

YuKawa unification : MSSM at large $\tan\beta$

Stuart Raby

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DEPARTMENT OF
PHYSICS

Outline

- SO(10) Yukawa unification
- Large $\tan \beta \sim 50$
- $m_{top}, m_{bottom}, m_{tau}$
- Soft SUSY breaking masses
 - Inverted scalar mass hierarchy
- Higgs masses
- Fermion masses and mixing
- Flavor violation

Hierarchical $SO(10)$ Yukawas

$$W \supset 16_3 \ 10 \ 16_3 + 16_3 \ 10 \ \frac{45}{M} \ 16_2 + \dots$$

Albright, Anderson, Babu, Barr, Barbieri, Berezhiani,
Blazek, Carena, Chang, Dermisek, Dimopoulos, Hall,
Masiero, Murayama, Pati, Raby, Romanino, Rossi,
Starkman, Wagner, Wilczek, Wiesenfeldt,
Willenbrock

Effective higher dimension operators,

Small rep's + Many predictions !!

Possible UV completion to strings !!

$$\lambda \quad 16_3 \quad 10 \quad 16_3$$

$$\lambda_t = \lambda_b = \lambda_\tau = \lambda_{\nu_\tau} \equiv \lambda$$

Note, CANNOT predict top mass due to
large SUSY threshold corrections to
bottom and tau mass

Hall, Rattazzi & Sarid

Carena, Olechowski, Pokorski & Wagner

So instead use Yukawa unification to predict
soft SUSY breaking masses !!

Bottom mass corrections

$$\frac{\delta m_b}{m_b} \propto \frac{\alpha_3 \mu M_g \tan \beta}{m_{\tilde{b}}^2} + \frac{\lambda_t^2 \mu A_t \tan \beta}{m_{\tilde{t}}^2} + \log \text{corr.}$$

$$\frac{\delta m_b}{m_b} \leq -2\%$$

Needed to fit data

$$\mu M_g > 0 \quad \Rightarrow \quad \mu A_t < 0$$

Yukawa Unification & Soft SUSY breaking

Blazek, Dermisek & Raby PRL 88, 111804 (2002)
PRD 65, 115004 (2002)

Baer & Ferrandis, PRL 87, 211803 (2001)

Auto, Baer, Balazs, Belyaev, Ferrandis & Tata
JHEP 0306:023 (2003)

Tobe & Wells NPB 663, 123 (2003)

Dermisek, Raby, Roszkowski & Ruiz de Austri
JHEP 0304:037 (2003)
JHEP 0509:029 (2005)

Baer, Kraml, Sekmen & Summy
JHEP 0803:056 (2008)
JHEP 0810:079 (2008)

$$\lambda \quad 16_3 \quad 10 \quad 16_3$$

$$\lambda_t = \lambda_b = \lambda_\tau = \lambda_{\nu_\tau} \equiv \lambda$$

Fit t,b,tau requires

$$A_0 \approx -2m_{16} \quad m_{10} \approx \sqrt{2}m_{16}$$

$$m_{16} > \text{few TeV} \quad \mu, M_{1/2} \ll m_{16}$$

$$\tan \beta \approx 50$$

Radiative EWSB requires

$$\Delta m_H^2 \equiv \frac{\left(m_{H_d}^2 - m_{H_u}^2\right)}{2m_{10}^2} \approx 13\%$$

Roughly $\frac{1}{2}$ comes
From RG running from

$$M_G \rightarrow m_{\nu_\tau}$$

Blazek, Dermisek & Raby

“Just so” = “NUHM”

Inverted scalar mass hierarchy

Bagger, Feng, Polonsky & Zhang
PLB473, 264 (2000)

Third family scalars lighter than first two !
Suppresses flavor & CP violation

$$A_0 \approx -2m_{16} \quad m_{10} \approx \sqrt{2}m_{16}$$

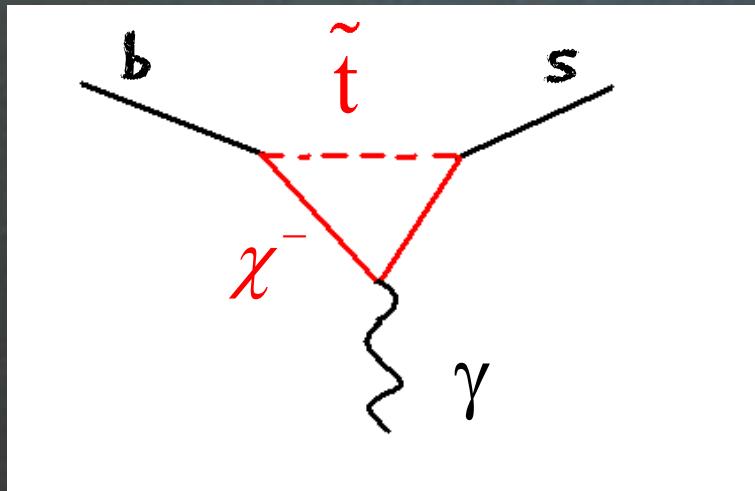
$$m_{16} > \text{few TeV} \quad \mu, M_{1/2} \ll m_{16}$$

$$\tan \beta \approx 50$$

Argue need Heavy scalars !

$$BR(B \rightarrow X_s \gamma) = (3.55 \pm 0.26) \times 10^{-4} \quad \text{Exp.}$$

$$BR(B \rightarrow X_s \gamma)_{SM} = (3.15 \pm 0.23) \times 10^{-4} \quad \text{NNLO Th.}$$



$$C_7^{eff} = C_7^{SM} + C_7^{SUSY}$$

$$C_7^{eff} \approx \pm C_7^{SM}$$

$$C_7^{\chi^+} \propto \frac{\mu A_t}{m^2} \tan \beta \times \text{sign}(C_7^{\text{SM}}) \approx \begin{cases} -2 C_7^{\text{SM}} \\ 0 \end{cases}$$

$$\mu M_g > 0 \Rightarrow \mu A_t < 0$$

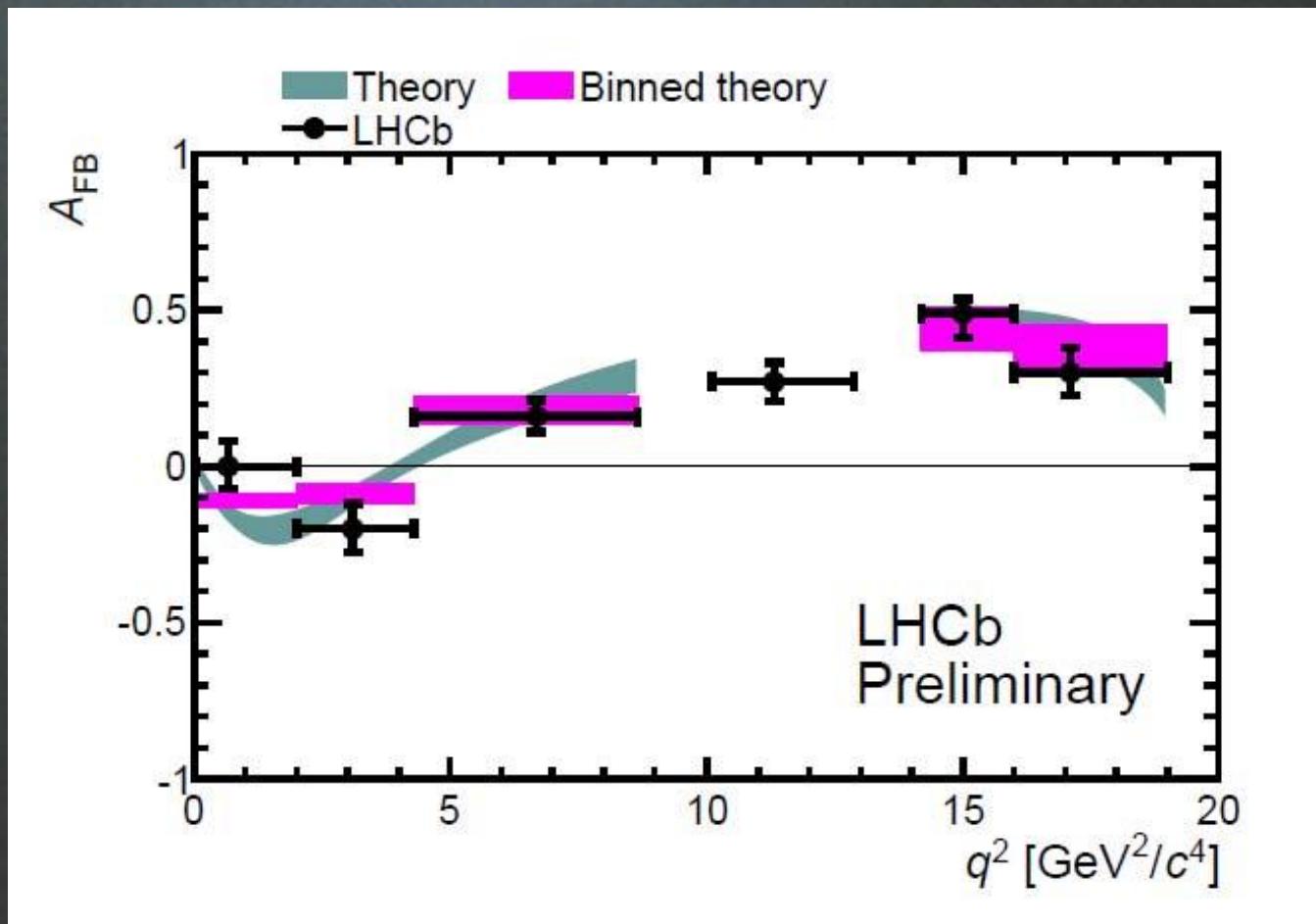
$$m_{16} \sim 4 - 5 \text{ TeV}$$

light squarks and sleptons !!

$$C_7^{\chi^+} \approx -2 C_7^{\text{SM}} \quad \text{or}$$

$$C_7 = C_7^{\text{SM}} + C_7^{\chi^+} \approx -C_7^{\text{SM}}$$

LHCb BR($B \rightarrow K^* \mu^+ \mu^-$) favors $C_7 \approx + C_7^{\text{SM}}$



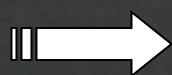
tension between $b \rightarrow s \gamma$ & $b \rightarrow s l^+ l^-$

Albrecht, Altmannshofer, Buras, Guadagnoli, & Straub

JHEP 0710:055 (2007)

$$C_7^{\chi^+} \approx 0 \quad \text{or}$$

$$C_7 = C_7^{\text{SM}} + C_7^{\chi^+} \approx +C_7^{\text{SM}}$$



$$m_{16} \geq 8 \text{ TeV}$$

Light Higgs mass

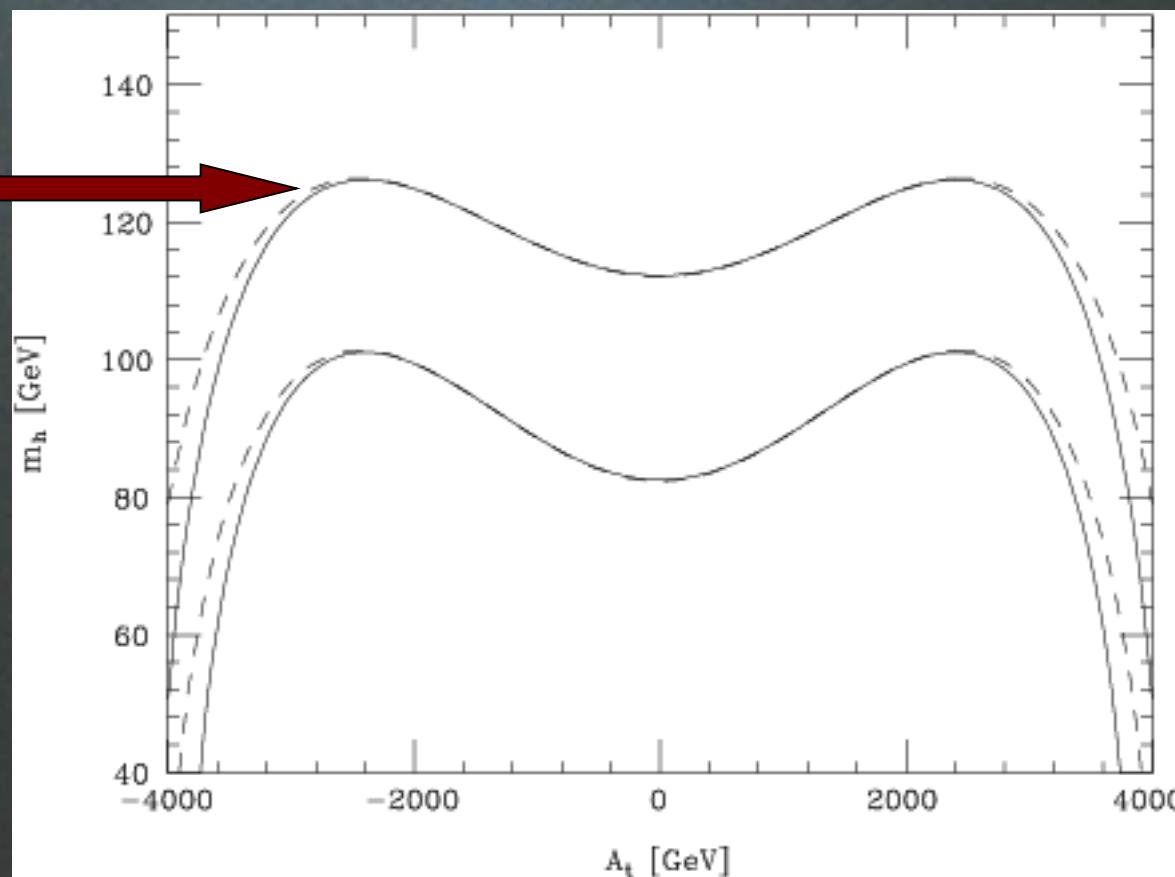
$$m_h^2 \approx M_Z^2 \cos^2 2\beta$$

$$+ \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \left[\ln \left(\frac{M_{SUSY}^2}{m_t^2} \right) + \frac{\chi_t^2}{M_{SUSY}^2} \left(1 - \frac{\chi_t^2}{12 M_{SUSY}^2} \right) \right]$$

$$\chi_t = A_t - \frac{\mu}{\tan \beta} \quad \frac{\chi_t}{M_{SUSY}} \sim \sqrt{6} \quad \text{Max mixing}$$

Large A_t & $M_{SUSY} \Rightarrow m_h \geq 125 \text{ GeV}$ Easy

Light Higgs mass



Carena,
Quiros &
Wagner '95

$\text{Br}(B_s \rightarrow \mu^+ \mu^-) :$
Light Higgs SM-like

$$\text{SM} : 3 \times 10^{-9} \quad \text{MSSM} : \sim (\tan \beta)^6 / m_A^4$$

CDF $1.8^{+1.8}_{-0.9} \times 10^{-8}$ (95% CL) w/ 7 fb^{-1}

$LHCb$ bound $< 4.5 \times 10^{-9}$ (95% CL) w/ 1 fb^{-1}

$$m_A \geq 1500 \text{ GeV}$$

$m_A \sim m_H \sim m_{H^\pm} \Rightarrow h \text{ SM-like}$

3 Family $SO(10)$ + family symmetry

Dermisek & Raby

PLB 622:327 (2005).

Dermisek, Harada & Raby PRD74, 035011 (2006)

Albrecht, Altmannshofer, Buras, Guadagnoli & Straub
JHEP 0710:055 (2007)

3 family SO_{10} SUSY Model

- $D_3 \times U(1)$ Family Symmetry
- Superpotential
- Yukawa couplings
- χ^2 analysis
- Charged fermion masses & mixing
- Neutrino masses & mixing

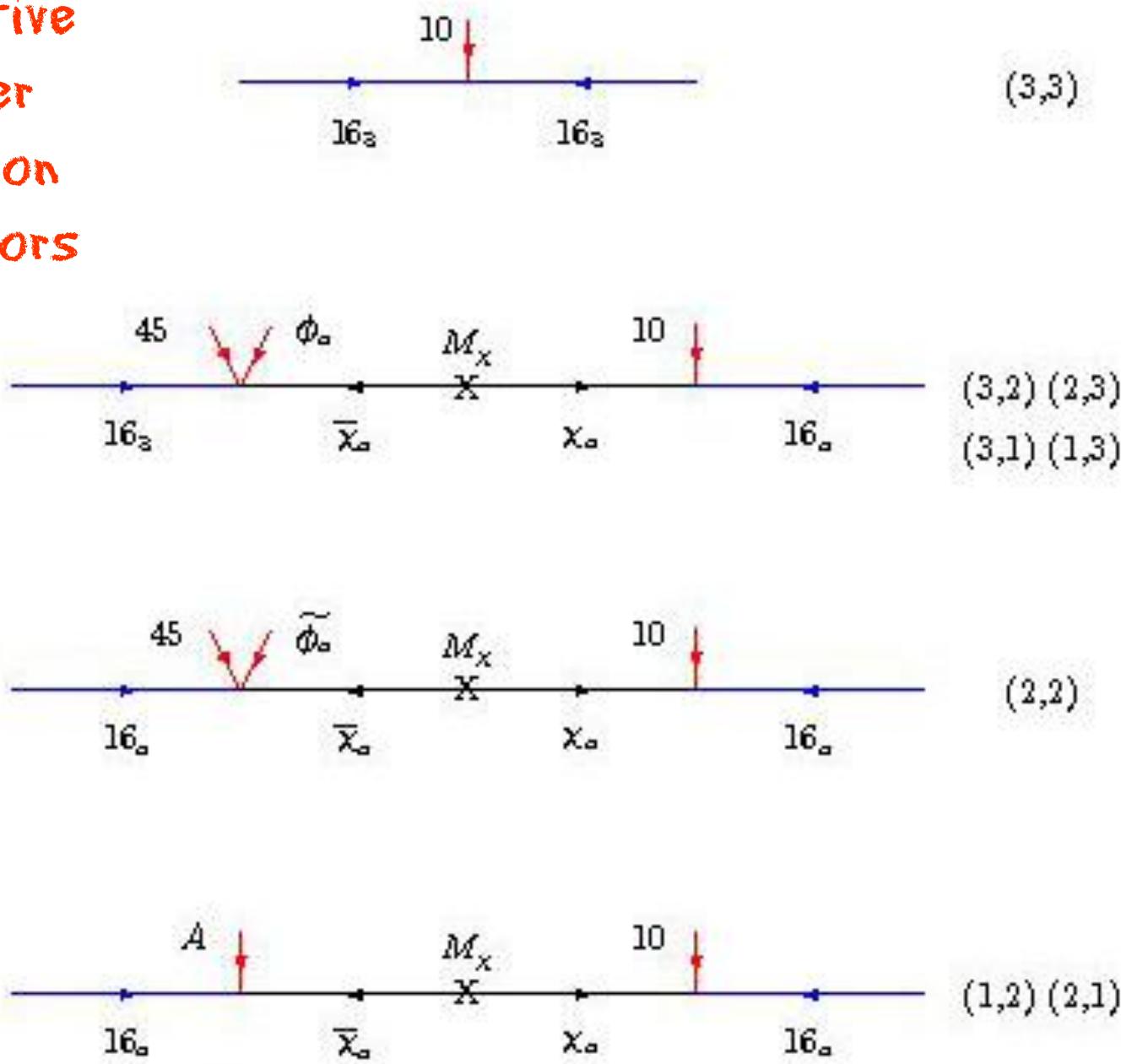
Superpotential for charged fermion Yukawa couplings

$$W_{ch. \text{ fermions}} = 16_3 10 16_3 + 16_a 10 \chi_a + \overline{\chi}_a \left(M_\chi \chi_a + 45 \frac{\phi_a}{M} 16_3 + 45 \frac{\phi_a}{M} 16_a + A 16_a \right)$$

$$\langle \phi \rangle = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \quad \langle \phi \rangle = \begin{pmatrix} 0 \\ \phi_2 \end{pmatrix} \quad \langle 45 \rangle = (B - L) M_G$$

Familon VEVs assumed

Effective higher dimension operators



$SO(10) \times (D_3 \times U(1))$ family sym.

Yukawa Unification for 3rd Family

7 real para's
+ 4 phases

+ 3 real Majorana
Neutrino masses

Dermisek & Raby
PLB 622:327 (2005)

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

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

$$Y_e = \begin{pmatrix} 0 & -\epsilon' & 3 \epsilon \xi \\ \epsilon' & 3 \tilde{\epsilon} & 3 \epsilon \\ -3 \epsilon \xi \sigma & -3 \epsilon \sigma & 1 \end{pmatrix} \lambda$$

$$Y_\nu = \begin{pmatrix} 0 & -\epsilon' \omega & \frac{3}{2} \epsilon \xi \omega \\ \epsilon' \omega & 3 \tilde{\epsilon} \omega & \frac{3}{2} \epsilon \omega \\ -3 \epsilon \xi \sigma & -3 \epsilon \sigma & 1 \end{pmatrix} \lambda$$

Extend to neutrino sector

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

$$\langle S_a \rangle = M_a \quad \langle S_3 \rangle = M_3 \quad \langle \overline{16} \rangle = V_{16}$$



Assume 3 new real para's

$$W_{neutrino} = \nu m_\nu^- \bar{\nu} + \bar{\nu} V N + \not{\nu}_2 NM_N N$$

$$Y_v=\begin{pmatrix}0&-\varepsilon'\omega&\frac{3}{2}\varepsilon\xi\omega\\\varepsilon'\omega&3\varepsilon\omega&\frac{3}{2}\varepsilon\omega\\-3\varepsilon\xi\sigma&-3\varepsilon\sigma&1\end{pmatrix}\lambda\qquad\omega=\frac{2\sigma}{(2\sigma-1)}$$

$$m_\nu=Y_v\frac{V}{\sqrt{2}}\sin\beta\qquad\qquad V=V_{16}\begin{pmatrix}0&\lambda_2&0\\\lambda_2&0&0\\0&0&\lambda_3\end{pmatrix}$$

$$M_N=diag\big(\,M_1\quad M_2\quad M_3\,\big)$$

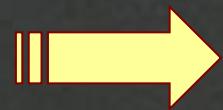


$$M_\nu = U_e^T \left(m_\nu \left(V^T \right)^{-1} M_N V^{-1} m_\nu^T \right) U_e$$

Using χ^2 analysis, fit

15 charged fermion & 5 neutrino
low energy observables with

11 arbitrary Yukawa & 3 Majorana mass
parameters



4 & 2 d.o.f. or 6 predictions

Global χ^2 analysis

Sector	#	Parameters
gauge	3	$\alpha_G, M_G, \epsilon_3,$
SUSY (GUT scale)	5	$m_{16}, M_{1/2}, A_0, m_{H_u}, m_{H_d},$
textures	11	$\epsilon, \epsilon', \lambda, \rho, \sigma, \tilde{\epsilon}, \xi,$
neutrino	3	$M_{R_1}, M_{R_2}, M_{R_3},$
SUSY (EW scale)	2	$\tan \beta, \mu$

24 parameters at GUT scale

compared to SM - 27 parameters

CMSSM - 32 parameters

Observable	Exp. value	Fit value	Pull (σ)
M_W	80.403	80.6	0.5
M_Z	91.1876	90.7	1.1
$G_F \times 10^5$	1.16637	1.16	0.3
$1/\alpha_{\text{em}}$	137.036	136.8	0.4
$\alpha_s(M_Z)$	0.1176	0.117	0.2
M_t	170.9	170.6	0.2
$m_b(m_b)$	4.2	4.22	0.3
$m_c(m_b)$	1.25	1.14	1.2
$m_s(2 \text{ GeV})$	0.095	0.107	0.5
$m_d(2 \text{ GeV})$	0.005	0.00741	1.2
$m_u(2 \text{ GeV})$	0.00225	0.00461	3.1
M_τ	1.777	1.78	0.1
M_μ	0.10566	0.106	0.1
M_e	0.000511	0.000511	0.0
$ V_{us} $	0.2258	0.225	0.6
$ V_{ub} \times 10^3$	4.1	3.26	2.1
$ V_{cb} $	0.0416	0.0416	0.1
$\sin 2\beta$	0.675	0.639	1.4
$\Delta m_{31}^2 \times 10^{21}$	2.6	2.6	0.0
$\Delta m_{21}^2 \times 10^{23}$	7.9	7.9	0.0
$\sin^2 2\theta_{12}$	0.852	0.852	0.0
$\sin^2 2\theta_{23}$	0.996	1.0	0.2
$\epsilon_K \times 10^3$	2.229	2.33	0.4
$\text{BR}(B \rightarrow X_s \gamma) \times 10^4$	3.55	2.86	1.3
$\text{BR}(B \rightarrow X_s \ell^+ \ell^-) \times 10^6$	1.6	1.62	0.0
$\Delta M_s / \Delta M_d$	35.05	31.1	1.1
$\text{BR}(B^+ \rightarrow \tau^+ \nu) \times 10^4$	1.31	0.517	1.7
total $\chi^2:$		27.4	

Albrecht et al.
JHEP 0710:055 (2007)

m_{16}	10000
μ	1200
$\text{BR}(B_s \rightarrow \mu^+ \mu^-) \times 10^8$	2.1
\hat{s}_0	0.14
$\text{BR}(\mu \rightarrow e \gamma) \times 10^{13}$	0.0026
$\delta a_\mu^{\text{SUSY}} \times 10^{10}$	+0.52
M_{h_0}	129
M_A	842
$m_{\tilde{t}_1}$	1903
$m_{\tilde{b}_1}$	2366
$m_{\tilde{\tau}_1}$	3933
$m_{\tilde{\chi}_1^0}$	60
$m_{\tilde{\chi}_1^+}$	120
$m_{\tilde{g}}$	506

Required $C_7 = +C_7^{SM}$

Yukawa unification : MSSM at Large $\tan \beta$

Work in progress with

Archana Anandakrishnan

Radovan Dermisek

Christopher Plumberg &

Aditi Raval

Using Higgs code of Pietro Slavich &

MicrOMEGAs ($B \rightarrow 5\gamma$, $B_s \rightarrow \mu^+ \mu^-$)

Preliminary
 $m_{16} = 10$ TeV

AnandaKrishnan,
 Dermisek,
 Plumberg,
 Raby, Raval

Observable	Exp. value	Fit value	Pull (σ)
M_W	80.44	80.58	0.
M_Z	91.1876	91.1876	0.0
$G_F \times 10^5$	1.16637	1.16689	0.445
$1/\alpha_{\text{em}}$	137.036	137.116	0.581
$\alpha_s(M_Z)$	0.1184	0.1182	0.285
M_t	172.9	172.2	0.61
$m_b(m_b)$	4.19	4.46	1.47
$M_b - M_c$	3.43	3.46	0.596
$m_c(m_b)$	1.29	1.27	0.2
$m_s(2 \text{ GeV})$	0.1	0.094	0.21
$m_d(2 \text{ GeV})/m_s(2 \text{ GeV})$	0.052	0.069	2.54
$1/Q^2(2 \text{ GeV})$	0.0019	0.00188	0.44
M_τ	1.777	1.777	0.07
M_μ	0.10566	0.10566	0.06
M_e	0.000511	0.000511	0.03
$ V_{us} $	0.2252	0.2249	0.32
$ V_{ub} \times 10^3$	3.89	2.996	2.0
$ V_{cb} $	0.0406	0.040	0.445
$\sin 2\beta$	0.673	0.614	2.6
$\Delta m_{31}^2 \times 10^{21}$	2.46	2.498	0.22
$\Delta m_{21}^2 \times 10^{23}$	7.54	7.51	0.06
$\sin^2 2\theta_{12}$	0.851	0.83	0.38
$\sin^2 2\theta_{23}$	0.958	0.979	0.38
$\sin^2 2\theta_{13}$	0.0956	0.0505	1.8
$\epsilon_K \times 10^3$	2.228	2.376	0.66
$\text{BR}(B \rightarrow X_s \gamma) \times 10^4$	3.55	2.75	2.4
$\text{BR}(B_s \rightarrow \mu^+ \mu^-) \times 10^9$	< 4.5	4.7	0.39
m_h	126	127.3	0.63
total χ^2 :			31.8

Preliminary
 $m_{16} = 15 \text{ TeV}$

AnandaKrishnan,
 Dermisek,
 Plumberg,
 Raby, Raval

Observable	Exp. value	Fit value	Pull (σ)
M_W	80.44	80.60	0.
M_Z	91.1876	91.1876	0.0
$G_F \times 10^5$	1.16637	1.16691	0.46
$1/\alpha_{\text{em}}$	137.036	136.80	1.68
$\alpha_s(M_Z)$	0.1184	0.1181	0.423
M_t	172.9	171.9	0.89
$m_b(m_b)$	4.19	4.17	0.11
$M_b - M_c$	3.43	3.36	1.44
$m_c(m_b)$	1.29	1.10	1.71
$m_s(2 \text{ GeV})$	0.1	0.095	0.16
$m_d(2 \text{ GeV})/m_s(2 \text{ GeV})$	0.052	0.069	2.38
$1/Q^2(2 \text{ GeV})$	0.0019	0.00188	0.38
M_τ	1.777	1.778	0.87
M_μ	0.10566	0.10564	0.17
M_e	0.000511	0.000511	0.0
$ V_{us} $	0.2252	0.2255	0.39
$ V_{ub} \times 10^3$	3.89	3.11	1.75
$ V_{cb} $	0.0406	0.0405	0.07
$\sin 2\beta$	0.673	0.627	1.98
$\Delta m_{31}^2 \times 10^{21}$	2.46	2.29	0.94
$\Delta m_{21}^2 \times 10^{23}$	7.54	7.46	0.17
$\sin^2 2\theta_{12}$	0.851	0.782	1.13
$\sin^2 2\theta_{23}$	0.958	0.982	0.38
$\sin^2 2\theta_{13}$	0.0956	0.0672	1.11
$\epsilon_K \times 10^3$	2.228	2.39	0.73
$\text{BR}(B \rightarrow X_s \gamma) \times 10^4$	3.55	3.46	0.26
$\text{BR}(B_s \rightarrow \mu^+ \mu^-) \times 10^9$	< 4.5	3.07	0
m_h	126	123.21	1.39
		total χ^2 :	33.80

m_{16}	10 TeV	15 TeV
A_0	-20 TeV	-30.5 TeV
μ	1669	772
$M_{1/2}$	182	220
χ^2	32	34
$\text{BR}(\mu \rightarrow e\gamma) \times 10^{13}$	0.0024	0.000045
M_{h_0}	127	123
M_A	1841	1229
$m_{\tilde{t}_1}$	1750	1649
$m_{\tilde{b}_1}$	2178	2717
$m_{\tilde{\tau}_1}$	4002	5552
$m_{\tilde{\chi}_1^0}$	104	136
$m_{\tilde{\chi}_1^+}$	214	281
$m_{\tilde{g}}$	700	879

Yukawa unification & Large $\tan \beta$

Good

Gauge coupling unif.

$m_h \geq 125$ GeV & SM-like

Inverted scalar mass hierarchy

- Suppresses FCNC
- $g \rightarrow t \bar{t} \chi^0, b \bar{b} \chi^0, t \bar{b} \chi^-, \dots$

Bad

Fine-tuned 1/1000

To do list -

- Is there an upper bound on $m_{16} ??$
- Chi2 contours for gluino mass ?
- Other UV BCs ??

Other boundary conditions at M_{GUT}

- DR3
- Non-universal gaugino masses
 - a. Gauge kinetic function
 - b. "Mirage mediation"

$$m_i^2 = Q_X^i D_X + (m_i^0)^2$$

$$m_{16}^{(3)} \leq m_{16}^{(1,2)}$$

Baer, Kraml & Sekmen

arXiv:0908.0134

“DR3”

	Q	U	D	L	E	N		H_U	H_D
Q_X^i	1	1	-3	-3	1	5		-2	2
m_i^0			\mathbf{m}_{16}						\mathbf{m}_{10}

Badziak, Olechowski & Pokorski

arXiv:0907.4709 (hep-ph)

$$\mu < 0, \quad M_3 : M_2 : M_1 = 1 : -\frac{3}{2} : -\frac{1}{2}$$

D – term splitting for scalars

Totally different spectrum

Mirage mediation BCs

$$\mu < 0, \quad M_i = \left(1 + \frac{\log\left(\frac{M_{Pl}}{m_{3/2}}\right)}{4\pi} \alpha_{GUT} b_i \alpha \right) M_0$$

D -term splitting for scalars