A possible experimental test of the neutrino mass seesaw mechanism.

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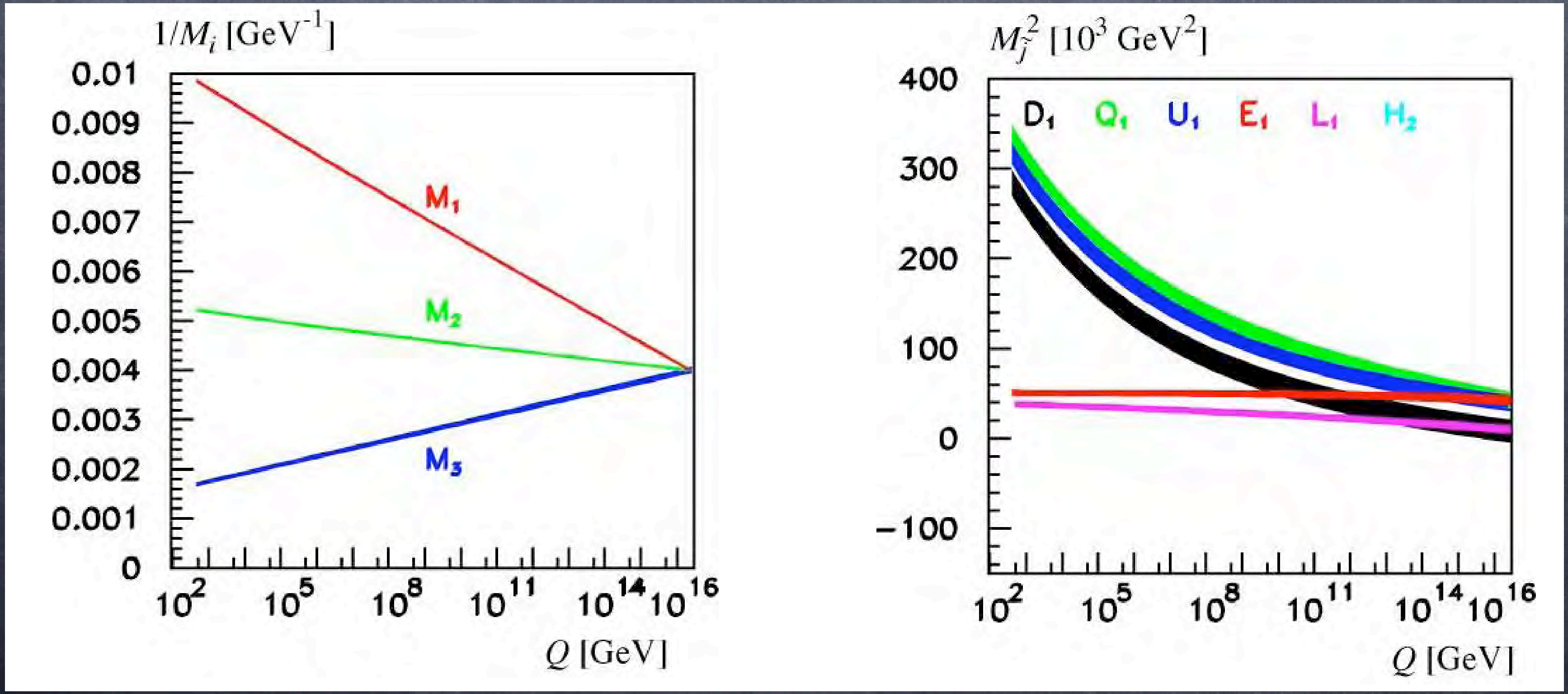
A Series of Fortunate Events.

- Suppose LHC discovers supersymmetry.
- Exact masses and couplings confirmed at ILC.
- Results look like:



Outline

- Seesaw Mechanism
- Grand Unification
- A Combined Approach
- Experimental Prospects
- Conclusions

Massive Neutrinos

- From atmospheric/solar neutrino oscillation, at least two neutrino species massive. Lower bound on the heaviest:

$$m_3 \geq (\Delta m_{23}^2)^{1/2} \simeq 0.05 \text{ eV}$$

- $0\nu 2\beta$ experiment limits $\langle m_\nu \rangle_{ee} \lesssim 0.9 - 0.3 \text{ eV}$
- Cosmological limits $\sum_i m_{\nu_i} \lesssim 0.62 - 0.17 \text{ eV}$
- All consistent with heaviest neutrino being

$$m_{\nu_3} \sim 0.1 \text{ eV}$$

Seesaw Mechanism

- Massive Majorana neutrinos generic in extensions of the Standard Model:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

$$\frac{1}{\Lambda}\mathcal{L}_5 = \frac{1}{2\Lambda}(LH)(LH) \to \frac{1}{2}\frac{v^2}{\Lambda}\nu_L\nu_L$$

$$m_\nu \sim 0.1 \text{ eV} \Rightarrow \Lambda \sim 10^{14} \text{ GeV}$$

Unprovable?

Seesaw Mechanism

- Identify Λ as the mass of new gauge singlets

$$\mathcal{L}_{Seesaw} = -\frac{1}{2}\mathbf{M}_N N_i N_j + \mathbf{y}(L_i H) N_j$$
$$\rightarrow \frac{1}{2}[\mathbf{y}_{\ell i}(\mathbf{M}_N)^{-1}_{\ell k}\mathbf{y}_{jk}](L_i H)(L_j H)$$

$$(m_\nu)_{ij} = \frac{\mathbf{y}_{\ell i}\mathbf{y}_{jk}}{(\mathbf{M}_N)_{\ell k}} v^2$$

- If $\mathbf{y} \sim \mathcal{O}(1)$, $\mathbf{M}_N \sim \mathcal{O}(10^{14}\ \mathrm{GeV})$
- For at least 2 generations of massive neutrinos, M_N must have rank ≥ 2
- So at least 2 singlets N

Testing Seesaw

- In SUSY can look for lepton flavor violation:
  - Proportional to off-diagonal terms in slepton mass matrix $m^2_{\tilde{L}}$
  - Assuming $m^2_{\tilde{L}}$ diagonal at high scale (universality), then LFV-inducing off-diagonal elements $\propto \mathrm{y}^2$ due to RG running.

Not only model-dependent, but impossible to distinguish at low energy

A New Scheme

- Assume the following:
  - $0\nu2\beta$ confirms Majorana neutrino masses.
  - LHC discovers SUSY, confirmed at ILC
  - RGE running of low energy masses consistent with GUT at high scales
    - Gravity mediated ~~SUSY~~

A New Scheme

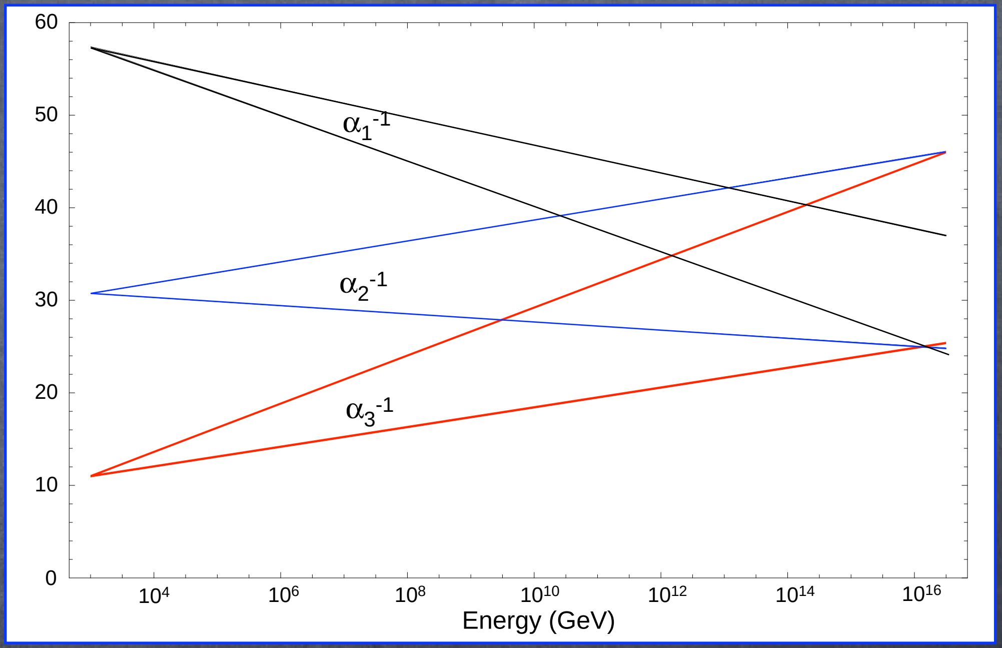
- If we can be convinced of GUT, then we have both low energy (via experiment) and high energy (via GUT) boundary conditions.
- New physics between Λ_{SUSY} and Λ_{GUT} would be strongly constrained in order to satisfy both sets of boundary conditions.

What would convince us of GUT?

Gauge Unification

$$SU(3)_C \times SU(2)_L \times U(1)_Y \subseteq G \; (G = SU(5), SO(10), \ldots)$$

- In SM, gauge couplings unify at $\Lambda_{GUT} \sim 10^{15}$ GeV
- Adding SUSY `improves' unification at slightly higher $\Lambda_{GUT} \sim 1.2 \times 10^{16}$ GeV
- SM anomaly cancellation & charge quantization hint at unifying principle.



Gauge Unification

- In SUSY, gaugino masses obey `GUT relation'

$$\frac{M_1(\mu)}{\alpha_1(\mu)} = \frac{M_2(\mu)}{\alpha_2(\mu)} = \frac{M_3(\mu)}{\alpha_3(\mu)} = \frac{M_{1/2}}{\alpha_{GUT}}$$

- True regardless of new matter content as long as it comes in complete multiplets of G.
- Also independent of pattern of symmetry breaking.

So measuring gaugino masses can only confirm gauge coupling unification

SU(5) Unification

- `Vanilla' SU(5) ruled out by proton decay, but still simplest example of unification.

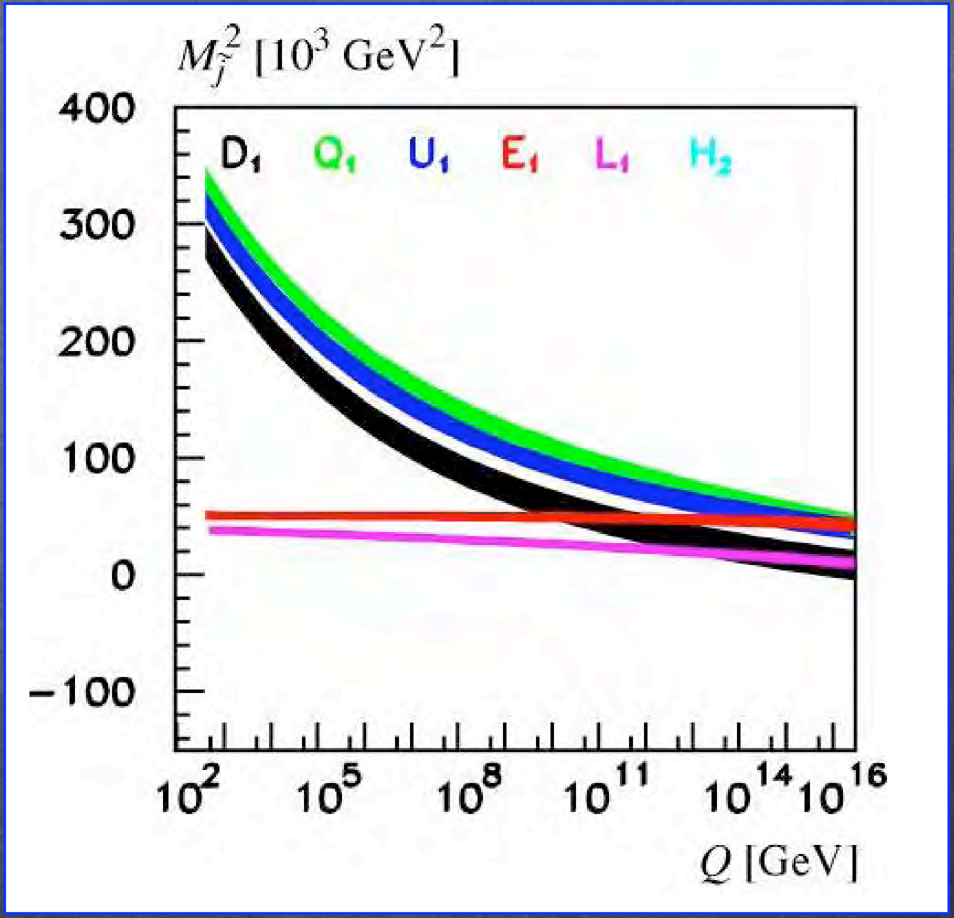
$$\{Q, u^c, e^c\} = \mathbf{10} \quad \{d^c, L\} = \bar{\mathbf{5}} \quad H_u \subseteq \bar{\mathbf{5}}$$

$$\{g, W, Z, \gamma\} \subseteq \mathbf{24} \quad H_d \subseteq \mathbf{5}$$

- Measuring superpartner unification for all 3 generations would give 9 `coincidences' in favor of GUT.

Sfermion Masses

- Sfermion mass terms have no equivalent to GUT relation.
- Consistency of high and low energy boundary conditions not guaranteed for all matter content.
- Thus we need gravity-mediated ~~SUSY~~.



A Combined Approach

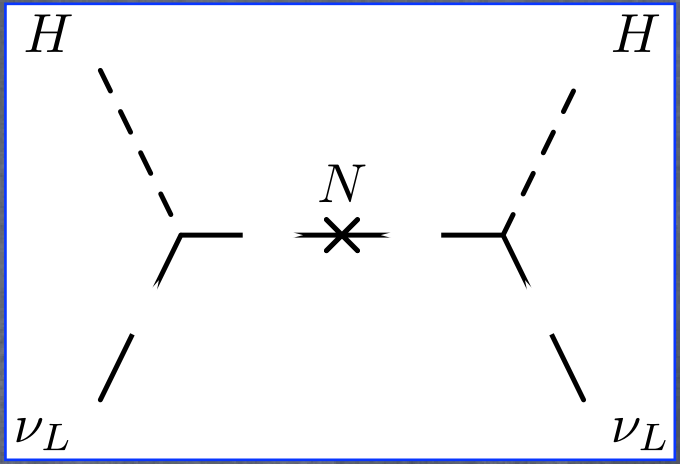
- Seeing unification of sfermion masses suggests matter content is MSSM+singlets
    - i.e. standard seesaw mechanism
- Alternative neutrino mass models require new non-singlets, which would modify sfermion RGEs, destroying apparent unification.
    - Enumerate alternative models; test to see whether lack of unification can be experimentally distinguished.

Seesaw Redux

- Type I seesaw combines

  $$\bar{\mathbf{5}} \times \mathbf{5} = \mathbf{1} + \mathbf{24}$$

  Need either $3(\mathbf{1})$ or $3(\mathbf{24})$ for 3 massive neutrinos



- Type II seesaw uses triplet T

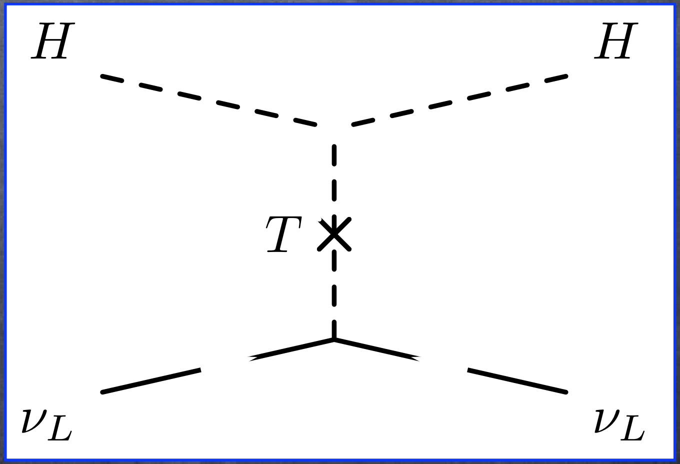
  $$\mathcal{L}_{II} = \mathbf{y}LL\bar{T} + y' H_u H_u T + \frac{1}{2} M_T T\bar{T}$$

  Need symmetric combination

  $$\bar{\mathbf{5}} \times \bar{\mathbf{5}} = \bar{\mathbf{15}} + \mathbf{10}$$

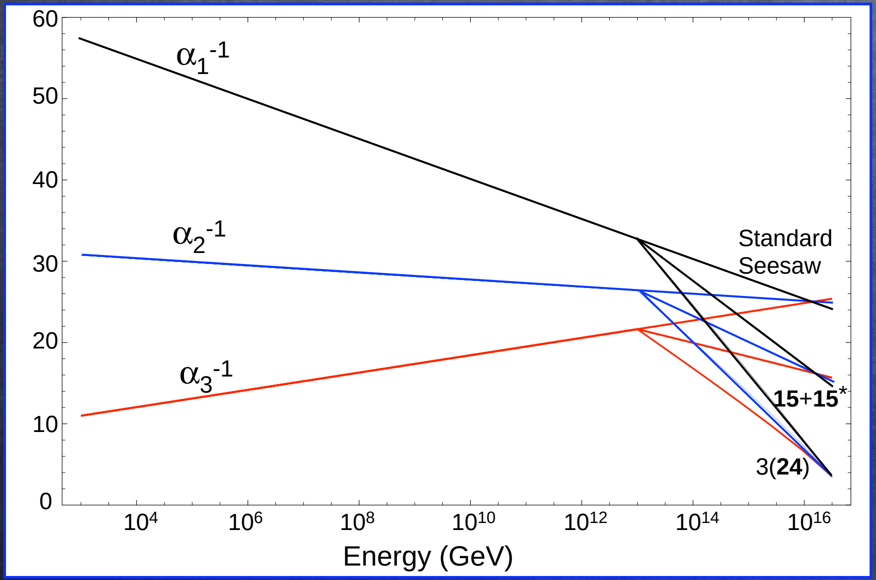
  Rank 3 mass matrix only needs

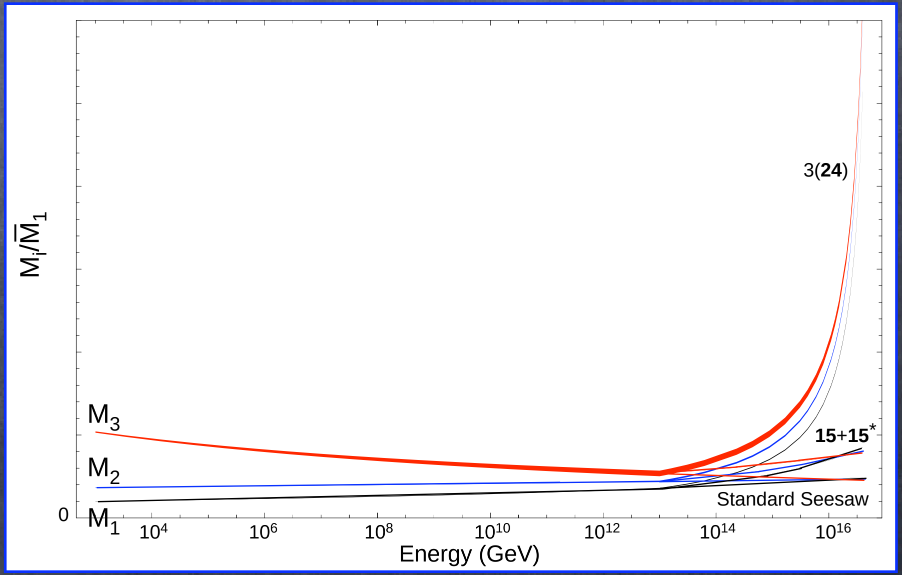
  $$\mathbf{15} + \bar{\mathbf{15}}$$



Gauge Running

- Run αs to Λ_{GUT} assuming all SUSY d.o.f turned on at 1 TeV.
- For each seesaw model, add new multiplets at $M_N = M_T = 10^{13},\ 10^{14},\ 10^{15}$ GeV
- In `standard' seesaw, run gaugino M_i and sfermion $m^2_{\tilde{X}}$ down from Λ_{GUT} to 1 TeV. Run back up with additional particle content.





Sfermion Running

$$\{Q, u^c, e^c\} = \mathbf{10} \quad \{d^c, L\} = \bar{\mathbf{5}}$$

- At leading order, combinations $(m^2_{\tilde{X}} - m^2_{\tilde{Y}})/M_1^2(1 \text{ TeV})$ independent of overall mass scales $M_{1/2},\ m_0^2$
- To run masses and couplings at 2nd order, need unification masses

$$\frac{d\alpha_i}{dt} = \frac{1}{2\pi}[S_i(R) - 3C(G_i)]\alpha_i^2 + \cdots$$

$$\frac{dM_i}{dt} = \frac{1}{2\pi}[S_i(R) - 3C(G_i)]M_i + \cdots$$

$$\frac{dm_X^2}{dt} = -\frac{2}{\pi}\alpha_i M_i^2 C(r_i) + \frac{1}{4\pi}C_1(r_1)\alpha_1 S + \frac{1}{(4\pi)^2}C_i(r_i)\sigma_i + \cdots$$

$\propto m^2_{\tilde{X}}$

Sfermion Running

- Need to work in gravity-mediated ~~SUSY~~ to avoid additional non-trivial gauge multiplets
- Use the SNOWMASS points

	1	2	3	4	5
m_0 (GeV)	400	400	200	800	100
$M_{1/2}$ (GeV)	400	400	100	200	300
A_0 (GeV)	0	0	0	0	300
$\tan\beta$	2	10	2	10	2.1
sgn μ	$+$	$+$	$-$	$+$	$+$

Distinguishing Models

- 3 Observables:

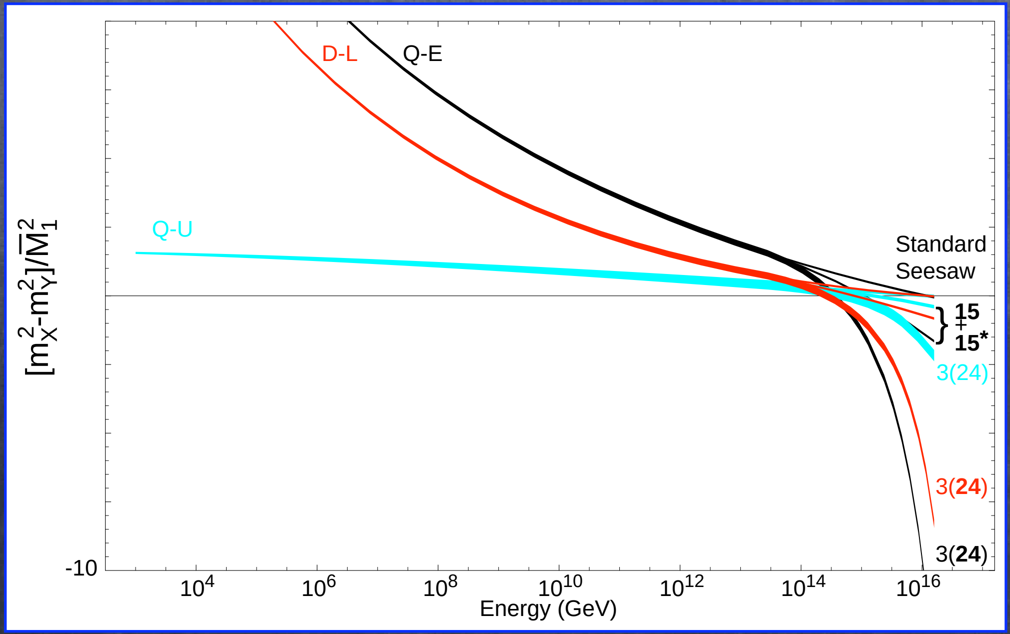
$$(m^2_{\tilde{Q}} - m^2_{\tilde{U}})/M_1^2(1\ \mathrm{TeV})$$
$$(m^2_{\tilde{Q}} - m^2_{\tilde{E}})/M_1^2(1\ \mathrm{TeV})$$
$$(m^2_{\tilde{D}} - m^2_{\tilde{L}})/M_1^2(1\ \mathrm{TeV})$$

- 3 Models to compare:

MSSM+ $3(\mathbf{1})$

MSSM+ $3(\mathbf{24})$

MSSM+ $\mathbf{15} + \bar{\mathbf{15}}$



Experimental Prospects

- Low energy measurement errors make unification hard to confirm.
- How well can we measure $\alpha_i, M_i, m_{\tilde{X}}$?

$\alpha_1^{-1}(M_Z)$	59.00 ± 0.02
$\alpha_2^{-2}(M_Z)$	29.57 ± 0.03
$\alpha_3(M_z)$	0.1213 ± 0.0018

- ILC expected to have 0.1% error on gaugino/slepton mass measurements.

Experimental Prospects

Squark Masses

- LHC: unknown Center-of-Mass energies
  - Mass edge measurements
  - LHC alone: 9 GeV error on 500 GeV squark.
  - Use ILC to reduce errors on neutralinos:

    ATLAS: 1% error

    CMS: 0.8% error
  - Main problem: 1% measurement error on jet energies at LHC

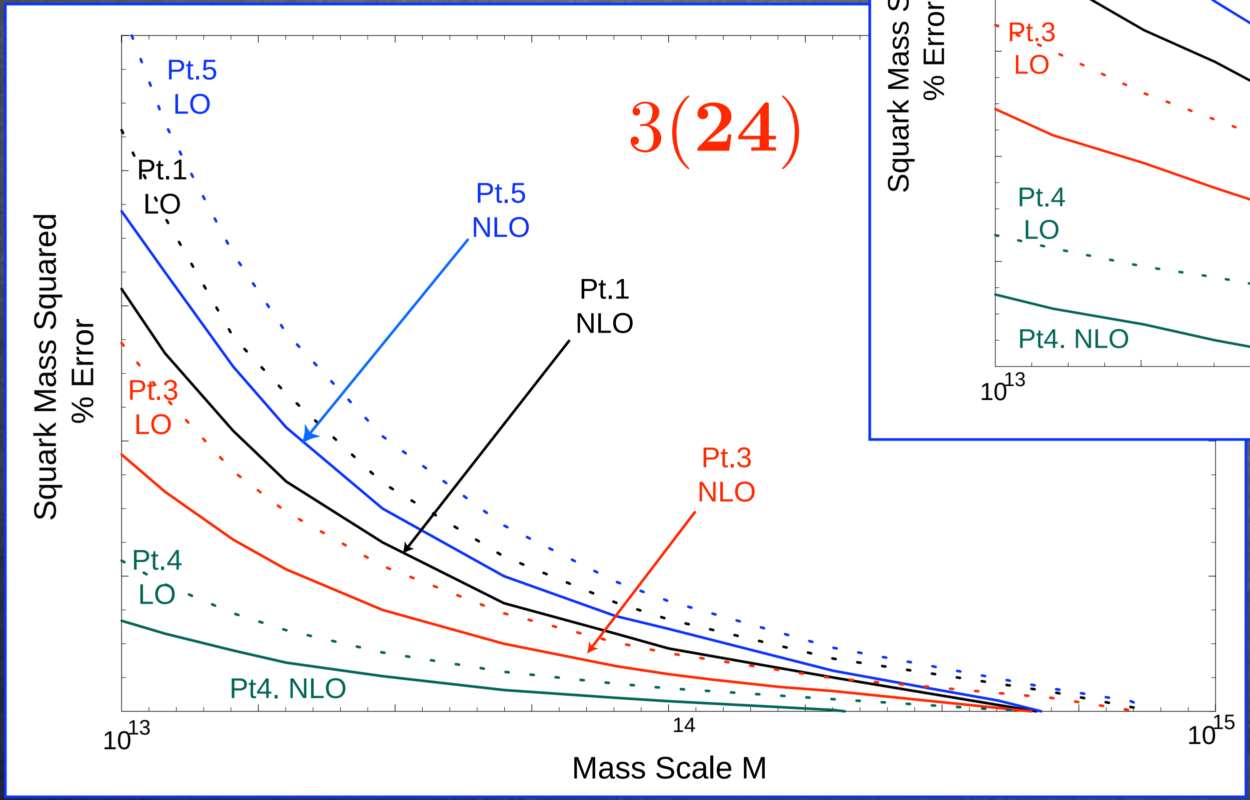
Experimental Prospects

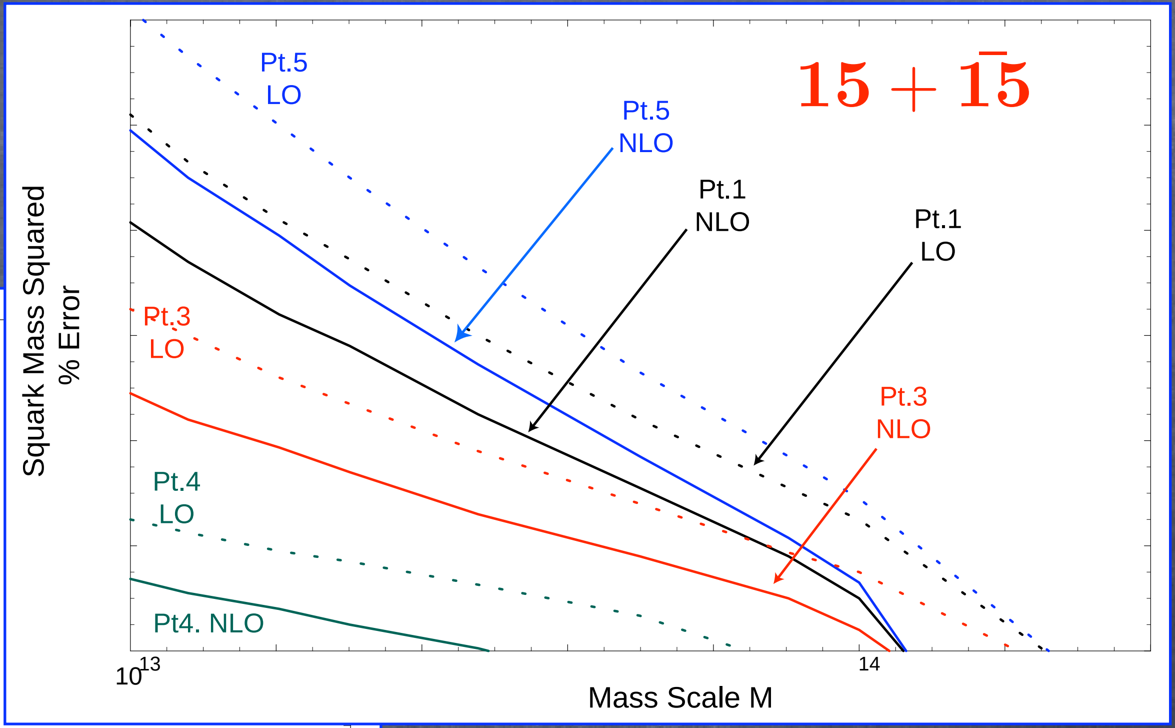
- ILC: searches haven't been optimized, backgrounds haven't been accounted for
  - Threshold scans: 0.5% error on left-handed, 0.5-1% error on right-handed
  - Use kinematics from both squarks in pair production to constrain mass: 0.4-1%
    - Depends greatly on number of available decay channels
- Optimistically, 1% error at LHC, 0.5% at ILC

Is this sufficient?

Experimental Reach

Maximum allowable error to distinguish model from standard seesaw (3σ)





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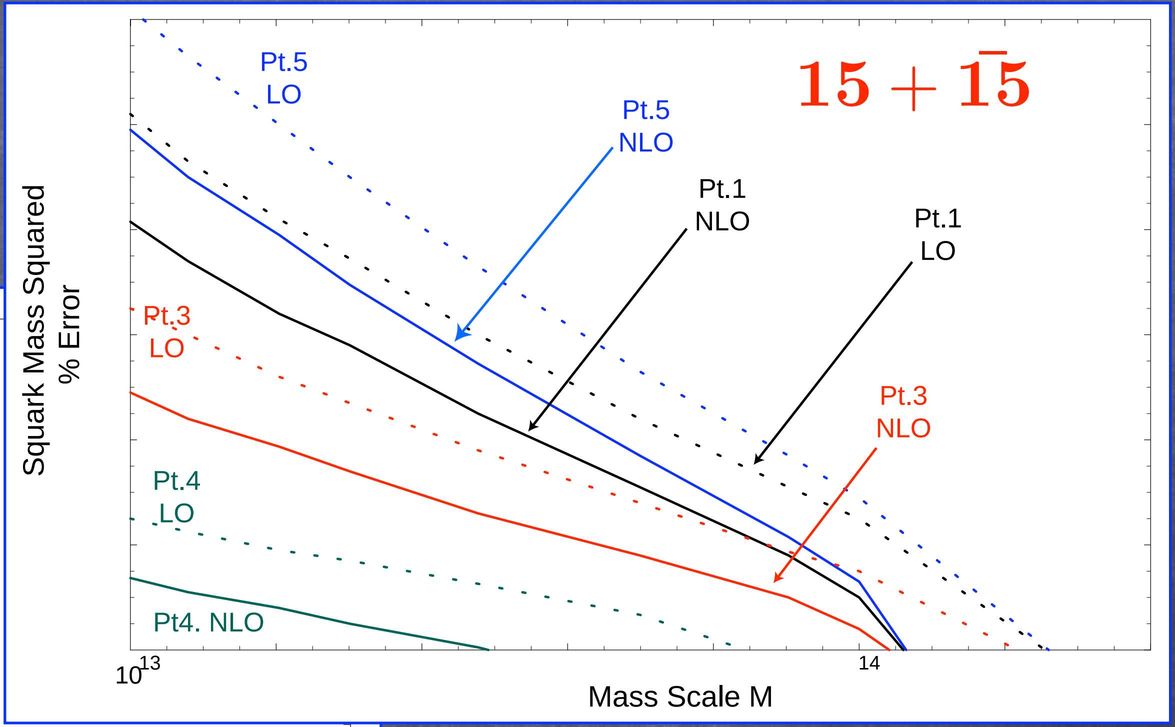

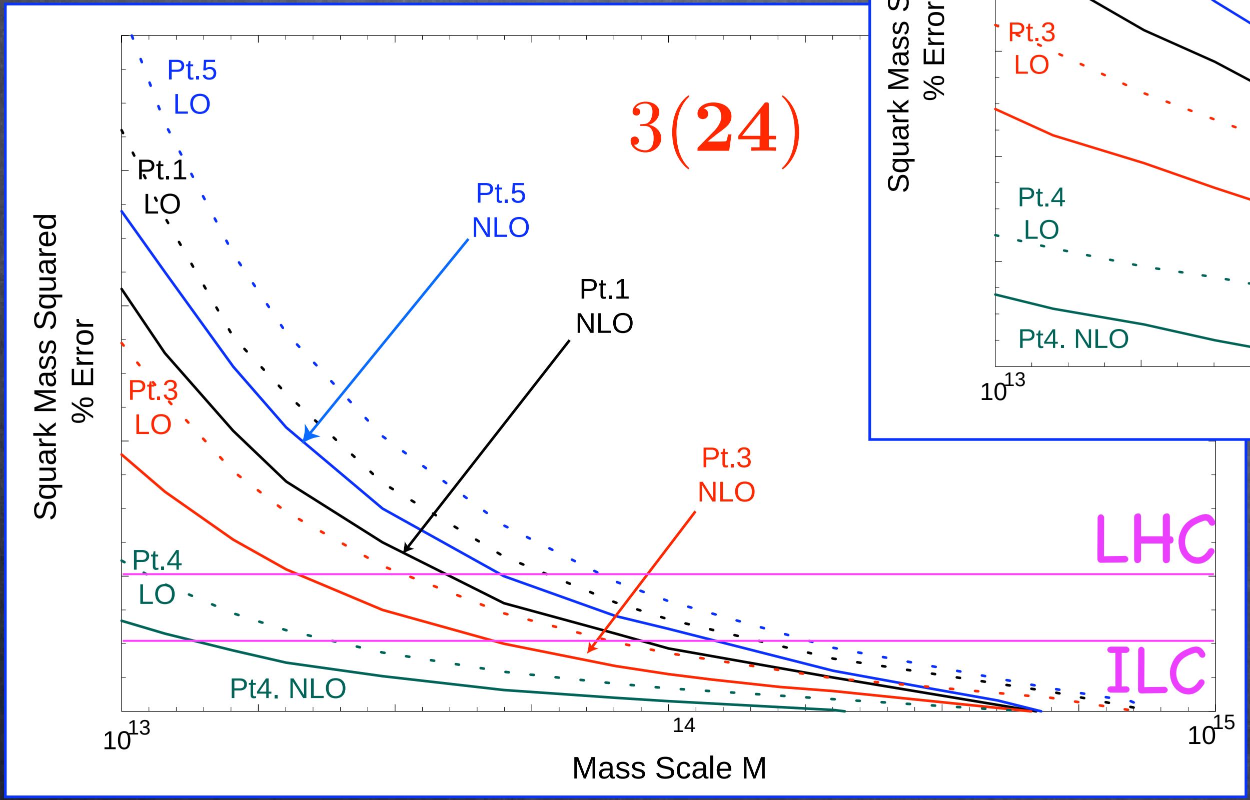

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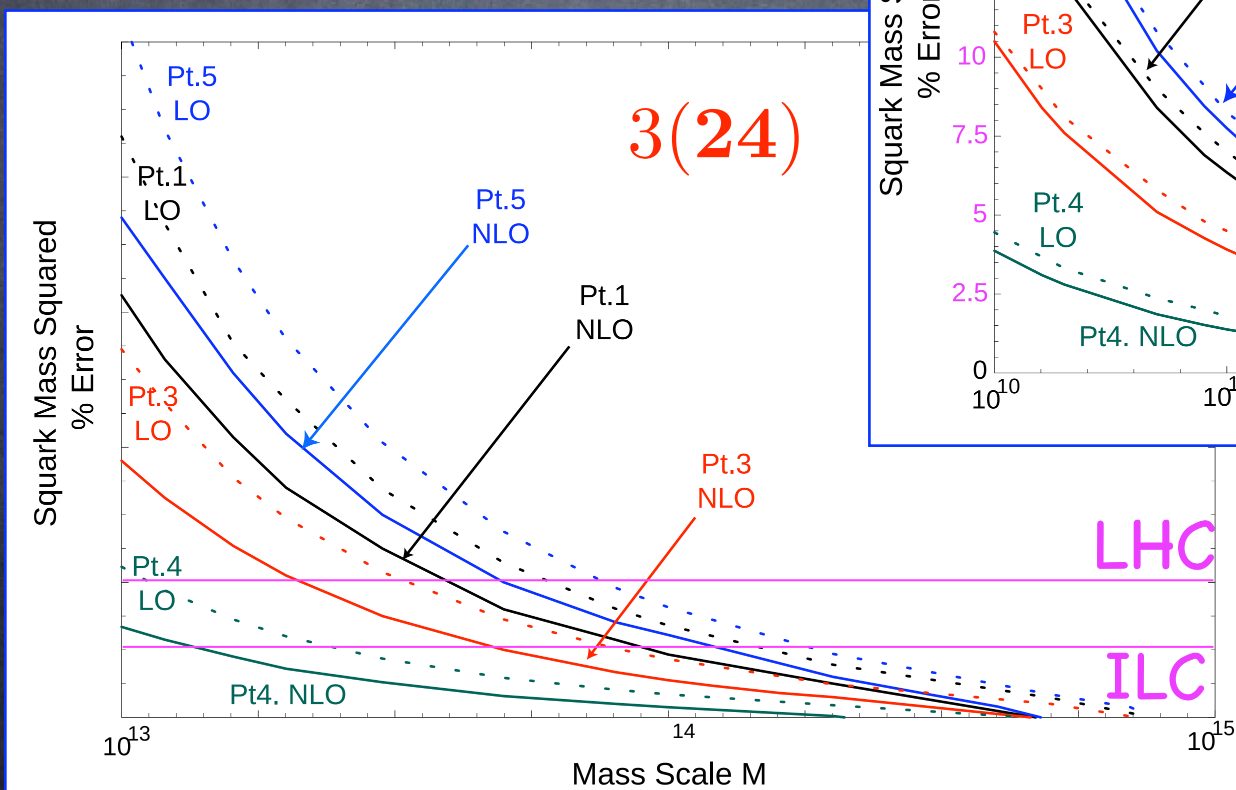

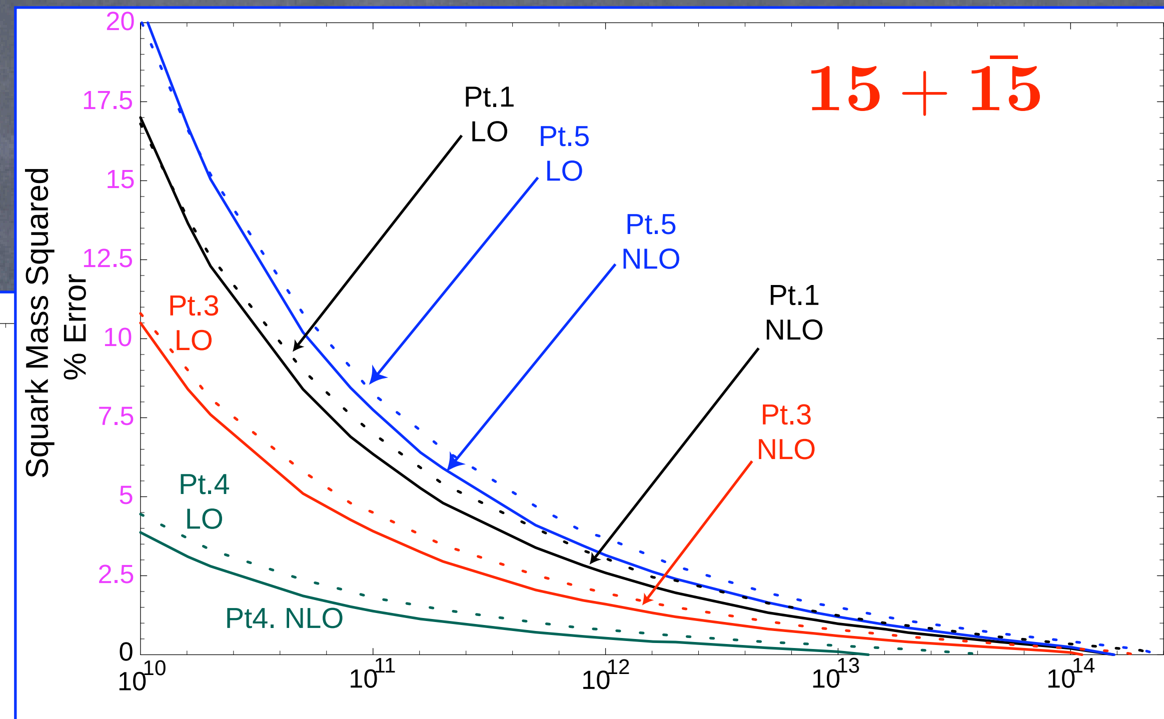

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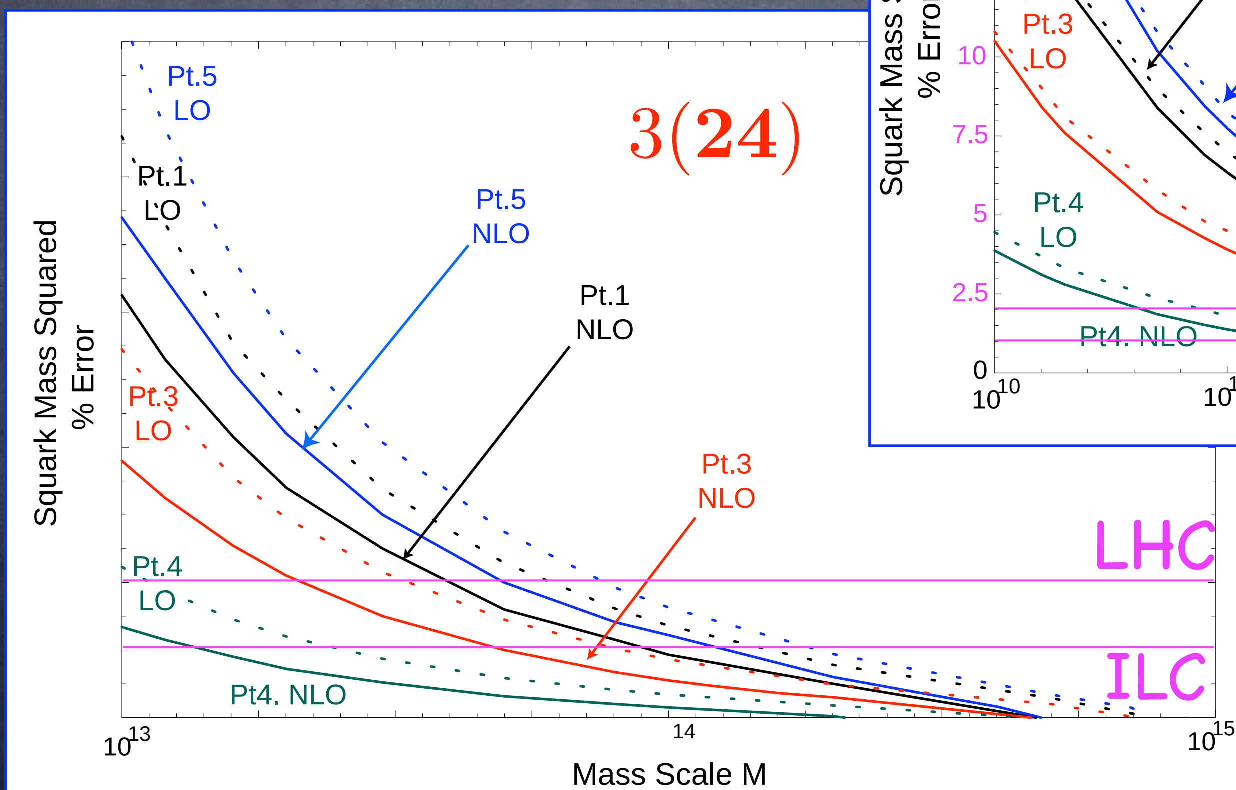

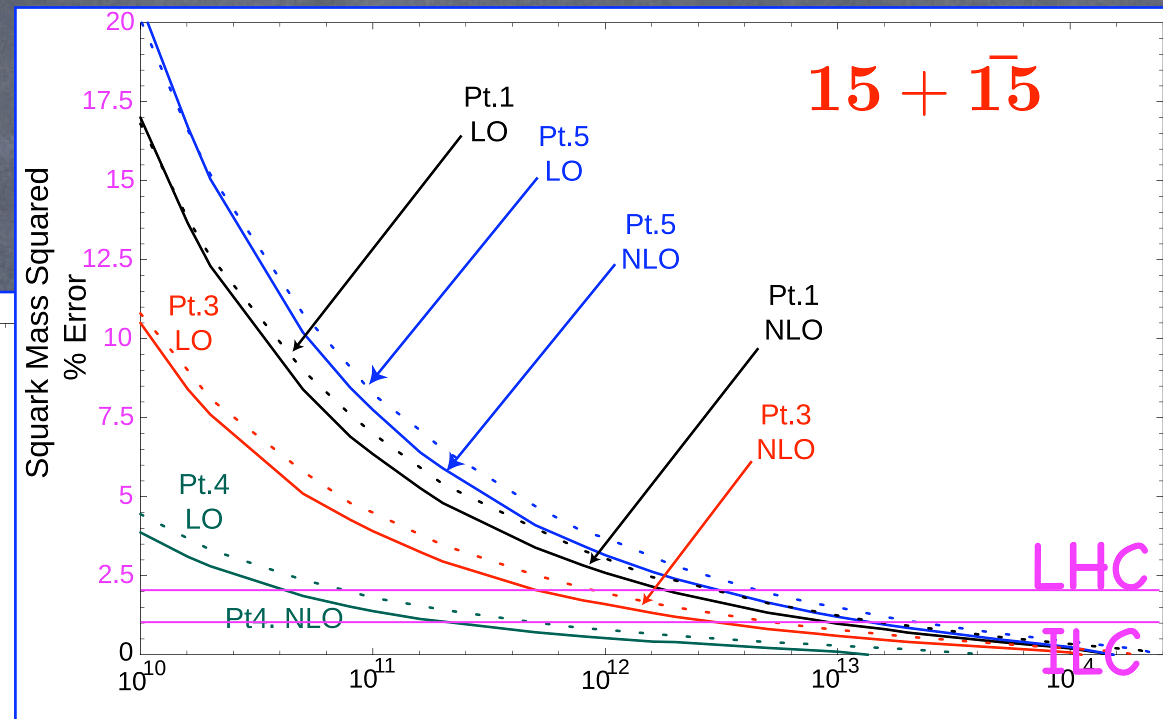

Leptogenesis

- If baryon asymmetry comes from thermal leptogenesis:
  - Can place limits on seesaw:
    $$10^9\ \mathrm{GeV} \lesssim M_N \lesssim 10^{11}\ \mathrm{GeV}$$
  - Model dependent: reheat temperature, neutrino spectrum, leptogenesis assumption...
    - BUT: Suggests M_N may fall in experimentally accessible region.

Conclusions

- Suppose we find: Majarona neutrinos, gravity-mediated supersymmetry and grand unification...
  - Then could rule out neutrino masses mediated by 24 reps of SU(5) up to $\sim 10^{14}$ GeV
  - Mediation by 15 reps ruled out up to $\sim 5 \times 10^{12}$ GeV
- Unlike lepton flavor violation, we will be able to tell if the high energy conditions are such that this method applies

Conclusions

- If we do not see unification, cannot conclude a non-standard seesaw mechanism.
- Experimental reach also strongly constrained by mSUGRA parameters:
  - Poor resolution when m_0^2 large
  - Large ~~SUSY~~ mass terms for new multiplets also a concern
- Method maybe applicable to theories with other high scale particle content (e.g. axions)