Recent Developments in String Phenomenology

Joseph Conlon (Oxford University)

Bad Honnef BSM Workshop

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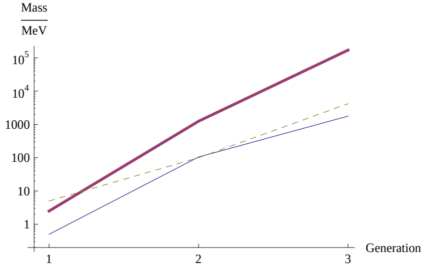
Chalk and Cheese?

Figure: String theory and phenomenology?

Open Problems

- What breaks the electroweak symmetry?
- Why is $\frac{M_{weak}}{M_{Planck}} \sim 10^{-15}$?
- What explains the fermion mass spectrum?



- Why is the preferred axion scale $10^9\text{GeV} \lesssim f_a \lesssim 10^{12}\text{GeV}$?
- Why are neutrinos so light: $0.05\text{eV} \lesssim m_\nu \lesssim 0.3\text{eV}$?

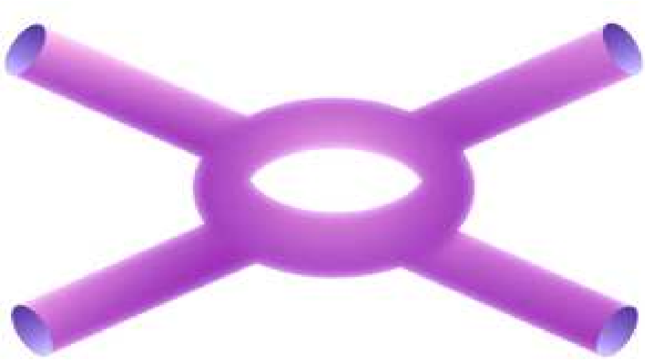
Open Problems

Experimental guidance is coming!

String Theory

These questions cannot all be solved within the (Supersymmetric) Standard Model alone.

To address them, a more fundamental approach is needed...



String Theory

String theory is our best guess for a fundamental theory, and has given important insights into quantum gravity, algebraic geometry, black holes and quantum field theory.

Can string theory do the same for particle physics?

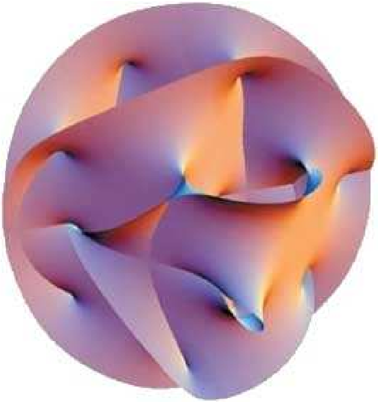
Can our best fundamental theory really *fail* to give insight into the open problems of BSM physics?

String Theory

- String theory is where one is led by studying quantised relativistic strings.
- It encompasses lots of areas (black holes, quantum field theory, quantum gravity, mathematics, particle physics....) and is studied by lots of different people.
- This talk is on string phenomenology - the part of string theory that aims at connecting to the Standard Model and its extensions.
- It aims to provide an overview of this area.

String Theory

Strings are compactified on Calabi-Yau manifolds.



String Theory

String theory translates traditional field theoretic questions about matter content, scales and couplings into geometric questions about the Calabi-Yau and the branes/bundles that are on it.

Physical questions are reinterpreted as geometric questions - broadly speaking two approaches:

- What geometric structures you can put *on* a Calabi-Yau? (model building)
- What are the deformations of a *given* geometry? (moduli stabilisation)

String Phenomenology

Work on string phenomenology falls into several categories:

- Model building - constructing geometries that reproduce/explain(?) the matter content and interactions of the Standard Model.
- Moduli stabilisation - fixing the moduli of the compactification, addressing supersymmetry breaking, cosmological evolution.
- Phenomenology of strings - strings at colliders

Model Building

Various approaches in string theory to realising Standard Model-like spectra:

- $E_8 \times E_8$ heterotic string with gauge bundles
- Type I string with gauge bundles
- IIA/IIB D-brane constructions
- Heterotic M-Theory
- M-Theory on G2 manifolds
- F-theory GUTs

Grand Unified Theories

Several phenomenological features suggest GUTs are on the right track:

- Precision gauge coupling unification in the MSSM
- Arrangement of quarks and leptons into complete $SU(5)$ multiplets with correct hypercharge assignments.
- Success of b/τ mass unified mass relations.

Grand Unified Theories

However 4-dimensional GUTs have several problems:

- GUT group must be broken by large representations (e.g. **126** Higgs multiplet)
- Doublet-triplet splitting - Higgs does not come in complete $SU(5)$ representations.
- Yukawa unification does not work that well for first two matter families.

What do stringy GUTs look like, and how do they work?

Heterotic String

Start with an $E_{8,vis} \times E_{8,hid}$ gauge group in ten dimensions.

The gauge group is broken and chiral matter generated by an appropriate choice of gauge field in the Calabi-Yau.

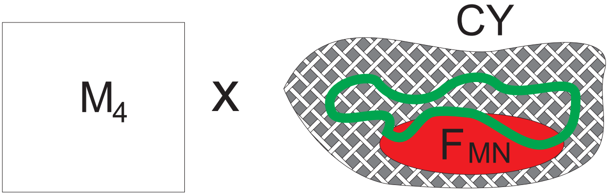
$$E_{8,vis} \times E_{8,hid} \to SU(5)_{vis} \times E_{8,hid}, E_{6,vis} \times E_{8,hid}$$

Further Wilson lines are needed to break to the Standard Model.

Requires a holomorphic, stable vector bundle to break to a GUT.

GUT breaking carried out by discrete Wilson lines in the internal Calabi-Yau.

Heterotic String



Schematic of heterotic compactification: the gauge bundle F_{MN} breaks the $E_8 \times E_8$ gauge group and sources chiral zero modes, which extend throughout the bulk space.

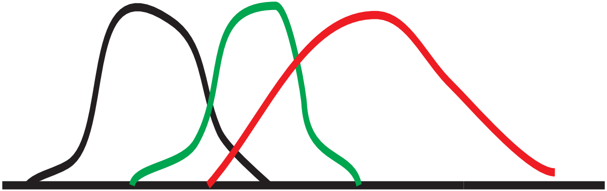
Heterotic String

Weakly coupled heterotic string is a global construction.

Gauge fields propagate on the bulk of the Calabi-Yau.

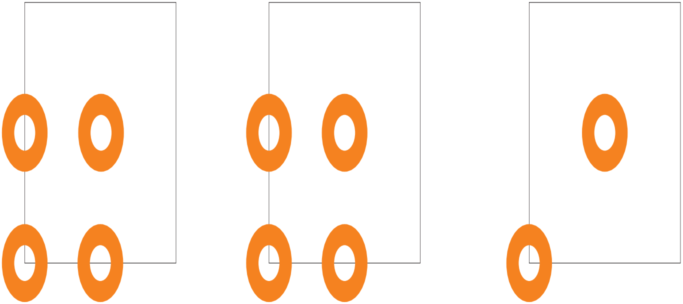
$$\alpha_{GUT} \sim \frac{1}{\mathcal{V}}, \qquad M_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}.$$

String scale is necessarily close to the Planck scale.
Yukawa couplings come from wavefunction overlap.



Heterotic Orbifolds

At particular points in the moduli space Calabi-Yau becomes an orbifold. On orbifolds string theory can be quantised and exact string interactions can be computed.



Heterotic Orbifolds

At orbifold point geometric cycles shrink to zero size and are localised on orbifold fixed points. Gauge flux on collapsing cycles becomes localised at the fixed point.

Heterotic orbifolds represent one particular (computable) limit of heterotic Calabi-Yau compactifications - precise relationship studied by (Nibbelink, Trapletti, Vaudevrange...)

An old program (dates back to mid-80s) but recently rejuvenated (Local grand unifications, heterotic mini-landscape...) (Nilles, Ramos-Sanchez, Ratz, Vaudevrange...)

Heterotic Orbifolds

Different orbifold fixed points have different GUT gauge groups due to different local gauge flux.

Fixed points may have

$$G_{SM} \in \mathcal{G}_1 = SO(10),$$

$$G_{SM} \in \mathcal{G}_2 = E_6,$$

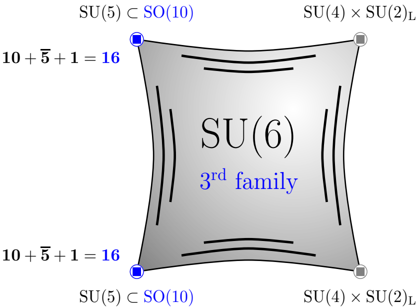
$$G_{SM} \in \mathcal{G}_3 = SU(4) \times SU(2) \times SU(2).$$

4d gauge group is the bulk intersection

$$G_{4d} = \mathcal{G}_1 \cap \mathcal{G}_2 \cap \mathcal{G}_3 = SU(3) \times SU(2) \times U(1)$$

Heterotic Orbifolds

Different matter generations can localise at different fixed points, or be supported in the bulk. (figure from 0806.3905 Nilles et al)



GUT is broken globally but preserved locally - GUT structure for SM families.

Heterotic Orbifolds

Various interesting phenomenological features:

- Potential Yukawa hierarchies
- Attractive matter content
- Natural GUT structures

Heterotic Orbifolds

Advantages:

- Can scan over many models
- Fertile region - many MSSM spectra can be found (Z_6 orbifolds)
- Many GUT structures are present

Disadvantages:

- Orbifold point is very particular in moduli space - why should moduli be fixed there?
- Moduli stabilisation and supersymmetry breaking

Smooth Heterotic Compactifications

These are the oldest phenomenological string compactifications (Candelas, Horowitz, Strominger, Witten 1985).

We need to satisfy anomaly cancellation

$$c_2(F) = \mathrm{Tr}(F \wedge F) = \mathrm{Tr}(\mathcal{R} \wedge \mathcal{R}) = c_2(\mathcal{R}).$$

and the Hermitian Yang-Mills equations:

$$F_{ab} = F_{\bar{a}\bar{b}} = g^{a\bar{b}} F_{a\bar{b}} = 0.$$

The simplest solution is the standard embedding $F = \mathcal{R}$.

Calabi-Yau has $SU(3)$ holonomy and so $F \in SU(3)$. Commutant of $SU(3)$ in E_8 is E_6 and low energy gauge group is $E_6 \times E_8$.

Smooth Heterotic Compactifications

How to generalise the standard embedding?

Need (poly)-stable holomorphic vector bundles satisfying $c_2(F) = c_2(\mathcal{R})$.

Low energy gauge group is determined by structure group of F:

$$\begin{aligned}
\mathcal{F} \in SU(3) &\rightarrow \mathcal{G} = E_6 \times E_8. \\
\mathcal{F} \in SU(4) &\rightarrow \mathcal{G} = SO(10) \times E_8. \\
\mathcal{F} \in SU(5) &\rightarrow \mathcal{G} = SU(5) \times E_8.
\end{aligned}$$

Further Wilson line breaking reduces to Standard Model.

Hard (mathematical) task is to prove stability of the vector bundle - recent progress in these areas.

Smooth Heterotic Compactifications

Subject (stable vector bundles) is mathematical by its nature.

Several individual models have been constructed over recent years (Blumenhagen, Bouchard, Braun, Cvetic, Donagi, He, Moster, Ovrut, Reinebacher, Weigand).

'Heterotic standard model' (Ovrut and Penn group) - exact MSSM spectrum with an additional unbroken $U(1)_{B-L}$.

Models with $U(N)$ bundles (Blumenhagen, Moster, Weigand)

Is it possible to have general classes of models?

Smooth Heterotic Compactifications

Recently techniques of monad bundles have allowed enumeration of large classes of stable vector bundles on Calabi-Yaus. Anderson, Gray, He, Lukas

This allows scans over thousands of models at a time - analogue of 'mini-landscape' scans in heterotic orbifold models.

A new 'heterotic standard model' with the exact MSSM spectrum has recently been found, as part of the development of an algorithmic approach to string phenomenology.

Smooth Heterotic Compactifications

Advantages:

- More general than orbifold models
- New techniques to scan over many models

Disadvantages:

- No CFT description, algebraic geometry techniques are hard.
- Moduli stabilisation and supersymmetry breaking

D-brane constructions

Solitonic objects (D-branes) carry worldvolume gauge fields.

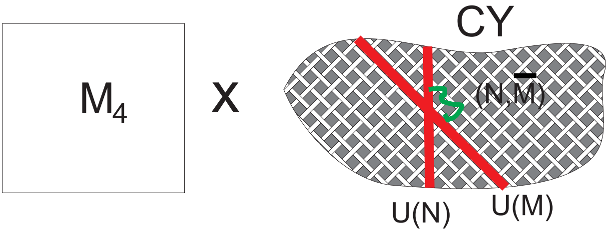
Intersections of two D-branes give chiral matter on the intersection.

Models of intersecting D-branes can give non-abelian gauge groups with chiral matter and may provide a basis for realising the Standard Model. (Blumenhagen, Cvetic, Gmeiner, Honecker, Ibanez, Lust, Marchesano, Shiu, Stieberger, Uranga,....)

Stability of D-branes requires classifying special Lagrangian cycles/coherent sheaves on a Calabi-Yau.

D-brane constructions lead to non-GUT approaches to reconstructing the Standard Model spectrum.

D-brane constructions



Schematic of IIA D-brane compactification: D-branes wrap geometric cycles in the Calabi-Yau and chiral matter is supported on D-brane intersections.

D-brane constructions

- Strength of gauge group is determined by volume of cycle Σ_i wrapped by D-brane:

$$\alpha_i \sim \frac{1}{\mathrm{Vol}(\Sigma_i)}, \qquad M_s \sim \frac{M_P}{\sqrt{\mathrm{Vol}(CY)}}.$$

- As $\mathrm{Vol}(\Sigma_i)$ and $\mathrm{Vol}(CY)$ are not necessarily connected, string scale can be much lower than the Planck scale.
- Can imagine Standard Model constructions with string scales close to the TeV scale.

Branes at Singularities

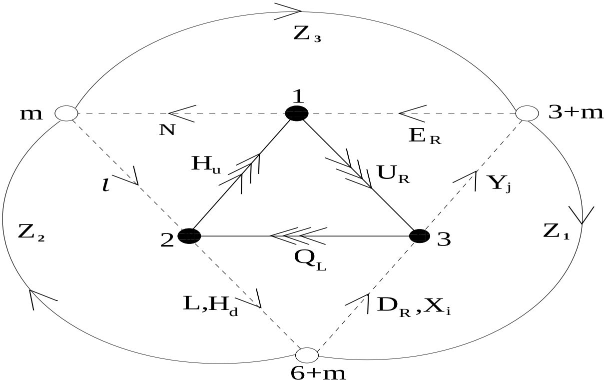
One can also built models with D3/D7 branes at singlarities. (Aldazabal, JC, Ibanez, Krippendorf, Maharana, Quevedo, Uranga, Verlinde, Wijnholt)

Models are highly local - all matter and gauge groups are supported on a single point-like singularity.

These are a limited class of models, but they have attractive features:

- CFT control in many cases
- Decoupling of gauge and gravitational interactions

Branes at Singularities



D-brane Gepner Models

Can also do equivalent of D-brane models at the Gepner points in moduli space (Schellekens...).

No geometric interpretation, but CFT is exactly soluble and so all computations can be performed.

Gepner CFTs are highly algorithimised and provide the largest class of MSSM-like models.

Such models are restricted to the Gepner point (so moduli stabilisation cannot be addresses) but provide an enormous class of models.

D-brane Models

Advantages:

- Easy geometric interpretation and CFT techniques.
- Naturally incorporates low string scales and non-GUT structures.
- Closer fit to moduli stabilisation

Disadvantages:

- Naturally incorporates low string scales and non-GUT structures.
- Cannot include GUTs

F-theory constructions

(Blumenhagen, Donagi, Grimm, Hebecker, Heckman, Marsano, Saulina, Schafer-Nameki, Vafa, Watari, Wijnholt, ...)

- An extension of D-brane constructions which includes certain non-perturbative effects.
- Branes are geometrised as the singularities of an 8-dimensional space: includes D-branes and also further exceptional branes.
- Shares properties of brane constructions such as localisation of gauge groups, but also naturally allows for the possibility of GUT models.
- Can also have the string scale be much lower than the Planck scale.

F-theory constructions

GUT breaking is accomplished by hypercharged flux $F \in U(1)_Y$.

Commutant of $U(1)_Y$ in $SU(5)$ is $SU(3) \times SU(2) \times U(1)$, and so flux breaks GUT group down to Standard Model.

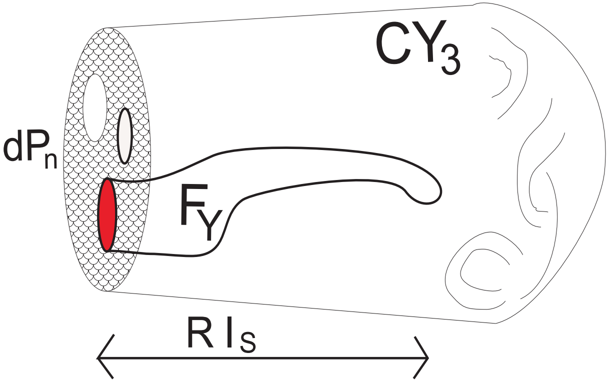
However to avoid inducing a mass for $U(1)_Y$ via the Green-Schwarz mechanism and the coupling

$$\int C_2 \wedge F_{U(1)_Y},$$

need the flux to wrap a cycle that is nontrivial locally but trivial globally.

Crucial geometric condition on the geometry.

F-theory constructions



F-theory constructions

Advantages:

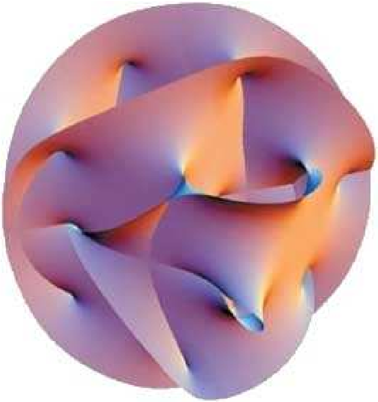
- Brane-like objects with GUT properties
- Link to IIB suggests fit with moduli stabilisation

Disadvantages:

- No CFT or microscopic description
- Failure of gauge coupling unification?

Moduli Stabilisation

Strings are compactified on Calabi-Yau manifolds.



Moduli Stabilisation

Geometric deformations of Calabi-Yau manifolds appear as (naively) massless scalars in 4 dimensions.

Calabi-Yaus have two basic deformations:

- Kähler (size) deformations: modifying the Kähler form $J = \sum t^i \omega^i$ of the Calabi-Yau.
- Complex structure (shape) deformations modifying the complex structure of the Calabi-Yau.

Kähler deformations are counted by $h^{1,1}(\mathcal{M})$ and complex structure deformations are counted by $h^{2,1}(\mathcal{M})$.

Moduli Stabilisation

It is necessary to give masses to moduli to avoid fifth forces bounds.

The process of moduli stabilisation is also closely tied to supersymmetry breaking.

Moduli stabilisation is best described in the framework of 4-dimensional supergravity.

We need to determine the

- Kähler potential, $\mathcal{K}(\Phi, \bar{\Phi})$.
- Superpotential, $W(\Phi)$.

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

Moduli Stabilisation

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

Moduli potential is a potential for scalar fields.

- Can be used to try and realise inflation in string theory. lots and lots of people...
- Also is very important for understanding supersymmetry breaking - minima of V can break supersymmetry and generate soft terms.
- We look at supersymmetry breaking in more detail.

Moduli Stabilisation (IIB)

The Kähler potential is

$$\mathcal{K} = -2 \underbrace{\ln \mathcal{V}(T+\bar{T})}_{\text{Kähler}} - \underbrace{\ln\left(i\int \Omega \wedge \bar{\Omega}(U,\bar{U})\right)}_{\text{complex structure}} - \underbrace{\ln(S+\bar{S})}_{\text{dilaton}}$$

Three-form fluxes can stabilise the dilaton and complex structure moduli:

$$W = \int G_3 \wedge \Omega$$

Gives an effective no-scale model:

$$\begin{aligned} \mathcal{K} &= -2\ln \mathcal{V}(T+\bar{T}), \\ W &= W_0. \end{aligned}$$

Broken supersymmetry and vanishing vacuum energy.

Moduli Stabilisation: Fluxes

- Fluxes carry an energy density which generates a potential for the cycle moduli.
- In IIB compactifications, 3-form fluxes generate a superpotential (Giddings, Gukov, Kachru, Polchinski, Sethi, Vafa, Taylor, Witten)

$$
\begin{aligned}
K &= -2\ln(\mathcal{V}) - \ln\left(i\int \Omega \wedge \bar{\Omega}\right) - \ln(S + \bar{S}) \\
W &= \int (F_3 + iSH_3) \wedge \Omega \equiv \int G_3 \wedge \Omega.
\end{aligned}
$$

- This stabilises the dilaton and complex structure moduli.

$$D_S W = D_U W = 0.$$

$$W = \int G_3 \wedge \Omega = W_0.$$

Moduli Stabilisation: Fluxes

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

No-scale model :

- vanishing vacuum energy
- broken susy
- T unstabilised

No-scale is broken perturbatively and non-pertubatively.

Moduli Stabilisation: KKLT

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

- Non-perturbative ADS superpotential.
- The T-moduli are stabilised by solving $D_T W = 0$.
- This gives a susy AdS vacuum which is uplifted by anti-branes/magnetic fluxes/IASD 3-form fluxes/F-terms/something else.
- Susy breaking is sourced by the uplift. (Choi, Nilles, ...)

Moduli Stabilisation: KKLT

KKLT stabilisation has three phenomenological problems:

1. No susy hierarchy: fluxes prefer $W_0 \sim 1$ and $m_{3/2} \gg 1\text{TeV}$.
2. Susy breaking not well controlled - depends entirely on uplifting.
3. α' expansion not well controlled - volume is small and there are large flux backreaction effects.

Moduli Stabilisation: Large-Volume

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

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

- Include perturbative as well as non-perturbative corrections to the scalar potential.
- Add the leading α' corrections to the Kähler potential (Becker-Becker-Haack-Louis).
- These descend from the $\mathcal{R}^4$ term in 10 dimensions.
- This leads to dramatic changes in the large-volume vacuum structure. Balasubramanian, Berglund, JC, Quevedo, Suruliz, Cicoli.....

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

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

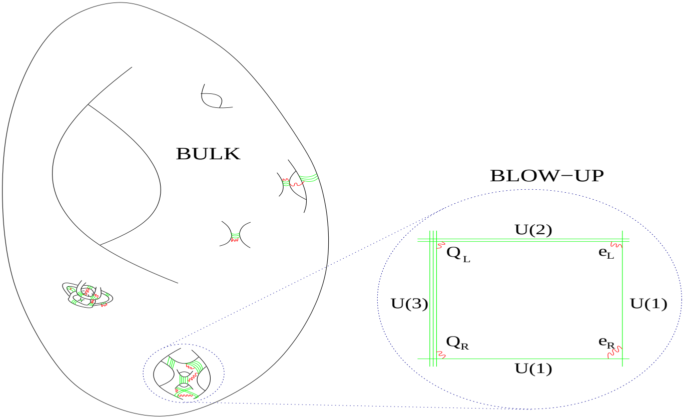
$$V = -\frac{|W_0|^2 (\ln \mathcal{V})^{3/2}}{\mathcal{V}^3} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

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 $\mathcal{V} \sim 10^{15}$.
- D7-branes wrapped on small cycle carry the Standard Model: need $T_s \sim 20(2\pi\sqrt{\alpha'})^4$.
- The vacuum is pseudo no-scale and breaks susy...

Phenomenology of strings

So far have describe approaches to building string models reproducing Standard Model features and how to stabilise extra-dimensional geometry.

Who cares?

Are there any differences between string theory and 4-dimensional effective quantum field theory?

If not, then what is the point of the subject?

What are examples of stringy added value?

Phenomenology of strings

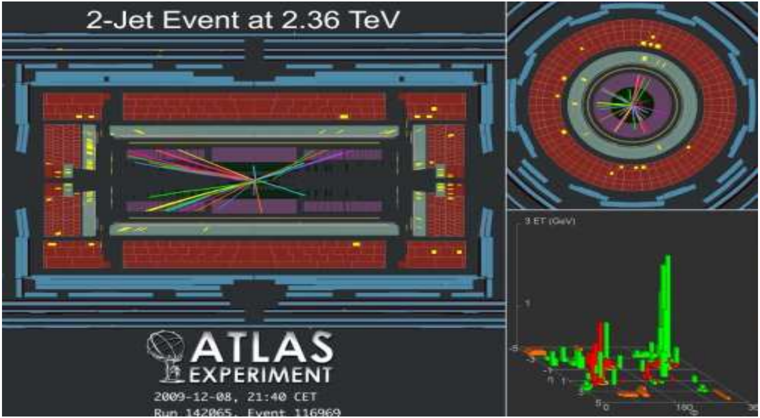
String phenomenology naturally includes the phenomenology of strings.

What if the quantum gravity scale was a TeV? (Antoniadis, Lykken...)

How would we tell? What would be the distinctive features of TeV-scale gravity and strings?

Phenomenology of strings

How to distinguish



Phenomenology of strings

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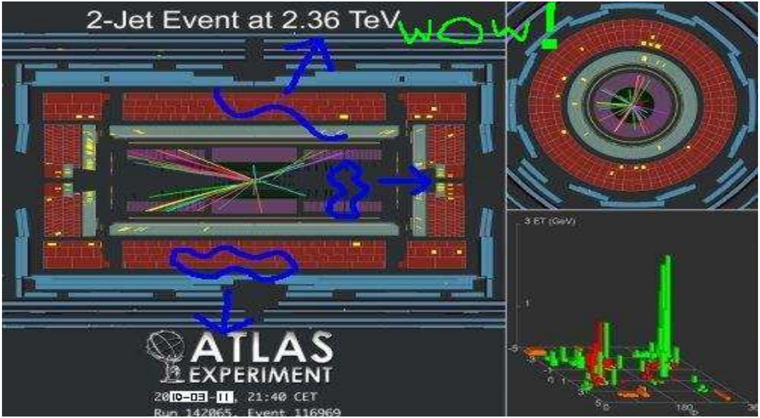
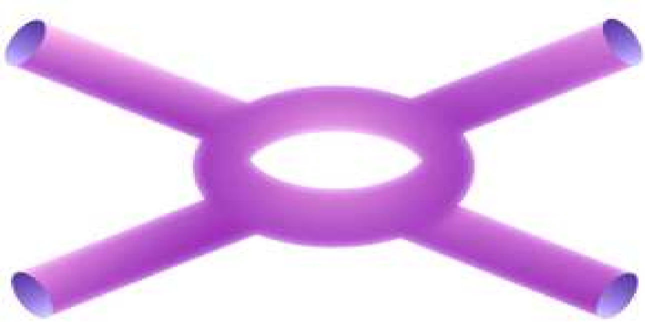


Phenomenology of strings

Yes! (Lust, Stieberger, Schlotterer, Taylor)

If strings are at a TeV then string scattering is important:



Phenomenology of strings

String scattering can be computed via vertex operators:

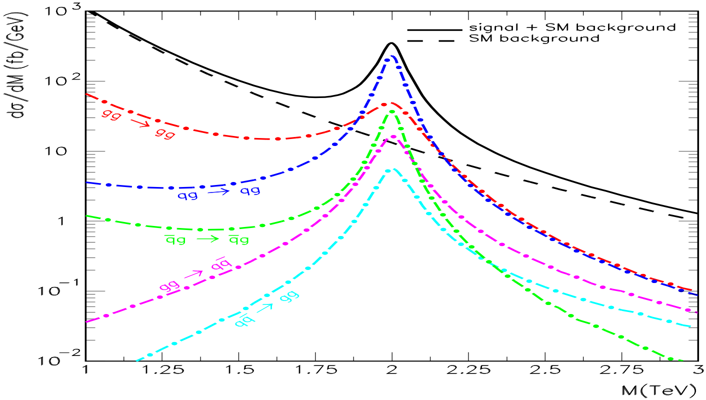
$$\int d^2 z_i \langle \mathcal{V}(k_1, a_1)\mathcal{V}(k_2, a_2)\mathcal{V}(k_3, a_3)\mathcal{V}(k_4, a_4)\rangle.$$

Stringy form factors compared to field theory amplitudes:

$$V(s,t,u) = \frac{\Gamma(1 - s/M_s^2)\Gamma(1 - u/M_s^2)}{\Gamma(1 - u/M_s^2)}.$$

Stringy states give resonances in $2 \rightarrow 2$ scattering amplitudes - can also compute $2 \rightarrow 3$ and other amplitudes using string techniques.

Phenomenology of strings



(Picture: 0808.4097 Anchordoqui et al) Spectacular direct signals of strings!

The MSSM Flavour Problem

The LHC hopes to discover supersymmetry.

But why should any new susy signatures occur at all?

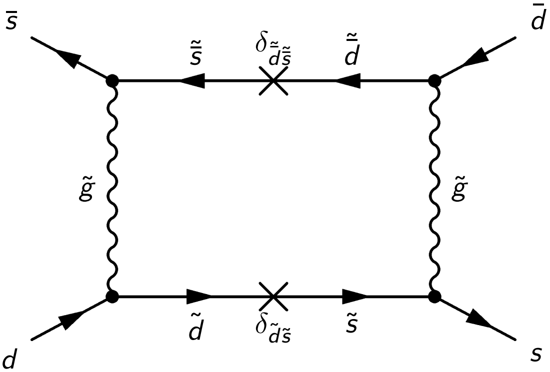
One major problem:

Why hasn't supersymmetry been discovered already?

Compare with

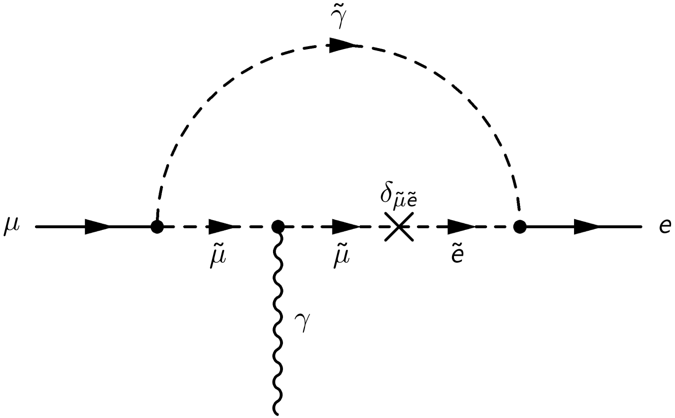
- The c quark - predicted before discovery through its contribution to FCNCs (the GIM mechanism)
- The t quark - mass predicted accurately through loop contributions at LEP I.

The MSSM Flavour Problem



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

The MSSM Flavour Problem



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

The MSSM Flavour Problem

SUSY is a happy bunny if soft terms are flavour universal.

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

Why should this be?

- Answer to flavour problem significantly affects all of susy phenomenology.
- This problem cannot be addressed purely within effective field theory - needs UV completion.

The MSSM Flavour Problem

- The flavour problem says that supersymmetry breaking cannot know about flavour physics.
- *A priori*, this is unnatural - why should the susy breaking sector be entirely ignorant of flavour?
- String theory can give a natural answer. (Choi, JC ...)

The size and shape fields of the Calabi-Yau are factorised

$$\Phi_{all} = \Psi_{Kahler} \oplus \chi_{complex}$$

Ψ and χ represent two distinct and decoupled sectors.

$$\mathcal{K} = -2 \underbrace{\ln \mathcal{V}(T + \bar{T})}_{\text{Kähler}} - \underbrace{\ln \left(i \int \Omega \wedge \bar{\Omega}(U, \bar{U}) \right)}_{complexstructure} - \underbrace{\ln(S + \bar{S})}_{dilaton}$$

The MSSM Flavour Problem

We have

$$\Phi_{all} = \Psi_{Kahler} \oplus \chi_{complex}$$

with Ψ and χ representing two distinct and decoupled sectors.

It turns out that

1. Ψ_{Kahler} gives rise to supersymmetry breaking.
2. $\chi_{complex}$ generates the flavour structure: $Y_{\alpha\beta\gamma} = Y_{\alpha\beta\gamma}(\chi)$.

Supersymmetry breaking and flavour physics decouple and soft terms are flavour universal!

The origin of this decoupling is the geometric properties of Calabi-Yaus.

The End

- I have tried to provide an overview of the area of string phenomenology
- Apologies to everyone I missed out/ misrepresented/ under-referenced/ over-referenced.
- Subject is a vibrant area covering topics from algebraic geometry to collider physics.
- Have described issues of model building, moduli stabilisation and phenomenological examples of stringy 'added value'.