Strings, SUSY and LHC

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The LHC

What is the LHC?

The greatest experiment on earth!

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}

The TeVatron:

- $p\bar{p}$ collider
- a collision energy of 1.8TeV
- a current *total* integrated luminosity of 3.5fb^{-1}.

The LHC

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

Cross-sections are

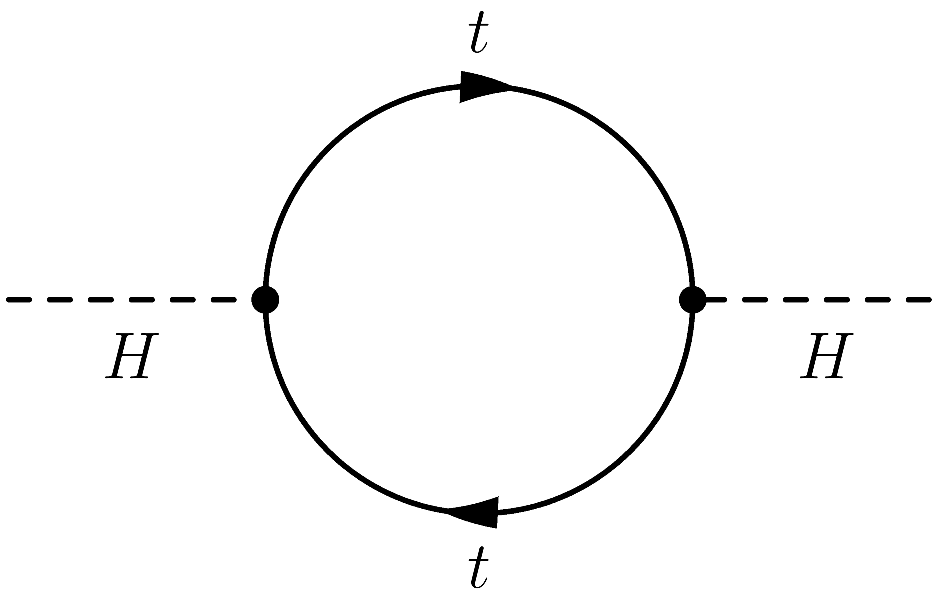
$$\begin{aligned}
\sigma_{pp\to b\bar{b}} &\sim 7 \times 10^{11} fb \\
\sigma_{pp\to t\bar{t}} &\sim 9 \times 10^{5} fb \\
\sigma_{pp\to H} &\sim 5 \times 10^{4} fb \\
\sigma_{pp\to ZZ} &\sim 2 \times 10^{4} fb \\
\sigma_{pp\to susy} &\sim (1 \to 10) \times 10^{3} fb
\end{aligned}$$

Design luminosity is

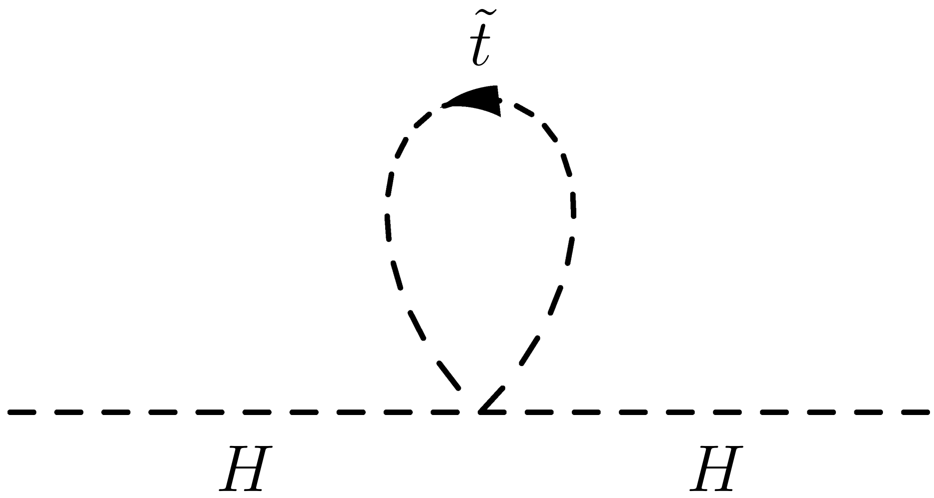
$$\mathcal{L} = 100\text{fb}^{-1}\text{year}^{-1}$$

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 $\mathcal{L}_{soft} = \mathcal{L}_{susy} +$

$$\frac{1}{2}[M_3\lambda_{\tilde{g}}\lambda_{\tilde{g}} + M_2\tilde{W}^a\tilde{W}^a + M_1\tilde{B}\tilde{B} + h.c.] + \epsilon_{\alpha\beta}[-bH_d^\alpha H_u^\beta$$
$$-H_u^\alpha\tilde{Q}_i^\beta\tilde{A}_{uij}\tilde{U}_j^c + H_d^\alpha\tilde{Q}_i^\beta\tilde{A}_{dij}\tilde{D}_j^c + H_d^\alpha\tilde{L}_i^\beta\tilde{A}_{eij}\tilde{E}_j^c + h.c.]$$
$$+m_{H_d}^2|H_d|^2 + m_{H_u}^2|H_u|^2 + \tilde{Q}_i^\alpha m_{Qij}^2\tilde{Q}_j^{\alpha*}$$
$$+\tilde{L}_i^\alpha m_{Lij}^2\tilde{L}_j^{\alpha*} + \tilde{U}_i^{c*}m_{Uij}^2\tilde{U}_j^c + \tilde{D}_i^{c*}m_{Dij}^2\tilde{D}_j^c + \tilde{E}_i^{c*}m_{Eij}^2\tilde{E}_j^c$$

Susy is explicitly broken by:

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scalar masses $m^2\phi\bar{\phi}$, gaugino masses $M\lambda\lambda$,

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: $h_0, H_0, A, H^{\pm}$

SUSY Phenomenology

SUSY introduces new strongly interacting particles at the TeV scale.

Gluon $g \longrightarrow$ Gluino $\tilde{g}$

Quark $q \longrightarrow$ Squark $\tilde{q}$

A pp machine is a colour collider and a squark/gluino factory

$$p + p \longrightarrow \tilde{g} + \tilde{g}, \tilde{g} + \tilde{q}, \tilde{q} + \tilde{q}$$

Squarks and gluinos are abundantly produced and have long decay chains.

SUSY Phenomenology

LHC SUSY phenomenology is the study of cascade decays of squarks and gluinos.

$$
\begin{aligned}
p + p &\longrightarrow \tilde{g} + \tilde{g} \\
\tilde{g} &\longrightarrow \tilde{t} + t \\
&\longrightarrow \tilde{\chi}_1^+ + b + W + b \\
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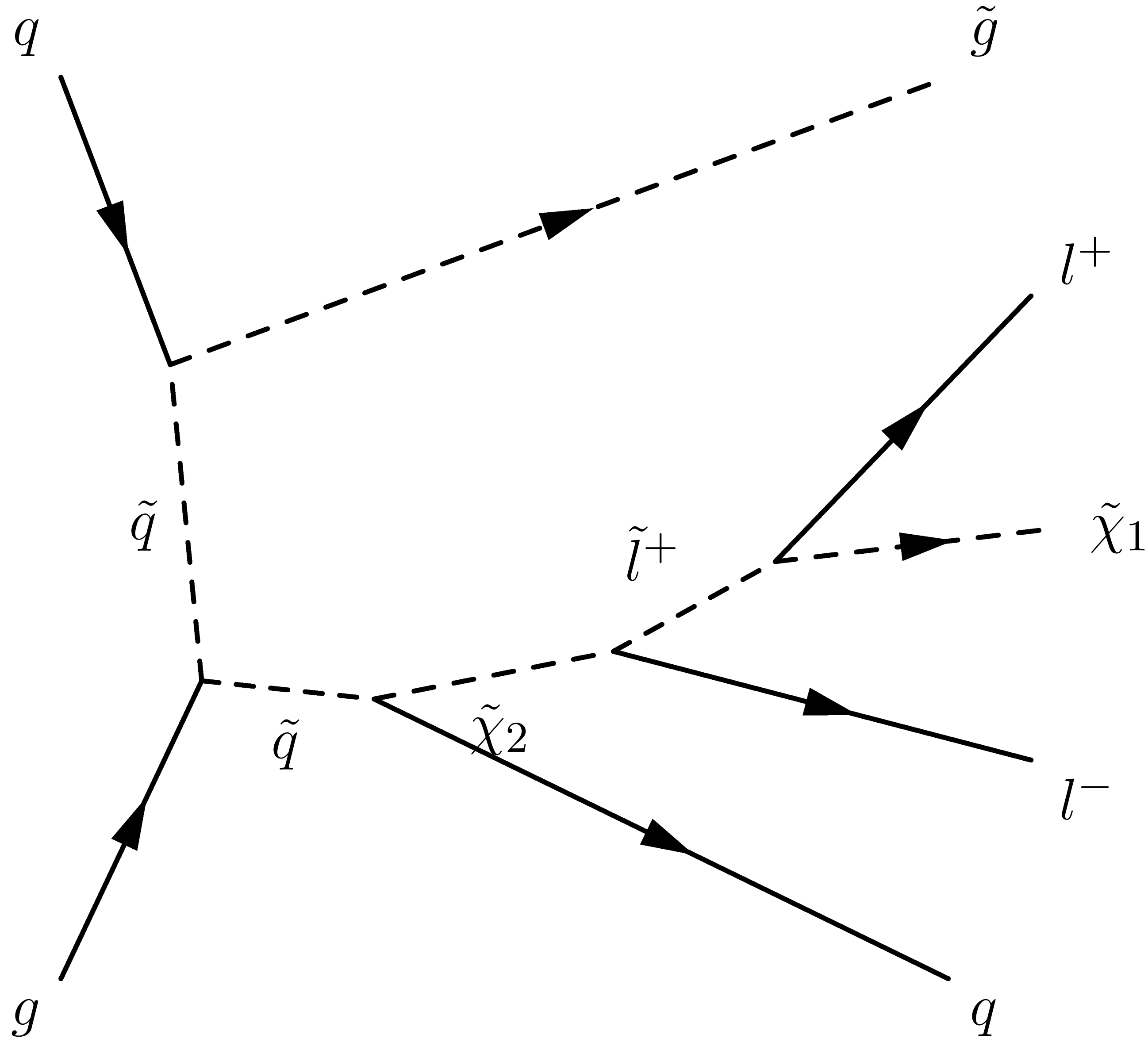
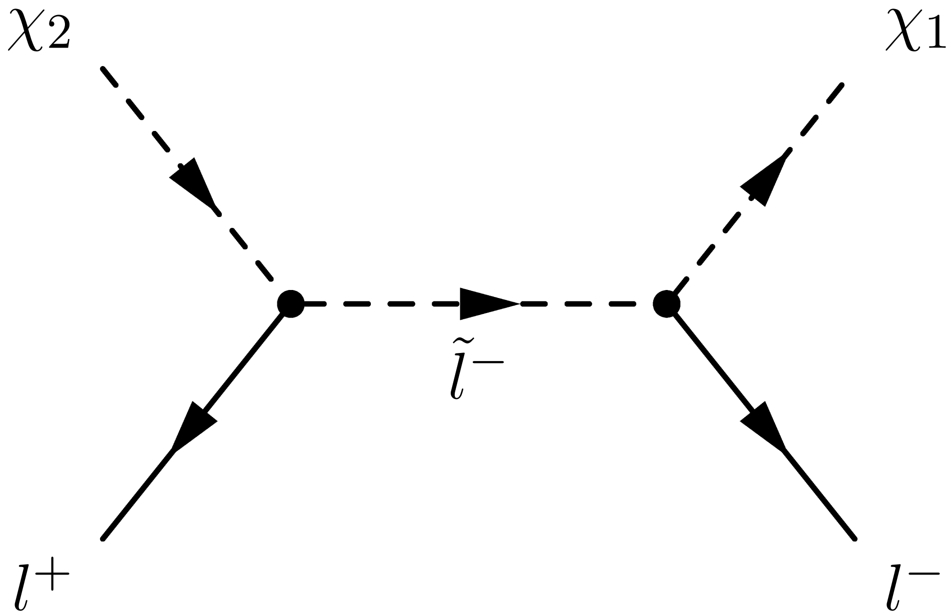
SUSY events are complex, with

multi-jets, multi-leptons, missing E_T.

SUSY Phenomenology



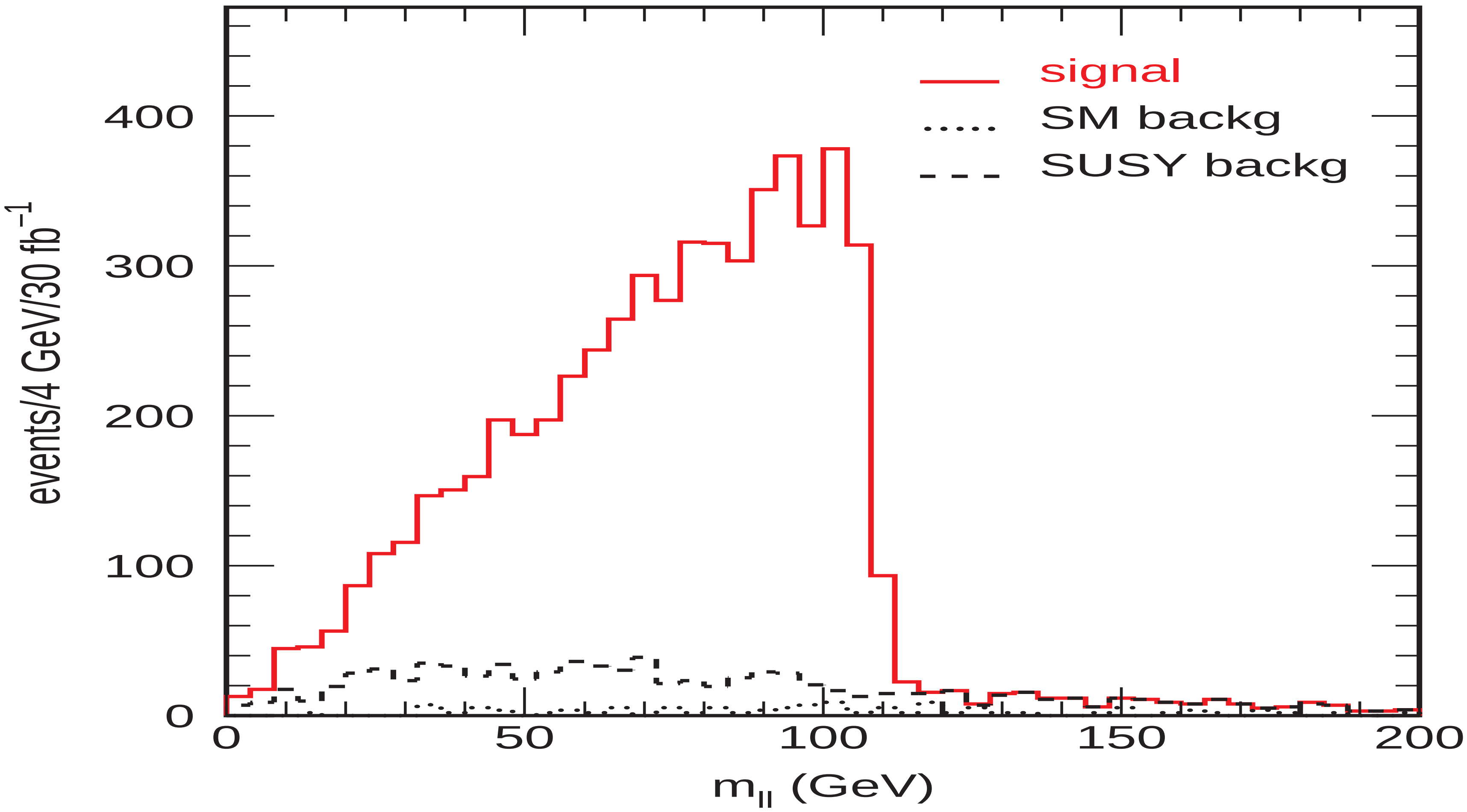
SUSY Spectroscopy



$$Max(M_{l^+l^-}) = M_{\tilde{\chi}_2}\sqrt{1-\frac{M_{\tilde{l}}^2}{M_{\tilde{\chi}_2}^2}}\sqrt{1-\frac{M_{\tilde{\chi}_1}^2}{M_{\tilde{l}_2}^2}}$$

This decay chain gives a characteristic edge.

SUSY Spectroscopy



(ATLAS TDR)

SUSY Spectroscopy

- Other sparticle masses can be measured through kinematic edges, thresholds and endpoints.
- If TeV SUSY is present, the LHC will find it.

The LHC will measure

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The LHC will measure

with moderate accuracy combinations of some of the parameters of

the MSSM Lagrangian.

- A hadron collider is messy - many MSSM parameters cannot be measured.
- For example, A-terms and particle spins are very hard to measure.

SUSY Breaking

- Susy phenomenology is the study of supersymmetry breaking
- What is the origin and underlying structure of the MSSM soft parameters?
- How is supersymmetry broken?

SUSY Breaking

Gravity exists - SUSY is a local symmetry.

Phenomenology of susy breaking is classified by gravitino mass

$$m_{3/2} = e^{K/2} W$$

$m_{3/2} \gtrsim 1$TeV : gravity mediation, moduli mediation, anomaly mediation

$m_{3/2} \ll 1$TeV : gauge mediation

Focus on gravity (moduli) mediation:

- natural in string theory
- Higgs potential automatically at weak scale
- only need to solve the hierarchy problem once!

Supersymmetry

We need

$$m_{3/2} = e^{K/2} W \ll 1$$

Big question:

Why is $m_{3/2}$ so small?

Does the hierarchy come from $e^{K/2}$ or W?

Strings and SUSY

- Low-energy supersymmetry is a great channel to connect string theory to experiment
- The compactification geometry can break supersymmetry
- The compactification geometry determines the sparticle masses
- The existence of low energy supersymmetry can be correlated to very different physics (such as axions).

Strings and SUSY

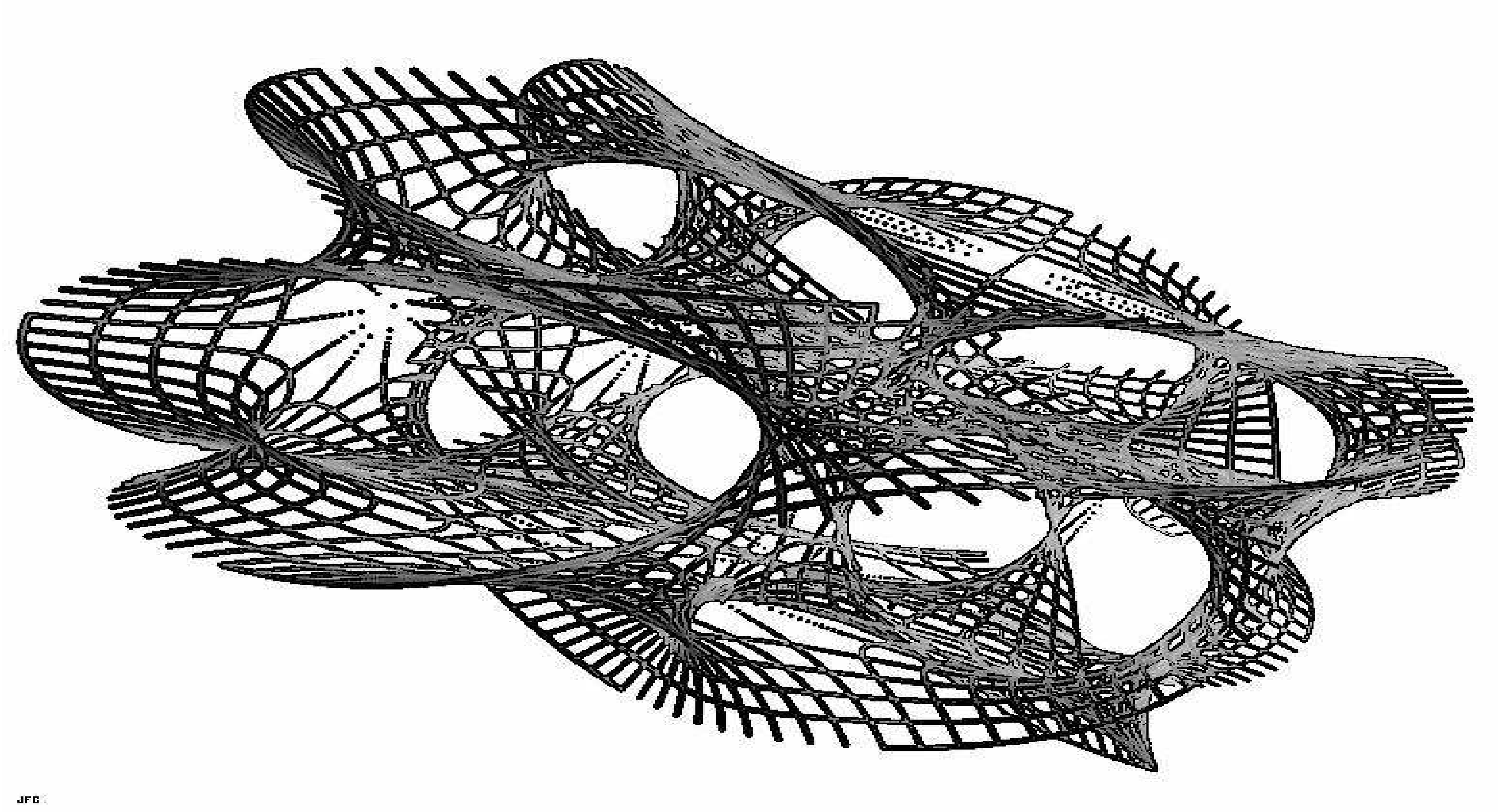
How to realise the Standard Model - heterotic, IIA, IIB?

How to break supersymmetry?

How to generate the hierarchy?

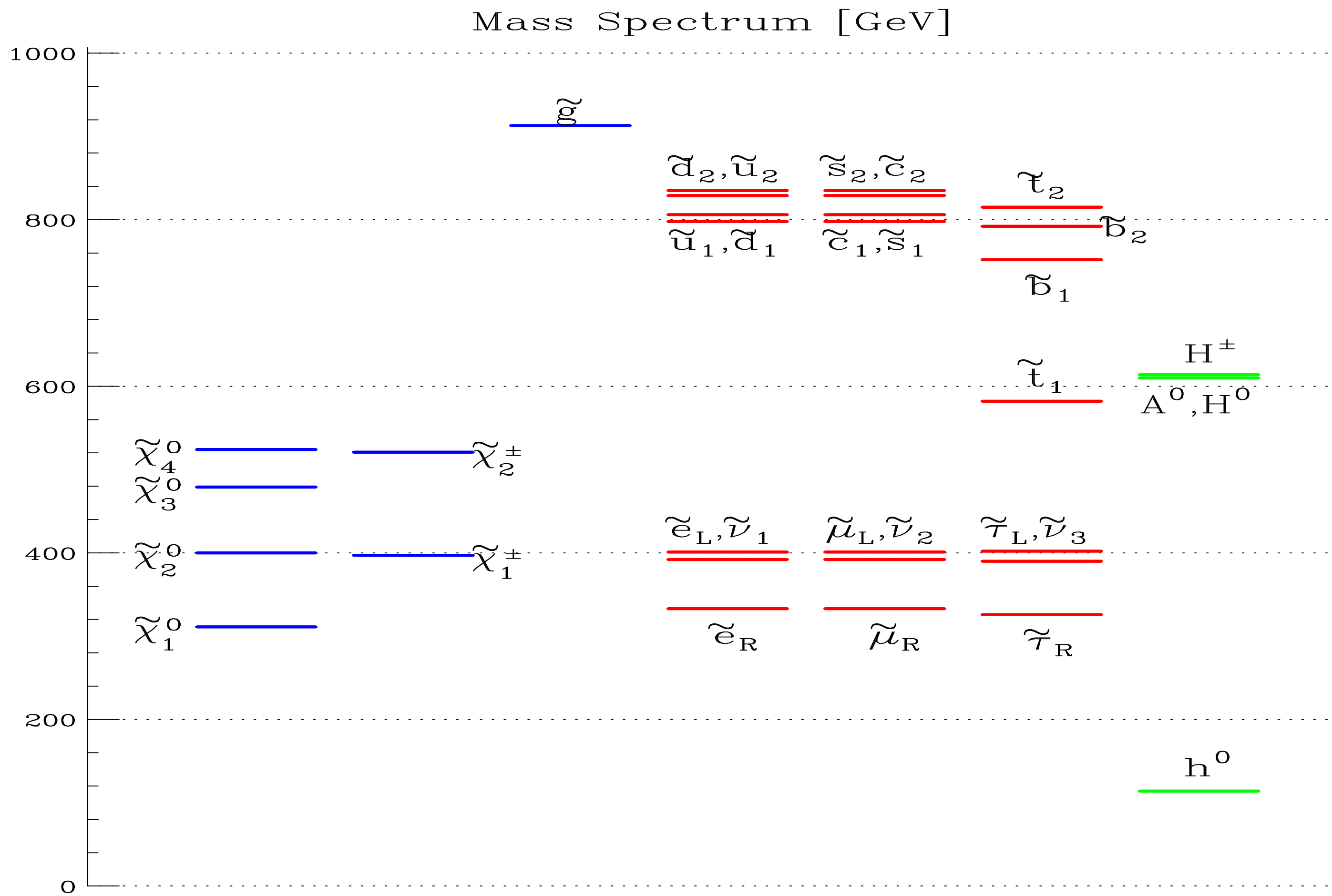
Strings and SUSY

How to go from this...



Strings and SUSY

...to this?



Strings and SUSY

1. Compactify.
2. Work out effective four-dimensional theory.
3. Minimise the moduli potential.
4. Compute the moduli F-terms *in vacuo*.
5. Compute the moduli couplings to Standard Model.
6. Compute the high-scale soft breaking terms.
7. Run soft terms to low energy and compute MSSM Lagrangian.
8. Feed Lagrangian into a Monte Carlo and study the collider phenomenology.

Strings and SUSY

To study the moduli potential and supersymmetry breaking:

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

$$
V = e^{\hat{K}} (\hat{K}^{i\bar{j}} D_i \hat{W} D_{\bar{j}} \bar{\hat{W}} - 3|\hat{W}|^2)
$$

Strings and SUSY

Moduli scalar potential is

$$V = \left(K_{i\bar{j}} F^i F^{\bar{j}} - 3 m_{3/2}^2 M_P^2 \right)$$

Supersymmetry breaking occurs if

$$F^i = e^{K/2} K^{i\bar{j}} (\partial_{\bar{j}} W + (\partial_{\bar{j}} K) W) \neq 0.$$

F-terms parametrise supersymmetry breaking.

No phenomenological restriction on nature of minimum.

Strings and SUSY

We know

$$V = e^K \left(K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2 \right).$$

On physics grounds we expect

$$V = M_s^4 \Big(\text{stuff} \Big).$$

and

$$M_s = e^{-\phi} \frac{M_P}{\sqrt{\mathcal{V}_s}}.$$

Holomorphy prevents T, S appearing in W, suggesting

$$K = -2\ln(\mathcal{V}_s) - 4\ln(g_s)$$

Strings and SUSY

Fields must be written in holomorphic variables:

IIB(D3/D7):

$$T = e^{-\phi}\text{Vol}(\Sigma_4) + iC_4, \;\; U = \int_{\Sigma_3} \Omega, \;\; S = e^{-\phi} + ic_0$$

The moduli space Kähler potential is

$$\hat{K} = -2\ln(\mathcal{V}_E) - \ln\left(i\int \Omega \wedge \bar{\Omega}\right) - \ln(S + \bar{S})$$

This can be rigorously derived through dimensional reduction.

Flux Compactifications

- 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

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

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

$$V = e^{\hat{K}}\left(\sum_{U,S}\hat{K}^{\alpha\bar{\beta}}D_\alpha W\,D_{\bar{\beta}}\bar{W} + \sum_T \hat{K}^{i\bar{j}}D_i W\,D_{\bar{j}}\bar{W} - 3|W|^2\right)$$

$$= e^{\hat{K}}\left(\sum_{U,S}\hat{K}^{\alpha\bar{\beta}}D_\alpha W\,D_{\bar{\beta}}\bar{W}\right)$$

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 $\mathcal{V} \gg 1$,

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

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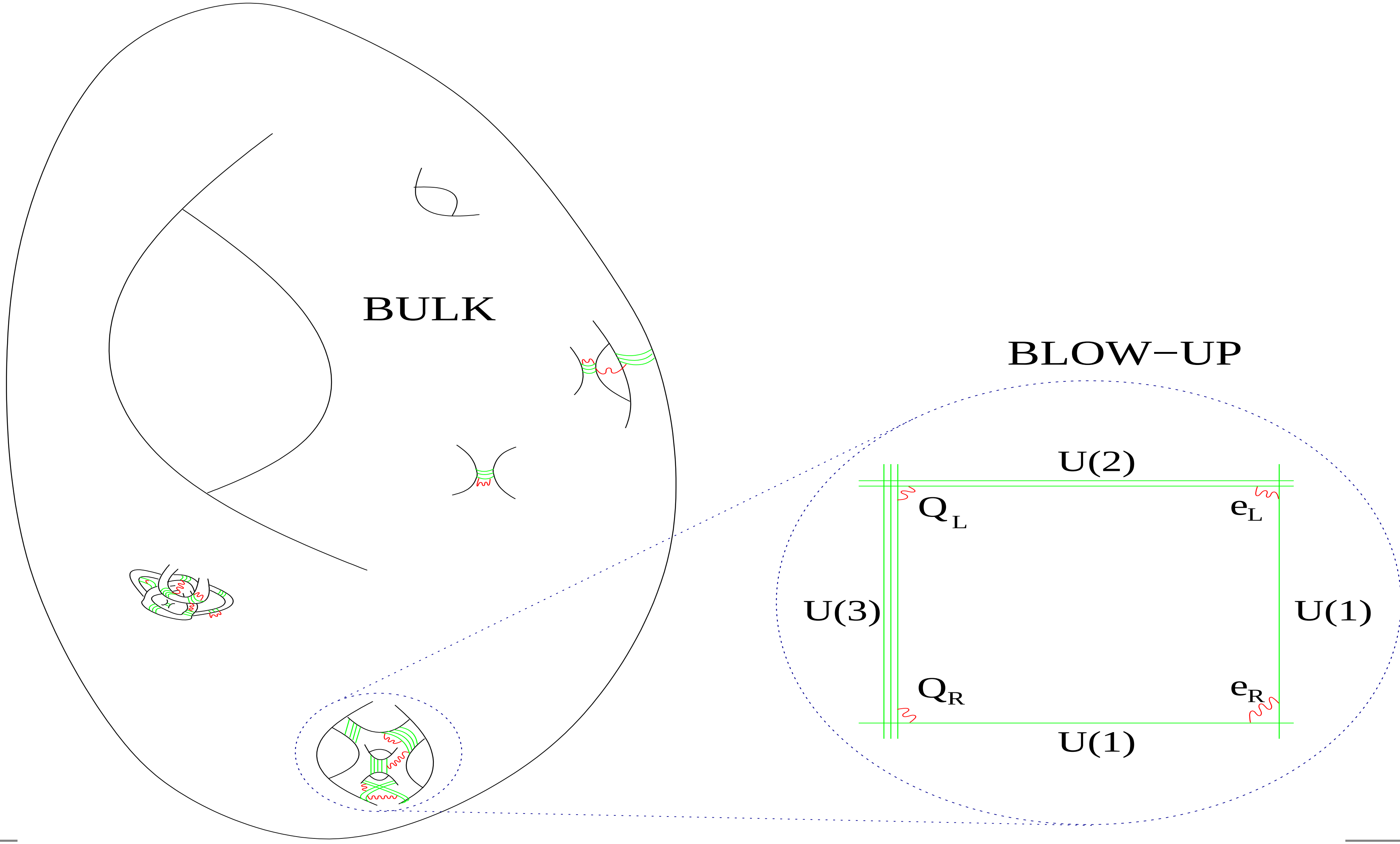
$$V = -\frac{|W_0|^2 (\ln \mathcal{V})^{3/2}}{\mathcal{V}^3} + \frac{\xi |W_0|^2}{g_s^{3/2} \mathcal{V}^3}.$$

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...

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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

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

Soft Terms

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

Couplings to visible matter determine the soft terms.

Soft Terms

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

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

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

Soft Terms

The matter metrics $\tilde{K}_{\alpha\bar{\beta}}$ can be computed if we know where the Standard Model is realised.

For example, in the large-volume models with the Standard Model on D7 branes wrapping a blow-up cycle,

$$\tilde{K}_{\alpha\bar{\beta}} = \frac{{\tau_s}^{1/3}}{\mathcal{V}^{2/3}} k_{\alpha\bar{\beta}}(U, \bar{U}), \;\; f_a = T_s + h_a(F) S$$

Soft Terms

High-scale soft terms are

$$
\begin{aligned}
M_i &= \frac{F^s}{2\tau_s} \equiv M, \\
m_{\alpha\bar{\beta}} &= \frac{M}{\sqrt{3}} \tilde{K}_{\alpha\bar{\beta}}, \\
A_{\alpha\beta\gamma} &= -M \, \hat{Y}_{\alpha\beta\gamma}, \\
B &= -\frac{4M}{3}.
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Big question:

How is the Standard Model realised?

Strings and Flavour Physics

The MSSM has a flavour problem: we need

$$m_{\tilde{u}} = m_{\tilde{c}}, m_{\tilde{d}} = m_{\tilde{s}}, ...$$

Squark mass universality to $\sim 0.5\%$ is constrained by $K_0 - \bar{K}_0$ mixing.

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Why isn't susy breaking sensitive to flavour physics?

Strings and Flavour Physics

For flavour universality, we require

$$
\begin{aligned}
m^2_{\alpha\bar{\beta}} &= m^2 K_{\alpha\bar{\beta}}, \\
A_{\alpha\beta\gamma} &= A Y_{\alpha\beta\gamma}, \\
\phi_{M_1} &= \phi_{M_2} = \phi_{M_3} = \phi_A.
\end{aligned}
$$

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

Strings and Flavour Physics

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:

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

Strings and Flavour Physics

4. The visible metric factorises.

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

5. 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.

Strings and Flavour Physics

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Totally *ad hoc* in effective field theory!

Strings and Flavour Physics

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
- $$IIB : \Psi_{susy} \to T, \chi_{flavour} \to U,$$
  $$IIA : \Psi_{susy} \to U, \chi_{flavour} \to T.$$
- In flux compactifications susy breaking factorises:

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

Strings and Flavour Physics

- The structure of Calabi-Yau moduli space provides a solution to the flavour problem of the MSSM

Naturalness in string theory $\neq$

Naturalness in effective field theory

Open Problem

Find a compactification with:

- The Standard Model matter content and Yukawa couplings
- All moduli stabilised in a controlled fashion
- Hierarchically low susy breaking $m_{3/2} \sim 1$TeV
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Predict all soft terms and MSSM spectrum, and compare with experiment!

Conclusions