GRADUIERTENKOLLEG
Particle Physics at the Energy Frontier of New Phenomena

Constraining the see-saw with $\mu \longrightarrow e\gamma$

Cristoforo Simonetto

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Outline

Motivation

Experiment

Neutrino mixing $\Rightarrow$ small neutrino masses

Theory

Asymmetry in the particle content

Quarks		Leptons	
Q	$(3, 2, \frac{1}{6})$	L	$(1, 2, -\frac{1}{2})$
$\bar{d}$	$(\bar{3}, 1, \frac{1}{3})$	$\bar{e}$	$(1, 1, 1)$
$\bar{u}$	$(\bar{3}, 1, -\frac{2}{3})$		

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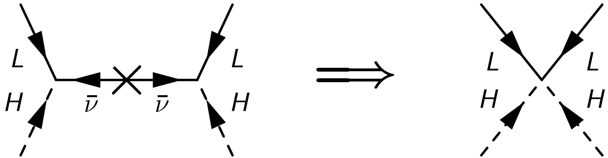
- $\mathrm{U}(1)$ charges such that Yukawa couplings are possible
- $\bar{\nu}$ is necessary for a complete $\mathrm{SO}(10)$ representation

Mechanism

- The most general Lagrangian

$$\mathcal{L}^{\text{int}} = + \bar{d}\mathbf{Y_d} Q H^* + \bar{u}\mathbf{Y_u} Q H + \bar{e}\mathbf{Y_e} L H^* + \bar{\nu}\mathbf{Y}_{\boldsymbol{\nu}} L H - \frac{1}{2}\bar{\nu}\mathbf{M}\bar{\nu}^T + \text{h.c.}$$

- Right-handed neutrino mass $\mathbf{M}$ naturally much larger than EW scale $\langle H^0 \rangle$
- Effective description



- At tree level

$$\bar{\nu}\mathbf{Y}_{\boldsymbol{\nu}} L H - \frac{1}{2}\bar{\nu}\mathbf{M}\bar{\nu}^T \quad \longrightarrow \quad -\frac{1}{2} H^* L^T \; \mathbf{Y}_{\boldsymbol{\nu}}^T \mathbf{M}^{-1} \mathbf{Y}_{\boldsymbol{\nu}} \; L H$$

Phenomenology

The see-saw mass formula

To break EW symmetry, the Higgs gets a vev $\langle H^0 \rangle$.
It results a (left-handed) neutrino mass

$$\mathcal{L}_{\text{eff}}^{\text{int}} \supset -\frac{1}{2}\nu_L^T \boxed{\langle H^0 \rangle^2 \mathbf{Y}_{\boldsymbol{\nu}}{}^T \mathbf{M}^{-1} \mathbf{Y}_{\boldsymbol{\nu}}} \nu_L \equiv -\frac{1}{2}\nu_L^T \boxed{\mathbf{m}_{\boldsymbol{\nu}}} \nu_L$$

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Discussion

- The (left-handed) neutrino mass is the only effect $\propto \frac{1}{\mathbf{M}}$
- "$\frac{2}{3}$" of the neutrino mass matrix $\mathbf{m_\nu}$ have been determined experimentally
- Other fermion masses $\propto \mathbf{Y} \langle H^0 \rangle$, neutrino mass $\propto \frac{1}{\mathbf{M}} \mathbf{Y}^2 \langle H^0 \rangle^2$
  $\Rightarrow$ Neutrinos are naturally much lighter
- Neutrino oscillation $\Rightarrow 10^{-2}$ eV $\lesssim \mathbf{m_\nu} \lesssim 1$ eV $\Leftarrow$ Tritium decay
- For $\mathbf{Y_\nu} \sim 1$ it follows 10^{13} GeV $\lesssim \mathbf{M} \lesssim 10^{15}$ GeV
- BUT: Higgs is naturally as heavy as the heaviest particle

Outline

Motivation

In the context of the see-saw

- See-saw works as in the SM
- SUSY is the only (viable, calculable) theory valid to high scales with a (technically) natural light Higgs
- The see-saw can lead to more effects

In general

- Only possibility to combine space–time and internal symmetries
- Gauge coupling unification
- Dark matter candidate
- ...

Basics of the νMSSM

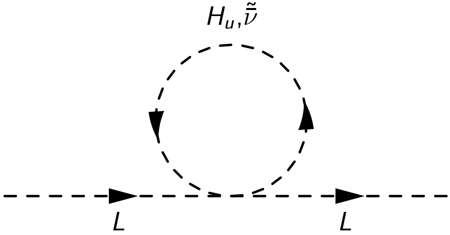
- double field content + second Higgs doublet

fermion	scalar
$Q, \bar{d}, \bar{u}, L, \bar{e}, \bar{\nu}$	$\tilde{Q}, \tilde{\bar{d}}, \tilde{\bar{u}}, \tilde{L}, \tilde{\bar{e}}, \tilde{\bar{\nu}}$
$\tilde{H}_d, \tilde{H}_u$	H_d, H_u
$\tilde{g}, \tilde{W}^{\pm}, \tilde{W}^0, \tilde{B}$	$g, W^{\pm}, Z^0, \gamma$

- SUSY couplings can be derived from SM couplings
- $\not{\mathrm{SUSY}}$ couplings depend on the breaking mechanism
- In the following we will focus on $\not{\mathrm{SUSY}}$ scalar masses $\tilde{L}^\dagger \mathbf{m_L^2} \tilde{L}$, $\tilde{\bar{e}} \mathbf{m_e^2} \tilde{\bar{e}}^\dagger$, $\tilde{\bar{\nu}} \mathbf{m_\nu^2} \tilde{\bar{\nu}}^\dagger$, ...
- Usual assumption $\mathbf{m_L^2}$, $\mathbf{m_e^2}$, $\mathbf{m_\nu^2}$,... $\propto \mathbb{1}$ at $\not{\mathrm{SUSY}}$ scale to satisfy constraints from flavor physics

Generation of $(\mathbf{m_L^2})_{21}$ via the RGEs

If $\not{\text{SUSY}}$ is mediated at a scale $\Lambda \gtrsim \mathbf{M}$



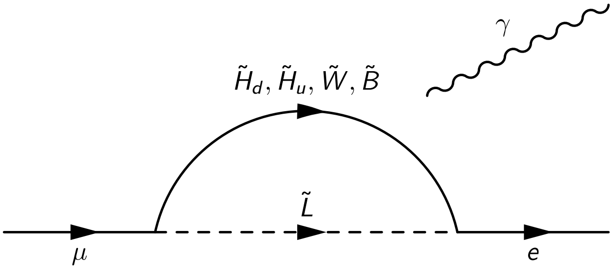
$$\mathbf{m_L^2}(\text{below } \mathbf{M}) \approx \mathbf{m_L^2}(\Lambda) - \frac{2}{16\pi^2}\left[\mathbf{m_L^2}(\Lambda) + \mathbf{m_\nu^2}(\Lambda) + \mathbf{m_{H_u}^2}(\Lambda)\right] \mathbf{Y}_\nu^\dagger \log\left(\frac{\Lambda}{\mathbf{M}}\right) \mathbf{Y}_\nu$$

$$\boxed{(\mathbf{m_L^2})_{21} \approx -\frac{6}{16\pi^2} m_{\text{SUSY}}^2 \left(\mathbf{Y}_\nu^\dagger \log\left(\frac{\Lambda}{\mathbf{M}}\right) \mathbf{Y}_\nu\right)_{21}}$$

Outline

1. The see-saw
   - Motivation
   - Mechanism
2. Supersymmetry
   - Motivation
   - Basics of the νMSSM
   - Generation of $(\mathbf{m}_{\mathbf{L}}^{2})_{21}$ via the RGEs
3. $\mu \longrightarrow e\gamma$
   - $\mu \to e\gamma$ in the νMSSM
   - Experimental status
4. Constraints on the see-saw
5. Summary

$\mu \longrightarrow e\gamma$ in the νMSSM



$$\mathrm{BR}(\mu \to e\gamma) \approx \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m_L^2})_{21}|^2}{m_{\mathrm{SUSY}}^8} \tan^2\beta$$

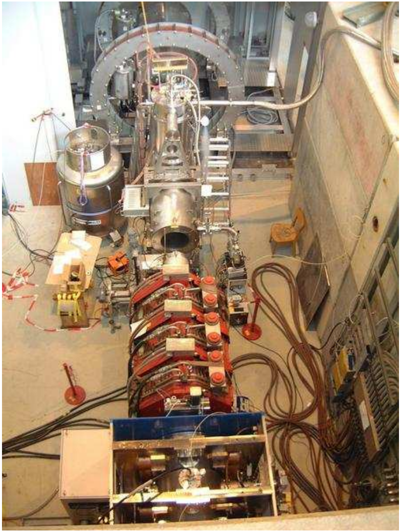
Experimental status

MEGA

- was running from 1993–1995 at the Los Alamos Laboratory
- collected $\sim 10^{14}$ muon decays
- no evidence for $\mu \to e\gamma$
- $\mathrm{BR}(\mu \to e\gamma) < 10^{-11}$

Experimental status

The MEG experiment



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MEG

- runs from end of 2008 at PSI in Switzerland
- 3 month have already been analysed corresponding to $\sim 10^{14}$ muon decays
- no evidence for $\mu \to e\gamma$
- Aim: $\mathrm{BR}(\mu \to e\gamma) < 10^{-13}$

Outline

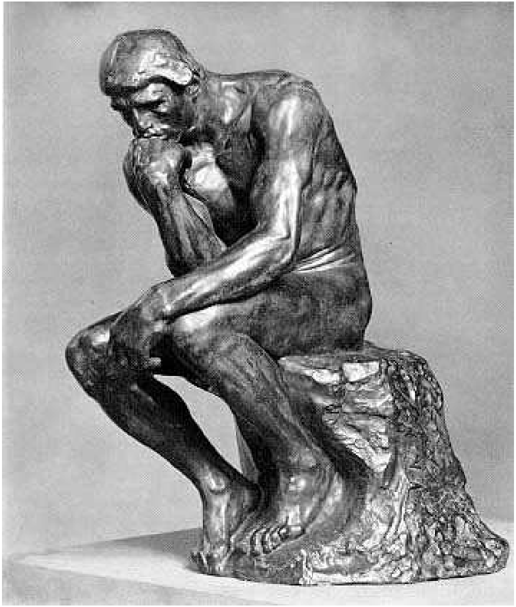
- See-saw mass formula: $\mathbf{m}_\nu = \left\langle H_u^0 \right\rangle^2 (\mathbf{Y_\nu}^T \mathbf{M}^{-1} \mathbf{Y_\nu})$
- Generation of $(\mathbf{m_L^2})_{21}$: $(\mathbf{m_L^2})_{21} \approx -\frac{6}{16\pi^2} m_{\mathrm{SUSY}}^2 \left(\mathbf{Y_\nu}^\dagger \log\left(\frac{\Lambda}{\mathbf{M}}\right) \mathbf{Y_\nu} \right)_{21}$
- Bound from $\mu \to e\gamma$: $10^{-11} > \mathrm{BR}(\mu \to e\gamma) \approx \frac{\alpha^3}{G_F^2} \frac{|(\mathbf{m_L^2})_{21}|^2}{m_{\mathrm{SUSY}}^8} \tan^2\beta$

+

Assumptions

- hierarchical $\mathbf{Y_\nu}$, i.e. $Y_1 \ll Y_2 \ll Y_3$
- Absence of cancellations

$\Downarrow$ Some algebra $\Downarrow$



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$$Y_1 \lesssim 4 \times 10^{-2} \left(\frac{\mathrm{BR}(\mu\to e\gamma)}{10^{-11}}\right)^{1/4} \left(\frac{m_{\mathrm{SUSY}}}{200\ \mathrm{GeV}}\right) \left(\frac{\tan\beta}{10}\right)^{-1/2}$$

$$M_1 \lesssim 5 \times 10^{12}\ \mathrm{GeV} \left(\frac{\mathrm{BR}(\mu\to e\gamma)}{10^{-11}}\right)^{1/2} \left(\frac{m_{\mathrm{SUSY}}}{200\ \mathrm{GeV}}\right)^2 \left(\frac{\tan\beta}{10}\right)^{-1}$$

Outline

Summary

Framework

- See-saw
- MSSM

} νMSSM

Underlying new physics searches

- Muon number violation: MEGA, MEG, PRISM/PRIME
- Supersymmetry: LHC

Result

Upper bound on

- the lightest right handed neutrino mass
- the smallest neutrino Yukawa coupling

Discussion

Two points of view:

- **Amazing!**
- **So what? Any consequence?**

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  $\longrightarrow$ **Learn about physics at very high scales!**

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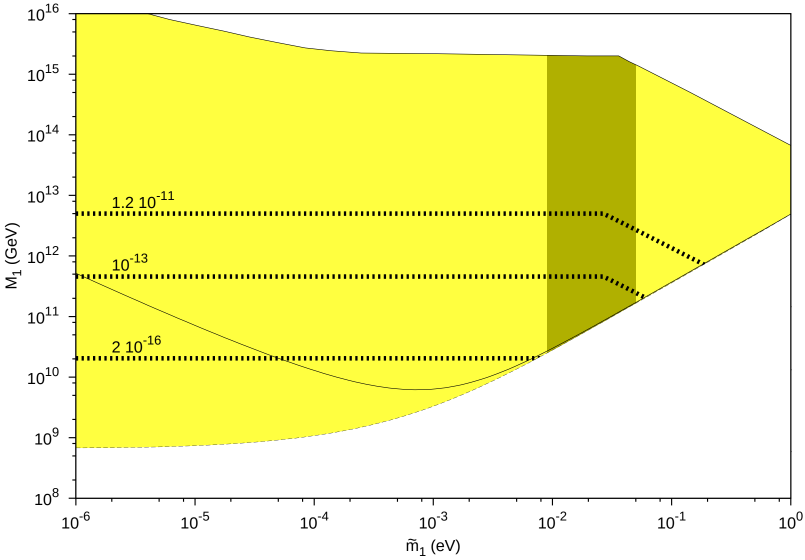
Two points of view:

- **Amazing!**

  $\longrightarrow$ **Learn about physics at very high scales!**

- **So what? Any consequence?**

  $\longrightarrow$ **Leptogenesis could be ruled out.**



10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
M_1 (GeV)
1.2 10^{-11}
10^{-13}
2 10^{-16}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
$\tilde{m}_1$ (eV)