ν-tral Naturalness

Brian Batell
CERN

with Matthew McCullough - arXiv:1504.04016

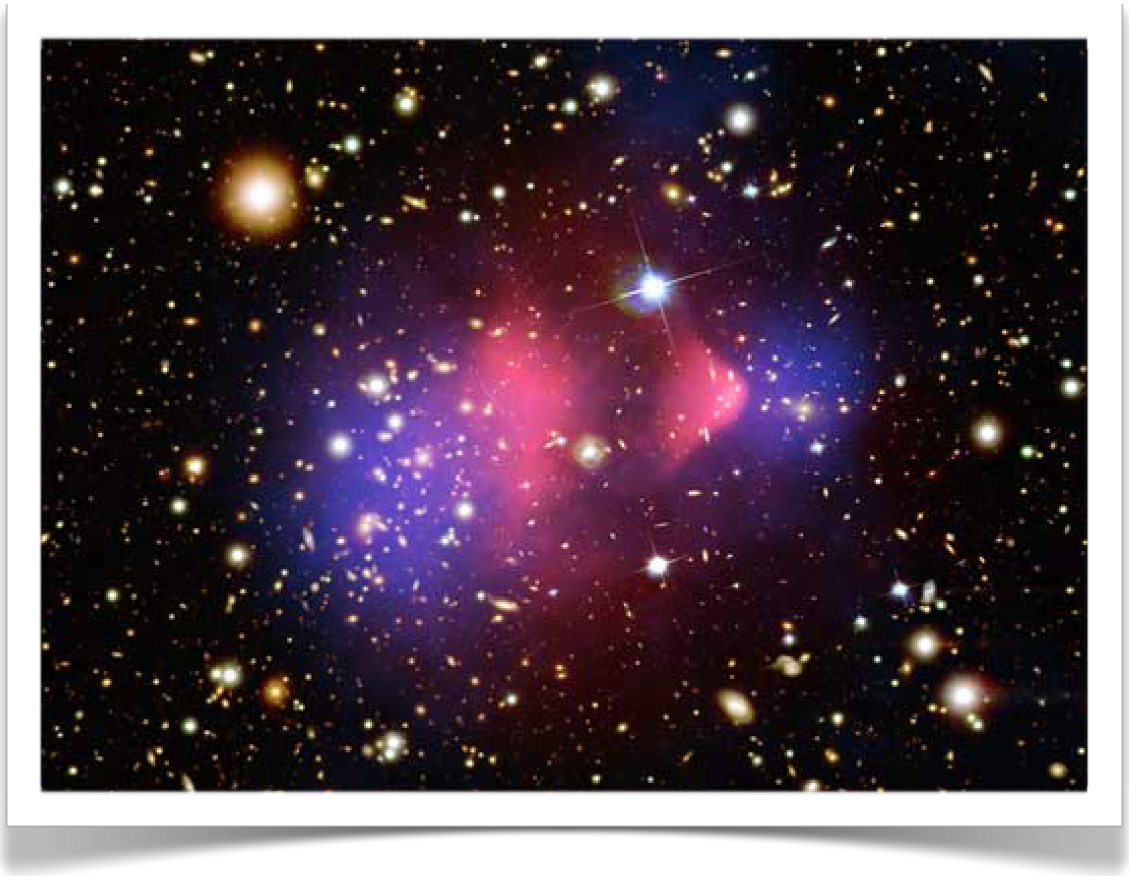
CERN-CKC TH Institute on Neutral Naturalness
April 23-26, 2015

Neutral Naturalness predicts new ***neutral*** particles

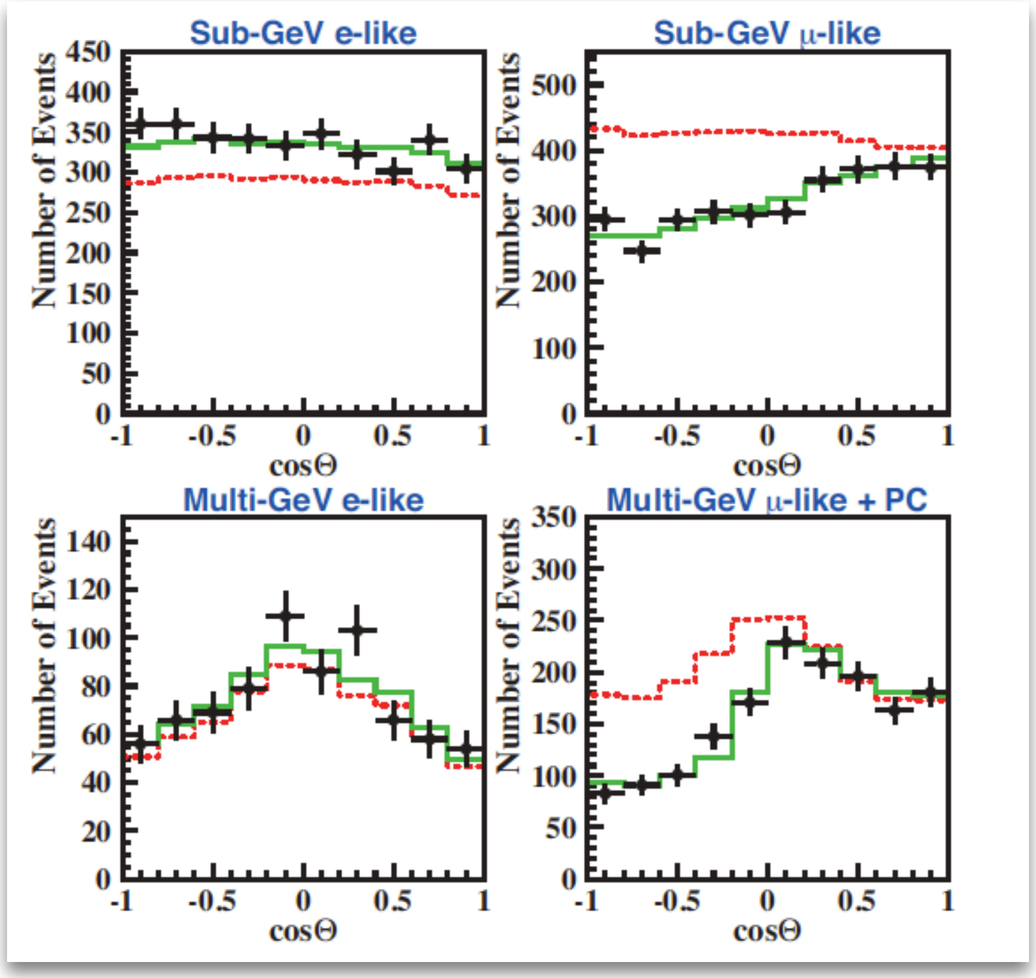
At the very least, there are neutral top partners

There are compelling empirical hints for new ***neutral*** particles in Nature!

Dark Matter



Neutrino Mass

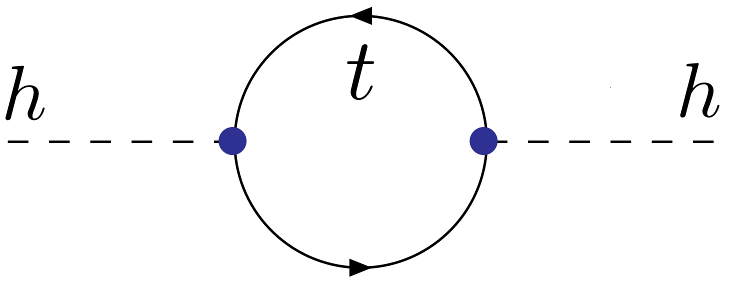


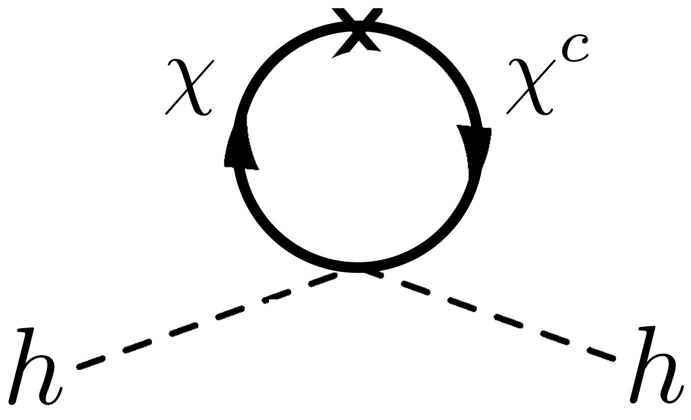
Can the new ***neutral*** states responsible for naturalness explain these empirical mysteries?

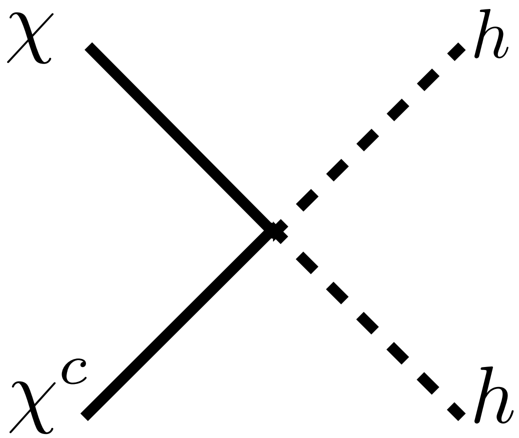
The Dark Top

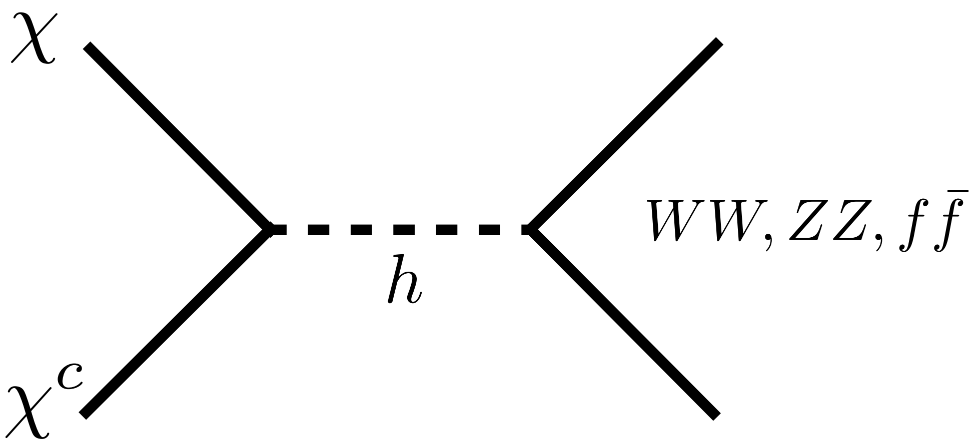
Poland, Thaler

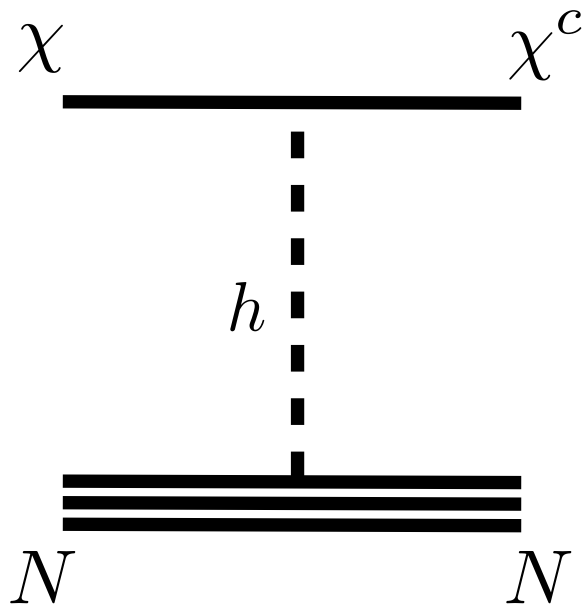
Naturalness











Annihilation

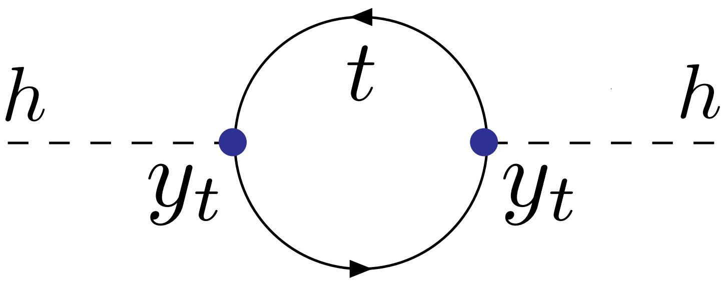
Scattering

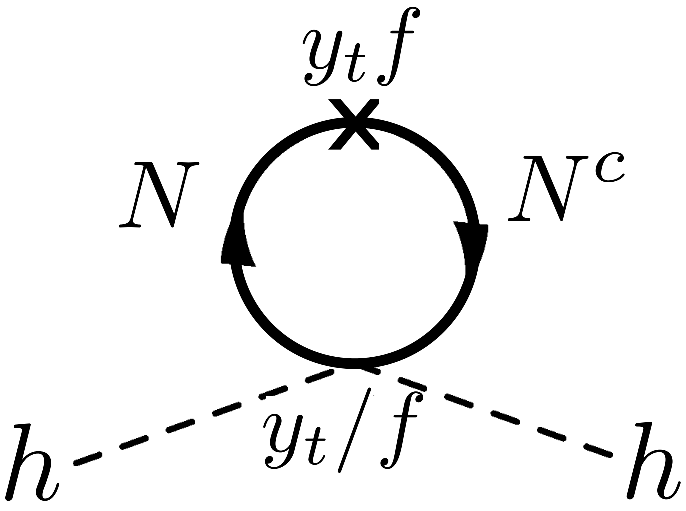
Natural Neutrinos

BB, McCullough

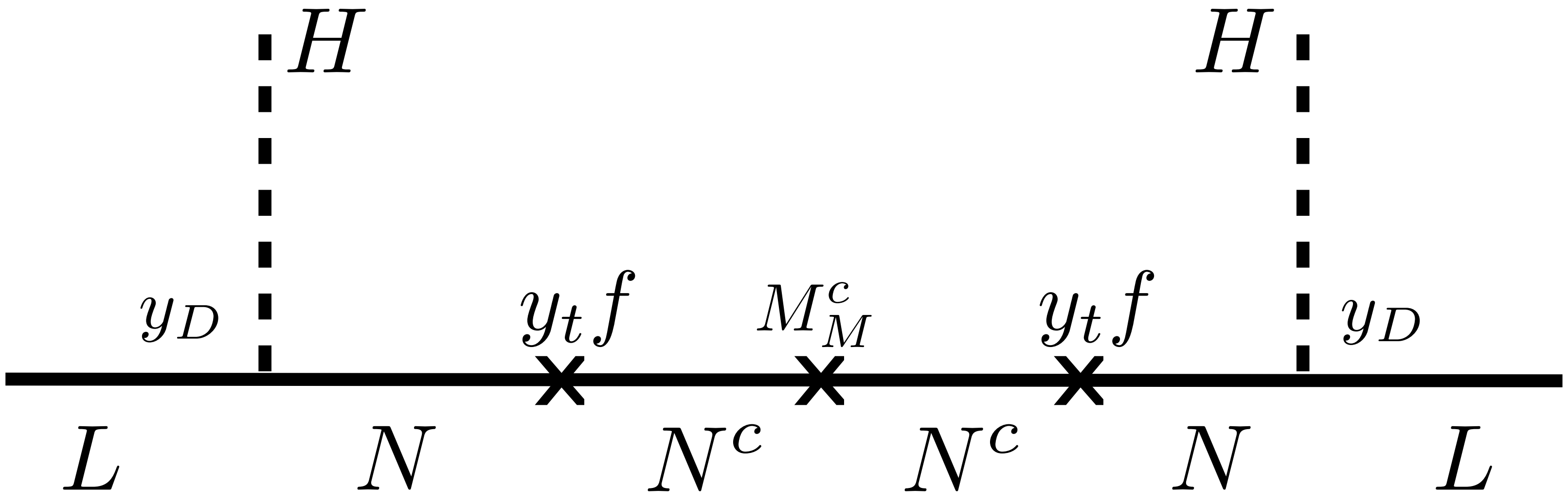
Right Handed Neutrinos are the Top Partners

Naturalness





See-saw



General aspects of Natural Neutrinos

- Higgs is a pseudo-Nambu-Goldstone boson of G/H coset
- Color enlarged to $SU(3) \times SU(3) \times Z_2$ or $SU(6)$
- Identify new $SU(3)$ factor as the flavor symmetry $SU(3)_N$ of RHN
- To generate neutrino masses $SU(3)_N$ must be broken at low energies
- Naturalness robustly predicts a TeV-scale see-saw
- Collective breaking of Lepton number - large neutrino Yukawa allowed
- Naturalness - connects number of colors to number of RHNs

A “simplified model” of Natural Neutrinos

- pNGB Higgs described by non-linear-sigma field

$$\Sigma = e^{i\Pi/f}\Sigma_0, \quad \Pi = \pi^a T^a, \quad \langle \Sigma_0 \rangle = f \sim \text{TeV}$$

- 3rd generation quarks and RHN top partner embedded in *G* multiplet

$$Q \supset (q, N), \quad Q^c \supset (t^c, N^c)$$

- Top Yukawa coupling

$$\begin{aligned} \mathcal{L} &= \lambda_t Q \Sigma Q^c + \text{h.c.} \\ &= \lambda_t \left[q^A h t^c_A + f\left(1 - \frac{h^\dagger h}{2f^2}\right) N^i N^c_i + \ldots \right] + \text{h.c.}, \end{aligned}$$

Coupling structure enforces cancellation of Λ^2

- RHN mass (Dirac) - $M_N = \lambda_t f + \mathcal{O}(v^2/f^2)$ ~ TeV

Tuning from top and RHN loop (standard story...):

- Correction to Higgs mass:

$$\delta\mu^2 = -\underbrace{\frac{3\lambda_t^2}{8\pi^2}}_{\text{top loop}}\Lambda^2 \rightarrow -\frac{3\lambda_t^2}{8\pi^2}\underbrace{m_N^2 \log}_{\text{top+RHN loops}}\frac{\Lambda^2}{m_N^2}$$

$$m_N \sim \lambda_t f \ll \Lambda$$

RHN mass

- Naive estimate of tuning:

$$\Delta^{-1} = \left|\frac{2\delta\mu^2}{m_h^2}\right|^{-1}$$

➡

This is order 10% for

$$f = 700\ \mathrm{GeV}, \quad \Lambda = 5\ \mathrm{TeV}$$

(unregulated top loop
gives ~ 1% tuning)

Breaking of $SU(3)_N$

- If $SU(3)_N$ is unbroken, neutrino mass is forbidden

➡ Must be explicitly broken global or
spontaneously broken gauge symmetry

- 2 loop top-gluon contribution to tuning:

$$\delta\mu^2 = \frac{3y_t^2 g_3^2}{4\pi^4}\Lambda^2$$

This is order 10% for $\Lambda \sim 5\,\mathrm{TeV}$

- Running of top-Higgs and RHN-Higgs couplings RG evolve differently
  - Gives parametrically/numerically similar contribution to 2 loop gluon above

Craig, Katz, Strassler, Sundrum

- Alternatively, we can gauge $SU(3)_N$ and spontaneously break at a scale $M_{V_N} \sim f$ which will further reduce tuning

Neutrino masses

- There are 6 new singlet Weyl-fermions: $N_i, N_i^c, \quad i = 1, 2, 3$

- There is one $SU(3)_N$ invariant mass term coming from top Yukawa:

$$\mathcal{L} \supset M_N N N^c + \text{h.c.}, \qquad M_N = \lambda_t f + \mathcal{O}(v^2/f)$$

- We now explicitly break $SU(3)_N$ - most general renormalizable terms:

$$\mathcal{L} \supset y_D L H N + y_D^c L H N^c + \frac{1}{2} M_M N N + \frac{1}{2} M_M^c N^c N^c + \text{h.c.}$$

See-saw

- In the basis $(\nu \; N \; N^c)$ the neutrino mass matrix is

$$\mathcal{M} = \begin{pmatrix} 0 & M_D & M_D^c \\ M_D^T & M_M & \hat{M}_N \\ M_D^{cT} & \hat{M}_N^T & M_M^c \end{pmatrix}$$

- Determinant:

$$|\mathcal{M}| \sim M_D(M_M^c M_D - M_N M_D^c) + M_D^c(M_D^c M_M - M_N M_D)$$

- At least two of couplings must be non-zero to generate neutrino mass - collective breaking of lepton number

Non-zero mass-terms	Approximate neutrino masses
M_D, M_D^c	$\sim M_D M_D^c / M_N$
M_D, M_M^c	$\sim M_D^2 M_M^c / M_N^2$
M_M, M_D^c	$\sim {M_D^c}^2 M_M / M_N^2$

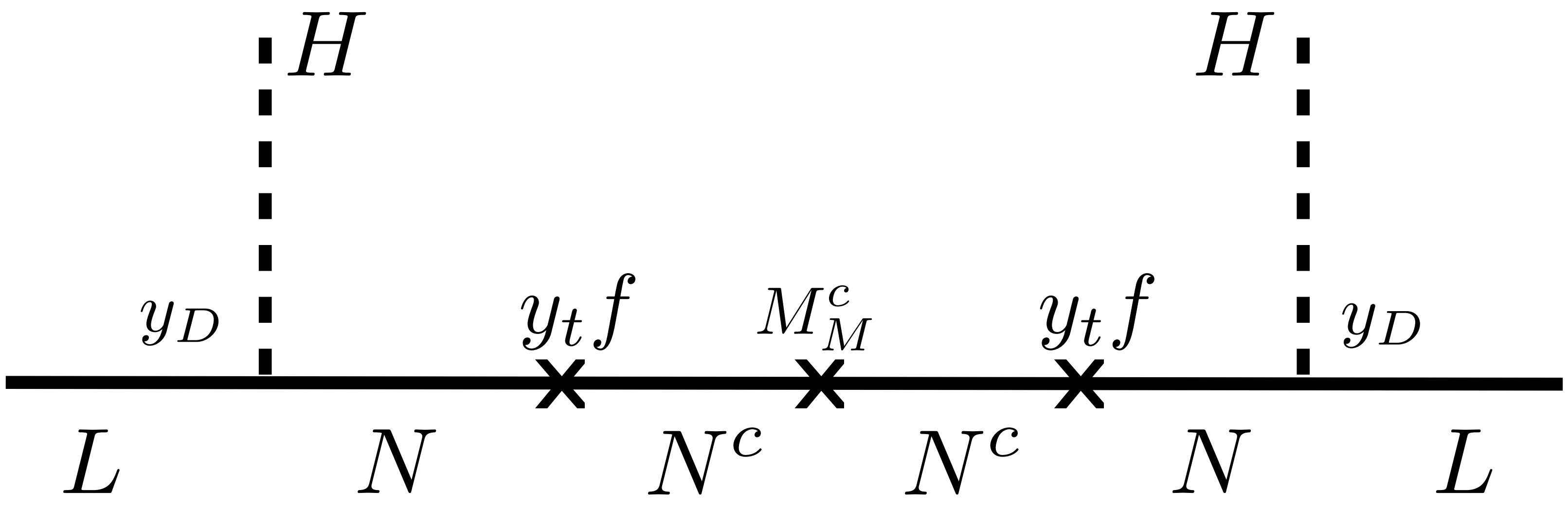
} Linear seesaw

Malinsky, Romao, Valle

} Inverse seesaw

Mohapatra, Valle

Example: inverse seesaw



$$m_\nu \sim \frac{y_D^2\, v^2\, M_M^c}{M_N^2}$$

➡ Both y_D and M_M^c must be non-zero

- y_D can be large, novel phenomenological consequences ...
- y_D shouldn't be too large, Naturalness suggests $y_D \lesssim \mathcal{O}(0.1)$
- Majorana mass softly breaks the global symmetry, should be less than about $f \sim \mathrm{TeV}$

Model 1: $G/H = SU(6) \times SU(3)/SU(2)$

- Same structure as the Dark Top

Poland, Thaler

- Symmetry breaking $SU(3)/SU(2)$ yields 8-3 = 5 pNGBs (ignore singlet)

$$\Sigma_0^T = (0,0,f) \qquad \Pi = \pi^a T^a = \begin{pmatrix} 0 & 0 & h_1 \\ 0 & 0 & h_2 \\ h_1^\dagger & h_2^\dagger & 0 \end{pmatrix} + \dots, \qquad \Sigma = \begin{pmatrix} ih_1 \dfrac{\sin(|h|/f)}{|h|/f} \\ ih_2 \dfrac{\sin(|h|/f)}{|h|/f} \\ f\cos(|h|/f) \end{pmatrix}$$

- Top, neutrino embeddings:

$$Q \sim (\mathbf{6}, \bar{\mathbf{3}}) \sim \begin{pmatrix} q & 0 \\ 0 & N \end{pmatrix} \qquad Q^c \sim (\bar{\mathbf{6}}, \mathbf{1}) \sim \begin{pmatrix} t^c & N^c \end{pmatrix}$$

- Top Yukawa

$$\begin{aligned} \mathcal{L} &= \lambda_t Q \Sigma Q^c + \text{h.c.} \\ &= \lambda_t \left[q^A h t^c_A + f\left(1 - \frac{h^\dagger h}{2f^2}\right) N^i N^c_i + \dots \right] + \text{h.c.}, \end{aligned}$$

Same structure as simplified model

Model **2**: $G/H = SU(6)\times SO(5)/SO(4)$

$$SO\underbrace{(5)/SO}_{}(4)$$

Preserves custodial symmetry

Agashe, Contino, Pomarol

- Symmetry breaking $SO(5)/SO(4)$ yields 10-6 = 4 pNGBs

$$\Sigma = \Sigma_0 e^{-i\Pi/f}, \quad \Pi = \sqrt{2} h^a T^a$$

$$\Sigma_0 = (0,0,0,0,f)$$

$$\Sigma = \frac{\sin|h|/f}{|h|/f}\begin{pmatrix} h_1 \\ h_2 \\ h_3 \\ h_4 \\ |h|\cot|h|/f \end{pmatrix}$$

- Top, neutrino embeddings:

$$Q \sim (\mathbf{6},\mathbf{5}) = \frac{1}{\sqrt{2}}\begin{pmatrix} b & -ib & t & it & 0 \\ \mathcal{E} & i\mathcal{E} & \mathcal{N} & i\mathcal{N} & \sqrt{2}N \end{pmatrix} \qquad Q^c \sim (\bar{\mathbf{6}},\bar{\mathbf{1}}) \sim \begin{pmatrix} t^c & N^c \end{pmatrix}$$

- Top Yukawa

$$\begin{aligned} \mathcal{L} &\supset \lambda_t Q\Sigma Q^c + \text{h.c.} \\ &= \lambda_t\left[q^A h t^c_A + \underbrace{L^i h^\dagger}_{} N^c_i + f\left(1-\frac{h^\dagger h}{f^2}\right) N^i N^c_i + \ldots\right] + \text{h.c.} \end{aligned}$$

New electroweak doublet $L^T = (\mathcal{N},\mathcal{E})$

Model 3: $G/H = SU(6) \times SU(4)/SU(3)$

- This is just the Twin Higgs Chacko, Goh, Harnik ’05
- Symmetry breaking $SU(4)/SU(3)$ yields 15-8 = 7 pNGBs

$$\Sigma_0 = (0,0,0,f) \qquad \Pi = \pi^a T^a = \begin{pmatrix} 0 & 0 & 0 & h_1 \\ 0 & 0 & 0 & h_2 \\ 0 & 0 & 0 & 0 \\ h_1^\dagger & h_2^\dagger & 0 & 0 \end{pmatrix} + \ldots, \qquad \Sigma = \begin{pmatrix} ih_1 \dfrac{\sin(|h|/f)}{|h|/f} \\ ih_2 \dfrac{\sin(|h|/f)}{|h|/f} \\ 0 \\ f\cos(|h|/f) \end{pmatrix}$$

- Top, neutrino embeddings:

$$Q^c \sim (\mathbf{6}, \bar{\mathbf{4}}) \sim \begin{pmatrix} q & 0 \\ 0 & N \end{pmatrix} \qquad Q^c \sim (\bar{\mathbf{6}}, \mathbf{1}) \sim \begin{pmatrix} t^c & N^c \end{pmatrix}$$

- Top Yukawa

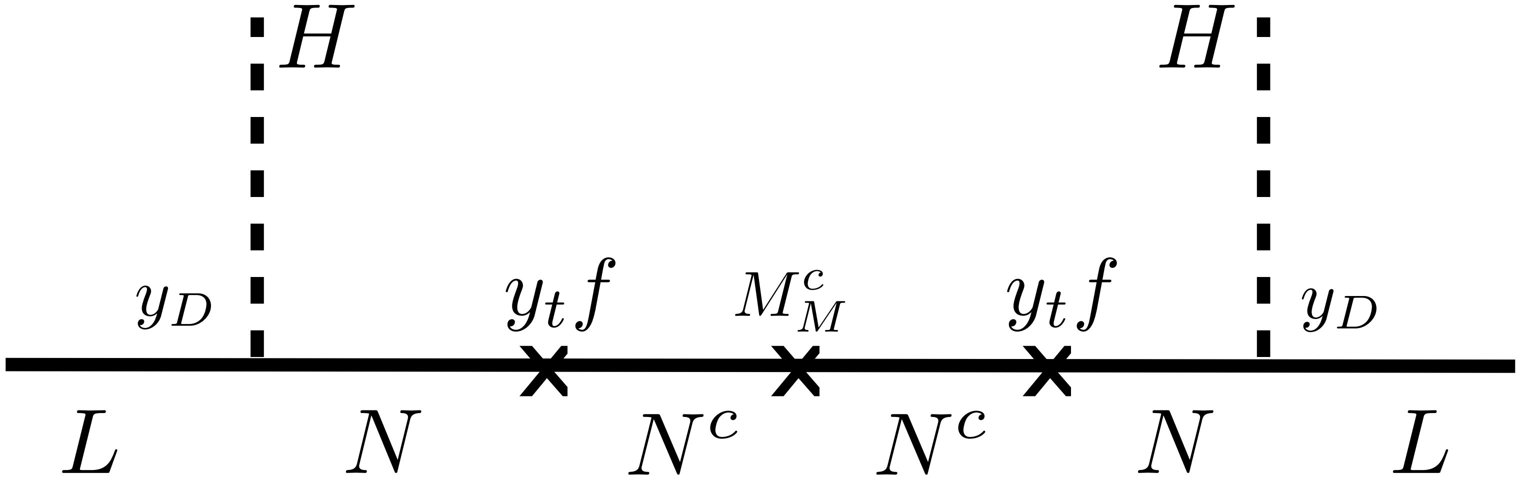
$$\begin{aligned} \mathcal{L} &= \lambda_t Q \Sigma Q^c + \text{h.c.} \\ &= \lambda_t \left[i q^A h t^c_A + f \left(1 - \frac{h^\dagger h}{2f^2} \right) N^i N^c_i + \ldots \right] + \text{h.c.}, \end{aligned}$$

Same structure as
simplified model

Neutrino masses

- Let us restrict to the case of the "inverse" seesaw

$$\mathcal{M} = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_N \\ 0 & M_N^T & M_M^c \end{pmatrix}$$



- For one generation, we have

$$m_\nu \approx \frac{M_D^2 M_M^c}{M_N^2},$$

Collective breaking of Lepton Number

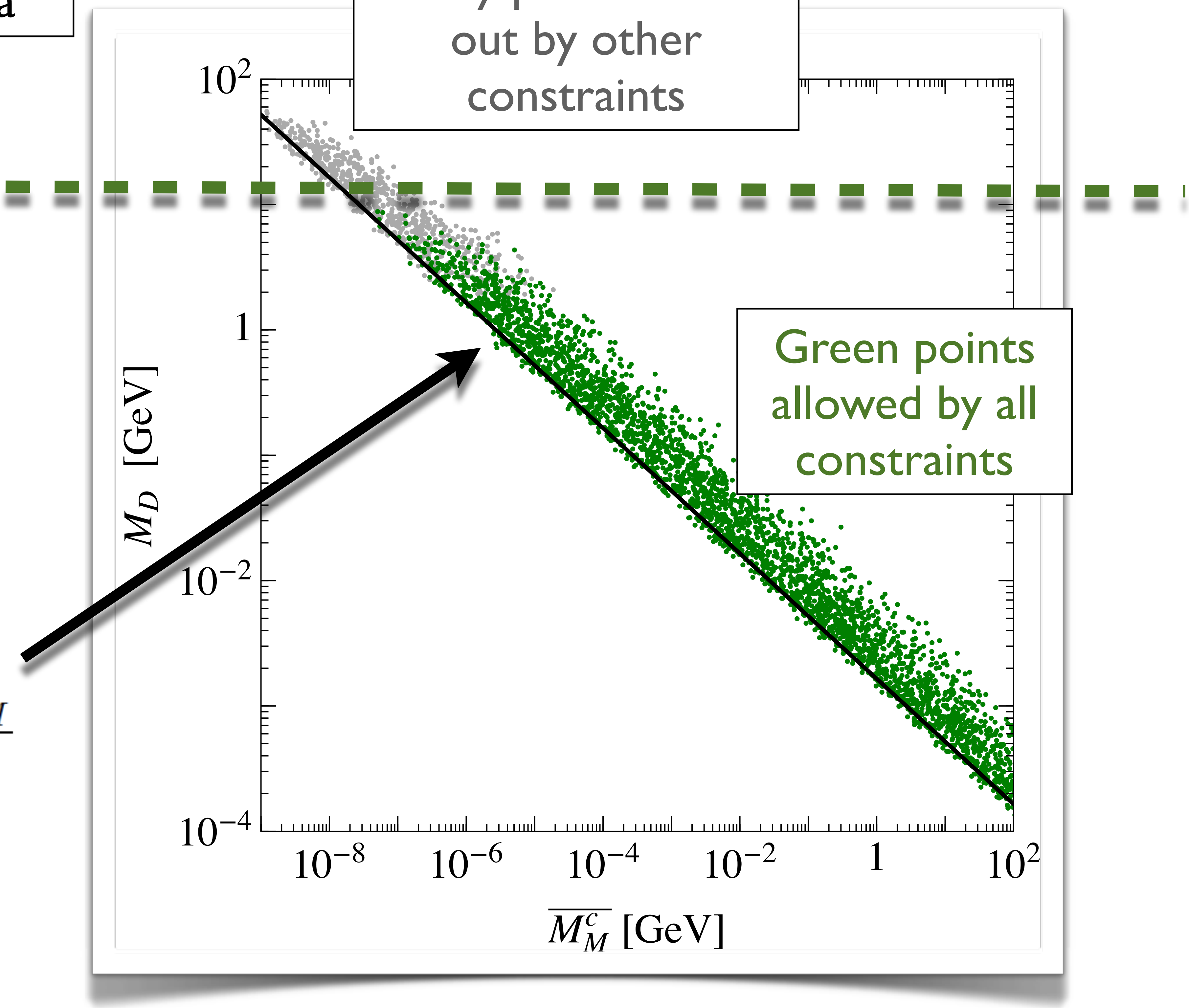
$$m_{N,\pm} \approx \pm\left(M_N + \frac{M_D^2}{2M_N}\right) + \frac{M_M^c}{2},$$

Pseudo-Dirac Fermions,
split by Majorana mass

- The light neutrino mass matrix is given by

$$\mathcal{M}_\nu \simeq M_D^T M_N^{-1} M_M^c M_N^{-1} M_D.$$

All points
reproduce neutrino
oscillation data



Gray points ruled
out by other
constraints

Green points
allowed by all
constraints

$$m_\nu \approx \frac{M_D^2 M_M^c}{M_N^2}$$

Non-unitarity of the PMNS matrix

$$\nu_i = \underbrace{(\nu \quad N \quad N^c)_i}_{\text{Gauge eigenstates}} \xrightarrow[\text{Unitary Transformation}]{} \hat{\nu}_i = \underbrace{(\nu_{\text{light}} \quad N_{\text{heavy}})_i}_{\text{Mass eigenstates}}$$

- Diagonalize:

$$\nu_i = U_{ij}\hat{\nu}_j \qquad \text{where } U \text{ is a unitary matrix}$$

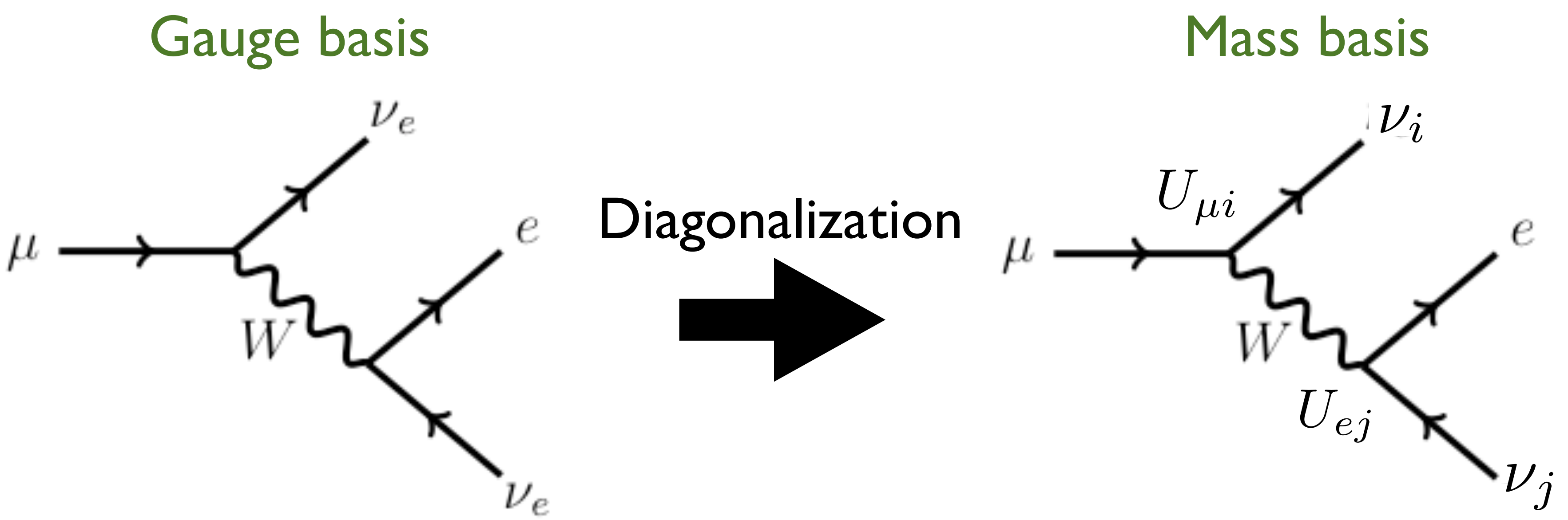
- However, the 3x3 sub-matrix, $\tilde{U}$, describing the light neutrino mixing is no longer unitary (especially if Dirac Yukawas are large):

$$\tilde{U}\tilde{U}^\dagger \neq \mathbf{1}$$

- This violation of unitarity in the PMNS matrix can show up in a host of precision experiments...

PMNS non-unitarity

- Example- Fermi Constant (determined from muon lifetime measurement)



Gauge basis

Mass basis

Diagonalization

$$\frac{\hbar}{\tau_\mu} = \frac{G_\mu^2 m_\mu^5}{192\pi^3} F(\rho) \left[1 + H_1(\rho) \frac{\widehat{\alpha}(m_\mu)}{\pi} + H_2(\rho) \frac{\widehat{\alpha}^2(m_\mu)}{\pi^2} \right]$$

- If PMNS is non-unitary, the prediction is modified:

$$G_\mu^2 = G_F^2 (\widetilde{U}\widetilde{U}^\dagger)_{\mu\mu} (\widetilde{U}\widetilde{U}^\dagger)_{ee} \qquad (\tilde{U}\tilde{U}^\dagger)_{\mu\mu}, (\tilde{U}\tilde{U}^\dagger)_{ee} \neq 1$$

PMNS non-unitarity affects numerous weak interaction observables:

- W, Z boson decays (including invisible Z width)
- Z-pole asymmetries
- W-boson mass
- Weak mixing angle measurements
- Lepton flavor universality tests (W, tau-lepton and meson decays)
- Lepton Flavor violating decays (see next slide)
- Quark Flavor CKM parameters

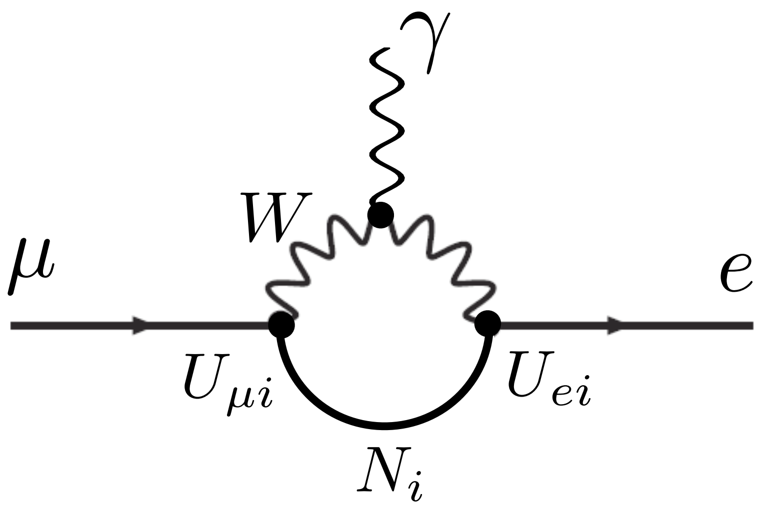
We apply the following constraints from a recent global fit:

Antusch, Fischer ’14

$$\boxed{\begin{aligned} 1-(UU^\dagger)_{ee} &< 0.0018, \\ 1-(UU^\dagger)_{\mu\mu} &< 0.0007, \\ 1-(UU^\dagger)_{\tau\tau} &< 0.005, \end{aligned}}$$

Lepton Flavour Violation

- Large Yukawa couplings possible in Inverse or Linear Seesaw can enhance LFV processes
  - e.g. $\mu \to e\gamma$:



$$\mathrm{Br}(\mu \to e\gamma) = \frac{\alpha_W^3 s_W^2}{256\pi^2} \frac{m_\mu^5}{m_W^4 \Gamma_\mu} \left| \sum_{i=1}^{9} U_{\mu i} U_{ei}^* G\left(\frac{m_{N,i}^2}{m_W^2}\right) \right|^2$$

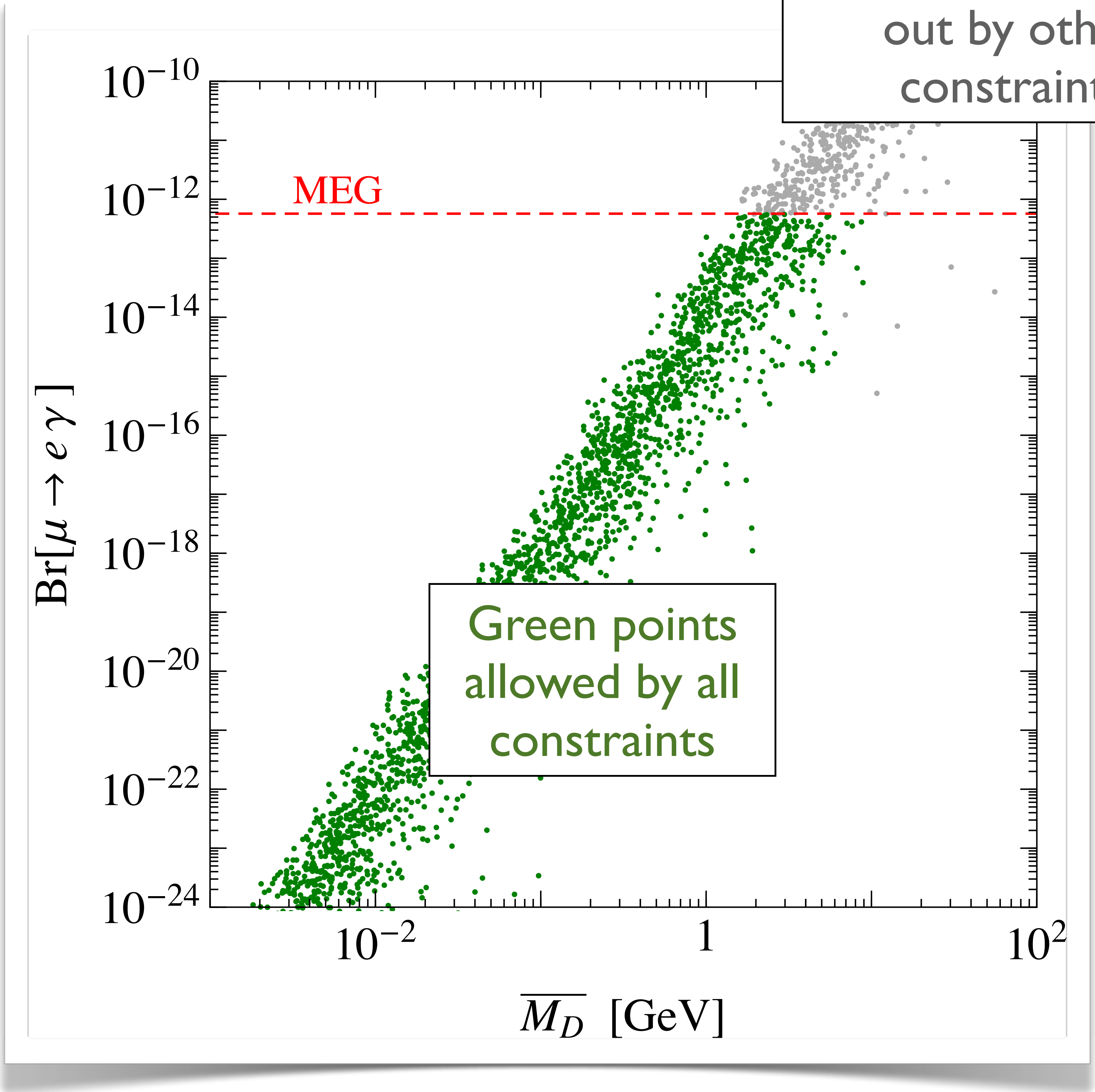
- Strong constraints from MEG experiment

$$\mathrm{Br}(\mu \to e\gamma)_{\mathrm{MEG}} < 5.7 \times 10^{-13}$$

- Potentially exciting prospects in future LFV experiments

e.g., Mu2E, Mu3e, MEG-II, COMET, DeeMee, Prism, Belle-II

All points reproduce neutrino oscillation data



Gray points ruled out by other constraints

Green points allowed by all constraints

Signals of the RHN at LHC and future colliders

- Decays of RHN proceed through Yukawa couplings - signatures include leptons, MET, & jets

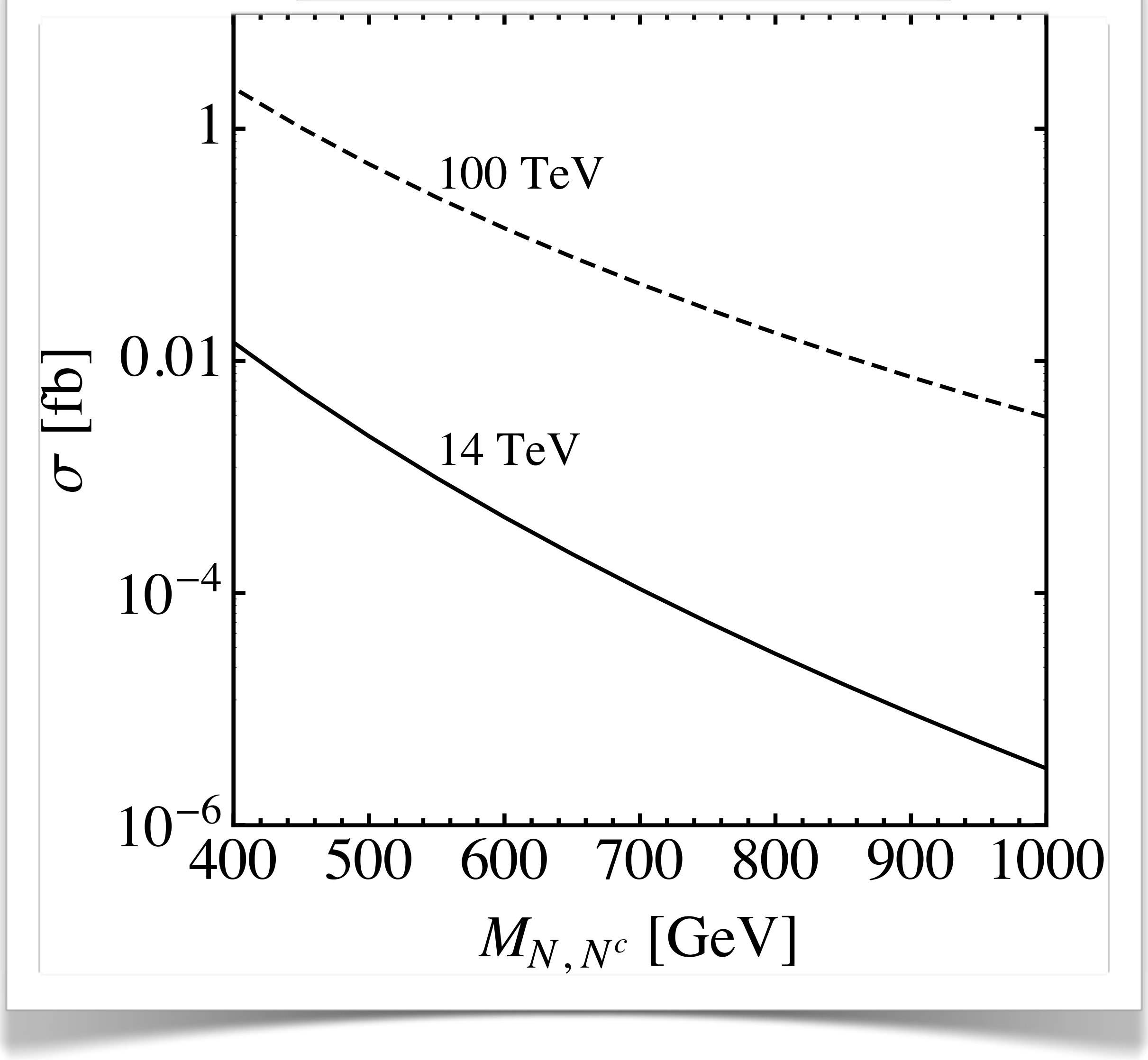
$$\begin{aligned} N, N^c &\to h\nu \\ N, N^c &\to Z\nu \\ N, N^c &\to W^+ l, W^- \bar{l} \end{aligned}$$

- RHN coupling to Higgs is large; dictated by naturalness, global symmetry - production via Higgs exchange

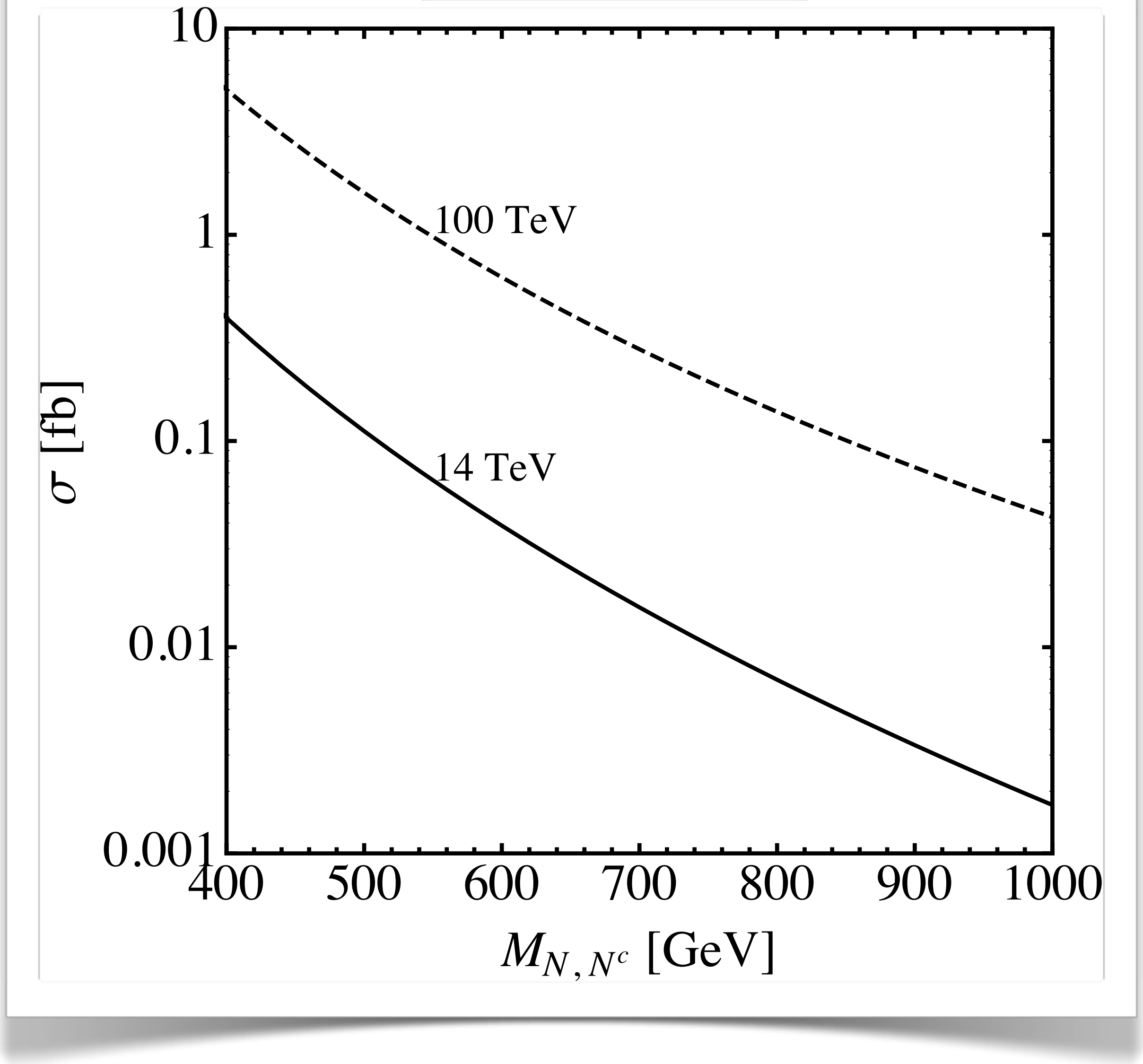
$$\lambda_t \frac{v}{f} h N N^c + \mathrm{h.c.} \quad \Longrightarrow \quad \begin{aligned} pp \to h^* &\to N N^c \\ e^+ e^- \to Z h^* &\to Z N N^c \end{aligned}$$

- RHN Yukawa coupling can be relatively large

$$y_D L H N, \quad y_D^c L H N^c \quad \Longrightarrow \quad \begin{aligned} pp \to W^* &\to \ell N \\ pp \to Z^* &\to \nu N \\ e^+ e^- \to Z^* &\to \nu N \end{aligned}$$



$pp \to h^* \to NN^c$



$pp \to \nu N$

- LHC: 10 - 100 signal events - very challenging (hopeless?)
- Future 100 TeV pp collider - 100s - 1000s of signal events

Detailed studies needed to determine prospects

Outlook

- LHC is testing naturalness; colored top partners face significant constraints - motivates neutral top partners
- Other strong evidence for neutral states in Nature... can they also play a role in naturalness?
- Natural Neutrinos - Right Handed Neutrinos are the top partners
- TeV scale seesaw is dictated by naturalness
- Yukawa couplings can be large, leads to novel low energy signatures
- Direct collider probes are challenging - studies needed, but clearly will need future facilities to begin probing natural parameter space
- Many interesting questions remain - leptogenesis? dark matter?