GUT and Neutrino Mass Models

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The 3-Flavor Era in Neutrino Physics!

- Exciting Time in ν Physics: recent hints/evidences of large θ_{13} from T2K, MINOS, Double Chooz, Daya Bay and RENO
- Latest 3 neutrino global analysis:

Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno (2012)
[see also, Gonzalez-Garcia, Maltoni, Salvado, Schwetz (2012)]

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 ⊕ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

➡ Evidence of $\theta_{13} \neq 0$
➡ hints of $\theta_{23} \neq \pi/4$
➡ expectation of Dirac CP phase δ

➡ no clear preference for hierarchy
➡ Absolute neutrino mass scale?
➡ Majorana vs Dirac?

Need For Precision Measurements

(i) Absolute mass scale: Why $m_\nu << m_{u,d,e}$?

- seesaw mechanism: most appealing scenario ⇒ Majorana
  - GUT scale (type-I, II) vs TeV scale (type-II, III, inverse seesaw)
- TeV scale new physics (warped extra dimension, U(1)′) ⇒ Dirac or Majorana

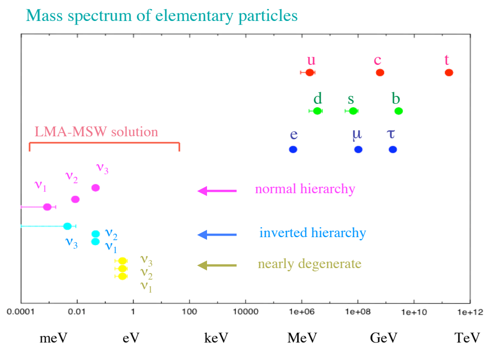
(ii) Flavor Structure: Why neutrino mixing large while quark mixing small?

- neutrino anarchy: no parametrically small number — Hall, Murayama, Weiner (2000); de Gouvea, Murayama (2003)
  - near degenerate spectrum, large mixing
  - still alive and kicking — de Gouvea, Murayama (2012)
  - heterotic string theory connection
- family symmetry: there's a structure, expansion parameter (~~symmetry~~ effect)
  - mixing result from dynamics of underlying symmetry
  - leptonic symmetry (normal or inverted)
  - for quarks and leptons: quark-lepton connection ↔ GUT (normal)
- Alternative?

- In this talk: assume 3 generations, no LSND/MiniBoone/Reactor Anomaly

Planck 2013 Data Release: N_{eff} = 3.26 ± 0.35 ⇒ sterile neutrino marginally consistent

Origin of Mass Hierarchy and Mixing

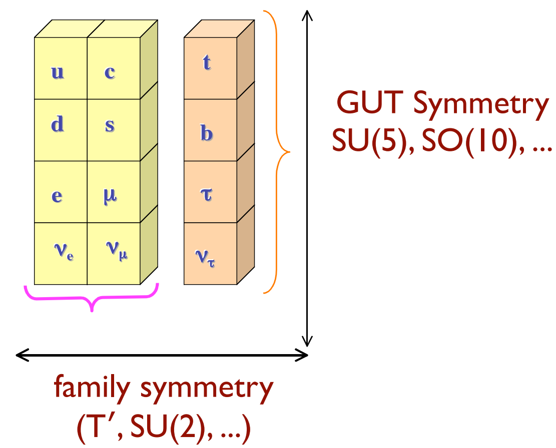


- In the SM: 22 physical quantities which seem unrelated
- Question arises whether these quantities can be related
- No fundamental reason can be found in the framework of SM
- less ambitious aim ⇒ reduce the # of parameters by imposing symmetries
  - SUSY Grand Unified Gauge Symmetry
    - GUT relates quarks and leptons: quarks & leptons in same GUT multiplets
      - one set of Yukawa coupling for a given GUT multiplet ⇒ intra-family relations
    - seesaw mechanism naturally implemented
    - proton decay, leptogenesis, LFV charged lepton decay
  - Family Symmetry
    - relate Yukawa couplings of different families
      - inter-family relations ⇒ further reduce the number of parameters

⇒ Experimentally testable *correlations* among physical observables

Origin of Mass Hierarchy and Mixing

- Several models have been constructed based on
  - GUT Symmetry [SU(5), SO(10)] ⊕ Family Symmetry G_F
- Family Symmetries G_F based on continuous groups:
  - U(1)
  - SU(2)
  - SU(3)



- Recently, models based on discrete family symmetry groups have been constructed
  - A_4 (tetrahedron)
  - T´ (double tetrahedron)
  - S_3 (equilateral triangle)
  - S_4 (octahedron, cube)
  - A_5 (icosahedron, dodecahedron)
  - Δ_{27}
  - Q_4

Motivation: Tri-bimaximal (TBM) neutrino mixing

Discussion on Discrete gauge anomaly: Araki, Kobayashi, Kubo, Ramos-Sanchez, Ratz, Vaudrevange (2008)

Tri-bimaximal Neutrino Mixing

- Tri-bimaximal Mixing Pattern

Harrison, Perkins, Scott (1999)

$$U_{TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

$$\sin^2\theta_{\mathrm{atm,\,TBM}} = 1/2 \qquad \sin^2\theta_{\odot,\mathrm{TBM}} = 1/3 \qquad \sin\theta_{13,\mathrm{TBM}} = 0.$$

- General approach:
  - PMNS = LO prediction (TBM, BM, ...) + corrections
  - corrections:
    - higher order terms in super potential (family symmetry)
    - contributions from charged lepton sector (GUT symmetry)

Non-Abelian Finite Family Symmetry A4

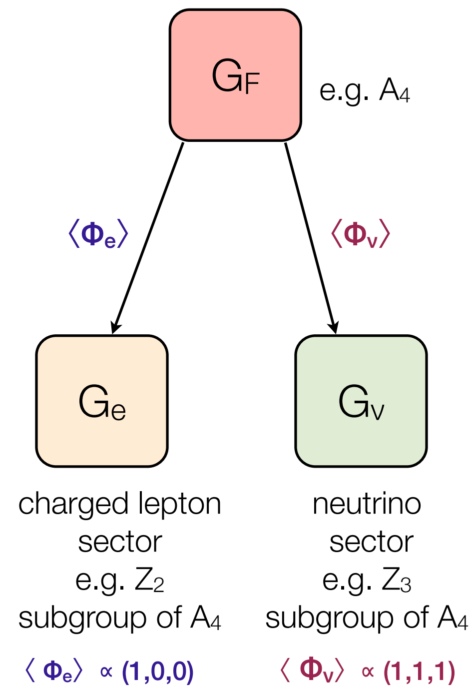
- TBM mixing matrix: can be realized with finite group family symmetry based on A_4 Ma, Rajasekaran (2001); Babu, Ma, Valle (2003); ...

- A_4: even permutations of 4 objects

  S: (1234) → (4321)

  T: (1234) → (2314)

- a group of order 12
- Invariant group of tetrahedron



- TBM arises from misalignment of symmetry breaking patterns

An Example: a SUSY SU(5) x T´ Model

M.-C.C, K.T. Mahanthappa
Phys. Lett. B652, 34 (2007);
Phys. Lett. B681, 444 (2009)

- GUT compatible ⇒ Double Tetrahedral Group T´

[cf. Talk by KT Mahanthappa]

- Symmetries ⇒ 10 parameters in Yukawa sector ⇒ 22 physical observables
  - neutrino mixing angles from group theory (CG coefficients)
  - TBM: misalignment of symmetry breaking patterns
    - neutrino sector: T' → G_{TST2} , charged lepton sector: T' → G_T
  - GUT symmetry ⇒ deviation from TBM related to quark mixing θ_c

M.-C.C, K.T. Mahanthappa,
Phys. Lett. B681, 444 (2009)

  - **complex CG's of T´ ⇒ Novel Origin of CP Violation**
    - CP violation in both quark and lepton sectors entirely from group theory
    - connection between leptogenesis and CPV in neutrino oscillation

before θ_{13} discovery

Sum Rules: Quark-Lepton Complementarity

Quark Mixing

mixing parameters	best fit	3σ range
θ^q_{23}	2.36°	2.25° - 2.48°
θ^q_{12}	12.88°	12.75° - 13.01°
θ^q_{13}	0.21°	0.17° - 0.25°

Lepton Mixing

mixing parameters	best fit	3σ range
θ^e_{23}	42.8°	35.5° - 53.5°
θ^e_{12}	34.4°	31.5° - 37.6°
θ^e_{13}	5.6°	≤ 12.5°

- QLC-I (BM)
  $\theta_c + \theta_{sol} \cong 45^o$ Raidal, '04; Smirnov, Minakata, '04
  $\theta^q_{23} + \theta^e_{23} \cong 45^o$
- QLC-II (TBM)
  $\tan^2\theta_{sol} \cong \tan^2\theta_{sol,TBM} + (\theta_c / 2) * \cos\delta_e$ Ferrandis, Pakvasa; King; Dutta, Mimura; M.-C.C., Mahanthappa
  $\theta^e_{13} \cong \theta_c / 3\sqrt{2}$
- testing sum rules: a *more* robust way to distinguish different classes of models

measuring leptonic mixing parameters to the precision of those in quark sector

Intensity Frontier

after θ_{13} discovery

Sum Rules: Quark-Lepton Complementarity

Quark Mixing

mixing parameters	best fit	3σ range
θ^q_{23}	2.36°	2.25° - 2.48°
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θ^q_{13}	0.21°	0.17° - 0.25°

Lepton Mixing

mixing parameters	best fit	3σ range
θ^e_{23}	38.4° ↓	35.1° - 52.6°
θ^e_{12}	33.6°	30.6° - 36.8°
θ^e_{13}	8.9° ↑	7.5° -10.2°

- QLC-I $\theta_C + \theta_{sol} \cong 45^o$ Raidal, '04; Smirnov, Minakata, '04

  (BM) $\theta^q_{23} + \theta^e_{23} \cong 45^o$ ☜ **inconsistent @ 2σ**

- QLC-II $\tan^2\theta_{sol} \cong \tan^2\theta_{sol,TBM} + (\theta_C / 2) * \cos\delta_e$ Ferrandis, Pakvasa; King; Dutta, Mimura; M.-C.C., Mahanthappa

  (TBM) $\theta^e_{13} \cong \theta_C / 3\sqrt{2}$ ☜ **Too small**

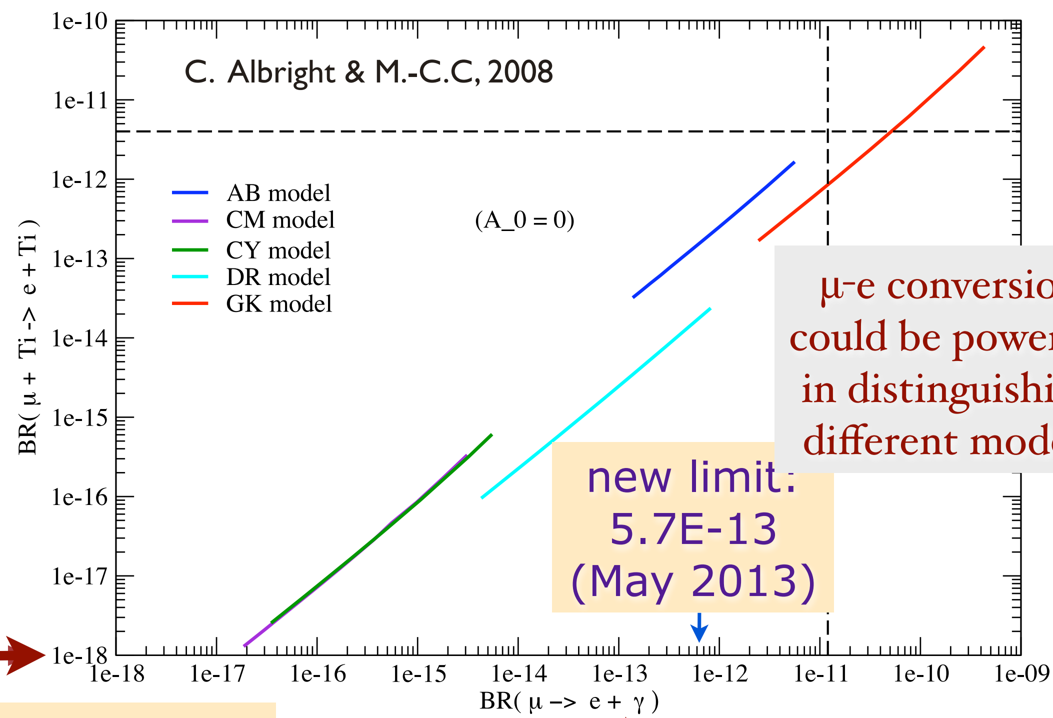
- testing sum rules: a *more* robust way to distinguish different classes of models

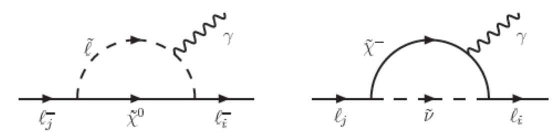
measuring leptonic mixing parameters to the precision of those in quark sector

Intensity Frontier

Other Correlations: Rare CLFV Processes

- SUSY GUTs: Lepton flavor violating charged lepton decays [cf. Talk by Andre de Gouvea]
  - five viable SUSY SO(10) models with dark matter constraints in cMSSM:





μ-e conversion could be powerful in distinguishing different models

new limit: 5.7E-13 (May 2013)

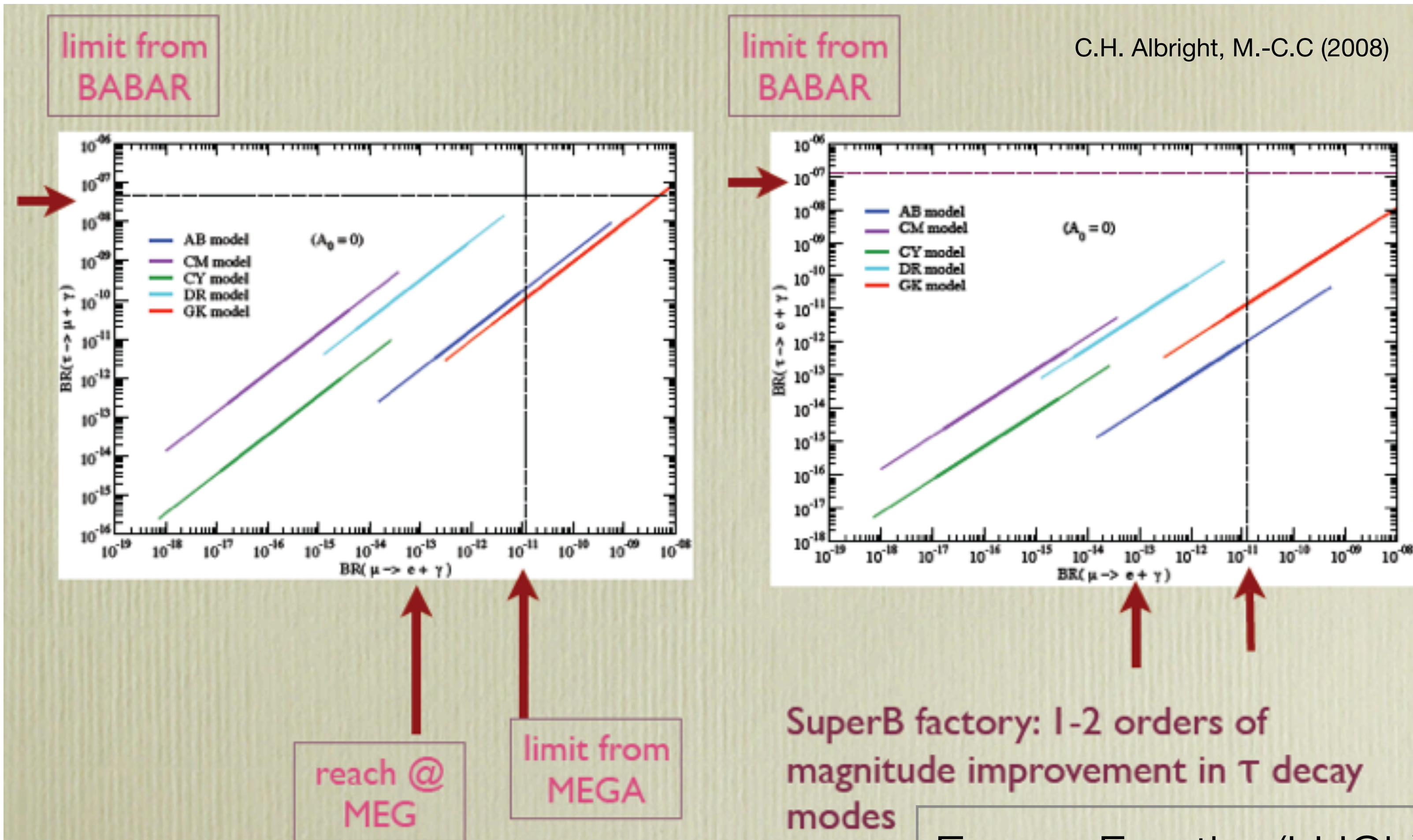
sensitivity of proposed Mu2e exp

reach at MEG

- individual branching fraction: strong dependence on soft SUSY parameters
- correlations between branching fractions: ***strong dependence on flavor structure***

Intensity Frontier (mu2e, ...)

Other Correlations: Rare CLFV Processes



Energy Frontier (LHCb)

Other Possibilities

- Beyond TBM and BM mixing pattern:
  - Golden Ratio for solar angle

$\tan^2\theta_{sol} = 1/\Phi^2 = 0.382$, ($1.4\sigma$ below best fit)

$\Phi = (1 + \sqrt{5}) / 2 = 1.62$

Datta, Ling, Ramond, '03;
Z2 x Z2: Kajiyama, Raidal, Strumia, '07;
A5: Everett, Stuart, '08; ...

[cf. Talk by Lisa Everett]

  - Dodeca Mixing Matrix from D_{12} Symmetry

J. E. Kim, M.-S. Seo (2010)

leading order:

$\theta_C = 15^o$, $\theta_{sol} = 30^o$, $\theta_{atm} = 45^o$

$$V_{\rm PMNS} = U_l^\dagger U_\nu = \begin{pmatrix} \cos\frac{\pi}{6} & \sin\frac{\pi}{6} & 0 \\ -\frac{1}{\sqrt{2}}\sin\frac{\pi}{6} & \frac{1}{\sqrt{2}}\cos\frac{\pi}{6} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}}\sin\frac{\pi}{6} & \frac{1}{\sqrt{2}}\cos\frac{\pi}{6} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$12 = 360^o / 30^o \Rightarrow Z_{12}$

$15^o \Rightarrow Z_2$

$\Big\}\ Z_{12} \times Z_2 = D_{12}$

$\theta_C + \theta_{sol} = 45^o$ (not from GUT symmetry)

breaking of D_{12} :

$\theta_C = 15^o \rightarrow 13.4^o$

$\theta_{sol} = 30^o + O(\varepsilon)$, $\theta_{13} = O(\varepsilon)$

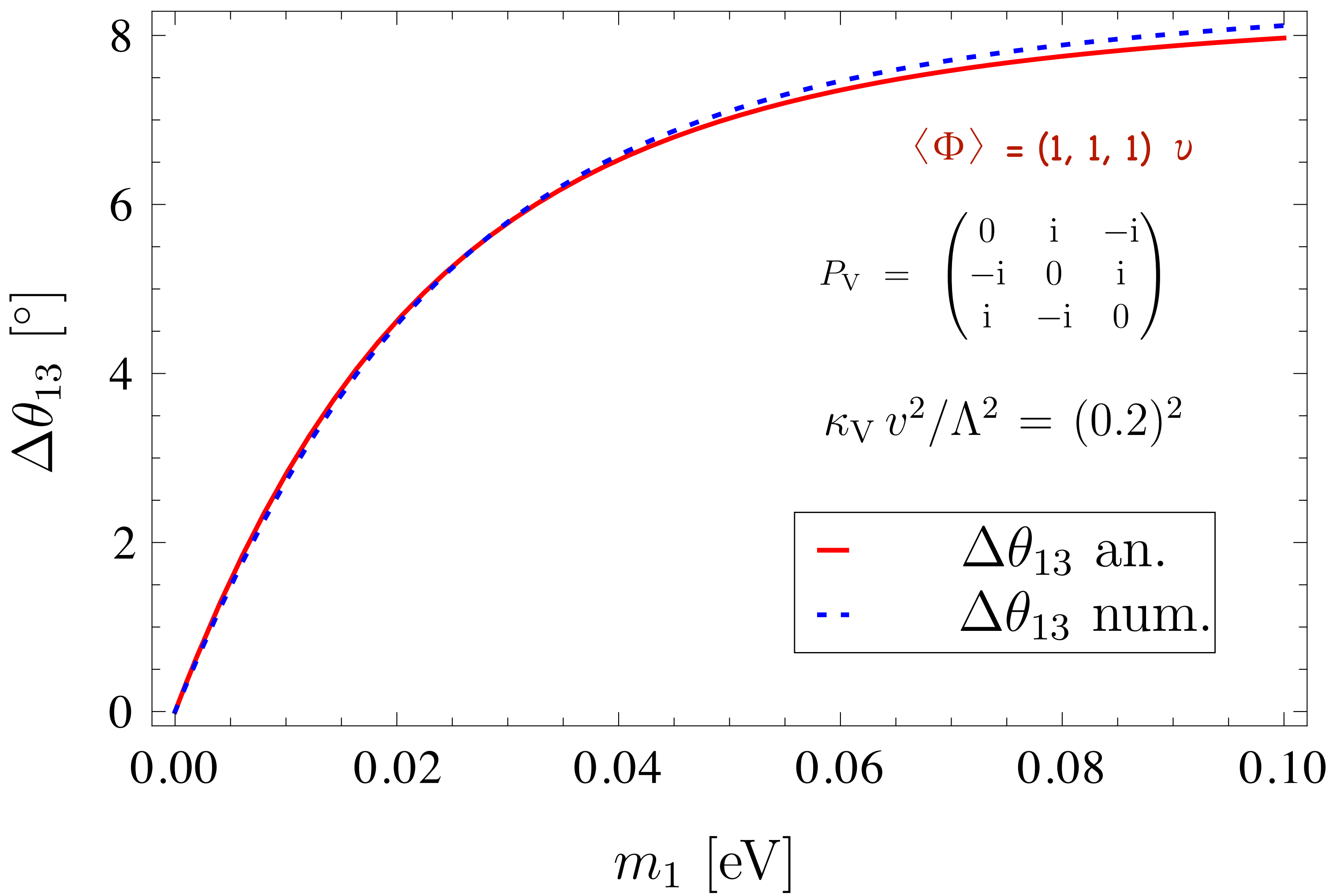
Kähler Corrections

Leurer, Nir, Seiberg (1993); Dudas, Pokorski, Savoy (1995); Dreiner, Thomeier (2003);

- Contributions from Supergravity:
  - higher order terms in Kähler potential induced (and determined) by VEVs of flavon fields (flavor Higgses) $\mathcal{K}_L = 1 - 2xP$
    - non-trivial flavor structure in ***P*** can be induced
    - can't be forbidden by conventional symmetry
    - while similar in structure to RG corrections, can be along different directions than RG
    - size of Kähler corrections generically dominate RG corrections (no loop suppression, contributions from copies heavy states)
    - non-zero CP phases can be induced

An Example: Enhanced θ13 in A4

M.-C.C., Fallbacher, Ratz, Staudt (2012)

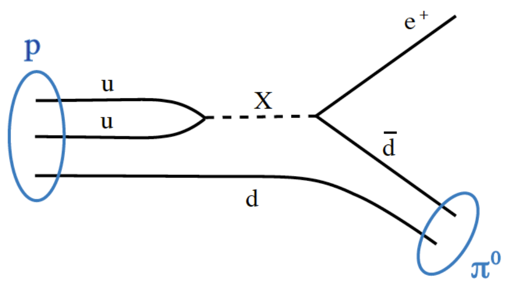


Theoretical understanding of Kähler corrections crucial in achieving precision compatible to experimental accuracy.

Knowledge Frontier

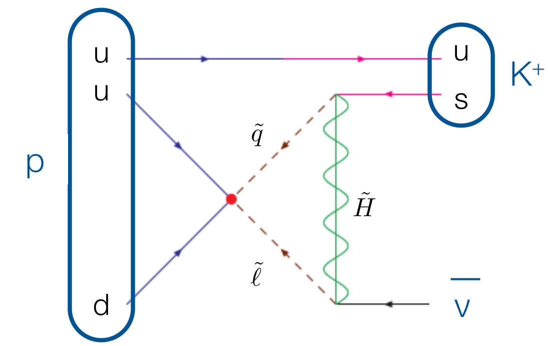
Proton Decay

- GUT predicts proton decay



X: exotic heavy gauge bosons

SUSY GUTs: additional contributions mediated by superpartners



$\tilde{H}$: color-triplet Higgsinos

lifetime: $\tau_p \propto M_X^4$ $\qquad$ $\tau_p \propto M_{\tilde{H}}^2$

[cf. Talk by Radovan Dermisek]

- Experimental Limits

$\tau(p \to e^+\pi^0) > 8.2 \times 10^{33}$ years (90% CL, SuperK 2009) $\Rightarrow M_X > 5 \times 10^{15}$ GeV

$\tau(p \to \overline{\nu}K^+) > 2.3 \times 10^{33}$ years (90% CL, SuperK 2005) $\Rightarrow M_{\tilde{H}} > 10^{19}$ GeV !!

Dermisék, Mafi, Raby, 2000 for reasonable soft SUSY masses

A recent updated study: Babu, Pati, Tavartkiladze (2010)

GUTs and doublet-triplet splitting

Review: MCC, Fallbacher, Ratz (212)

Suppressing the mu term in the MSSM

Assumptions:

- Consistency with unification
- Anomaly freedom

⇒ Only R symmetries can forbid the mu term in the MSSM

No-Go for R symmetries in 4D GUTs

assumptions:

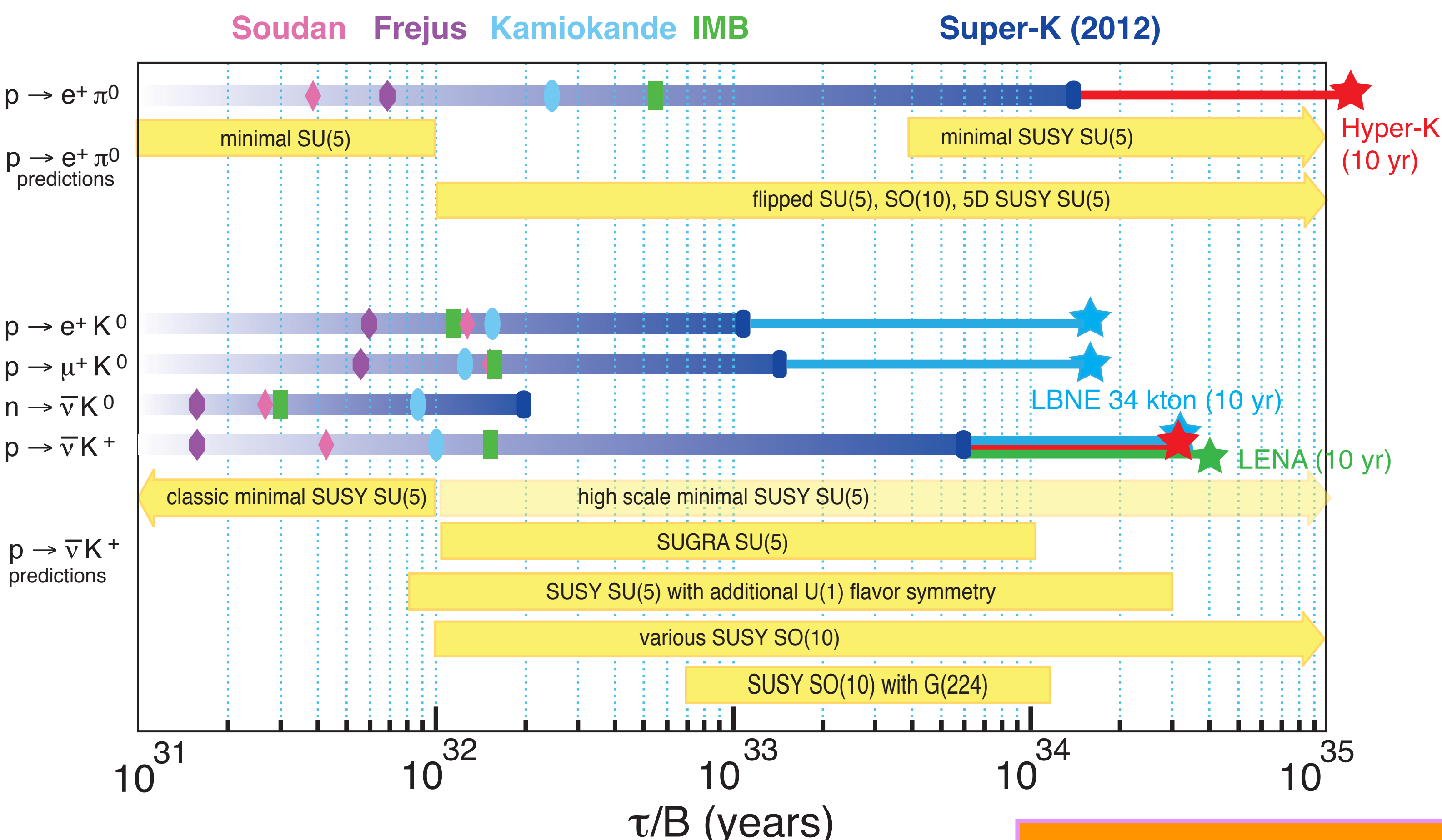
- GUT model in four dimensions based on G ⊃ SU(5)
- GUT symmetry breaking is spontaneous
- only finite number of fields

⇒ Impossible to have MSSM spectrum (w/o exotics) and residual R symmetries

⇒ higher-dimensional models of Grand Unification (dim 5 decay suppressed, dim 6 decay enhanced)

Experimental Limits Confront Theory

Talks by K.S. Babu, E. Kern, ISOUPS2013



Intensity Frontier

Dirac Neutrino Mass and the μ Term

M.-C. C., Michael Ratz, Christian Staudt, Patrick Vaudrevange, (2012)

- R-symmetries: Anomaly-free, SU(5)-consistent, allow Yukawa couplings
  - absence of perturbative mu term ⇒ constraints on R charges of Hu, Hd
    - ➜ non-perturbative mu term ~ TeV automatically arise

$$\mu \sim \langle \mathscr{W} \rangle / M_{\mathrm{P}}^2 \sim m_{3/2}$$

  - absence of perturbative Weinberg operator ⇒ constraints on R charges of leptons
    - ➜ non-perturbative, realistic Dirac neutrino mass automatically arise

$$Y_\nu \sim \frac{m_{3/2}}{M_{\mathrm{P}}} \sim \frac{\mu}{M_{\mathrm{P}}}$$

  - solutions automatically forbid dim-4 and suppress dim-5 proton decay of the MSSM
  - all superpotential B and L violating operators to all orders with Hilbert basis method

R. Kappl, M. Ratz, C. Staudt (2011)

    - an example: $\mathbb{Z}_8^R$ symmetry
      - ➡ Δ L = 2 operators forbidden ⇒ no neutrinoless double beta decay
      - ➡ ΔL = 4 operators allowed ⇒ new LNV processes

anomaly-free, SU(5) compatible R symmetries simultaneously solve mu problem, naturally small Dirac neutrino masses

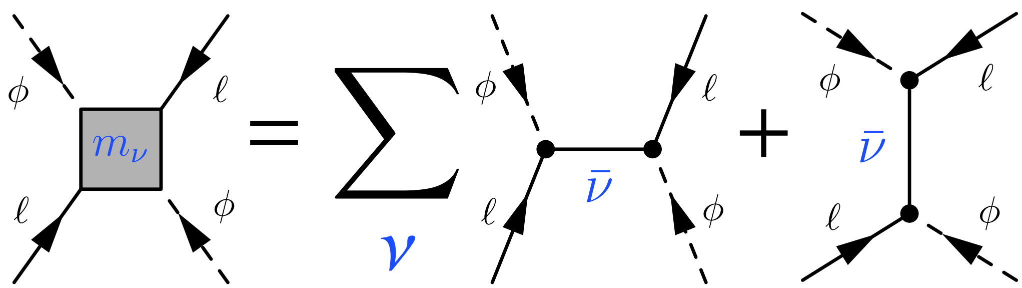
Heterotic Seesaw

Talk by Michael Ratz at BeNE 2012

- heterotic string models: O(100) RH neutrinos

Buchmüller, Hamaguchi, Lebedev, Ramos-Sánchez, Ratz (2007)

- O(100) contributions to the effective neutrino mass operator



  - Effective suppression

$$m_\nu \sim \frac{v^2}{M_*}$$

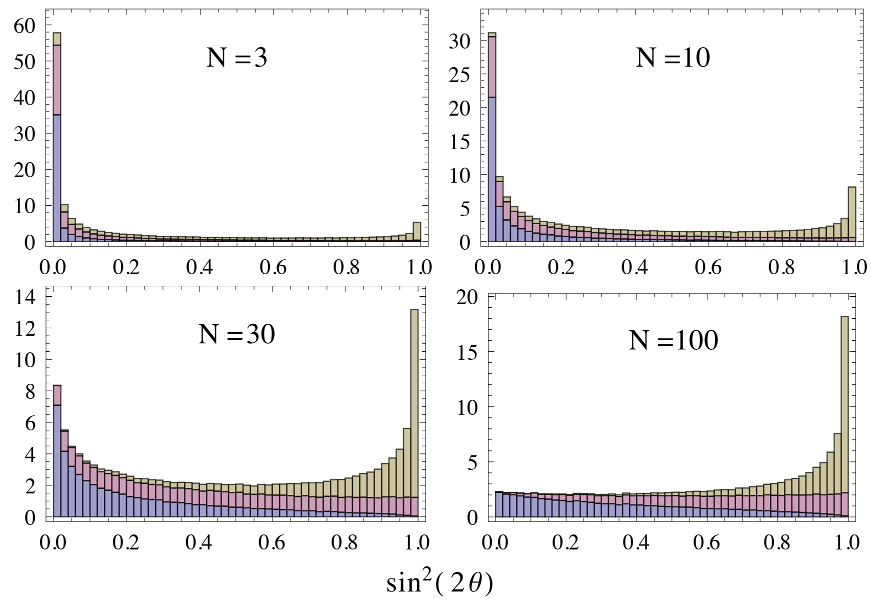
$$M_* \sim \frac{M_{\mathrm{GUT}}}{10...100}$$

Heterotic Seesaw

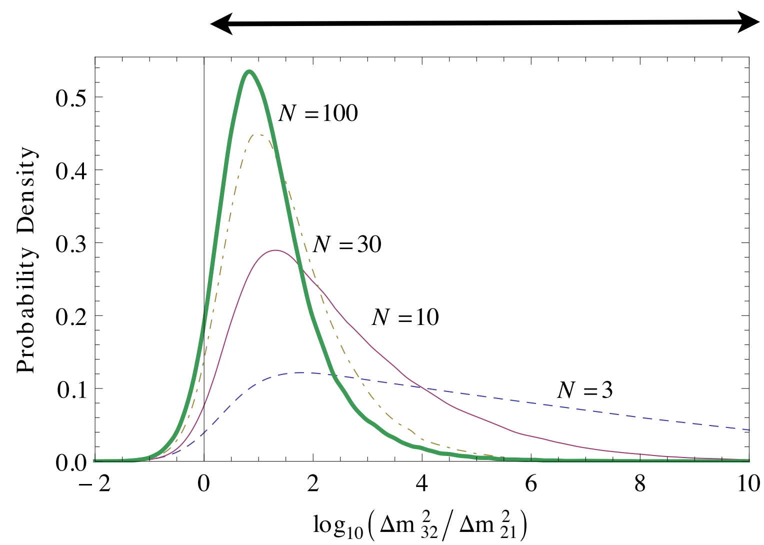
Talk by Michael Ratz at BeNE 2012

- statistical expectations with large N (= # of RH neutrinos)
  ⇒ anarchy

preference for large mixing angles



preference for normal hierarchy

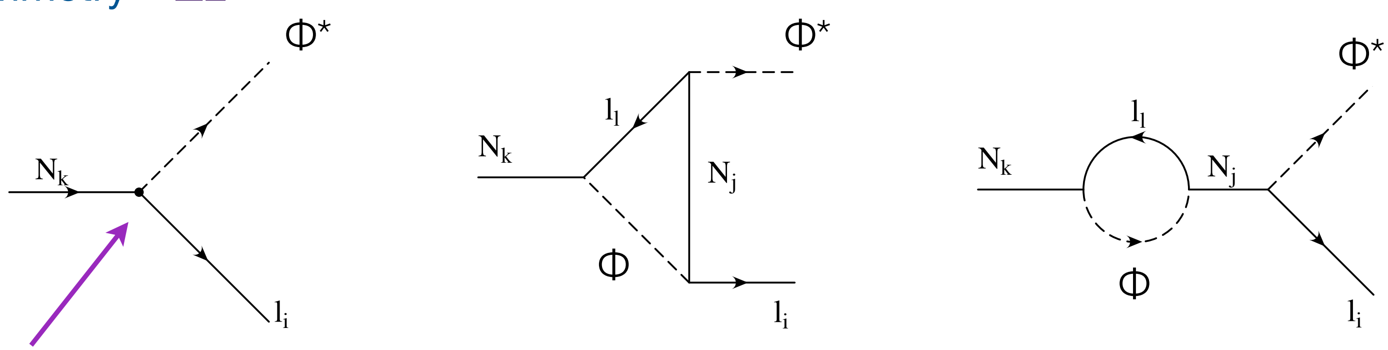


Feldstein, Klemm (2012)

Leptogenesis

Fukugita, Yanagida, 1986

- RH heavy neutrino decay:
  - quantum interference of tree-level & one-loop diagrams ⇒ primordial lepton number asymmetry   ΔL



neutrino Yukawa interactions

leptons   antileptons

Leptonic CP violation ⇒ $\Delta L \propto \left[\Gamma(N_1 \to \ell_\alpha \Phi) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{\Phi})\right] \neq 0$

⇔ neutrino parameters

Cosmic Frontier

Leptogenesis ⇔ CPV in Neutrino Oscillation

- models for neutrino masses:
  - additional symmetries
  - reduce the number of parameters ⇒ model dependent connection possible
- rank-2 mass matrix (may be realized by symmetry)
  - models with 2 RH neutrinos (2 x 3 seesaw) Kuchimanchi & Mohapatra, 2002
  - sign of baryon asymmetry ↔ sign of CPV in ν oscillation Frampton, Glashow, Yanagida, 2002
- all CP come from a single source
  - minimal models with spontaneous CP violation:
    - SM + vectorial quarks + singlet scalar Branco, Parada, Rebelo, 2003
    - minimal LR model: only 1 physical leptonic CP phase M.-.C.C, Mahanthappa, 2005
    - SCPV in SO(10): $<126>_{B-L}$ complex Achiman, 2004, 2008
  - SUSY SU(5) x T′ Model: M.-.C.C, Mahanthappa, 2009
    - group theoretical origin of CP violation ⇒ only low energy lepton phases ≠ 0

In all models, non-zero Dirac CP phase required for leptogenesis

"Non-standard" Leptogenesis

- Gravitino problem:

For light gravitino mass,

BBN constraints ⇒ $T_{RH} < 10^{(5\text{-}6)}$ GeV

⟷ tension! ⟷

Sufficient leptogenesis

⇒ $T_{RH} > M_R > 2 \times 10^9$

- Possible ways to avoid the tension:
  - resonant leptogenesis (near degenerate RH neutrinos) Pilaftsis, 1997
    - TeV scale leptogenesis possible
    - possible collider tests Pilaftsis, Underwood, 2003
  - soft leptogenesis Boubekeur, 2002; Grossman, Kashti, Nir, Roulet, 2003; D'Ambrosio, Giudice, Raidal, 2003
    - CP phase in soft SUSY parameters
  - Dirac leptogenesis K. Dick, M. Lindner, M. Ratz, D. Wright, 2000; H. Murayama, A. Pierce, 2002
    - connections to LFV B. Thomas, M. Toharia, 2006
  - non-thermal leptogenesis
    - inflaton decay Fuji, Hamaguchi, Yanagida, 2002

N-Nbar Oscillation ⇔ Leptogenesis Scale

- Neutrino Experiments → “archeological” evidence for leptogenesis
- n-nbar oscillation searches → complementarity test of leptogenesis (baryogenesis) mechanisms
  - constrain the scale of leptogenesis
- observation of neutron antineutron oscillation K.S. Babu, R.N. Mohapatra, 2012
  - new physics with $\Delta B = 2$ at $10^{(5\text{-}6)}$ GeV
  - erasure of matter-antimatter generated at high scale, e.g. standard leptogenesis

▸ Low scale leptogenesis scenarios preferred

Toward the Theory of Leptogenesis:

Buchmuller, Fredenhagen, 2000;
Simone, Riotto 2007;
Lindner, Muller 2007

Classical Boltzmann Equations

⬇

Quantum Boltzmann Equations

(Closed-time-path formulation for non-equilibrium QFT)

Schwinger, 1961; Mahanthappa, 1962;
Bakshi, Mahanthappa, 1963;
Keldysh, 1965

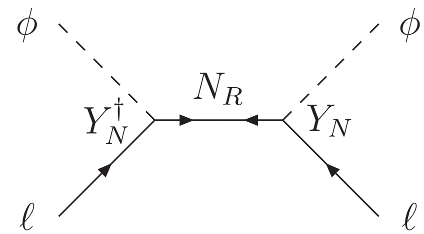
Knowledge Frontier

TeV Scale Seesaw Models

For a recent review:
M.-C. C., J.R. Huang, arXiv:1105.3188

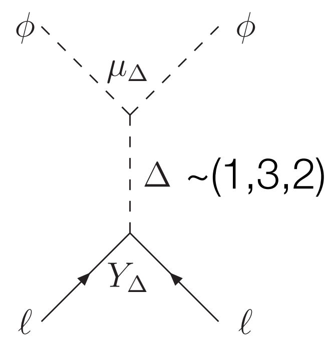
- With new particles:
  - type-I seesaw
    - generally decouple from collider physics

Kersten, Smirnov, 2007



  - type-II seesaw Lazarides, 1980; Mohapatra, Senjanovic, 1980
    - TeV scale doubly charged Higgs ⇔ small couplings
    - unique signatures:

$$\Delta^{++} \to e^+ e^+,\ \mu^+ \mu^+,\ \tau^+ \tau^+$$

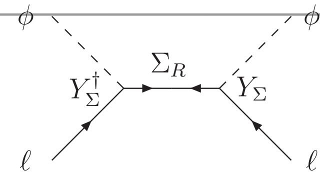


    - decay BR ↔ mass ordering

Perez, Han, Huang, Li, Wang, ‘08; Han, Mukhopadhyaya, Si, Wang, ‘07; Akeroyd, Aoki, Sugiyama, ‘08; ...

Energy Frontier

TeV Scale Seesaw Models



Σ_R: ~(1,3,0)

- With new particles:
  - type-III seesaw Foot, Lew, He, Joshi, 1989; Ma, 1998
    - TeV scale triplet decay : observable displaced vertex

$$\tau \leq 1 \text{ mm} \times \left(\frac{0.05 \text{ eV}}{\sum_i m_i}\right)\left(\frac{100 \text{ GeV}}{\Lambda}\right)^2$$

Franceschino, Hambye, Strumia,2008

    - neutral component Σ^0 can be dark matter candidate E. J. Chun, 2009
  - Radiative Seesaw
    - Zee-Babu model (neutrino mass at 2 loop) Zee 1986; Babu, 1989
      - singly+doubly charged SU(2) singlet scalars
    - neutrino mass at higher loops: TeV scale RH neutrinos Krauss, Nasri, Trodden, 2003; E. Ma, 2006; Aoki, Kanemura, Seto, 2009
    - loop particles can also have color charges
      - enhanced production cross section Perez, Han, Spinner, Trenkel, 2011

TeV Scale Seesaw Models

- With new interactions:
  - SUSY LR Model:
    - tested via searches for W_R

Azuleos et al 06; del Aguila et al 07, Han et al 07; Chao, Luo, Xing, Zhou, '08; ...

- More Naturally: inverse seesaw or higher dimensional operators or Extra Dim
  - inverse seesaw Mohapatra,1986; Mohapatra, Valle, 1986; Gonzalez-Garcia, Valle, 1989
    - non-unitarity effects

Intensity Frontier

    - enhanced LFV (both SUSY and non-SUSY cases)
    - correlation

Hirsch, Kernreiter, Romao, del Moral, 2010

$$\frac{\mathrm{BR}(\tilde{\chi}_1^\pm \to \tilde{N}_{1+2} + \mu^\pm)}{\mathrm{BR}(\tilde{\chi}_1^\pm \to \tilde{N}_{1+2} + \tau^\pm)} \propto \frac{\mathrm{BR}(\mu \to e + \gamma)}{\mathrm{BR}(\tau \to e + \gamma)}$$

SUSY Flavor

- Family symmetry:
  - if symmetry breaking at TeV ⇒ signatures at colliders
    - non-anomalous, non-universal U(1)' at TeV M.-C. C., de Gouvea, Dobrescu (2006)
      - probing flavor through Z' decays at colliders M.-C. C., J.-R. Huang (2009)
  - with SUSY: superpartners charged under family symmetry, can probe (indirectly) flavor sector even for high symmetry breaking scale
    - inverse hierarchy for sfermions

global U(2) Dine, Leigh, Kagan '93; Pomarol, Tommasini '95; Barbieri, Davali, Hall '96; Barbieri, Hall, Romanino, '97; ...

anomalous U(1) Dudas, Pokorski, Savoy '95; Dudas, Grojean, Pokorski, Savoy '96; Nelson, Wright '97;

Correlations among Observables

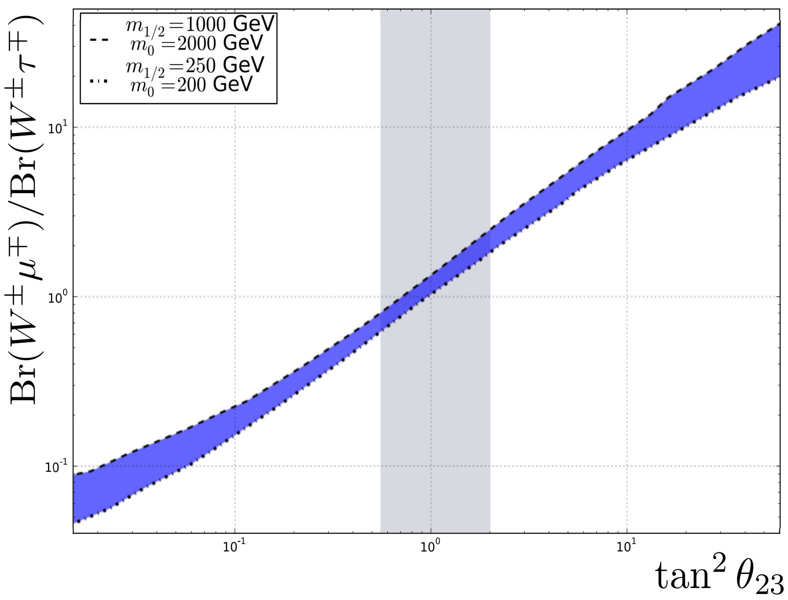
- Example: MSSM with bi-linear R-Parity Violation

de Campos, Eboli, Hirsch, Margo, Porod, Restrepo, Valle, 2010

$$\mathcal{W}_R = \epsilon_i \hat{L}_i \hat{H}_u$$

- mixing angle ↔ neutralino decay

$$\tan^2\theta_{\rm atm} \simeq \frac{BR(\tilde{\chi}_1^0 \to \mu^\pm W^\mp)}{BR(\tilde{\chi}_1^0 \to \tau^\pm W^\mp)}$$



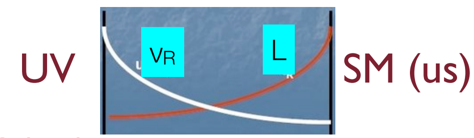
[cf. Talk by Prashant Sarawat]

Energy Frontier

Curing FCNC Problem: Family Symmetry vs MFV

$$\psi_{(0)} \sim e^{(1/2-c)ky}$$

- low scale new physics severely constrained by flavor violation
- Warped Extra Dimension



  - wave function overlap ⇒ naturally small Dirac mass
  - non-universal bulk mass terms (c) ⇒ FCNCs at tree level ⇒ Λ > O(10) TeV
  - fine-tuning required to get large mixing and mild mass hierarchy
  - Minimal Flavor Violation quark sector: A. Fitzpatrick, G. Perez, L. Randall (2007) lepton sector: M.-C.C., H.B. Yu (2008)

$$C_e = aY_e^\dagger Y_e, \quad C_N = dY_\nu^\dagger Y_\nu, \quad C_L = c(\xi Y_\nu Y_\nu^\dagger + Y_e Y_e^\dagger)$$

  - T´ symmetry in the bulk for quarks & leptons: M.-C.C., K.T. Mahanthappa, F. Yu (2009) A4 for leptons: Csaki, Delaunay, Grojean, Grossmann (2008)
    - TBM mixing: common bulk mass term, no tree-level FCNCs
    - TBM mixing and masses decouple: no fine-tuning
    - can accommodate both normal & inverted mass orderings

- **Family Symmetry: alternative to MFV to avoid FCNCs in TeV scale new physics**
  - **many family symmetries violate MFV, possible new FV contributions**

Summary & Discussions

- Intensity Frontier: probe high (GUT) scale physics not accessible to collider experiments
  - CP violation (neutrino experiments, ...)
  - Baryon number non-conservation (nucleon decay searches, N-Nbar oscillation, ...)
  - Lepton number non-conservation (neutrino-less double beta decay)
  - Charged Lepton flavor violation (CLFV)
  - Majorana vs Dirac (neutrino-less double beta decay)
- Cosmic Frontier
  - N_eff
  - absolute mass scale of neutrinos
  - leptogenesis
- Energy Frontier
  - CLFV predictions in GUT flavor models
  - new particles and interactions in TeV scale seesaws
  - correlations in TeV scale (SUSY) seesaws