Signatures of low scale type I+III See-saw models

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1 June 2010

[Planck '10, CERN]

See-saw

- With the degrees of freedom of the SM
- ν masses parametrized by Weinberg d = 5 effective operator

$$\mathcal{O}_\nu^{d=5} = y_\nu^{ij} \frac{L_i H L_j H}{\Lambda}$$

S. Weinberg, PRL43 (1979)

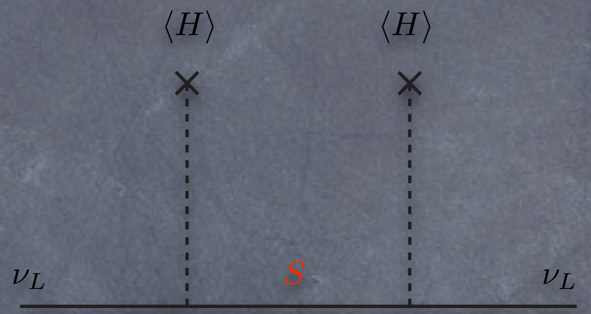
- In the basis with diagonal charged leptons

$$\frac{v^2}{\Lambda} y_\nu^* = U_{PMNS} m_\nu^{diag} U_{PMNS}^T$$

  - y describes the flavour structure
  - Λ signals the appearance of new physics
- Only 3 ways of producing the Weinberg operator at tree-level*
  - by exchange of 3 types of heavy particles

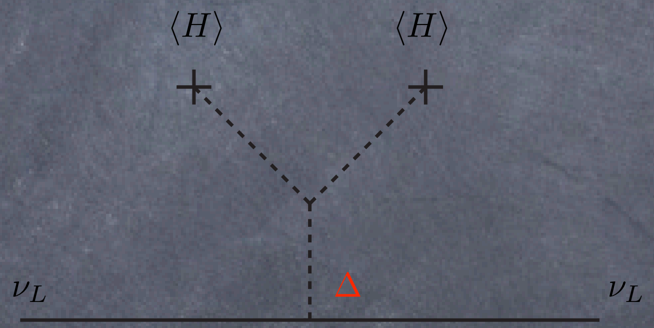
See-saw

- fermion singlet S = (1, 1, 0) TYPE I SEESAW



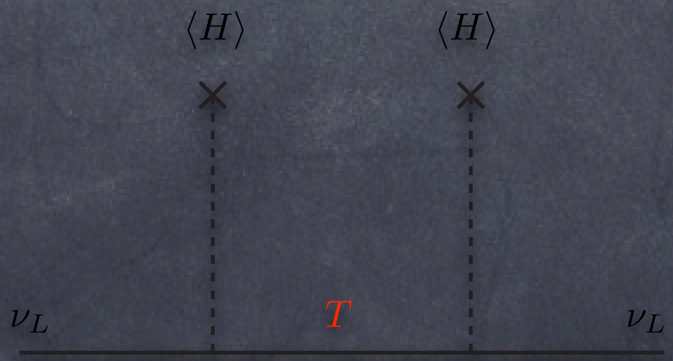
Minkowski, PLB67 (1977)
Gell-Mann, Ramond, Slansky, Rev. Mod. Phys. 50 (1978)
Glashow, NATO Adv. Study Inst. Ser. B Phys. 59 (1979)
Yanagida, Prog. Theo. Phys. 64 (1980)
Mohapatra and G. Senjanovic, PRL44 (1980)

- boson weak triplet Δ = (1, 3, 2) TYPE II SEESAW



Magg, Wetterich, PLB94 (1980)
Lazarides, Shafi and Wetterich, NPB181 (1981)
Mohapatra, Senjanovic, PRD23 (1981)

- fermion weak triplet T = (1, 3, 0) TYPE III SEESAW



Foot, Lew, He, Joshi, Z.Phys.C44 (1989)

Testable See-saw

- Neutrinoless double beta - probes the Weinberg operator (however, also other NP contributions are possible)

$$\mathcal{O}_\nu^{d=5} = y_\nu^{ij} \frac{L_i H L_j H}{\Lambda}$$

c.f. Mohapatra,
Senjanovic,
PRD23 (1981)

- Integrating out heavy mediators produces dim-6 operators - suppressed by the same scale Λ
- Generically, GUT models predict $\Lambda \leq \Lambda_{GUT}$
  - Difficult to probe the origin of the mass operator directly at a collider
  - Tiny effects due to dim-6 operator contributions
    - decouple faster than dim-5

Testable See-saw

- TeV - scale see-saw can be probed
  - Direct production of mediators at the LHC
  - LFV effects at low energies
- Under what conditions?
  - Light mediators -> tiny Yukawa eigenvalues
  - Need other (gauge) couplings for efficient production
    - Type II or III
  - Large LFV effects typically require some fine-tuning but are possible
    - U_{PMNS} non-unitary in type I, III
    - Charged LFV processes at tree level in type III

del Aguila, Aguilar-Saavedra, Pittau, hep-ph/0703261
Franceschini, Hambye, Strumia, 0805.1613
del Aguila, Aguilar-Saavedra, 0808.2468
Arhrib et al., 0904.2390

Abada et al., 0707.4058
He & Oh, 0902.4082
Arhrib, Benbrik and Chen, 0903.1553
J.F.K. & Nemevsek, 0908.3451

Antusch et al. hep-ph/0607020

General parametrization of "minimal" see-saw models

- Consider type III (two triplets) and mixed I+III (singlet and triplet) scenarios

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

- The lightest neutrino is massless and there is only one physical Majorana phase
- Ibarra-Ross parameterization applies (e.g. for inverted hierarchy): Ibarra & Ross, hep-ph/0307051

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

- The size of the Yukawa couplings determined by single complex parameter z
  - Increases exponentially with Im(z) (Re(z) becomes irrelevant as Im(z)>>1)
- LFV effects can become visible due to possible cancellations
  - The higher the seesaw scale, the more severe fine-tuning is needed
- Measuring lightest mediator decays constrains z, θ_{13}, phases δ, Φ

Low-energy phenomenology

Antusch et al. hep-ph/0607020
Abada et al., 0707.4058
C. Biggio, 0806.2558
He & Oh, 0902.4082
Arhrib, Benbrik and Chen, 0903.1553
J.F.K. & Nemevsek, 0908.3451

Diagonalization of the neutral and charged lepton mass matrices

- produces mixing of chiral and vector-like fermions
- alters interactions with W, Z ($f_i=(e,\mu,\tau,T^-)$, $f_j'=(\nu_1,\nu_2,\nu_3,T^0,S)$)

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

Tree-level Z-mediated LFV

- LFV lepton decays: μ->3e, τ->3μ, τ->eeμ, τ->μμe
- μ-e conversion in nuclei
- LFV semileptonic tau decays: $\tau\to h^0 e$, $\tau\to h^0\mu$, ($h^0=\pi^0,\eta^{(\prime)},\phi$)
- Leptonic Z decay width at LEP: Z->ll′

Tree-level LFU violation in charged currents:

- GF determination from muon lifetime
- At low energies: (h->μν)/(h->eν), (τ->hν)/(h->eν), (τ->hν)/(h->μν), (h=π,K)
- At colliders: (W->lν)/(W->l′ν)

Loop-induced

- LFV: μ->eγ, τ->eγ, τ->μγ
- Anomalous lepton magnetic moments: (g-2)μ

- In minimal models all effects predicted and correlated in terms of (m_T, m_S, Im(z))
- The most stringent bound fixes all other low-energy phenomenology for all lepton families

Bounds

- The strictest bound on the μeZ coupling is obtained by the μ-e conversion in a nucleus

$$Br_{\mu e} = \Gamma_{conv.}/\Gamma_{capture};$$

$$Br_{\mu e}^{Au} < 7 \times 10^{-13} \,@\, 90\% \, CL$$
$$Br_{\mu e}^{Ti} < 4.3 \times 10^{-12} \,@\, 90\% \, CL$$

SINDRUM II,
PLB317 (1993);
Eur.Phys.J. C47 (2006);

  - Tree-level Z exchange dominates

$$\boxed{|L_{12}^Z|^2 + |R_{12}^Z|^2 < 10^{-15}}$$

Kitano, Koike & Okada, hep-ph/0203110
J.F.K. & Nemevsek, 0908.3451

    - Im(z) < 7.5(7.1) for one triplet and one singlet [normal (inverted) hierarchy at m_S=m_T=100GeV]
    - Im(z) < 7.1(6.7) for two triplets
  - Mild dependence on θ_{13} and the unknown phases (Φ)
    - bounds obtained by varying in allowed ranges

Bounds

- Comparison of bounds:

Process	Bound on Im(z) ($m_T=100$GeV)
μ-e conv.	<7
l->3l′	<8
l->l′γ	<10
τ->hl	<11
Z->ll′	<12
LFU	<12

τ -> 3 l give the best tau-e and tau-μ bounds*

Radiative LFV decays are suppressed

More constrained at low energies than direct W measurements

Other observables studied, found not relevant (h->ll′, $(g-2)_\mu$,...)

- Differences between normal/inverted hierarchy and III vs I+III scenarios not crucial (in the minimal models)
- Mild dependence on the Majorana phase (θ_{13}, δ irrelevant)
- Im(z) sensitivity logarithmic!

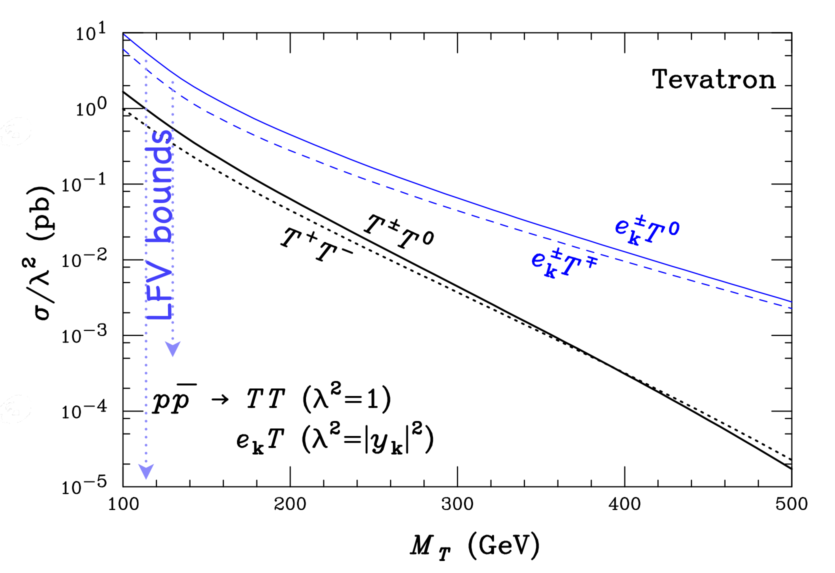
*Relevant for non-minimal models

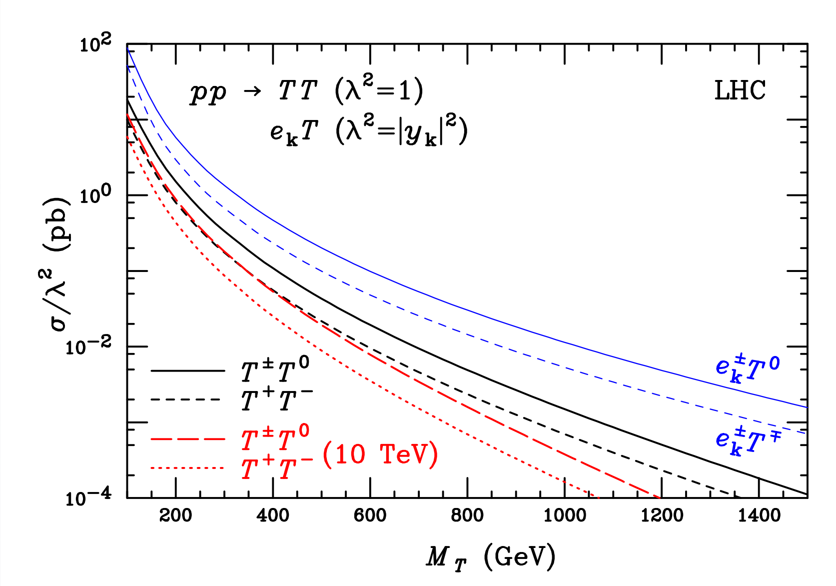
Production and detection of lightest triplet at colliders

Arhrib et al., 0904.2390

- Searches for heavy charged fermions at LEP constrain $m_T > 100$ GeV
- In minimal models, triplet life-time bounded from above:
  - $\tau_T < 0.5$ mm $(200\text{GeV}/m_T)^2$ (for NH; 5.6 times shorter in IH)
  - Possibly displaced (secondary) vertices, no charged tracks
- Drell-Yan type production:

$$q\bar{q}' \to W^{*\pm} \to T^{\pm}T^{0}, \quad q\bar{q}' \to W^{*\pm} \to T^{0}\ell^{\pm},$$
$$q\bar{q} \to \gamma^{*}, Z^{*} \to T^{+}T^{-}, \quad q\bar{q} \to Z^{*} \to T^{\pm}\ell^{\mp}.$$

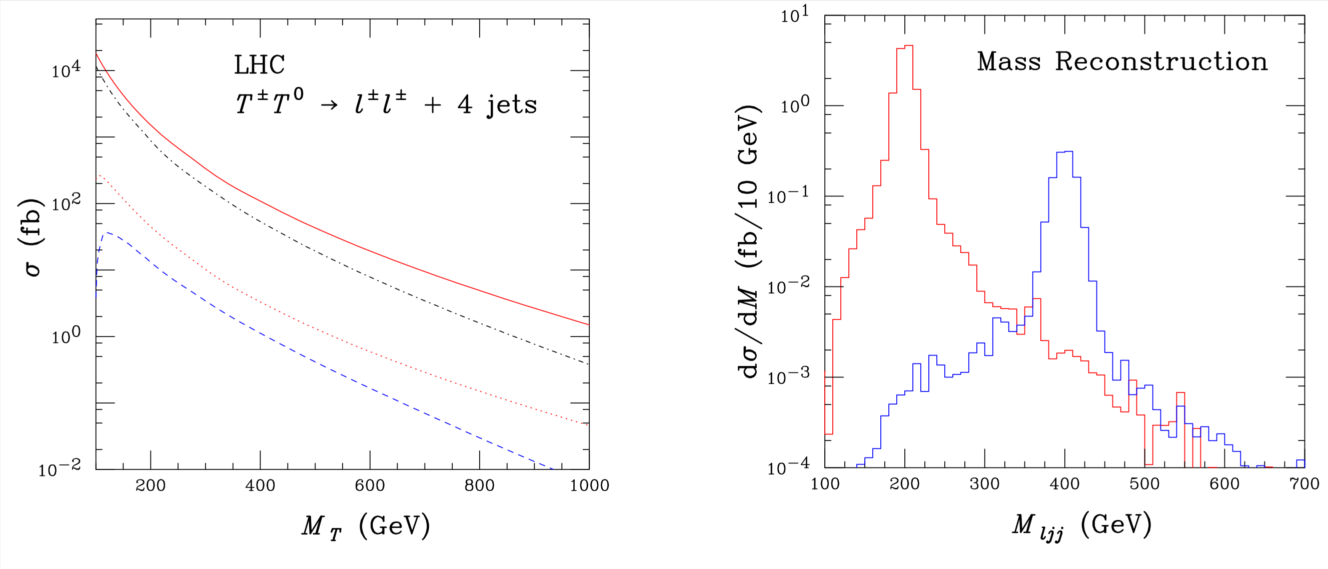




Production and detection of lightest triplet at colliders

Arrhrib et al., 0904.2390

- Same-sign lepton pair signature: $T^0T^\pm \to (\ell^\pm W^\mp)(\ell^\pm Z/h) \to \ell^\pm\ell^\pm + 2j_{(W)} + 2j_{(Z)}$



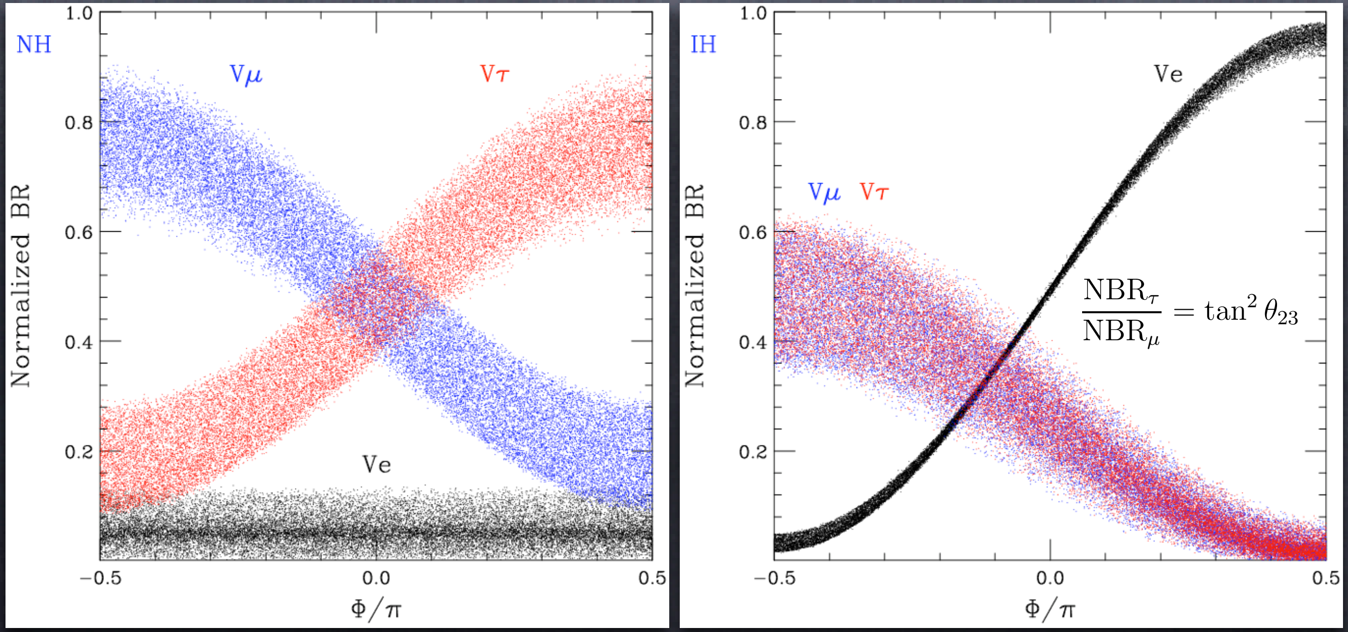
No missing E_T, invariant mass reconstruction possible (l+2j)

projected LHC Sensitivity up to 700GeV with 100 fb^{-1} @ 14TeV

Other signatures can be important l^+l^-+4j, $2l^+$+l^-+2j, etc.

Franceschini, Hambye, Strumia 0805.1613
del Aguila, Aguilar-Saavedra, 0808.2468

- Decays of lightest triplet: $NBR_i \equiv \dfrac{BR(Ve_i)}{\sum_k BR(Ve_k)} = \dfrac{|y_T^i|^2}{\sum_k |y_T^k|^2}$



Normalized branching ratios versus Majorana phase for NH (left) and IH (right) in minimal models. Im(z) ≥ 2

- Discriminating power between NH/IH
- Sensitivity to Majorana phase

Beyond minimal I+III see-saw models

- Adding another heavy fermion increases the number of free parameters
- Strong correlations between different channels still remain:

$$L^Z_{e\mu} \simeq \frac{v^2}{2}\sum_{\alpha=1}^{n_T} y^*_{\alpha e} y_{\alpha\mu}/m^2_\alpha$$

$$= \sum_{\alpha=1}^{n_T}\sum_{i,j=1}^{3}\left[\sqrt{m^\nu_i m^\nu_j}/m_\alpha\right] O^*_{\alpha i} O_{\alpha j} U_{ei} U^*_{\mu j},$$

  - sum is over all elements of the orthogonal matrix O, regardless of the flavour
  - enlarging the $\tau\ell$ transitions by enhancing a single element of O will generically affect the μe channel
  - Some (additional) fine-tuning (alignment) of phases needed to break these correlations

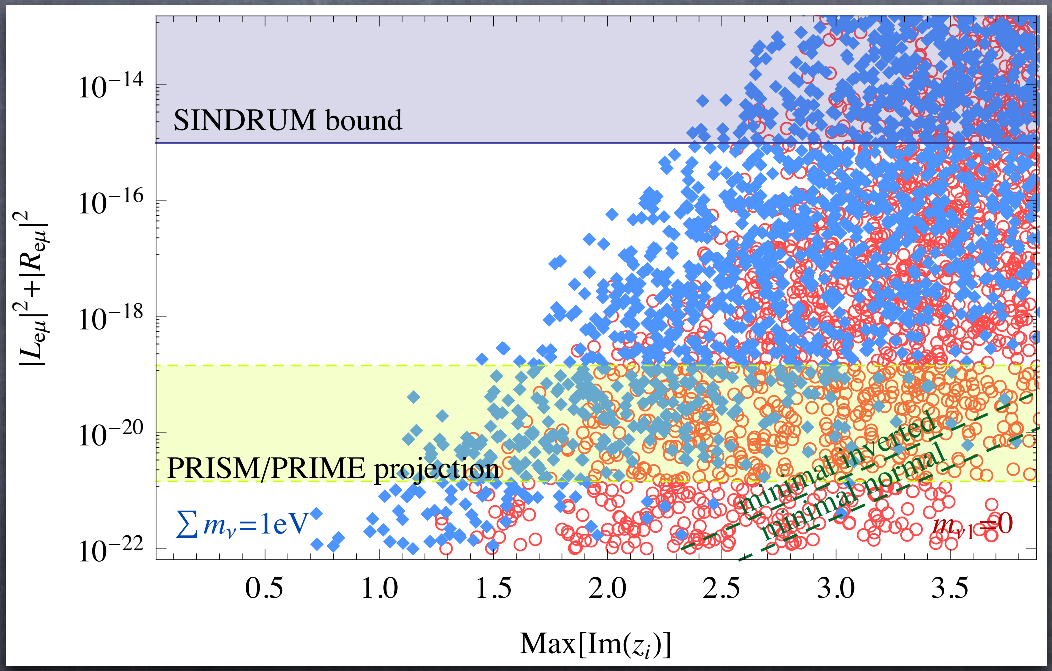
He et al., 0907.1607

Beyond minimal I+III see-saw models

- Adding extra triplets the overall scale of light neutrino masses is free
- In degenerate scenario with $m_\nu \approx$eV experiments (μ-e conv.) are already sensitive to values of $\mathrm{Im}(z_i) \lesssim 4$.

PRISM/PRIME exp.
C. Ankenbrandt et al., physics/0611124

J.F.K. & Nemevsek, 0908.3451



Can expect positive LFV signals with natural values of Yukawas in the next generation of experiments!

- Life-time limits of triplets relaxed (<10cm for T^+, ~∞ for T^0)

Franceschini, Hambye, Strumia, 0805.1613

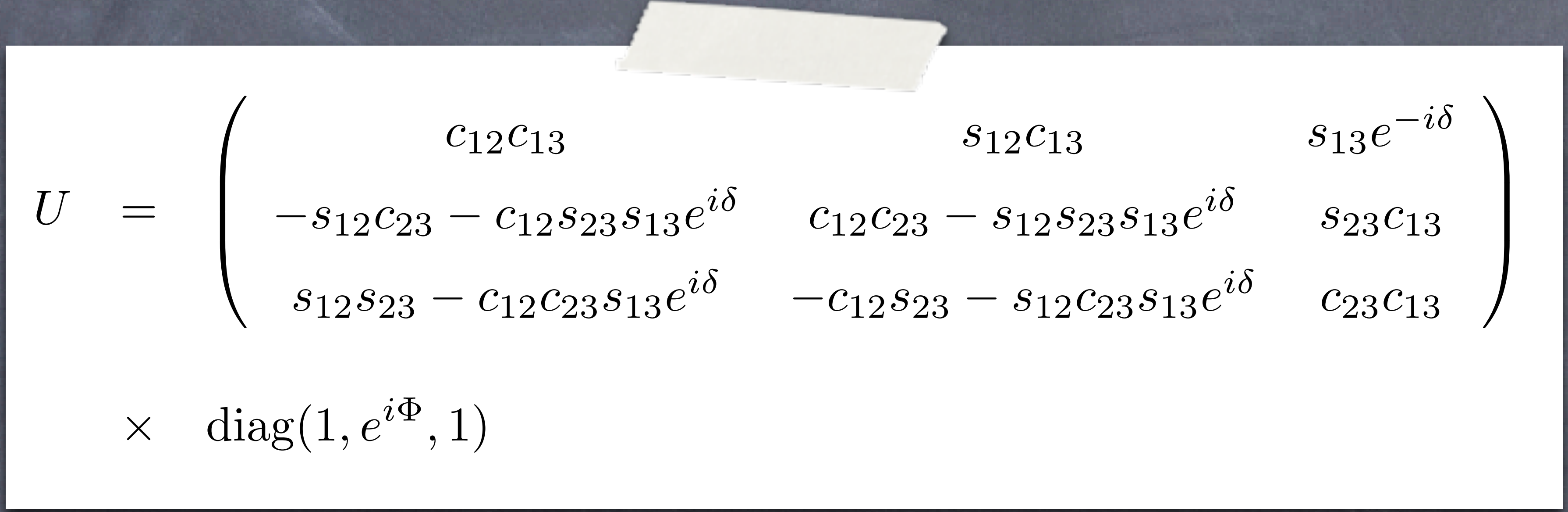
  - Challenging detection at colliders!

Conclusions

- TeV-scale I+III see-saw models can be probed using low-energy observables and high-energy colliders
    - presently best limits from μ-e conversion in nuclei
        - in minimal models make most other bounds irrelevant for the foreseeable future - positive observation would signal LFV beyond minimal I+III See-saw
        - still far from natural Yukawa values
    - non-minimal models could soon be probed in the interesting parameter space region
- Important interplay with direct detection at high-energy colliders
    - in minimal models possible to probe NH/IH, Majorana phase
    - non-minimal models could escape direct detection @ LHC

Backup slides

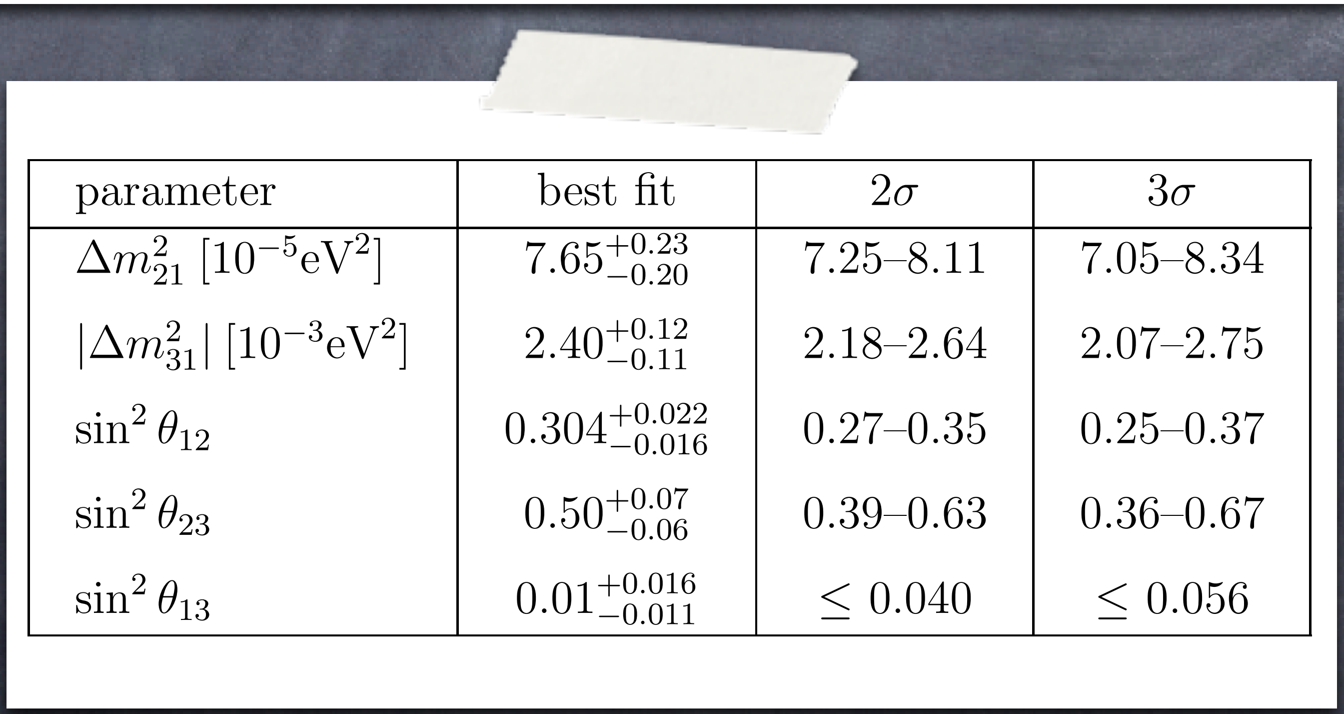
PMNS Matrix
& neutrino parameters



$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\times \quad \mathrm{diag}(1, e^{i\Phi}, 1)$$

c.f.
Schwetz, Tortola, Valle
0808.2016



parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

Neutrino masses from experiments

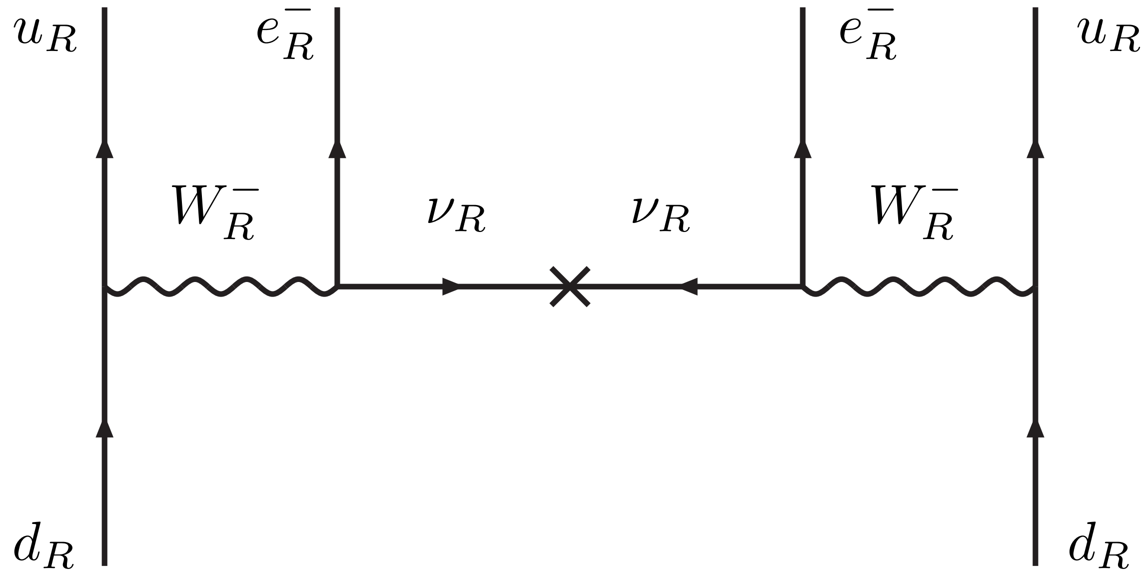
- β decay:
- 0νββ decay:

$$m_{\nu_e} = \left(\sum_i |V_{ei}^2|\; m_i^2\right)^{1/2} = \left(\cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}\right)^{1/2}$$

$$|m_{ee}| = \left|\sum_i V_{ei}^2\; m_i\right| = \left|\cos^2\theta_{13}(m_1\cos^2\theta_{12} + m_2 e^{2i\alpha}\sin^2\theta_{12}) + m_3 e^{2i\beta}\sin^2\theta_{13}\right|.$$

- But:

LR symmetry with low W_R, ν_R masses has a nonzero $0\nu2\beta$ decay even with y_D, $m_\nu \to 0$



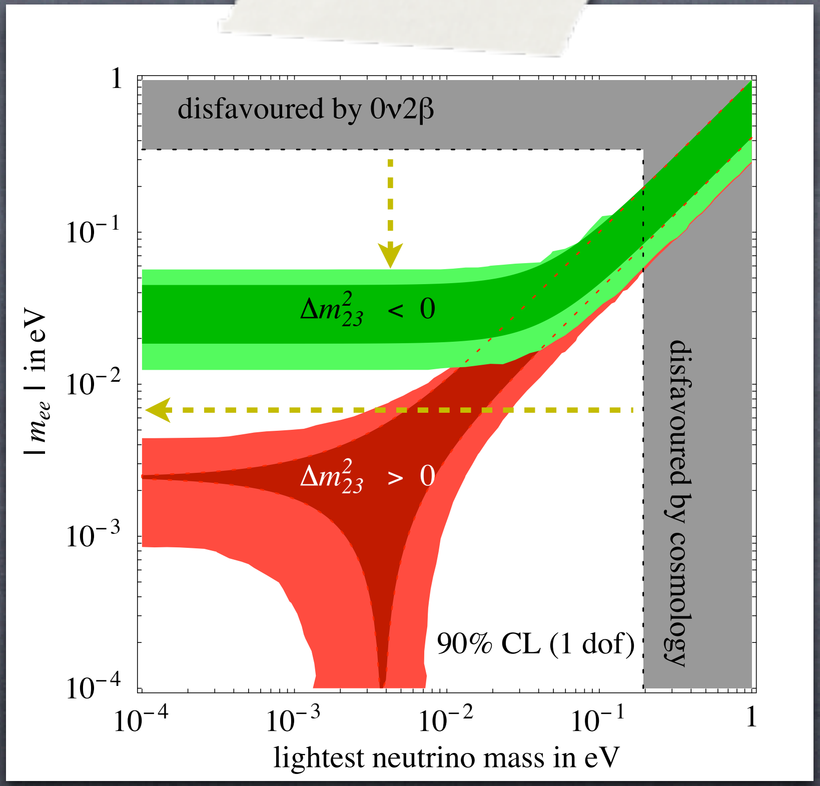
c.f. Mohapatra,
Senjanovic,
PRD23 (1981)

Minimal See-saw

- Present data require two massive neutrinos
  - in normal/inverse hierarchy
- In type I/III can be accomplished using a combination of two mediators of any type
  - neutrino masses cannot be degenerate
  - atmospheric scale sets the largest mass

Minimal See-saw

- Can be excluded by direct neutrino mass measurements



Feruglio, Strumia, Vissani
hep-ph/0201291

- Can also be tested via direct production and decays of mediators

Minimal See-saw

- Type III example:
  - For rank-3 ν mass (R complex orthogonal 3 × 3) too many unknowns:

    $$v y_T^i = \sqrt{m_T} \sum_j U_{ij} \sqrt{m_\nu^j} R_{ji}(z_1, z_2, z_3)$$ (for lightest mediator)

    Casas & Ibarra, hep-ph/0103065

    - $z_{1,2,3}$ → 6 real
    - neutrino mass → 1 real
    - θ_{13}, δ, $\Phi_{1,2}$ from U (PMNS) → 4 real
  - Hard to disentangle useful information for neutrino parameters from only 3 measurements $|y_T^i|$ of the lightest mediator

Minimal See-saw

- Type III example: For rank-2 ν mass

Ibarra & Ross, hep-ph/0307051

  - Normal hierarchy:

$$v y_T^i = \sqrt{m_T}\left(U_{i2}\sqrt{m_\nu^2}\cos z + U_{i3}\sqrt{m_\nu^3}\sin z\right)$$

  - Inverted hierarchy:

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

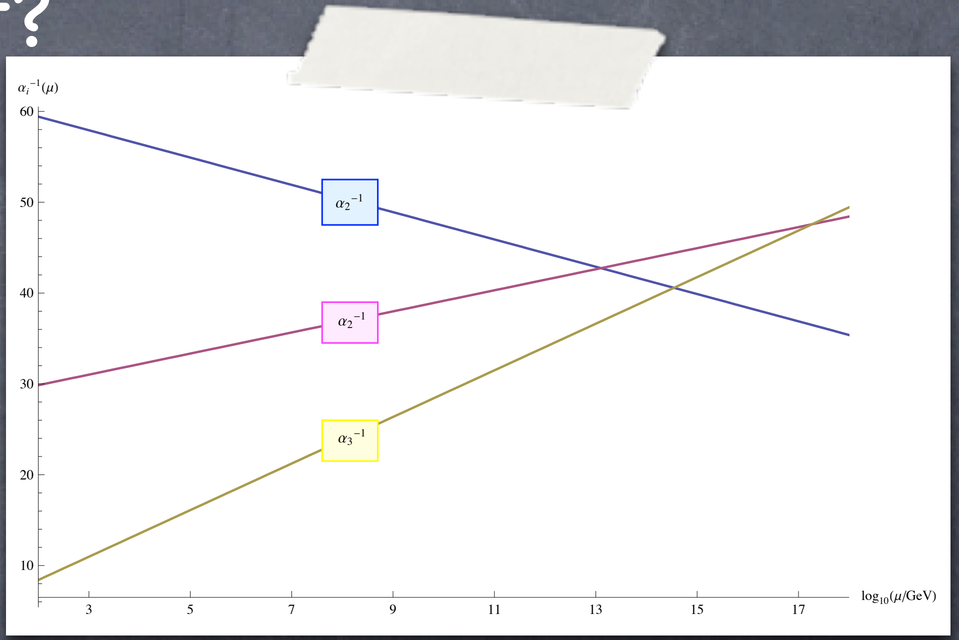
- U = PMNS matrix, z = arbitrary complex number
- Measuring lightest mediator decays constrains z, θ_{13}, phases δ, Φ

A minimal predictable model

- 1) ≤ TeV mediator mass
- 2) gauge quantum numbers (type III seesaw)
- 3) decays mainly through yukawas
- 4) light neutrino mass matrix of rank 2

A minimal predictable model

- Why is the minimal non-supersymmetric Georgi-Glashow SU(5) ruled out?
  - Minimal: $24_H+5_H+3(10_F+\bar{5}_F)$
  - gauge couplings do not unify
  - neutrinos (almost) massless



$$\mathcal{L}_Y = 10^i_F Y_1^{ij} 10^j_F 5_H + 5^*_H 10^i_F Y_2^{ij} \bar{5}^j_F + \frac{1}{\Lambda}\left[\bar{5}^i_F 6_H Y_3^{ij} 5_H \bar{5}^j_F\right]$$

- $\Lambda > 100\, M_{GUT} > 10^{17}$GeV (perturbativity) $m_\nu \approx Y_3 \frac{v^2}{\Lambda} \lesssim 10^{-4}\mathrm{eV}$

A minimal predictable model

Bajc, Senjanovic, hep-ph/0612029
Bajc, Nemevsek, Senjanovic,
hep-ph/0703080

- Add just one extra fermionic 24_F
- Under $SU(3)_C \times SU(2)_W \times U(1)_Y$ decomposition
  - $24_F = (1, 1)_0 + (1, 3)_0 + (8, 1)_0 + (3, 2)_{5/6} + (3, 2)_{-5/6}$
- Extra states (m_3 , m_8 , $m_{(3,2)}$) with respect to the minimal model → RGE change
  - For $M_{GUT} \geq 10^{15.5}$ GeV (p decay) → $m_3 \leq 1\text{TeV}$
  - Mixed type I+III see-saw with rank 2 neutrino mass matrix

Low-energy phenomenology

- In minimal models all effects predicted and correlated in terms of (m_T, m_S, Im(z))
- Charged fermion LFV Z couplings scale as $\sim e^{2\mathrm{Im}(z)}/m_T$
    - Maximal for smallest allowed $m_T \approx 100\mathrm{GeV}$
    - Required fine-tuning measured in $\sim e^{2\mathrm{Im}(z)}$
        - Yukawas considered natural for Im(z)<1
- The most stringent bound fixes all other low-energy phenomenology for all lepton families

General parametrization of minimal see-saw models

- Diagonalization of the neutral and charged lepton mass matrices

$$M_\ell = \begin{pmatrix} v/\sqrt{2}\, y_\ell^{ij}\delta^{ij} & 0 \\ v\ y_T^i & m_T \end{pmatrix} \text{ and } M_\nu = \begin{pmatrix} 0_{3\times 3} & v\ y_T^i & v\ y_S^i \\ v\ y_T^j & m_T & 0 \\ v\ y_S^j & 0 & m_S \end{pmatrix}$$

$$\hat{M}_\ell = U^{+\dagger} M_\ell U^-,\ \hat{M}_\nu = U^{0T} M_\nu U^0$$

- produces mixing of chiral and vector-like fermions
- alters interactions with W, Z ($f_i=(e,\mu,\tau,T^-)$, $f_j^{'}=(\nu_1,\nu_2,\nu_3,T^0,S)$)

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

LFV coupling matrices

$$\begin{aligned} L^{W}_{ij} &= U^{-*}_{\alpha i} U^{0}_{\alpha j}/\sqrt{2} + U^{-*}_{\beta i} U^{0}_{\beta j}, & R^{W}_{ij} &= U^{+*}_{\beta i} U^{0*}_{\beta j}, \\ L^{Z}_{ij} &= (s_w^2 - 1/2) U^{-*}_{\alpha i} U^{-}_{\alpha j} - c_w^2 U^{-*}_{\beta i} U^{-}_{\beta j}, & R^{Z}_{ij} &= s_w^2 U^{+*}_{\alpha i} U^{+}_{\alpha j} - c_w^2 U^{+*}_{\beta i} U^{+}_{\beta j}, \\ L'^{Z}_{ij} &= -U^{0*}_{\alpha i} U^{0}_{\alpha j}/2, & R'^{Z}_{ij} &= 0. \end{aligned}$$

- (Non-)unitarity relations

c.f. G. C. Branco, L. Lavoura and J. P. Silva,
Int. Ser. Monogr. Phys. 103 (1999)

$$\begin{aligned} L^{W}_{ik} L^{W*}_{jk} &= (U^{-*}_{\alpha i} U^{0}_{\alpha k}/\sqrt{2} + U^{-*}_{\beta i} U^{0}_{\beta k})(U^{-}_{\alpha' j} U^{0*}_{\alpha' k}/\sqrt{2} + U^{-}_{\beta' j} U^{0*}_{\beta' k}) \\ &= 1/2 U^{-*}_{\beta i} U^{-}_{\beta j}, \\ L^{Z}_{ij} &= (1/2 - c_w^2) U^{-*}_{\alpha i} U^{-}_{\alpha j} - c_w^2 U^{-*}_{\beta i} U^{-}_{\beta j} \\ &= -1/2 U^{-*}_{\beta i} U^{-}_{\beta j}, \\ R^{W}_{ik} R^{W*}_{jk} &= -R^{Z}_{ij}. \end{aligned}$$

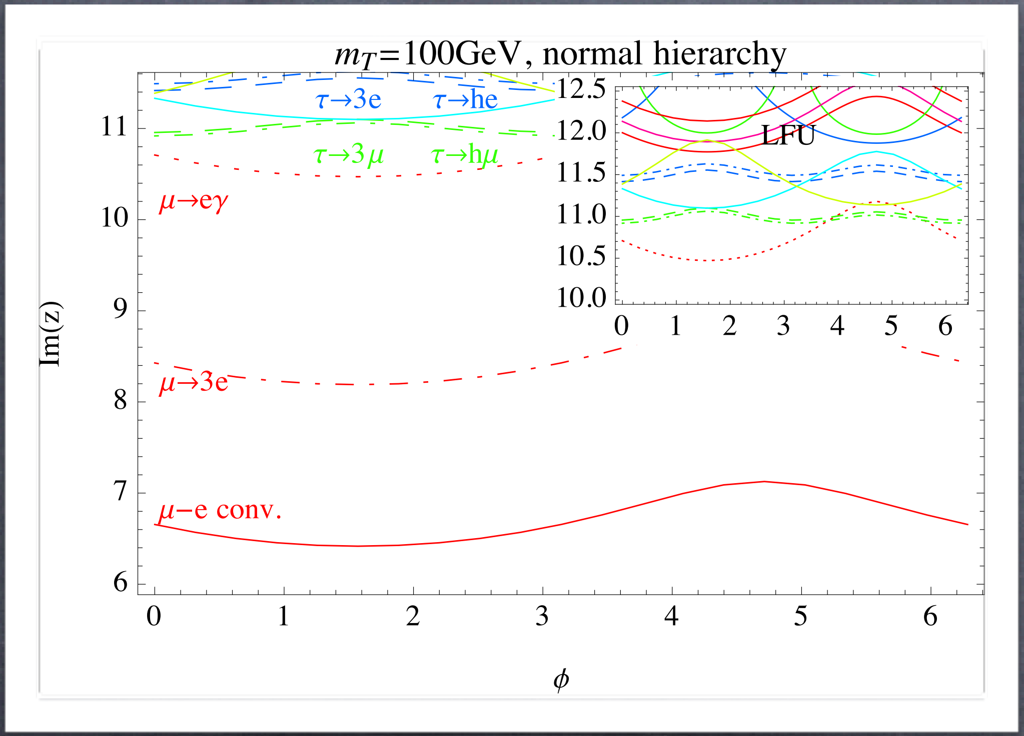
Results

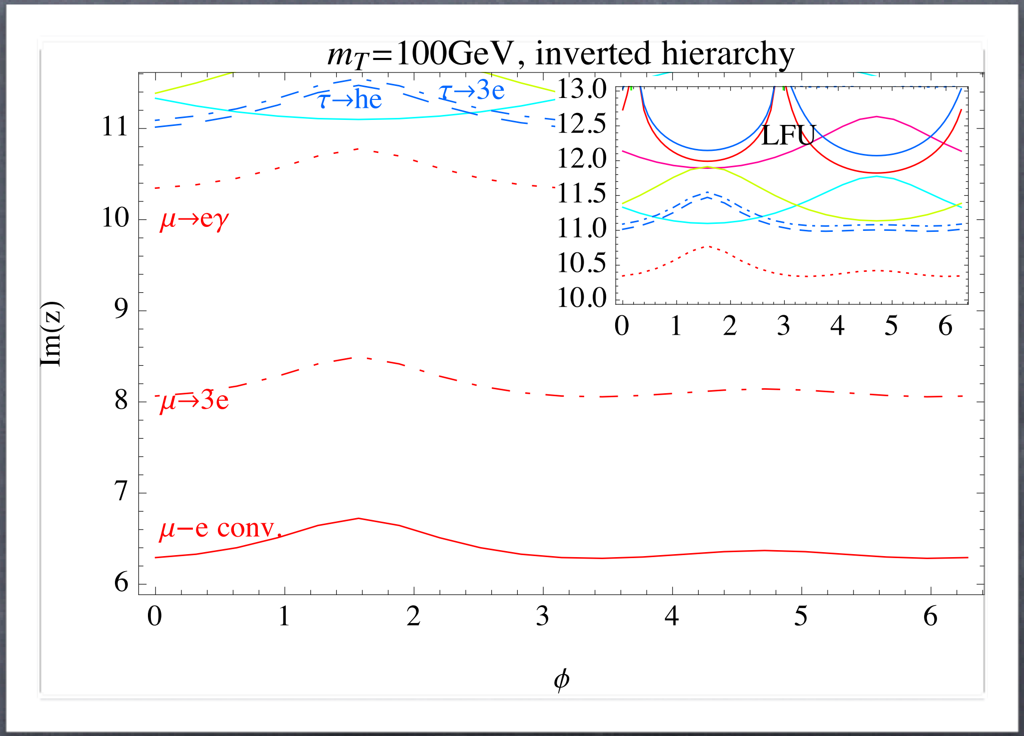
- l -> 3l′
  - τ -> 3 e gives the best tau-e bound*
- τ -> h l
  - τ -> π^0 μ gives the best tau-μ bound*
- Radiative LFV decays are suppressed!
- Flavour conserving leptonic Z widths more constraining than LFV ones
- Charged current LFU more constrained at low energies than from direct W measurements
- Many other observables studied, found not relevant (h->ll′, $(g-2)_\mu$,…)

*Relevant for non-minimal models

Results

- Comparison of bounds:





- Differences between normal/inverted hierarchy and III vs I+III scenarios not crucial (in the minimal models)
- Mild dependence on the Majorana phase (θ_{13}, δ irrelevant)
- Im(z) sensitivity logarithmic!

Conclusions

- Future improvements:

PRISM/PRIME exp.
C. Ankenbrandt et al.,
physics/0611124

  - Planned μ-e nuclear conversion sensitivity of 10^{-16} or even 10^{-18} on $Br_{\mu e}$
    - would constrain Im(z) to 4.1 (3.7) in case of the minimal I+III model and to 3.7(3.4) for the minimal type III
    - In non-minimal models $\mathrm{Im}(z_i) < 1$ could be probed

MEG Collab.
Nuovo Cim.123B (2008)

    - Orders of magnitude better than projected MEG sensitivity for μ->eγ ($\mathrm{Im}(z) \leq 9$)

Kitano, Koike and Okada,
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    - Allows to distinguish type I and III contributions