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

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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

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

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 !!

$$\lambda \; 16_3 \; 10 \; 16_3$$

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

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

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

$$\delta m_b / m_b \le -2\%$$

Needed to fit data

$$\mu M_{\tilde{g}} > 0 \quad \Rightarrow \quad \mu A_t < 0$$

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)

MSO$_{10}$SM ™

$$\lambda \; 16_3 \; 10 \; 16_3$$

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

Fit t,b,tau requires

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

$$m_{16} > \textit{few}\ \text{TeV} \qquad \mu, M_{1/2} << m_{16}$$

$$\tan\beta \approx 50$$

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 ½ comes from RG running from

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

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

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

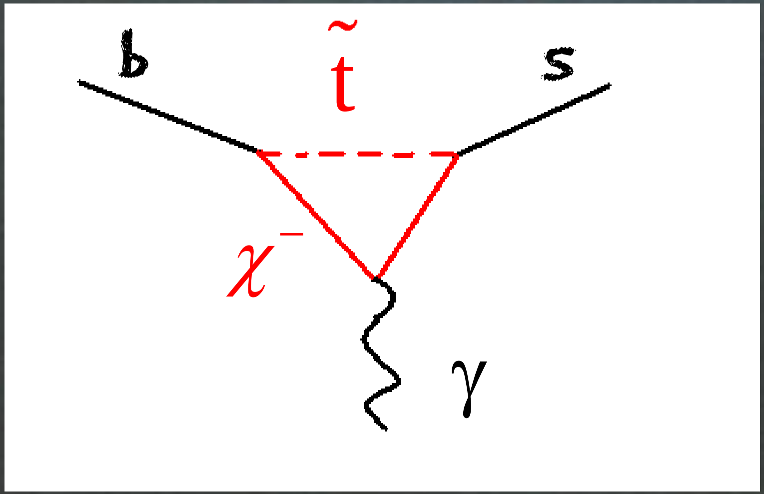
$$m_{16} > few \text{ TeV} \qquad \mu, M_{1/2} << m_{16}$$

$$\tan\beta \approx 50$$

Argue need Heavy scalars !

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

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



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

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

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

$$\mu M_{g} > 0 \Rightarrow \mu A_{t} < 0$$

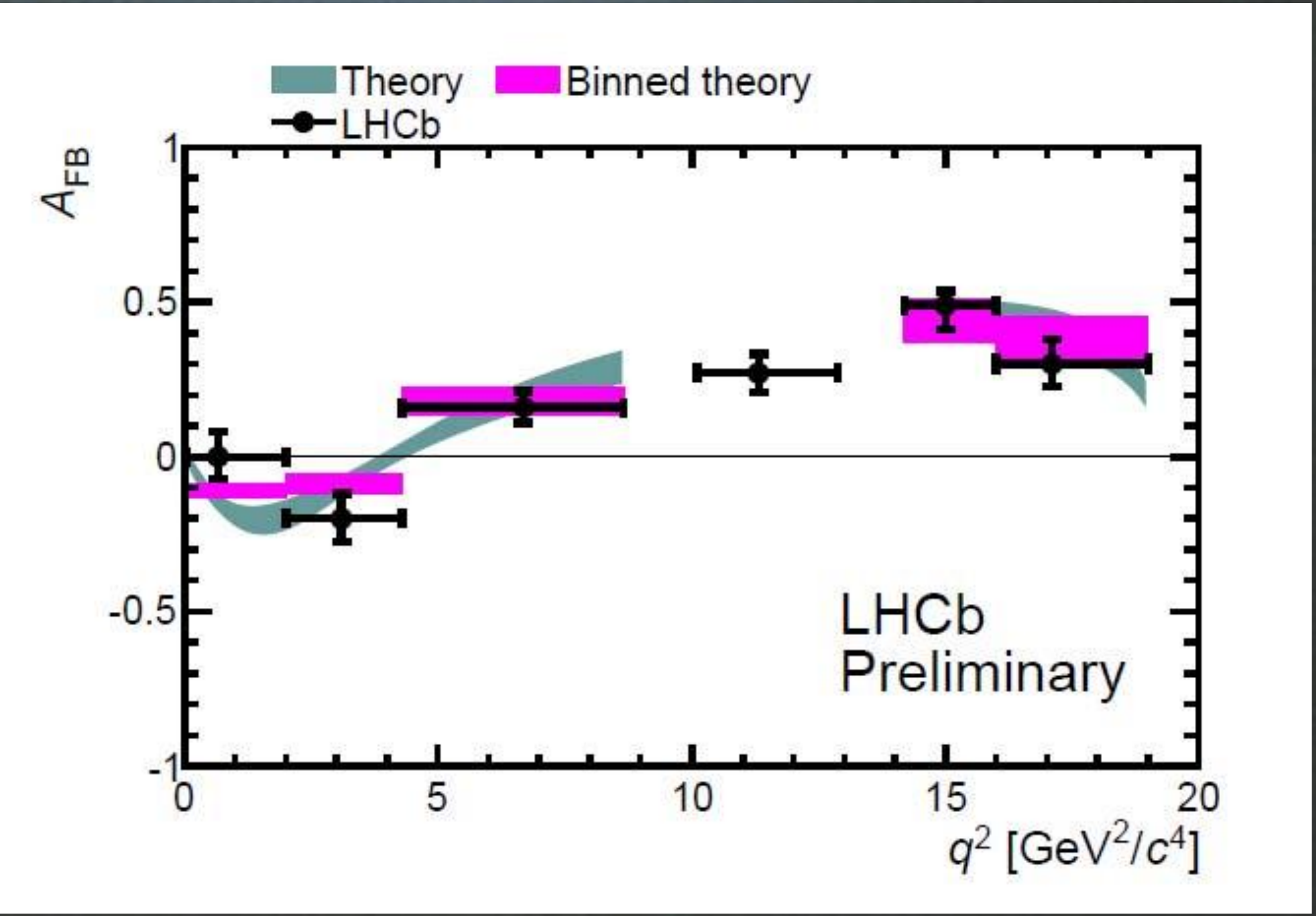
$$m_{16} \sim 4-5 \text{ TeV}$$

light squarks and sleptons !!

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

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

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



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

Albrecht, Altmannshofer, Buras, Guadagnoli, & Straub

JHEP 0710:055 (2007)

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

$$\mathrm{C}_7 = C_7^{\mathrm{SM}} + C_7^{\chi^+} \approx +C_7^{\mathrm{SM}}$$

$$\Rightarrow \quad m_{16} \geq 8\ \mathrm{TeV}$$

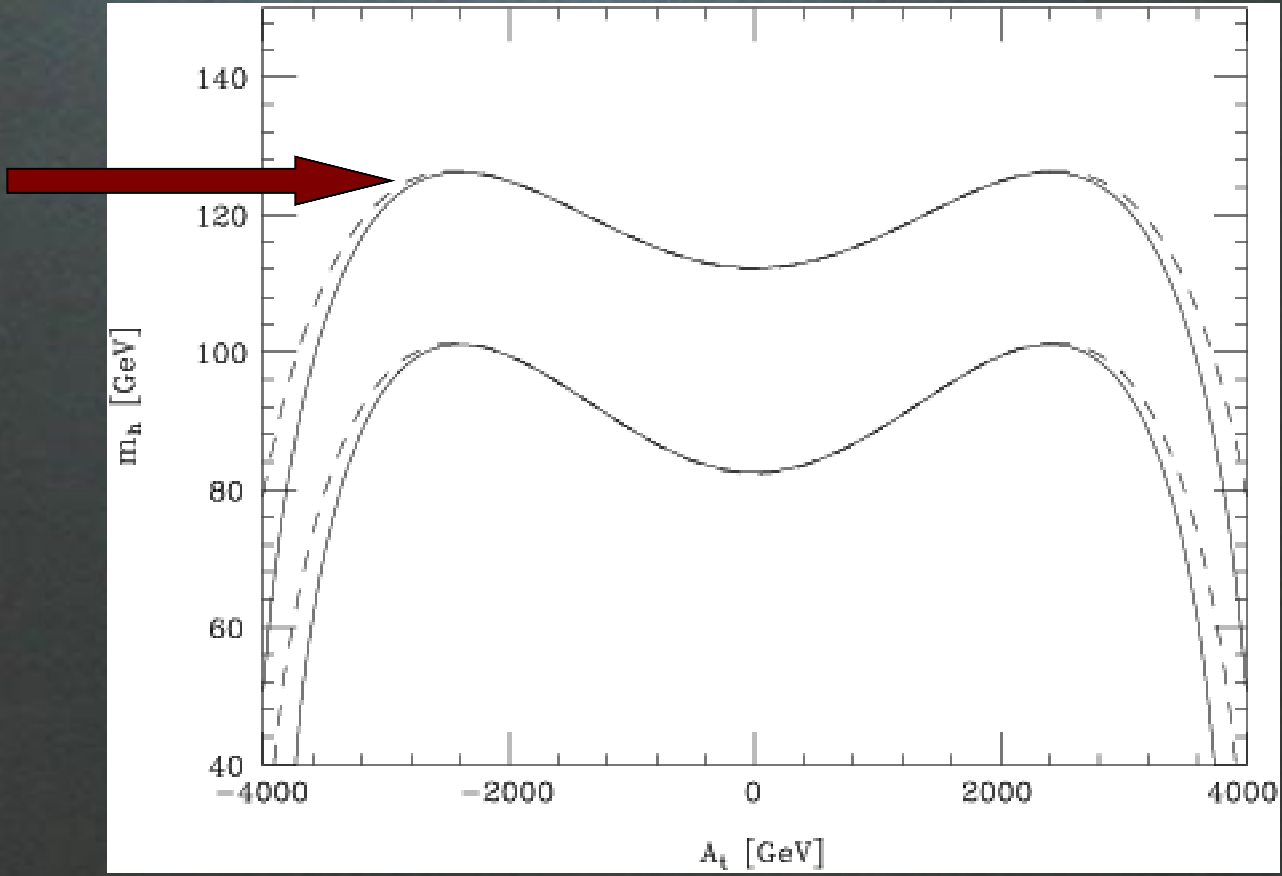
Light Higgs mass

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right)\right]$$

$$X_t = A_t - \mu / \tan\beta \qquad X_t / M_{SUSY} \sim \sqrt{6} \quad \text{Max mixing}$$

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

Light Higgs mass



Carena, Quiros & Wagner '95

Br(B_s -> $\mu^+ \mu^-$): Light Higgs SM-like

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

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

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

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

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

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

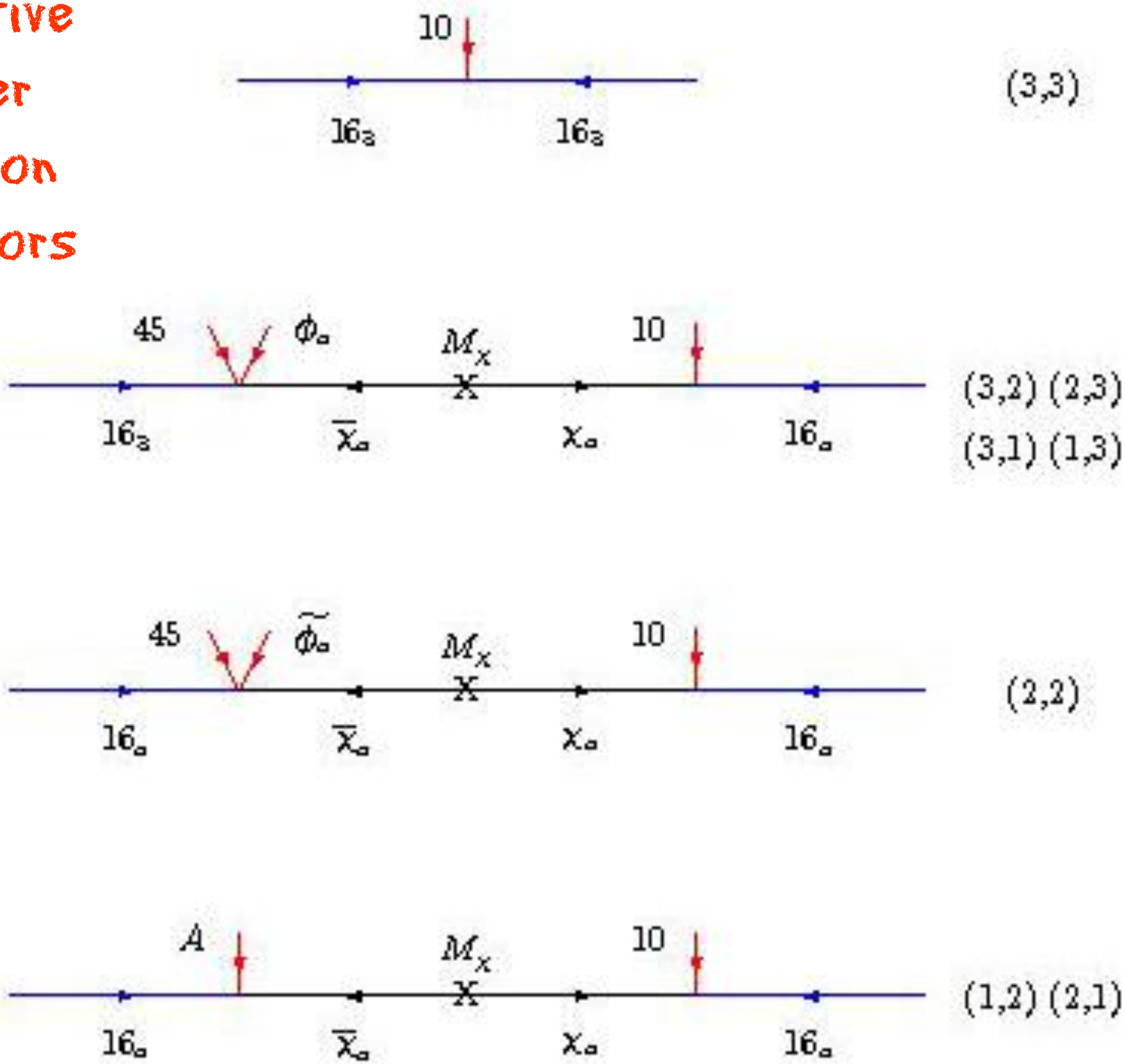
$$W_{ch.\,fermions} = 16_3 10 16_3 + 16_a 10 \chi_a$$

$$+ \overline{\chi_a}\left(M_\chi \chi_a + 45\frac{\phi_a}{M} 16_3 + 45\frac{\phi_a}{M} 16_a + A 16_a \right)$$

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

Familon VEVs assumed

Effective higher dimension operators



SO(10) x (D_3 x 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).

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

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

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

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

Georgi - Jarlskog relation

$$\mathrm{M}_{GUT} \qquad\qquad\qquad \mathrm{M}_{Z}$$

$$m_\mu \sim 3 m_s \quad \rightarrow \quad \mathrm{m}_s \sim m_\mu$$

$$m_e \sim \frac{1}{3} m_d \quad \rightarrow \quad \mathrm{m}_d \sim 9 m_e$$

Renormalization group invariant

$$200 \sim m_\mu / \mathrm{m}_e = 9 \; \mathrm{m}_s / \mathrm{m}_d$$

Extend to neutrino sector

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

$$\langle S_a \rangle = M_a \qquad \langle S_3 \rangle = M_3 \qquad \langle \overline{16} \rangle = v_{16}$$

Assume 3 new real para's

$$W_{neutrino} = \nu m_\nu \bar{\nu} + \bar{\nu} V N + \tfrac{1}{2} N M_N N$$

$$Y_\upsilon = \begin{pmatrix} 0 & -\varepsilon'\omega & \tfrac{3}{2}\varepsilon\xi\omega \\ \varepsilon'\omega & 3\varepsilon\omega & \tfrac{3}{2}\varepsilon\omega \\ -3\varepsilon\xi\sigma & -3\varepsilon\sigma & 1 \end{pmatrix} \lambda$$

$$\omega = 2\sigma / (2\sigma - 1)$$

$$m_\nu = Y_\nu \frac{v}{\sqrt{2}} \sin\beta$$

$$V = v_{16} \begin{pmatrix} 0 & \lambda_2 & 0 \\ \lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}$$

$$M_N = diag\begin{pmatrix} M_1 & M_2 & M_3 \end{pmatrix}$$

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

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	α_G, M_G, ϵ_3,
SUSY (GUT scale)	5	m_{16}, $M_{1/2}$, A_0, m_{H_u}, m_{H_d},
textures	11	ϵ, ϵ', λ, ρ, σ, $\tilde{\epsilon}$, ξ,
neutrino	3	M_{R_1}, M_{R_2}, M_{R_3},
SUSY (EW scale)	2	$\tan\beta$, μ

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
$1/\alpha_{em}$	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
$m_s(2\,\mathrm{GeV})$	0.095	0.107	0.5
$m_d(2\,\mathrm{GeV})$	0.005	0.00741	1.2
$m_u(2\,\mathrm{GeV})$	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
$\Delta m^2_{31} \times 10^{21}$	2.6	2.6	0.0
$\Delta m^2_{21} \times 10^{23}$	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
$\mathrm{BR}(B \to X_s\gamma) \times 10^4$	3.55	2.86	1.3
$\mathrm{BR}(B \to X_s\ell^+\ell^-) \times 10^6$	1.6	1.62	0.0
$\Delta M_s/\Delta M_d$	35.05	31.1	1.1
$\mathrm{BR}(B^+ \to \tau^+\nu) \times 10^4$	1.31	0.517	1.7
		total χ^2:	**27.4**

Albrecht et al.

JHEP 0710:055 (2007)

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

Christopher Plumberg

Using

3 family GUT code and support from

Radovan Dermisek + Aditi Raval,

Higgs code of Pietro Slavich &

MicrOMEGAs ($B \to s\gamma$, $B_s \to \mu^+\mu^-$)

Preliminary

m_{16} = 10 TeV

Anandakrishnan, Plumberg, Raby

Observable	Exp. value	Fit value	Pull (σ)
M_W	80.44	80.55	
M_Z	91.1876	91.1876	
$G_F \times 10^5$	1.16637	1.166	0.293
$1/\alpha_{em}$	137.036	136.987	0.359
$\alpha_s(M_Z)$	0.1184	0.1182	0.247
M_t	172.9	172.4	0.51
$m_b(m_b)$	4.19	4.49	**1.69**
$M_b - M_c$	3.43	3.46	0.642
$m_c(m_b)$	1.29	1.299	0.08
$m_s(2\,\mathrm{GeV})$	0.1	0.092	0.27
$m_d(2\,\mathrm{GeV})/m_s(2\,\mathrm{GeV})$	0.052	0.07	**2.72**
$1/Q^2(2\,\mathrm{GeV})$	0.0019	0.00189	0.35
M_τ	1.777	1.777	0.09
M_μ	0.10566	0.10566	0.07
M_e	0.000511	0.000511	0.03
$\|V_{us}\|$	0.2252	0.2249	0.29
$\|V_{ub}\| \times 10^3$	3.89	2.995	**2.0**
$\|V_{cb}\|$	0.0406	0.0397	0.67
$\sin 2\beta$	0.673	0.615	**2.5**
$\Delta m^2_{31} \times 10^{21}$	2.46	2.457	0.017
$\Delta m^2_{21} \times 10^{23}$	7.54	7.52	0.039
$\sin^2\theta_{12}$	0.307	0.295	0.32
$\sin^2\theta_{23}$	0.398	0.433	0.47
$\sin^2\theta_{13}$	0.0245	0.0132	**1.7**
$\epsilon_K \times 10^3$	2.228	2.43	0.92
$\mathrm{BR}(B \to X_s\gamma) \times 10^4$	3.55	2.99	**1.7**
$\mathrm{BR}(B \to \mu^+\mu^-) \times 10^9$	< 4.5	4.6	0.13
m_h	126	127.8	**0.88**
		total χ^2:	**30.4**

Preliminary

m_{16} = 15 TeV

Anandakrishnan, Plumberg, Raby

Observable	Exp. value	Fit value	Pull (σ)
M_W	80.44	80.61	
M_Z	91.1876	91.1876	
$G_F \times 10^5$	1.16637	1.16604	0.27
$1/\alpha_{em}$	137.036	136.95	0.58
$\alpha_s(M_Z)$	0.1184	0.1191	**1.13**
M_t	172.9	171.5	0.34
$m_b(m_b)$	4.19	4.21	0.13
$M_b - M_c$	3.43	3.38	0.87
$m_c(m_b)$	1.29	1.11	**1.58**
$m_s(2\,\mathrm{GeV})$	0.1	0.096	0.11
$m_d(2\,\mathrm{GeV})/m_s(2\,\mathrm{GeV})$	0.052	0.067	**2.33**
$1/Q^2(2\,\mathrm{GeV})$	0.0019	0.00187	0.50
M_τ	1.777	1.776	0.07
M_μ	0.10566	0.10566	0.0
M_e	0.000511	0.000511	0.0
$\lvert V_{us}\rvert$	0.2252	0.2249	0.25
$\lvert V_{ub}\rvert \times 10^3$	3.89	3.05	**1.90**
$\lvert V_{cb}\rvert$	0.0406	0.0400	0.45
$\sin 2\beta$	0.673	0.623	**2.13**
$\Delta m^2_{31} \times 10^{21}$	2.46	2.45	0.01
$\Delta m^2_{21} \times 10^{23}$	7.54	7.53	0.02
$\sin^2\theta_{12}$	0.307	0.287	0.035
$\sin^2\theta_{23}$	0.398	0.531	**1.73**
$\sin^2\theta_{13}$	0.0245	0.0158	**1.32**
$\epsilon_K \times 10^3$	2.228	2.25	0.14
$\mathrm{BR}(B \to X_s\gamma) \times 10^4$	3.55	3.41	0.41
$\mathrm{BR}(B \to \mu^+\mu^-) \times 10^9$	< 4.5	1.65	0
m_h	126	123.7	**1.11**
		total χ^2:	**25.35**

Preliminary

m_{16} = 20 TeV

Anandakrishnan, Plumberg, Raby

Observable	Exp. value	Fit value	Pull (σ)
M_W	80.44	80.7	
M_Z	91.1876	91.1876	
$G_F \times 10^5$	1.16637	1.1670	0.56
$1/\alpha_{em}$	137.036	136.108	0.52
$\alpha_s(M_Z)$	0.1184	0.1188	0.670
M_t	172.9	170.5	**2.15**
$m_b(m_b)$	4.19	4.27	0.49
$M_b - M_c$	3.43	3.44	0.37
$m_c(m_b)$	1.29	1.12	**1.48**
$m_s(2\,\mathrm{GeV})$	0.1	0.10	0.0
$m_d(2\,\mathrm{GeV})/m_s(2\,\mathrm{GeV})$	0.052	0.068	**2.43**
$1/Q^2(2\,\mathrm{GeV})$	0.0019	0.0019	0.0
M_τ	1.777	1.776	0.04
M_μ	0.10566	0.10565	0.006
M_e	0.000511	0.000511	0.0
$\lvert V_{us}\rvert$	0.2252	0.2251	0.08
$\lvert V_{ub}\rvert \times 10^3$	3.89	3.27	**1.39**
$\lvert V_{cb}\rvert$	0.0406	0.0399	0.51
$\sin 2\beta$	0.673	0.663	0.39
$\Delta m^2_{31} \times 10^{21}$	2.46	2.51	0.32
$\Delta m^2_{21} \times 10^{23}$	7.54	7.48	0.11
$\sin^2\theta_{12}$	0.307	0.290	0.45
$\sin^2\theta_{23}$	0.398	0.456	0.76
$\sin^2\theta_{13}$	0.0245	0.0055	**2.87**
$\epsilon_K \times 10^3$	2.228	2.45	0.99
$\mathrm{BR}(B \to X_s\gamma) \times 10^4$	2.99	3.46	**1.68**
$\mathrm{BR}(B \to \mu^+\mu^-) \times 10^9$	< 4.5	4.5	0.03
m_h	126	125.5	**1.39**
		total χ^2:	**29.74**

m_{16} A_0 μ $M_{1/2}$	10 TeV −20 TeV 1279 243	15 TeV −30.5 TeV 775 219	20 TeV −41 TeV 1169 249
χ^2	30	25	29
$\mathrm{BR}(\mu \to e\gamma) \times 10^{13}$	0.00224	0.000045	0.000024
M_{h_0}	128	124	125
M_A	1741	751	2252
$m_{\tilde{t}_1}$	1811	1655	2526
$m_{\tilde{b}_1}$	2251	2739	3782
$m_{\tilde{\tau}_1}$	4043	5591	7813
$m_{\tilde{\chi}_1^0}$	129	136	162
$m_{\tilde{\chi}_1^+}$	260	280	341
$m_{\tilde{g}}$	850	883	1041

Yukawa unification & Large tan β

Good

Gauge coupling unif.

$m_h \geq 125$ GeV & SM-like

Inverted scalar mass hierarchy

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

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"

DR3

Baer, Kraml & Sekmen

arXiv:0908.0134

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

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

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

Non-univ. Gauginos - Gaugino Kinetic function

Badziak, Olechowski & Pokorski

arXiv:0907.4709 (hep-ph)

$$\mu < 0, \; M_3 : M_2 : M_1 = 1 : -{}^{3}\!/_{2} : -{}^{1}\!/_{2}$$

$$+ \quad D - \text{term splitting for scalars}$$

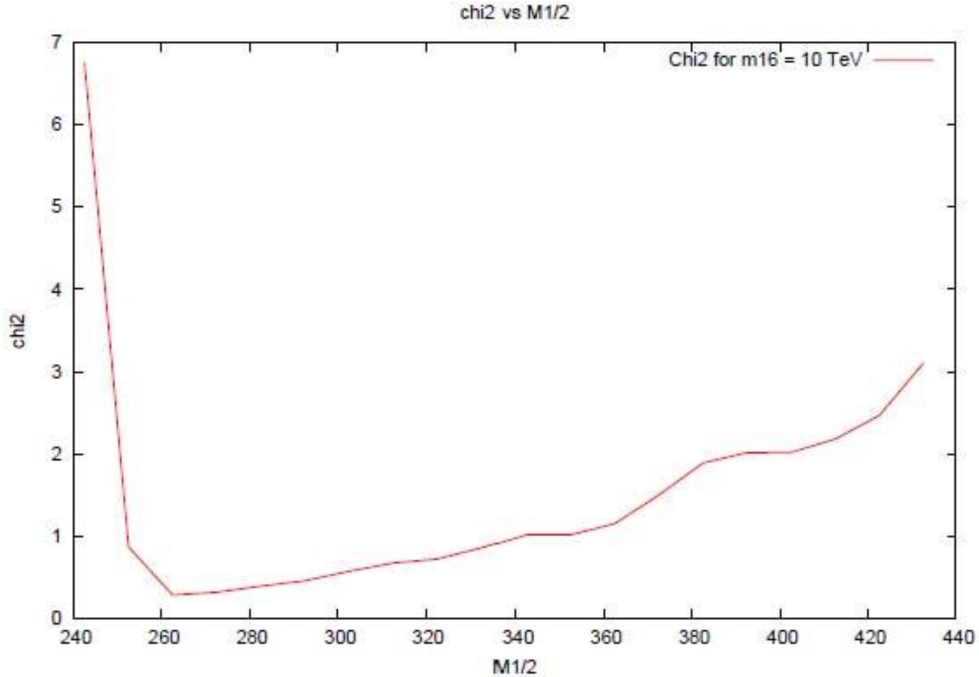
Totally different spectrum

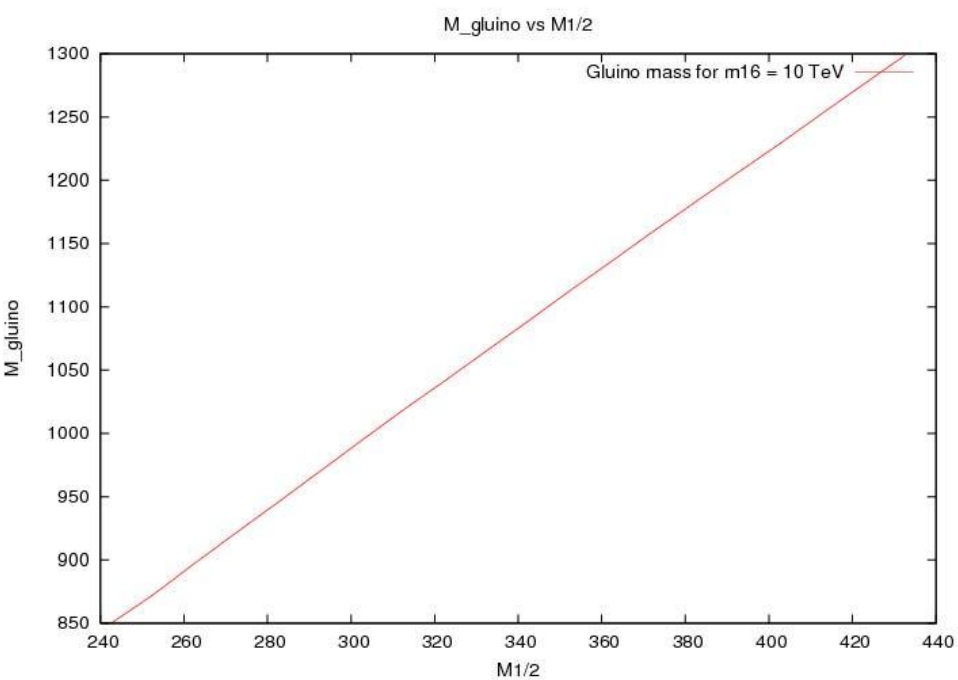
Non-univ gauginos – Mirage mediation BCs

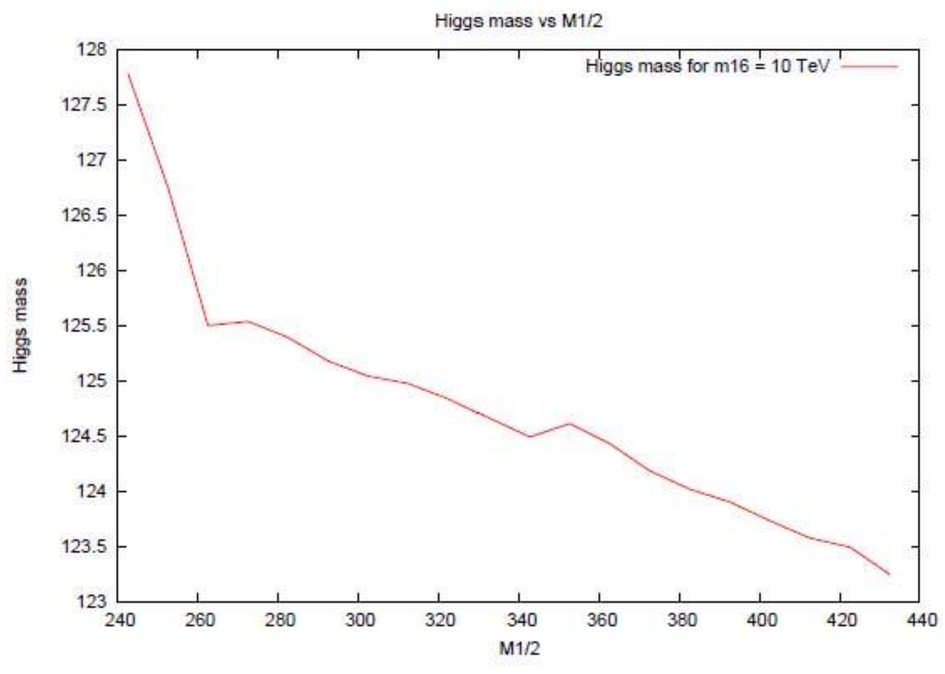
$$\mu < 0,\;\; M_i = \left(1 + \frac{\log\left(M_{Pl} / m_{3/2} \right)}{4\,\pi}\, \alpha_{GUT}\, b_i\, \alpha \right) M_0$$

$+ \quad D -$ term splitting for scalars

Extra slide


chi2 vs M1/2
Chi2 for m16 = 10 TeV
chi2
M1/2
0
1
2
3
4
5
6
7
240
260
280
300
320
340
360
380
400
420
440


M_gluino vs M1/2
Gluino mass for m16 = 10 TeV
M_gluino
M1/2
850
900
950
1000
1050
1100
1150
1200
1250
1300
240
260
280
300
320
340
360
380
400
420
440


Higgs mass vs M1/2
Higgs mass for m16 = 10 TeV
Higgs mass
M1/2
123
123.5
124
124.5
125
125.5
126
126.5
127
127.5
128
240
260
280
300
320
340
360
380
400
420
440