Scales of supersymmetry breaking and flavour theories

The new LHC lower bounds on the superpartner masses , stronger for the first two genertations of squarks than for the third one,

revive the interest in the flavour dependent sfermion spectrum.

Bounds on the gluino mass ~ 1.5 TeV

Model dependent bounds but lets take them at face value

Suppose there is some truth in the naturalness arguments and the data will confirm flavour dependent squark spectrum, with the inverted hierarchy pattern.

An obvious interesting question: is the fermion and sfermion flavour dependence
linked to each other?

One is tempted to expect that both can be explained by a theory of flavour

(NO MUST, OF COURSE…)

Do „good” fermion mass models hint to inverted hierarchy for sfermions?

SEVERAL SCALES IN SFERMION MASSES?

Theories of fermion masses are based on

- horizontal (family) symmetries and Froggatt-Nielsen mechanism

- fermion wave function renormalisation effects, or equivalently overlap of localised fermion wave functions in extra dimension

LET's FOCUS ON THE FIRST CATEGORY

EARLY PAPERS ON SIMILAR AND RELATED QUESTIONS:

WITH FLAVOUR U(2) GLOBAL SYMMETRY

3rd generation of sfermions can be light, 1st and 2nd can be heavier, to reconcile naturalness with FCNC constraints

Dine, Leigh, Kagan ' 93
Pomarol, Tommasini ' 95
Barbieri, Davali, Hall '96
Barbieri, Hall, Romanino '97

ROOM FOR THE SPLITING BUT IT'S NOT PREDICTED;
ONE MASS SCALE

WITH ANOMALOUS U(1) (GAUGED) FLAVOUR SYMMETRY

Fermion mass model-motivated „inverted hierarchy" of sfermion spectrum (follows from fermion hierarchy)

Dudas, SP, Savoy ' 95
Dudas, Grojean, SP, Savoy ' 96
Nelson, Wright ' 97
Chankowski, Lavignac, SP ' 05 – FCNC phenomenology
………

F-TERM AND D-TERM CONTRIBUTION TO SFERMION MASSES;
TWO SCALES IF D-TERM SUPERSYMMETRY BREAKING

A CLOSER LOOK AT THE TWO CLASSES OF MODELS

- HOW WELL THE TWO CLASSES OF MODELS DO FOR THE FERMION MASSES AND MIXING?
- WHAT ABOUT THE SFERMION SECTOR AND THE FCNC CONSTRAINTS?

U(2): very predicitve; 2 parameters

[19] R. Barbieri, L. Hall and A. Romanino, Phys. Lett. **B401**, 47 (1997)

[22] R. Barbieri, L. Hall and A. Romanino, Nucl. Phys. **B551**, 93 (1999).

[23] R. Barbieri, G. Dvali and L. Hall, Phys. Lett. **B377**, 76 (1996).

$$\cdot \begin{pmatrix} 0 & \epsilon' & 0 \\ \epsilon' & \epsilon & O(\epsilon) \\ 0 & O(\epsilon) & 1 \end{pmatrix}$$

$$|V_{us}| = \left| \sqrt{\frac{m_d}{m_s}} - e^{i\phi} \sqrt{\frac{m_u}{m_c}} \right|$$

$$\left| \frac{V_{ub}}{V_{cb}} \right| = \sqrt{\frac{m_u}{m_c}} \quad \textbf{?}$$

$$\left| \frac{V_{td}}{V_{ts}} \right| = \sqrt{\frac{m_d}{m_s}}$$

(FOR UP, DOWN AND LEPTONS)
LEFT-RIGHT SYMMETRIC YUKAWAS;

$$Y_{i2} << Y_{i3}, i = 2, 3$$

ALL ROTATION ANGLES ARE SMALL

$$\sqrt{m_d/m_s} = 0.22 \pm 0.02$$

$$\sqrt{m_u/m_c} = 0.046 \pm 0.008,$$

$$|V_{us}| = 0.2253 \pm 0.0007$$

$$|V_{ub}/V_{cb}| = 0.085 \pm 0.004$$

$$|V_{td}/V_{ts}| = 0.22$$

U(1) MODELS: LESS PREDICTIVE, MORE PARAMETERS,

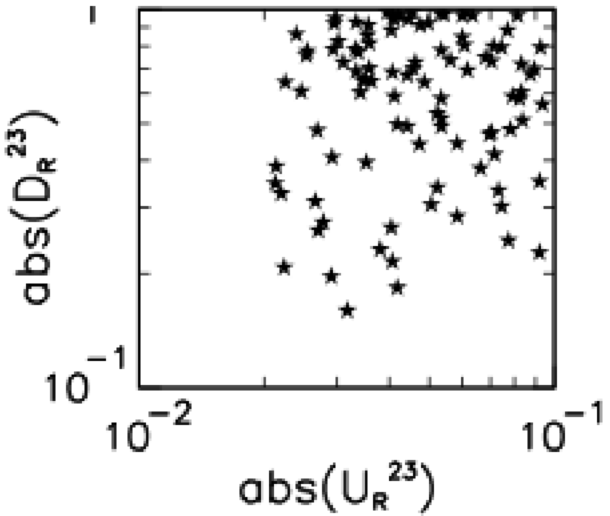
BUT DESCRIBE THE FERMION DATA BETTER

$$q_{L\ 1,2,3} : \quad (3,2,0)$$
$$d^c_{1,2,3} : \quad (1,0,0)$$
$$u^c_{1,2,3} : \quad (3,2,0)$$

$$Y_D = \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon & 1 & 1 \end{pmatrix}$$

THE DATA DONT LIKE THE HIERARCHY $Y_{32} << Y_{33}$

CHANKOWSKI,KOWALSKA, LAVIGNAC, SP '05



THE DOWN QUARK YUKAWA MATRIX EXIBITS INTERESTING CORRELATION:
A MATRIX THAT GIVES GOOD FIT TO DATA NEEDS LARGE RIGHT-HANDED ROTATION ELEMENT V_{32}

FOR $0.07 < V_{ub}/V_{cb} < 0.1$

EXP: 0.085 (0.004)

A SOLUTION TO THE $|V_{ub}/V_{cb}|$ PROBLEM

$$\begin{pmatrix} 0 & \epsilon' & 0 \\ \epsilon' & 0 & O(\epsilon) \\ 0 & O(1) & 1 \end{pmatrix}$$

[21] R. Roberts, A. Romanino, G. Ross, L. Velasco-Sevilla, hep-ph/0104088.

COMPARISON OF THE TWO CLASSES OF MODELS IN THE SFERMION SECTOR AND FOR THE FCNC

U(2)

- ALMOST DEGENERATE 1&2 GENERATION SQUARKS
- DIAGONALISATION OF YUKAWA MATRICES WITH All ROTATIONS SMALL
- ONE SCALE

$$m_1^2 - m_3^3 \approx m_3^2$$

- **GLUINO HEAVIER THAN 1.5 TeV !**

$\longrightarrow$ VERY WEAK BOUNDS FOR SQUARK MASSES

OVERALL CONCLUSION: TENSION FOR FERMIONS; FINE FOR FCNC WITH LOW SINGLE MASS SCALE

U(1)

$$(\tilde{m}^2)^{AB} = c^{AB}\, m_F^2\, \lambda^{|q_A - q_B|} + q_A\, m_D^2\, \delta_{AB}$$

where q_A is fixed by fermion masses and

$$m_F^2 \sim m_D^2 \quad \text{or (better)} \quad m_F^2 < m_D^2$$

generated by soft mass of $\tilde{\chi}^-$

D-term susy breaking

U(1)

- PREDICT INVERTED HIERARCHY

- LARGE OFF-DIAGONAL (1,2) MATRIX ELEMENTS OF THE SFERMION MASS MATRIX IN THE SCKM BASIS BECAUSE OF THE DIFFERENT U(1) CHARGES OF THE FIRST TWO GENERATIONS

- NEEDS LARGE HIERARCHY, m_D/m_F TO SATISFY FCNC CONSTRAINTS AND TO KEEP THE 3rd FAMILY LIGHT

- FIRST TWO GENERATIONS ~50 TeV!

OVERALL CONCLUSION: U(1) GOOD FOR THE FERMION SECTOR BUT NOT SATISFACTORY FOR SFERMIONS

MINIMAL SET-UP COMBINING THE VIRTUES OF BOTH

$$SU(2)_{global} \times U(1)_{gauged} (\times SU(5)_{GUT})$$

DUDAS, von GERSDORFF, SP, ZIEGLER, TO APPEAR

(see ROBERT's TALK)

SEVERAL INTERESTING FEATURES:

FERMION SECTOR- VERY GOOD DESCRIPTION; CORRECTION TO

$$V_{ub}/V_{cb}$$

CORRELATED WITH LARGE R-HANDED ROTATION

$$V_{32}^{d}$$

SFERMION SECTOR AND FCNC CONSTRAINTS-ANY HINT FOR TWO SCALES?

$$\tilde{m}_{10}^2 = \tilde{m}_D^2 \begin{pmatrix} X_{10} & 0 & 0 \\ 0 & X_{10} & 0 \\ 0 & 0 & 0 \end{pmatrix} + \tilde{m}_F^2 \begin{pmatrix} c_{11}^I & 0 & 0 \\ 0 & c_{11}^I + c_{22}^I \epsilon_\phi^2 & c_{12}^I \epsilon_\phi \epsilon_u \\ 0 & c_{12}^{I*} \epsilon_\phi \epsilon_u & c_{33}^I \end{pmatrix}_{I=q,u,e} ,$$

$$\tilde{m}_{\bar{5}}^2 = \tilde{m}_D^2 \begin{pmatrix} X_{\bar{5}} & 0 & 0 \\ 0 & X_{\bar{5}} & 0 \\ 0 & 0 & X_3 \end{pmatrix} + \tilde{m}_F^2 \begin{pmatrix} c_{11}^I & 0 & 0 \\ 0 & c_{11}^I + c_{22}^I \epsilon_\phi^2 & c_{12}^I \epsilon_\phi \epsilon_d / \epsilon_3 \\ 0 & c_{12}^{I*} \epsilon_\phi \epsilon_d / \epsilon_3 & c_{33}^I \end{pmatrix}_{I=d,l} ,$$

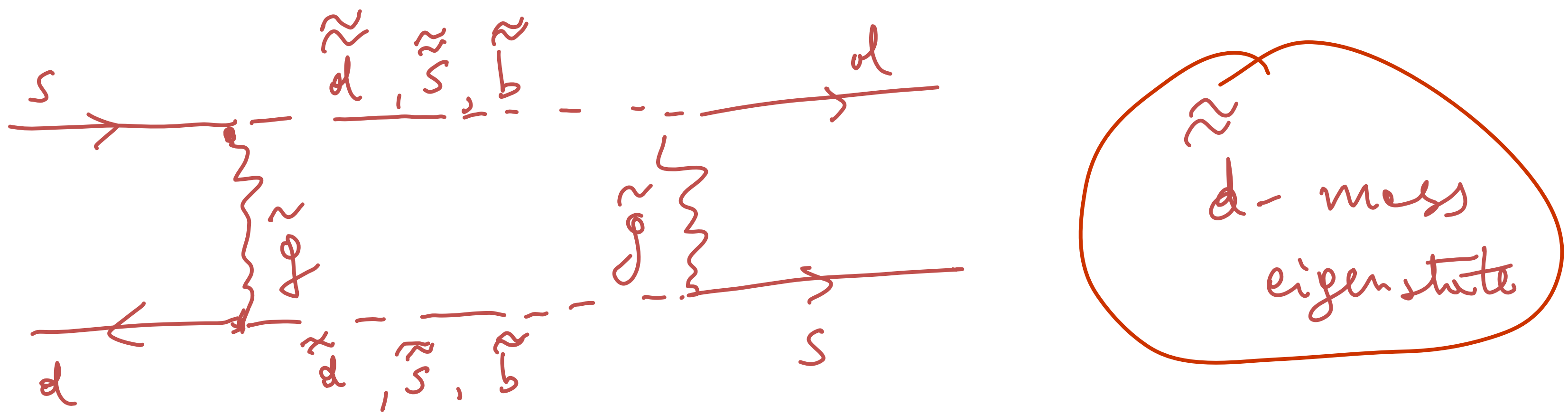
APPROXIMATELY DIAGONAL

TAKE THE BOUNDS FROM ϵ_K

$$Q_{LL} = C_{LL} \overline{d}_L^{\alpha} \gamma^{\mu} s_L^{\alpha} \, \overline{d}_L^{\beta} \gamma_{\mu} s_L^{\beta}$$

LL, RR and LLRR OPERATORS

More about basis



in the squark mass eigenstate basis,

IN THE APPROXIMATION OF DIAGONAL SFERMION MASS MATRICES IN THE ORIGINAL BASIS, THE COUPLINGS ARE GIVEN BY THE QUARK ROTATION MATRICES

WILSON COEFFICIENTS C

$$(\Sigma_i Z_{id} Z^*_{is})(\Sigma_i Z_{jd} Z^*_{js}) I(m_i^2, m_j^2)$$

$$= (Z_{3d} Z^*_{3s})^2 [I(m_1^2, m_1^2) - 2I(m_1^2, m_3^2) + I(m_3^2, m_3^2)]$$

IN THE APPROXIMATION OF DIAGONAL SFERMION MASS MATRICES

$$Z_{3d} Z^*_{3s} = V^d_{31} V^{*d}_{32}$$

MANIFEST SUPERSYMMETRIC GIM (e.g. LALAK, SP, ROSS)

FCNC EFFECT in the (1,2) SECTOR DEPENDS ON THE

$\tilde{m}_d = \tilde{m}_s$ AND $\tilde{m}_b$ SPLITING

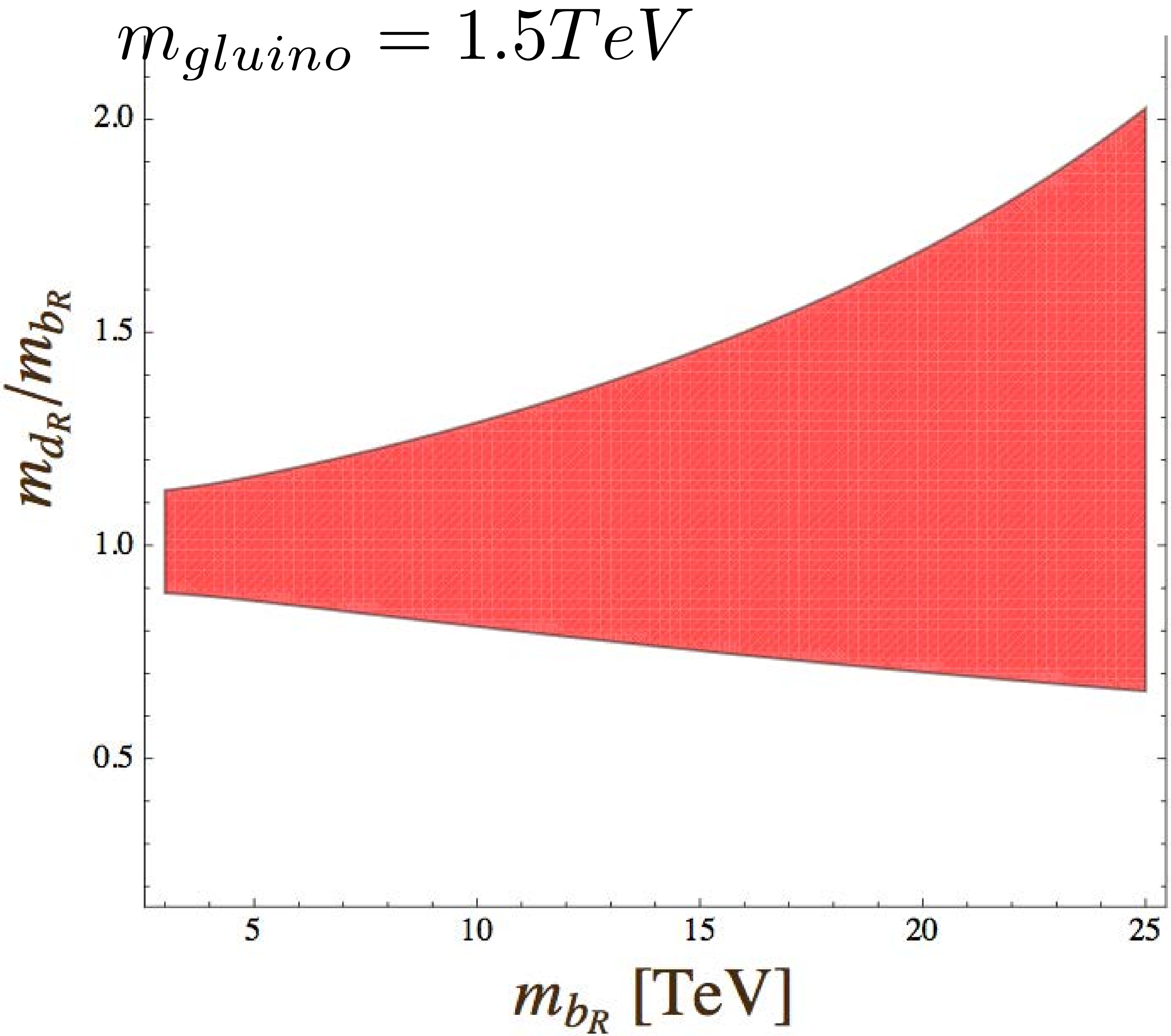
THE SPLITING IS FIXED BY THE CHARGES AND ORDER ONE COEFFICIENTS OF m_F CONTRIBUTION

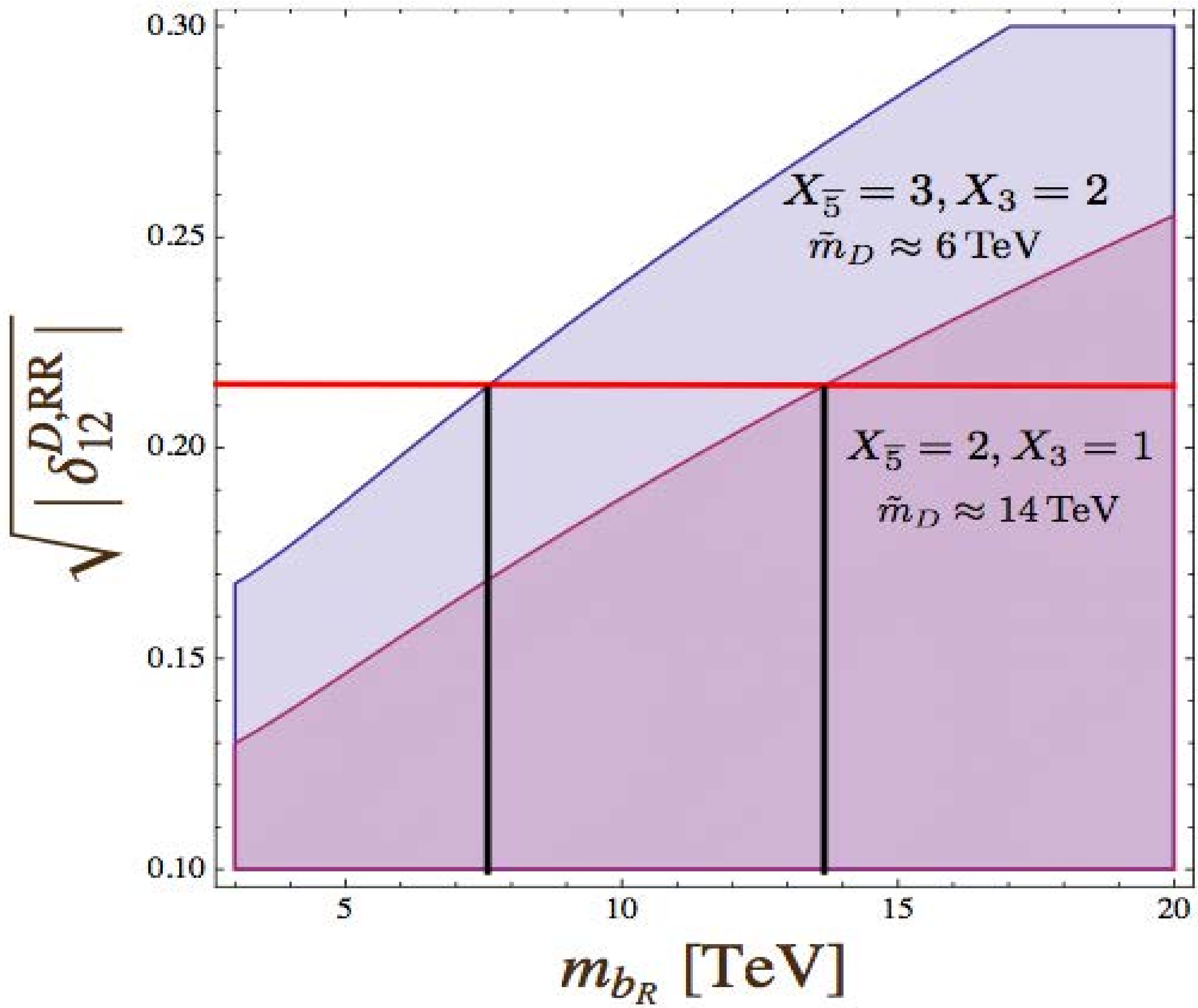
FOR 1.5 TeV GLUINO, NO BOUNDS FROM LL SECTOR BECAUSE LEFT HANDED ROTATIONS ARE SMALL

Stop can be light,

INTERESTING BOUNDS FROM RR SECTOR BECAUSE OF LARGE R –HANDED ROTATIONS NEEDED FOR A GOOD FIT IN THE FERMION SECTOR

NEED FOR TWO SCALES, IF we want to have light stop


$m_{gluino} = 1.5TeV$
2.0
1.5
1.0
0.5
m_{d_R}/m_{b_R}
5
10
15
20
25
m_{b_R} [TeV]



0.30
0.25
0.20
0.15
0.10
5
10
15
20
$X_{\bar{5}} = 3, X_3 = 2$
$\tilde{m}_D \approx 6\,\mathrm{TeV}$
$X_{\bar{5}} = 2, X_3 = 1$
$\tilde{m}_D \approx 14\,\mathrm{TeV}$
$\sqrt{|\delta_{12}^{D,\mathrm{RR}}|}$
m_{b_R} [TeV]

SUMMARY

IN A LARGE CLASS OF MODELS:

- **FERMION SECTOR REQUIRES DOWN QUARK YUKAWA MATRICES THAT NEED LARGE R-HANDED ROTATIONS FOR THEIR DIAGONALISATION IN THE (2,3) SECTOR**

- **THIS DOES IMPLY A TWO SCALE PATTERN FOR SQUARK MASSES, PROVIDED THE STOPS ARE TO REMAIN LIGHT FOR NATURALNESS; THE RIGHT HANDED SBOTTOM HAS TO BE HEAVY**

- **SU(2)xU(1) FLAVOUR SYMMETRY COMBINES THE VIRTUES OF U(2) AND U(1) MODELS, AND AVOIDS THEIR DEFECTS**

END

BACKUP

VEVS

$$\langle \phi^a \rangle = \epsilon_\phi \Lambda \begin{pmatrix} 0 \\ \Lambda \end{pmatrix}$$

$$\langle \chi \rangle = \epsilon_\chi \Lambda$$

Free parameters $\epsilon_\phi = \dfrac{\langle \phi \rangle}{\Lambda}$

$$\epsilon_\chi = \frac{\langle \chi \rangle}{\Lambda}$$

Λ – "flavour" scale

Yukawa matrices

$$Y_u \sim \begin{pmatrix} 0 & \epsilon'_u & 0 \\ \epsilon'_u & \epsilon_u^2 & \epsilon_u \\ 0 & \epsilon_u & 1 \end{pmatrix}$$

$$Y_d \sim Y_e \sim \begin{pmatrix} 0 & \epsilon'_u \epsilon_d / \epsilon_u & 0 \\ \epsilon'_u \epsilon_d / \epsilon_u & \epsilon_u \epsilon_d & \epsilon_3 \epsilon_u \\ 0 & \epsilon_d & \epsilon_3 \end{pmatrix}$$

Very good description of the fermion masses and mixings, with, e.g.

$\epsilon_X \sim \epsilon_\phi \sim 0.2$

$X_{10} = 3$ $X_\phi = -2$

$\tan\beta = 10$

$X_{\bar{5}} = 3$ $X_3 = 1$

Yukawa matrices depend on 4 small parameters and 4 phases (after using the freedom of phase rotations of the quark fields)

$$\epsilon_u = \epsilon_\phi \, \epsilon_\chi^{\,x_{10} + x_\phi} \, , \qquad \epsilon_d = \epsilon_\phi \, \epsilon_\chi^{\,x_{\bar{5}} + x_\phi}$$

$$\epsilon'_u = \epsilon_\chi^{\,2 x_{10}} \, , \qquad \epsilon_3 = \epsilon_\chi^{\,x_3}$$

In U(2) model

$$X_{10} = X_{\overline{5}} = -X_{\Phi} = 1$$

$$X_3 = 0 \quad , \quad \chi^2 \to \chi$$

Simple example

Gauged U(1) family symmetry, spontaneously broken by a vev of a single familon field χ with U(1) charge -1

Fermion charges (all $\geq$ 0):

left-handed doublets Q_L^i : q_i

left-handed singlets $U_i^C,\, D_i^C$: $u_i,\, d_i$

Higgs field $q_H = 0$

$$C_u^{AB}\,\hat{U}_A^c\hat{Q}_B\hat{H}_u\left(\frac{\hat{\Phi}}{M}\right)^{\bar{u}_A+q_B+h_u} \quad .$$

$$Y_u^{AB} \;=\; C_u^{AB}\,\epsilon^{\bar{u}_A+q_B+h_u}\;, \quad Y_d^{AB} \;=\; C_d^{AB}\,\epsilon^{\bar{d}_A+q_B+h_d}\;,$$

D - term supersymmetry breaking:

a model with two fields χ^-, χ^+

with $U(1)$ charges $-1, +1$;

F - I term $\xi \approx \epsilon^2 M_{Pl}^2$

D - term

$$\frac{g^2}{2} D = \frac{g^2}{2}\left(\sum_i q_i |Q_i|^2 + |\chi^+|^2 - |\chi^-|^2 + \xi\right)^2$$

we get $|\chi^-|^2 = \xi \Rightarrow$ unbroken susy

But add $W = m\,\chi^-\chi^+$

new scale $m \ll M_{PL}$

Minimization gives

$\langle \chi^+ \rangle = 0 \qquad \langle \chi^- \rangle^2 = \xi - \frac{m^2}{g^2}$ F–N field

$F_{\chi^+} = m\sqrt{\xi - \frac{m^2}{g^2}} \qquad F_{\chi^-} = 0$

$\langle D \rangle = \frac{m^2}{g^2}$, $\qquad \frac{F^2}{M_{PL}^2} \simeq \frac{m^2\xi}{M_{PL}^2} \sim D\epsilon^2$

Conclusions for supersymmetric family symmetry models (Lalak,SP, Ross):

they can remain consistent with the bounds on FCNC and CP violation for superpartner physical masses $\leq$O(1 TeV) but generically require strong flavour blind renormalisation effects on the squark masses. This requires $m_{1/2}/m_0 \gtrsim 7$

e.g. $m_{1/2} = 300\text{GeV}, \; m_0 \sim 50\text{GeV}$

$$m_{\tilde{g}} = 900\text{GeV}, \; m_{\tilde{q}} = 800\text{GeV}$$

(similar to the fits to the precision data)

$$
\begin{aligned}
L_{eff} &= \frac{\alpha_s^2}{216\tilde{m}_{qij}^2}((\delta^d_{12\,LL})^2(\bar{d}_L\gamma_\mu s_L\bar{d}_L\gamma_\mu s_L)\times f(x) \\
&+ (\delta^d_{12\,RR})^2(\bar{d}_R\gamma_\mu s_R\bar{d}_R\gamma_\mu s_R)\times f'(x) \\
&+ (\delta^d_{12\,LL})(\delta^d_{12\,RR})(\bar{d}_R s_L\bar{d}_L s_R)\times f''(x) + \ldots + \text{h.c.})
\end{aligned}
$$

q	ij	$(\delta^q_{ij})_{MM}$	$\langle\delta^q_{ij}\rangle$
d	12	$0.01 \sim \epsilon^2$	$0.0007 \sim \epsilon^4$
d	13	$0.07 \sim \epsilon$	$0.025 \sim \epsilon^2$
d	23	$0.21 \sim \epsilon$	$0.07 \sim \epsilon$
u	12	$0.035 \sim \epsilon^2$	$0.003 \sim \epsilon^3$

Experimental bounds

Fermion mass model-motivated „inverted hierarchy" spectrum

3rd generation light, 1st and 2nd heavy

Dudas, SP, Savoy ' 95 – horizontal U(1) and D term breaking
Dudas, Grojean, SP, Savoy ' 96 – horizonal U(1) and D term breaking
Nelson, Wright ' 97 – horizontal U(1) and D term breaking
Chankowski, Lavignac, SP ' 05 – FCNC phenomenology

………
Craig, Essig, Franco, Kachru, Torroba ' 10 – dynamical SUSY breaking models
Aharony, Berdichevsky, Berkooz, Hochberg, Robles-Llana ' 10 – CFT models
Craig et al. ' 12 – flavour mediation

DUDAS, GERSDORFF, SP, ZIEGLER, to be published

Sfermion masses

$$\frac{F^2}{M^2}\left(\frac{\chi}{M}\right)^{|q_i - q_j|} Q_i^{+} Q_j$$

$\underbrace{\frac{F^2}{M^2}}$ F-term supersymmetry breaking

Hence

$$(\tilde{m}^2)^{AB} = c^{AB}\, m^2 \lambda^{|q_A - q_B|}$$

$m^2 = \frac{F^2}{M^2}$, $c^{AB} \sim O(1)$, $c^{AA} - c^{BB} \sim O(1)$

D-terms supersymmetry breaking with gauged U(1) (Binétruy, Dudas; Dvali, Pomarol 1996)

$\Rightarrow$ TWO SCALES $(F, D) \nearrow (m_F, m_D)$