Towards the Standard Model
and
via D-branes at Singularities

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Based on work with
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Dima Malyshev
Matt Buican
Dave Morrison
The landscape of all possible string constructions of the SM:
The landscape of all possible string constructions of the SM:

\[ \circ = \text{the right one!} \]
The "correspondence principle"

"Occam's razor"
The "correspondence principle":

"a new theory should explain all phenomena for which the preceding theory is known to be valid"

"one of the tools available to physicists for selecting theories corresponding to reality"

"Occam’s razor":

"entia non sunt multiplicanda praeter necessitatem"

"when competing theories have equal predictive power, pick the one that introduces the fewest assumptions and postulates the fewest hypothetical entities."
• Can one obtain the SM via a ‘decoupling limit’ of string theory?

• Look for a string construction of the SM in which all geometric data are in one-to-one correspondence with SM parameters.
The landscape of all possible string constructions of the SM

\[ o = \text{the right one!} \]
The landscape of all possible string constructions of the SM

IIB with D–branes at CY–singularities

o = the right one!
The landscape of all possible string constructions of the SM

IIB with D–branes at CY–singularities

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The landscape of all possible string constructions of the SM

\[ \text{IIB with D–branes at CY–singularities} \]

\[ \circ = \text{the right one!} \]
Conjecture: * every string model* that exhibits a gauge hierarchy admits a duality frame such that all gauge dynamics is described by open strings attached to D-branes near a CY singularity......

* almost

* with low energy susy
Motivation: can take a formal decoupling limit, in which all gauge invariant coupling constants are frozen, and tuned via (non-normalizable) deformations of the local geometry:
Fractional brane = bound state of wrapped D7, D5 or D3-branes

\[ \text{ch}(F) = (Q_7, Q_5, Q_3) \]
\[ = (r, p_a, q) \]
\[ r = \text{rank}(F) \]
\[ p_a = \int_{\alpha} c_1(F) \]
\[ q = \text{ch}_2(F). \]

\[ \#(F_i, F_j) = r_i d_j - r_j d_i \]
\[ d = c_1(F) \cdot k \]
Gauge theory/Geometry Dictionary

Superpotential = Complex Structure
Gauge Couplings = periods of NS 2-form $B$
FI-Parameters = periods of Kahler form $J$
Symmetry breaking = bound state formation

$$Z(F) = \int_X e^{-B+iJ} \text{Tr}(e^F) \sqrt{Td}$$

$$\frac{4\pi}{g_{\text{YM}}^2} = e^{-\phi}|Z(F)|$$

$$\zeta = \frac{1}{\pi} \log(Z(F))$$
THREE GENERATIONS OF MATTER

I   II   III

2.75 1300 178000
UP    CHARM  TOP

6  110  4500
DOWN  STRANGE  BOTTOM

0.511 105.7 1777
ELECTRON  MUON  TAU

< 3 \cdot 10^{-6}  < 0.19  < 18.2
νₑ  νµ  ντ

FORCE CARRIERS: BOSONS

\( \frac{2}{3} \)  91188
Z^0

\(-\frac{1}{3}\)  80430
W⁺/W⁻

\(-1\)  \(< 10^{-28}\)
PHOTON

\(0\)
three: 0

GLUON

MATTER CONSTITUENTS: FERMIONS

QUARKS

LEPTONS

The Standard Model
fundamental particle zoo

ALL Masses in MeV;
ANIMAL Masses
SCALE WITH
PARTICLE Masses
A minimal quiver realization of the SM-model: "Spanish Quiver"
The "cover quiver":

\[\text{Diagram of a quiver with five nodes and directed edges.}\]
SM quiver, without orientifolding:

\[
\begin{array}{c}
\text{U}(2) \\
\text{U}(3) \quad \text{H}_d \\
\text{U}(1) \\
\text{U}(1)^6
\end{array}
\]

\[
\begin{array}{c}
\text{Q} \\
\text{L} \\
\text{U} \\
\text{D} \\
\text{E}
\end{array}
\]
This quiver gauge theory can be obtained as the worldvolume gauge theory on a single D3-brane on a $dP_8$ singularity with an $A_2$ singularity associated with the two 2-cycles $\alpha_1$ and $\alpha_2$: 

![Diagram of quiver with labeled cycles](image-url)
Fractional brane = bound state of wrapped D7, D5 or D3-branes

\[
\text{ch}(F') = (Q_7, Q_5, Q_3) = (r, p_a, q)
\]
\[
r = \text{rank}(F')
\]
\[
p_a = \int_{\alpha_a} c_1(F')
\]
\[
q = \text{ch}_2(F').
\]

\[
\#(F_i, F_j) = r_i d_j - r_j d_i
\]
\[
d = c_1(F') \cdot k
\]
In remainder: will show how to eliminate all the extra $U(1)$ gauge symmetries, except for hypercharge.
How $U(1)$ symmetries get eliminated.....

- Non-anomalous $U(1)'s \leftrightarrow$ degree zero 2-cycles $\alpha_a$ in $X$.

- The D-brane action contains the linear coupling $C \wedge F$ with

\[
C = r \, c_X + p_a \, c^a + q \, C_2
\]

\[
c^a = \int_{\alpha_a} C_4 \quad \quad c_x = \int_x C_6
\]
• Let $\omega_\alpha$ denote a basis of normalizable harmonic 2-forms on $Y$:

$$G_{\alpha\beta} = \int_Y \omega_\alpha \wedge \ast \omega_\beta$$

• Every $\omega_\alpha$ gives rise to a Stuckelberg field, via

$$C_4 = \sum_\alpha c^\alpha \omega_\alpha \quad d\rho_\alpha = G_{\alpha\beta} \ast dc^\beta$$

• Introduce the matrix of periods

$$\Pi^a_\alpha = \int_{\alpha_a} \omega_\alpha$$
• The mass term for the $U(1)$ vector bosons reads:

$$m^2 = G_{XX} r^2 + G^\alpha\beta \Pi^a_\alpha \Pi^b_\beta p^a p^b$$

For our specific SM construction via a $dP_8$ singularity, this result implies that hypercharge is a massless gauge symmetry, provided:

$$\Pi^4_\alpha = \int_{\alpha_4} \omega_\alpha = 0 \quad \forall \alpha$$
<table>
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<tr>
<th></th>
<th>$Q_i$</th>
<th>$u^c_i$</th>
<th>$d^c_i$</th>
<th>$\ell_i$</th>
<th>$e^c_i$</th>
<th>$\nu^c_i$</th>
<th>$H^u_i$</th>
<th>$H^d_i$</th>
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<td>$\bar{3}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$SU(2)_L$</td>
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<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$U(1)_Y$</td>
<td>$1/6$</td>
<td>$-2/3$</td>
<td>$1/3$</td>
<td>$-1/2$</td>
<td>1</td>
<td>0</td>
<td>$1/2$</td>
<td>$-1/2$</td>
</tr>
</tbody>
</table>
Some directions for near future:

- $U(1)$ breaking, via D-instantons $\rightarrow \mu=$ terms.

$$\delta W = \mathcal{A}(\Phi) e^{-\mu_3 \text{Vol}(\Sigma_\alpha)} + i\rho_\alpha$$

- SUSY breaking, via gauge mediation or otherwise

- Phenomenology!

- Monopoles, confinement

- Unification of coupling constants, GUTs
• "Swampland" of non-compact CY singularities:
  can not be embedded inside a compact CY.
GAUGE THEORY
STRONG FORCE
OPEN STRINGS
CLOSED STRINGS
$1/N$
AdS/QCD
D3
cone-like singularity
+EM+Weak
SM-
SM
on a
+GRAVITY
Compact
Calabi-Yau

Compact Calabi-Yau

cone-like singularity

D3

SM
on a
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Diagram:

SM on a D3
cone–like singularity

Compact Calabi–Yau
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SM on a D3
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Compact Calabi-Yau