Mirror Mediation

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Talk Structure

- The LHC
- Supersymmetry and the MSSM Flavour Problem
- Flavour Universality in Effective Field Theory
- Flavour Universality in String Theory
- Moduli Stabilisation
- Conclusions

The LHC

The LHC is coming! The LHC is coming!

The LHC

The LHC:

- pp collider
- a collision energy of 14TeV
- first collisions summer 2008
- a design luminosity of 100fb^{-1}year^{-1}
- A cost to the UK of < (1 pint of beer) person^{-1} year^{-1}
- has an unprecedented ability to probe the TeV-scale.

Compare with the TeVatron:

- a collision energy of 1.96TeV
- a current *total* integrated luminosity of 3.5fb^{-1}.

The LHC

$$\mathcal{N}_{events} = \sigma \times \mathcal{L}$$

Cross-sections are

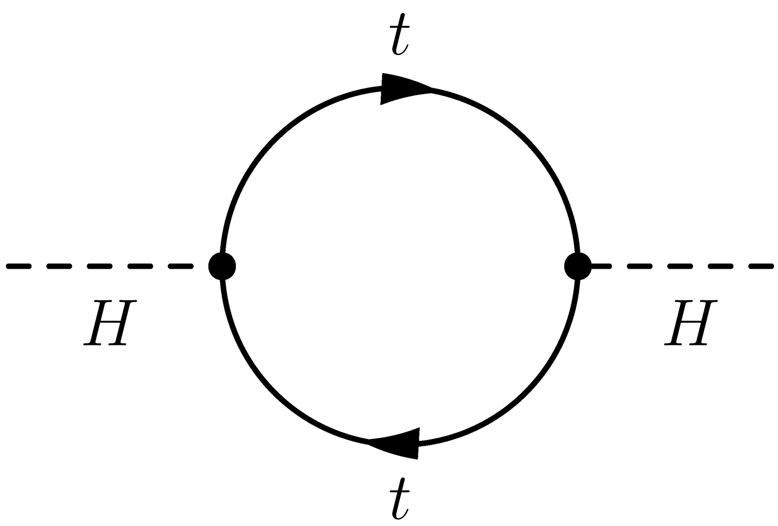
$$\begin{aligned} \sigma_{pp\to b\bar{b}} &\sim 7 \times 10^{11} fb \\ \sigma_{pp\to t\bar{t}} &\sim 9 \times 10^{5} fb \\ \sigma_{pp\to H} &\sim 5 \times 10^{4} fb \\ \sigma_{pp\to ZZ} &\sim 2 \times 10^{4} fb \\ \sigma_{pp\to susy} &\sim (1 \to 10) \times 10^{3} fb \end{aligned}$$

Design luminosity is

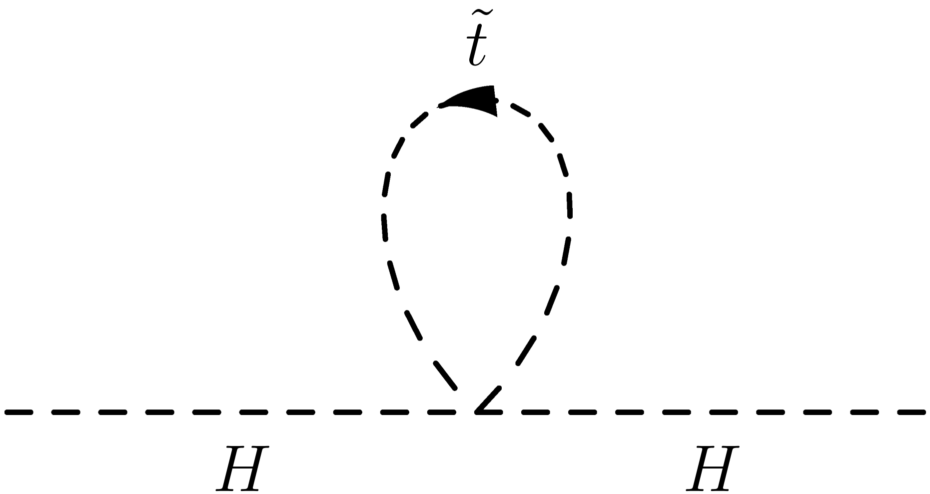
$$\mathcal{L} = 100\text{fb}^{-1}\text{year}^{-1}$$

Supersymmetry

Supersymmetry is a great solution to the gauge hierarchy problem:



$$\sim \quad \Lambda^2$$



$$\sim \quad -\Lambda^2$$

Supersymmetry

TeV supersymmetry

- stabilises the Higgs mass against radiative corrections
- gives a good dark matter candidate
- explains gauge symmetry breaking through radiative electroweak symmetry breaking
- is compatible with LEP I precision electroweak data
- is the prime candidate for new physics discovered at the LHC

Supersymmetry

The MSSM soft Lagrangian is $\mathcal{L}_{soft} = \mathcal{L}_{susy} +$

$$\frac{1}{2}[M_3 \lambda_{\tilde{g}} \lambda_{\tilde{g}} + M_2 \tilde{W}^a \tilde{W}^a + M_1 \tilde{B}\tilde{B} + h.c.] + \epsilon_{\alpha\beta}[-b H_d^\alpha H_u^\beta$$

$$-H_u^\alpha \tilde{Q}_i^\beta \tilde{A}_{uij} \tilde{U}_j^c + H_d^\alpha \tilde{Q}_i^\beta \tilde{A}_{dij} \tilde{D}_j^c + H_d^\alpha \tilde{L}_i^\beta \tilde{A}_{eij} \tilde{E}_j^c + h.c.]$$

$$+m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + \tilde{Q}_i^\alpha m_{Qij}^2 \tilde{Q}_j^{\alpha *}$$

$$+\tilde{L}_i^\alpha m_{Lij}^2 \tilde{L}_j^{\alpha *} + \tilde{U}_i^{c*} m_{Uij}^2 \tilde{U}_j^c + \tilde{D}_i^{c*} m_{Dij}^2 \tilde{D}_j^c + \tilde{E}_i^{c*} m_{Eij}^2 \tilde{E}_j^c$$

Susy is explicitly broken by:

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trilinear scalar A-terms $A_{ijk}\phi^i\phi^j\phi^k$, B-term $b\epsilon_{\alpha\beta}H_u^\alpha H_d^\beta$.

Supersymmetry

The MSSM Spectrum is:

- Gluino $\tilde{g}$, squarks $\tilde{q}$,
- Sleptons $\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$, sneutrinos $\tilde{\nu}$
- Neutralinos $\tilde{\chi}_1, \tilde{\chi}_2, \tilde{\chi}_3, \tilde{\chi}_4$ ($\tilde{B}$, $\tilde{Z}$, $\tilde{H}_1$, $\tilde{H}_2$)
- Charginos $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
- Higgs fields: $h_0, H_0, A, H^\pm$

The MSSM Flavour Problem

The MSSM is new TeV-scale physics. One major problem:

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Why hasn't its effects shown up already?

Compare with

- The c quark - predicted before discovery through its contribution to FCNCs (the GIM mechanism)
- The t quark - mass predicted accurately through loop contributions at LEP I.

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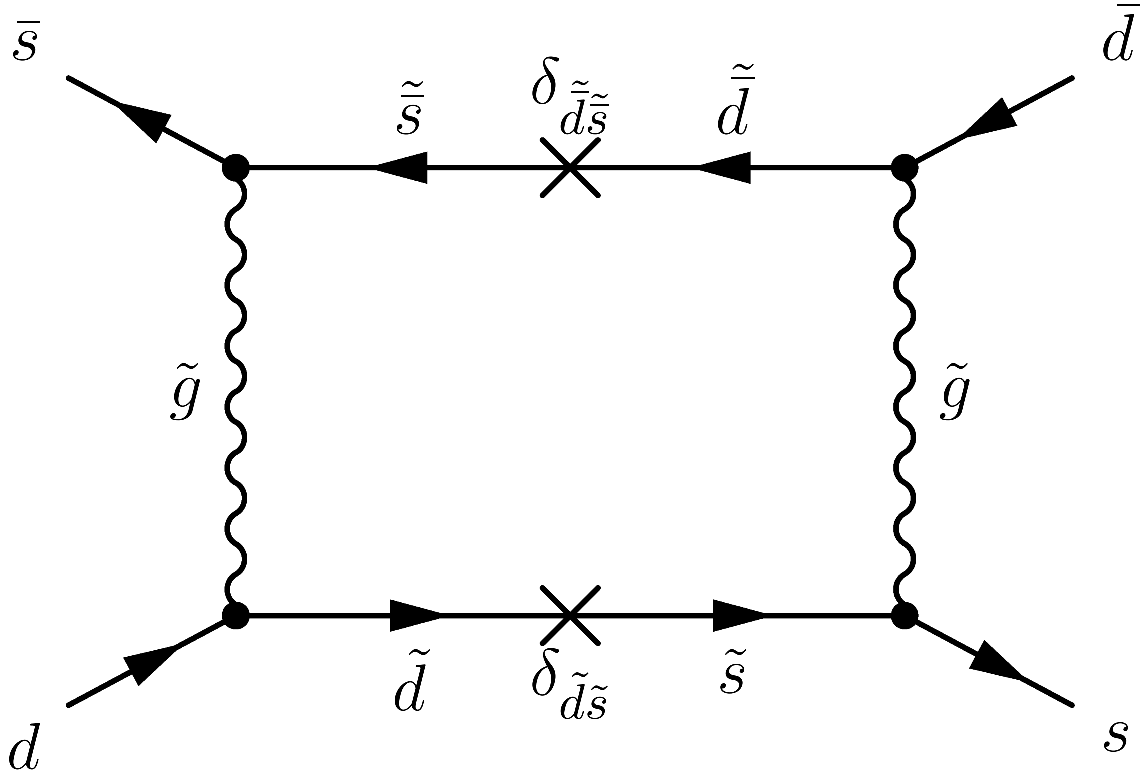
- The t quark - mass predicted accurately through loop contributions at LEP I.

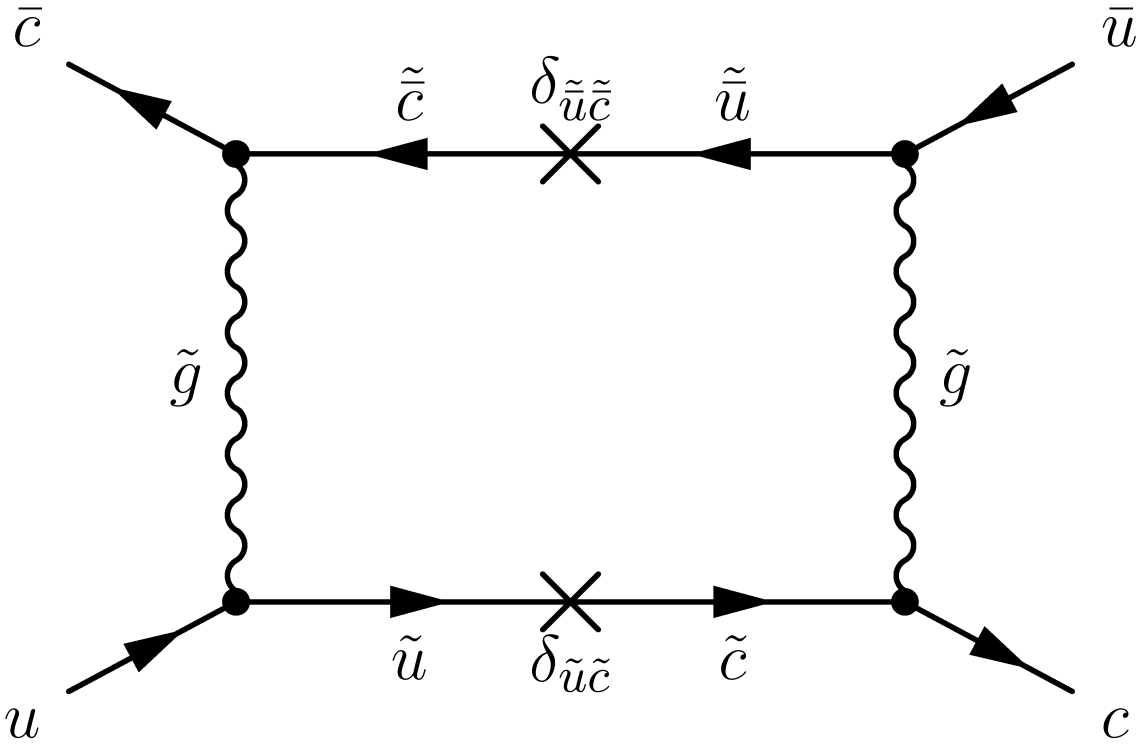
Why haven't we seen SUSY effects?

The MSSM Flavour Problem



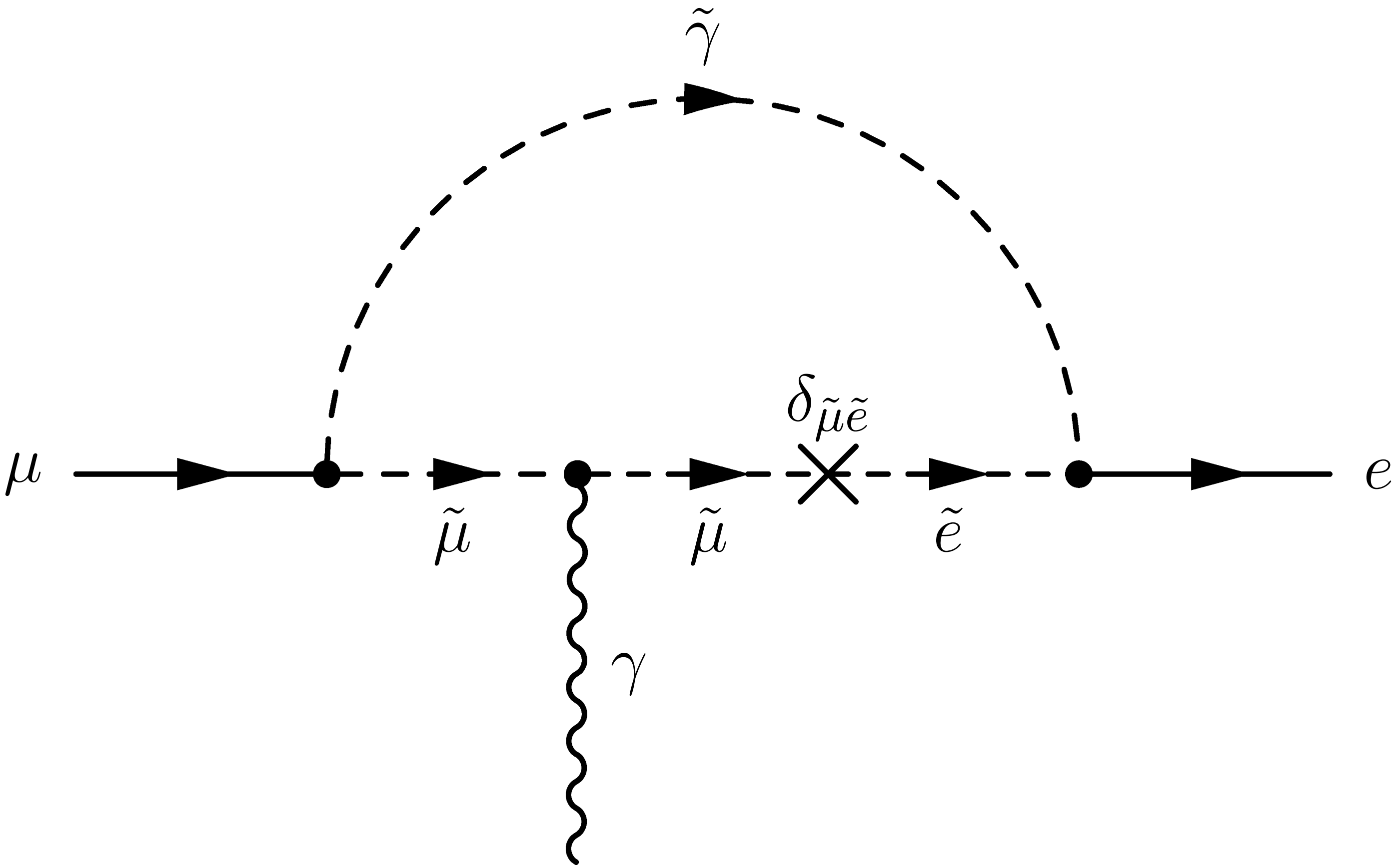
The MSSM gives new contributions to $K_0 - \bar{K}_0$ mixing.

The MSSM Flavour Problem



The MSSM gives new contributions to $D_0 - \bar{D}_0$ mixing.

The MSSM Flavour Problem



The MSSM generates new contributions to $BR(\mu \to e\gamma)$.

The MSSM Flavour Problem

- Low energy flavour experiments already highly constrain the MSSM parameter space.
- This arises through the requirement of no large new contributions to $K_0 - \bar{K}_0$ mixing, $D_0 - \bar{D}_0$ mixing, $BR(\mu \to e\gamma)$....
- New TeV particles with generic couplings would have showed up already in violations from SM measurements

Universality in Effective Field Theory

SUSY does not generate large new FCNCs provided the soft terms are flavour universal.

Soft terms must be family-independent and insensitive to flavour.

For flavour universality, we require

$$
\begin{aligned}
m^2_{Q,\alpha\bar{\beta}} &= m^2_Q \tilde{K}_{\alpha\bar{\beta}}, \\
A_{\alpha\beta\gamma} &= A Y_{\alpha\beta\gamma}, \\
\phi_{M_1} &= \phi_{M_2} = \phi_{M_3} = \phi_A .
\end{aligned}
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Universal scalar masses, A-terms proportional to the Yukawa couplings, gaugino mass phases are aligned.

Universality in Effective Field Theory

Why should this happen?

- One proposal - gauge mediated supersymmetry breaking.

  Unfortunately this generates many other phenomenological problems ($\mu/B\mu$ problem, additional hierarchies required...).

- In this talk we look at the structure of soft terms within supergravity and string theory.

Universality in Effective Field Theory

- To compute soft terms, we expand K and W in powers of matter fields C^α,

$$\begin{aligned} W &= \hat{W}(\Phi) + \mu(\Phi) H_1 H_2 + \frac{1}{6} Y_{\alpha\beta\gamma}(\Phi) C^\alpha C^\beta C^\gamma + \ldots, \\ K &= \hat{K}(\Phi, \bar{\Phi}) + \tilde{K}_{\alpha\bar{\beta}}(\Phi, \bar{\Phi}) C^\alpha C^{\bar{\beta}} + [Z H_1 H_2 + h.c.] + \ldots, \\ f_a &= f_a(\Phi). \end{aligned}$$

Universality in Effective Field Theory

Soft scalar masses $m^2_{i\bar{j}}$ and trilinears $A_{\alpha\beta\gamma}$ are given by

$$\begin{aligned}
\tilde{m}^2_{\alpha\bar{\beta}} &= (m^2_{3/2} + V_0)\tilde{K}_{\alpha\bar{\beta}} \\
&\quad -\bar{F}^{\bar{m}}F^n\left(\partial_{\bar{m}}\partial_n\tilde{K}_{\alpha\bar{\beta}} - (\partial_{\bar{m}}\tilde{K}_{\alpha\bar{\gamma}})\tilde{K}^{\bar{\gamma}\delta}(\partial_n\tilde{K}_{\delta\bar{\beta}})\right) \\
A'_{\alpha\beta\gamma} &= e^{\hat{K}/2}F^m\Big[\hat{K}_m Y_{\alpha\beta\gamma} + \partial_m Y_{\alpha\beta\gamma} \\
&\quad -\left((\partial_m\tilde{K}_{\alpha\bar{\rho}})\tilde{K}^{\bar{\rho}\delta}Y_{\delta\beta\gamma} + (\alpha\leftrightarrow\beta) + (\alpha\leftrightarrow\gamma)\right)\Big]. \\
M_a &= \frac{F^m\partial_m f_a}{\mathrm{Re}(f_a)}
\end{aligned}$$

Similar expressions hold for μ and $B\mu$.

Universality in Effective Field Theory

Sufficient conditions for flavour universality:

1. Hidden sector factorises

$$\Phi_{hidden} = \Psi_{susy} \oplus \chi_{flavour}.$$

2. The kinetic terms are decoupled

$$\mathcal{K}(\Phi, \bar{\Phi}) = \mathcal{K}_1(\Psi + \bar{\Psi}) + \mathcal{K}_2(\chi, \bar{\chi}),$$

3. The superpotential Yukawas depend only on $\chi_{flavour}$:

$$Y_{\alpha\beta\gamma}(\Psi, \chi) = Y_{\alpha\beta\gamma}(\chi).$$

4. The gauge kinetic functions depend only on Ψ fields:

$$f_a(\Psi, \chi) = \sum_i \lambda_i \Psi_i.$$

Universality in Effective Field Theory

5. The visible metric factorises.

$$\mathcal{K}_{\alpha\bar{\beta}}(\Psi, \bar{\Psi}, \chi, \bar{\chi}) = h(\Psi + \bar{\Psi}) k_{\alpha\bar{\beta}}(\chi, \bar{\chi})$$

6. Ψ breaks susy, χ does not:

$$D_{\Psi_i} W \neq 0, D_{\chi_j} W = 0.$$

If all these assumptions hold, susy breaking generates flavour universal soft terms.

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Totally *ad hoc* in effective field theory!

Universality in Effective Field Theory

$$
\begin{aligned}
\tilde{m}^2_{\alpha\bar{\beta}} &= (m^2_{3/2} + V_0)\tilde{K}_{\alpha\bar{\beta}} \\
&\quad - \bar{F}^{\bar{\Psi}_j} F^{\Psi_i} \left(\partial_{\bar{\Psi}_j} \partial_{\Psi_i} \tilde{K}_{\alpha\bar{\beta}} - (\partial_{\bar{\Psi}_j} \tilde{K}_{\alpha\bar{\gamma}}) \tilde{K}^{\bar{\gamma}\delta} (\partial_{\Psi_i} \tilde{K}_{\delta\bar{\beta}}) \right) \\
&= (m^2_{3/2} + V_0)\tilde{K}_{\alpha\bar{\beta}} - \bar{F}^{\bar{\Psi}_j} F^{\Psi_i} \Bigg(\partial_{\bar{\Psi}_j} \partial_{\Psi_i} h(\Psi, \bar{\Psi}) \\
&\quad - \frac{\partial_{\bar{\Psi}_j} h(\Psi, \bar{\Psi}) \partial_{\Psi_i} h(\Psi, \bar{\Psi})}{h(\Psi, \bar{\Psi})} \Bigg) k_{\alpha\bar{\beta}}(\chi, \bar{\chi}) \\
&= \Bigg((m^2_{3/2} + V_0) h \\
&\quad \bar{F}^{\bar{\Psi}_j} F^{\Psi_i} \left(\partial_{\bar{\Psi}_j} \partial_{\Psi_i} - \frac{\partial_{\bar{\Psi}_j} h \partial_{\Psi_i} h}{h} \right) \Bigg) (\Psi, \bar{\Psi}) k_{\alpha\bar{\beta}}(\chi, \bar{\chi})
\end{aligned}
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Universality in Effective Field Theory

$$
\begin{aligned}
A'_{\alpha\beta\gamma} &= e^{\hat{K}/2} F^m \Big[\hat{K}_m Y_{\alpha\beta\gamma} + \partial_m Y_{\alpha\beta\gamma} \\
&\quad - \Big((\partial_m \tilde{K}_{\alpha\bar{\rho}}) \tilde{K}^{\bar{\rho}\delta} Y_{\delta\beta\gamma} + (\alpha \leftrightarrow \beta) + (\alpha \leftrightarrow \gamma) \Big) \Big]. \\
&= e^{\hat{K}/2} F^{\Psi_i} \Big[\hat{K}_{\Psi_i} Y_{\alpha\beta\gamma} + \partial_{\Psi_i} Y_{\alpha\beta\gamma} \\
&\quad - \Big(((\partial_{\Psi_i} h) k_{\alpha\bar{\rho}}) h^{-1} k^{\bar{\rho}\delta} Y_{\delta\beta\gamma} + (\alpha \leftrightarrow \beta) + (\alpha \leftrightarrow \gamma) \Big) \Big] \\
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\end{aligned}
$$

A-terms proportional to Yukawa couplings!

Universality in String Theory

String theory knows this structure!

- Calabi-Yau moduli space factorises in precisely this fashion.
- Kähler (T) and complex structure (U) moduli have factorised moduli spaces
- $$IIB : \Psi_{susy} \rightarrow T, \chi_{flavour} \rightarrow U,$$
  $$IIA : \Psi_{susy} \rightarrow U, \chi_{flavour} \rightarrow T.$$
- In flux compactifications susy breaking factorises:

$$F^T \neq 0, \qquad F^U = 0.$$

Universality in String Theory

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$$\Phi_{hidden} = \Psi_{susy} \bigoplus \chi_{flavour}.$$

$$\Phi_{moduli} = \Psi_{\text{Kähler(T)}} \bigoplus \chi_{\text{complex structure(U)}}.$$

The moduli space of Calabi-Yau manifolds has two distinct parts, Kähler and complex structure moduli.

Universality in String Theory

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$$\mathcal{K}(\Phi, \bar{\Phi}) = \mathcal{K}_1(\Psi + \bar{\Psi}) + \mathcal{K}_2(\chi, \bar{\chi}),$$

The moduli space Kähler potential is

$$K = -2\ln(\mathcal{V}(T+\bar{T})) - \ln\left(\int \Omega \wedge \bar{\Omega}(U, \bar{U})\right) - \ln(S+\bar{S})$$

The moduli space of Calabi-Yau manifolds has two distinct parts, Kähler and complex structure moduli.

Universality in String Theory

The T fields are defined as

$$T = \int_{\Sigma_4} e^{-\phi}\sqrt{g} + i\int_{\Sigma_4} C_4$$

The imaginary part of T is axionic and T has a perturbative shift symmetry,

$$T \to T + i\epsilon.$$

Perturbative quantities depend only on $(T + \bar{T})$.

Universality in String Theory

Example: T^6

$$\begin{aligned}\hat{K} &= -\ln\big((T_1+\bar{T}_1)(T_2+\bar{T}_2)(T_3+\bar{T}_3)\big)\\ &\quad -\ln\big((U_1+\bar{U}_1)(U_2+\bar{U}_2)(U_3+\bar{U}_3)\big)-\ln(S+\bar{S}).\end{aligned}$$

In the large-radius limit, Calabi-Yau moduli space factorises exactly into two distinct sectors - Kähler and complex structure moduli.

Universality in String Theory

3. The superpotential Yukawas depend only on $\chi_{flavour}$:

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Perturbativity would require $Y_{\alpha\beta\gamma}(T) \sim T^{\lambda}$.

The shift symmetry $T \to T + i\epsilon$ forbids this.

In perturbation theory, $Y_{\alpha\beta\gamma}(T, U) = Y_{\alpha\beta\gamma}(U)$.

Universality in String Theory

Example:

For toroidal compactifications, the superpotential Yukawas take the following form,

$$Y_{ijk}(U) = \vartheta \begin{bmatrix} \delta^r_{ijk} \\ 0 \end{bmatrix} (0; U^r I^r_{ab} I^r_{bc} I^r_{ca})$$

- No dependence on T
- A very complicated dependence on U.

Universality in String Theory

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D7 brane gauge kinetic function:

$$f_a = T + h_a(F) S.$$

- No U-dependence
- Linear dependence on T.

Universality in String Theory

5. The visible metric factorises.

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Universality in String Theory

5. The visible metric factorises.

$$\mathcal{K}_{\alpha\bar{\beta}}(\Psi, \bar{\Psi}, \chi, \bar{\chi}) = h(\Psi + \bar{\Psi}) k_{\alpha\bar{\beta}}(\chi, \bar{\chi})$$

This comes from the universal scaling property of physical Yukawa couplings

$$\hat{Y}_{\alpha\beta\gamma} = e^{\hat{K}/2} \frac{Y_{\alpha'\beta'\gamma'}}{(\tilde{K}_{\alpha\alpha'} \tilde{K}_{\beta\beta'} \tilde{K}_{\gamma\gamma'})^{\frac{1}{2}}}.$$

This arises from the origin of physical Yukawa couplings as due to wavefunction overlap.

Universality in String Theory

Example: For toroidal compactifications, the Kähler metric is

$$K_{ij}^{ab} = \delta_{ij} S^{-1/4} (T^1 T^2 T^3)^{-1/4} \times \prod_{I=1}^{3} U_I^{-(\frac{1}{2} \pm \frac{1}{2} \mathrm{sign}(\mathrm{I_{ab}}) \theta^{\mathrm{I}}_{\mathrm{ab}})} \left(\frac{\Gamma(\theta^1_{ab})\Gamma(\theta^2_{ab})\Gamma(1-\theta^1_{ab}-\theta^2_{ab})}{\Gamma(1-\theta^1_{ab})\Gamma(1-\theta^2_{ab})\Gamma(\theta^1_{ab}+\theta^2_{ab})} \right)$$

This has

- At leading order a universal scaling dependence on $(T + \bar{T})$
- Subleading (universal) corrections at $\mathcal{O}(\alpha'^2)$

Universality in String Theory

6. Ψ breaks susy, χ does not:

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Universality in String Theory

6. Ψ breaks susy, χ does not:

$$D_{\Psi_i} W \neq 0, D_{\chi_j} W = 0.$$

- This is a statement about the vacuum structure and is equivalent to $F^T \neq 0, F^U = 0$.
- The T fields break supersymmetry and the U fields do not.
- In IIB flux compactifications it turns out that these conditions are satisfied.

Moduli Stabilisation: Fluxes

- Flux compactifications can generate potentials for the moduli
- Fluxes source an energy density that depends on the size of cycles.
- In IIB, fluxes generate a superpotential

$$W = \int G_3 \wedge \Omega(U)$$

Moduli Stabilisation: Fluxes

$$\begin{aligned}
\hat{K} &= -2\ln\left(\mathcal{V}(T+\bar{T})\right) - \ln\left(i\int \Omega\wedge\bar{\Omega}(U)\right) - \ln\left(S+\bar{S}\right),\\
W &= \int G_3\wedge\Omega\,(U).\\
V &= e^{\hat{K}}\left(\sum_{U,S}\hat{K}^{\alpha\bar{\beta}}D_\alpha W D_{\bar{\beta}}\bar{W} + \sum_T \hat{K}^{i\bar{j}}D_i W D_{\bar{j}}\bar{W} - 3|W|^2\right)\\
&= e^{\hat{K}}\left(\sum_{U,S}\hat{K}^{\alpha\bar{\beta}}D_\alpha W D_{\bar{\beta}}\bar{W}\right)
\end{aligned}$$

Stabilise S and U by solving $D_S W = D_U W = 0$.

Moduli Stabilisation: Fluxes

$$\begin{aligned}\hat{K} &= -2\ln\left(\mathcal{V}(T_i+\bar{T}_i)\right),\\ W &= W_0\,.\\ V &= e^{\hat{K}}\left(\sum_T \hat{K}^{i\bar{j}} D_i W D_{\bar{j}}\bar{W} - 3|W|^2\right)\\ &= 0\end{aligned}$$

No-scale model :

- vanishing vacuum energy
- broken susy ($F^T \neq 0, F^U = 0$)
- T unstabilised
- Goldstino is breathing mode $g_{\mu\nu} \to \lambda^2 g_{\mu\nu}$

Moduli Stabilisation: KKLT

$$\hat{K} = -2\ln(\mathcal{V}),$$
$$W = W_0 + \sum_i A_i e^{-a_i T_i}.$$

- Non-perturbative ADS superpotential.
- T-moduli are stabilised by solving $D_T W = 0$.
- Supersymmetric minimum: needs extra energy to break susy.
- No hierarchy in $m_{3/2}$.

Moduli Stabilisation: Large-Volume

$$\hat{K} = -2\ln\left(\mathcal{V} + \frac{\xi}{g_s^{3/2}}\right),$$

$$W = W_0 + \sum_i A_i e^{-a_i T_i}.$$

- Add the leading α' corrections to the Kähler potential.
- This leads to dramatic changes in the large-volume vacuum structure.

Moduli Stabilisation: Large-Volume

The simplest model $\mathbb{P}^4_{[1,1,1,6,9]}$ has two Kähler moduli.

$$\mathcal{V} = \left(\frac{T_b + \bar{T}_b}{2}\right)^{3/2} - \left(\frac{T_s + \bar{T}_s}{2}\right)^{3/2} \equiv \left(\tau_b^{3/2} - \tau_s^{3/2}\right).$$

If we compute the scalar potential, we get for $\mathcal{V} \gg 1$,

$$V = \frac{\sqrt{\tau_s} a_s^2 |A_s|^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{a_s |A_s W_0| \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

Moduli Stabilisation: Large-Volume

$$V = \underbrace{\frac{\sqrt{\tau_s} a_s^2 |A_s|^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{a_s |A_s W_0| \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2}}_{\text{Integrate out } \tau_s} + \frac{\xi |W_0|^2}{g_s^{3/2} \mathcal{V}^3}.$$

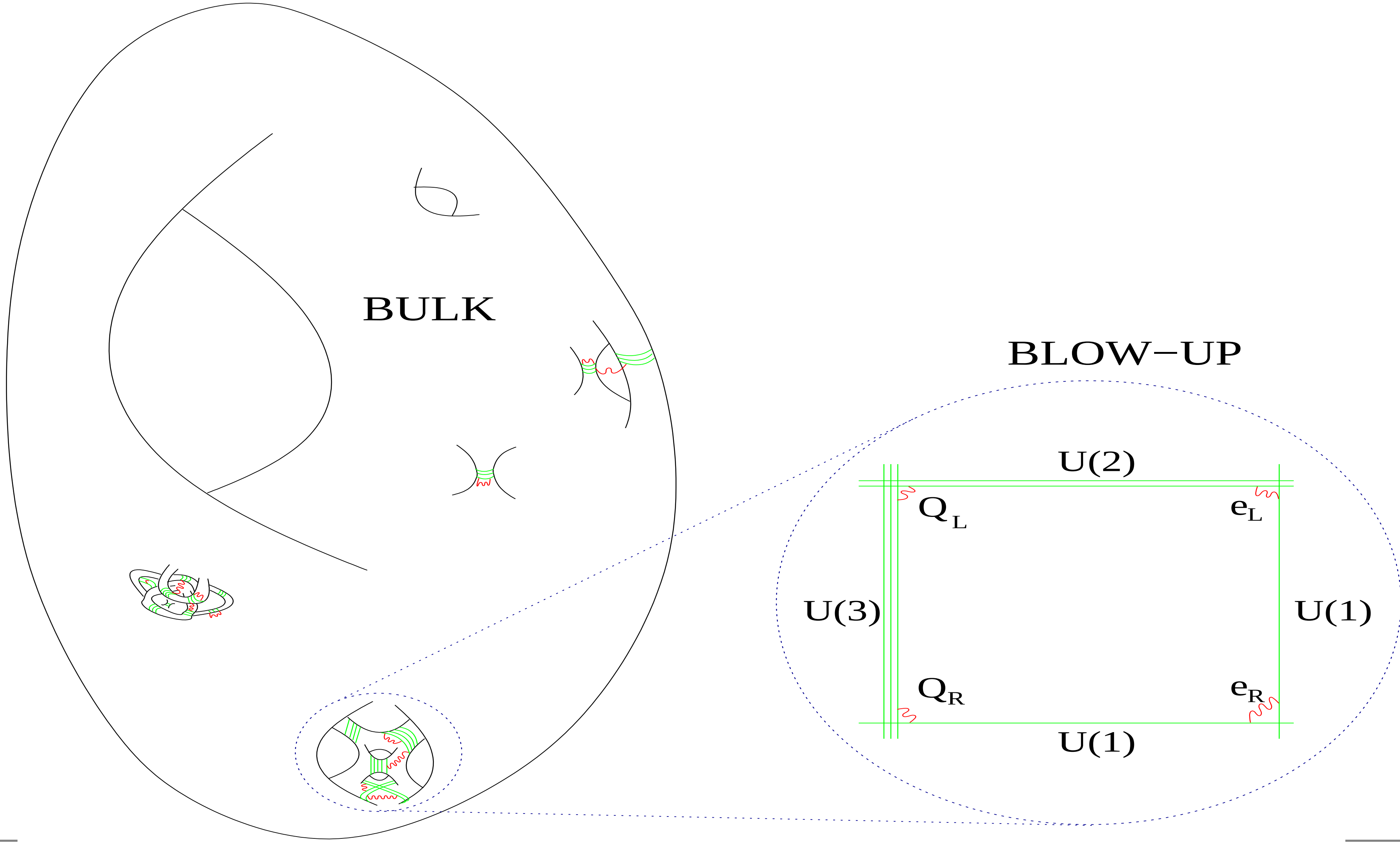
$$V = -\frac{|W_0|^2 (\ln \mathcal{V})^{3/2}}{\mathcal{V}^3} + \frac{\xi |W_0|^2}{g_s^{3/2} \mathcal{V}^3}.$$

A minimum exists at

$$\mathcal{V} \sim |W_0| e^{a_s \tau_s}, \qquad \tau_s \sim \frac{\xi^{2/3}}{g_s}.$$

This minimum is non-supersymmetric AdS and at exponentially large volume.

Moduli Stabilisation: Large-Volume



Moduli Stabilisation: Large-Volume

- The stabilised volume is exponentially large.
- The large volume lowers the string scale and gravitino mass through

$$m_s = \frac{M_P}{\sqrt{\mathcal{V}}}, \qquad m_{3/2} = \frac{M_P}{\mathcal{V}}.$$

- To solve the gauge hierarchy problem, need $\mathcal{V} \sim 10^{15}$.
- The vacuum is pseudo no-scale and breaks susy...

Moduli Stabilisation: Large-Volume

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- To solve the gauge hierarchy problem, need $\mathcal{V} \sim 10^{15}$.
- The vacuum is pseudo no-scale and breaks susy...
- Can generate the hierarchy and compute the moduli F-terms

$$F^{T_i} \neq 0, F^{U_j} = 0.$$

Corrections

- Factorisation holds at leading order.
- Factorisation is inherited from the underlying $\mathcal{N} = 2$ structure and holds in the large-radius limit.
- It is broken by e.g. loop corrections that are present in $\mathcal{N} = 1$ compactifications.
- Phenomenologically, this suggests soft terms that are

universal at leading order

with small subleading corrections

Conclusions

- String theory provides a natural solution to the flavour problems of the MSSM.
- Calabi-Yau moduli space factorises into Kähler and complex structure moduli.
- One sector is responsible for flavour, the the other for susy breaking.
- This factorisation is explicitly realised by IIB flux compactifications.

Conclusions

Naturalness in string theory $\neq$

Naturalness in effective field theory