Testing SUSY SO(10) at the LHC

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Outline

- SUSY SO(10) minimal model
- Yukawa unification – first order effects
- Global χ^2 analysis
- Fits
- Predictions
- Fine-tuning
- Conclusions

SO(10) Grand Unification

	State	Y $= \frac{2}{3}\Sigma(C) - \Sigma(W)$	Color C spins	Weak W spins
1	$\bar{\nu}$	0	$- - -$	$- -$
10	$\bar{e}$	2	$- - -$	$+ +$
	u_r	$\frac{1}{3}$	$+ - -$	$- +$
	d_r		$+ - -$	$+ -$
	u_b		$- + -$	$- +$
	d_b		$- + -$	$+ -$
	u_y		$- - +$	$- +$
	d_y		$- - +$	$+ -$
	$\bar{u}_r$	$-\frac{4}{3}$	$- + +$	$- -$
	$\bar{u}_b$		$+ - +$	$- -$
	$\bar{u}_y$		$+ + -$	$- -$
$\bar{5}$	$\bar{d}_r$	$\frac{2}{3}$	$- + +$	$+ +$
	$\bar{d}_b$		$+ - +$	$+ +$
	$\bar{d}_y$		$+ + -$	$+ +$
	ν	-1	$+ + +$	$- +$
	e		$+ + +$	$+ -$

Georgi
Fritzsch & Minkowski

spinor repsn. of SO(10) – 16

tensor product of 5 spin ½ w/ even no. + signs

Soft SUSY breaking terms

m_{16}^2 Universal scalar masses

$\mathrm{m}_{10}^2 \pm \Delta m_H^2 \rightarrow NUHM2$

A_0 Universal A parameter, μ, $\tan\beta$

$M_i \ (\lambda_i \lambda_i), \quad i = 1, 2, 3$

$$M_i = \left(1 + \frac{g_G^2 b_i \boxed{\alpha}}{16\pi^2} \log\left(\frac{M_{Pl}}{m_{16}} \right) \right) M_{1/2}$$

$\alpha = 0$ Universal or $\alpha \neq 0$ "Mirage"

$$\boxed{m_{16},\ m_{10} \pm \Delta m_H^2,\ A_0,\ M_{1/2}\ (\alpha),\ \mu,\ \tan\beta}$$

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 Phys. Lett. B 622, 327 (2005)

Baer, Kraml, Sekmen & Summy JHEP 0909 :005 (2009)

Anandakrishnan, Raby & Wingerter arXiv:1212.0542

Anandakrishnan & Raby arXiv:1303.5125

Anandakrishnan, Bryant & Raby arXiv:1404.5628

Poh & Raby arXiv:1505.00264

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

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

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

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

$$\delta m_b \Big/ m_b \leq -2\%$$

Needed to fit data

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

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AnandaKrishnan, Raby & Wingerter

arXiv:1212.0542

AnandaKrishnan, Bryant & Raby

arXiv:1404.5628

Global χ^2 analysis

3rd family only

Yukawa Unification

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

~ Universal Gaugino Masses

Fit t,b,tau requires

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

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

$$\tan\beta \approx 50$$

Inverted scalar mass hierarchy

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

Third family scalars lighter than first two !

Suppresses flavor & CP violation

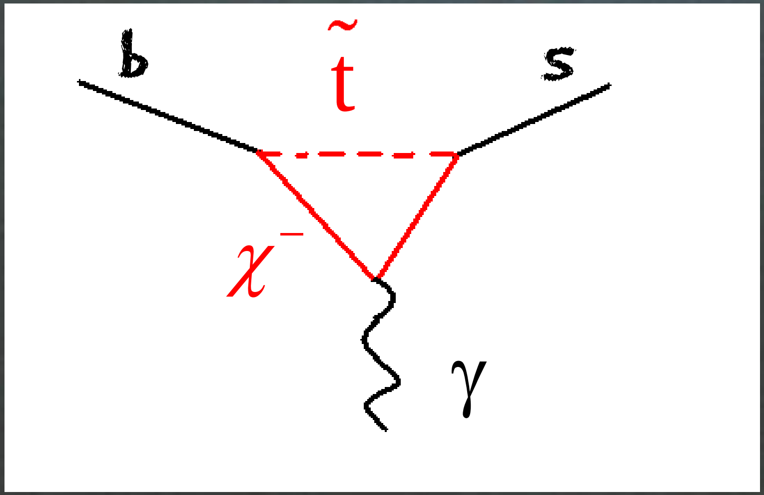
$$\boxed{\begin{array}{c} A_0 \approx -2m_{16} \quad m_{10} \approx \sqrt{2}m_{16} \\ m_{16} > few\ \mathrm{TeV} \qquad \mu, M_{1/2} << m_{16} \\ \tan\beta \approx 50 \end{array}}$$

Heavy scalars

Need Heavy scalars !

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

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



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

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

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

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

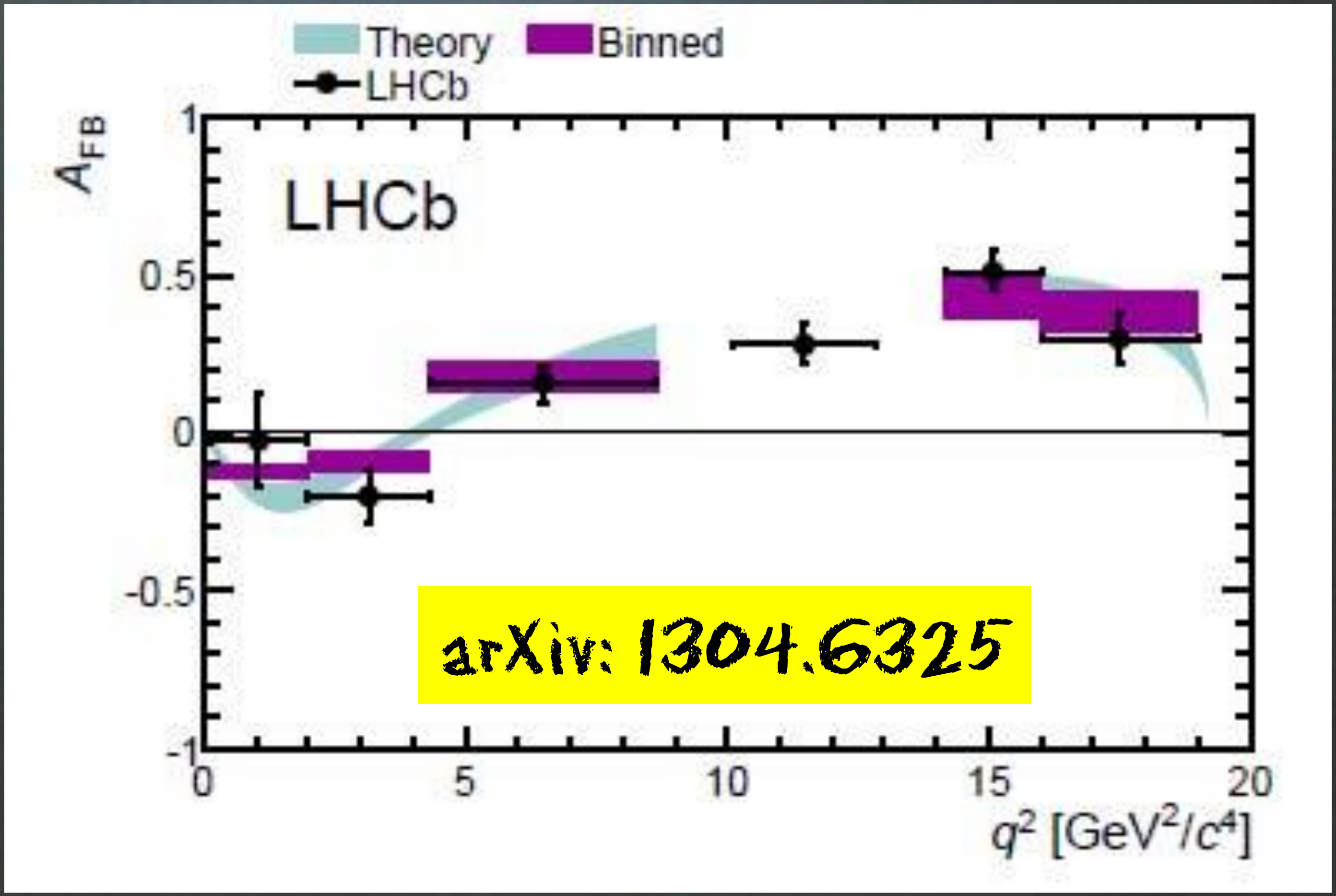
$m_{16} \sim 4-5 \text{ TeV}$

light squarks and sleptons !!

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

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

$LHCb$ $\mathrm{BR}(B \to K^{*}\ \mu^{+}\ \mu^{-})$ 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)

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

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

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

Albrecht, Altmannshofer, Buras, Guadagnoli, & Straub

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
$\boxed{M_{h_0}}$	$\boxed{129}$
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
$\boxed{m_{\tilde{g}}}$	$\boxed{506}$

Light Higgs

SM-like

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

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

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

$$LHCb \quad \left(2.9^{+1.1}_{-1.0}\right) \times 10^{-9}$$

$$\text{w/} \; 1 \, \text{fb}^{-1} \, (7\text{TeV}) + 2 \, \text{fb}^{-1} \, (8\text{TeV})$$

$$m_A \geq 1 \, \text{TeV}$$

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

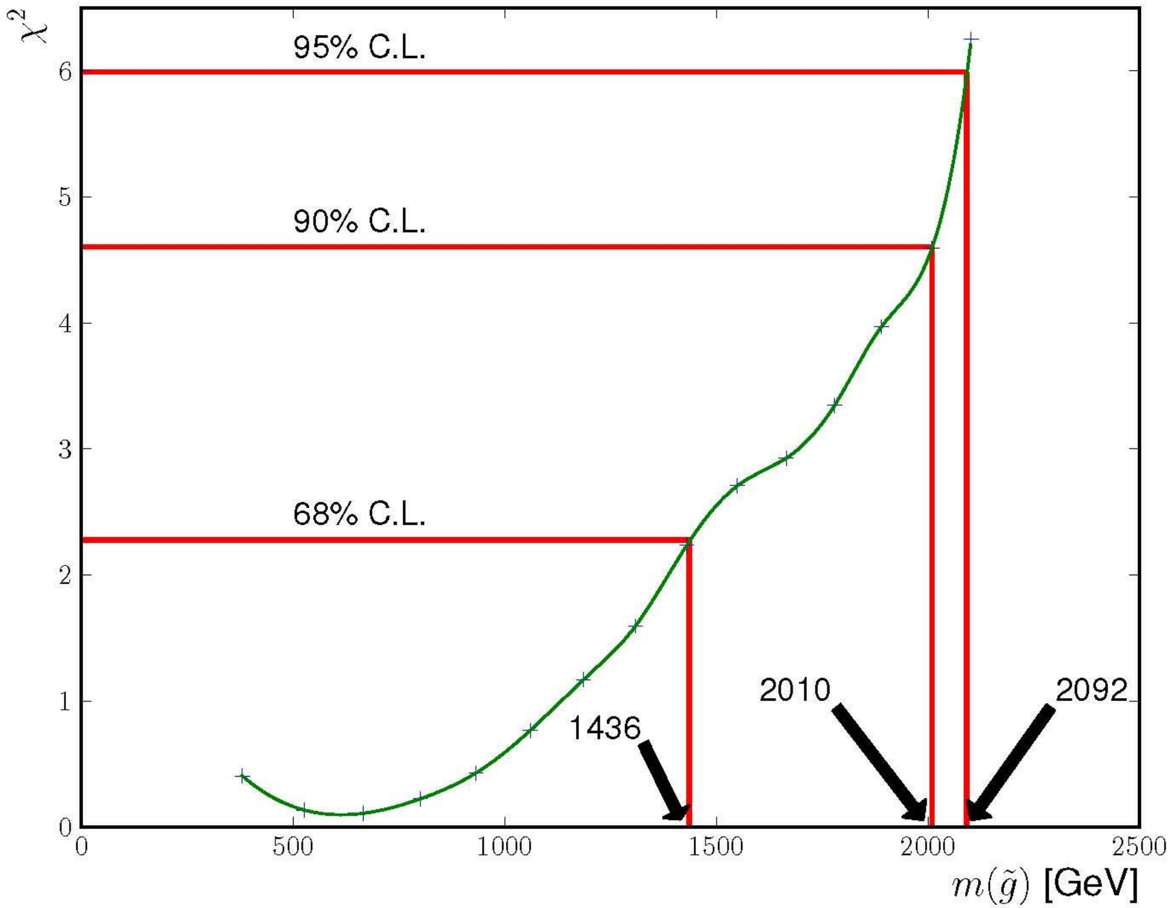
Summary
First order results
Third family only

- Universal scalar masses > 8 TeV
- Third family scalars much lighter
- Light Higgs is SM-like
- Gluino mass < 2.4 TeV

Gluino mass bound – Third family only

Anandakrishnan, Raby & Wingerter

m_{16} = 20 TeV, $M_{1/2}$ varied -> 2 d.o.f.



Three family model
gives good fits
to low energy data

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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)

Anandakrishnan, Raby & Wingerter
arXiv:1212.0542

Poh & Raby
arXiv:1505.00264

3 family SO_{10} SUSY Model

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

Superpotential for charged fermion Yukawa couplings

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

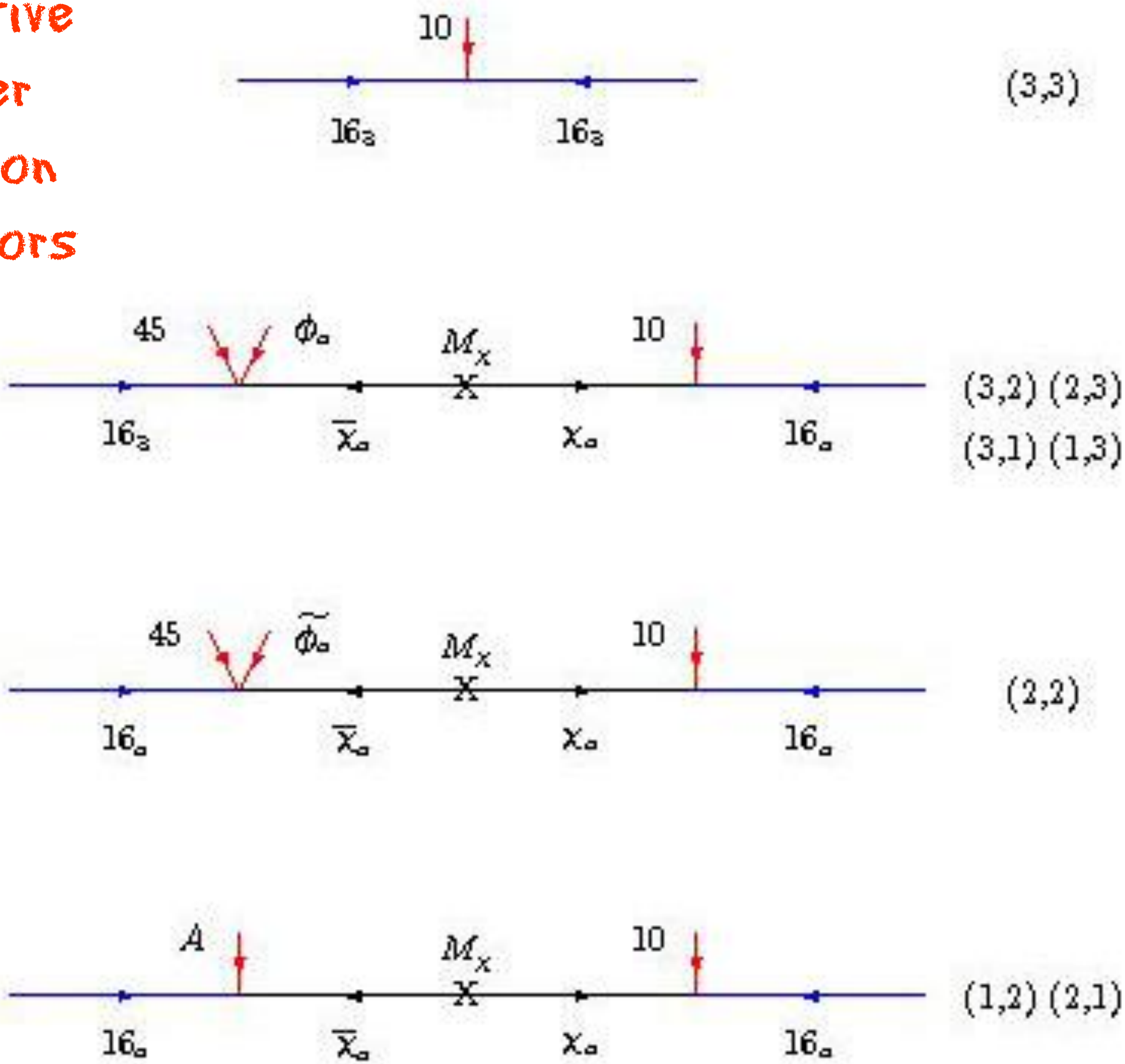
$$+\overline{\chi_a}\left(M_\chi \chi_a + 45\frac{\phi_a}{M}16_3 + 45\frac{\phi_a}{M}16_a + A16_a \right)$$

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

$$\langle\phi\rangle = \begin{pmatrix} 0 \\ \phi_2 \end{pmatrix} \qquad M_\chi = \left(1+\alpha\langle \mathrm{X}\rangle + \beta\langle \mathrm{Y}\rangle\right)M$$

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

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

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

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

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

Dermisek & Raby
PLB 622:327 (2005).

SO(10) x (D_3 x U(1) family sym.)
Yukawa Unification for 3rd Family

$$m_s \simeq \frac{1}{3} m_\mu, \qquad \frac{m_s}{m_d} \approx \frac{1}{9}\frac{m_\mu}{m_e}$$

$$\Leftrightarrow \langle \text{B-L} \rangle$$

$$\frac{m_u}{m_d} \leq 1, \qquad \frac{m_t}{m_b} \gg 1$$

$$\rho \propto \beta \langle \text{Y} \rangle$$

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

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

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

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

Extend to neutrino sector

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

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

Assume 3 new real para's

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

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

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

$$M_{R_1} = (\lambda_2\, v_{16})^2 / M_2,$$

$$M_{R_2} = (\lambda_2\, v_{16})^2 / M_1,$$

$$M_{R_3} = (\lambda_3\, v_{16})^2 / M_3$$

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

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

+ α for Mirage (well-tempered DM)

45 Low energy observables

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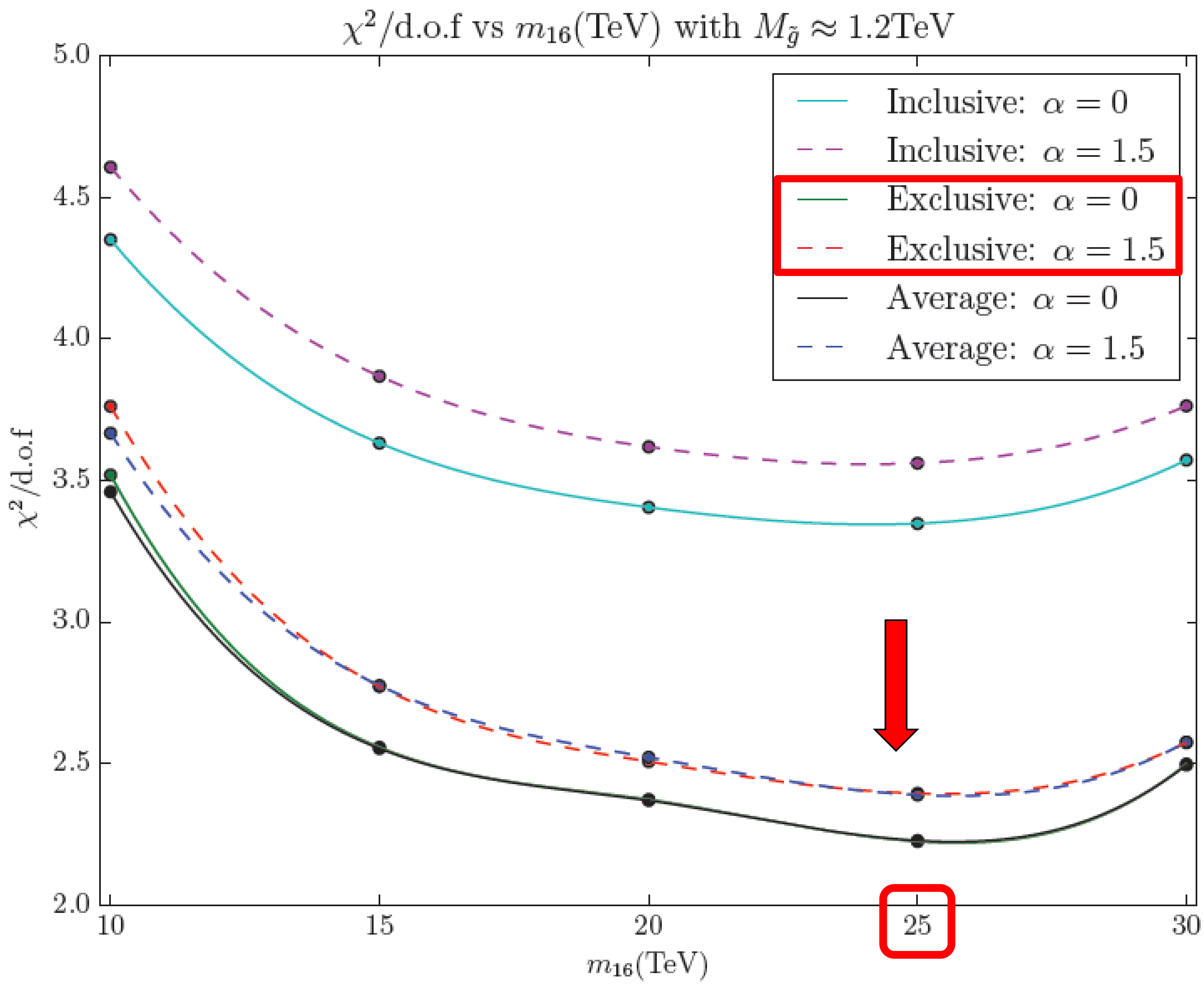
V_{ub} , V_{cb} [inclusive vs exclusive]



SUSY non-decoupling

m_{16}	Pull				
	10	15	20	25	30
M_W	0.2110	0.1878	0.1851	0.2320	0.3981
M_h	2.5474	1.1795	0.3454	0.1882	0.6582
$BR(B \to \tau\nu)$	1.1978	1.3952	1.3557	1.3588	1.3771
$F_L(B \to K^*\mu^+\mu^-)_{1 \leq q^2 \leq 6\mathrm{GeV}^2}$	0.2696	0.2488	0.2219	0.2101	0.2057
$P_4'(B \to K^*\mu^+\mu^-)_{1 \leq q^2 \leq 6\mathrm{GeV}^2}$	1.7066	1.7066	1.7066	1.7066	1.7066
$P_5'(B \to K^*\mu^+\mu^-)_{1 \leq q^2 \leq 6\mathrm{GeV}^2}$	2.4110	2.3432	2.2746	2.2451	2.2339
χ^2	14.1511	8.9744	7.2154	7.0206	7.5220

m_{16}	Fit Value					Exp. Value
	10	15	20	25	30	
M_W	80.4699	80.4606	80.4595	80.4784	80.5454	80.3850
M_h	117.9901	122.1303	124.6547	126.2697	127.6920	125.7000
$BR(B \to \tau\nu) \times 10^5$	6.6329	6.1340	6.2299	6.2223	6.1778	11.4000
$F_L(B \to K^*\mu^+\mu^-)_{1 \leq q^2 \leq 6\mathrm{GeV}^2}$	0.7434	0.7353	0.7251	0.7207	0.7191	0.6500
$P_4'(B \to K^*\mu^+\mu^-)_{1 \leq q^2 \leq 6\mathrm{GeV}^2}$	0.8174	0.6711	0.5921	0.5717	0.5657	0.5800
$P_4'(B \to K^*\mu^+\mu^-)_{14.18 \leq q^2 \leq 16\mathrm{GeV}^2}$	1.2190	1.2190	1.2190	1.2190	1.2190	-0.1800
$P_5'(B \to K^*\mu^+\mu^-)_{1 \leq q^2 \leq 6\mathrm{GeV}^2}$	-0.7301	-0.5529	-0.4625	-0.4335	-0.4235	0.2100

M_W receives contributions to ρ from stops

SUSY does not completely decouple

$$m_{\tilde{t}_1} \approx 5 \text{ TeV}, \quad m_{\tilde{b}_1} \approx 6 \text{ TeV}$$

for $\quad m_{16} \approx 25 \text{ TeV}$

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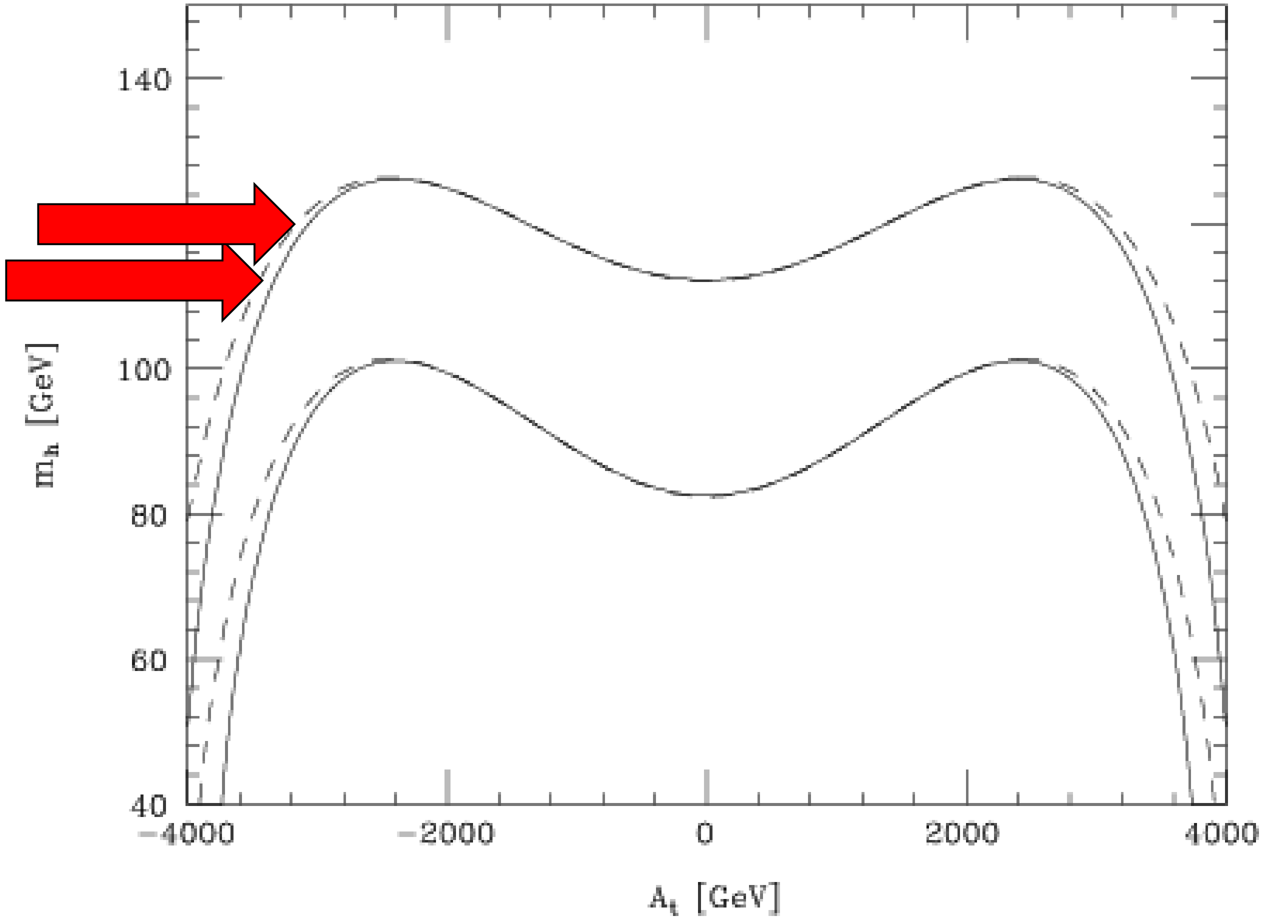
M_h $\frac{A_t}{M_{SUSY}}$ increases as m_{16} increases



Carena, Quiros & Wagner '95

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$B \to K^* \mu^+ \mu^-$

$$F_L\,, \quad P_5^{'}$$

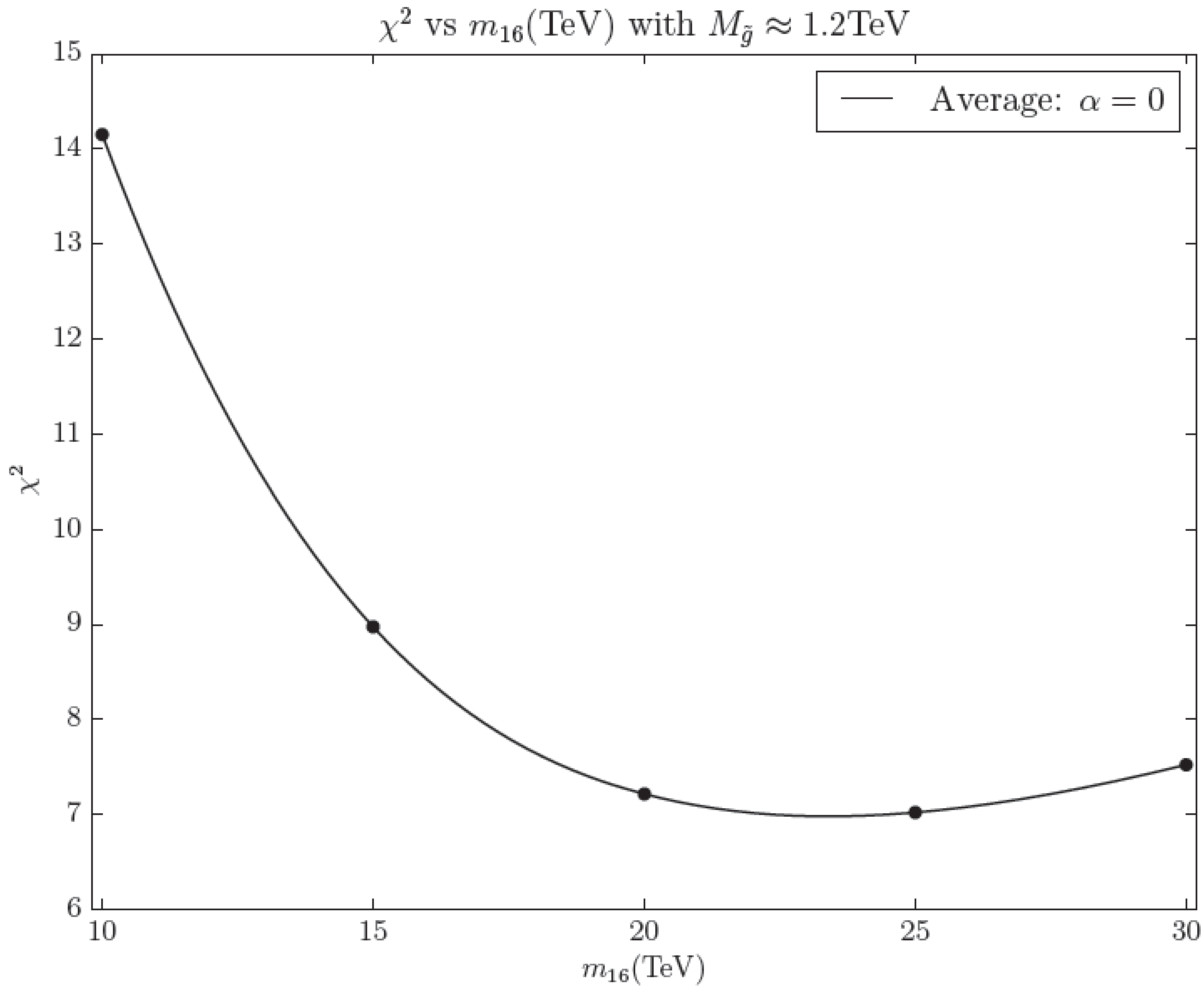
receive small correction in right direction

$C_7^{H^\pm}$ adds constructively *good*

$C_7^{\chi^\pm}$ adds destructively *bad*

but decreases as m_{16} increases

6 Observables only



Total χ^2 *fit*

$m_{16} = 25$ TeV

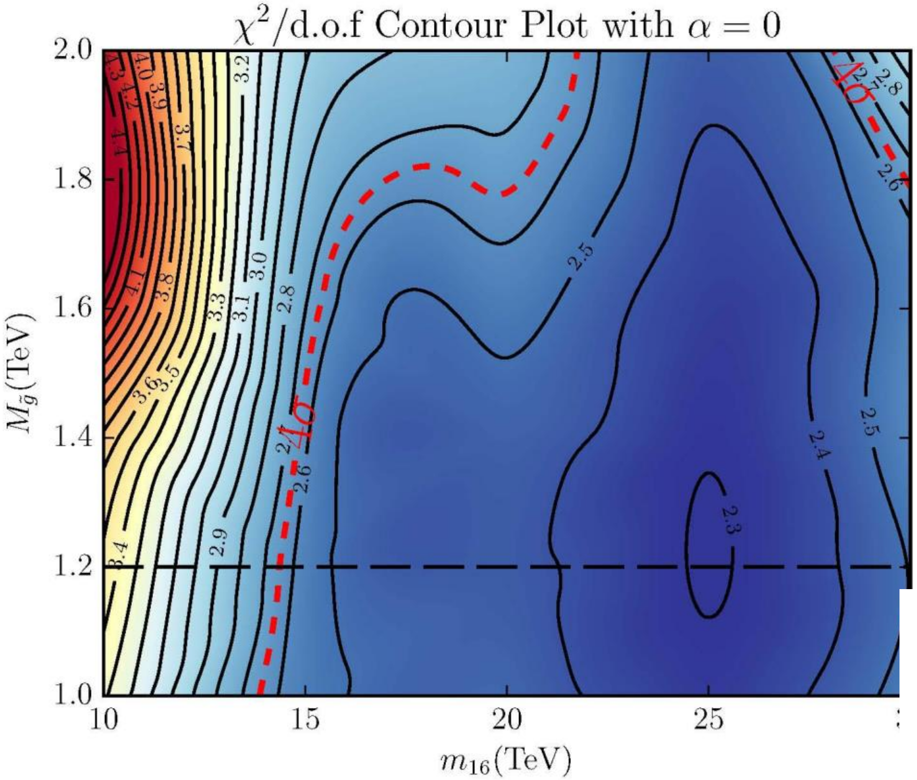
Observable	Fit	Exp.	Pull	σ
M_Z	91.1876	91.1876	0.0000	0.4535
M_W	80.4507	80.3850	0.1633	0.4025
$1/\alpha_{\rm em}$	137.7125	0.0073	0.9825	0.6886
$G_\mu \times 10^5$	1.1732	1.1664	0.5798	0.0117
$\alpha_3(M_Z)$	0.1188	0.1185	0.4140	0.0008
M_t	174.1882	173.2100	0.7927	1.2340
$m_b(m_b)$	4.1954	4.1800	0.4220	0.0366
m_τ	1.7781	1.7768	0.1417	0.0089
$M_b - M_c$	3.1568	3.4500	0.9175	0.3196
$m_c(m_c)$	1.2595	1.2750	0.5993	0.0258
$m_s(2\text{GeV})$	0.0939	0.0950	0.2147	0.0050
$m_d / m_s(2\text{GeV})$	0.0701	0.0513	$\boxed{2.8052}$	0.0067
$1/Q^2$	0.0018	0.0019	0.5139	0.0001
M_μ	0.1056	0.1057	0.1818	0.0005
$M_e \times 10^4$	5.1145	5.1100	0.1749	0.0256
$\lvert V_{us}\rvert$	0.2244	0.2253	0.6763	0.0014
$\lvert V_{cb}\rvert$	0.0404	0.0408	0.1729	0.0021
$\lvert V_{ub}\rvert \times 10^3$	3.1033	3.8500	0.8681	0.8601
$\lvert V_{td}\rvert \times 10^3$	8.8101	8.4000	0.6817	0.6016
$\lvert V_{ts}\rvert$	0.0396	0.0400	0.1531	0.0027
$\sin 2\beta$	0.6270	0.6820	$\boxed{2.8562}$	0.0193
ϵ_K	0.0022	0.0022	0.2052	0.0002
$\Delta M_{B_s}/\Delta M_{B_d}$	35.3739	35.0345	0.0479	7.0854
$\Delta M_{B_d} \times 10^{13}$	3.9433	3.3370	0.7681	0.7894

$\theta_{13} \approx 7^o$

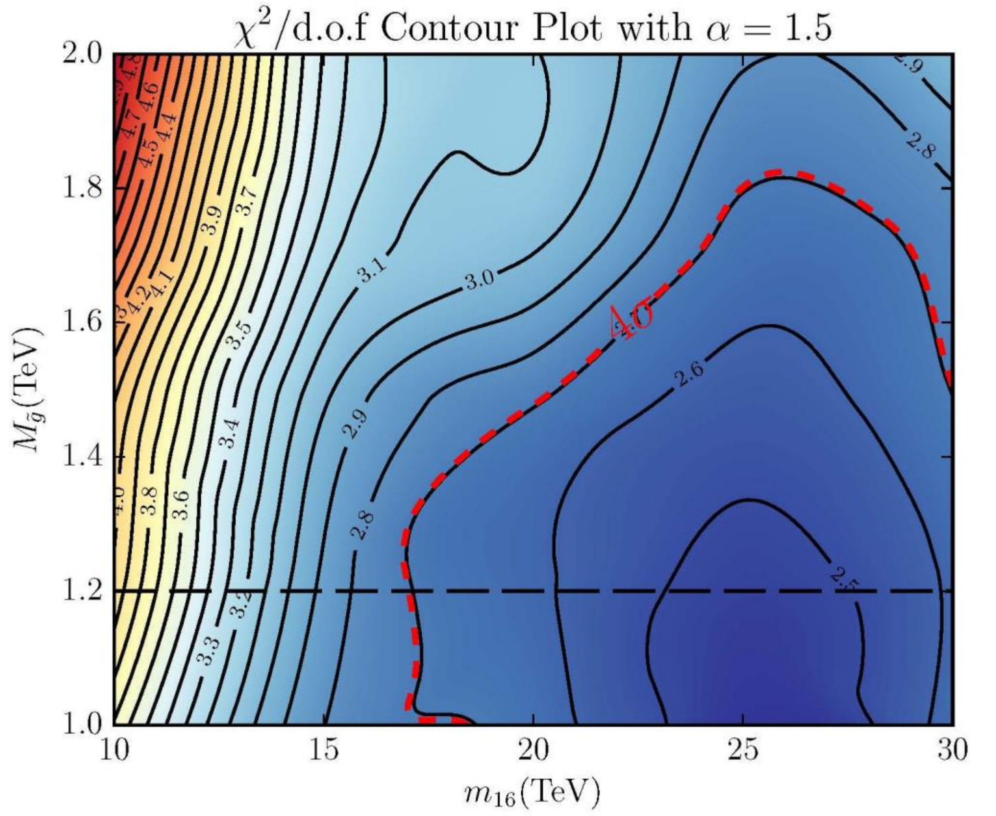
Observable	Fit	Exp.	Pull	σ
$m_{21}^2 \times 10^5$	7.6562	7.5550	0.1886	0.5364
$m_{31}^2 \times 10^3$	2.4631	2.4620	0.0077	0.1455
$\sin^2\theta_{12}$	0.3170	0.3070	0.2689	0.0370
$\sin^2\theta_{23}$	0.6264	0.5125	0.8722	0.1305
$\sin^2\theta_{13}$	0.0149	0.0218	$\boxed{2.1658}$	0.0032
M_h	124.5054	125.7000	0.3947	3.0265
$BR(B \to s\gamma) \times 10^4$	2.6840	3.4300	0.5789	1.2887
$BR(B_s \to \mu^+\mu^-) \times 10^9$	3.0247	2.8000	0.2429	0.9252
$BR(B_d \to \mu^+\mu^-) \times 10^{10}$	1.1022	3.9000	1.7323	1.6151
$BR(B \to \tau\nu) \times 10^5$	6.1884	11.4000	1.3727	3.7966
$BR(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2} \times 10^8$	4.7640	3.4000	0.2707	5.0381
$BR(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2} \times 10^8$	7.5110	5.6000	0.1336	14.3059
$q_0^2(A_{\mathrm{FB}}(B \to K^*\mu^+\mu^-))$	3.6690	4.9000	0.9579	1.2850
$F_L(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	0.7225	0.6500	0.2149	0.3374
$F_L(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	0.3108	0.3300	0.0726	0.2644
$P_2(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	0.0228	0.3300	$\boxed{2.5196}$	0.1219
$P_2(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	-0.4336	-0.5000	0.3364	0.1974
$P_4'(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	0.5820	0.5800	0.0050	0.4001
$P_4'(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	1.2190	-0.1800	1.7066	0.8198
$P_5'(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	-0.4455	0.2100	$\boxed{2.2578}$	0.2903
$P_5'(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	-0.7116	-0.7900	0.1552	0.5052
Total χ^2			48.8413	

Outline

- SUSY SO(10) minimal model
- Yukawa unification – first order effects
- Global χ^2 analysis – 3 families
- Fits
- Predictions – Poh & Raby arXiv:1505.00264
- Fine-tuning
- Conclusions


χ^2/d.o.f Contour Plot with $\alpha = 0$
$M_{\tilde{g}}$(TeV)
m_{16}(TeV)
4σ

$M_g \leq 2$ TeV


χ^2/d.o.f Contour Plot with $\alpha = 1.5$
$M_{\tilde{g}}$(TeV)
m_{16}(TeV)
4σ

Some Benchmark points

m_{16}	25	25	25	25
α	0	1.5	0	1.5
χ^2/d.o.f	2.158	2.275	2.220	2.505
$m_{\tilde{t}_1}$	4.903	5.011	4.909	5.249
$m_{\tilde{t}_2}$	6.021	6.120	6.033	6.301
$m_{\tilde{b}_1}$	5.989	6.088	6.455	6.606
$m_{\tilde{b}_2}$	6.454	6.541	6.445	6.267
$m_{\tilde{\tau}_1}$	9.880	9.931	9.912	10.040
$m_{\tilde{\tau}_2}$	15.369	15.365	15.393	15.516
$M_{\tilde{g}}$	1.202	1.187	1.613	1.690
$m_{\tilde{\chi}_1^0}$	0.203	0.551	0.279	0.900
$m_{\tilde{\chi}_2^0}$	0.404	0.665	0.538	1.018
$m_{\tilde{\chi}_1^+}$	0.404	0.665	0.538	1.018
$m_{\tilde{\chi}_2^+}$	1.128	1.243	1.232	1.537
M_A	2.194	2.082	2.477	3.352
$\sin\delta$	-0.289	-0.482	-0.520	-0.576
$BR(\mu \to e\gamma) \times 10^{13}$	1.108	1.430	1.239	1.340
$\mathrm{edm}_e \times 10^{30}$(e cm)	-1.403	-3.305	-1.763	-5.886

[TeV]

A BRIEF ASIDE

LHC bounds on the gluino mass

using benchmark points with $m_{16} = 20$ TeV and $\alpha = 0$ and 1.5 compared to CMS and ATLAS data

gluino branching ratios

NOT simplified models !!

Anandakrishnan, Bryant & Raby arXiv: 1404.5628

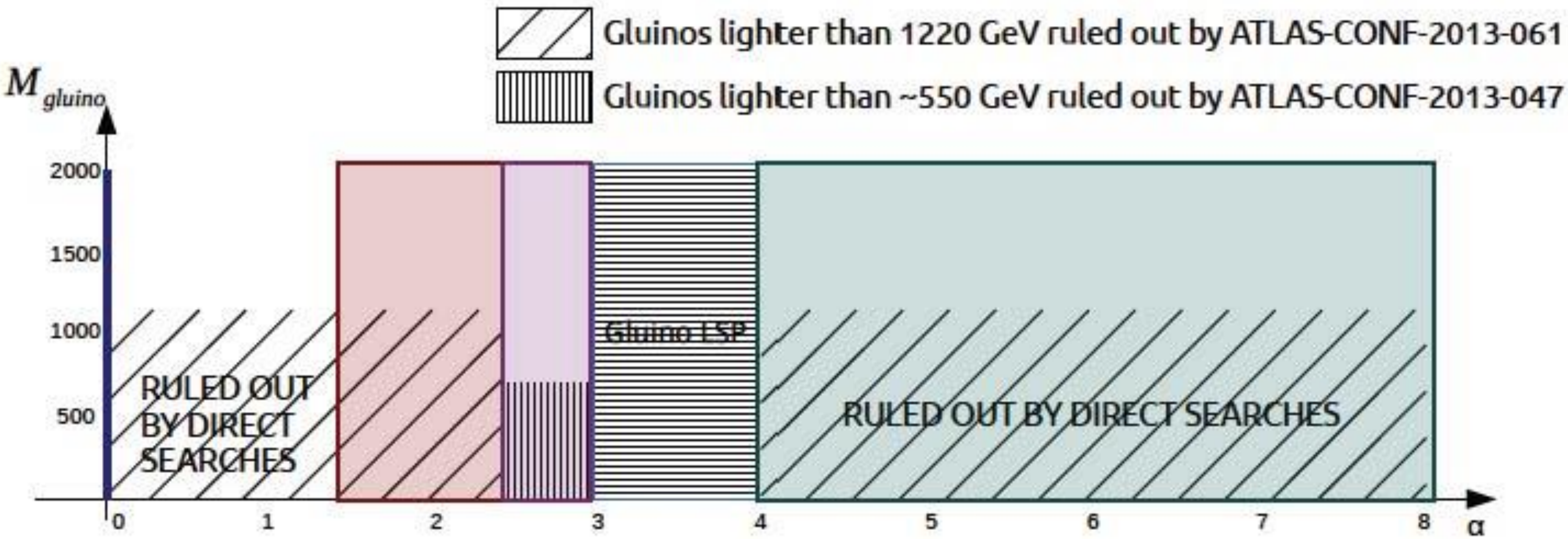
Most stringent signal region

$\sqrt{s} = 8$ TeV, 20.1 fb^{-1}

ATLAS-CONF-2013-061
final states with large missing transverse momentum, at least four, six, or seven jets, at least three jets tagged as b-jets, and either zero or at least one lepton.

baseline selection: ≥ 1 signal lepton (e, μ), $p_T^{j_1} > 90$ GeV, $E_T^{miss} > 150$ GeV, ≥ 4 jets with $p_T > 30$ GeV, ≥ 3 b-jets with $p_T > 30$ GeV					
Signal Region	N jets	E_T^{miss} [GeV]	m_T [GeV]	m_{eff}^{incl} [GeV]	$E_T^{miss}/\sqrt{H_T^{incl}}$ [GeV$^{\frac{1}{2}}$]
SR-1l-6J-B	≥ 6	> 225	> 140	> 800	> 5

CMS & ATLAS data using CHECKMATE



UNIVERSAL GAUGINO MASSES
$\alpha = 0$

- Very heavy scalars: ≥ 10 TeV
- Bino LSP: Over-abundant dark matter
- Good fits require light gluino < 2 TeV

BENCHMARK MODELS
Ua, Ub, Uc, Ud, Ue, Uf

$1.5 < \alpha < 2.5$

- Well-tempered neutralino dark matter

BENCHMARK MODELS DMa, DMb

$2.5 < \alpha < 3.0$

- Compressed gaugino spectrum

BENCHMARK MODELS: COa, COb

$\alpha > 4.0$

- Non-universal gaugino masses
- Wino/Wino-Higgsino LSP: Under abundant dark matter
- Good fits with heavier gluino masses

BENCHMARK MODELS
Ma, Mb, Mc, Md, Me, Mf

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Fine-tuning

Fine-Tuning of Benchmark Points with $\alpha = 0$ and $M_{\tilde{g}} \approx 1.2$TeV

Varying Parameters	m_{16}				
	10TeV	15TeV	20TeV	25TeV	30TeV
μ	140	190	210	360	490
$M_{1/2}$	260	340	400	430	450
m_{16}	12000	27000	47000	74000	110000
m_{H_d}	760	1500	3900	6100	8700
m_{H_u}	10000	23000	40000	62000	89000
A_0	9300	21000	39000	61000	85000
m_{16} with A_0/m_{16} fixed	22000	49000	87000	130000	190000
m_{16} with $m_{H_{u,d}}/m_{16}$ fixed	9500	22000	40000	62000	86000
m_{16} with $m_{H_{u,d}}/m_{16}$, A_0/m_{16} fixed	240	400	630	740	850

Fundamental Physics ??

Conclusions

- SO(10) Yukawa unification
- Boundary conditions at M_{GUT}

  ~ Universal or "Mirage" gaugino masses
- Light Higgs - SM-like

$$2.4 \geq m_{g} \geq 1.2 \text{ TeV}$$

- Three family model fits low energy data !!
- SUSY at Run II of LHC !
- BR($\mu \to e \gamma$) observable !

NOT "Natural" SUSY

BUT SUSY does not completely decouple

NOT "Split" SUSY

BUT gravitino & moduli sufficiently heavy
so NO cosmological problems

"SUSY on the Edge"

painting by Hans Werner Sahm