# Flavorful Supersymmetry

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## LHC is coming!

What signatures do we expect?

What can we learn?

## Approaches

New models, new signatures, …

New techniques, new tools, …

## Done with “old” theories? --- No

Weak scale supersymmetry

… New classes of signatures

in well-motivated, simple setups

# Outline

- Supersymmetry and flavor
- Flavorful SUSY: simple demonstration
- Superparticle spectrum
- LHC signatures -- probing the origin of flavor

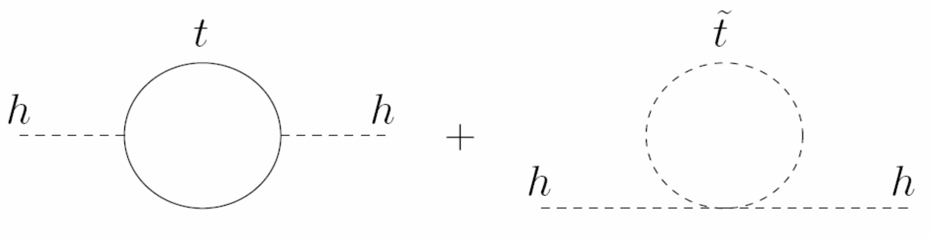
Based on work with
Michele Papucci and Daniel Stolarski

arXiv:0712.2074, arXiv:0802.2582

cf. also Feng, Lester, Nir, Shadmi, arXiv:0712.0674

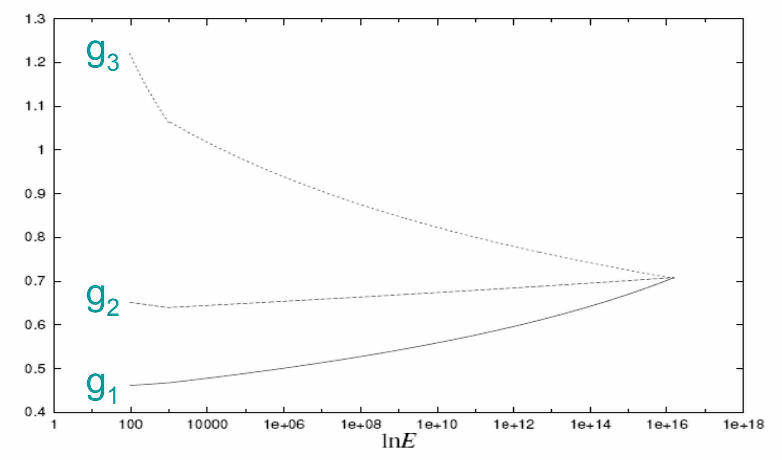
# Weak scale supersymmetry

## Stabilizing the weak scale




$m_h^2 \sim m_{SUSY}^2 \ln\Lambda$

## Gauge coupling unification




$M_{unif} \sim 10^{16}$ GeV

## Candidate for dark matter

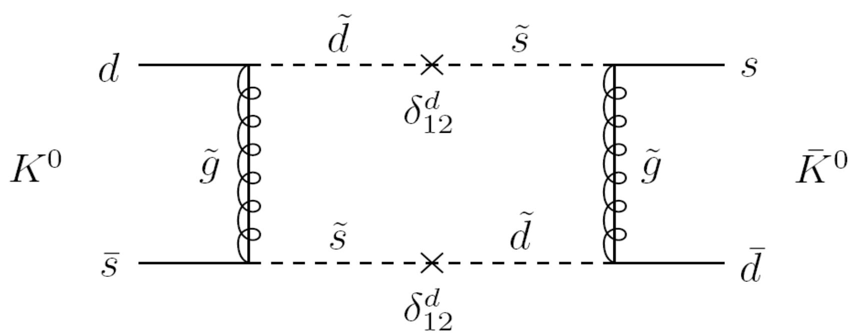
*R* parity $\rightarrow$ stable LSP

# Problem of FCNC and ~~CP~~

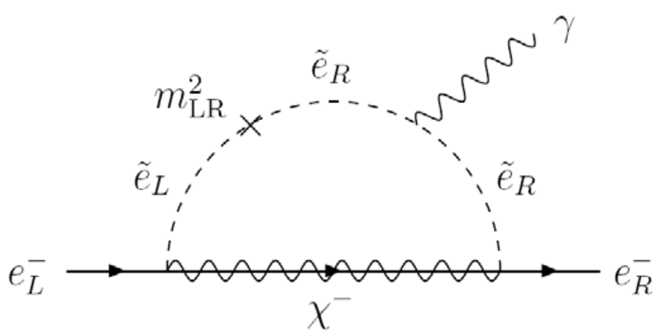
## Most of the SSM parameter region is excluded

$(m_{\tilde{q},\tilde{l}}^2)_{ij} \sim m_{\rm SUSY}^2$, $(a_{u,d,e})_{ij} \sim m_{\rm SUSY}$

FCNC: $K$-$\bar{K}$, $\mu \to e\gamma$, …




EDM for $e^-$, $n$, Hg, …




$m_{\rm SUSY} \gtrsim 1$ TeV or phase $\lesssim 10^{-2}$

A common solution

**Flavor universality:** $(m_{\tilde{q},\tilde{l}}^2)_{ij} \sim \delta_{ij}$ (or « $m_{\rm SUSY}^2$),
$(a_{u,d,e})_{ij} \sim (y_{u,d,e})_{ij}$ (or « $m_{\rm SUSY}$)

(at a scale where these masses are generated)

*e.g.* mSUGRA, gauge mediation, gaugino mediation, …

# Do we understand flavor?

Flavor shows an interesting pattern already in the SM

$$m_t, m_c, m_u \approx v\,(1, \epsilon^2, \epsilon^4)$$
$$m_{b,\tau}, m_{s,\mu}, m_{d,e} \approx v\,(\epsilon^2, \epsilon^3, \epsilon^4)$$

$$V_{\rm CKM} \approx \begin{pmatrix} 1 & \epsilon & \epsilon^2 \\ \epsilon & 1 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix} \quad V_{\rm MNS} \approx \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

No conclusive understanding of its origin yet

Do we need to go to flavor universality?

… Physics responsible for the SM flavor structure
may address the problem of flavor and *CP* in SUSY

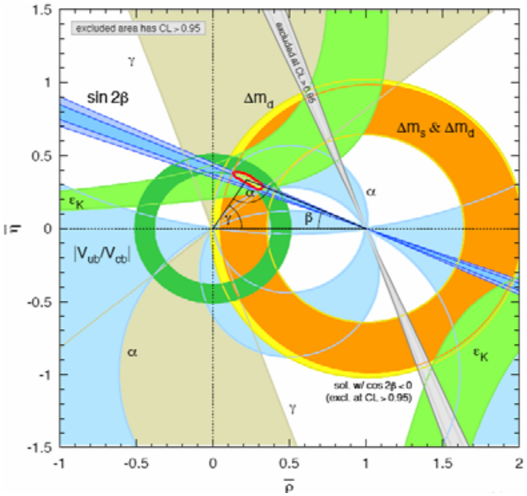
(Earlier) attempts:

- Flavor symmetry: Dine, Leigh, Kagan; Pouliot Seiberg; Pomarol, Tomassini; Barbieri, Hall, Dvali, Raby, Romanino; Nir, Seiberg, Leurer, Grossman, Feng, Shadmi; Kaplan, Schmaltz; King, Ross, Velasco-Sevilla, Vives, Antusch, Milansky; Hall, Murayama, Carone; …
- Higher dimensions / strong dynamics: Kaplan, Tait; Hall, Nomura; Abe, Choi, Jeong, Okumura; Nelson, Strassler; Kobayashi, Terao; …

# Constraints tightened

## Constraints from flavor tightened in the past years

| Observable | Measurement/Bound |
|---|---|
| $\Delta M_K$ | $(0.0 - 5.3) \times 10^{-3}$ GeV |
| $\varepsilon$ | $(2.232 \pm 0.007) \times 10^{-3}$ |
| $\lvert(\varepsilon'/\varepsilon)_{SUSY}\rvert$ | $< 2 \times 10^{-2}$ |
| $\Delta M_{B_d}$ | $(0.507 \pm 0.005)\ \mathrm{ps}^{-1}$ |
| $\sin 2\beta$ | $0.675 \pm 0.026$ |
| $\cos 2\beta$ | $> -0.4$ |
| $\mathrm{BR}(b \to (s+d)\gamma)(E_\gamma > 2.0\ \mathrm{GeV})$ | $(3.06 \pm 0.49) \times 10^{-4}$ |
| $\mathrm{BR}(b \to (s+d)\gamma)(E_\gamma > 1.8\ \mathrm{GeV})$ | $(3.51 \pm 0.43) \times 10^{-4}$ |
| $\mathrm{BR}(b \to s\gamma)(E_\gamma > 1.9\ \mathrm{GeV})$ | $(3.34 \pm 0.18 \pm 0.48) \times 10^{-4}$ |
| $A_{CP}(b \to s\gamma)$ | $0.004 \pm 0.036$ |
| $\mathrm{BR}(b \to s l^+ l^-)(0.04\ \mathrm{GeV} < q^2 < 1\ \mathrm{GeV})$ | $(11.34 \pm 5.96) \times 10^{-7}$ |
| $\mathrm{BR}(b \to s l^+ l^-)(1\ \mathrm{GeV} < q^2 < 6\ \mathrm{GeV})$ | $(15.9 \pm 4.9) \times 10^{-7}$ |
| $\mathrm{BR}(b \to s l^+ l^-)(14.4\ \mathrm{GeV} < q^2 < 25\ \mathrm{GeV})$ | $(4.34 \pm 1.15) \times 10^{-7}$ |
| $A_{CP}(b \to s l^+ l^-)$ | $-0.22 \pm 0.26$ |
| $\Delta M_{B_s}$ | $(17.77 \pm 0.12)\ \mathrm{ps}^{-1}$ |




PDG ('06)

| Process | Bound |
|---|---|
| $\mathrm{BR}(\mu \to e\,\gamma)$ | $1.2 \times 10^{-11}$ |
| $\mathrm{BR}(\mu \to e\,e\,e)$ | $1.1 \times 10^{-12}$ |
| $\mathrm{BR}(\mu \to e$ in Nuclei (Ti)$)$ | $1.1 \times 10^{-12}$ |
| $\mathrm{BR}(\tau \to e\,\gamma)$ | $1.1 \times 10^{-7}$ |
| $\mathrm{BR}(\tau \to e\,e\,e)$ | $2.7 \times 10^{-7}$ |
| $\mathrm{BR}(\tau \to e\,\mu\,\mu)$ | $2. \times 10^{-7}$ |
| $\mathrm{BR}(\tau \to \mu\,\gamma)$ | $6.8 \times 10^{-8}$ |
| $\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$ | $2 \times 10^{-7}$ |
| $\mathrm{BR}(\tau \to \mu\,e\,e)$ | $2.4 \times 10^{-7}$ |

Ciucini, Masiero, Paradisi, Silvestrini, Vempati, Vives ('07)

Need to avoid all these bounds "naturally"

# Not trivial to avoid the bounds

- Simple Froggatt-Nielsen (U(1) flavor symmetry)

$Q_1(q_1)$, $Q_2(q_2)$, $Q_3(q_3)$, $\varepsilon(-1)$ $\longrightarrow$ $\sin\theta_C \sim \varepsilon^{|q_1-q_2|}$

$$m^2_{\tilde{Q}} \propto \begin{pmatrix} O(1) & O(\epsilon^{|q_1-q_2|}) \\ O(\epsilon^{|q_1-q_2|}) & O(1) \end{pmatrix}$$

← too large … need to be < $O(10^{-4})$

1st two generation

- Pure alignment ($\Delta m_Q^2/m_Q^2 \sim 1$)

$$m_{\tilde{Q}}^2 = m_{\tilde{u}_L}^2 = m_{\tilde{d}_L}^2 \xrightarrow{\text{super-CKM basis}} \begin{array}{l} K\text{-}\bar{K}:\ |\sin\theta_{d_L}| < 0.01 \\ D\text{-}\bar{D}:\ |\sin\theta_{u_L}| < 0.1 \end{array}$$

$\Delta m_{\tilde{Q}}^2 = |(m_{\tilde{Q}}^2)_{11} - (m_{\tilde{Q}}^2)_{22}|$

$$\sin\theta_{u_L} - \sin\theta_{d_L} = \sin\theta_C$$

contradiction:
… need approximate degeneracy ~$O(0.1)$

cf. Feng, Lester, Nir, Shadmi

Need "almost" flavor universality?
→ eliminate anything interesting at the LHC?

Need complicated model building?

# SUSY can still be "flavorful"

## Consider the following simple setup (models later):

- SSM arises at some high scale $M_*$ ($\geq M_{\mathrm{unif}}$)
- Every field $\Phi$ carries a suppression factor $\varepsilon_\Phi$ for all (non-gauge) interactions ($\leftrightarrow$ enhancement of $\varepsilon_\Phi^{-2}$ in $Z_\Phi$)

$$W = (y_u)_{ij} Q_i U_j H_u \;\rightarrow\; \tilde{y}\, \epsilon_{Q_i} \epsilon_{U_j} Q_i U_j H_u$$

$$\tilde{y} : \begin{cases} O(1) & \text{for weakly coupled} \\ O(4\pi) & \text{for strongly coupled} \end{cases}$$

($\varepsilon_{H_u}$ omitted for simplicity)

$\varepsilon_\Phi$ are generation dependent

## → The origin of the SM flavor structure

$$\begin{aligned}
m_t, m_c, m_u &\approx \tilde{y}\,\langle H_u\rangle \left(\epsilon_{Q_3}\epsilon_{U_3},\ \epsilon_{Q_2}\epsilon_{U_2},\ \epsilon_{Q_1}\epsilon_{U_1}\right) \\
m_b, m_s, m_d &\approx \tilde{y}\,\langle H_d\rangle \left(\epsilon_{Q_3}\epsilon_{D_3},\ \epsilon_{Q_2}\epsilon_{D_2},\ \epsilon_{Q_1}\epsilon_{D_1}\right) \\
m_\tau, m_\mu, m_e &\approx \tilde{y}\,\langle H_d\rangle \left(\epsilon_{L_3}\epsilon_{E_3},\ \epsilon_{L_2}\epsilon_{E_2},\ \epsilon_{L_1}\epsilon_{E_1}\right) \\
m_{\nu_\tau}, m_{\nu_\mu}, m_{\nu_e} &\approx \frac{\tilde{y}^2\langle H_u\rangle^2}{M_N} \left(\epsilon_{L_3}^2,\ \epsilon_{L_2}^2,\ \epsilon_{L_1}^2\right)
\end{aligned}$$

$$V_{\mathrm{CKM}} \approx \begin{pmatrix} 1 & \epsilon_{Q_1}/\epsilon_{Q_2} & \epsilon_{Q_1}/\epsilon_{Q_3} \\ \epsilon_{Q_1}/\epsilon_{Q_2} & 1 & \epsilon_{Q_2}/\epsilon_{Q_3} \\ \epsilon_{Q_1}/\epsilon_{Q_3} & \epsilon_{Q_2}/\epsilon_{Q_3} & 1 \end{pmatrix} \qquad V_{\mathrm{MNS}} \approx \begin{pmatrix} 1 & \epsilon_{L_1}/\epsilon_{L_2} & \epsilon_{L_1}/\epsilon_{L_3} \\ \epsilon_{L_1}/\epsilon_{L_2} & 1 & \epsilon_{L_2}/\epsilon_{L_3} \\ \epsilon_{L_1}/\epsilon_{L_3} & \epsilon_{L_2}/\epsilon_{L_3} & 1 \end{pmatrix}$$

# SUSY breaking parameters

## Relevant operators:

### Gauginos:

$$\left[\eta_A \frac{X}{M_*} \mathcal{W}^{A\alpha}\mathcal{W}^A_\alpha\right]_{\theta^2} \qquad (A=1,2,3)$$

### Matter:

$$\left[(\kappa_\Phi)_{ij} \frac{X^\dagger X}{M_*^2} \Phi_i^\dagger \Phi_j\right]_{\theta^4}, \qquad \left[(\eta_\Phi)_{ij} \frac{X}{M_*} \Phi_i^\dagger \Phi_j\right]_{\theta^4} \qquad (\Phi=Q,U,D,L,E)$$

$$\left[(\zeta_u)_{ij} \frac{X}{M_*} Q_i U_j H_u\right]_{\theta^2}, \quad \left[(\zeta_d)_{ij} \frac{X}{M_*} Q_i D_j H_d\right]_{\theta^2}, \quad \left[(\zeta_e)_{ij} \frac{X}{M_*} L_i E_j H_d\right]_{\theta^2}$$

### Higgses:

$$\left[\kappa_{H_u} \frac{X^\dagger X}{M_*^2} H_u^\dagger H_u\right]_{\theta^4}, \quad \left[\kappa_{H_d} \frac{X^\dagger X}{M_*^2} H_d^\dagger H_d\right]_{\theta^4}, \quad \left[\eta_{H_u} \frac{X}{M_*} H_u^\dagger H_u\right]_{\theta^4}, \quad \left[\eta_{H_d} \frac{X}{M_*} H_d^\dagger H_d\right]_{\theta^4},$$

$$\left[\kappa_\mu \frac{X^\dagger}{M_*} H_u H_d\right]_{\theta^4}, \qquad \left[\kappa_b \frac{X^\dagger X}{M_*^2} H_u H_d\right]_{\theta^4}$$

## Scaling:

$$(\kappa_\Phi)_{ij} \approx \tilde{\kappa}_\Phi\, \epsilon_{\Phi_i}\epsilon_{\Phi_j}, \qquad (\eta_\Phi)_{ij} \approx \tilde{\eta}_\Phi\, \epsilon_{\Phi_i}\epsilon_{\Phi_j},$$

$$(\zeta_u)_{ij} \approx \tilde{\zeta}\, \epsilon_{Q_i}\epsilon_{U_j}, \quad (\zeta_d)_{ij} \approx \tilde{\zeta}\, \epsilon_{Q_i}\epsilon_{D_j}, \quad (\zeta_e)_{ij} \approx \tilde{\zeta}\, \epsilon_{L_i}\epsilon_{E_j}$$

Note: *O(1)* coefficients omitted, *e.g.* $(\kappa_\Phi)_{ij} \not\propto (\eta_\Phi)_{ij}$

# Soft ~~SUSY~~ parameters at $M_*$

$$M_A \approx \eta_A M_{\rm SUSY}, \qquad \mu \approx \kappa_\mu M_{\rm SUSY}^\dagger, \qquad b \approx (\kappa_b + \kappa_\mu \eta_H)|M_{\rm SUSY}|^2,$$

$$m_{H_u}^2 \approx m_{H_d}^2 \approx (\kappa_H + |\eta_H|^2)|M_{\rm SUSY}|^2, \qquad (m_\Phi^2)_{ij} \approx \{(\kappa_\Phi)_{ij} + (\eta_\Phi^\dagger \eta_\Phi)_{ij}\}|M_{\rm SUSY}|^2,$$

$$(a_u)_{ij} \approx \{(y_u)_{kj}(\eta_Q)_{ki} + (y_u)_{ik}(\eta_U)_{kj} + (y_u)_{ij}\eta_H\}M_{\rm SUSY} + \tilde\zeta\, \epsilon_{Q_i}\epsilon_{U_j} M_{\rm SUSY},$$

$$(a_d)_{ij} \approx \{(y_d)_{kj}(\eta_Q)_{ki} + (y_d)_{ik}(\eta_D)_{kj} + (y_d)_{ij}\eta_H\}M_{\rm SUSY} + \tilde\zeta\, \epsilon_{Q_i}\epsilon_{D_j} M_{\rm SUSY},$$

$$(a_e)_{ij} \approx \{(y_e)_{kj}(\eta_L)_{ki} + (y_e)_{ik}(\eta_E)_{kj} + (y_e)_{ij}\eta_H\}M_{\rm SUSY} + \tilde\zeta\, \epsilon_{L_i}\epsilon_{E_j} M_{\rm SUSY}$$

↖ : flavor nonuniversal

$M_{\rm SUSY} = F_X/M_*$

(*O(1)* coefficients omitted)

We have set $\kappa_{Hu} \sim \kappa_{Hd} \sim \kappa_H$ and $\eta_{Hu} \sim \eta_{Hd} \sim \eta_H$ for simplicity

*e.g.*

$$m_E^2 \approx \begin{pmatrix} \epsilon_{E_1}^2 & \epsilon_{E_1}\epsilon_{E_2} & \epsilon_{E_1}\epsilon_{E_3} \\ \epsilon_{E_1}\epsilon_{E_2} & \epsilon_{E_2}^2 & \epsilon_{E_2}\epsilon_{E_3} \\ \epsilon_{E_1}\epsilon_{E_3} & \epsilon_{E_2}\epsilon_{E_3} & \epsilon_{E_3}^2 \end{pmatrix} |M_{\rm SUSY}|^2$$

# The Yukawa couplings

$$(y_u)_{ij} \approx \tilde y\, \epsilon_{Q_i}\epsilon_{U_j}, \quad (y_d)_{ij} \approx \tilde y\, \epsilon_{Q_i}\epsilon_{D_j}, \quad (y_e)_{ij} \approx \tilde y\, \epsilon_{L_i}\epsilon_{E_j}$$

Flavor violation correlated with the Yukawa structure

# Low energy ~~flavor~~ and ~~CP~~

Superparticle masses obtain flavor universal pieces
by RGE, possible additional, *e.g.* GMSB, contributions…

$$(m_\Phi^2)_{ij} \to \begin{cases} (m_\Phi^2)_{ij} + \lambda_{\tilde{q}}^2\,|M_{\rm SUSY}|^2\delta_{ij} & \text{for } \Phi = Q, U, D \\ (m_\Phi^2)_{ij} + \lambda_{\tilde{l}}^2\,|M_{\rm SUSY}|^2\delta_{ij} & \text{for } \Phi = L, E \end{cases}$$

… model-indep. parameterization

(Other RG effects can be absorbed by redef. of $\eta_A$, $\eta_H$ and $\tan\beta$)

## Mass insertion parameters

$$(\delta_{ij}^f)_{XY} \equiv \frac{(\mathcal{M}^2_{\tilde{f},XY})_{ij}}{\mathcal{M}^2_{\tilde{f},\rm ave}}$$

($X,Y = L,R$ ; $f = u,d,e$)

are given by

$$(\delta_{ij}^u)_{LL} \approx \frac{1}{\lambda_{\tilde{q}}^2}\Big(\tilde{\kappa}_\Phi + |\tilde{\eta}_\Phi|^2\epsilon_{Q_3}^2\Big)\,\epsilon_{Q_i}\epsilon_{Q_j}, \quad (\delta_{ij}^u)_{RR} \approx \frac{1}{\lambda_{\tilde{q}}^2}\Big(\tilde{\kappa}_\Phi + |\tilde{\eta}_\Phi|^2\epsilon_{U_3}^2\Big)\,\epsilon_{U_i}\epsilon_{U_j},$$

$$(\delta_{ij}^u)_{LR} = (\delta_{ji}^u)_{RL}^* \approx \frac{1}{\lambda_{\tilde{q}}^2}\Big\{\tilde{y}\,\tilde{\eta}_\Phi(\epsilon_{Q_j}^2 + \epsilon_{U_i}^2) + \tilde{\zeta}\Big\}\,\epsilon_{Q_i}\epsilon_{U_j}\frac{v\sin\beta}{M_{\rm SUSY}}$$

and similarly for the d-type $\tilde{q}$ and charged $\tilde{l}$ sectors (and $\tilde{\nu}$ sector for LL)

# Choices of $\varepsilon_\Phi$

Factors $\varepsilon_\Phi$ are chosen to reproduce flavor of *q* and *l*

Here we take

$$\begin{aligned} \epsilon_{Q_1} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_q \boxed{\epsilon^2} & \epsilon_{U_1} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_q^{-1}\boxed{\epsilon^2} & \epsilon_{D_1} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_q^{-1}\alpha_\beta\boxed{\epsilon} \\ \epsilon_{Q_2} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_q \boxed{\epsilon} & \epsilon_{U_2} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_q^{-1}\boxed{\epsilon} & \epsilon_{D_2} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_q^{-1}\alpha_\beta\boxed{\epsilon} \\ \epsilon_{Q_3} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_q & \epsilon_{U_3} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_q^{-1} & \epsilon_{D_3} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_q^{-1}\alpha_\beta\boxed{\epsilon} \end{aligned}$$

$$\begin{aligned} \epsilon_{L_1} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_l \boxed{\epsilon} & \epsilon_{E_1} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_l^{-1}\alpha_\beta\boxed{\epsilon^2} \\ \epsilon_{L_2} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_l \boxed{\epsilon} & \epsilon_{E_2} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_l^{-1}\alpha_\beta\boxed{\epsilon} \\ \epsilon_{L_3} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_l \boxed{\epsilon} & \epsilon_{E_3} &\approx \tilde{y}^{-\frac{1}{2}}\alpha_l^{-1}\alpha_\beta \end{aligned}$$

with $\tan\beta \approx \alpha_\beta\,\epsilon^{-1}$

where $\varepsilon \sim O(0.05 - 0.1)$

This gives

$$\begin{aligned} m_t, m_c, m_u &\approx v\,(1, \epsilon^2, \epsilon^4) \\ m_{b,\tau}, m_{s,\mu}, m_{d,e} &\approx v\,(\epsilon^2, \epsilon^3, \epsilon^4) \\ m_{\nu_\tau}, m_{\nu_\mu}, m_{\nu_e} &\approx \frac{v^2}{M_N'}(1,1,1) \end{aligned}$$

$$V_{\rm CKM} \approx \begin{pmatrix} 1 & \epsilon & \epsilon^2 \\ \epsilon & 1 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix} \quad V_{\rm MNS} \approx \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

$\alpha_q$, $\alpha_l$, $\alpha_\beta \sim O(1)$: freedoms unfixed by the *q* and *l* data

# Constraints satisfied in wide regions

## Relevant constraints:

Quark sector:

*K*-$\bar{K}$, *D*-$\bar{D}$, *B*-$\bar{B}$, sin2β, *b*→*s*γ

$$\sqrt{|\mathrm{Re}(\delta^d_{12})^2_{LL/RR}|} \lesssim (10^{-2}\text{–}10^{-1}), \quad \sqrt{|\mathrm{Re}(\delta^d_{12})^2_{LR/RL}|} \lesssim (10^{-3}\text{–}10^{-2}), \quad \sqrt{|\mathrm{Re}(\delta^d_{12})_{LL}(\delta^d_{12})_{RR}|} \lesssim 10^{-3},$$

$$\sqrt{|\mathrm{Im}(\delta^d_{12})^2_{LL/RR}|} \lesssim (10^{-3}\text{–}10^{-2}), \quad \sqrt{|\mathrm{Im}(\delta^d_{12})^2_{LR/RL}|} \lesssim (10^{-4}\text{–}10^{-3}), \quad \sqrt{|\mathrm{Im}(\delta^d_{12})_{LL}(\delta^d_{12})_{RR}|} \lesssim 10^{-4},$$

$$|(\delta^u_{12})_{LL/RR}| \lesssim (10^{-2}\text{–}10^{-1}), \quad |(\delta^u_{12})_{LR/RL}| \lesssim 10^{-2}, \quad |(\delta^u_{12})_{LL}| = |(\delta^u_{12})_{RR}| \lesssim (10^{-3}\text{–}10^{-2}),$$

$$|(\delta^d_{13})_{LL/RR}| \lesssim (0.1\text{–}1), \quad |(\delta^d_{13})_{LR/RL}| \lesssim (10^{-2}\text{–}10^{-1}), \quad |(\delta^d_{13})_{LL}| = |(\delta^d_{13})_{RR}| \lesssim 10^{-2},$$

$$|(\delta^d_{23})_{LR/RL}| \lesssim 10^{-2}$$

Lepton sector:

μ→*e*γ

$$|(\delta^e_{12})_{LL}| \lesssim (10^{-4}\text{–}10^{-3}), \quad |(\delta^e_{12})_{LR/RL}| \lesssim (10^{-6}\text{–}10^{-5})$$

$m_{\tilde{q}}$ ~ 500 GeV
$m_{\tilde{l}}$ ~ 200 GeV

Flavor conserving:

*n* and *e* EDM

$$|\mathrm{Im}(\delta^u_{11})_{LR}| \lesssim 10^{-6}, \quad |\mathrm{Im}(\delta^d_{11})_{LR}| \lesssim 10^{-6}, \quad |\mathrm{Im}(\delta^e_{11})_{LR}| \lesssim 10^{-7}$$

*e.g.* Gabbiani *et al* ('96)
Masiero *et al* ('07)

## Bounds are strong for $W = (X/M_*)$(Yukawa) operators

For $\tilde{\zeta}$ ~ 1

$M_{\rm SUSY}$ > 5 TeV for $\tilde{y}$ ~ 1

$M_{\rm SUSY}$ > 1.5 TeV for $\tilde{y}$ ~ 4π

from μ→*e*γ and *e* EDM

$\tilde{\zeta}$ can be small: technically natural, (anomalous) symmetry, …

## For $\tilde{\zeta} \ll 1$ and others ~ $O(1)$

weakly coupled ($\tilde{y}$ ~ 1):

$$0.2 \lesssim \alpha_q \lesssim 3, \quad \frac{\alpha_q}{\alpha_\beta} \gtrsim 0.5, \quad \alpha_l \lesssim 0.3, \quad \frac{\alpha_l}{\alpha_\beta} \gtrsim 0.2$$

strongly coupled ($\tilde{y}$ ~ $4\pi$):

$$0.05 \lesssim \alpha_q \lesssim 10, \quad \frac{\alpha_q}{\alpha_\beta} \gtrsim 0.1, \quad \alpha_l \lesssim 1, \quad \frac{\alpha_l}{\alpha_\beta} \gtrsim 0.04$$

for $m_{\tilde{q}}$ = 500 GeV and $m_{\tilde{l}}$ = 200 GeV

assumed Higgs sector does not have $\not{CP}$
*e.g.* arg($b$) = arg($\mu$) or $|b| \ll |\mu|^2$

A wide parameter region is open
even for light superparticles

Supersymmetry can very well be “flavorful”
--- and can lead to “drastic” effects at the LHC

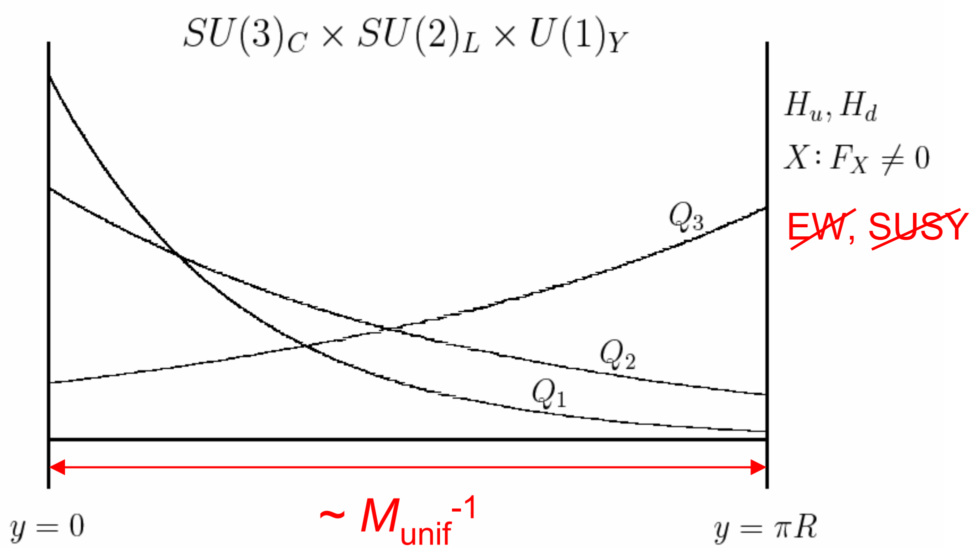
# Explicit Realizations

## A variety of ways of obtaining the pattern considered

higher dimensions, strong dynamics, flavor symmetry, …

Example:

- Spacetime enlarged to 5D
- Higgs and ~~SUSY~~ fields localized on the same brane
- Yukawa and ~~SUSY~~ both controlled by wavef. at the brane $\rightarrow$ $\varepsilon_\Phi$




Extensions:

- Dangerous $W = (X/M_*)$(Yukawa) ops. killed by $U(1)_{PQ}$
- Gauge med. (naturally ~ grav med.) provides universal contributions
- Combined with grand unification
- …

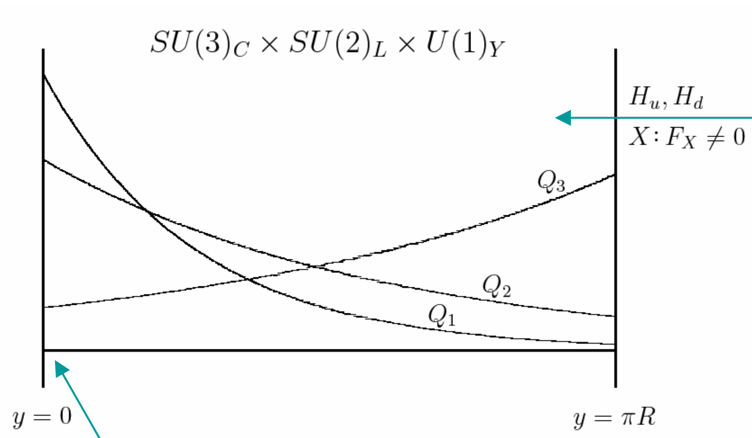
# It is not entirely trivial

At the leading order,

*e.g.*

$$m^2_{\tilde{Q}} \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix} M^2_{\rm SUSY}, \quad m^2_{\tilde{U}} \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix} M^2_{\rm SUSY}, \quad y_u \approx \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

# There are other flavor violating contributions




bulk gauge loop (~~flavor~~)

brane kinetic term (~~flavor~~) ⟹ canonical normalization

Kähler 4-point terms ⟹ radiative corrections (~~flavor~~)

# All these corrections under control

… can reproduce the patterns discussed

# Superparticle Spectrum

Nontrivial flavor structure at TeV … focus on RH $\tilde{e}_i$

If no intrinsic flavor violation (flavor universal), then

$$m_E^2 = \begin{pmatrix} m_{\tilde{e}}^2 - I_e & 0 & 0 \\ 0 & m_{\tilde{e}}^2 - I_\mu & 0 \\ 0 & 0 & m_{\tilde{e}}^2 - I_\tau \end{pmatrix}$$

$I_e : I_\mu : I_\tau \sim (y_e)_{11}^2 : (y_\mu)_{22}^2 : (y_\tau)_{33}^2$

at ~ TeV in the basis $(y_e)_{ij} = (y_e)_{ii}\delta_{ij}$

(i) interaction eigenstates = mass eigenstates

(ii) mass ordering of $\tilde{e}_i$ anticorrelated with that of $e_i$ ($I_{e,\mu,\tau} > 0$)

These are not true for the present case:

$$m_E^2(M_*) \approx \begin{pmatrix} \epsilon_{E_1}^2 & \epsilon_{E_1}\epsilon_{E_2} & \epsilon_{E_1}\epsilon_{E_3} \\ \epsilon_{E_1}\epsilon_{E_2} & \epsilon_{E_2}^2 & \epsilon_{E_2}\epsilon_{E_3} \\ \epsilon_{E_1}\epsilon_{E_3} & \epsilon_{E_2}\epsilon_{E_3} & \epsilon_{E_3}^2 \end{pmatrix} |M_{\rm SUSY}|^2$$

# Flavorful effects propagate to the weak scale

$$m_E^2 \approx \begin{pmatrix} m_{\tilde{e}}^2 - K_e & 0 & 0 \\ 0 & m_{\tilde{e}}^2 - K_\mu & 0 \\ 0 & 0 & m_{\tilde{e}}^2 - K_\tau \end{pmatrix} + \begin{pmatrix} \epsilon_{E_1}^2 & \epsilon_{E_1}\epsilon_{E_2} & \epsilon_{E_1}\epsilon_{E_3} \\ \epsilon_{E_1}\epsilon_{E_2} & \epsilon_{E_2}^2 & \epsilon_{E_2}\epsilon_{E_3} \\ \epsilon_{E_1}\epsilon_{E_3} & \epsilon_{E_2}\epsilon_{E_3} & \epsilon_{E_3}^2 \end{pmatrix} |M_{\rm SUSY}|^2$$

flavor universal    RGE effect    intrinsic flavor violation

$K_e : K_\mu : K_\tau \sim (y_e)_{11}{}^2 : (y_\mu)_{22}{}^2 : (y_\tau)_{33}{}^2$ for $(a_e)_{ij} \sim (y_e)_{ij}$

For the present parameterization

$$m_E^2 \approx \begin{pmatrix} \xi_{\tilde{e}}^2 - \tilde{y}^2\epsilon_{L_1}^2\epsilon_{E_1}^2 + \epsilon_{E_1}^2 & \epsilon_{E_1}\epsilon_{E_2} & \epsilon_{E_1}\epsilon_{E_3} \\ \epsilon_{E_1}\epsilon_{E_2} & \xi_{\tilde{e}}^2 - \tilde{y}^2\epsilon_{L_2}^2\epsilon_{E_2}^2 + \epsilon_{E_2}^2 & \epsilon_{E_2}\epsilon_{E_3} \\ \epsilon_{E_1}\epsilon_{E_3} & \epsilon_{E_2}\epsilon_{E_3} & \xi_{\tilde{e}}^2 - \tilde{y}^2\epsilon_{L_3}^2\epsilon_{E_3}^2 + \epsilon_{E_3}^2 \end{pmatrix} |M_{\rm SUSY}|^2$$

flavor universal    negative    either sign

## (i) interaction eigenstates ≠ mass eigenstates

## (ii) mass ordering of $\tilde{e}_i$ not strictly related with that of $e_i$

Any of $\tilde{e}_R$, $\tilde{\mu}_R$, $\tilde{\tau}_R$ can be the lightest --- “large” effect

Mass splitting much larger (*e.g.* $O(1)$ splitting for $\tilde{\tau}_R$ for $\varepsilon_{E_3} \sim O(1)$)

# LSP/NLSP

Phenomenology at colliders depends strongly on the LSP/NLSP species

Most likely

Lightest sfermion → one of $\tilde{e}_{R,i} \equiv \tilde{l}_R$

Lightest ino → $\tilde{B}$

Gravitino: $\tilde{G}$

Mass ordering between $\tilde{l}_R$, $\tilde{B}$, $\tilde{G}$ model dependent

(*e.g.* gaugino mass generation, universal contributions, …)

The case with a single scale $M_*$

$$m_{3/2} \simeq \frac{F_X}{\sqrt{3}M_{\rm Pl}} \qquad m_{\lambda,\tilde{q},\tilde{l}} \approx \frac{F_X}{M_*} \quad \xrightarrow[M_{\rm unif} \lesssim M_* \lesssim M_{\rm Pl}]{} \quad \frac{M_{\rm unif}}{M_{\rm Pl}} m_{\lambda,\tilde{q},\tilde{l}} \lesssim m_{3/2} \lesssim m_{\lambda,\tilde{q},\tilde{l}}$$

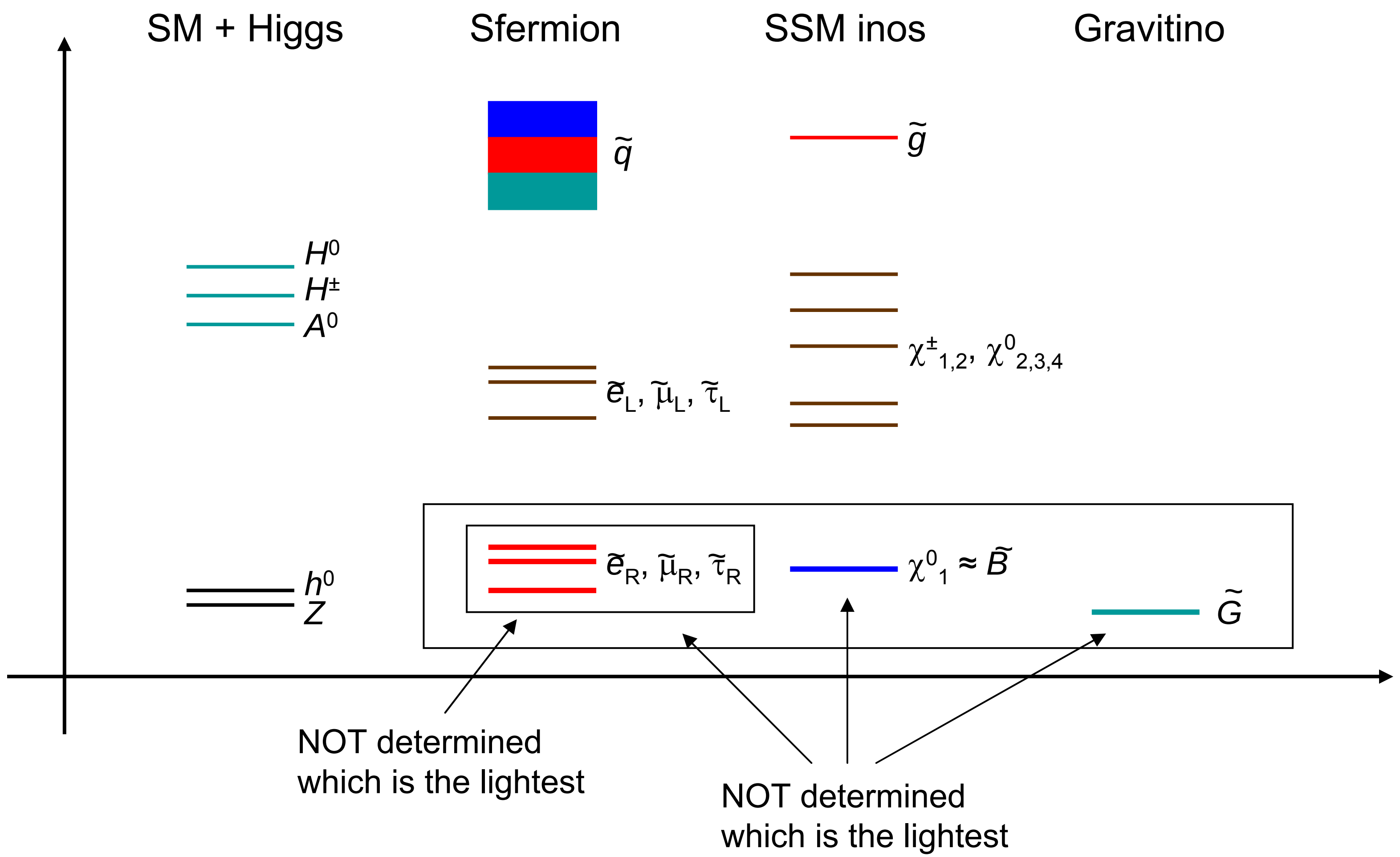
($\frac{M_{\rm unif}}{M_{\rm Pl}}$ ~ $10^{-2}$)

$m_{3/2}$ falls in the same range for many other cases, too

Models with gauge med. ~ grav med. with $M_{\rm mess}$ ~ $M_{\rm unif}$, …

# Overall pattern

## Typical superparticle spectrum



# LHC Signatures

## Rich signatures for general "flavorful" SUSY

Classify into 3 cases:

**(a) $m_{\tilde{G}} < m_{\tilde{l}_R} < m_{\tilde{B}}$**

NLSP is $\tilde{l}_R$ decaying into $\tilde{G}$ with

$$\tau_{\tilde{l}_R} \simeq \frac{48\pi\, m_{\tilde{G}}^2 M_{\rm Pl}^2}{m_{\tilde{l}_R}^5} \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{l}_R}^2}\right)^{-4}$$

which for $10^{-2} m_{\lambda,\tilde{q},\tilde{l}} < m_{3/2} < m_{\lambda,\tilde{q},\tilde{l}}$ is longer than ~ 100 sec

- stable charged tracks inside the main detector
- late decay of $\tilde{l}_R$ in a stopper detector

**(b) $m_{\tilde{l}_R} < m_{\tilde{B}}, m_{\tilde{G}}$**

$\tilde{l}_R$ is the LSP → stable charged tracks (cosmological problem?)

**(c) $m_{\tilde{B}}, m_{\tilde{G}} < m_{\tilde{l}_R}$ or $m_{\tilde{B}} < m_{\tilde{l}_R} < m_{\tilde{G}}$**

$\tilde{l}_R$ decays into $\tilde{B} + l$ inside the main detector

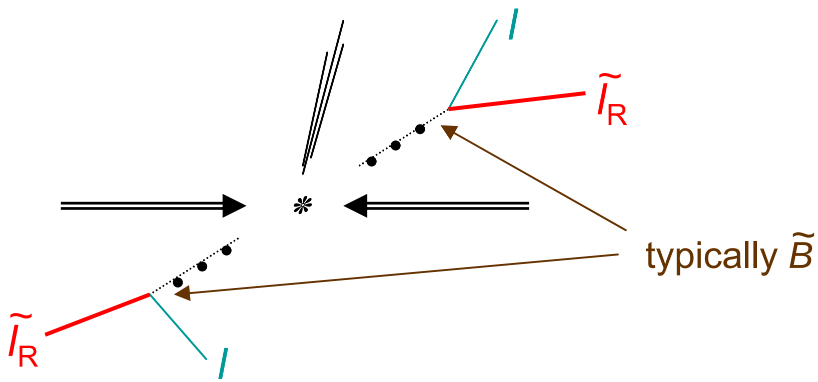
- missing energy events

# Case (a): Long-lived $\tilde{l}_R$

## Stable $\tilde{l}_R$ (in fact, both cases (a) and (b))

- Mass measured very precisely ≈ $O$(0.1-1%) (for $0.6 < \beta < 0.8$)
- Events fully reconstructed

## Flavor measurement




2 isolated leptons + 2 NLSP's (+ jets) ⟶ flavor measurement

Most of leptons have the same flavor as the NLSP, sometimes differ

Measurements of the the NNLSP flavor and
the NLSP-NNLSP mass difference also seem possible

… Physics that can be
done at an early stage

2 hard leptons + 2 (relatively) soft leptons + 2 NLSP's

# Late decay of long-lived $\tilde{l}_R$

## Late decay of $\tilde{l}_R$ may be measured

- NLSP stopped within the detector for $\beta < 0.4$
  - Look for particles that do not point back to the interaction area
- NLSP stopped in the rock just outside the detector
  - Some of the decay products will re-enter the detector

    (low statistics, cosmic neutrino backgroud, …)
  - Use tracker to determine where the NLSP stopped

    ⟶ extract pieces of the rock and study the decay in a quiet environment

De Roeck, Ellis, Giannotti, Moortgat, Olive, Pape

- Build a large stopper detector outside the main detector
  - NLSP's trapped
  - Decay products measured

Hamaguchi, Kuno, Nakaya, Nojiri; Feng, Smith

# Physics at a stopper detector

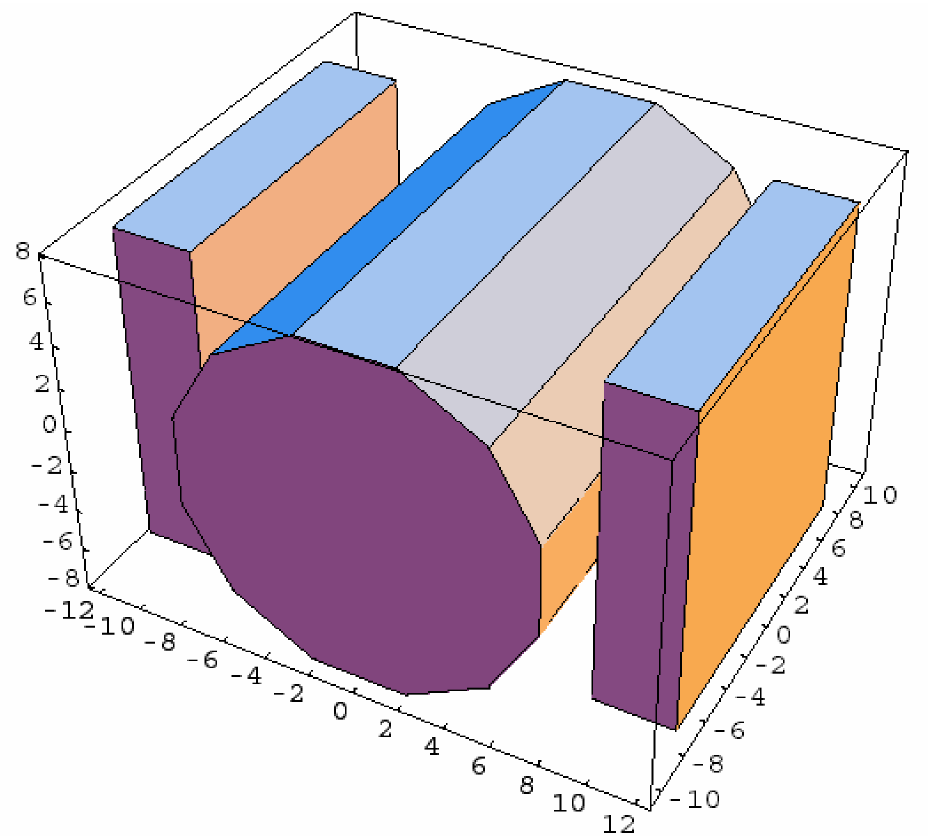
A stopper detector can
measure decay products

- Conventional scenario
  only consider a $\tilde{\tau}_R$ NLSP

- NLSP in flavorful SUSY
  could be $\tilde{e}_R$ or $\tilde{\mu}_R$

  → spectacular
  monochromatic *e* or $\mu$

  need to include a magnetic field for $\mu$




Hamaguchi, Nojiri, de Roeck, hep-ph/0612060

- make it easy to measure
  - the mass of $\tilde{G}$
  - the lifetime of NLSP

  → test supergravity relations Buchmuller, Hamaguchi, Ratz, Yanagida

- Flavor mixing angles can be measured … sensitivity of $O(10^{-2})$

cf. Hamaguchi, Ibarra

# Case (c): Neutralino (N)LSP

$\chi^0_1$ lighter than $\tilde{l}_R$: case (c)

All $\tilde{e}_{R,i}$ decay promptly $\rightarrow$ missing energy

Intrinsic flavor violation still measured

- $M_{T2}$ in Drell-Yan production
  - issue of statistics, …
- Multiple edges in flavor-tagged $M_{ll}$ distribution
  - need sizable flavor violating couplings
  - $\tilde{e}_{R,i}$ must be produced by $\chi^0_2$ decay … small Br
  - $\tilde{e}_{L,i}$ flavor structure can be studied if $m_{\tilde{e}_{L,i}} < m_{\chi^0_2}$

… warrants further study

cf. Bartl, Hidaka, Hohenwarter-Sodek, Kernreiter, Majerotto, Prpd; Bayatian *et al* …

In all cases (a,b,c), detailed study of $\tilde{q}$, $\tilde{l}$ masses

→ probing the origin of the flavor structure

# Conclusions

- Despite stringent constraints from low energy, supersymmetry may well be "flavorful"

  Simple scaling is enough to satisfy essentially all the low energy flavor and *CP* constraints

  … can be realized explicitly

- Rich phenomenology at colliders

  Both cases can be studied at the LHC for stable charged tracks and missing energy

  - Events fully reconstructed → precision (flavor) measurement
  - Rich physics at a stopper detector

- Direct window to the mechanism of flavor
- Better to be prepared for the possibility

*e.g.* software, analysis, detector design, …