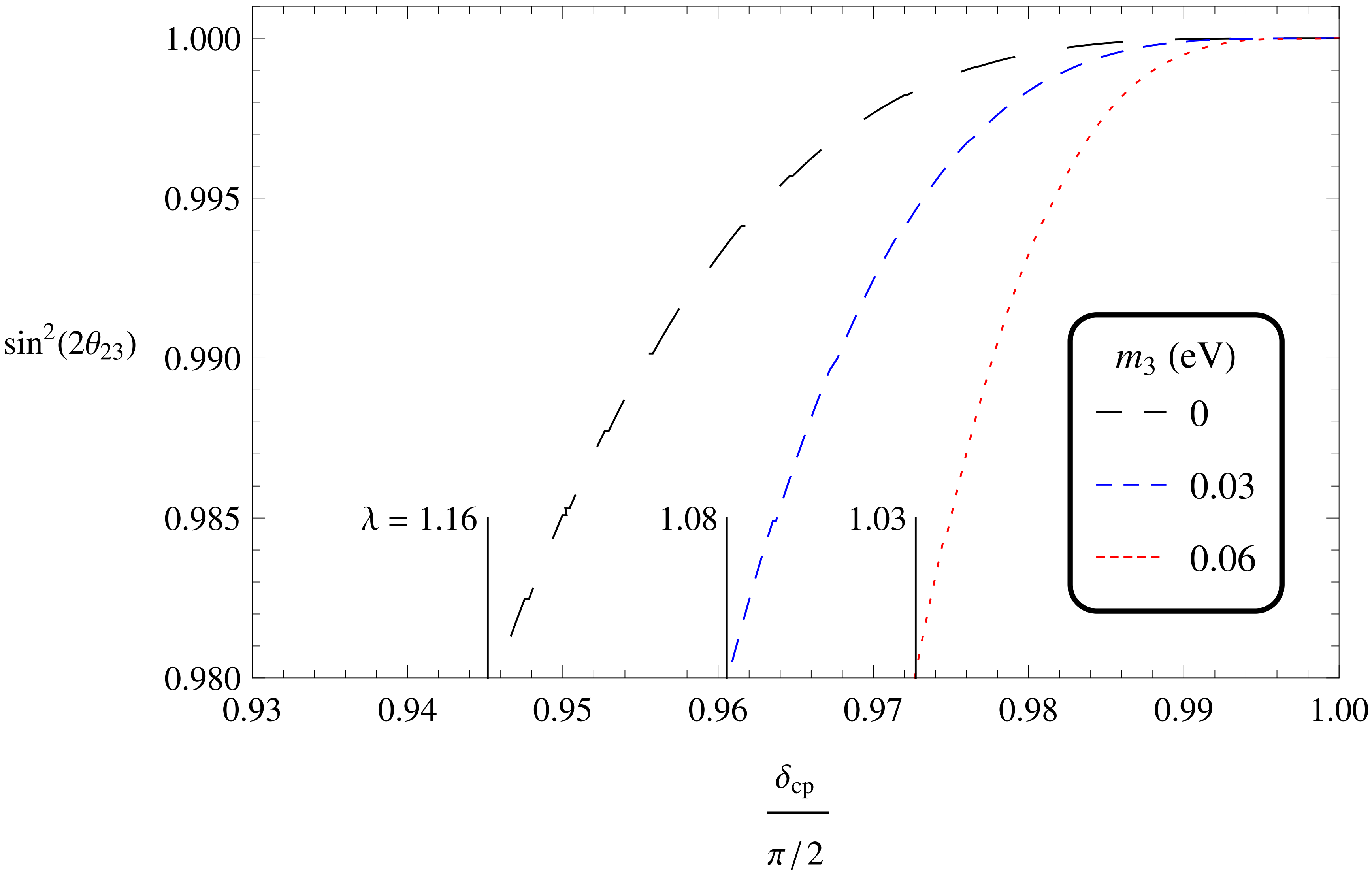
$(s_2 + is_3)/\sqrt{2} \sim \underline{1}'$, $(s_2 - is_3)/\sqrt{2} \sim \underline{1}''$, then the charged-lepton mass matrix is diagonal, and the one-loop induced neutrino mass matrix with real s scalars has the desirable form if $f_\mu = f_\tau$, allowing for arbitrary soft breaking of Z_3 with the $s_i s_j$ mass-squared terms.

Here $s_{1,2,3}$ are complex fields, but if the soft breaking terms $m^2_{ij} s_i s_j + H.c.$ have only real coefficients, then the same $\mathcal{M}_\nu$ is obtained.

Ma/Natale/Popov(2015):
If $f_\tau / f_\mu \neq 1$, then deviations from $\sin^2(2\theta_{23}) = 1$ and $\delta_{CP} = \pm\pi/2$ are predicted.



$\sin^2(2\theta_{23})$
1.000
0.995
0.990
0.985
0.980
0.94
0.95
0.96
0.97
0.98
0.99
1.00
$\frac{\delta_{cp}}{\pi/2}$
λ = 1.15
1.08
1.04
m_1 (eV)
0
0.03
0.06


sin$^2(2\theta_{23})$
1.000
0.995
0.990
0.985
0.980
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1.00
$\frac{\delta_{cp}}{\pi/2}$
λ = 1.16
1.08
1.03
m_3 (eV)
0
0.03
0.06

Conclusion

The notion that neutrino mass is radiatively induced by dark matter is a powerful indication of the scale of new physics, i.e. 1 TeV. Several examples already exist. A new radiative Type II seesaw mechanism is proposed with interesting predictions, such as $\xi^{++} \to W^+W^+$. It may have an underlying $B-L$ gauge symmetry, in which case the discovery of a Z_{B-L} boson at the LHC with unusual decay modes would be the key. A Z_3 flavor symmetry also fits well into this framework. Its soft breaking results in a testable pattern of neutrino mixing.