SO(10) Model for Fermion Masses

SUSY 05

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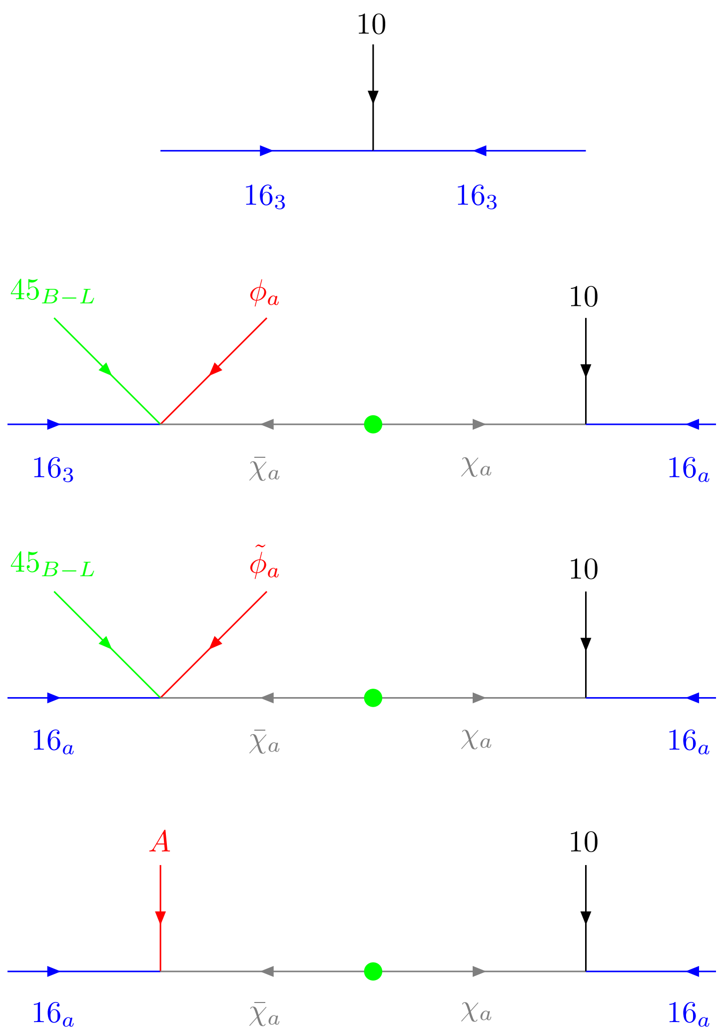
Outline

- SO(10) model with D_3 family symmetry
  - brief description of the model
  - mechanism for bi-large lepton mixing
  - fit for fermion masses and mixing
- Predictions:
  - 1-3 lepton mixing
  - neutrinoless double beta decay, J, ...
  - leptogenesis
  - SUSY & Higgs, $\Omega_\chi h^2$, $B_s \to \mu^+\mu^-$, ...
- Conclusions

SO(10) $\times D_3 \times [U(1) \times Z_2 \times Z_3]$ model

$$W_{ch.f.} = 16_3\ 10\ 16_3 + 16_a\ 10\ \chi_a + \bar{\chi}_a \left(M_\chi\ \chi_a + 45\ \frac{\phi_a}{\hat{M}}\ 16_3 + 45\ \frac{\tilde{\phi}_a}{\hat{M}}\ 16_a + A\ 16_a \right)$$



$$< \phi > = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \quad < \tilde{\phi} > = \begin{pmatrix} 0 \\ \tilde{\phi}_2 \end{pmatrix}$$

$$\bullet \ = M(\alpha X + \beta Y)$$

$$\epsilon \propto \phi_1 / M_G, \quad \tilde{\epsilon} \propto \tilde{\phi}_2 / M_G,$$

$$\xi = \phi_2/\phi_1, \quad \epsilon' \propto A/M_G, \quad \sigma = \frac{1+\alpha}{1-3\alpha}$$

$$Y_d = \begin{pmatrix} 0 & \epsilon' & -\epsilon\xi\sigma \\ -\epsilon' & \tilde{\epsilon} & -\epsilon\sigma \\ \epsilon\xi & \epsilon & 1 \end{pmatrix} \lambda$$

Neutrino sector

$$W_N = \overline{16}\,(\lambda_2\ N_a\ 16_a\ +\ \lambda_3\ N_3\ 16_3) + \ \frac{1}{2}\,(S_a\ N_a\ N_a\ \ +\ \ S_3\ N_3\ N_3)$$

$$\langle\overline{16}\rangle = v_{16}, \quad \langle S_a\rangle = M_a,\ a=1,2, \quad \langle S_3\rangle = M_3$$

$$W_{\nu,\bar{\nu},N}{}^{eff} = \nu\ m_\nu\ \bar{\nu} + \bar{\nu}\ V\ N + \frac{1}{2}\ N\ M_N\ N$$

with

$$V = v_{16}\begin{pmatrix} 0 & \lambda_2 & 0 \\ \lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}, \quad M_N = \mathrm{diag}(M_1,\ M_2,\ M_3)$$

effectively:

$$M_R = V\ M_N^{-1}\ V^T\ \equiv\ \mathrm{diag}\left(M_{R_1}, M_{R_2}, M_{R_3}\right),$$

$$M_{R_1}\ \ll\ M_{R_2}\ \ll\ M_{R_3}$$

Bi-large lepton mixing

$$W_{\nu,\bar{\nu}}{}^{eff} = \nu\ m_\nu\ \bar{\nu} + \frac{1}{2}\ \bar{\nu}\ M_R\ \bar{\nu}$$

$$m_\nu \simeq \begin{pmatrix} 0 & b & b \\ b & a & a \\ b & a & 1 \end{pmatrix} \lambda\ v_u, \qquad M_R = \begin{pmatrix} M_{R_1} & 0 & 0 \\ 0 & M_{R_2} & 0 \\ 0 & 0 & M_{R_3} \end{pmatrix}$$

$$b \ll a \ll 1, \qquad M_{R_1} \ll M_{R_2} \ll M_{R_3}$$

effective left-handed neutrino Majorana mass matrix:

$$\mathcal{M} = m_\nu\ M_R^{-1}\ m_\nu^T \equiv \mathcal{M}_1 + \mathcal{M}_2 + \mathcal{M}_3, \quad \mathcal{M}_1 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} \frac{(b\lambda v_u)^2}{M_{R_1}}, \ \ldots$$

- 2-3 mixing close to maximal, if $\mathcal{M}_1$ or $\mathcal{M}_2$ dominates
- bi-large mixing only if $\mathcal{M}_1$ and $\mathcal{M}_2$ contribute comparably with opposite overall phases
- $\sin\theta_{13} \simeq b/a \ll 1$

R.D. (2004)

Fit to fermion masses and mixing

Observable (masses in GeV)	Data (σ)	Theory	Pull
$G_\mu \times 10^5$	1.16637 (0.1%)	1.16635	< 0.01
α_{EM}^{-1}	137.036 (0.1%)	137.031	< 0.01
$\alpha_s(M_Z)$	0.1187 (0.002)	0.1184	0.02
M_t	174.3 (5.1)	175.36	0.04
$m_b(M_b)$	4.25 (0.25)	4.252	< 0.01
$M_b - M_c$	3.4 (0.2)	3.513	0.32
$m_c(m_c)$	1.2 (0.2)	1.03	0.72
m_s	0.105 (0.025)	0.114	0.13
m_d/m_s	0.0521 (0.0067)	0.0627	2.53
$Q^{-2} \times 10^3$	1.934 (0.334)	1.763	0.26
M_τ	1.777 (0.1%)	1.777	< 0.01
M_μ	0.10566 (0.1%)	0.10566	< 0.01
$M_e \times 10^3$	0.511 (0.1%)	0.511	< 0.01
V_{us}	0.22 (0.0026)	0.2192	0.09
V_{cb}	0.0413 (0.0015)	0.0407	0.15
V_{ub}	0.00367 (0.00047)	0.00332	0.56
V_{td}	0.0082 (0.00082)	0.00819	< 0.01
ϵ_K	0.00228 (0.000228)	0.00238	0.19
$\sin(2\beta)$	0.736 (0.049)	0.6757	1.51
$\Delta m^2_{31} \times 10^3$	2.3 (0.6)	2.407	0.03
$\Delta m^2_{21} \times 10^5$	7.9 (0.6)	7.866	< 0.01
$\sin^2\theta_{12}$	0.295 (0.045)	0.2851	0.05
$\sin^2\theta_{23}$	0.51 (0.13)	0.546	0.08
TOTAL χ^2			6.70

Input parameters:

$1/\alpha_G,\ M_G,\ \epsilon_3$

$\lambda,\ \epsilon,\ \sigma,\ \tilde{\epsilon},\ \rho,\ \epsilon',\ \xi$

$\Phi_\sigma,\ \Phi_{\tilde{\epsilon}},\ \Phi_\rho,\ \Phi_\xi$

$m_{16} = 3500$ GeV

$M_{1/2} = 450$ GeV

$A_0 = -6888.3$ GeV

$\mu(M_Z) = 247.9$ GeV

$(m_{H_d}/m_{16})^2 = 2.00$

$(m_{H_u}/m_{16})^2 = 1.71$

$\tan\beta = 49.98$

$M_{R_1} = 1.1 \times 10^{10}$ GeV

$M_{R_2} = -9.3 \times 10^{11}$ GeV

$M_{R_3} = 5.8 \times 10^{13}$ GeV

Neutrino masses, $\sin^2\theta_{13}$ and CP phases

m_{ν_3} (eV)	0.0492
m_{ν_2} (eV)	0.0096
m_{ν_1} (eV)	0.0037
$\sin^2\theta_{13}$	0.0024
J	0.0107
$\sin\delta$	0.98
α_1 (rad)	-1.286
α_2 (rad)	1.821
$\langle m_{\beta\beta}\rangle$ (eV)	0.00021
$m_{\nu_e}^{eff}$ (eV)	0.0065
ϵ_1	-1.16×10^{-7}

Exp. limit:

$$\sin\theta_{13}^2 < 0.031$$

Chooz, solar+KamLAND

at limits of future reactor exp.

observable at long baseline acc . exp.

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{ai}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

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

$$P = \mathrm{diag}\left(e^{i\alpha_1/2},\ e^{i\alpha_2/2},\ 1\right)$$

Neutrinoless double-beta decay, J, ...

m_{ν_3} (eV)	0.0492
m_{ν_2} (eV)	0.0096
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$\sin^2\theta_{13}$	0.0024
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Jarlskog parameter:

$$J = s_{12}c_{12}s_{13}c_{13}^2 s_{23}c_{23}\sin\delta$$

may be observable at long baseline exp.

neutrinoless double-beta decay:

$$\langle m_{\beta\beta}\rangle = \left|\ \sum_i U_{ei}^2\, m_{\nu_i}\ \right|$$

not observable in near-future exp.

eff. ν_e mass measured in low energy beta decay of tritium:

$$m_{\nu_e}^{eff} = \left(\sum_i |U_{ei}|^2\, m_{\nu_i}^2\right)^{1/2}$$

not observable in proposed exp.

Leptogenesis

m_{ν_3} (eV)	0.0492
m_{ν_2} (eV)	0.0096
m_{ν_1} (eV)	0.0037
$\sin^2\theta_{13}$	0.0024
J	0.0107
$\sin\delta$	0.98
α_1 (rad)	-1.286
α_2 (rad)	1.821
$\langle m_{\beta\beta}\rangle$ (eV)	0.00021
$m_{\nu_e}^{eff}$ (eV)	0.0065
ϵ_1	-1.16×10^{-7}

thermal leptogenesis:

$$8\times\epsilon_1 \approx -0.9\times 10^{-6}$$

required $\sim -10^{-6}$

moreover:

$m_{\nu_1}\simeq 0.004$ eV and $M_{R_1}\simeq 10^{10}$ GeV

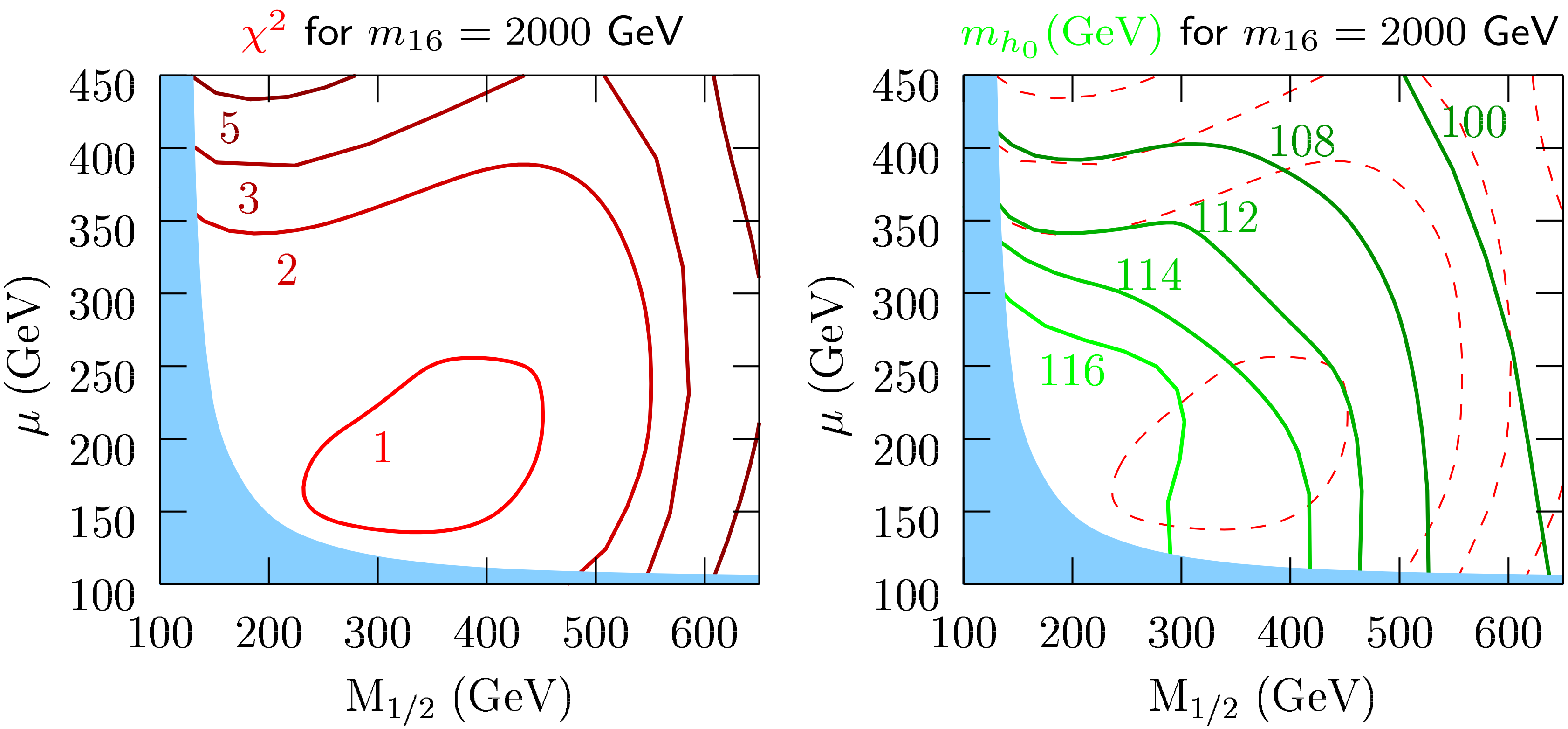
in the range where baryon asymmetry is entirely determined by neutrino properties! (no dependence on initial neutrino abundance or initial baryon asymmetry)

BUT gravitino problem!

CP asymmetry:

$$\epsilon_1 = -\frac{3}{16\pi}\frac{1}{(Y_\nu^T Y_\nu^*)_{11}}\sum_{i=2,3} Im\{([Y_\nu^\dagger Y_\nu]_{1i})^2\frac{M_{R_1}}{M_{R_i}}\}$$

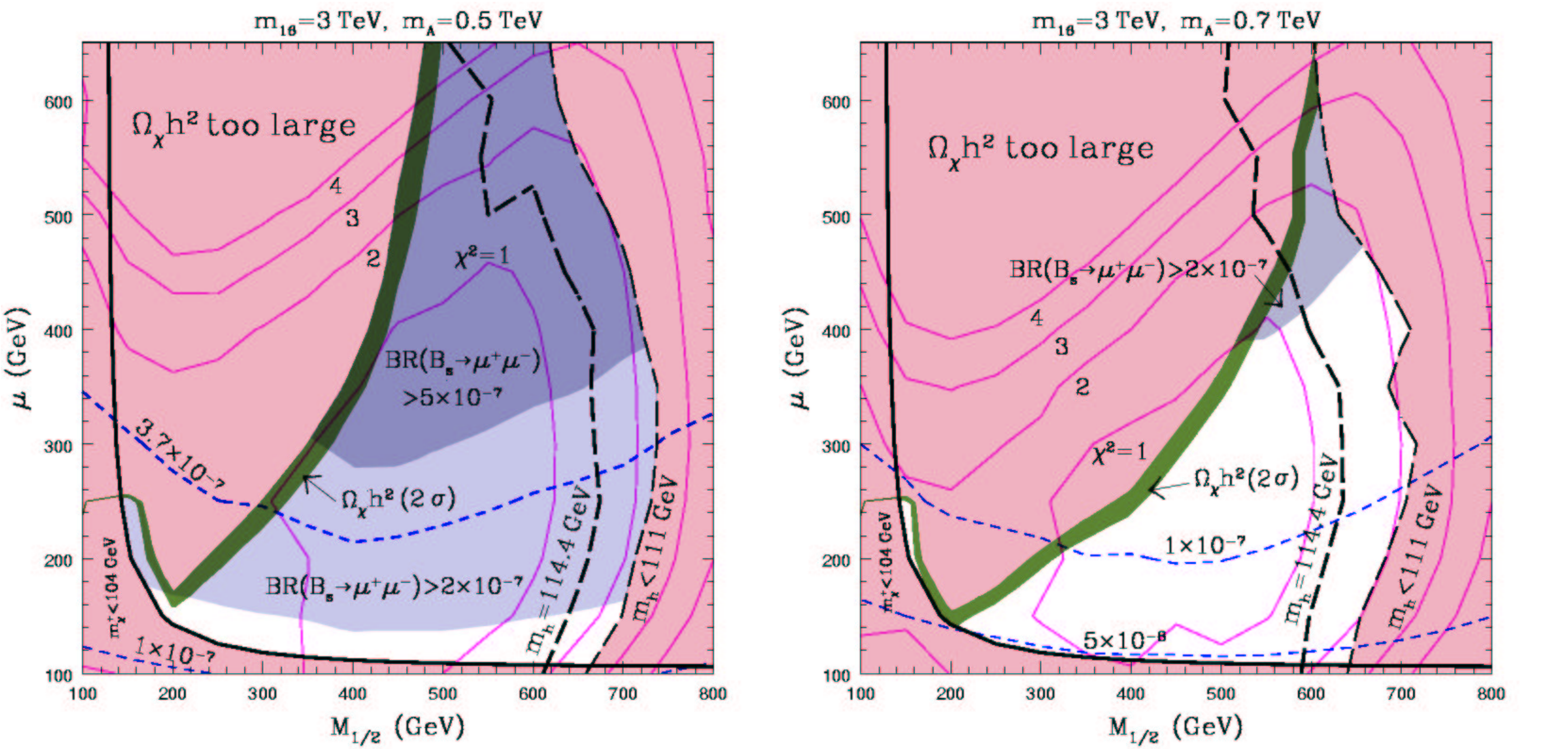
SUSY & Higgs, $\Omega_\chi h^2$, $B_s \to \mu^+\mu^-$, ...



$$\mu,\ M_{1/2} \ll m_{16}, \quad -A_0 \simeq \sqrt{2}m_{10} \simeq 2m_{16}, \quad \tan\beta \simeq 50$$

T. Blazek, R.D. and S. Raby, (2002)

SUSY & Higgs, $\Omega_\chi h^2$, $B_s \to \mu^+\mu^-$, ...



R.D., S. Raby, L. Roszkowski and R. Ruiz De Austri, (2003), (2005)

Conclusions

- SO(10) model with D_3 family symmetry
  - bi-large lepton mixing
  - excellent fit for fermion masses and mixing
- Predictions:
  - small 1-3 mixing
  - optimal for leptogenesis
  - tiny neutrinoless double beta decay, J, ...
  - accommodates $\Omega_\chi h^2$, $B_s \to \mu^+\mu^-$, ...
  - suppresses dim. 5 proton decay and flavor violation

R.D., A. Mafi, S. Raby, (2001)