# Restrictions on SUSY Breaking from Flavor Symmetries

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Based on work being done in collaboration with
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# Nothing but Problems with Flavor

## Standard Model

- $m_e = 511\,\text{keV} \ll m_t = 173\,\text{GeV}$
- Values of mixing angles not understood

## SUSY

- New source of flavor violation in soft SUSY breaking parameters
- No suppression of flavor-changing neutral currents expected
- Observations require suppression

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- Flavor symmetry $\rightsquigarrow$ Yukawa couplings zero

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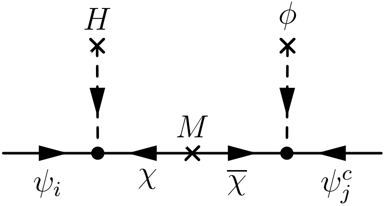
$$Y_{ij} \sim \frac{\langle\phi\rangle^n}{M^n} =: \epsilon^n$$

- Power $n$ of suppression depends on $i, j \rightsquigarrow$ mass hierarchy

Froggatt, Nielsen, Nucl. Phys. **B147**

# Underlying Theory




$\rightsquigarrow$ Effective operator $\frac{1}{M}\psi_i\psi_j^c H\phi$ at energies $\ll M$

# Towards a Cure II

- Non-Abelian symmetry, matter fields in 3D representation

$$\psi, \psi^c \sim \mathbf{3}$$

- Soft mass matrices $\propto \mathbb{1}$

$$m_0^2\, \widetilde{\psi}_1^\dagger \widetilde{\psi}_1 \text{ ok}$$
$$m_{12}^2\, \widetilde{\psi}_1^\dagger \widetilde{\psi}_2 \text{ forbidden}$$

- Symmetry breaking $\rightsquigarrow$ off-diagonal entries

$$m_{ij}^2 \sim m_0^2\, \epsilon^n$$

$\rightsquigarrow$ Flavor violation under control, predictions

Abel, Antusch, Calibbi, Feruglio, Hagedorn, Ishimori, Jones-Perez, Khalil, King, Kobayashi, Lebedev, Lin, Malinský, Merlo, Nomura, Ohki, Olive, Omura, Ross, Stolarski, Takahashi, Tanimoto, Velasco Sevilla, Vives,
hep-ph/0112260, hep-ph/0211279, hep-ph/0401064, 0708.1282, 0801.0428, 0803.0796, 0804.4620, 0807.3160, 0807.4625, 0807.5047, 0808.1380

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## This talk

- Possible patterns for SUSY breaking parameters
- Musings about predictivity
- Consider one specific model as an example
- Order-of-magnitude estimates

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- More general setup
- Accurate numerical study

Olive, Velasco Sevilla, 0801.0428

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Olive, Velasco Sevilla, 0801.0428

# Specific Example

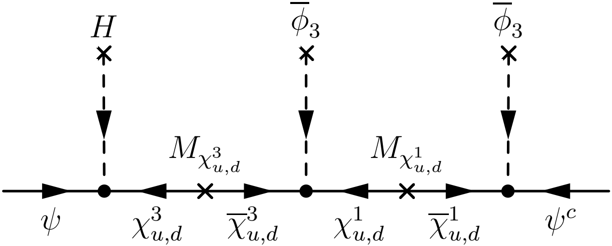
de Medeiros Varzielas, Ross, hep-ph/0507176

- $\mathrm{SU}(4)_{\mathrm{PS}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}}$ gauge symmetry
- $\mathrm{SU}(3) \times \mathrm{U}(1) \times \mathrm{U}(1)'$ flavor symmetry
- $\psi, \psi^c \sim \mathbf{3}$
- Flavons $\overline{\phi}_3, \overline{\phi}_{23}, \overline{\phi}_{123} \sim \overline{\mathbf{3}}$
- Symmetry breaking in 2 steps: $\mathrm{SU}(3) \to \mathrm{SU}(2) \to$ nothing

$$Y^u \sim \begin{pmatrix} 0 & \epsilon_u^2 \epsilon_d & -\epsilon_u^2 \epsilon_d \\ \epsilon_u^2 \epsilon_d & -2\frac{\epsilon_u^3}{\epsilon_d} & 2\frac{\epsilon_u^3}{\epsilon_d} \\ -\epsilon_u^2 \epsilon_d & 2\frac{\epsilon_u^3}{\epsilon_d} & 1 \end{pmatrix} \quad , \quad Y^d \sim \begin{pmatrix} 0 & \epsilon_d^3 & -\epsilon_d^3 \\ \epsilon_d^3 & \epsilon_d^2 & -\epsilon_d^2 \\ -\epsilon_d^3 & -\epsilon_d^2 & 1 \end{pmatrix}$$

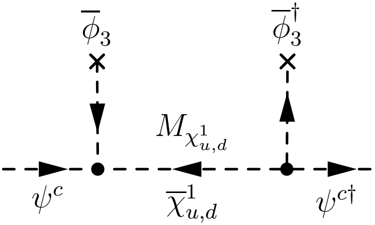
$$\epsilon_u \approx 0.05 \quad , \quad \epsilon_d \approx 0.15$$

# Origin of Yukawa Couplings




- $Y^{u,d}_{33} \sim \dfrac{\langle\overline{\phi}_3\rangle^2}{M_{\chi^3_{u,d}} M_{\chi^1_{u,d}}}$
- Messenger masses $M_{\chi_u} \neq M_{\chi_d}$ due to $SU(2)_R$ breaking
- $\chi^3_{u,d} \sim \overline{\mathbf{3}}$ of SU(3)

# Consequences for Soft Masses

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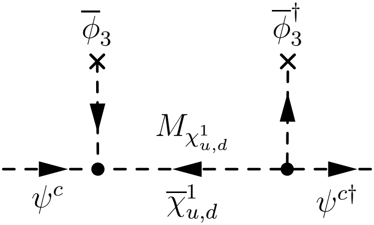


- $(\widetilde{m}_u^2)_{33} \sim m_0^2 + \frac{\langle\overline{\phi}_3\rangle^2}{M^2_{\chi^1_u}}$
- No messenger coupling to $\psi\overline{\phi}_3 \rightsquigarrow (\widetilde{m}_Q^2)_{33} = m_0^2$
- Tri-bimaximal mixing intact after canonical normalization

  Antusch, King, Malinský, 0712.3759

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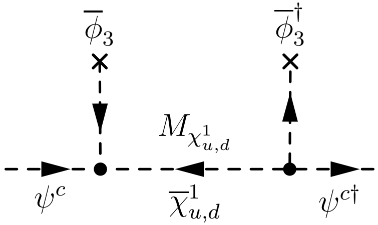

- $(\widetilde{m}^2_u)_{33} \sim m_0^2 + \frac{\langle\overline{\phi}_3\rangle^2}{M^2_{\chi^1_u}}$ — recall $Y^u_{33} \sim \frac{\langle\overline{\phi}_3\rangle^2}{M_{\chi^3_u} M_{\chi^1_u}}$
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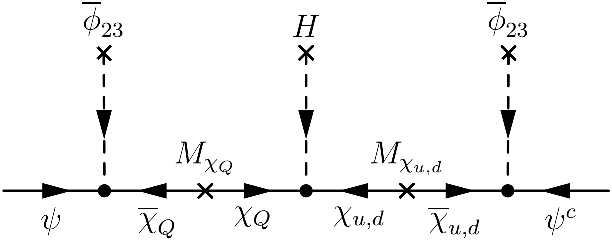
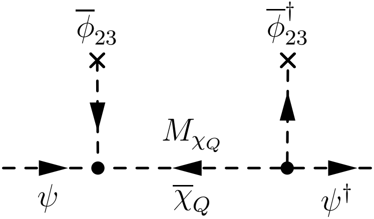
  Antusch, King, Malinský, 0712.3759
- Only $M_{\chi^1_u}$ enters soft masses $\rightsquigarrow$ no prediction

# Predictive Messenger Sector



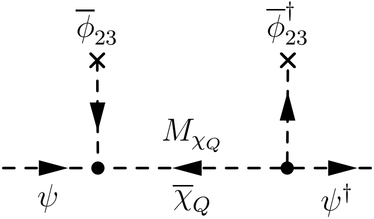

- $Y_{23}^{u,d} \sim \dfrac{\langle\overline{\phi}_{23}\rangle^2}{M_{\chi_Q} M_{\chi_{u,d}}} =: \epsilon_{u,d}^2$
- All messengers SU(3) singlets
- Use this type for all Yukawa couplings except $Y_{33}$

# Soft Masses Again




- Recall $Y^{u,d}_{23} \sim \dfrac{\langle \overline{\phi}_{23} \rangle^2}{M_{\chi_Q} M_{\chi_{u,d}}} =: \epsilon^2_{u,d}$
- $(\widetilde{m}^2_{u,d,Q})_{23} \sim \dfrac{\langle \overline{\phi}_{23} \rangle^2}{M^2_{\chi_{u,d,Q}}} =: \widetilde{\epsilon}^2_u \, , \, \widetilde{\epsilon}^2_d \, , \, \widetilde{\epsilon}^2_Q$

# Soft Masses Again




- Recall $Y_{23}^{u,d} \sim \frac{\langle \overline{\phi}_{23} \rangle^2}{M_{\chi_Q} M_{\chi_{u,d}}} =: \epsilon_{u,d}^2$
- $(\widetilde{m}^2_{u,d,Q})_{23} \sim \frac{\langle \overline{\phi}_{23} \rangle^2}{M^2_{\chi_{u,d,Q}}} =: \widetilde{\epsilon}_u^2 \,, \widetilde{\epsilon}_d^2 \,, \widetilde{\epsilon}_Q^2$
- Off-diagonal elements in all soft mass matrices
- Relations between expansion parameters
  - $\widetilde{\epsilon}_Q \widetilde{\epsilon}_u = \epsilon_u^2$
  - $\widetilde{\epsilon}_Q \widetilde{\epsilon}_d = \epsilon_d^2$
- None of them can be arbitrarily small

# Complete Matrices

$$\widetilde{m}_f^2 \sim m_0^2 \begin{pmatrix} 1 & \widetilde{\epsilon}_f^2\,\epsilon_d^2 & \widetilde{\epsilon}_f^2\,\epsilon_d^2 \\ \cdot & 1+\widetilde{\epsilon}_f^2 & \widetilde{\epsilon}_f^2 \\ \cdot & \cdot & 1 \end{pmatrix} \quad , \quad f = u,\, d,\, Q$$

See also Antusch, King, Malinský, `0708.1282`

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- Sleptons analogous with $\widetilde{\epsilon}_L\,\widetilde{\epsilon}_e = \epsilon_d^2$
- Trilinear couplings: similar, but a bit more complicated

# Running to Low Energy

- Results so far valid at high energy $\sim M_{\text{GUT}}$
- Renormalization group evolution $\rightsquigarrow$ low-energy parameters
- Rough estimate
  Antusch, King, Malinský, 0708.1282,
  Bertolini, Borzumati, Masiero, Ridolfi, Nucl. Phys. **B353**
  - Diagonal entries at low energy:

$$
\begin{aligned}
(\widetilde{m}_q^2)_{ii} &\sim 25\, m_0^2 \\
(\widetilde{m}_L^2)_{ii} &\sim 4\, m_0^2 \\
(\widetilde{m}_e^2)_{ii} &\sim 2\, m_0^2
\end{aligned}
$$

  - Off-diagonal elements do not change order of magnitude
  - $Y_\nu$ does not contribute because $M_3 > M_{\text{GUT}}$

# Super-CKM Basis

- In SCKM basis = basis with diagonal Yukawa couplings:

$$\widetilde{m}^2_{d,\mathrm{RR}} \sim m_0^2 \begin{pmatrix} 25 & \widetilde{\epsilon}_d^2\, \epsilon_d & \widetilde{\epsilon}_d^2\, \epsilon_d + \epsilon_d^3 \\ \cdot & 25 & \widetilde{\epsilon}_d^2 + \epsilon_d^2 \\ \cdot & \cdot & 25 \end{pmatrix}$$

- 12- and 13-elements enlarged by factor $\sim 1/\epsilon_d$

  Ross, Velasco Sevilla, Vives, hep-ph/0401064

- Cancellations possible in principle
- $\widetilde{m}^2_{d,\mathrm{LL}}$ analogous with $\widetilde{\epsilon}_d \to \widetilde{\epsilon}_Q$
- $\widetilde{m}^2_{e,\mathrm{LL}}$ analogous with $\widetilde{\epsilon}_d \to \widetilde{\epsilon}_L$ , $25 \to 4$

# Experimental Constraints

Ciuchini, Masiero, Paradisi, Silvestrini, Vempati, Vives, hep-ph/0702144

- Flavor-changing neutral currents: $\Delta m_K$, $b \to s\gamma$, $\mu \to e\gamma$ etc.
- Mass insertion approximation $\rightsquigarrow$ constraints on

$$(\delta^d_{\mathrm{RR}})_{ij} := \frac{(\widetilde{m}^2_{d,\mathrm{RR}})_{ij}}{(\widetilde{m}^2_{d,\mathrm{RR}})_{ii}} \quad , \quad \ldots$$

- Depend on $\tan\beta$, sparticle masses

# Experiment vs. Model Predictions

Simple example:

$$\widetilde{\epsilon}_Q = \widetilde{\epsilon}_d = \widetilde{\epsilon}_L = \widetilde{\epsilon}_e = \epsilon_d \approx 0.15 \quad , \quad \widetilde{\epsilon}_u = \frac{\epsilon_u^2}{\epsilon_d} \approx 0.02$$

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| $(\delta^d_{\mathrm{RR}})_{12}$ | $\frac{\widetilde{\epsilon}_d^2\,\epsilon_d}{25} \sim 10^{-4}$ | $9 \cdot 10^{-3}$ |
| $(\delta^d_{\mathrm{LL}})_{12}$ | $\frac{\widetilde{\epsilon}_Q^2\,\epsilon_d}{25} \sim 10^{-4}$ | $1 \cdot 10^{-2}$ |
| $(\delta^d_{\mathrm{LL}})_{23}$ | $\frac{\widetilde{\epsilon}_Q^2}{25} \sim 10^{-3}$ | $2 \cdot 10^{-1}$ |
| $(\delta^e_{\mathrm{LL}})_{12}$ | $\frac{\widetilde{\epsilon}_L^2\,\epsilon_d}{4} \sim 8 \cdot 10^{-4}$ | $6 \cdot 10^{-4}$ |

- Constraints in quarks sector easily satisfied
- Some tension in lepton sector with $\mu \to e\gamma$
- Only weak constraints on $\delta^u$ and $\delta^e_{\mathrm{RR}}$ $\rightsquigarrow$ easily satisfied

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- Only weak constraints on $\delta^u$ and $\delta^e_{RR} \rightsquigarrow$ easily satisfied
- $\delta_{LR}$: situation qualitatively similar, more tension with $\mu \to e\gamma$
  Antusch, King, Malinský, 0708.1282

# Conclusions

- Non-Abelian flavor symmetries can solve flavor problems
- Predictions for SUSY-breaking parameters
- Predictivity depends on messenger sector
- Example with SU(3) symmetry: experimental constraints satisfied
- Stay tuned for more