M Theory and the LHC

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Supersymmetry: From M Theory to the LHC
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and other work in progress
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- In the last two decades things have changed: non-perturbative regimes were found, and new corners of String/M Theory have been opened to phenomenology.

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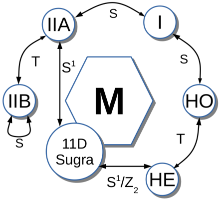

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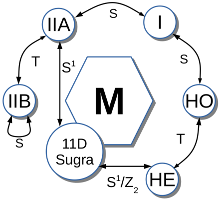

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- In $d = 11$, M Theory is a maximal SUSY theory with 32 real supersymmetric charges. In order to have $\mathcal{N} = 1$ in $d = 4$ we have to compactify on a manifold with G_2 holonomy.

Outline

1. Introduction and Motivation
   - Motivation
   - Introduction to M Theory Model Building
2. $SO(10)$ SUSY GUTs from M Theory
3. Recent developments and current work [to appear]
4. Conclusions and future work

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- Moduli fields are generically charged under discrete symmetries of K and acquire vevs $\Rightarrow$ Kahler interactions with matter will generate effective superpotential terms.

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- All possible $\mathcal{W}$ commute between them $\Rightarrow$ each $\mathcal{W}$ is a diagonal element of the GUT group and the breaking pattern is rank preserving.

- A convenient way of representing $\mathcal{W}$ is

$$\mathcal{W} = \sum_m \frac{1}{m!} \left(\frac{i2\pi}{n} \sum_j a_j Q_j \right)^m ,$$

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- Doublet-triplet problem solution for $SU(5)$ (hep-ph/1102.0556): $\mathcal{W} = \mathrm{diag}(\eta^\delta, \eta^\delta, \eta^\delta, \eta^\gamma, \eta^\gamma)$, $\eta^n = 1$, $3\delta + 2\gamma = 0 \mod n$:

$$\overline{\mathbf{5}} = \overline{D} \oplus H_d \to \eta^\delta \overline{D} \oplus \eta^\gamma H_d$$

with $\mu H_u H_d$ being effectively generated by Kahler potential interactions with moduli, Giudice-Masiero mechanism

$$K \supset \frac{s}{m_{Pl}} H_u H_d + \text{h.c.} \to \mu_{eff} \sim \frac{\langle s \rangle m_{3/2}}{m_{Pl}} \sim \mathcal{O}(\text{TeV}),$$

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as, in M theory, $m_{3/2} \sim \mathcal{O}(10\text{TeV})$, $\langle s \rangle \sim 0.1 m_{Pl}$.
- Furthermore, from usual SUGRA expressions, soft scalar masses are $\mathcal{O}(m_{3/2}) \sim \mathcal{O}(10 \text{ TeV})$, while $m_{1/2} \ll \mu$ (hep-ph/0801.0478).

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    - The presence of light coloured states will ruin unification *as they do not form a full GUT multiplet*.
    - Moduli vevs break the discrete symmetry, leading to to proton-decay interactions from Kahler interactions (c.f. Giudice-Masiero for μ terms).

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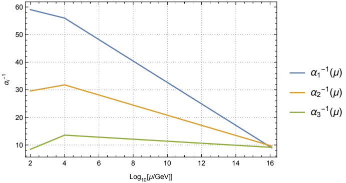

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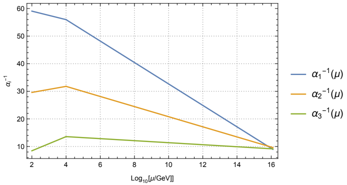

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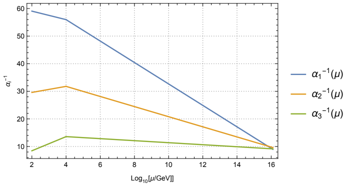

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- The addition of an extra family has other benefits for model building: $N_X, \overline{N}_X$ vevs $(v_X, \overline{v}_X)$ **break the rank of the gauge group** and **generate Right-handed neutrinos Majorana masses**.

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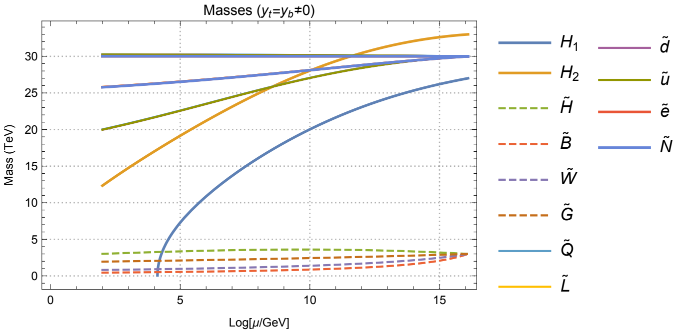
- A (generic) RGE analysis of the spectrum with universal soft terms



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- Futhermore there is a problematic bilinear RPV contribution:

$$K \supset \frac{s}{m_{Pl}^2} N_X L H_u + \text{h.c.},$$

as see-saw requirements $v_X \sim 10^{16}$ GeV this leads to an effective term $\mathcal{O}(100 \text{ GeV})$ while the upper bound $\lesssim \mathcal{O}(\text{ GeV})$ (hep-ph/0004115) $\Rightarrow$ appeal for non-generic moduli discrete charges configurations that further suppress the Kahler potential term.

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  - We need to break the extra $U(1)$ at the field theory level, which is a challenge task on its own.
  - How can we consolidate a high-scale vev with B-RPV bounds?

- Realistic Yukawa textures: if we consider that the UV spectrum has n $\mathbf{16}$ and m $\overline{\mathbf{16}}$, so for $n - m = 3$ the mass matrix

$$\mathbf{16}_i M_{ij} \overline{\mathbf{16}}_j \tag{1}$$

has at most rank$= 3$. Furthermore, if some of the UV states absorb Wilson line phases then the matrix will generally *not* be $SO(10) \Rightarrow$ the light spectrum will be composed of 3 effective $\mathbf{16}$ which will not have $SO(10)$ textures.

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- Symmetry breaking: we can employ a variation of a Kolda-Martin mechanism (Phys.Rev. D53 (1996) 3871-3883 , [hep-ph/9503445]) where $(N_X, \overline{N}_X)$ system is aligned in the D-flat direction of the potential. In conjugation with the above solution, v_X needs not to be $\mathcal{O}(10^{16})$ GeV any more, hence evading the dangerous B-RPV operators.

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1. Introduction and Motivation
   - Motivation
   - Introduction to M Theory Model Building
2. $SO(10)$ SUSY GUTs from M Theory
3. Recent developments and current work [to appear]
4. Conclusions and future work

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  - Collider signatures and phenomenology of the new light-sates.

Thank you!

Backup slides: Hierarchy M Theory

- In M Theory, moduli are stabilised and SUSY is broken by a confining hidden sector (hep-th/0701034).
- The hidden sector allows for a two chiral supermultiplets that originate a condensate,ϕ, due to two gauge groups $SU(P) \times SU(Q)$.
- Due to axionic PQ symmetry, the hidden sector superpotential is non-perturbative

$$W_{hidd} \sim c_1 \phi^{-2/P} e^{-\sum N_i s_i 2\pi/P} + c_2 e^{-\sum N_i s_i 2\pi/Q}$$

  c_i are complex numbers with order 1 module, N_i are determined by the homologies of the hidden 3-cycles.
- The above construction *formally* fixes all moduli and, since

$$m_{3/2} \propto e^K |W_{hidd}|$$

  hierarchy for the visible sector.

Backup slides: Hierarchy M Theory

- Numerical studies with reasonable, expectable, values for parameters return $m_{3/2} \sim \mathcal{O}(10 \text{ TeV})$.
- Through usual SUGRA formulae, one can find the order of the values for soft terms and μ term (Giudice-Masiero) as hidden (moduli and mesonic) fields acquire vevs.
- The gaugino GUT-scale mass is suppressed as it is (to leading order) set by the F-term of the hidden mesonic field, which can be found in M Theory to be suppressed in comparison with other vevs.

Backup slides: Multiplet **10** don't save naive doublet-triplet splitting solution

- Consider an additional $\mathbf{10}^h$ multiplet, without Wilson line phases: $\mathbf{10}^h \to \eta^\xi \mathbf{10}^h$.
- All the possible gauge invariant couplings between $\mathbf{10}^w$ and $\mathbf{10}^h$ are

$$W \supset \mathbf{H}_d^T \cdot \mu_H \cdot \mathbf{H}_u + \overline{\mathbf{D}}^T \cdot M_D \cdot \mathbf{D},$$

where μ_H and M_D are two 2×2 superpotential mass parameters matrices, $\mathbf{H}_{u,d}^T = \left(H_{u,d}^w, H_{u,d}^h\right)$, $\overline{\mathbf{D}}^T = \left(\overline{D}^w, \overline{D}^h\right)$, and $\mathbf{D}^T = \left(D^w, D^h\right)$.

- **There is no choice of vanishing constraints that leaves one eigenvalue of μ_H light while keeping both masses of M_D heavy.**

Backup slides: RPV violating terms from the Kahler potential

- Consider the relevant Kahler potential operators

$$K \supset \frac{s}{M_{Pl}^2} DQQ + \frac{s}{M_{Pl}^2} De^c u^c + \frac{s}{M_{Pl}^2} DNd^c + \\ + \frac{s}{M_{Pl}^2} \overline{D} d^c u^c + \frac{s}{M_{Pl}^2} \overline{D} QL.$$

- The effective potential may be calculated a la Giudice-Masiero to be

$$W_{eff} \supset \lambda DQQ + \lambda De^c u^c + \lambda DNd^c + \\ + \lambda \overline{D} d^c u^c + \lambda \overline{D} QL,$$

where

$$\lambda \approx \frac{1}{M_{Pl}^2} \left(\langle s \rangle m_{3/2} + \langle F_s \rangle \right) \sim 10^{-14}.$$

Backup slides: Proton decay and coloured triplets lifetime

- The proton-decay rate can be estimated by

$$\Gamma_p \approx \frac{\left|\lambda^2\right|^2}{16\pi^2} \frac{m_p^5}{m_D^4}.$$

- $m_D \sim \mathcal{O}(10)$ TeV, so the proton lifetime is

$$\tau_p = \Gamma_p^{-1} \sim 10^{38} \text{ yrs.}$$

- The D triplet decay rate can also be estimated

$$\tau_D = \Gamma_D^{-1} \sim \left(\lambda^2 m_D\right)^{-1} \sim 0.1 \text{ sec},$$

which is consistent with BBN constraint.

Backup slides: The vector-like family splitting and unification

- Such solution exists if either $\mathbf{16}_X$ or $\overline{\mathbf{16}}_X$ absorb Wilson line phases. Considering

$$\mathbf{16}_X \to \eta^x \left(\eta^{-3\gamma} L \oplus \eta^{3\gamma+\delta} e^c \oplus \eta^{3\gamma-\delta} N \oplus \eta^{-\gamma-\delta} u^c \oplus \right.$$
$$\left. \oplus \eta^{-\gamma+\delta} d^c \oplus \eta^{\gamma} Q \right).$$

  and $\overline{\mathbf{16}}_X \to \eta^{\overline{x}}\, \overline{\mathbf{16}}_X$, the splitting condition is given by

$$\overline{d^c}_X d^c_X : x - \gamma + \delta + \overline{x} = 0 \mod n,$$

  while forbidding all the other self couplings from $\mathbf{16}_X \overline{\mathbf{16}}_X$.

- The remaining states of $\mathbf{16}_X, \overline{\mathbf{16}}_X$ get a TeV scale μ-term from moduli vevs.
- Unification scale is found to be $M_{\mathrm{GUT}} \sim 10^{16}$ GeV, with $\alpha_u^{-1} \sim 9.6$.

Backup slides: On the extra $\mathbf{16}_X, \overline{\mathbf{16}}_X$ family

- $N_X, \overline{N}_X$ vevs (v_x) generate Right-handed neutrinos Majorana masses that then generate a see-saw mechanism

$$\frac{1}{M_{Pl}} \overline{N}_X \overline{N}_X N^m N^m : \ M_{\text{Majorana}} \sim \frac{{v_X}^2}{M_{Pl}}$$

- There are other consequences one has to study.
  - Potential mixing with regular matter through the effective μ-terms

$$\mu \mathbf{16}^m \overline{\mathbf{16}}_X .$$

  - R-Parity violating (RPV) interactions through the Kahler terms

$$K_{RPV} \supset \frac{s}{M_{Pl}^3} \mathbf{16}_X \mathbf{16}^m \mathbf{16}^m \mathbf{16}^m + \frac{s}{M_{Pl}^2} \mathbf{10}^w \mathbf{16}_X \mathbf{16}^m .$$

Backup slides: On the extra $\mathbf{16}_X, \overline{\mathbf{16}}_X$ family

- To study the potential mixing consider up-type quarks mass matrix.
- Schematically, $W \supset \overline{U} \cdot M_U \cdot U$, where $U^T = \left(u_i, \overline{u^c}_X, u_X\right)$, $\overline{U}^T = (u_i^c, \overline{u}_X, u_X^c)$, with $i = 1, 2, 3$, and

$$M_U \sim \begin{pmatrix} y_u^{ij}\langle H_u\rangle & \mu_X^i & \lambda_X^i\langle H_u\rangle \\ \mu_X^j & \lambda_{\overline{XX}}\langle H_d\rangle & \mu_{XX} \\ \lambda_X^j\langle H_u\rangle & \mu_{XX} & \lambda_{XX}\langle H_u\rangle \end{pmatrix}$$

  where y_u are EWS Yukawas, μ-terms $\sim \mathcal{O}(\text{ TeV})$, and $\lambda \sim \mathcal{O}(10^{-14})$.
- In the limit $\lambda_X^i, \lambda_X^j, \lambda_{XX}, \lambda_{\overline{XX}} \to 0$ and $yv/\mu \ll 1$, one can find that the light states are composed of states from $\overline{\mathbf{16}}$, which are the ones that couple *differently* to Z and $W^\pm$. Therefore, neutral current and CKM unitariy are safe.
- **To leading order in λs ordinary matter eigenstates do not mix matter with extra matter.**

Backup slides: $N_X, \overline{N}_X$ vevs and RPV

- RPV interactions arise from the Kahler potential terms and are effectively described by the superpotential

$$W_{RPV} \supset \lambda \frac{v_X}{M_{Pl}} L L e^c + \lambda \frac{v_X}{M_{Pl}} Q L e^c + \lambda \frac{v_X}{M_{Pl}} u^c d^c d^c + \lambda v_X L H_u .$$

which after a small rotation $\mathcal{O}(v_X/m_{pl})$ in (H_d, L) space reads

$$W_{RPV} \supset y_e \frac{v_X}{m_{pl}} L L e^c + y_d \frac{v_X}{m_{pl}} L Q d^c + \lambda \frac{v_X}{m_{pl}} u^c d^c d^c .$$

- In $SO(10)$, neutrinos have the same Dirac mass as the up-type quarks. A realistic τ-neutrino physical mass requires

$$M_{\text{Majorana}} \gtrsim 10^{14}\ \text{GeV} \Rightarrow v_X \sim 10^{16}\ \text{GeV}.$$

- Bilinear RPV coupling is constrained by neutrino mass limits to be $\lambda v_X \lesssim \mathcal{O}(1\ \text{GeV}) \Rightarrow v_X \lesssim 10^{14}$ GeV, therefore we must appeal to non-generic geometrical suppression for the respective Kahler potential term.

Backup slides: $N_X, \overline{N}_X$ vevs and RPV

- There is decay channel for the LSP, and its lifetime can be estimated as

$$\tau_{LSP} \simeq \frac{10^{-13}\,\text{sec}}{(v_X/m_{pl})^2}\left(\frac{m_0}{10\ \text{TeV}}\right)^4\left(\frac{100\ \text{GeV}}{m_{LSP}}\right)^5,$$

  for $m_0 \sim 10$ TeV, $m_{LSP} \sim 100$ GeV, $v_X/m_{pl} \sim 10^{-2}$ for realistic neutrino masses, one finds $\tau_{LSP} \sim 10^{-9}\,$sec.
- **The LSP is not a good dark matter (DM) candidate. Fortunately *M*-theory provides axions as DM.**