The Potential Fate of Local Model Building

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Motivation and Outline

- F-Theory Model Building: Generalisation of type IIB intersecting branes
- Usually, consider local models: Focus on brane stack or points within the stack and decouple bulk of the compactification manifold
- Advantage: Simple, physics basically fixed by symmetry
- Obvious question: Existence of global completion

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- F-Theory Model Building: Generalisation of type IIB intersecting branes
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- Advantage: Simple, physics basically fixed by symmetry
- Obvious question: Existence of global completion
- GUT models need to address proton stability
- Dimension-four proton decay: Forbidden by matter parity or variants – should be defined locally
- Dimension-five proton decay: Use zero mode assignment, i.e. additional $U(1)$ symmetries present in the setup

Contents

Global, Semilocal, Local

[Beasley, Heckman, Vafa; Donagi, Wijnholt; Marsano, Saulina, Schäfer-Nameki; Hayashi, Kawano, Tatar, Watari; Dudas, Palti; Choi, . . .]

For F-Theory models, different degrees of locality:

- *Global* model: Specify full compactification space (CY fourfold) – complete, consistent

  [Blumenhagen, Grimm, Jurke, Weigand; Grimm, Krause, Weigand; Knapp, Kreuzer, Mayrhofer, Walliser; Collinucci, Savelli; Braun, Hebecker, CL, Valandro,. . .]

- *Semilocal* model: Focus on the GUT surface (brane stack) and matter curves within S – decouples bulk of compactification space
- *Local* model: Consider only points where matter curves intersect and interactions are localised – simple, hope for predictivity because of local constraints. Certain question cannot be answered, existence of global completion is not guaranteed.

8D Gauge Theory Description

- "Brane" picture: $SU(5)$ gauge theory on 7-branes (8D), matter and interactions localised on intersections: curves and points of higher symmetry, potentially up to E_8
- Focus on GUT surface $\rightsquigarrow$ 8D E_8 GUT, broken to $SU(5)$ by adjoint Higgs
- Actually, rank-preserving breaking

$$E_8 \longrightarrow (SU(5) \times SU(5)_\perp) \longrightarrow SU(5) \times U(1)^4$$

- Extra $U(1)$'s generically massive – but remain as *global selection rules* [Grimm, Weigand]

Higgs in $SU(5)_\perp$

Higgs field takes values in $SU(5)_\perp$ – matter curves now visible as vanishing loci of Higgs eigenvalues:

$$\text{Higgs} \quad \Phi \sim \begin{pmatrix} t_1 & & & & \\ & t_2 & & & \\ & & t_3 & & \\ & & & t_4 & \\ & & & & t_5 \end{pmatrix}, \qquad \sum_i t_i = 0$$

Matter curves:

$$\mathbf{10}: t_i = 0\,, \qquad\qquad \mathbf{5}: -(t_i + t_j) = 0\,,\ i \neq j$$

t_i double as charges under the extra $U(1)$s: for allowed couplings, t_i sum up to zero.
Monodromies can identify some t_i: At least $\mathbb{Z}_2$ required for tree-level top quark Yukawa coupling $\mathbf{10}_{\text{top}}\mathbf{10}_{\text{top}}\mathbf{5}_{H_u}$

Superpotential Couplings

$$W_{\text{good}} = \mu \mathbf{5}_{H_u} \bar{\mathbf{5}}_{H_d} + Y_u \mathbf{5}_{H_u} \mathbf{10}_M \mathbf{10}_M + Y_d \bar{\mathbf{5}}_{H_d} \bar{\mathbf{5}}_M \mathbf{10}_M$$

$$\begin{aligned} W_{\text{bad}} &= \beta \mathbf{5}_{H_u} \bar{\mathbf{5}}_M + \lambda \bar{\mathbf{5}}_M \bar{\mathbf{5}}_M \mathbf{10}_M && \text{dim-3/4} \\ &+ W^1 \mathbf{10}_M \mathbf{10}_M \mathbf{10}_M \bar{\mathbf{5}}_M + W^2 \mathbf{10}_M \mathbf{10}_M \mathbf{10}_M \bar{\mathbf{5}}_{H_d} && \\ &+ W^3 \bar{\mathbf{5}}_M \bar{\mathbf{5}}_M \mathbf{5}_{H_u} \mathbf{5}_{H_u} + W^4 \bar{\mathbf{5}}_M \bar{\mathbf{5}}_{H_d} \mathbf{5}_{H_u} \mathbf{5}_{H_u} && \Big\} \text{dim-5} \end{aligned}$$

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Some terms related by interchange $\bar{\mathbf{5}}_{H_d} \leftrightarrow \bar{\mathbf{5}}_M$ – forbidden by $\mathbb{Z}_2$ matter parity: [Dimopoulos, Raby, Wilczek; Ibanez, Ross; Dreiner, Luhn, Thormeier]

	$\mathbf{5}_{H_u}, \bar{\mathbf{5}}_{H_d}$	$\mathbf{10}_M, \bar{\mathbf{5}}_M$
P_M	$+1$	-1

Superpotential Couplings

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	$\mathbf{5}_{H_u}, \bar{\mathbf{5}}_{H_d}$	$\mathbf{10}_M, \bar{\mathbf{5}}_M$
P_M	$+1$	-1

Weinberg operator W^3 and $W^1 \supset QQQL$, $\bar{u}\bar{u}\bar{d}\bar{e}$ still allowed.

Model Requirements

For the local model we require

- P_M defined locally
- heavy top quark (i.e. rank-one up-type Yukawa matrix at tree level – down-type Yukawas can be rank-zero or rank-one)
- No dim-5 proton decay (the W^1 operator forbidden at all orders)
- Masses for all quarks and leptons after switching on VEVs

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- Masses for all quarks and leptons after switching on VEVs

Local model building freedom: Freely choose

- Monodromy (at least $\mathbb{Z}_2$ for heavy top)
- Assignment of matter and Higgs zero modes to curves
- Singlet VEVs (for matter parity even singlets)

Matter Parity

Define $\mathbb{Z}_2$ matter parity in terms of the t_i (i.e. as subgroup of $SU(5)_\perp$):

$$P_M = (-1)^{c_i t_i} \ , \quad c_i = 0, 1 \qquad (\text{defined} \mod 2)$$

- Monodromy $t_1 \leftrightarrow t_2$ requires $c_1 = c_2 = 1$
- Down-type masses require even number of $c_i = 1$

Hence, two choices of matter parity:

$$\text{Case I:} \quad P_M = (-1)^{t_1+t_2+t_3+t_4}$$
$$\text{Case II:} \quad P_M = (-1)^{t_1+t_2}$$

Case I: Matter and VEV Assignment

Matter $\mathbf{10}$ Curves			
$\mathbf{10}_1$	$t_{1,2}$	$-$	top
$\mathbf{10}_2$	t_3	$-$	
$\mathbf{10}_3$	t_4	$-$	
Matter $\mathbf{5}$ Curves			
$\mathbf{5}_3$	$-t_{1,2} - t_5$	$-$	
$\mathbf{5}_5$	$-t_3 - t_5$	$-$	
$\mathbf{5}_6$	$-t_4 - t_5$	$-$	
Even Singlet Curves			
$\mathbf{1}_1$	$\pm(t_{1,2} - t_3)$	$+$	
$\mathbf{1}_2$	$\pm(t_{1,2} - t_4)$	$+$	
$\mathbf{1}_4$	$\pm(t_3 - t_4)$	$+$	
$\mathbf{1}_7$	$t_1 - t_2$	$+$	

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$\mathbf{5}_5$	$-t_3 - t_5$	$-$	
$\mathbf{5}_6$	$-t_4 - t_5$	$-$	
	Even Singlet Curves		
$\mathbf{1}_1$	$\pm(t_{1,2} - t_3)$	$+$	
$\mathbf{1}_2$	$\pm(t_{1,2} - t_4)$	$+$	
$\mathbf{1}_4$	$\pm(t_3 - t_4)$	$+$	
$\mathbf{1}_7$	$t_1 - t_2$	$+$	

- W^1 without singlets:

$$\mathbf{10}_1\mathbf{10}_1\mathbf{10}_2\bar{\mathbf{5}}_6\,,$$
$$\mathbf{10}_1\mathbf{10}_1\mathbf{10}_3\bar{\mathbf{5}}_5\,,$$
$$\mathbf{10}_1\mathbf{10}_2\mathbf{10}_3\bar{\mathbf{5}}_3$$

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Matter **10** Curves			
$\mathbf{10}_1$	$t_{1,2}$	$-$	top
$\mathbf{10}_2$	t_3	$-$	no matter
$\mathbf{10}_3$	t_4	$-$	matter
Matter 5 Curves			
$\mathbf{5}_3$	$-t_{1,2}-t_5$	$-$	matter
$\mathbf{5}_5$	$-t_3-t_5$	$-$	no matter
$\mathbf{5}_6$	$-t_4-t_5$	$-$	matter
Even Singlet Curves			
$\mathbf{1}_1$	$\pm(t_{1,2}-t_3)$	$+$	
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$\rightsquigarrow$ no matter on $\mathbf{10}_2$, $\mathbf{5}_5$

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$\mathbf{5}_5$	$-t_3 - t_5$	$-$	no matter
$\mathbf{5}_6$	$-t_4 - t_5$	$-$	matter
	Even Singlet Curves		
$\mathbf{1}_1$	$\pm(t_{1,2} - t_3)$	$+$	
$\mathbf{1}_2$	$\pm(t_{1,2} - t_4)$	$+$	
$\mathbf{1}_4$	$\pm(t_3 - t_4)$	$+$	
$\mathbf{1}_7$	$t_1 - t_2$	$+$	

- W^1 without singlets:

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- W^1 with singlets:

e.g. $\mathbf{10}_1\mathbf{10}_1\mathbf{10}_3\bar{\mathbf{5}}_6\mathbf{1}_4\,,$

$\mathbf{10}_1\mathbf{10}_1\mathbf{10}_3\bar{\mathbf{5}}_3\mathbf{1}_1$

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Even Singlet Curves			
$\mathbf{1}_1$	$\pm(t_{1,2}-t_3)$	$+$	no VEV
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$\rightsquigarrow$ no matter on $\mathbf{10}_2$, $\mathbf{5}_5$

- W^1 with singlets:

e.g. $\mathbf{10}_1\mathbf{10}_1\mathbf{10}_3\bar{\mathbf{5}}_6\mathbf{1}_4\,,$

$\mathbf{10}_1\mathbf{10}_1\mathbf{10}_3\bar{\mathbf{5}}_3\mathbf{1}_1$

$\rightsquigarrow$ no VEVs for $\mathbf{1}_1$, $\mathbf{1}_4$

- W^1 will not be generated at any order: lack of t_3 factor

Case I: Down-Type Higgs

Higgs-like **5** Curves		Down-type Yukawas
$\bar{\mathbf{5}}_{H_u}$	$-t_1 - t_2$	
$\bar{\mathbf{5}}_1$	$-t_{1,2} - t_3$	
$\bar{\mathbf{5}}_2$	$-t_{1,2} - t_4$	
$\bar{\mathbf{5}}_4$	$-t_3 - t_4$	

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Higgs-like **5** Curves		Down-type Yukawas
$\bar{\mathbf{5}}_{H_u}$ ↯	$-t_1 - t_2$	No masses at tree level or with singlets
$\bar{\mathbf{5}}_1$	$-t_{1,2} - t_3$	
$\bar{\mathbf{5}}_2$ ↯	$-t_{1,2} - t_4$	No masses at tree level or with singlets
$\bar{\mathbf{5}}_4$	$-t_3 - t_4$	

- Down-type Higgs needs a factor of t_3 to allow for Yukawa couplings (at any order)

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$\bar{\mathbf{5}}_{H_u}$ ↯	$-t_1 - t_2$	No masses at tree level or with singlets
$\bar{\mathbf{5}}_1$ ↯	$-t_{1,2} - t_3$	either rank-two Yukawa matrix, or no up-type masses with singlets
$\bar{\mathbf{5}}_2$ ↯	$-t_{1,2} - t_4$	No masses at tree level or with singlets
$\bar{\mathbf{5}}_4$	$-t_3 - t_4$	

- Down-type Higgs needs a factor of t_3 to allow for Yukawa couplings (at any order)
- Down-type Yukawa should not be rank-two

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Higgs-like **5** Curves		Down-type Yukawas
$\bar{\mathbf{5}}_{H_u}$ ⚡	$-t_1 - t_2$	No masses at tree level or with singlets μ term
$\bar{\mathbf{5}}_1$ ⚡	$-t_{1,2} - t_3$	either rank-two Yukawa matrix, or no up-type masses with singlets
$\bar{\mathbf{5}}_2$ ⚡	$-t_{1,2} - t_4$	No masses at tree level or with singlets
$\bar{\mathbf{5}}_4$	$-t_3 - t_4$	

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- String-scale μ term for both Higgses on one curve

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$\bar{\mathbf{5}}_2$	⚡	$-t_{1,2} - t_4$	No masses at tree level or with singlets
$\bar{\mathbf{5}}_4$	✓	$-t_3 - t_4$	Rank-one Yukawa matrix, bottom quark heavy

- Down-type Higgs needs a factor of t_3 to allow for Yukawa couplings (at any order)
- Down-type Yukawa should not be rank-two
- String-scale μ term for both Higgses on one curve
- $\bar{\mathbf{5}}_4 = \bar{\mathbf{5}}_{H_d}$ is unique choice, tree-level coupling $\bar{\mathbf{5}}_{H_d}\mathbf{10}_{\text{top}}\bar{\mathbf{5}}_3$

Case I: Yukawas and CKM

- Third generation: $\mathbf{10}_1$ and $\bar{\mathbf{5}}_3$,light generations: $\mathbf{10}_3$ and $\bar{\mathbf{5}}_6$
- Higgses: $\bar{\mathbf{5}}_{H_u}$ and $\bar{\mathbf{5}}_4$, only $\langle \mathbf{1}_2 \rangle \sim \epsilon$ required at first order
- Ignore $\langle \mathbf{1}_7 \rangle$, $\mathcal{O}(1)$ coefficients and nontrivial splits
- Yukawa matrices (schematically):

$$Y^u \sim Y^d \sim \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon^2 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

- CKM matrix:

$$V_{\text{CKM}} \sim \begin{pmatrix} 1 & 1 & \epsilon \\ 1 & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

- Masses and mixings possible (though not a great fit)
- Degeneracy because three generations come from two curves

Semilocal Approach

[Friedman, Morgan, Witten; Donagi, Wijnholt]

Now *semilocal* picture: Consider GUT surface using spectral cover approach

Main aim: Find homology classes of matter curves which allow to find the flux restrictions and thus the zero mode spectrum.

Two types of fluxes (actually, G four-form flux):

- $U(1) \subset SU(5)_\perp$ fluxes on matter curves (from the transverse branes): Determines (chiral) 4D zero modes for full GUT multiplets (by index theorem). These are still free parameters up to anomaly cancellation requirements.
- Hypercharge flux on S (globally trivial so hypercharge stays unbroken): Restrictions to matter curves splits $SU(5)$ multiplets; homological relations between matter curves lead to relations between the splittings.

Case I: Doublet-Triplet Splitting fails

- Higgs sector:

	$(\mathbf{3},\mathbf{1})$	$(\mathbf{1},\mathbf{2})$
$\mathbf{5}_{H_u}$	$M_{\mathbf{5}_{H_u}}$	$M_{\mathbf{5}_{H_u}} + N_8$
$\mathbf{5}_1$	$M_{\mathbf{5}_1}$	$M_{\mathbf{5}_1} - N_8$
$\mathbf{5}_2$	$M_{\mathbf{5}_2}$	$M_{\mathbf{5}_2} - N_8$
$\mathbf{5}_4$	$M_{\mathbf{5}_4}$	$M_{\mathbf{5}_4} + N_8$

- We can pairwise decouple unwanted triplets from $\mathbf{5}_{H_u}$ and $\mathbf{5}_2$, and from $\mathbf{5}_1$ and $\mathbf{5}_4$ by coupling to VEV for $\mathbf{1}_2$
- However:

$$\#(\text{doublets from } \mathbf{5}_{H_u}, \mathbf{5}_2) = \#(\text{triplets from } \mathbf{5}_{H_u}, \mathbf{5}_2)$$

- Problem persists even when allowing exotics from the matter sector
- Separately, down-type Higgs on $\mathbf{5}_4$ cannot be realised
- Matter sector can be engineered easily
- Similar result for case II

Conclusions

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- Local model is very constrained: Two cases only
- Neither case can be embedded in semilocal framework (using spectral cover) – first step towards global realisation fails
- Problem is doublet-triplet splitting in the Higgs sector, even when allowing for exotic matter
- Predictivity of local point in question – Crucial model features required to have nonlocal origin?

Conclusions

- Analysed F-Theory GUT in local and semilocal approach
- Goal: Use locally defined matter parity and additional $U(1)$s to ensure proton stability
- Local model is very constrained: Two cases only
- Neither case can be embedded in semilocal framework (using spectral cover) – first step towards global realisation fails
- Problem is doublet-triplet splitting in the Higgs sector, even when allowing for exotic matter
- Predictivity of local point in question – Crucial model features required to have nonlocal origin?
- Possible loopholes: Matter representations might be more subtle than simple group theory intuition suggests

  [Ceccotti, Heckman, Vafa; Donagi Wijnholt] [Esole, Yau; Marsano, Schäfer-Nameki]