Natural Neutrinos

Brian Batell
CERN

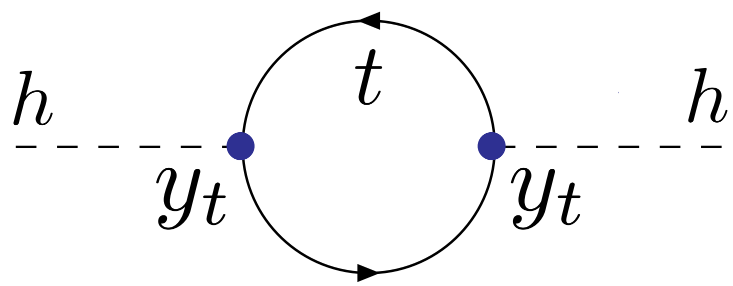
with Matthew McCullough - arXiv:1504.04016

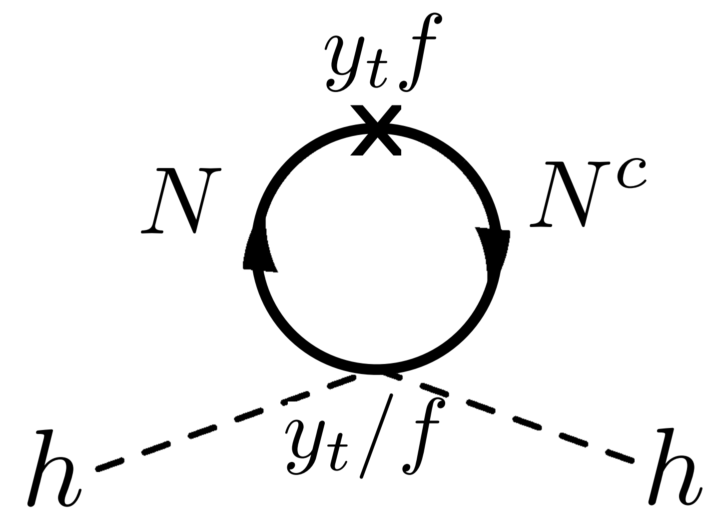
Nu@Fermilab
May 23, 2015

Basic idea:

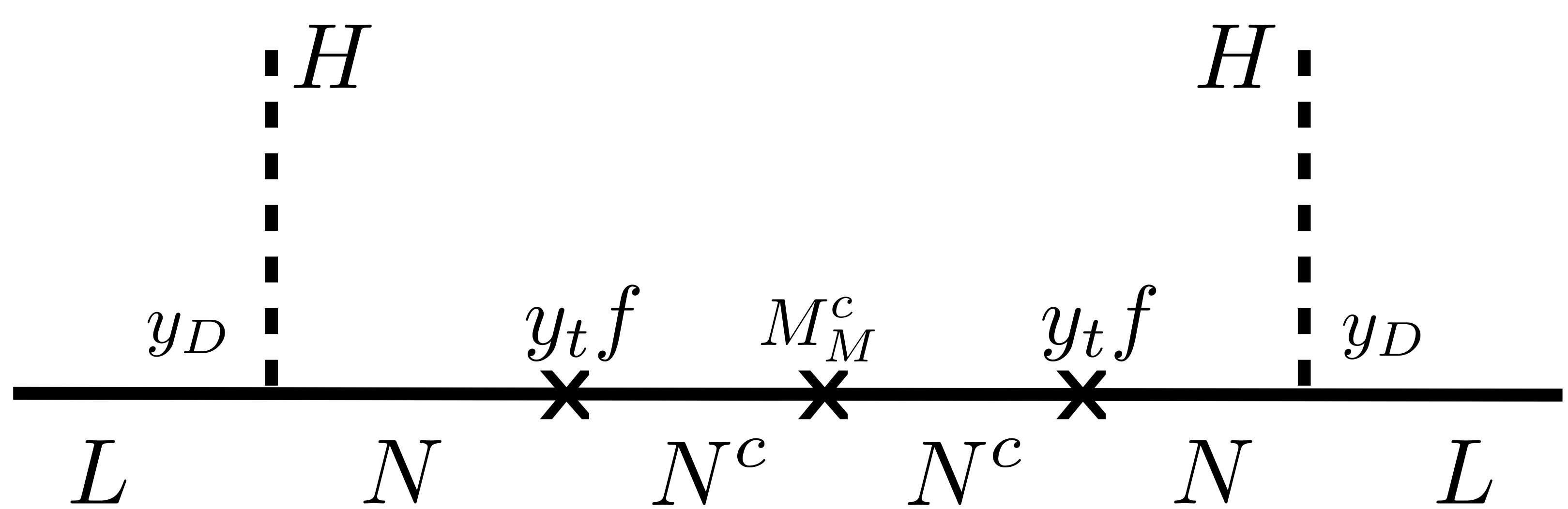
Right Handed Neutrinos are the Top Partners

Naturalness



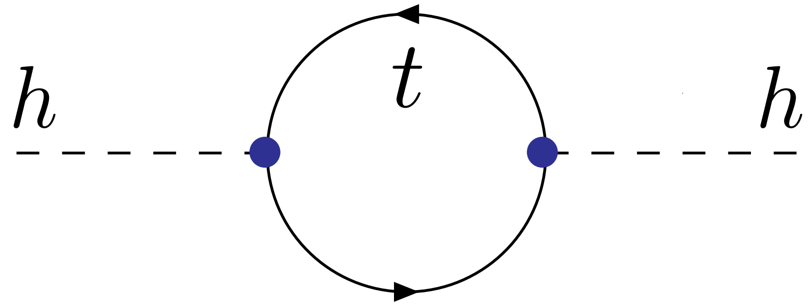


Neutrino Mass



Motivation: Neutral Naturalness

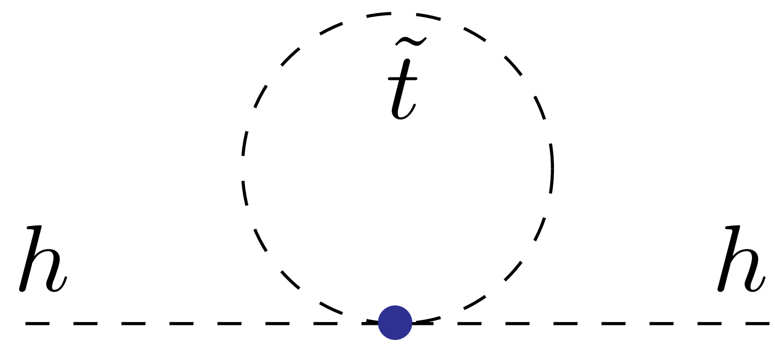
Naturalness



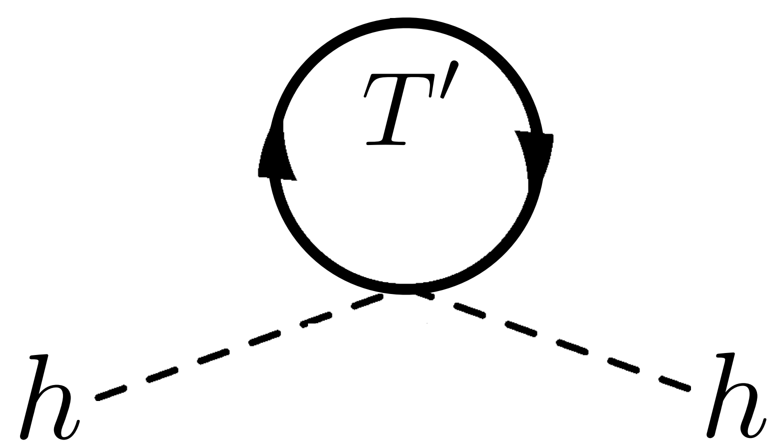
$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$

Top Partners:

Stops
(SUSY)

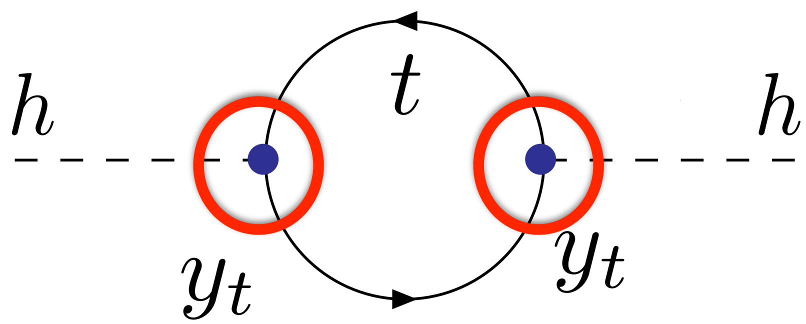


Fermionic T’
(Composite/pNGB Higgs)

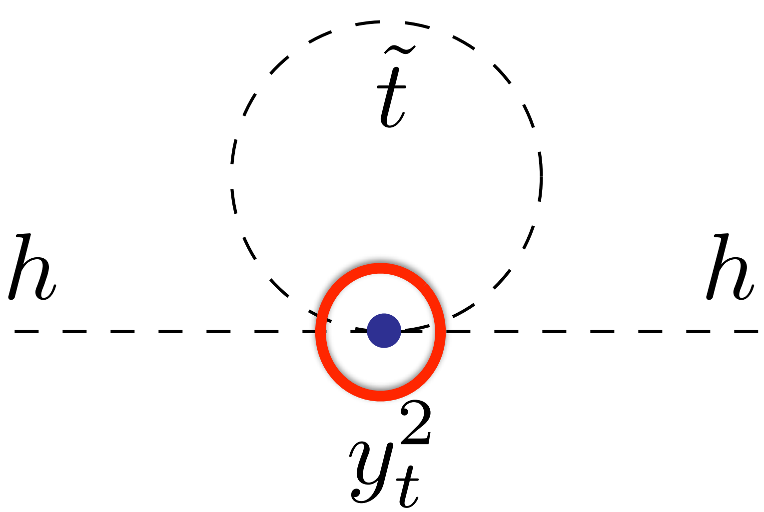


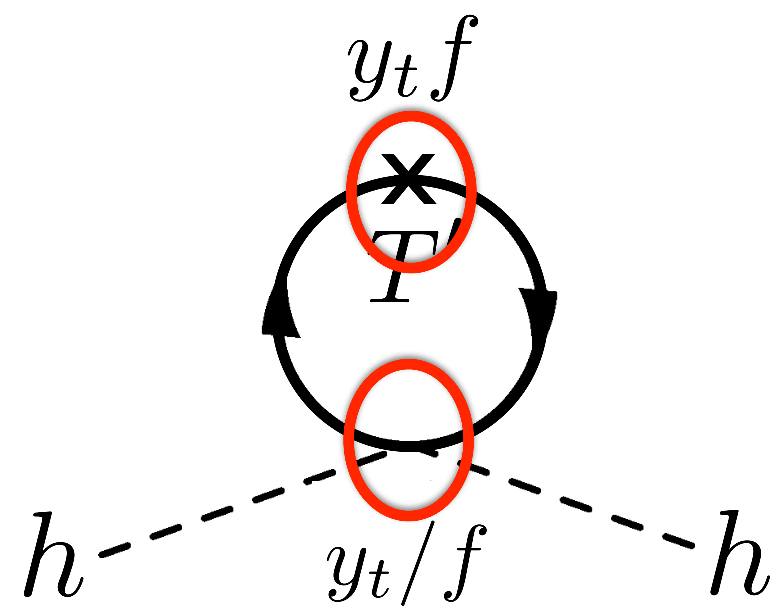
Cancellation of Λ^2 due to

1. Supersymmetry or Global Symmetry → Equality of Couplings



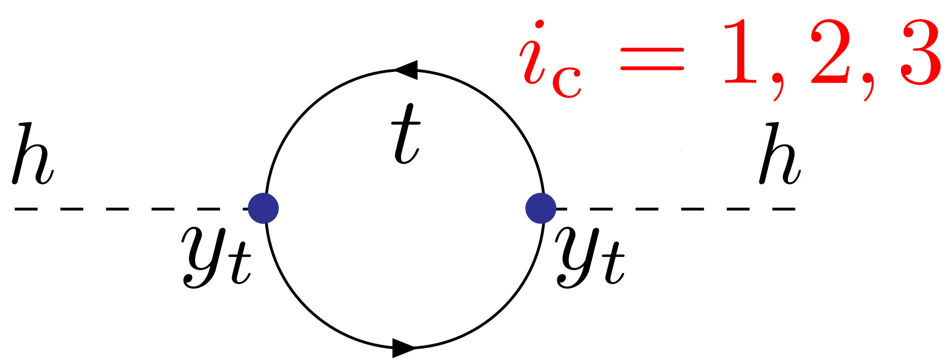
$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$$



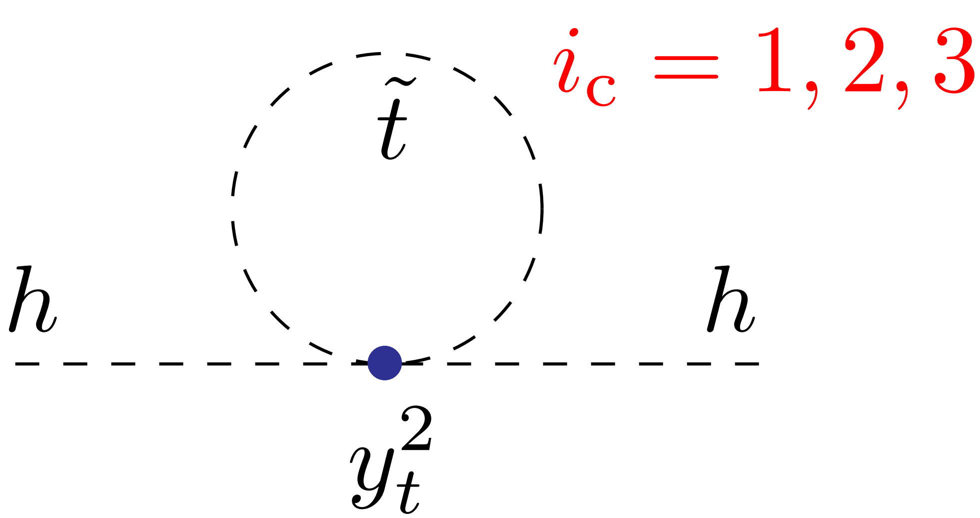


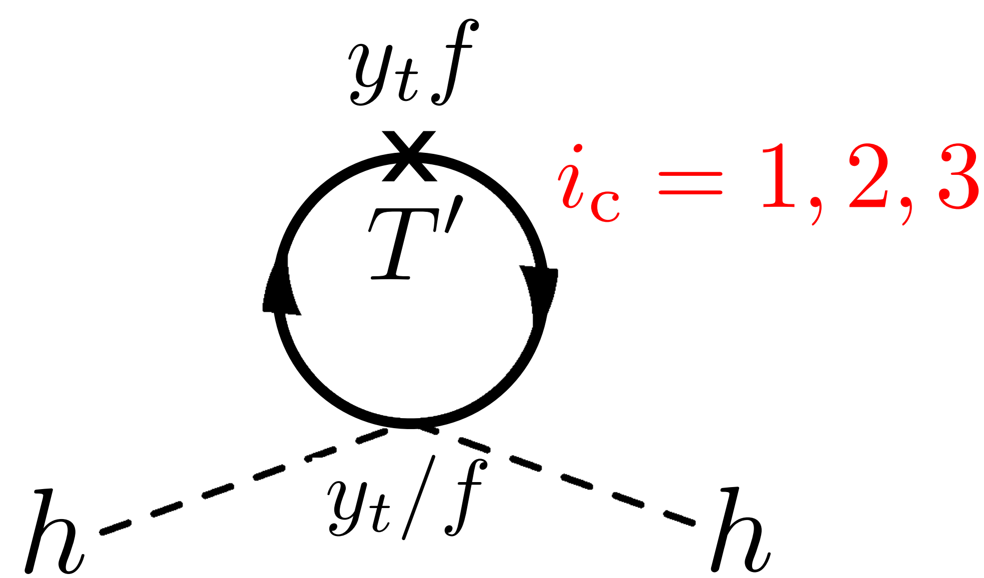
Cancellation of Λ^2 due to

2. $SU(3)_c$ $\Rightarrow$ Equality of # d.o.f.



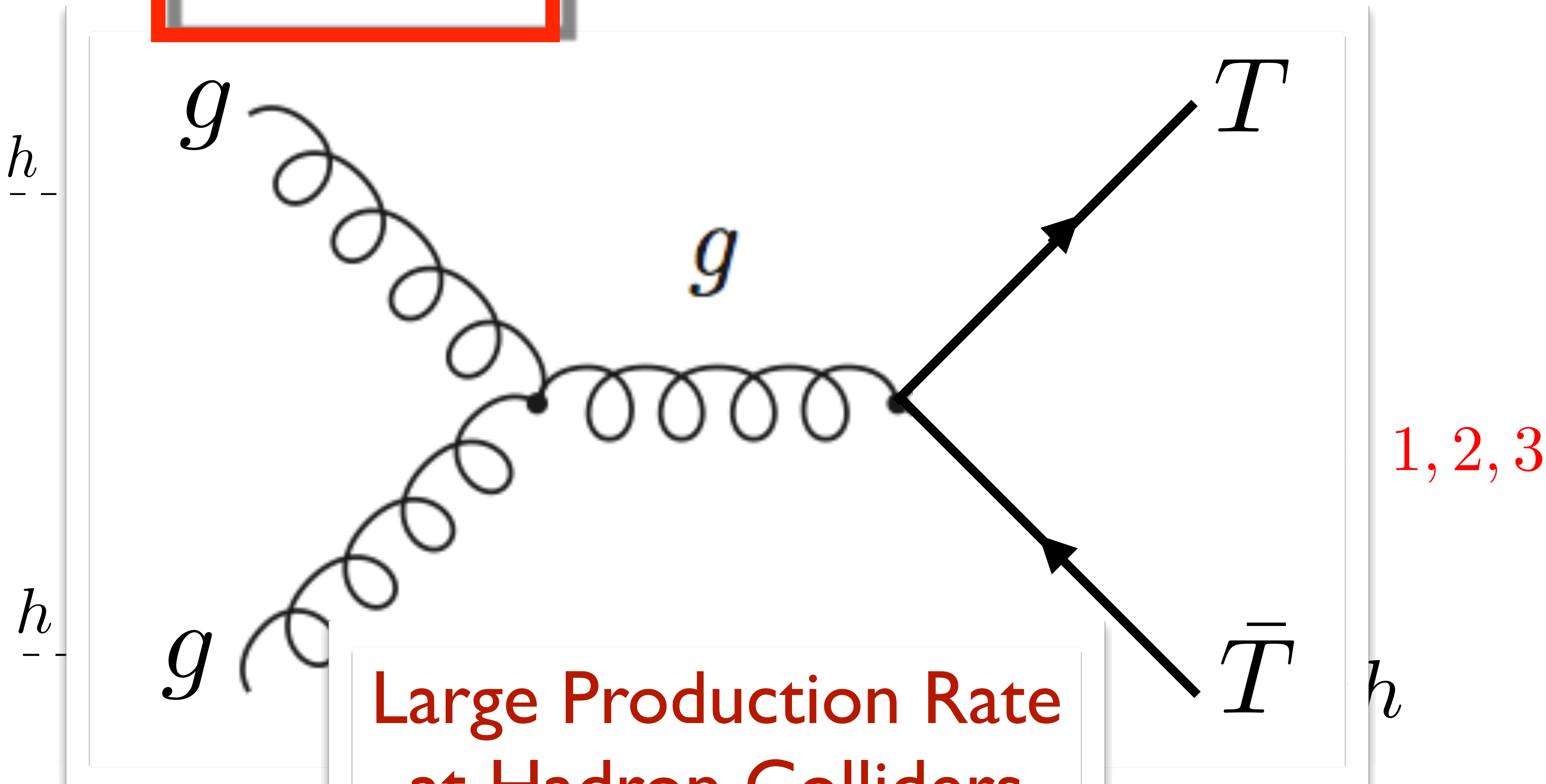
$$\delta m_h^2 = -\frac{3 y_t^2}{8\pi^2}\Lambda^2$$





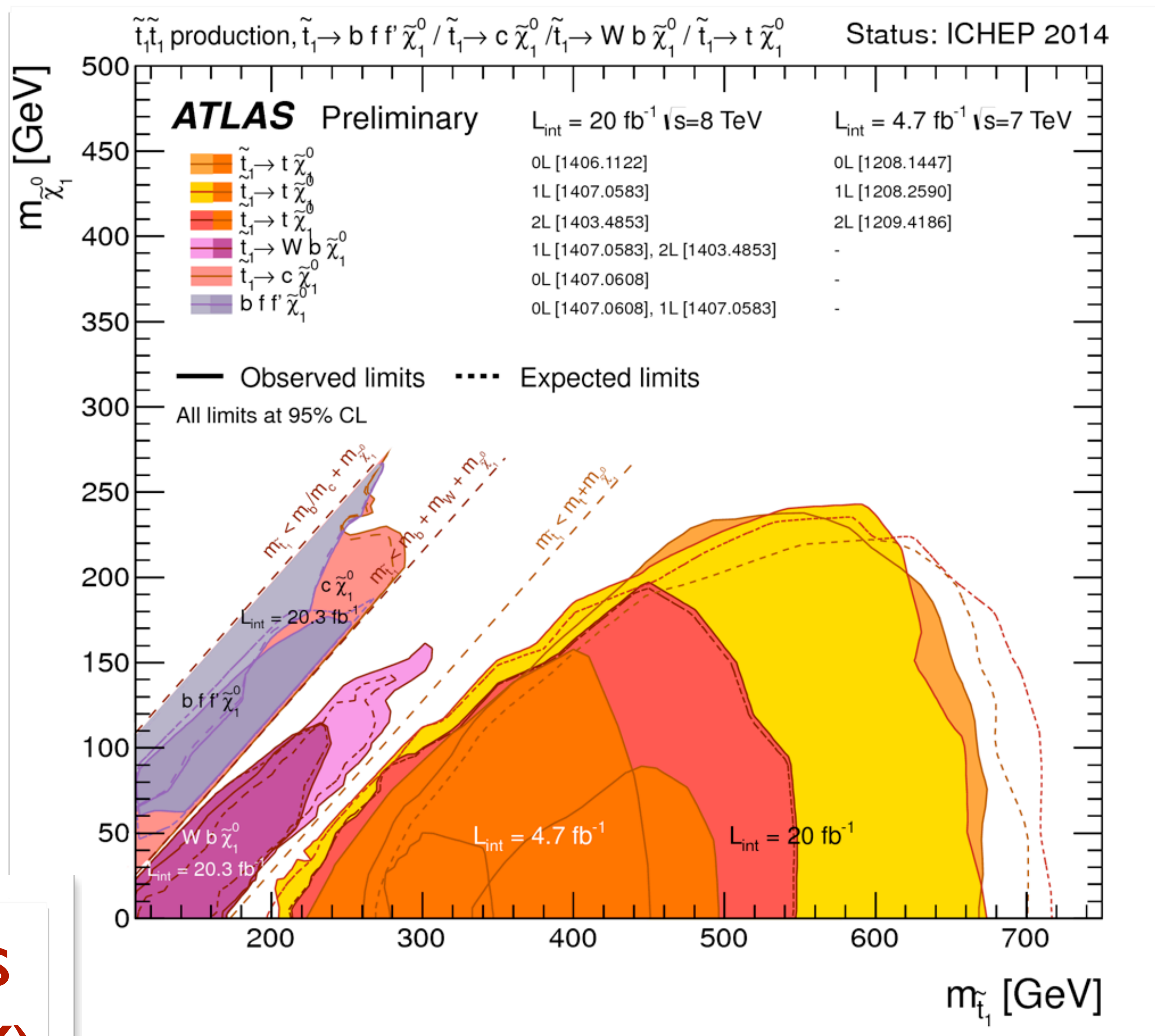
Cancellation of Λ^2 due to

2. $\boxed{SU(3)_c}$ → Equality of # d.o.f.



Large Production Rate at Hadron Colliders

Where are the Top Partners?



Stops (SUSY)

Neutral Naturalness: The Twin Higgs

[Chacko, Goh, Harnik]

$$\mathrm{SM}_A \xleftrightarrow{\;|H_A|^2|H_B|^2\;} \mathrm{SM}_B$$

- Mirror copy of the Standard Model

- Higgs sector has an approximate global SU(4) symmetry

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \qquad V(H) = -m^2 H^\dagger H + \lambda (H^\dagger H)^2$$

- The SM Higgs is a pseudo-Nambu-Goldstone Boson

$$\langle H \rangle = f \qquad SU(4) \to SU(3)$$

$n_G = 15 - 8 = 7$ pNGBs -- 4 of these (H_A) make up SM Higgs

The Twin Top

- Enlarge color to $SU(3)_A \times SU(3)_B \times Z_2$

- Yukawa: $\lambda_t\, H_A\, Q_A\, t^c_A + \lambda_t\, H_B\, Q_B\, t^c_B$

Coupling equality enforced by Z_2

Quadratic divergences: $$-\frac{3\lambda_t^2}{8\pi^2}\Lambda^2(|H_A|^2 + |H_B|^2) = -\frac{3\lambda_t^2}{8\pi^2}\Lambda^2|H|^2$$

Λ^2 respects $SU(4)$ - No mass induced for the pNGB Higgs

Color neutral top partners

Direct searches for top partners evaded!

There are other compelling hints for neutral particles in nature…

neutrino mass and oscillations!

Elegantly explained by the addition of ***neutral*** fermions N

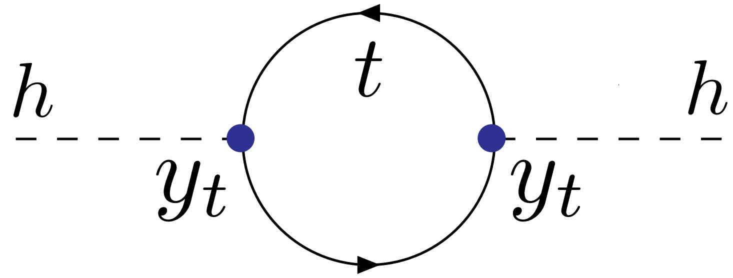
$$y_\nu \, L \, H \, N + \frac{1}{2} \, M \, N^2 + \mathrm{h.c.}$$

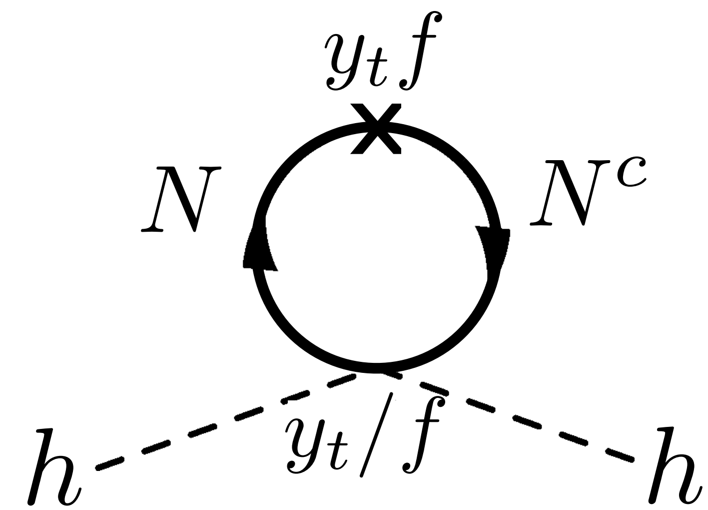
Natural Neutrinos

[BB, McCullough]

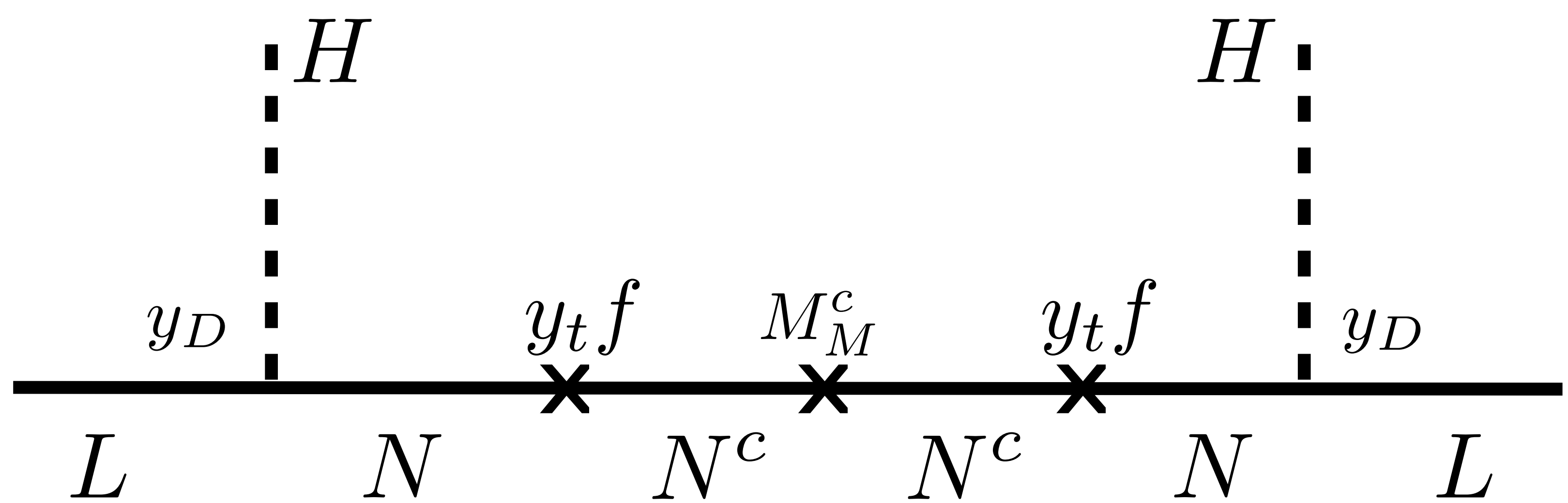
Right Handed Neutrinos are the Top Partners

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
- Predicts TeV-scale see-saw - rigidly tied to naturalness
- Certain limits realize "Inverse" and "Linear" seesaws (can have large Yukawas) with a rich phenomenology
- 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 RHNs 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 scale

Example model: $G/H = SU(6) \times SU(3)/SU(2)$

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

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

- 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

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

Same structure as simplified model

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

- Correction to Higgs mass:

$$\delta\mu^2 = \underbrace{-\frac{3\lambda_t^2}{8\pi^2}\Lambda^2}_{\text{top loop}} \to \underbrace{-\frac{3\lambda_t^2}{8\pi^2} m_N^2 \log\frac{\Lambda^2}{m_N^2}}_{\text{top+RHN loops}} \qquad \underbrace{m_N \sim \lambda_t f \ll \Lambda}_{\text{RHN mass}}$$

- 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:

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

- 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	$\sim {M_D^c}^2 M_M / M_N^2$

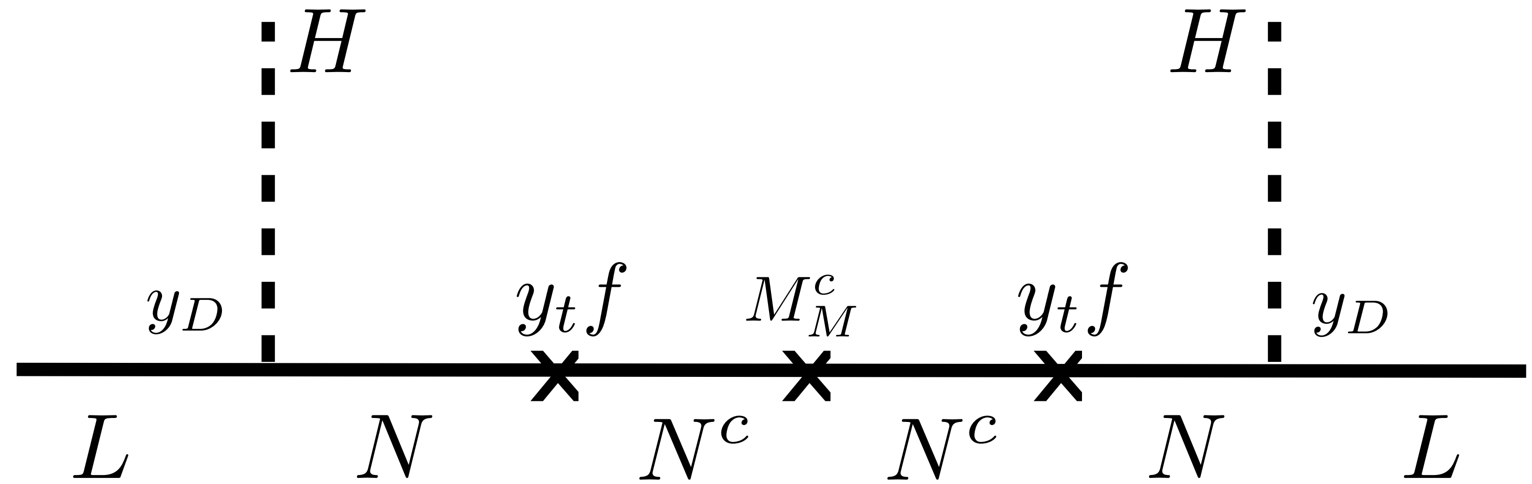
Linear seesaw [Malinsky, Romao, Valle]

Inverse seesaw [Mohapatra, Valle]

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

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

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

Collective breaking of Lepton Number

Pseudo-Dirac Fermions,
split by Majorana mass

- The light neutrino mass matrix is given by

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

Neutrino oscillation data

$$\Delta m^2_{21}\,[10^{-5}\,\mathrm{eV}^2] = 7.50^{+0.19}_{-0.17} \quad (7.50^{+0.19}_{-0.17}),$$
$$\Delta m^2_{31}\,(\Delta m^2_{32})\,[10^{-3}\,\mathrm{eV}^2] = 2.547^{+0.047}_{-0.047} \quad (-2.449^{+0.048}_{-0.047}),$$
$$\sin^2\theta_{12} = 0.304^{+0.013}_{-0.012} \quad (0.304^{+0.013}_{-0.012}),$$
$$\sin^2\theta_{23} = 0.452^{+0.052}_{-0.028} \quad (0.579^{+0.025}_{-0.037}),$$
$$\sin^2\theta_{13} = 0.0218^{+0.0010}_{-0.0010} \quad (0.0219^{+0.0011}_{-0.0010}),$$

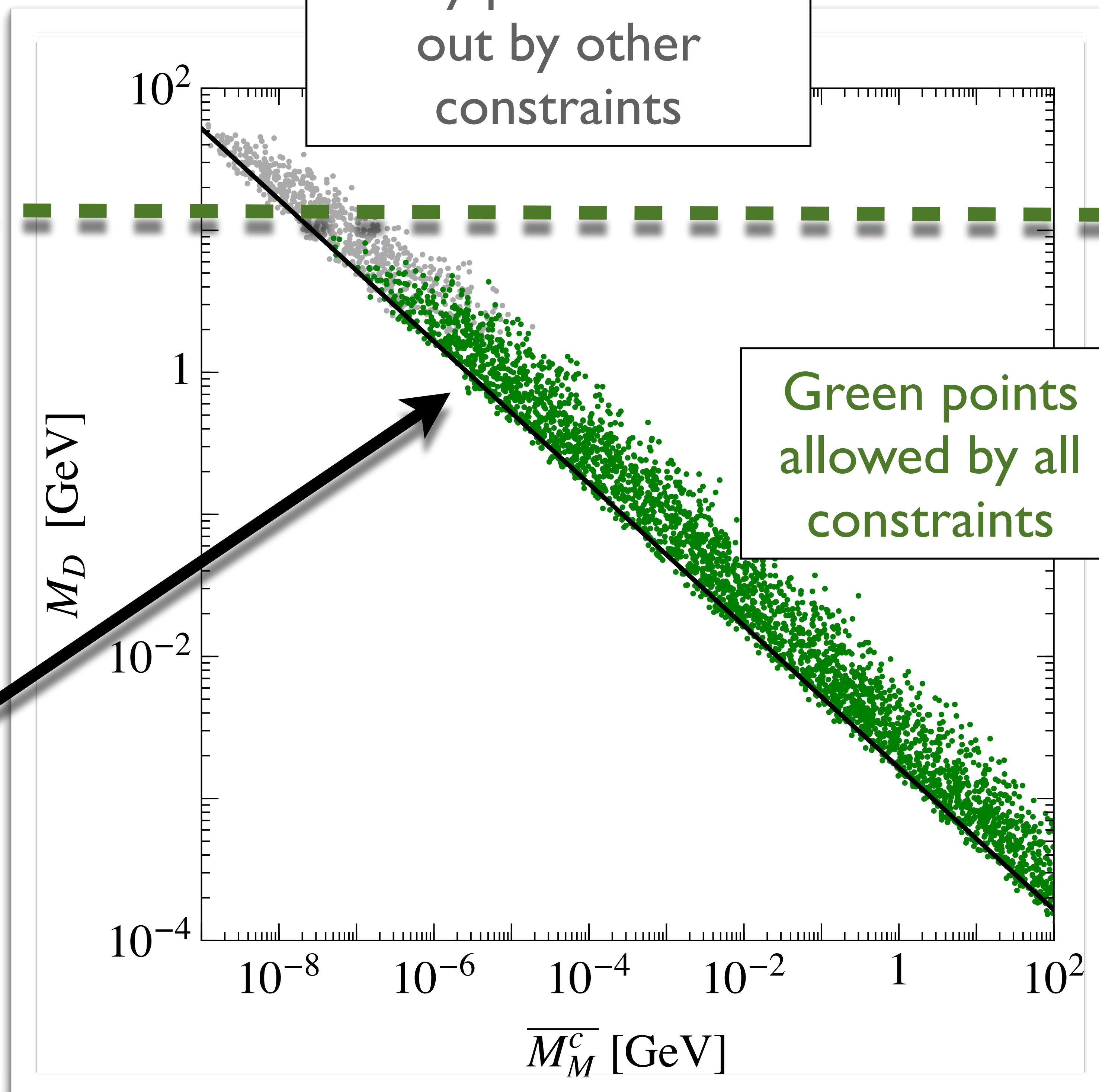
- Dirac mass parameterized via Casas-Ibarra

$$M_D = M_N\,(M_M^c)^{-1/2}\,R\,(m_\nu)^{1/2}\,U^\dagger_{\mathrm{PMNS}}, \qquad R^T R = 1$$

- Scan in R and Majorana masses, check various constraints

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

See also talks by Ross-Lonergan, Le Dall

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

- 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 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
- Quark Flavor CKM parameters

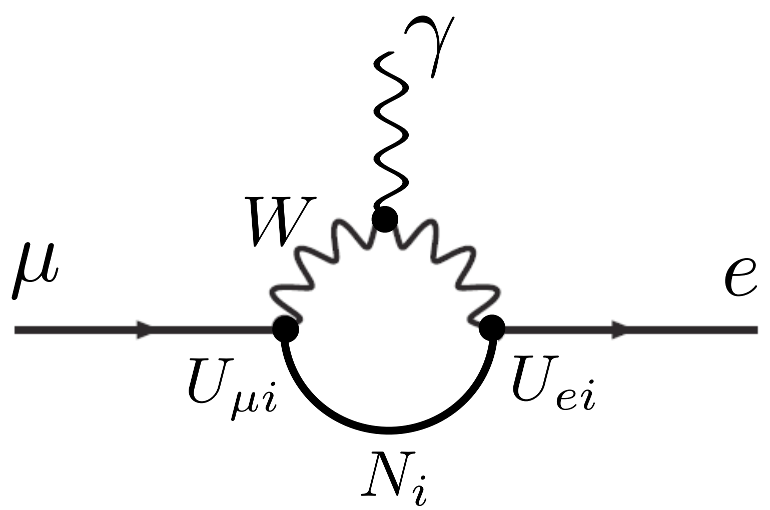
We apply the following constraints from a recent global fit:

[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. $\mu \to e\gamma$:



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

[Ilakovac,Pilaftsis '95]

- Strongest constraint comes from MEG experiment

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

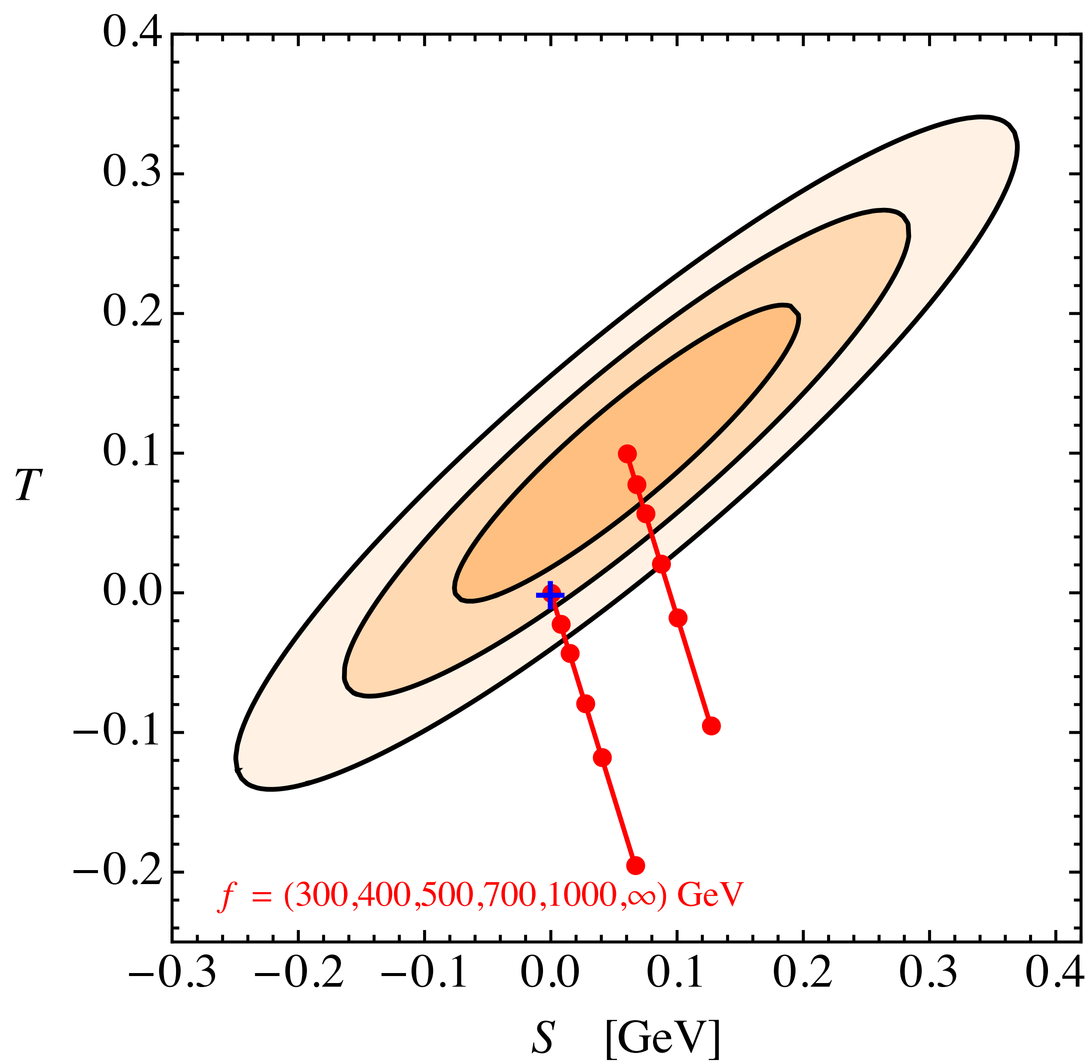
- Exciting prospects in future LFV experiments

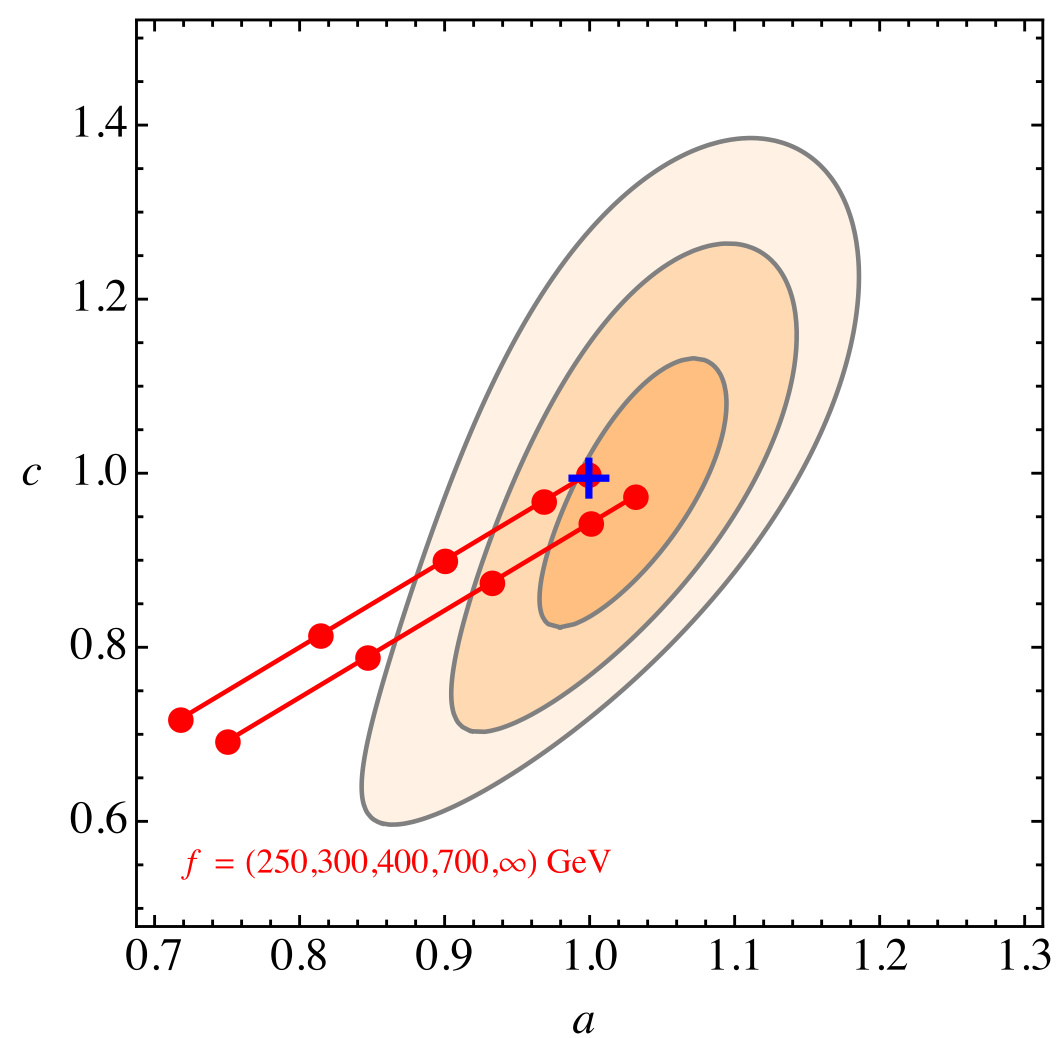
e.g., Mu2E, Mu3e, MEG-II, COMET, DeeMee, Prism, Belle-II

Electroweak precision and Higgs

- Higgs is a pNGB, correction to hVV and $hf\bar{f}$ coupling

$$a = \frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}}, \qquad c = \frac{g_{hff}}{g_{hff}^{\mathrm{SM}}}, \qquad\qquad a, c \sim 1 + \mathcal{O}\left(\frac{v^2}{f^2}\right)$$





Probes $f \sim 500 - 1000\,\mathrm{GeV}$

Signals of the RHN at LHC and future colliders

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

$$N, N^c \rightarrow h\nu$$
$$N, N^c \rightarrow Z\nu$$
$$N, N^c \rightarrow W^+ l, W^- \bar{l}$$

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

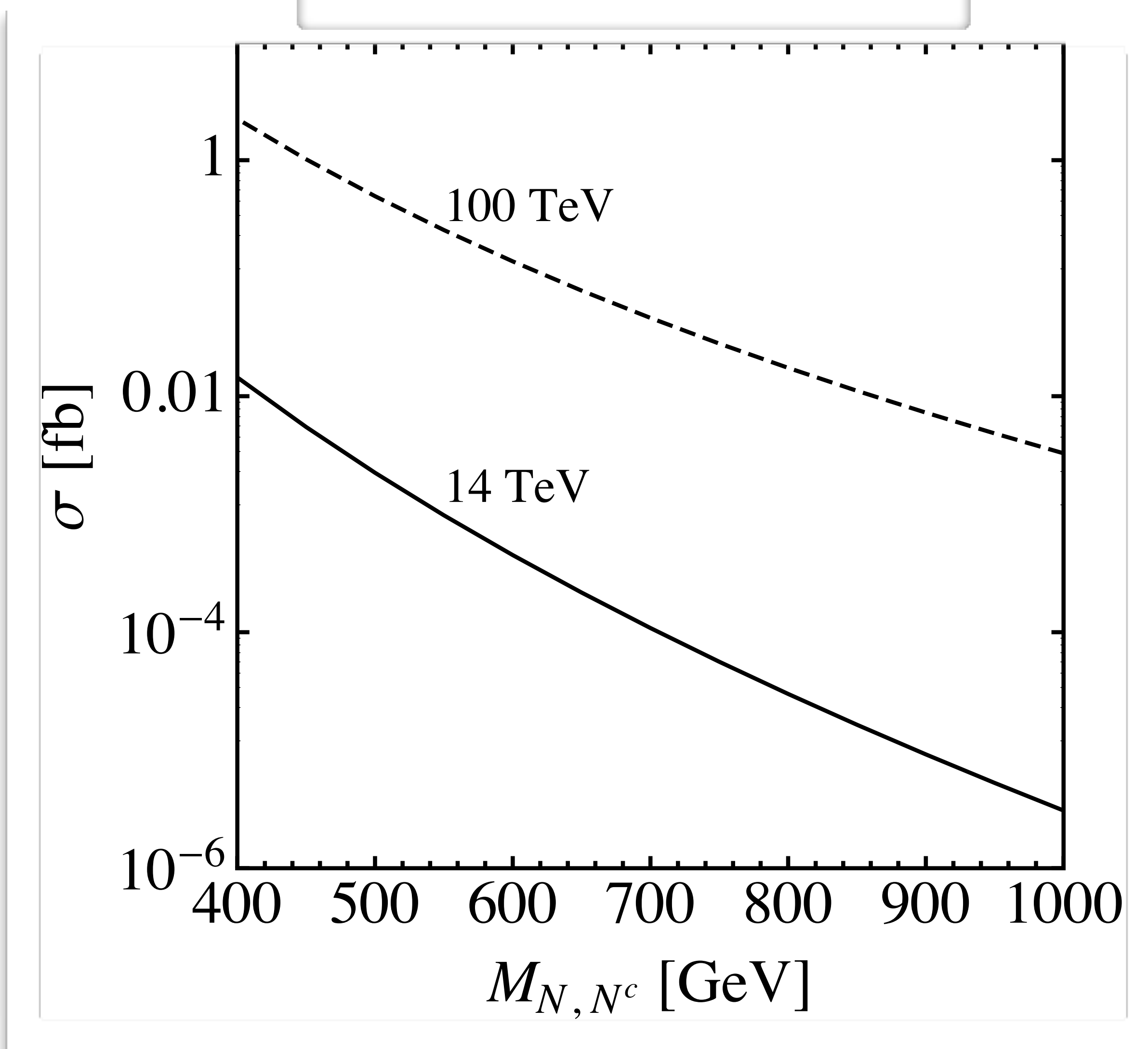
$$\lambda_t \frac{v}{f} h N N^c + \mathrm{h.c.} \quad \Rightarrow \quad \begin{array}{c} pp \rightarrow h^* \rightarrow N N^c \\ e^+ e^- \rightarrow Z h^* \rightarrow Z N N^c \end{array}$$

- RHN Yukawa coupling can be relatively large

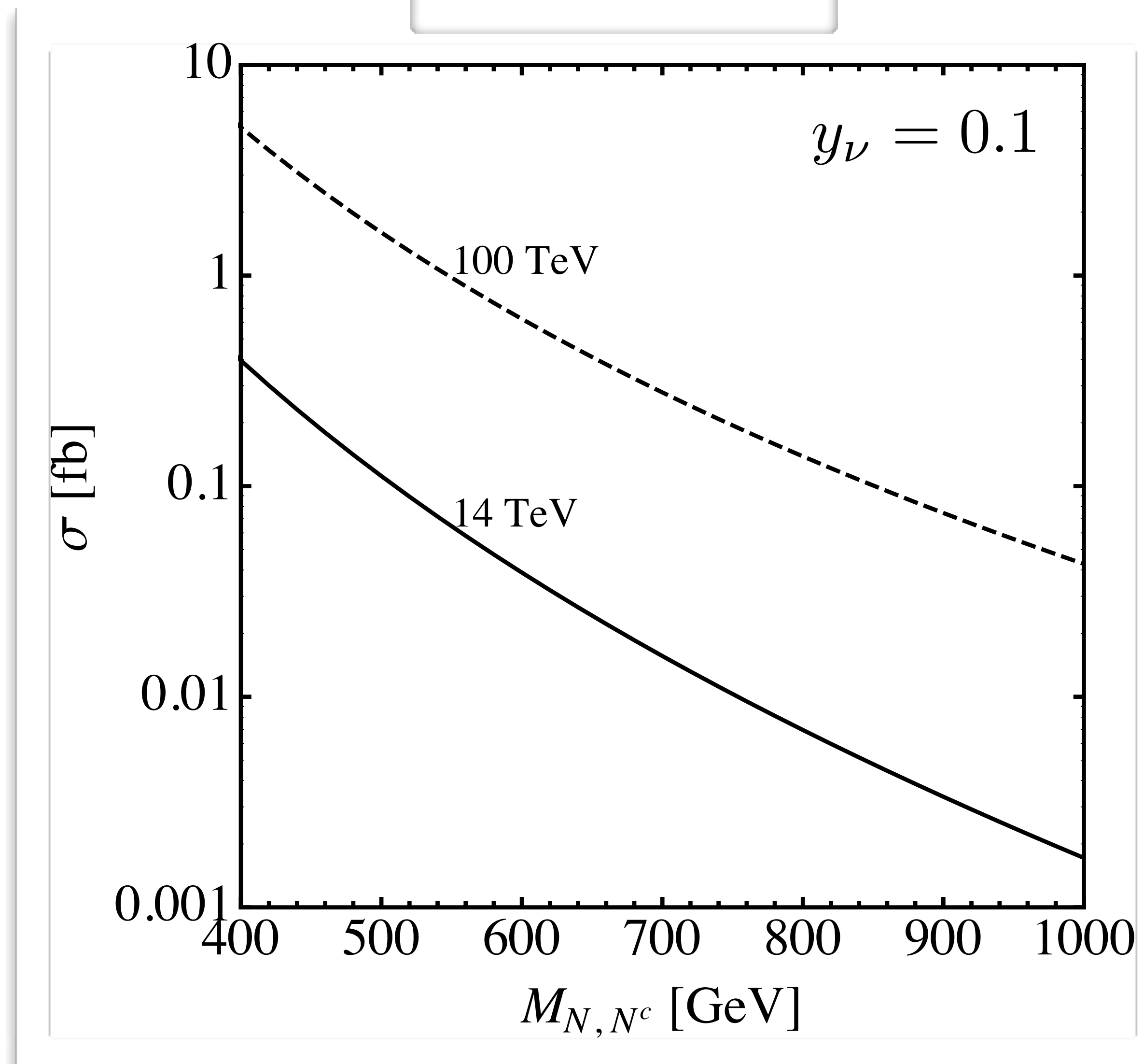
$$y_D L H N, \quad y_D^c L H N^c \quad \Rightarrow \quad \begin{array}{r} pp \rightarrow W^* \rightarrow \ell N \\ pp \rightarrow Z^* \rightarrow \nu N \\ e^+ e^- \rightarrow Z^* \rightarrow \nu N \end{array}$$

See also talks by Deppisch, Ruiz, Dev, Marcano

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



$pp \to \ell N$



- 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

- Natural Neutrinos - Right handed neutrinos are the top partners
  - Difficult to probe directly at LHC
  - TeV scale seesaw is dictated by naturalness
  - Collective lepton number breaking; framework for inverse & linear, seesaws; rich low energy phenomena
- Many interesting questions remain:
  - Leptogenesis, Dark Matter?
  - UV completions; SUSY, Composite Higgs...?
  - Neutrino flavor generation and $SU(3)_N$ breaking?