A natural explanation for large neutrino mixing

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Work done in collaboration with

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Outline

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1. Introduction
2. High Scale Mixing Unification Hypothesis
3. Majorana case
4. Dirac Case
5. Scale of HSMU and SUSY
6. Conclusion and Future Work

Introduction

- Neutrinos are probably the most mysterious and ill understood of all known particles
- In past neutrinos have thrown up quite a few surprises: They still keep on surprising us !!
- Recent measurements conclusively show $\theta_{13} \neq 0$[1]: The latest "surprise"
- Measurement of θ_{13} was long awaited: Provides crucial test of several candidate models
- Is there a "natural" way of understanding non-zero and "relatively large" θ_{13}?
- In this talk we discuss one such possibility: **High Scale Mixing Unification (HSMU)**

[1] T2K, MINOS, DAYA-BAY, RENO and Double Chooz Collaborations

Current Experimental Scenario

- Global Fits for neutrino oscillation parameters[2]:

Quantity	Best Fit ± 1-σ	3-σ Range
$\theta_{12}/^\circ$	$33.36^{+0.81}_{-0.78}$	31.09 – 35.89
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.3}_{-1.3}$	35.8 – 54.8
$\theta_{13}/^\circ$	$8.66^{+0.44}_{-0.46}$	7.19 – 9.96
$\delta_{\rm CP}/^\circ$	300^{+66}_{-138}	0 – 360
Δm^2_{21} $(10^{-5}$ eV$^2)$	$7.50^{+0.18}_{-0.19}$	7.00 – 8.09
Δm^2_{31} $(10^{-3}$ eV$^2)$ (N)	$2.473^{+0.070}_{-0.067}$	2.276 – 2.695
Δm^2_{23} $(10^{-3}$ eV$^2)$ (I)	$2.427^{+0.042}_{-0.065}$	2.242 – 2.649

- Averaged electron neutrino mass (m_β): MAINZ, TROITSK $m_\beta < 2$ eV, KATRIN sensitivity ≈ 0.2 eV
- Neutrinoless Double Beta Decay: Not Observed (Effective Majorana mass $m_{\beta\beta} < 0.38$ eV)

[2] M. C. Gonzalez-Garcia, etal. JHEP 1212, 123 (2012)

Open Questions

- Despite tremendous amount of theoretical and experimental research our understanding of neutrinos is still poor
- Nature of neutrinos: Dirac or Majorana?
- Mass of neutrinos: Hierarchical or quasi degenerate?
- Mass Hierarchy: Normal or Inverted?
- CP violation: δ_{CP}?
- Octant of θ_{23}: $\theta_{23} < 45^\circ$ or $\theta_{23} > 45^\circ$?
- Why lepton and quark mixing parameters are so different?

Outline

Unification

- Unification: An old idea and quite fruitful notion
- Has lead to much advancement in our understanding: Electro-Magnetism, Electro-Weak force etc
- Current research: Unification of various fundamental forces
- Grand Unified Theories (GUTs): Unification of gauge couplings
- Key Ingredient: Quarks and Leptons in same multiplet
- Flavor structure of quarks and leptons: Not totally disconnected
- Interesting possibility: "High Scale" Unification of CKM and PMNS mixing parameters[3]

[3] R. N. Mohapatra, M. K. Parida and G. Rajasekaran, Phys. Rev. D **69**, 053007 (2004), hep-ph/0301234.

Unification of CKM and PMNS mixing parameters

- How is this possible? Numerically they are so different from each other!!
- Maybe unification at higher scales e.g GUT scale?
- Quark mixing angles don't change much (SM/MSSM RG running) due to hierarchical nature of quark masses
- What about neutrino mixing angles?
- Large radiative magnification of PMNS angles is required!
- Can be realized within Minimal Supersymmetric Standard Model (MSSM)[4]

[4] R. N. Mohapatra, M. K. Parida and G. Rajasekaran, Phys. Rev. D **69**, 053007 (2004), hep-ph/0301234.

Outline

High Scale Mixing Unification Hypothesis

General Framework

- Model independent approach: Assume HSMU at some "High Scale"
- Details of the "High Scale" theory not needed
- Below High Scale: MSSM + Type-I seesaw mechanism
- Effective left handed neutrino mass matrix

$$m_\nu = -M_D (f v_R)^{-1} M_D^T$$

- Right handed neutrinos integrated out below their mass threshold

High Scale Mixing Unification Hypothesis

General Framework

- Below seesaw scale: Effective dimension five neutrino mass operator

$$\mathcal{L}_{MSSM+\kappa} = \mathcal{L}_{MSSM} - \frac{1}{4}\kappa_{ij}\mathbf{l}^i_a \varepsilon^{ab}\mathbf{h}^{(u)}_b \mathbf{l}^j_c \varepsilon^{cd}\mathbf{h}^{(u)}_d \Big|_{\theta\theta}$$

- Testing HSMU: Need to run down the masses and mixing parameters from High Scale to low scale (M_Z)
- RG running between High Scale and seesaw scale: Using standard MSSM RG equations within framework of Type-I seesaw mechanism
- Below seesaw scale: RG running with dim-5 operator added to MSSM
- Below SUSY breaking scale: RG running with dim-5 operator added to SM

RG equations for masses

$$\frac{\mathrm{d}m_i}{\mathrm{d}t} = \frac{m_i}{16\pi^2}\left[\alpha + C f_\tau^2 \, F_i\right] \, ,$$

where $t = \ln(\mu)$, μ is the renormalization scale and F_i (with $i = 1, 2, 3$) are defined as

$$\begin{aligned} F_1 &= 2s_{12}^2\, s_{23}^2 - s_{13}\, \sin 2\theta_{12}\, \sin 2\theta_{23} \cos\delta + 2s_{13}^2\, c_{12}^2\, c_{23}^2 \, , \\ F_2 &= 2c_{12}^2\, s_{23}^2 + s_{13}\, \sin 2\theta_{12}\, \sin 2\theta_{23} \cos\delta + 2s_{13}^2\, s_{12}^2\, c_{23}^2 \, , \\ F_3 &= 2\, c_{13}^2\, c_{23}^2 . \end{aligned}$$

Casas NPB(2000), Antush JHEP(2005)

In SM and MSSM, α and f_τ are

$$\begin{aligned} \alpha_{\mathrm{MSSM}} &= -\frac{6}{5}g_1^2 - 6g_2^2 + \frac{6y_t^2}{\sin^2\beta}, \qquad f_{\tau,\mathrm{MSSM}}^2 = \frac{y_\tau^2}{\cos^2\beta}, \\ \alpha_{\mathrm{SM}} &= -3g_2^2 + 2y_\tau^2 + 6\left(y_t^2 + y_b^2\right) + \lambda, \qquad f_{\tau,\mathrm{SM}}^2 = y_\tau^2 . \end{aligned}$$

Here y_f, $(f = \tau, t, b)$ represent the Yukawa coupling, g_i are gauge couplings and λ is Higgs self-coupling in SM.

RG equations for mixing angles

$$\begin{aligned}
\frac{\mathrm{d}\theta_{12}}{\mathrm{d}t} &= -\frac{C f_\tau^2}{32\pi^2}\,\sin 2\theta_{12}\, s_{23}^2\,\frac{|m_1 e^{i\phi_1}+m_2 e^{i\phi_2}|^2}{\Delta m_{21}^2}+\mathscr{O}(\theta_{13}),\\
\frac{\mathrm{d}\theta_{13}}{\mathrm{d}t} &= -\frac{C f_\tau^2}{32\pi^2}\sin 2\theta_{12}\sin 2\theta_{23}\frac{m_3}{\Delta m_{32}^2\,(1+\xi)}\\
&\times\ [m_1\ cos(\phi_1-\delta)-(1+\xi)m_2\ cos(\phi_2-\delta)-\xi\ m_3\ cos\delta]+\mathscr{O}(\theta_{13}),\\
\frac{\mathrm{d}\theta_{23}}{\mathrm{d}t} &= -\frac{C f_\tau^2}{32\pi^2}\,\sin 2\theta_{23}\,\frac{1}{\Delta m_{32}^2}\left[c_{12}^2|m_2 e^{i\phi_2}+m_3|^2+s_{12}^2\frac{|m_1 e^{i\phi_1}+m_3|^2}{1+\xi}\right]\\
&+\ \mathscr{O}(\theta_{13}),
\end{aligned}$$

Casas NPB(2000), Antush JHEP(2005)

where δ is Dirac phase, ϕ_1, ϕ_2 are Majorana phases and

$$\xi = \frac{\Delta m_{21}^2}{\Delta m_{32}^2}, \qquad \Delta m_{21}^2 = m_2^2 - m_1^2, \qquad \Delta m_{32}^2 = m_3^2 - m_2^2,$$

$$C = 1 \quad \text{in MSSM}, \qquad C = -\frac{3}{2} \quad \text{in SM}.$$

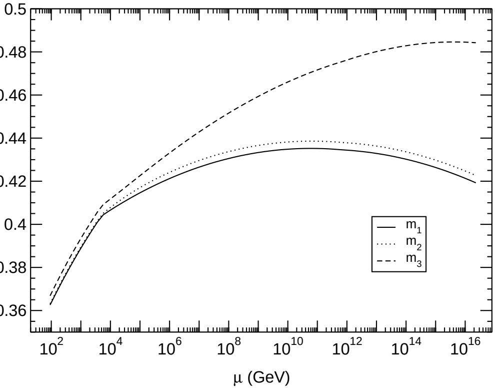
HSMU: Initial Conditions & Assumptions

- Assume HSMU realized at GUT scale i.e. 2×10^{16} GeV
- Choice of seesaw scale: HSMU realized for varied range of seesaw scale [For definiteness 10^{12} GeV]
- SUSY breaking scale: 2 TeV
- Larger values of $\tan\beta$: Enhanced magnification [We choose $\tan\beta = 55$]
- Dependence on these parameters: Discussed in later part of talk
- Large radiative magnification: Quasi degenerate neutrinos
- Assumed normal hierarchy
- Assumed no CP violation in leptonic sector: Dirac as well as Majorana phases taken zero

Implementing HSMU: Two step process

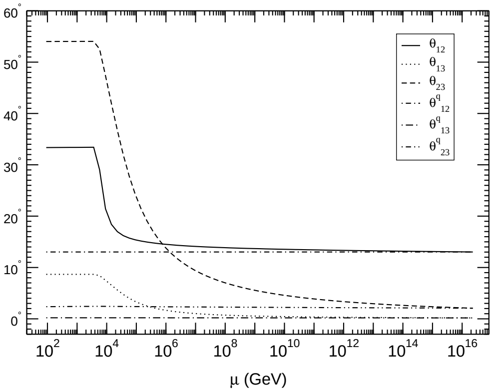
- **Bottom - Up**
- Start from known values of gauge couplings, quark mixing angles, masses of quarks and charged leptons at low energies (M_Z)
- Use RG equations: Obtain the corresponding values at high energies
- HSMU hypothesis: Take neutrino mixing angles same as the quark mixing angles at the unification scale
- **Top - Down**
- Neutrino masses at high scale: Unknown parameters
- Determine these three parameters such that: Low energy values of the oscillation parameters i.e. $\Delta m_{12}^2, \Delta m_{23}^2, \theta_{12}, \theta_{23}$ and θ_{13} agree with their present experimental ranges

The RG evolution of neutrino masses m_i



- All masses decrease from unification scale to M_Z.
- RG running of m_3 fastest: Splitting gets narrowed down.
- Acquire nearly degenerate masses at M_Z.

The RG evolution of neutrino mixing angles θ_{ij}



- Hierarchical quark masses: RG running in quark sector is almost negligible
- RG running of leptonic mixing angles
  $$\frac{d\theta_{12}}{dt} \propto \frac{m^2}{\Delta m^2_{21}}$$
  $$\frac{d\theta_{13}}{dt}, \frac{d\theta_{23}}{dt} \propto \frac{m^2}{\Delta m^2_{32}}$$
- Quasi-degenerate neutrinos: Large angle magnification in leptonic sector

Numerical results on the evolution of masses and mixing

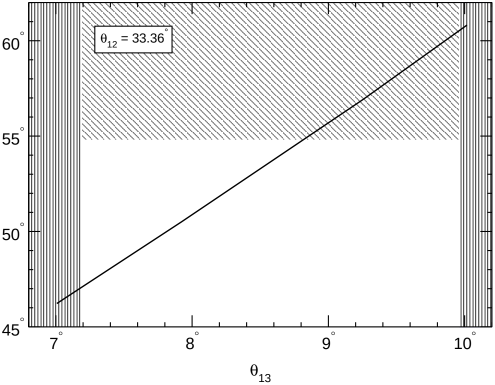
	I	II	III
m_1^0(eV)	0.4196	0.4146	0.4286
m_2^0(eV)	0.4230	0.4180	0.4320
m_3^0(eV)	0.4843	0.4786	0.4946
m_1(eV)	0.3626	0.3582	0.3703
m_2(eV)	0.3632	0.3589	0.3709
m_3(eV)	0.3668	0.3625	0.3746
$\Delta m_{21}^2(\text{eV}^2)_{RG}$	4.30×10^{-4}	4.49×10^{-4}	4.20×10^{-4}
$\Delta m_{32}^2(\text{eV}^2)_{RG}$	2.67×10^{-3}	2.62×10^{-3}	2.78×10^{-3}
$M_{\tilde{e}}/M_{\tilde{\mu},\tilde{\tau}}$	1.94	1.84	2.16
$\Delta m_{21}^2(\text{eV}^2)_{th}$	-3.55×10^{-4}	-3.73×10^{-4}	-3.44×10^{-4}
$\Delta m_{32}^2(\text{eV}^2)_{th}$	-2.74×10^{-4}	-2.16×10^{-4}	-3.82×10^{-4}
$\Delta m_{21}^2(\text{eV}^2)_{tot}$	7.50×10^{-5}	7.58×10^{-5}	7.59×10^{-5}
$\Delta m_{32}^2(\text{eV}^2)_{tot}$	2.40×10^{-3}	2.40×10^{-3}	2.40×10^{-3}
$\theta_{23}/^\circ$	54.03	53.93	54.18
$\theta_{13}/^\circ$	8.66	8.67	8.67
$\theta_{12}/^\circ$	33.36	31.14	35.87

Testing HSMU: Values of $m_{\beta\beta}$ and m_β

- Threshold corrections needed, to obtain Δm^2_{21} within 3-σ range[5].
- Mean Mass m lie in the range of $(\sim 0.34 - 0.38)$ eV.
- No CP violation: "Effective Majorana mass" $m_{\beta\beta} \equiv \left[\sum_i U^2_{ei}\, m_i\right]$ and "Averaged electron neutrino mass" $m_\beta \equiv \left[\sum_i |U_{ei}|^2\, m_i^2\right]^{1/2}$ are approximately same as mean mass
- Present limits:
  - GERDA limit $\longrightarrow (0.2 - 0.4)$ eV on $< m_{\beta\beta} >$
  - EXO-200 limit $\longrightarrow (0.14 - 0.38)$ eV on $< m_{\beta\beta} >$ $(0\nu 2\beta$ decay);
  - MAINZ, TROITSK limit $\longrightarrow (< 2)$ eV on $< m_\beta >$ (Tritium β decay); KATRIN reach $\longrightarrow (0.2)$ eV
- Predicted values within reach of present experiments: Serve as important tests of HSMU

[5] Mohapatra, Parida, Rajasekaran PRD 71(2005)

Octant of θ_{23}



- Since $\frac{d\theta_{13}}{dt}, \frac{d\theta_{23}}{dt} \propto \frac{m^2}{\Delta m_{32}^2}$: RG evolution of θ_{13} and θ_{23} correlated
- All other oscillation parameters are at their best-fit values.
- Non maximal θ_{23} i.e. $\theta_{23} > 45°$: Lies in second octant for the whole 3-σ range of θ_{13}.
- Shaded regions lie outside 3-σ range.
- For a fixed value of θ_{13}: Effect of variation of θ_{12} on θ_{23} is negligible.

Summary, so far

- HSMU realized for Majorana neutrinos: Requires quasi-degeneracy and normal hierarchy
- Several important predictions:
  - $m_{\beta\beta}$ and m_β in range of $(\sim 0.34 - 0.38)$ eV
  - Normal hierarchy
  - Non maximal θ_{23}: Lies in second octant
- These predictions can be tested in present and near future experiments like GERDA, EXO-200, KATRIN, INO, T2K, NOνA, LBNE, Hyper-K, PINGU

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2. High Scale Mixing Unification Hypothesis
3. Majorana case
4. **Dirac Case**
5. Scale of HSMU and SUSY
6. Conclusion and Future Work

Nature of Neutrinos: Dirac or Majorana?

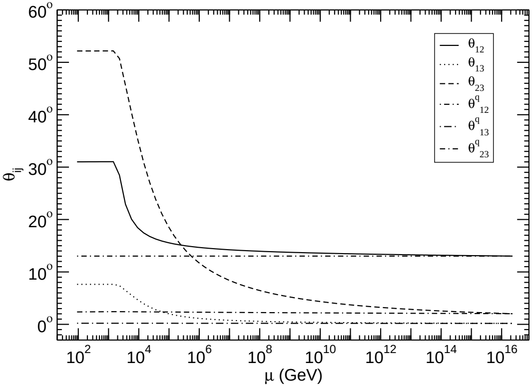
- One of the most important open questions in neutrino physics: Whether neutrinos are Dirac or Majorana particles
- Current understanding: Dirac neutrinos as plausible as Majorana ones [6]
- Neutrinoless double beta decay experiments: Dedicated ongoing experiments to determine the nature of neutrinos.
- No conclusive evidence: Neutrinoless double beta decay experiments have not seen any signal so far[7].
- Instructive to see if HSMU can be implemented for Dirac Neutrinos as well

[6] Murayama PRL (2002), Smirnov hep-ph/0411194, Mohapatra hep-ph/0412099
[7] Agostini:2013,Auger:2012,Gando:2012,Alessandria:2011

HSMU for Dirac Neutrinos

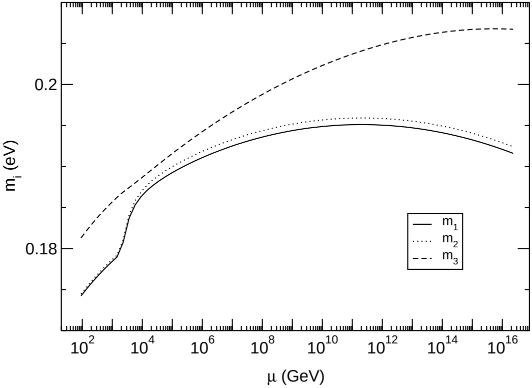
- HSMU hypothesis: More natural for Dirac neutrinos than Majorana neutrinos
- If neutrinos are Majorana particles: The PMNS-matrix has 6 independent parameters; 3-mixing angles, 1-Dirac phase and 2-Majorana phases
- On the other hand CKM-matrix has only 4 independent parameters: 3-mixing angles and 1-Dirac phase
- Clear mismatch between number of parameters on two sides and hence a one-to-one correspondence is impossible
- HSMU for Majorana Case: One has to treat the Majorana phases as free parameters
- HSMU for Dirac Neutrinos: CKM and PMNS mixing parameters can be mapped in a one-to-one correspondence with each other at the unification scale.
- Clear and unambiguous predictions
- Implementing is same as Majorana case.

The RG evolution of neutrino mixing angles θ_{ij}

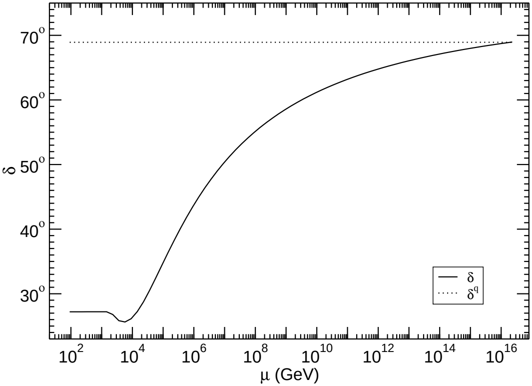


- Quasi-degenerate neutrinos: Large angle magnification in leptonic sector

The RG evolution of neutrino masses m_i



The RG evolution of Dirac Phase



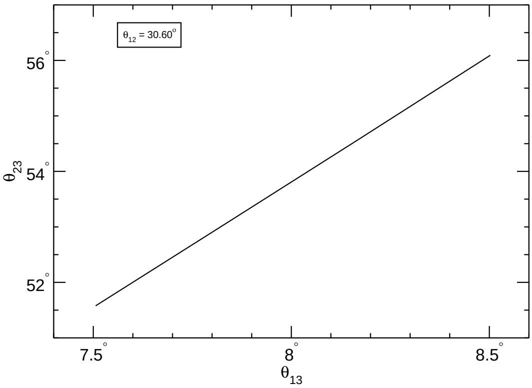
Numerical results

- Bottom-up running:
  $\theta_{12}^{0,q} = 13.02°$, $\theta_{13}^{0,q} = 0.17°$, $\theta_{23}^{0,q} = 2.03°$ and $\delta_{CP}^{0,q} = 68.93°$.
- Following HSMU, the neutrino mixing parameters at unification scale are taken to be same as those of quark mixing parameters.
- At unification scale, we choose:
  $m_2^0 = 0.1925\ eV$, $\Delta m_{21}^2 = 2.960 \times 10^{-4}\ eV^2$, $\Delta m_{32}^2 = 5.718 \times 10^{-3}\ eV^2$.
- Top-down running:
  $\theta_{12} = 31.20°$, $\theta_{13} = 7.22°$, $\theta_{23} = 50.35°$, $\delta_{CP} = 28.12°$,
  $m_2 = 0.1746$ eV, $\Delta m_{sol}^2 = 7.917 \times 10^{-5}\ eV^2$ and $\Delta m_{atm}^2 = 2.399 \times 10^{-3}\ eV^2$.

Numerical results

- All low scale parameters are within their 3-σ range.
- Threshold corrections are NOT required.
- The sum of neutrino masses $\sum m_i = 0.530$ eV, where $i = 1, 2, 3$. Within the range of PLANCK (2015) data; $\sum m_i = 0.17 - 0.72$ eV (depending on the choice of priors).
- The "averaged electron neutrino mass" $m_\beta = 0.175$ eV (slightly below the present reach of KATRIN experiment).

Octant of θ_{23}



- Correlated RG evolution of θ_{13} and θ_{23}: θ_{23} non maximal and in second octant

Summary, so far

- HSMU can be realized for both Dirac as well as Majorana neutrinos
- Several important predictions for Dirac case:
  - "Averaged electron neutrino mass" m_β: Slightly below KATRIN's proposed sensitivity
  - Normal hierarchy
  - Non maximal θ_{23}: Lies in second octant
- These predictions can be tested in present and near future experiments like GERDA, EXO-200, KATRIN, INO, T2K, NOνA, LBNE, Hyper-K, PINGU

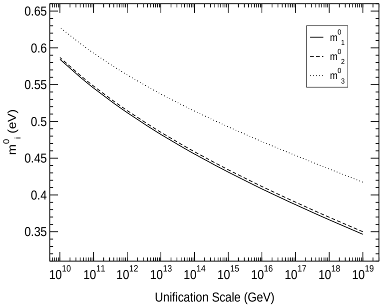
Outline

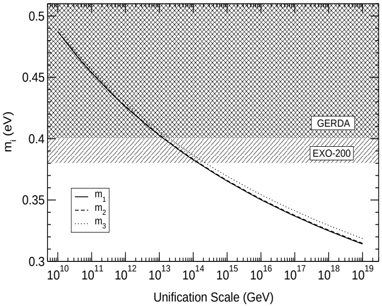
Variation of Unification Scale

- So far we assumed HSMU to be realized at GUT scale
- HSMU does not depend on "details" of GUT scale theory
- Instructive to analyze the effect of variation of HSMU scale
- Similarly SUSY breaking scale and $\tan\beta$ were taken as 2 TeV and 55, respectively
- Important to analyze the dependence of HSMU on these

Unification Scale Variation

Majorana Neutrinos

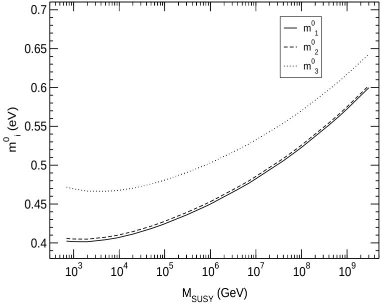


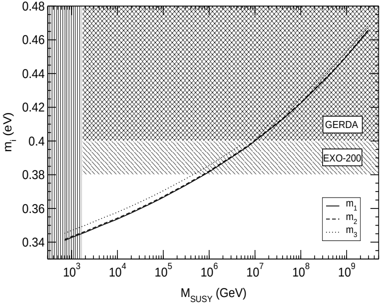


- Here, we have taken $M_{SUSY} = 2$ TeV and $\tan\beta = 55$.
- All neutrino oscillation parameter kept fixed to their best fit value
- Bounds from $0\nu\beta\beta$ decay provide tightest constraints on the lowest possible value of HSMU scale [should be above $10^{14} GeV$]
- The shaded regions are excluded by $0\nu\beta\beta$ decay experiments

SUSY Breaking Scale Variation

Majorana Neutrinos

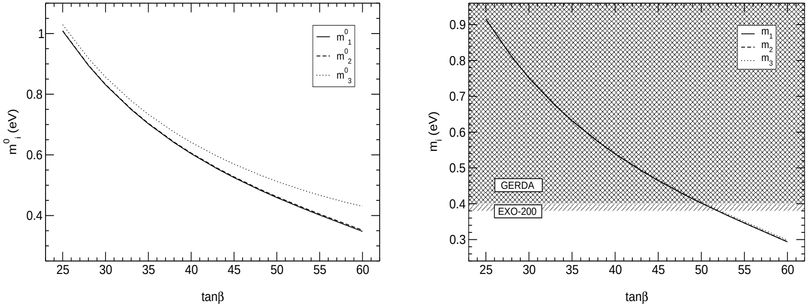




- Here, the unification scale $= 2 \times 10^{16}$ GeV and $\tan\beta = 55$.
- All neutrino oscillation parameter kept fixed to their best fit value
- The shaded regions are excluded by $0\nu\beta\beta$ decay experiments
- HSMU consistent with experimental constraints for SUSY breaking scales lie below $10^6 GeV$

Choice of $\tan\beta$

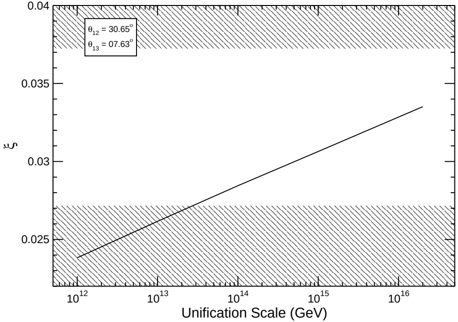
Majorana Neutrinos



- Here, the unification scale $= 2 \times 10^{16}$ GeV and $M_{SUSY} = 2$ TeV.
- All neutrino oscillation parameter kept fixed to their best fit value
- The shaded regions are excluded by $0\nu\beta\beta$ decay experiments
- Experimental constraints imply large values of $\tan\beta$

Scale of HSMU

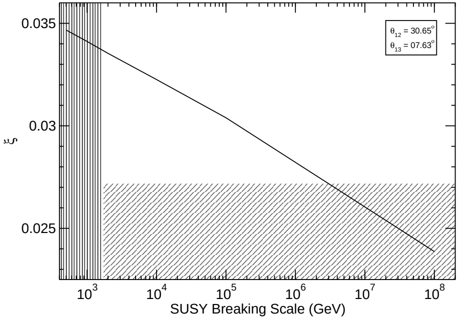
Dirac Neutrinos



- Here, we have taken $M_{SUSY} = 2$ TeV and $\tan\beta = 55$.
- Present constraints from Tritium Beta decay are rather weak
- The neutrino oscillation data, in particular $\xi = (\Delta m^2_{sol}/\Delta m^2_{atm})$, provides tightest constraints on the scale of HSMU [that should be above $2 \times 10^{13} GeV$]

SUSY Breaking Scale

Dirac Neutrinos



- Unification scale $= 2 \times 10^{16}$ GeV and $\tan\beta = 55$.
- The upper bound on M_{SUSY} turns out to be around 4×10^6 GeV
- Experimental constraints require large values of $\tan\beta$

Outline

Conclusions and Future Work

- High Scale Mixing Unification (HSMU) of PMNS and CKM parameters is an interesting possibility
- It can be realized with both Dirac and Majorana type neutrinos
- It naturally leads to non zero and "relatively large" values of θ_{13} consistent with present global fits
- It leads to several predictions which can be test by present and near future experiments
- The scale of HSMU is roughly same as that of Grand Unified theories
- This opens up the possibility of realizing HSMU through a GUT
- Construction of such a GUT theory will put HSMU on a firmer footing

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- It can be realized with both Dirac and Majorana type neutrinos
- It naturally leads to non zero and "relatively large" values of θ_{13} consistent with present global fits
- It leads to several predictions which can be test by present and near future experiments
- The scale of HSMU is roughly same as that of Grand Unified theories
- This opens up the possibility of realizing HSMU through a GUT
- Construction of such a GUT theory will put HSMU on a firmer footing

THANK YOU !!