Charged lepton flavor violation in type III seesaw

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Neutrino mass

- Neutrino oscillations

Δm^2_{21}	$7.6 \times 10^{-5} \mathrm{eV}^2$
$\lvert\Delta m^2_{31}\rvert$	$2.4 \times 10^{-3} \mathrm{eV}^2$
$\sin^2\theta_{12}$	0.3
$\sin^2\theta_{23}$	0.5
$\sin^2\theta_{13}$	0.01

⇒ at least 2 massive

- Beta decay & cosmology $m_\nu^{max} \lesssim \mathrm{eV}$

- Nature unknown: Majorana vs. Dirac

Whodunit?

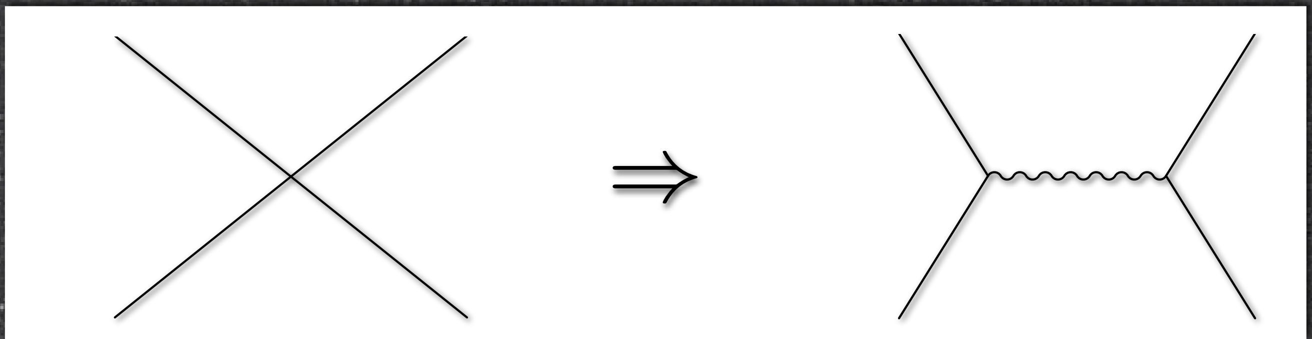
- Not the renormalizable SM

$$\nu_L \text{ only} \Rightarrow m_\nu = 0$$

- Non-renormalizable operators
  - d=5 Weinberg operator

$$\mathcal{O}_W = y_{ij} \frac{L_i H L_j H}{\Lambda}$$

  - Yukawa and scale unknown
- Analogous to Fermi



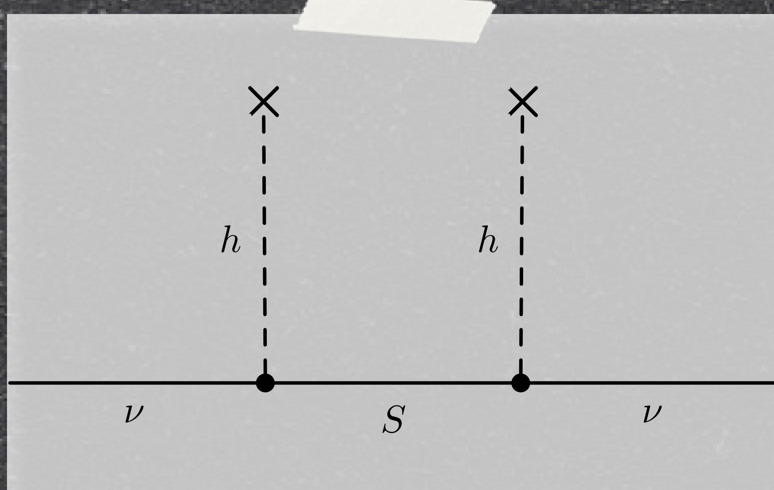
- What is the theory behind $\mathcal{O}_W$?

Seesaw

- Simplest way to get at tree level $\mathcal{O}_W$: add a single representation (fermion/boson)

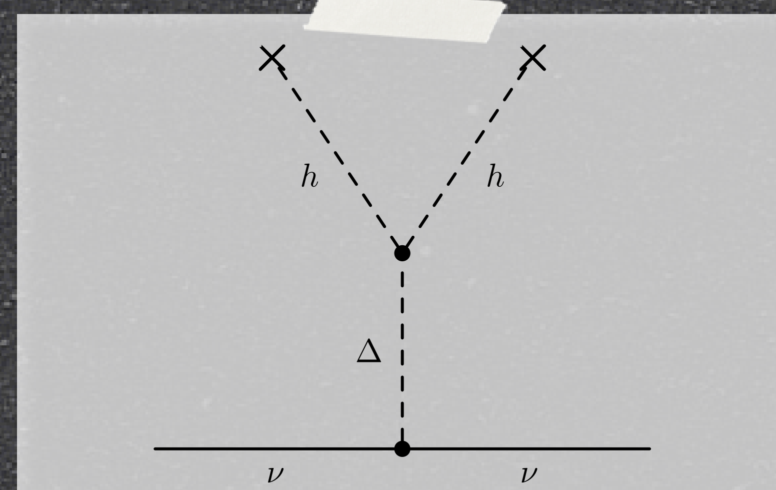
- Three different possibilities

(Ma, 80)



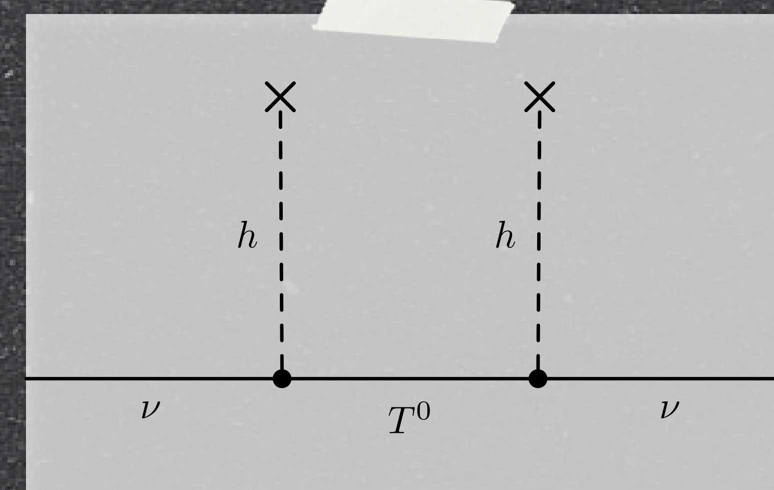
Type I

(Minkowski 77, Yanagida 79, Gell-Man, Ramond, Slansky 79, Mohapatra, Senjanović 80)



Type II

(Magg, Wetterich 80, Lazarides, Shafi, Wetterich 81, Mohapatra, Senjanović 81)



Type III

(Foot, Lew, He, Joshi, 89)

Testing the origin

- Seesaw as a language is arbitrary

$$m_\nu = -\frac{v^2}{2} Y^T M^{-1} Y$$

- A theory with seesaw is needed to constrain M and Y
- SO(10) and Pati-Salam usually at high scale
  - hard to probe, unless additional assumptions are made
- What about the simplest SU(5)?

Simple GUTs

- Simplest option based on SU(5) (Georgi, Glashow 74)
  - no unification of gauge couplings
  - neutrinos massless
  - wrong mass relations
- Minimal extension of SU(5)
  - add 15 Higgs, type II (Doršner, Perez 05)
  - add 24 Fermion, type I+III (Bajc, Senjanović 07)

Fermionic adjoint

$$24_F = (8,1)_0 + (3,1)_0 + (1,1)_0 + (3,2)_{\pm 5/6}$$

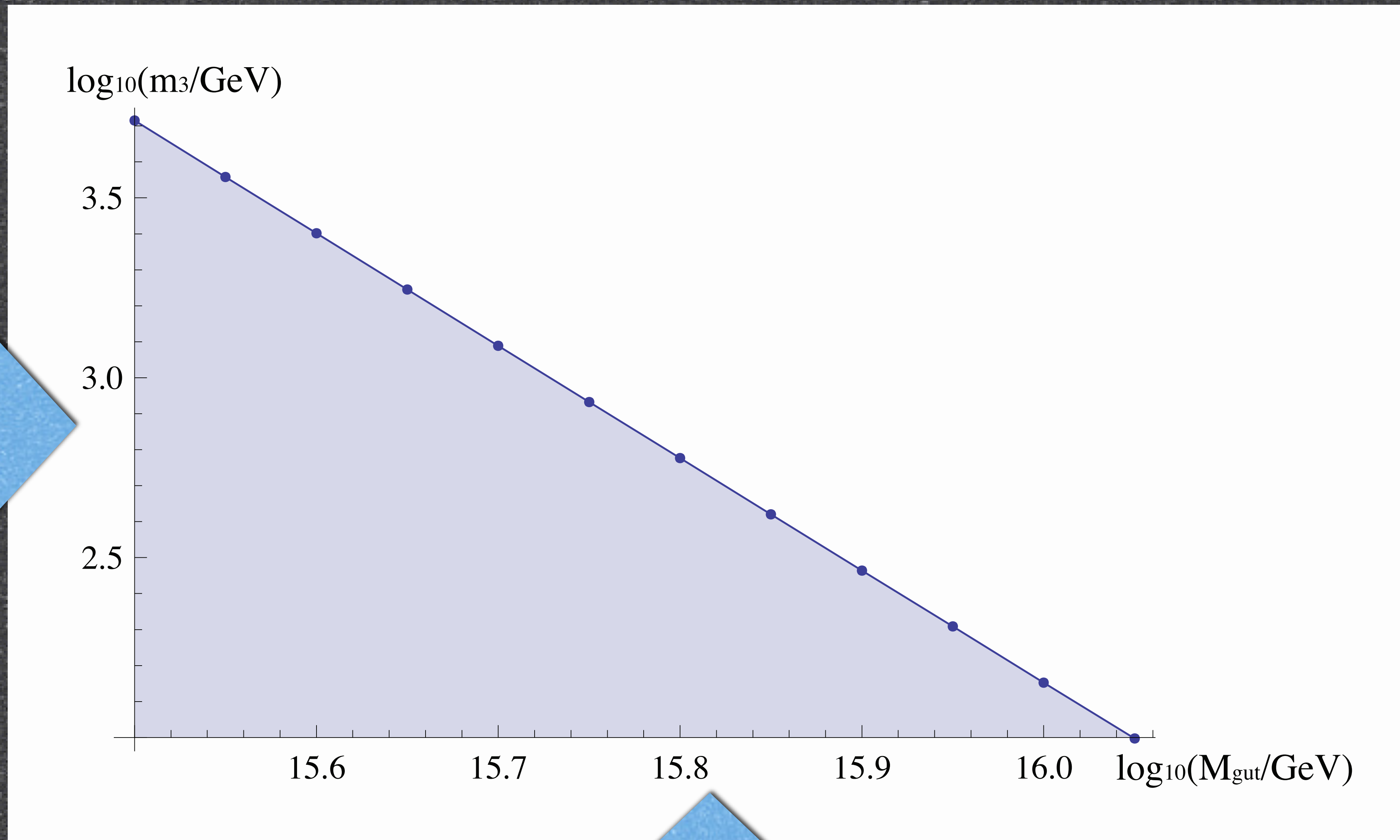
- Both triplet and singlet in one rep.

$$\mathcal{L}_\ell = y_S \overline{L} H S + y_T \overline{L} H T + m_T \overline{T} T + m_S \overline{S} S + \text{h.c.}$$

$$(m_\nu)_{ij} = -\frac{v^2}{2} \left(\frac{y_T^i y_T^j}{m_T} + \frac{y_S^i y_S^j}{m_S} \right)$$

- Rank 2, one neutrino massless, no 4th gen.
- Change in RGE => Unification constraints
- What are the mass scales?

p-decay



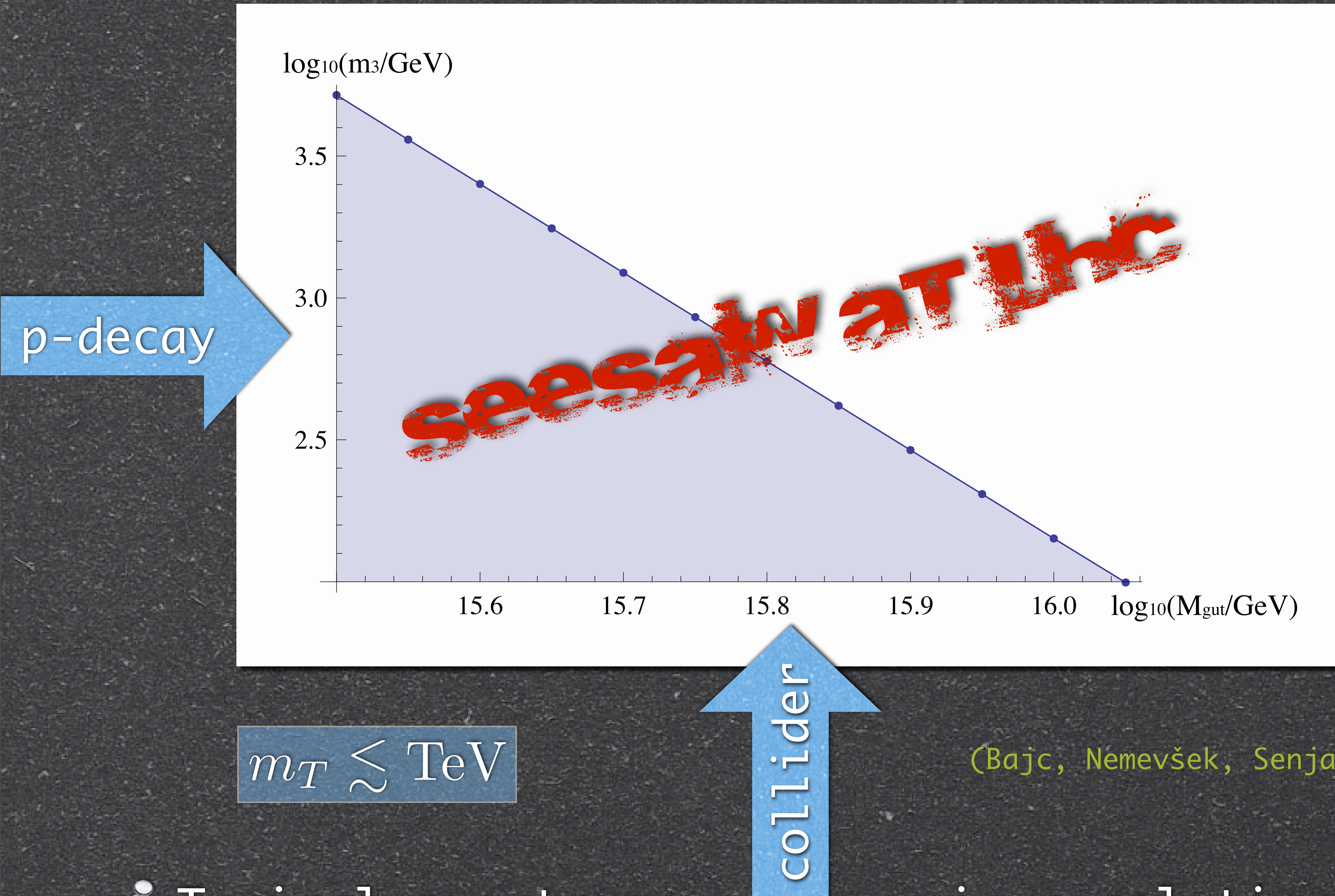
collider

$m_T \lesssim \mathrm{TeV}$

(Bajc, Nemevšek, Senjanović 07)

- Typical spectrum, unique solution

$$m_T \simeq 10^3\mathrm{GeV},\ m_8 \simeq 10^8\mathrm{GeV},\ m_{GUT} \gtrsim 10^{15.5}\mathrm{GeV}$$



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Triplet adjoint

- Yukawas in charged and neutral sector

$$M_\ell^{\rm diag} = U^{+\dagger} \begin{pmatrix} v\sqrt{2} y_\ell^{ij}\delta^{ij} & 0 \\ v y_T^i & m_T \end{pmatrix} U^-, \; \hat{M}_\nu^{\rm diag} = U^{0T} \begin{pmatrix} 0_{3\times 3} & v y_T^i & v y_S^i \\ v y_T^i & m_T & 0 \\ v y_S^i & 0 & m_S \end{pmatrix} U^0$$

- In the physical basis chiral and vector-like fermions mix
  - Suppressed right-handed couplings
  - FCNCs at tree level, non-unitary L^W

$$f_i = \left(e, \mu, \tau, T^-\right), \; f_i' = \left(\nu_e, \nu_\mu, \nu_\tau, T^0, S\right)$$

$$\mathcal{L}_{int} = -e\,\overline{f}_i \not{A} f_i + \frac{g}{c_w}\,\overline{f}_i \not{Z} (L^Z P_L + R^Z P_R)_{ij} f_j + g\,\overline{f}_i' \not{W}^+ (L^W P_L + R^W P_R)_{ij} f_j + \text{h.c.}$$

Feynman rules

- Interactions for type I+III (Kamenik, Nemevšek 09)
- General expressions, exact relations
- Arbitrary # of singlets/triplets

$$L^W_{ij} = U^{0*}_{\alpha i} U^-_{\alpha j}/\sqrt{2} + U^{0*}_{\beta i} U^-_{\beta j}$$
$$R^W_{ij} = U^0_{\beta i} U^+_{\beta j}$$
$$L^Z_{ij} = (s^2_w - 1/2) U^{-*}_{\alpha i} U^-_{\alpha j} - c^2_w U^{-*}_{\beta i} U^-_{\beta j}$$
$$R^Z_{ij} = s^2_w U^{+*}_{\alpha i} U^+_{\alpha j} - c^2_w U^{+*}_{\beta i} U^+_{\beta j}$$

- Non-unitarity of W => non universality of Z

$$\left(L^{W\dagger} L^W\right)_{ij} = -L^Z_{ij}, \quad i \neq j$$ same for R

- Helps understand W loops

Expansions

- Expand mixing matrices for small values of

$$\varepsilon_i = v\, y_T^i / m_T, \quad \varepsilon'_i = v\, y_T^i\, m_i / m_T^2$$

$$U^+ = \begin{pmatrix} 1-\frac{1}{2}|\varepsilon'_e|^2 & 0 & 0 & {\varepsilon'_e}^* \\ 0 & 1-\frac{1}{2}|\varepsilon'_\mu|^2 & 0 & {\varepsilon'_\mu}^* \\ 0 & 0 & 1-\frac{1}{2}|\varepsilon'_\tau|^2 & {\varepsilon'_\tau}^* \\ -\varepsilon'_e & -\varepsilon'_\mu & -\varepsilon'_\tau & 1-\sum_i \frac{1}{2}|\varepsilon'_i|^2 \end{pmatrix},$$

$$U^- = \begin{pmatrix} 1-\frac{1}{2}|\varepsilon_e|^2 & -\frac{1}{2}\varepsilon_e^*\varepsilon_\mu & -\frac{1}{2}\varepsilon_e^*\varepsilon_\tau & \varepsilon_e^* \\ -\frac{1}{2}\varepsilon_e\varepsilon_\mu^* & 1-\frac{1}{2}|\varepsilon_\mu|^2 & -\frac{1}{2}\varepsilon_\mu^*\varepsilon_\tau & \varepsilon_\mu^* \\ -\frac{1}{2}\varepsilon_e\varepsilon_\tau^* & -\frac{1}{2}\varepsilon_\mu\varepsilon_\tau^* & 1-\frac{1}{2}|\varepsilon_\tau|^2 & \varepsilon_\tau^* \\ -\varepsilon_e & -\varepsilon_\mu & -\varepsilon_\tau & 1-\frac{1}{2}\sum_i |\varepsilon_i|^2 \end{pmatrix},$$

- Gives the suppression for right-handed

$$R_{ij}^Z = 2\frac{m_i m_j}{m_T^2} L_{ij}^Z$$

- Similar expansion for U^0

Testing seesaw

- Reconstructing the neutrino mass matrix?
- Invert the seesaw (Casas, Ibarra 01)

$$y_T^i = \sqrt{m_T} U_{ij} \sqrt{m_\nu^j} O_{ji}$$

- Minimal case with two mediators (Ibarra, Ross 03)
- General orthogonal O one complex parameter z, no overall scale for light neutrinos
- Predicted low scale motivates
  - LHC searches, measuring decay rates
  - Look for LFV, get additional information

Collider search

- Search for a fermionic triplet at the LHC

  (del Aguila, Aguilar-Saavedra 08,
  Franceschini, Hambye, Strumia 07,
  Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović 09)

  - Drell-Yan production & same-sign dileptons
  - Reach of 450 (700) GeV for 10 (100)/fb
- Dominant decay rates sensitive to Yukawas

$$\Gamma(T^- \to Z e_i^-) = \frac{m_T}{32\pi} \left|y_T^i\right|^2 \left(1 - \frac{m_Z^2}{m_T^2}\right)^2 \left(1 + 2\frac{m_Z^2}{m_T^2}\right)$$

$$\sum_j \Gamma(T^- \to W^- \nu_j) = \frac{m_T}{16\pi} \sum_j \left|y_T^j\right|^2 \left(1 - \frac{m_W^2}{m_T^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_T^2}\right)$$

$$\Gamma(T^0 \to W^\mp e_i^\pm) = \frac{m_T}{32\pi} \left|y_T^i\right|^2 \left(1 - \frac{m_W^2}{m_T^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_T^2}\right)$$

$$\sum_j \Gamma(T^0 \to Z \nu_j) = \frac{m_T}{32\pi} \sum_j \left|y_T^j\right|^2 \left(1 - \frac{m_Z^2}{m_T^2}\right)^2 \left(1 + 2\frac{m_Z^2}{m_T^2}\right)$$

- Non-sensitive channel(s) slower

Lepton flavor violation

- Non-universal Z coupling leads to
  - Tree level on-shell $Z \to \ell_i \ell_j$
  - Tree level three body decays $\ell_i \to \ell_j \ell_k \bar{\ell}_l$
  - Tree level $\mu \to e$ conversion
  - Neutral meson decays $\pi^0 \to e\mu,\ J/\Psi \to \ell_i \ell_j \ldots$
  - Semileptonic τ decays $\tau \to h^0 \ell,\ h^0 = \pi^0, \eta^{(\prime)}, \Phi$
- Non-unitary W coupling (LFU)

$$\frac{h^0 \to e\nu}{h^0 \to \mu\nu}, \frac{h^0 \to e\nu}{\tau \to h^0 \nu}, \frac{h^0 \to e\nu}{\tau \to h^0 \nu}, h^0 = \pi, K$$

- Loop processes $\ell_i \to \ell_j \gamma$ and $(g-2)_\mu$

LFV continued

- Non-unitary of PMNS and rare processes studied also in type III
  (Antusch et al. 06, Abada et al. 07, Biggio, 08, He, Oh 09)
- We use the Ibara-Ross parametrization

$$v y_T^i = \sqrt{m_T}\left(U_{i1}\sqrt{m_\nu^1}\cos z + U_{i2}\sqrt{m_\nu^2}\sin z\right)$$
$$v y_S^i = \sqrt{m_S}\left(-U_{i1}\sqrt{m_\nu^1}\sin z + U_{i2}\sqrt{m_\nu^2}\cos z\right)$$

- Yukawa couplings grow with Im(z), a single parameter governs the size, Re(z) negligible
- Correlation between channels depend on measurable mixings, sensitive to the Majorana phase
- Signal possible with small neutrino mass, d=5 and d=6 decouple, but not arbitrarily
- Best channel $\mu - e$ constrains τ decays and y_S

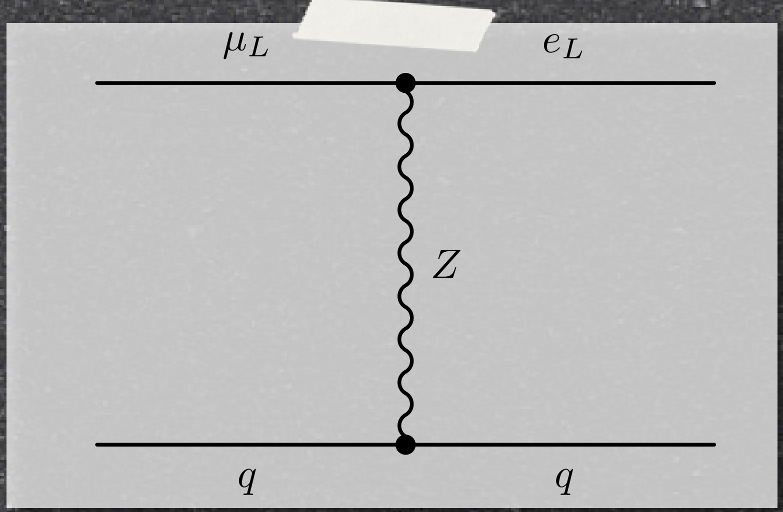
$\mu - e$ conversion

- Muonic atom is formed, search for a monoenergetic electron
- Low background (beam related), high precision
- Nuclear effects, rich physics
  (Czarnecki 97, Czarnecki, Marciano, Melnikov 99, Kuno, Okada 99)
- A detailed numerical calculation (Kitano, Koike, Okada 99)
- Different operators from high-energy theory considered (S, V, D)
- Published experimental bounds by SINDRUM II

Titanium	$< 4.3 \times 10^{-12}$	(Dohmen et al. 93)
Gold	$< 7 \times 10^{-13}$	(Bertl et al. 06)

Best limit in type III

- Conversion proceeds at tree level

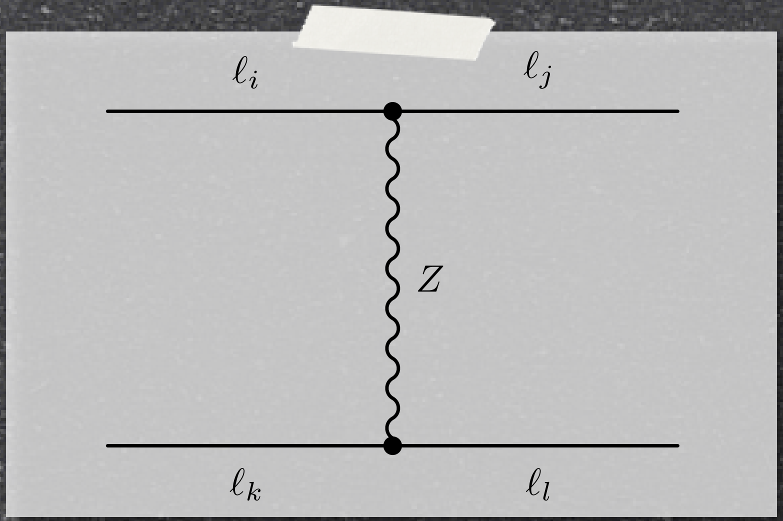


$$Br_{\mu e} \propto |L^Z_{12}|^2 + |R^Z_{12}|^2 < 10^{-15}$$

- Loops and Higgs small
- Sets the limit on Im(z) in minimal models with two mediators
- Im(z)<7.1(6.7) for one triplet and singlet at 100 GeV for normal (inverted) hierarchy
- Im(z)<6.4(6.1) for two triplets
- Depends on Majorana phase, not Re(z)
- Yukawa couplings $y^i_S \simeq y^i_T \lesssim 10^{-3.5}$

Rare decays

- Tree-level $\ell \to 3\ell$



$$\Gamma_{\ell_i \to \ell_{j \neq k} \ell_k \bar{\ell}_k} = \frac{G_F^2}{48\pi^3} m_{\ell_i}^5 \left(|L_{ij}^Z|^2 + |R_{ij}^Z|^2\right)\left(|L_{kk}^Z|^2 + |R_{kk}^Z|^2\right)$$

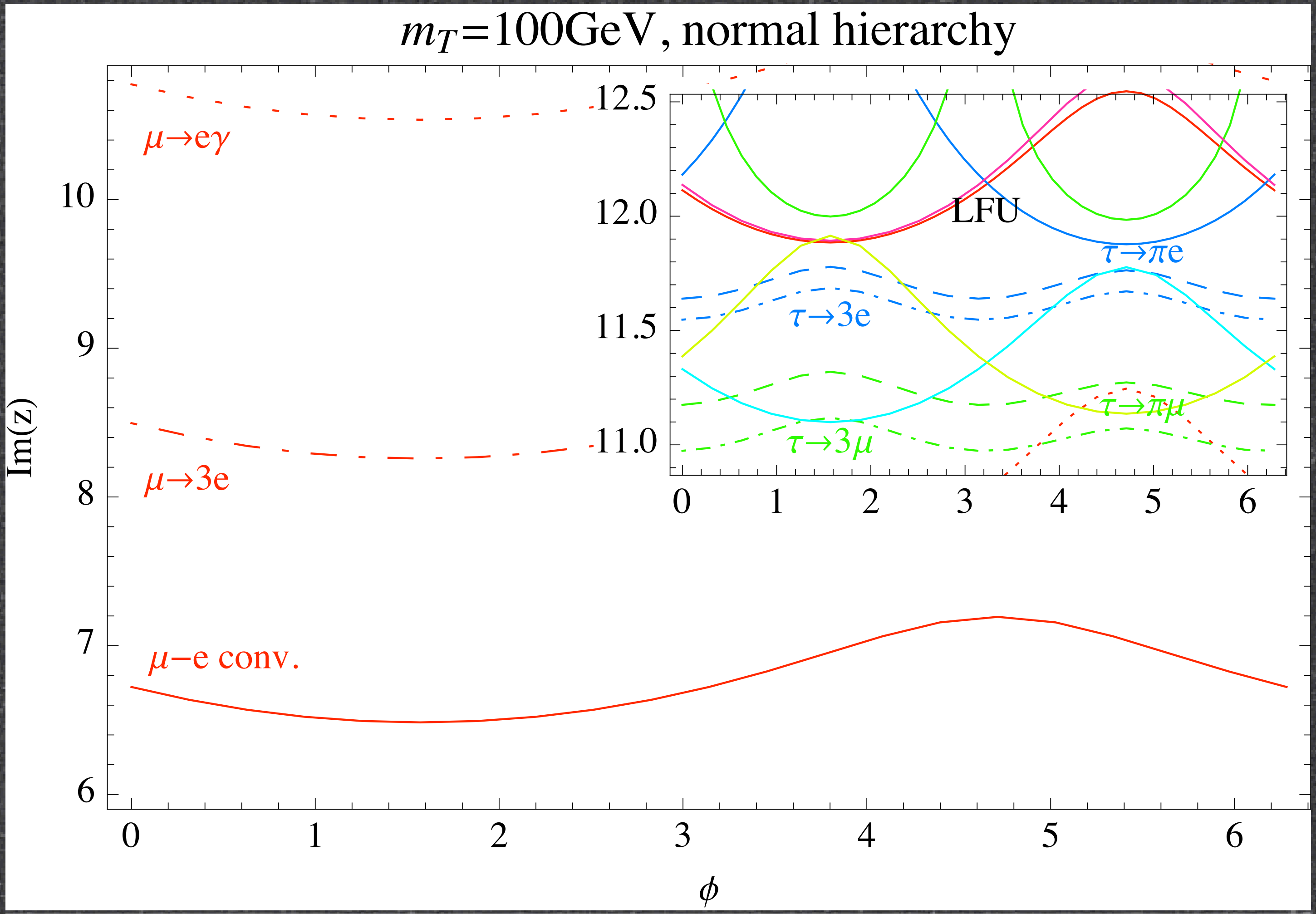
  - Experiment $Br_{\tau-\ell} \lesssim 10^{-8},\ Br_{\mu-e} < 10^{-12}$
  - Best bound for the τ channel

- Radiative decay $\ell \to \ell' \gamma$ (Kamenik, Nemevšek 09)
  - Calculated in R_ξ gauge
  - Arbitrary masses of external particles
  - Intricate cancellation of divergencies
  - Cancellation of $\xi_{w,z}$ in the finite parts
  - Arbitrary left&right couplings

Other channels

- Two parameters govern all channels
- Small singlet coupling, no production at colliders
- Observed tau decays rule out the model

process	Im(z)
$\mu - e$ conv.	< 7
$\ell \to 3\ell'$	< 8
$\ell \to \ell'\gamma$	< 10
$\tau \to h^0\ell$	< 11
$Z \to \ell\ell'$	< 12
LFU	< 12
$h^0 \to \ell\ell'$	< 14



Non-minimal models

- Adding more than two mediators
  - Overall neutrino scale unknown
  - Three complex parameters for O
- Some correlations remain, since O is summed over

$$L^Z_{e\mu} = \sum_{\alpha=1}^{n_T} \sum_{i,j=1}^{3} \left(\sqrt{m_i^\nu m_j^\nu} / m_\alpha \right) O_{\alpha i} O_{\alpha j} U_{ei} U_{\mu j}$$

  - tau can be larger, additional fine-tuning
- In non-minimal models a non-sensitive channel opens

$$\Gamma(T^\pm \to T^0 \pi^\pm) \simeq \frac{2 G_F^2 f_\pi^2 |V_{ud}|^2}{3\pi} \Delta m_T^3$$

Outlook

- Flavor effects in meson and tau decays hopeless
- Projections for MEG and search for $\mu \to 3e$

$Br_{\mu \to e\gamma} @ 10^{-14}$ $Br_{\mu \to 3e} @ 10^{-13}$

Limited by detector sensitivity

- Best hope is $\mu - e$ conversion
- Proposals by COMET/PRISM at J-PARC and Fermilab

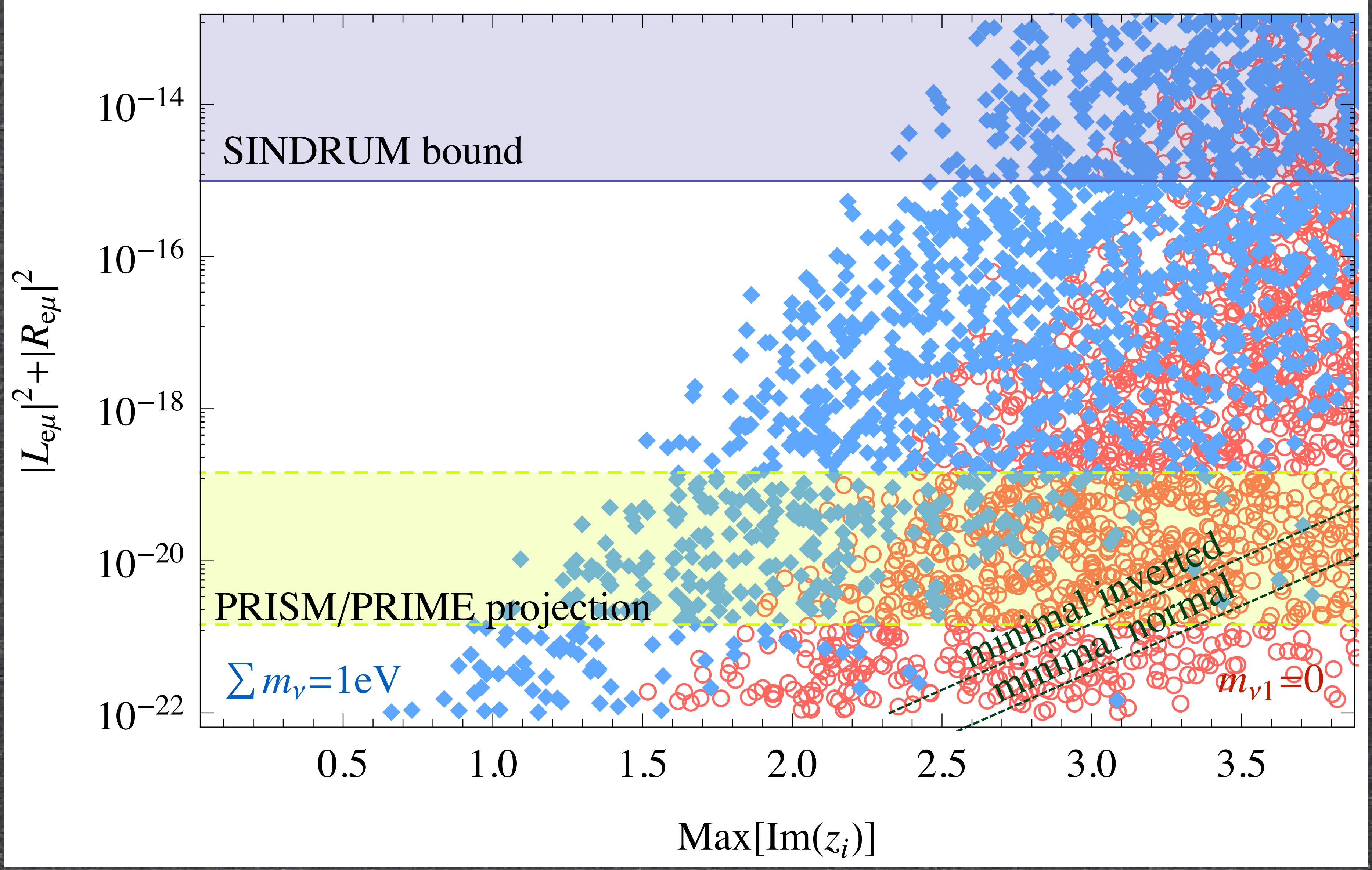
$Br_{\mu \to e} @ 10^{-16} - 10^{-18}$

Limited by the beam

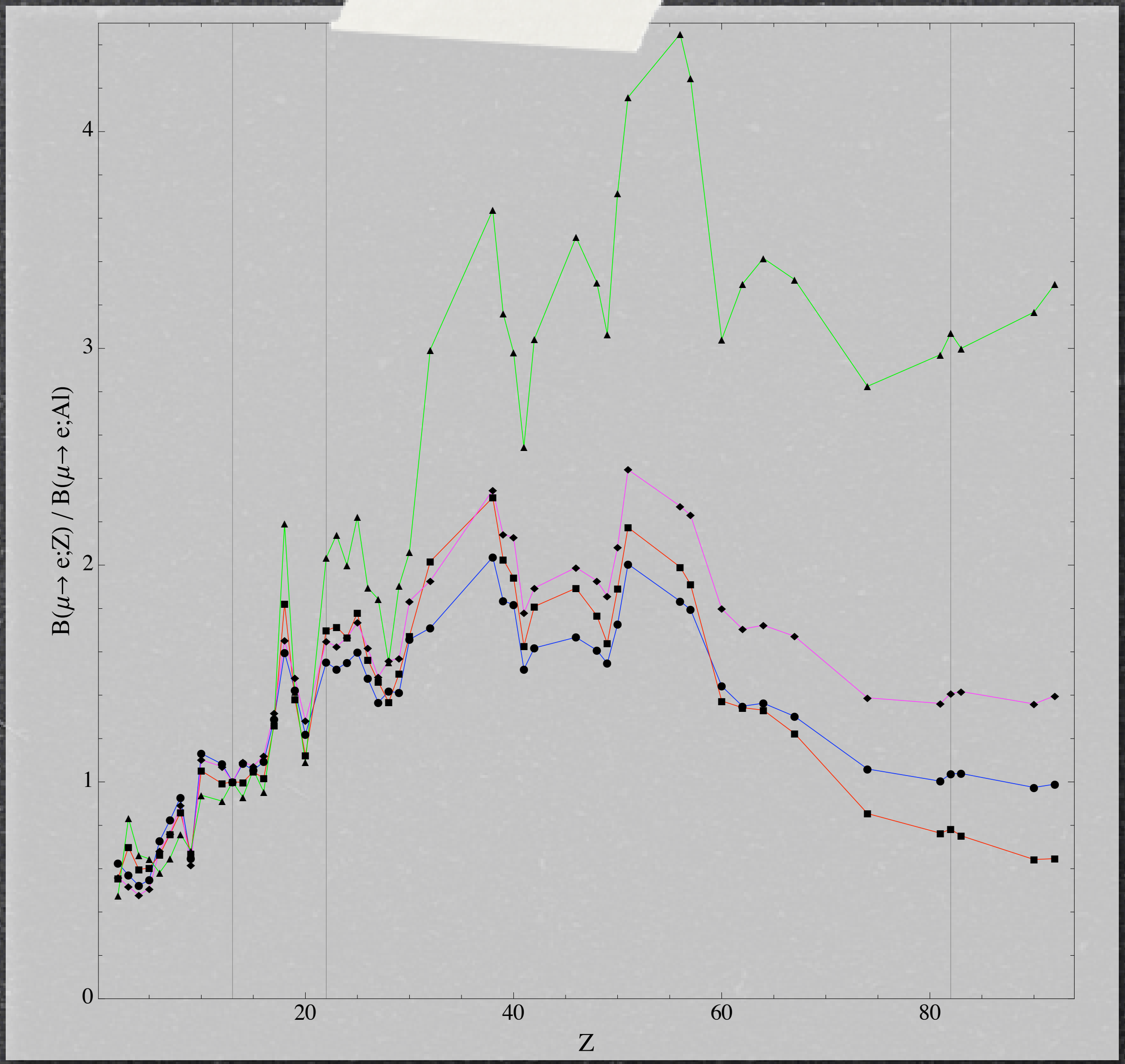
4-6 ORDERS OF MAGNITUDE!

Future sensitivity

- Probes Im(z) around 3 for minimal models
  - a signal fixes triplet ratios at LHC! (Bajc et al. 07)
- Im(z) < 1 for three triplets, natural Yukawas



Additional info



- Conversion rate is nucleus-dependent

  (Kitano, Koike, Okada 99)

- One mediator hypothesis testable with
  - 5% precision (two light)
  - 20% precision (light-heavy)

  (Cirigliano, Kitano, Okada, Tuzon 09)

- Polarized muons give information on CP phases

  (Davidson 08, Ayazi, Farzan 08)

- Hopeless for seesaw,very exciting for left-right

  (Bajc, Nemevšek, Senjanović 09)

Conclusions

- Minimal extension of SU(5)
  - add a fermionic adjoint
  - fix unification with a light weak triplet
  - proton decay constrains m_T < TeV
- Type I+III seesaw at low scale
  - produce triplets at LHC
  - reach of 450 - 700 GeV
  - decays measure Yukawa couplings
- Ibarra-Ross parametrization
  - a single complex parameter => correlations

Conclusions

- LFV in minimal models
  - governed by a single Im(z)
  - best channel mu-e conversion
  - constrains tau channels and singlet production
- Non-minimal models
  - more freedom, less tight correlations
  - possible future signal with natural Yukawas
- Additional discrimination possible
  - test different nuclei
  - measure polarization

Thank you!