# The String Origin of Flavor Violation

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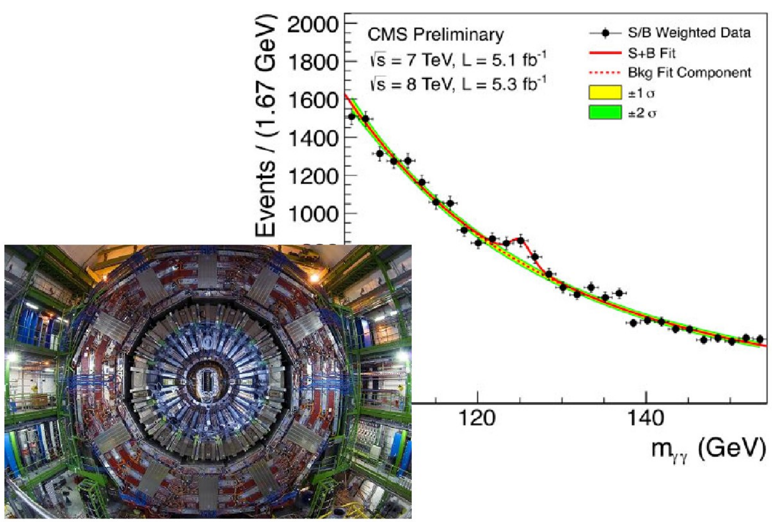
# SUSY after the Higgs discovery

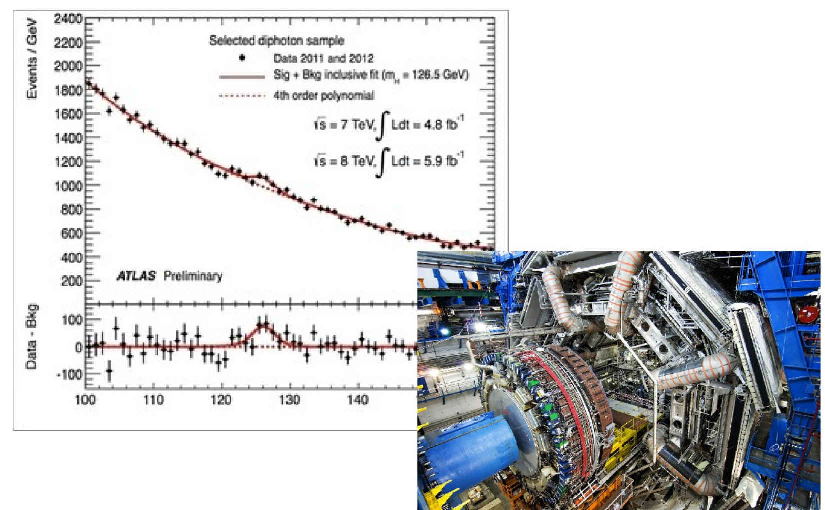
One of the most appealing features of SUSY is that the Higgs mass is related to the SUSY particle spectrum radiatively

$$m_{h^0}^2 \lesssim m_Z^2 \cos^2(2\beta) + \delta_{\text{loops}}$$

$$\delta_{\text{loops}} \sim 0.1\, m_t^2 \ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

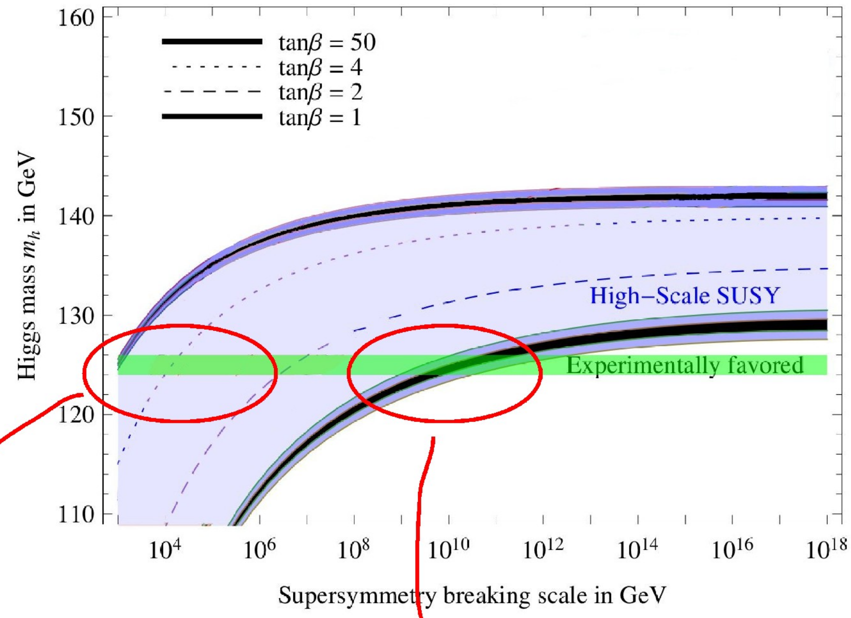
Knowing the Higgs mass thus gives us a lot of indirect information about the SUSY particle spectrum



# SUSY after the Higgs discovery

*(fig. adapted from Degrassi et al. 1205.6497)*




*See Hebecker's talk...*

$\tan\beta \gg 1$
favored by GUT paradigm

$\tan\beta \simeq 1$
large fine-tuning

Consistent with LHC direct searches: colored SUSY particles > 1 TeV

# SUSY and Flavor

- But SUSY has also big theoretical drawbacks: huge flavor problem

  (MSSM ~ 120 extra param.)

- In 4d QFT this is usually solved by hand. E.g. CMSSM: 5 param. out of ~120

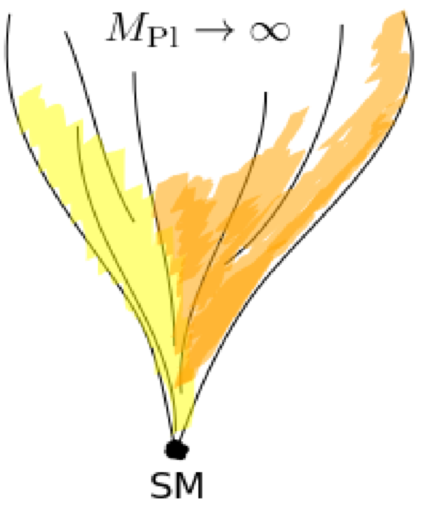
- At generic points of the parameter space, SUSY particles can contribute to FCNC processes

  (e.g. neutral meson mixing and CP-violation, $\Delta L \neq 0$ transitions...)

String Theory provides a microscopic framework for flavor and SUSY-breaking... but trades the flavor problem for a huge landscape of vacua

Can we make statements about flavor for large classes of String Theory vacua?

# Local models




Local model building:

1) visible sector localized in the extra dim.

2) gravity can be decoupled while keeping gauge interactions on

Pros: Allows quite generic predictions in terms of few parameters that encode the local geometry.

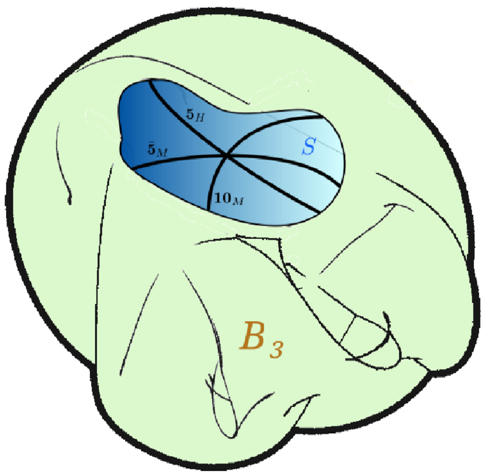
Cons: 1.- There can be strong constraints on the local geometry coming from its global embedding [Ludeling, Nilles, Stephan '11][Cicoli et al. '13]

2.- If LO vanishes, global effects are particularly important

# Local models

Local IIB/F-theory SU(5) GUTs: SU(5) gauge and matter inside 7-branes that wrap a 4-cycle $S$ in the 6d internal space $B_3$.

[Beasly, Heckman, Vafa '08], [Donagi, Wijholt '08]




$$\alpha_{\rm GUT}^{-1} = \frac{{\rm Vol}(S)}{8\pi^4 g_s \alpha'^2}$$

$$M_{\rm Pl} = \frac{\sqrt{2\,{\rm Vol}(B_3)}}{4\pi^3 g_s \alpha'^2}$$

$$M_{\rm GUT} = \left(\frac{2\alpha_{\rm GUT}}{\alpha'^2 g_s}\right)^{1/4}$$

In local models we can expand the effective action in powers of

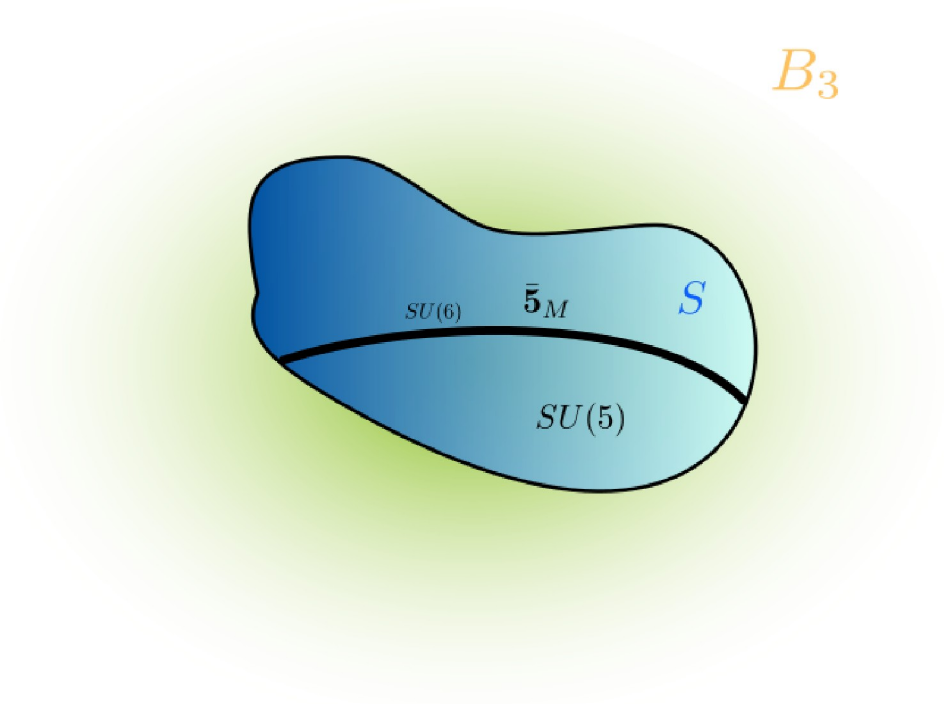
$$\varrho \equiv \frac{{\rm Vol}(S)^{1/4}}{{\rm Vol}(B_3)^{1/2}} = \left(\frac{\sqrt{2}\,M_{\rm GUT}}{\alpha_{\rm GUT}\,M_{\rm Pl}}\right)^{1/3} \ll 1$$

Perturbative for: $M_{\rm GUT} \ll 3.5 \times 10^{17}\ {\rm GeV}$

# Local models

To leading order in such expansion 7-branes well-described by twisted 8d SYM compactified on $S$ [Beasly, Heckman, Vafa '08], [Donagi, Wijholt '08]

$$\mathcal{L}_{\rm SYM} = {\rm Tr}\left(D_a \Phi D^a \bar{\Phi} - \frac{1}{4} F_{ab} F^{ab}\right)$$




$$SU(6) \to SU(5) \times U(1)$$

$$\mathbf{35} \to \mathbf{24_0} \oplus \mathbf{1_0} \oplus \mathbf{5_{-1}} \oplus \bar{\mathbf{5}}_\mathbf{1}$$

$$\boxed{\langle \Phi \rangle = \frac{m}{2} x Q}$$

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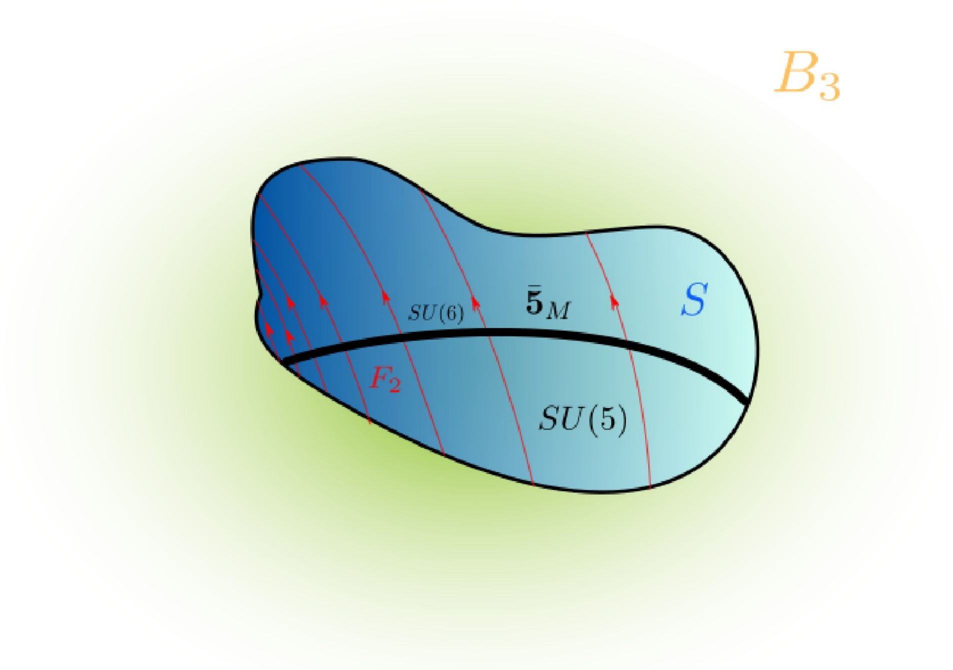


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$$\langle \Phi \rangle = \frac{m}{2} x Q$$

4d chirality requires magnetization:

$$\langle F_2 \rangle = iM(dx \wedge d\bar{x} - dy \wedge d\bar{y})Q$$

Such local background preserves *N* = 1 SUSY in 4d

# Local models

4d theory from Kaluza-Klein reduction of the 8d theory:

$$\Psi_{8\mathrm{d}} = \sum_i \phi^{(i)}_{4\mathrm{d}}(x_\mu) \times \psi^{(i)}_{\mathrm{int}}(z)$$

Internal wavefunctions satisfy Hamiltonian system of 3 quantum harmonic oscillators with shifted vacuum energy.

$$\mathbb{H}\,\psi^{(i)}_{\mathrm{int}}(z,\bar{z}) \;=\; m^2_{\phi^{(i)}}\,\psi^{(i)}_{\mathrm{int}}(z,\bar{z}) \qquad \psi^{(i)}_{\mathrm{int}}(z,\bar{z}) = \begin{pmatrix} a^{(i)}_{\bar{x}} \\ a^{(i)}_{\bar{y}} \\ \varphi^{(i)} \end{pmatrix}$$

Wavefunctions of charged 4d massless scalars:

$$\psi^{(0)}_{\bar{\mathbf{5}}_i}(z,\bar{z}) \;\propto\; \begin{pmatrix} M-\lambda \\ 0 \\ m \end{pmatrix} \psi^{+}_i(z,\bar{z}) \qquad \psi^{\pm}_i(z,\bar{z}) \;\propto\; f_i(y)\exp\left[-\frac{\lambda}{2}|x|^2 \pm \frac{M}{2}|y|^2\right]$$

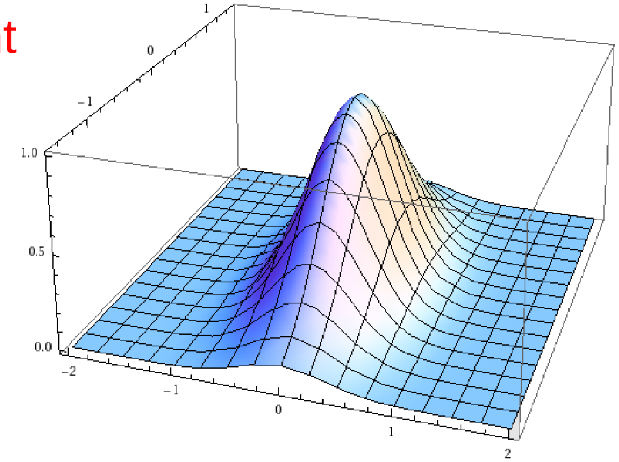
$$\psi^{(0)}_{\mathbf{5}_i}(z,\bar{z})^{\dagger} \;\propto\; \begin{pmatrix} M+\lambda \\ 0 \\ m \end{pmatrix} \psi^{-}_i(z,\bar{z}) \qquad \lambda \equiv \sqrt{M^2+m^2}$$

# Local models

Wavefunctions localized in *S*. Can expand the background around localization point

$$M < 0 \; : \quad \bar{\mathbf{5}} \;\; \text{normalizable}$$

$$M > 0 \; : \quad \mathbf{5} \;\; \text{normalizable}$$




$$\psi^{(0)}_{\bar{\mathbf{5}}_i}(z,\bar{z}) \;\propto\; \begin{pmatrix} M-\lambda \\ 0 \\ m \end{pmatrix} \psi_i^{+}(z,\bar{z})$$

$$\psi^{(0)}_{\mathbf{5}_i}(z,\bar{z})^{\dagger} \;\propto\; \begin{pmatrix} M+\lambda \\ 0 \\ m \end{pmatrix} \psi_i^{-}(z,\bar{z})$$

$$\psi_i^{\pm}(z,\bar{z}) \;\propto\; f_i(y)\exp\left[-\frac{\lambda}{2}|x|^2 \pm \frac{M}{2}|y|^2\right]$$

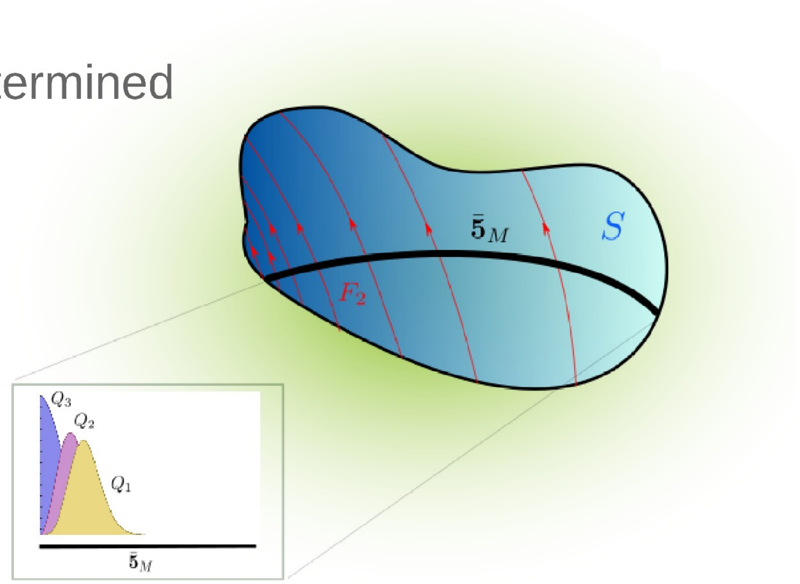
$$\lambda \equiv \sqrt{M^2+m^2}$$

# Local models

Holomorphic factor (and degeneracy) determined globally.

$$f_i(y) = y^{3-i} + \mathcal{O}\left(y^4\right) \ , \quad i = 1, 2, 3$$

Different families localized at different regions in the 4-cycle.




$$\psi^{(0)}_{\bar{\mathbf{5}}_i}(z,\bar{z}) \propto \begin{pmatrix} M-\lambda \\ 0 \\ m \end{pmatrix} \psi_i^+(z,\bar{z})$$

$$\psi_i^{\pm}(z,\bar{z}) \propto f_i(y) \exp\left[-\frac{\lambda}{2}|x|^2 \pm \frac{M}{2}|y|^2\right]$$

$$\psi^{(0)}_{\mathbf{5}_i}(z,\bar{z})^{\dagger} \propto \begin{pmatrix} M+\lambda \\ 0 \\ m \end{pmatrix} \psi_i^-(z,\bar{z})$$

$$\lambda \equiv \sqrt{M^2 + m^2}$$

# Local models

This local approach has been very fruitful in studying the flavor structure of Yukawa couplings. In models where the 3 families are in the same matter curve one has to leading order in the local expansion:

$$Y_{ijk} \propto \int_S d^2z\, d^2\bar{z}\; \psi^{(i)}_{\text{int.}}\, \psi^{(j)}_{\text{int.}}\, \psi^{(k)}_{\text{int.}} \quad \Rightarrow \quad Y_{ijk} \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

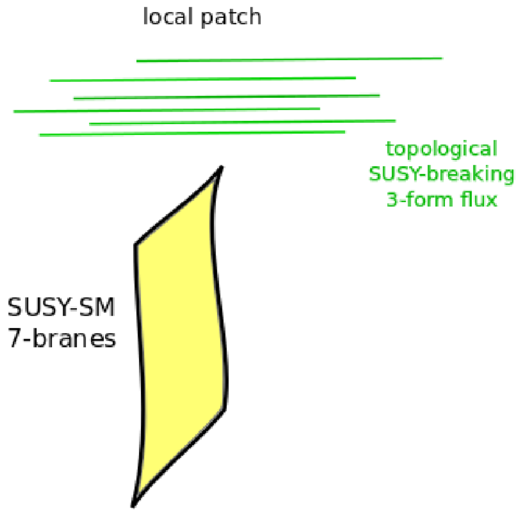
[Cecotti, Cheng, Heckman, Vafa '08 – '09]
[Hayashi, Kawano, Tatar, Watari '09 – '10]
[Aparicio, Font, Ibanez, Marchesano '09 – '12]
[Conlon, Palti '09]
...

Can we extend this approach to compute soft terms (and their flavor structure) in local models?

# Local soft terms

Microscopically soft terms in the worldvolume of 7-branes are determined by the local background near the brane

(in 4d language: soft terms are defined in the limit $M_{\rm Pl} \to \infty$ )




Local expansion of 7-brane DBI+CS action ⇒ soft terms [PGC, Ibanez, Uranga '04]

In some cases (e.g. KKLT) the local background can be very involved / difficult to be related to the sources (gaugino cond., anti-branes...) Microscopic approach not very suited (though still valid) for those cases.

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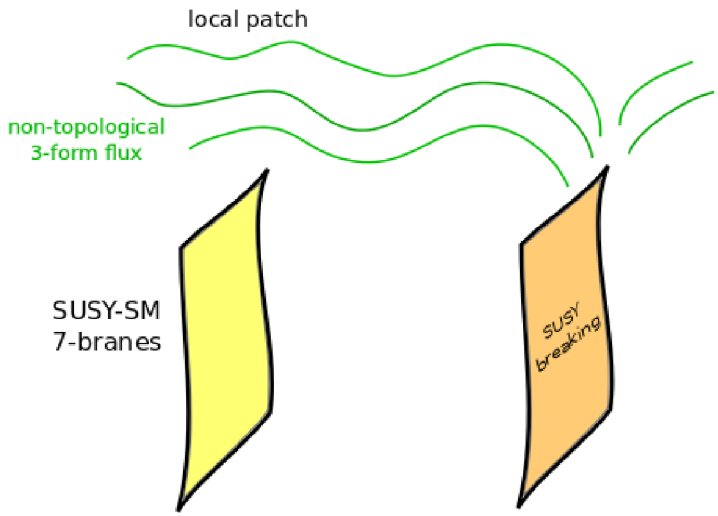


...same spirit than
[Giddings, Maharana '05]
[Baumann et al. '06]

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# Local soft terms

On simplest situations we may have a local density of NSNS & RR (0,3)-flux near GUT 7-branes. Often the leading contribution in LVS (F-term breaking by local Kahler modulus) [Conlon et al. '05 - '09]

$$B_2 = g_s \alpha' \pi i \left( G(z,\bar{z})\, \bar{\Phi}\, d\bar{x} \wedge d\bar{y} - G^*(z,\bar{z})\, \Phi\, dx \wedge dy \right) + \ldots$$

Effective 8d action is modified to leading order in local expansion:

$$\mathcal{L}_{8\mathrm{d}} = \mathrm{Tr}\left( D_a \Phi D^a \bar{\Phi} \;-\; \frac{1}{4} F_{ab} F^{ab} \;-\; \frac{g_s}{2} |G|^2 |\Phi|^2 \right)$$

[PGC, Ibanez, Uranga '04]

Plugging in the above local wavefunctions, gives the 4d soft masses for the scalars localized in matter curves (7-brane intersections):

$$m_{ij}^2 = \frac{g_s}{4\mathrm{Vol}(S)} \int_S d^2 z d^2 \bar{z} \sqrt{g_4}\, |G|^2 \left( 1 - \left| \frac{M}{m} \right| \right) \psi_i^+ (\psi_j^+)^*$$

# Local soft terms

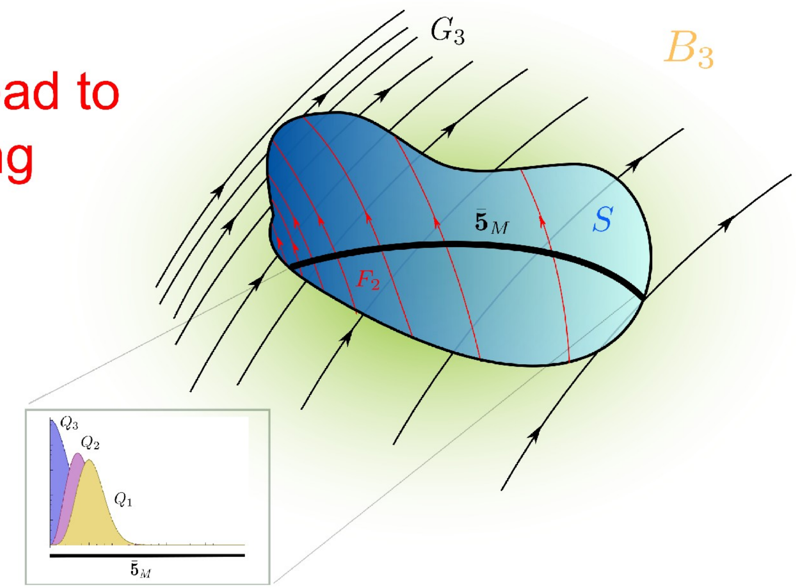
$$m_{ij}^2 = \frac{g_s}{4\mathrm{Vol}(S)} \int_S d^2z d^2\bar{z} \sqrt{g_4}\, |G|^2 \left(1 - \left|\frac{M}{m}\right|\right) \psi_i^+ (\psi_j^+)^*$$

Constant densities of magnetization and 3-form flux reproduce the standard (flavor universal) 4d supergravity result:

[Lust, Reffert, Stieberger '04]
[Font, Ibanez '04]

$$m_{ij}^2 = \frac{g_s}{4} \delta_{ij} |G_0|^2 \left(1 - \left|\frac{M_0}{m}\right|\right)$$

Non-constant densities generically lead to non-universalities (possibly originating from thresholds).



# Flavor non-diagonal soft terms

E.g. consider $\bar{\mathbf{5}}$ matter curve containing right-handed down squarks and left-handed sleptons.

Expanding local closed and open string flux densities around localization point:

$$|G(z,\bar{z})|^2 \;=\; |G_0|^2 \left(1 \;+\; G_y^*\, y + G_y\, \bar{y} \;+\; G_{y\bar{y}}\, |y|^2 \;+\; \ldots\right)$$

$$M(z,\bar{z}) = M_0 \left(1 + M_y^* y + M_y \bar{y} + M_{y\bar{y}} |y|^2 + \ldots\right)$$

leads to soft mass matrix in terms of parameters of local background:

$$\begin{pmatrix} m_{\tilde{q}}^2 + \delta m_1^2 & m_{12}^2 & m_{13}^2 \\ (m_{12}^2)^* & m_{\tilde{q}}^2 + \delta m_2^2 & m_{23}^2 \\ (m_{13}^2)^* & (m_{23}^2)^* & m_{\tilde{q}}^2 + \delta m_3^2 \end{pmatrix}$$

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Hierarchical structure:

$$m_{\tilde{q}}^2 \; > \; m_{12}^2, m_{23}^2 \; > \; \delta m_i^2, m_{13}^2$$

Non-const. magnetization + constant 3-form flux

$$m_{\tilde{q}}^2 = \frac{g_s}{4}|G_0|^2\left(1 - \left|\frac{M_0}{m}\right|\right)$$

$$\delta m_i^2 = \frac{g_s}{4}|G_0|^2 \frac{M_{y\bar{y}}}{q|m|}(4-i)$$

$$m_{i(i+1)}^2 = \frac{g_s}{4}|G_0|^2 \frac{kM_y}{|m|}\sqrt{\frac{|M_0|}{q}}$$

Constant magnetization + non-const. 3-form flux

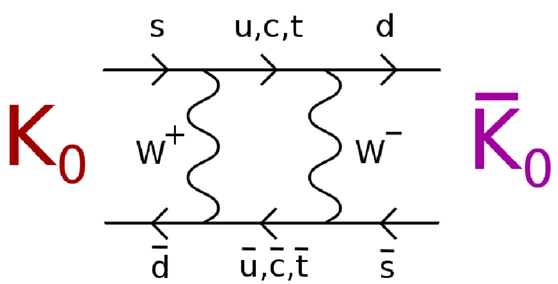
$$m_{\tilde{q}}^2 = \frac{g_s}{4}|G_0|^2\left(1 - \left|\frac{M_0}{m}\right|\right)$$

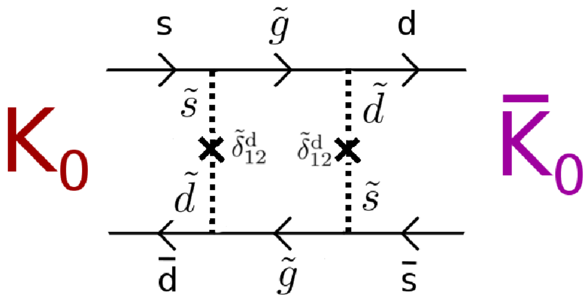
$$\delta m_i^2 = \frac{g_s}{4}|\hat{G}_0|^2 G_{y\bar{y}} \frac{4-i}{q|M_0|}$$

$$m_{i(i+1)}^2 = \frac{g_s k}{4}\frac{|\hat{G}_0|^2 G_y}{\sqrt{q|M_0|}}$$

# Flavor non-diagonal soft terms

Strongest experimental constraints in squark sector come from the $K^0 - \overline{K}^0$ system.




Work in the mass insertion approximation: [Hagelin, Kelley, Tanaka '94]

$$\tilde{\delta}^{\rm d}_{12} = \frac{\left(U_{\rm d}\, m^2_{\rm soft}\, U^\dagger_{\rm d}\right)_{12}}{m^2_{\tilde{q}}} = \frac{2m^2_{12}\cos 2\theta + (m^2_{22} - m^2_{11})\sin 2\theta}{2m^2_{\tilde{q}}}$$

Current experimental bounds require at the low-energy scale:

[Giudice, Nardecchia, Romanino '08]

$$\left|{\rm Re}\ \tilde{\delta}^{\rm d}_{12}\right| < 4.2 \times 10^{-2}\ \frac{m_{\tilde{q}}}{350\ {\rm GeV}}$$ (from $\Delta m_K$ mass difference)

$$\left|{\rm Im}\ \tilde{\delta}^{\rm d}_{12}\right| < 1.8 \times 10^{-3}\ \frac{m_{\tilde{q}}}{350\ {\rm GeV}}$$ (from CP-violation)

# Flavor non-diagonal soft terms

From scalings of the local background parameters

$$M_0 \sim \frac{2\pi n}{\mathrm{Vol}(S)^{1/2}} \qquad M_y \sim \frac{2\,c_{y,F}}{\mathrm{Vol}(S)^{1/4}} \qquad M_{y\bar{y}} \sim \frac{4\,c_{y\bar{y},F}}{\mathrm{Vol}(S)^{1/2}}$$

$$m \sim \frac{\eta}{2\pi\alpha'} \qquad G_y \sim \frac{2\,c_{y,G}}{\mathrm{Vol}(B_3)^{1/6}} \qquad G_{y\bar{y}} \sim \frac{4\,c_{y\bar{y},G}}{\mathrm{Vol}(B_3)^{1/3}}$$

~ 30 % non-universality at $M_{\mathrm{GUT}}$ :

$$\tilde{\delta}^{\mathrm{d}}_{12} \sim 1.4 \times \frac{c_{y,G}}{\sqrt{|n|}} \left(\frac{M_{\mathrm{GUT}}}{M_{\mathrm{Pl}}\,\alpha_{\mathrm{GUT}}}\right)^{1/3}$$ (non-constant closed string flux)

$$\tilde{\delta}^{\mathrm{d}}_{12} \sim \frac{1}{\eta}\left(\frac{M_{\mathrm{GUT}}}{M_{\mathrm{st}}}\right)^2 \left(1.28 \cdot c_{y,F}\sqrt{|n|}\cos 2\theta - 0.41 \cdot c_{y\bar{y},F}\sin 2\theta\right)$$ (non-constant magnetization)

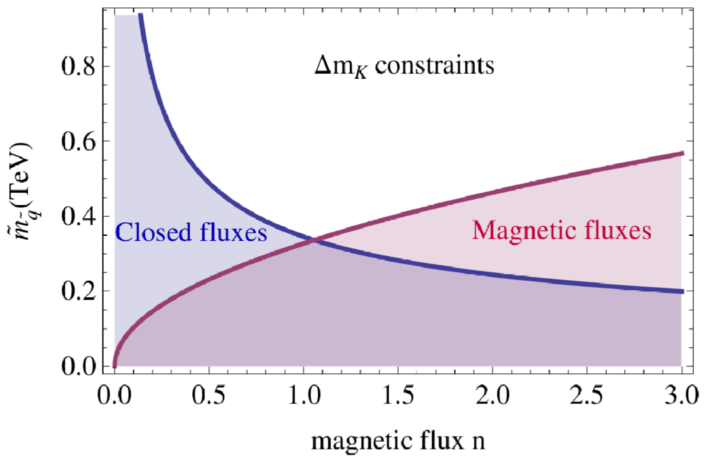
RG running from $M_{\mathrm{GUT}}$ to $M_{\mathrm{SS}}$ (mostly due to SUSY-gauge couplings) leads to extra suppression:

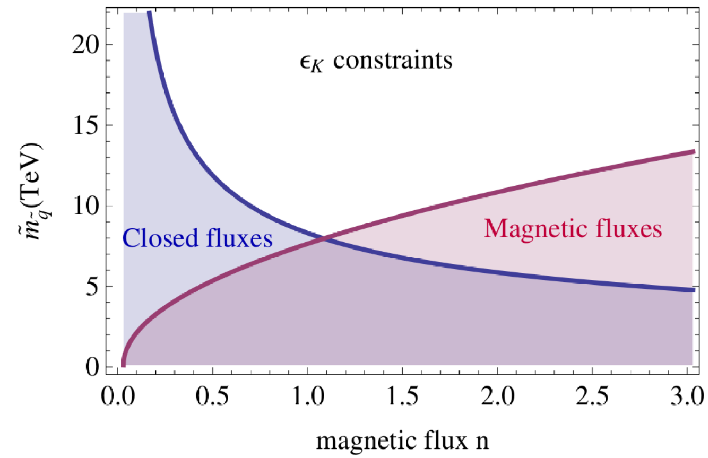
$$\tilde{\delta}^{\mathrm{d}}_{12}\Big|_{M_{\mathrm{GUT}}} \to \frac{\tilde{\delta}^{\mathrm{d}}_{12}}{1+g(t)\xi^2}\Bigg|_{M_{\mathrm{SS}}}$$

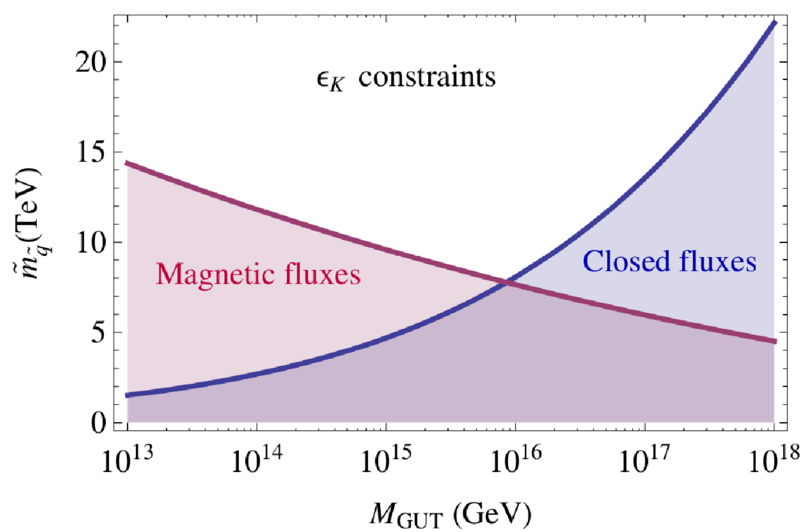
for squarks: $1 + g(t)\xi^2 \sim 10$

# Flavor non-diagonal soft terms

Limits on average squark mass for $\mathcal{O}(1)$ parameters:




$$m_{\tilde{q}} \gtrsim 8 \text{ Tev}$$

# Flavor non-diagonal soft terms

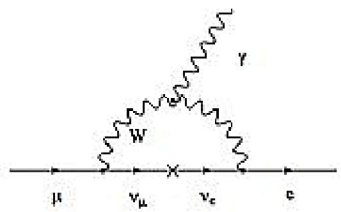
Similar off-diagonal slepton soft masses at $M_{\rm GUT}$ : $\tilde{\delta}^{\rm d}_{12} \sim \tilde{\delta}^{\rm l}_{12}$

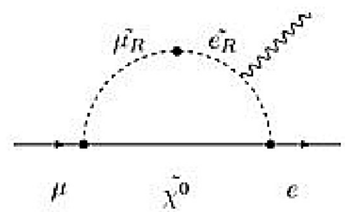
However different running to $M_{\rm SS}$ (less suppression) $\tilde{\delta}^{\rm l}_{12}\Big|_{M_{\rm GUT}} \to \sim \frac{\tilde{\delta}^{\rm l}_{12}}{2}\Big|_{M_{\rm SS}}$

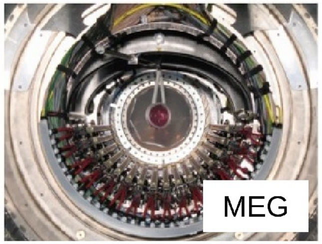
Strongest experimental constraints from unobserved $\mathrm{BR}(\mu \to e\gamma)$

[Arana-Catania, Heinemeyer, Herrero '13]

$$|\tilde{\delta}^{\rm l}_{12}| \;<\; 4\times 10^{-4}\left(\frac{m_{\tilde{l}}}{500\ \mathrm{GeV}}\right)^2$$

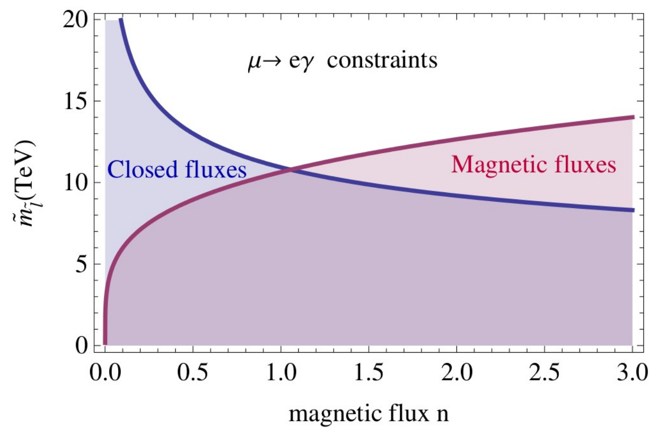


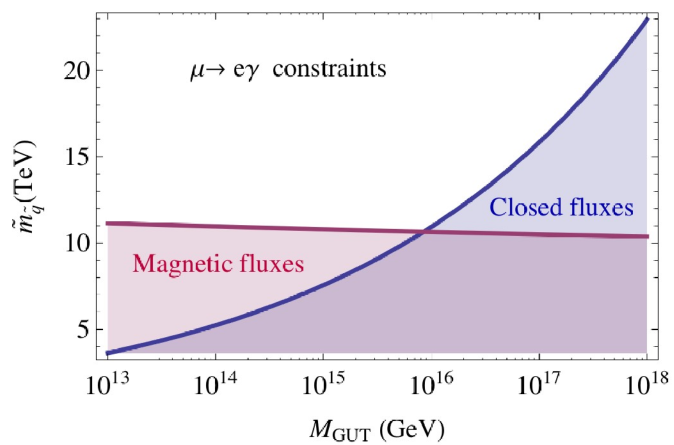




[Adam et al. '13]

Bounds on average slepton mass for $\mathcal{O}(1)$ parameters:




$$m_{\tilde{l}} \gtrsim 11\ \mathrm{TeV}$$

# Conclusions

We extended the microscopic computation of 7-brane soft terms to fields localized on matter curves, relevant for IIB/F-theory GUTs.

Generic non-constant open/closed string flux densities lead to non-universalities of ~ 30 % at $M_{\rm GUT}$ . RG provides extra dilution, (mainly for squarks) but bounds from CP-violation in kaons and the $\mathrm{BR}(\mu \to e\gamma)$ typically result in sfermions heavier than ~ 8 – 10 TeV.

Recall that sleptons at ~ 10 TeV in a SU(5) GUT usually require squarks at ~ 25 TeV or more...

*See Marchesano's talk...*

These limits could be relaxed if e.g. some flavor symmetry forbids linear variation of the fluxes. Subleading quadratic terms also dangerous (typically require sleptons heavier than ~ 4 - 5 TeV).

# Conclusions

May seem discouraging for LHC, though given numerical uncertainties we cannot exclude squarks being discovered at LHC. Consistent with observed Higgs mass, $m_H \simeq 126\ \mathrm{GeV}$ .

Some future directions: .

- Focused on simplest case of local (0,3)-flux.
  Generalization to other backgrounds in preparation w/ L. E. Ibáñez and I. Valenzuela...
- Similar limits expected to hold in other settings (IIA/$G_2$, heterotic...).
- More through analysis including third generation fermions.
- IIB/F-theory realization of inverted sfermion mass hierarchies.
  [Badziak et al. '12]
- Relation between non-constant fluxes and thresholds