Durham
December 21, 2005

The Shape of the Standard Model

Based on work with

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Herman Verlinde

LHC: By 2008, string theory must show its hand!

String phenomenology traditionally follows a top-down approach:

- Pick a Calabi-Yau compactification (and an E_8 bundle).
- Derive the low energy effective field theory – e.g. an E_6 GUT.
- Set up a symmetry breaking mechanism towards the MSSM.

The D-brane era introduced an alternative approach:

- Use intersecting D-branes to directly construct the MSSM.

Problem with both approaches:

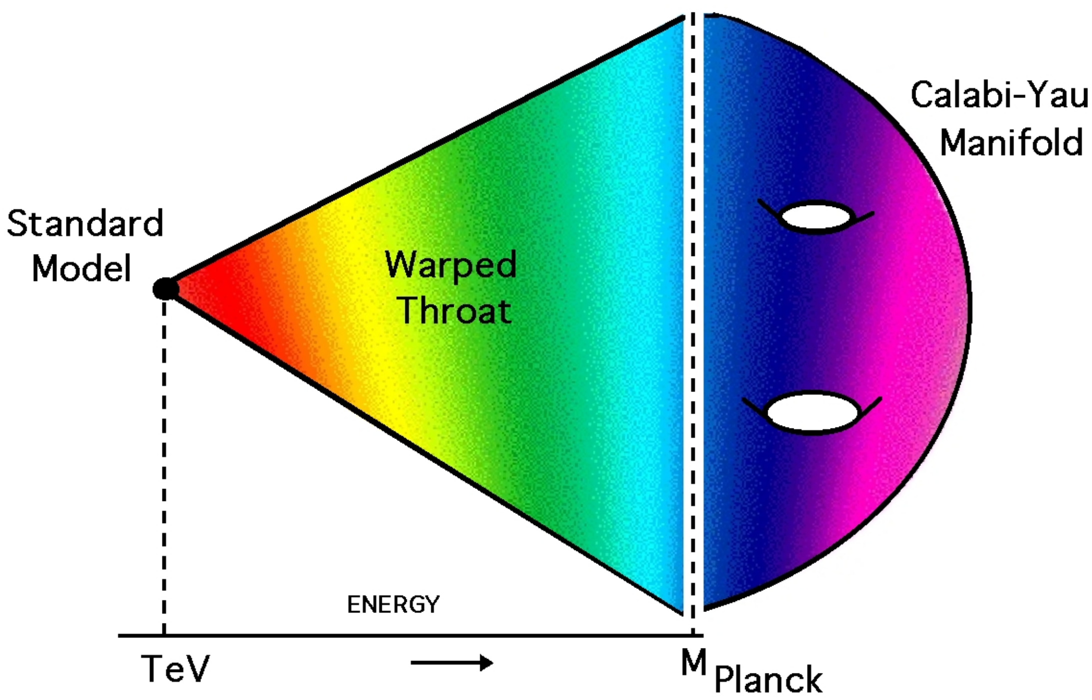
Moduli stabilization $\leftrightarrow$ The Landscape.

Stated a bit more accurately:

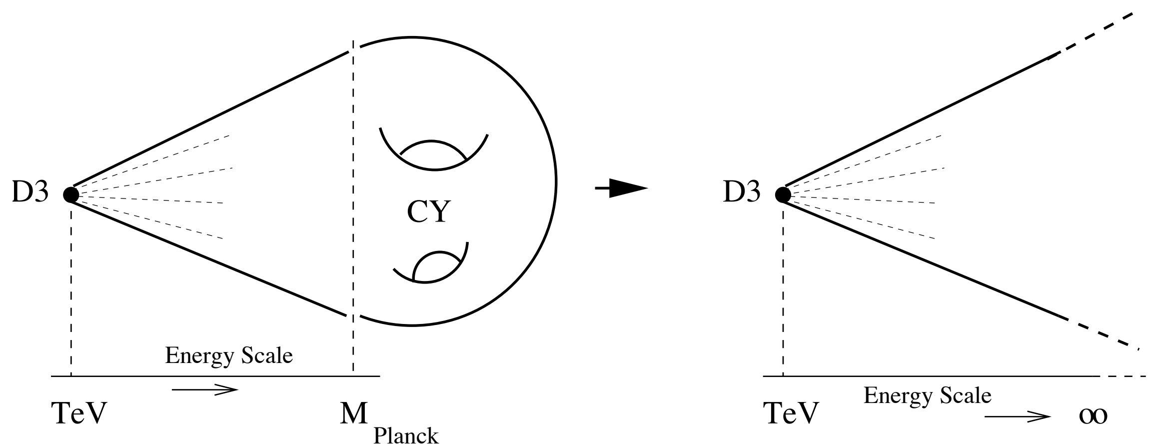
The traditional, optimistic point of view on string phenomenology has been that its dual unification program – tame the Planckian realm of physics and describe all elementary particle and forces – will require a highly constrained mathematical framework, from which we can extract specific predictions for particle physics. The landscape makes clear that this is probably not true!

So, to connect string theory with particle physics, it seems opportune to develop a framework in which we do not need to commit to any detailed assumptions about physics at the Planck scale.

A holographic perspective on string phenomenology:



A bottom-up perspective on string phenomenology:

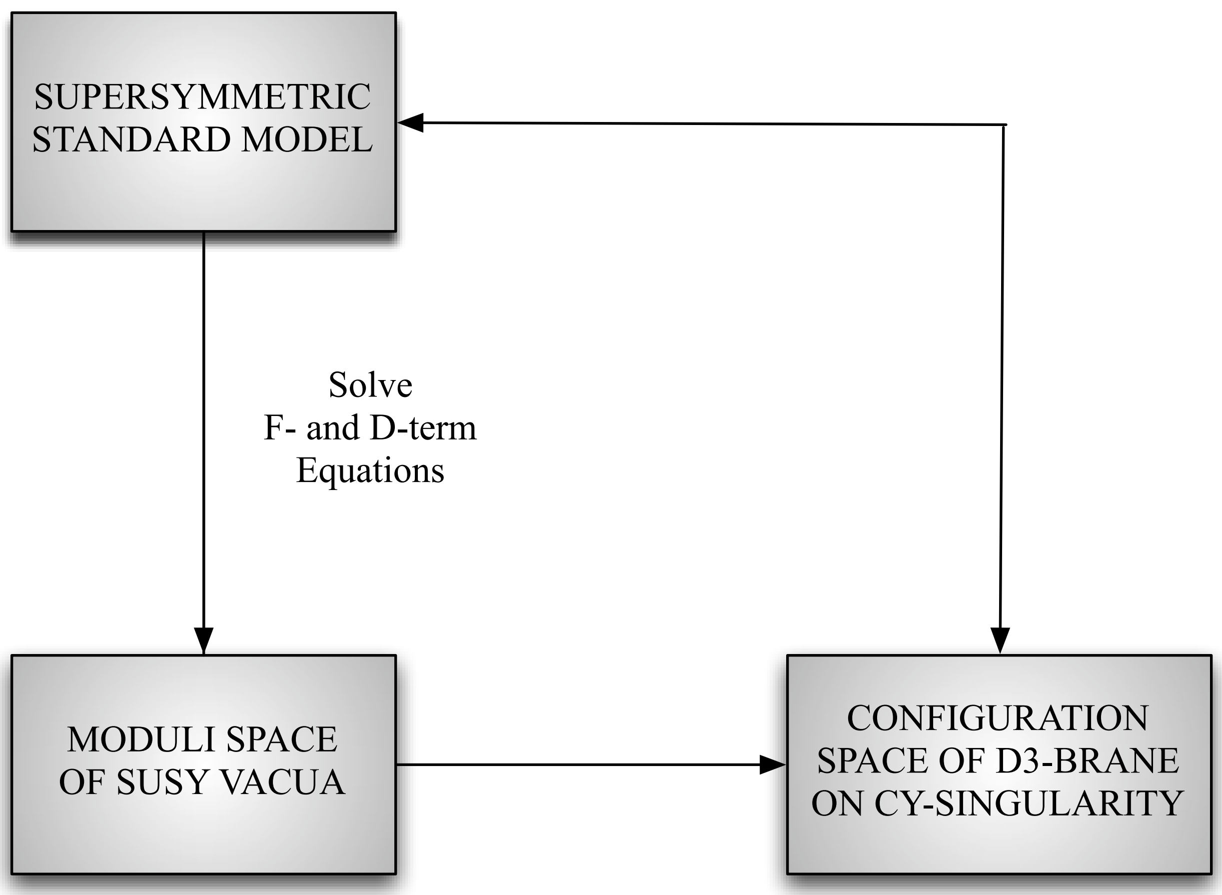


- Open strings only: D3-brane(s) at a CY Singularity
- Decoupling limit: freeze out all closed string moduli

$\Longrightarrow$ they become tunable parameters!

Decouple the Landscape!

Bottom-Up Strategy: "Shape of the Standard Model"



Our result:

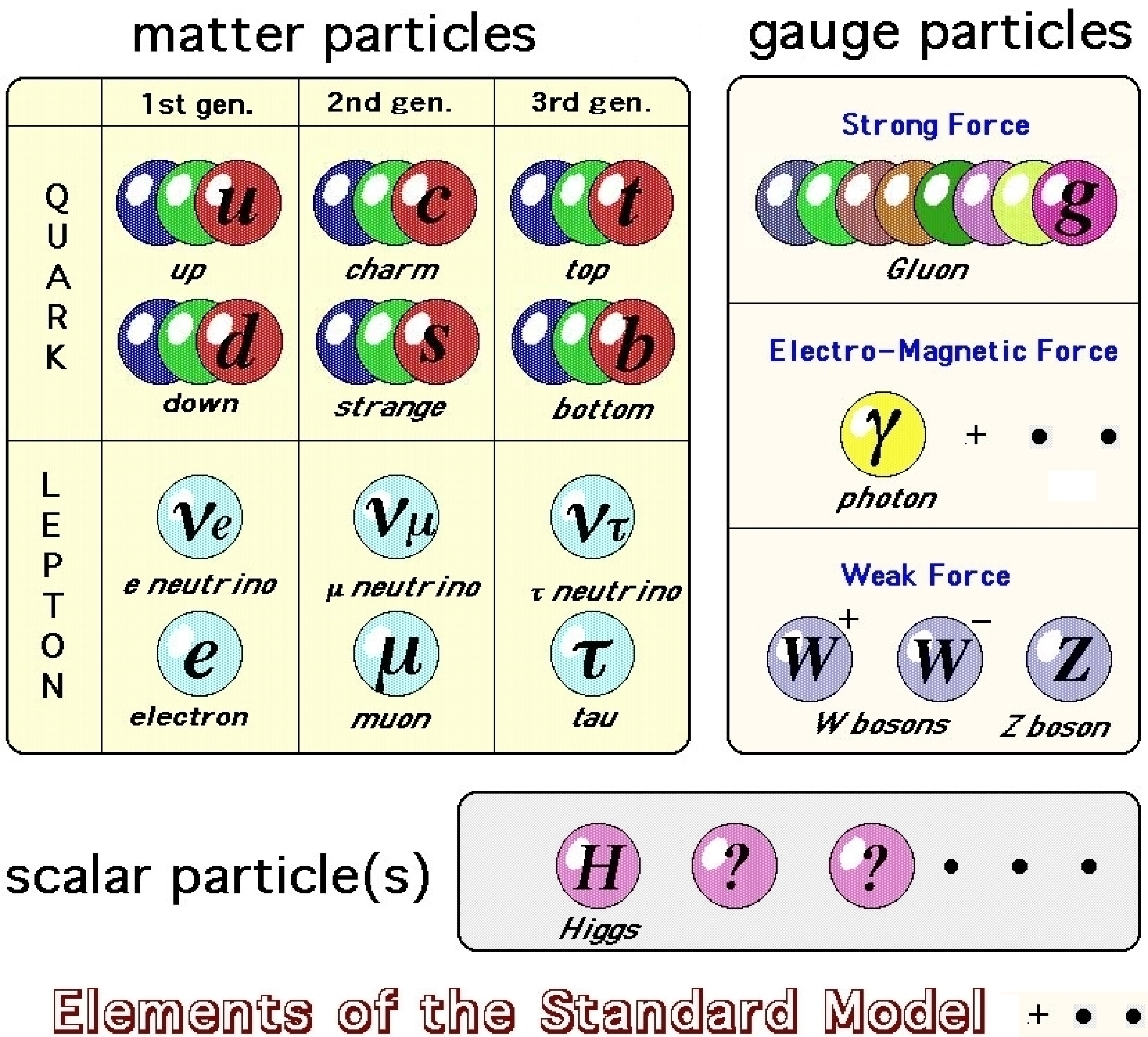
(hep-th/0508089, M. Wijnholt, HV)

A D3-brane on a partially resolved del Pezzo 8 singularity has the particle content and interactions of the MSSM

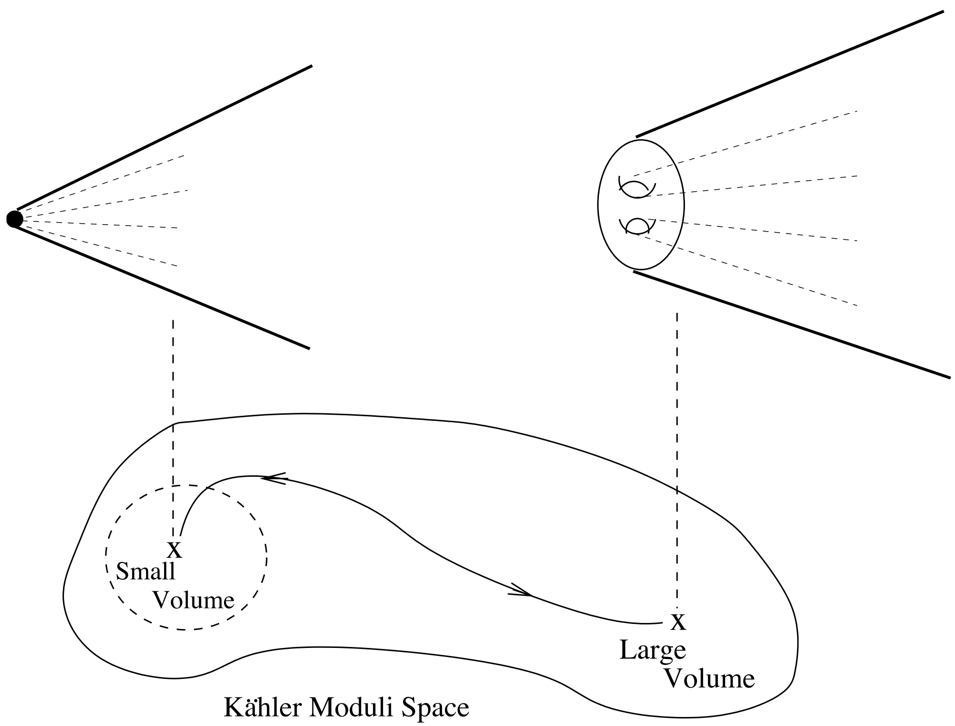
with

* Some extra Higgs fields

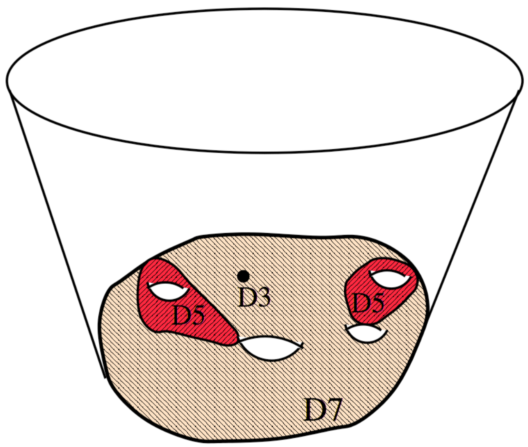
* Some extra Z' bosons


matter particles
gauge particles
1st gen.
2nd gen.
3rd gen.
QUARK
u
up
c
charm
t
top
d
down
s
strange
b
bottom
LEPTON
ν_e
e neutrino
ν_μ
μ neutrino
ν_τ
τ neutrino
e
electron
μ
muon
τ
tau
Strong Force
g
Gluon
Electro-Magnetic Force
γ
photon
+ • •
Weak Force
W^+
W^-
Z
W bosons
Z boson
scalar particle(s)
H
Higgs
? ? • • •
Elements of the Standard Model
+ • •

Geometric perspective:

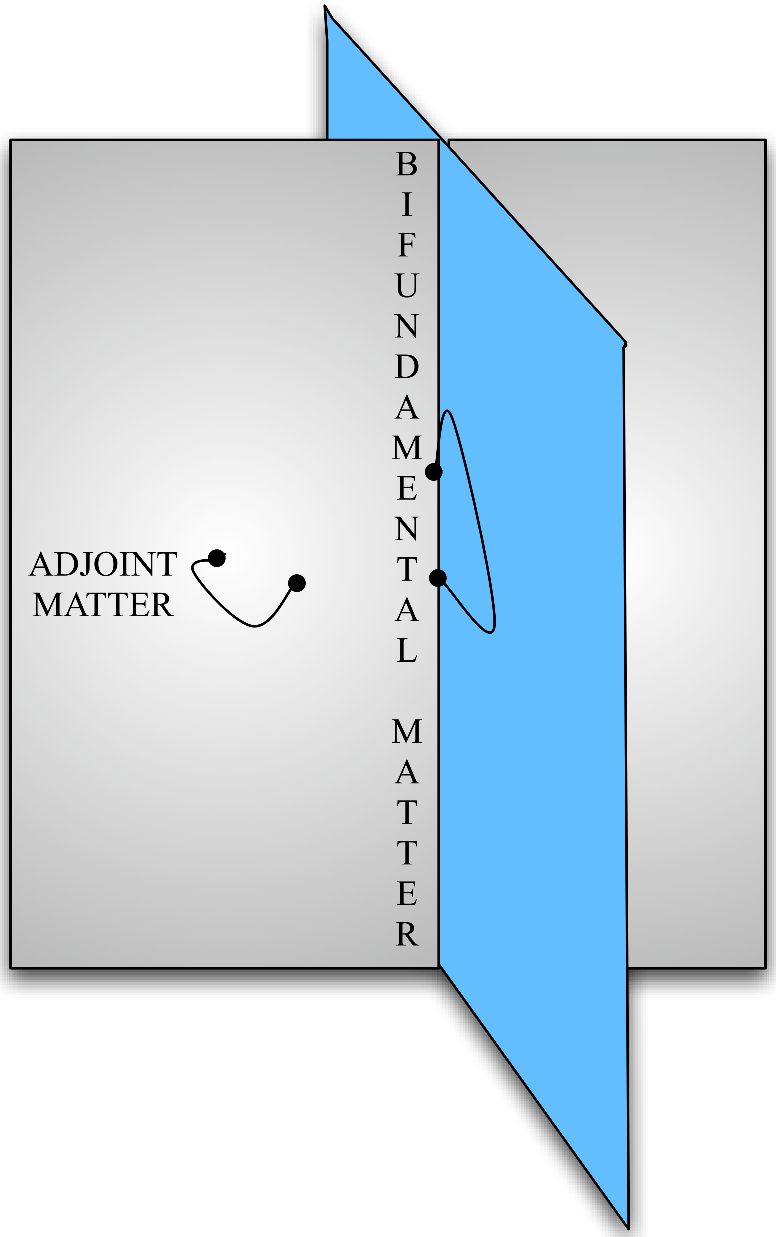


Fractional brane = bound state of wrapped D7, D5 or D3-branes



It is characterized by a 3-component charge vector:

$$\begin{aligned}\mathrm{ch}(F_i) &= (\ Q_7\ ,\ Q_5\ ,\ Q_3\ ) \\ &= (\mathrm{rk}(F), c_1(F), \mathrm{ch}_2(F))\end{aligned}$$


BIFUNDAMENTAL MATTER
ADJOINT MATTER

With these ingredients, let's start to prepare our first recipe:

A single D3-brane on a CY singularity splits up as a sum

of fractional branes $\{F_i\}$ with multiplicities n_i such that:

$$\sum_i n_i \, \mathrm{ch}(F_i) \;=\; (\,0\,,\,0\,,\,1\,)$$

$\Longrightarrow$ A Moose ! Quiver theory with gauge group:

$$\prod_i U(n_i)$$

chiral fields in $(n_i, \bar{n}_j)$ = geometric intersection number:

$$\#(F_i, F_j) = \mathrm{rk}(F_i)\mathrm{deg}(F_j) - \mathrm{deg}(F_i)\mathrm{rk}(F_j)$$

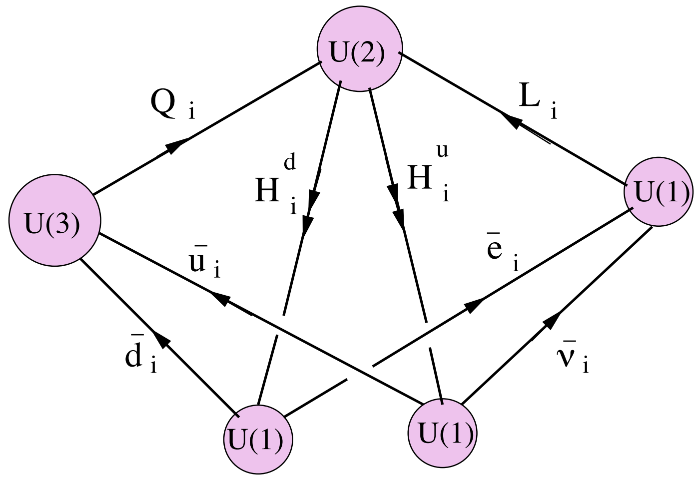
How to draw a Moose: Quiver diagram for D3 on CY singularity

- A node = $U(n_i)$ gauge multiplet
- Oriented line = chiral field in $(n_i, \bar{n}_j)$
- At each node: equal number of incoming and outgoing lines.

Extra: (for "exceptional collections")

- No lines return to the same node $\Longrightarrow$ no adjoint matter
- One type of lines between nodes $\Longrightarrow$ only chiral matter

MQSSM: Minimal Quiver Extension of the Standard Model:



- Two non-anomalous $U(1)$'s:

$$Y = \tfrac{1}{3}Y_3 - Y_0 + \tfrac{1}{2}(Y_u - Y_d)$$
$$B-L = \tfrac{1}{3}Y_3 - Y_0$$

- Two pairs of Higgs doublets per generation: follows from rule c)

- Only hypercharge survives when $\langle \nu_i \rangle \neq 0$

Challenges:

- Engineer the above quiver from D3-brane on a CY singularity

- Eliminate unwanted extra features: extra Z''s and Higgs's

- Break supersymmetry and tune couplings to observed values

A del Pezzo 8 is a complex 4-manifold with nine 2-cycles:

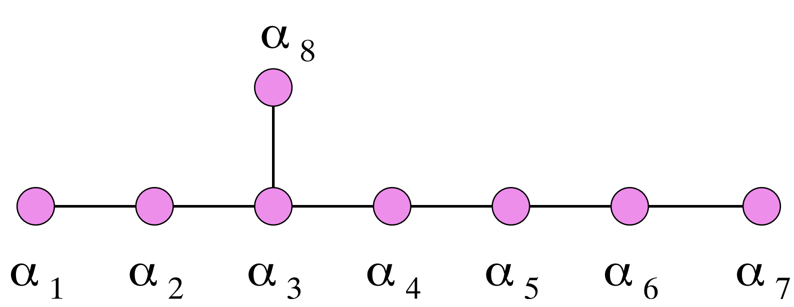
$$h \cdot h = 1 \qquad e_i \cdot e_j = -\delta_{ij} \qquad h \cdot e_i = 0$$

Another useful basis of 2-cycles is (K, α_i) with:

$$k = -3h + \sum_i e_i \qquad \alpha_i = e_i - e_{i+1}, \quad i = 1,.,7 \qquad \alpha_8 = h - e_1 - e_2 - e_3\,,$$

The cycles α_i that span the E_8-root lattice:

$$\alpha_a \cdot \alpha_b = -A_{ab}; \qquad k \cdot k = 2; \qquad k \cdot \alpha_a = 0$$



A "three block exceptional collection" on dP_8:

$$\mathrm{ch}(F_i) = (1, h - e_i, 0) \qquad i = 1, .., 4$$

$$\mathrm{ch}(F_i) = (1, -k + e_i, 1) \qquad i = 5, .., 8$$

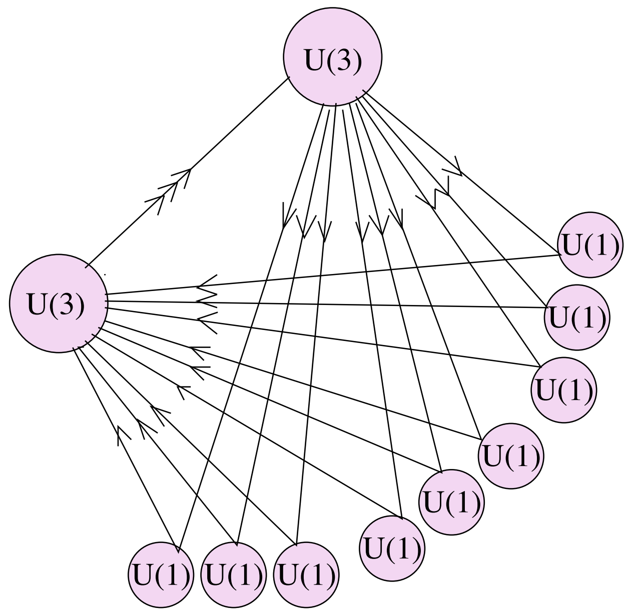
$$\mathrm{ch}(F_9) = (1, 2h - \sum_{i=1}^{4} e_i, 0)$$

$$\mathrm{ch}(F_{10}) = (3, -k + \sum_{i=5}^{8} e_i, -\tfrac{1}{2})$$

$$\mathrm{ch}(F_{11}) = (6, -3k + 2\sum_{i=5}^{8} e_i, \tfrac{1}{2})$$

$\Longrightarrow$ Quiver gauge theory with $U(3) \times U(3) \times U(1)^9$ gauge group

Quiver diagram for a D3-brane on a dP_8-singularity:



Same as for a D3-brane on C^3/Δ_{27} !

Partial dictionary:

Complex structure $\longleftrightarrow$ Superpotential W

Blow-up modes $\longleftrightarrow$ FI-parameters ζ

Govern moduli space of D3-brane vacua via F- and D-flatness conditions:

$$\frac{\partial W}{\partial \phi^a} = C_{abc}\,\phi^b\,\phi^c = 0 \qquad\qquad \sum_a |\phi^+_{ia}|^2 - \sum_b |\phi^-_{ib}|^2 = \zeta_i$$

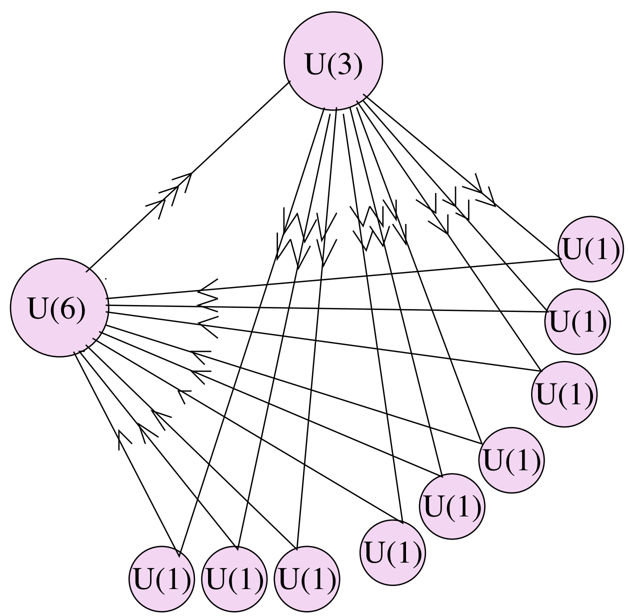
Periods of 2-forms $\longleftrightarrow$ Gauge couplings

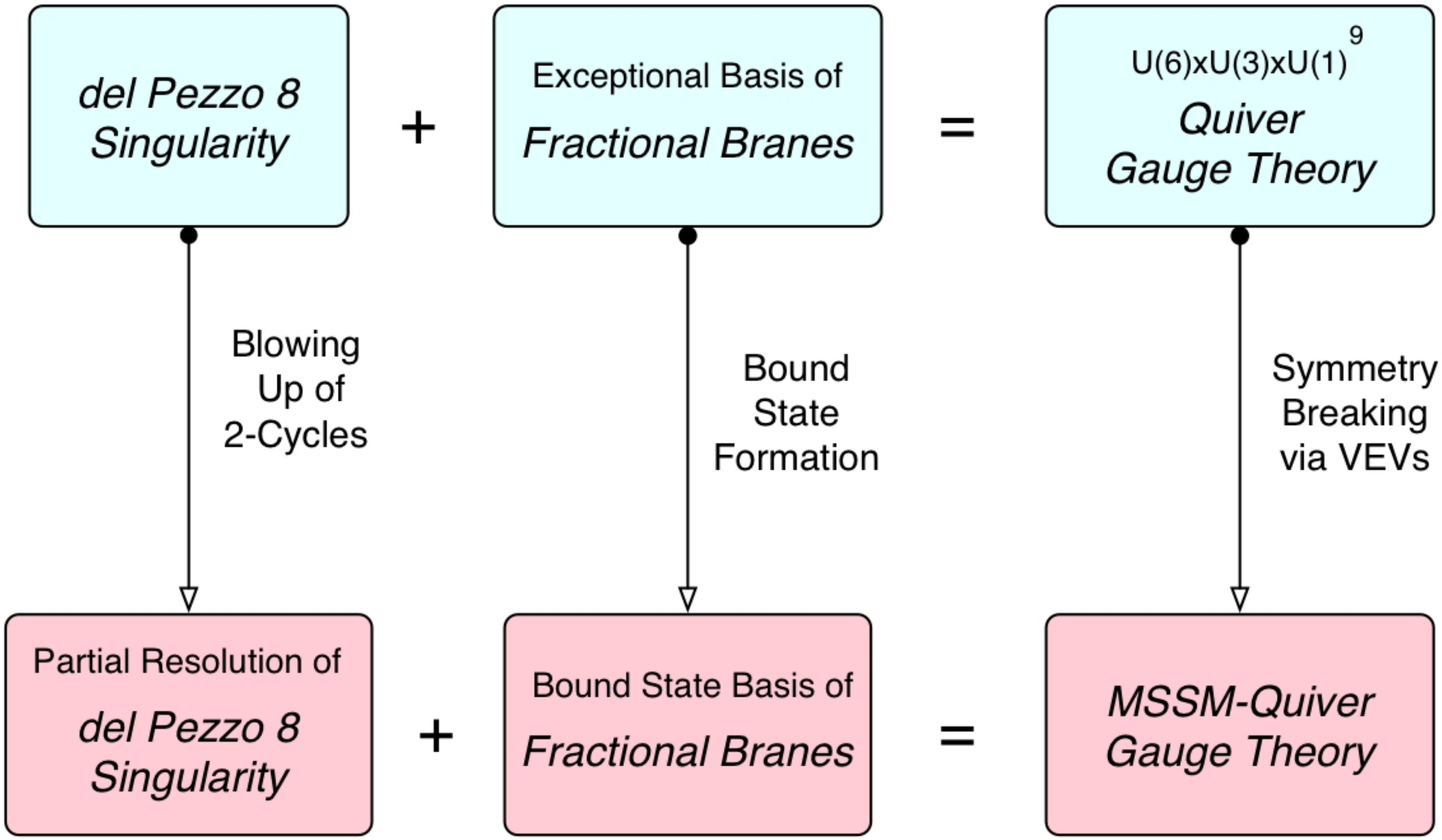
RR-field strengths $\longleftrightarrow$ Soft parameters

Applying a Seiberg duality to the F_{10}-node, translates into the replacement:

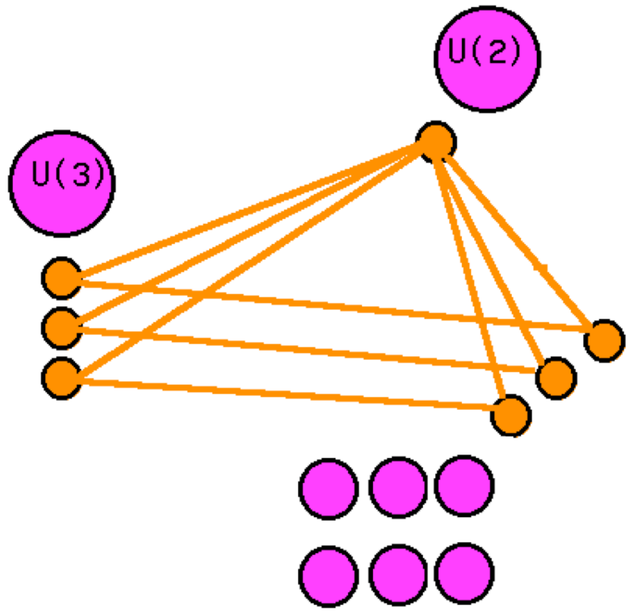
$$\mathrm{ch}(\tilde{F}_{11}) = -\mathrm{ch}(F_{11}) + 3\,\mathrm{ch}(F_{10})$$

New quiver diagram:



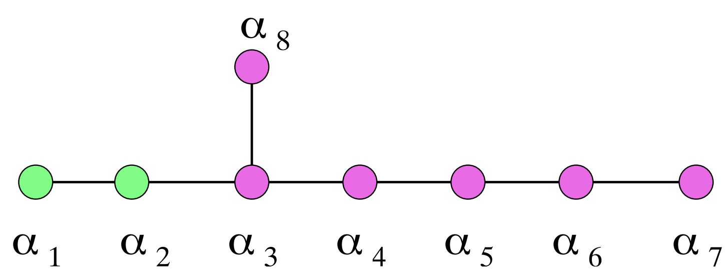

del Pezzo 8 Singularity
+
Exceptional Basis of
Fractional Branes
=
U(6)xU(3)xU(1)^9
Quiver Gauge Theory
Blowing Up of 2-Cycles
Bound State Formation
Symmetry Breaking via VEVs
Partial Resolution of
del Pezzo 8 Singularity
+
Bound State Basis of
Fractional Branes
=
MSSM-Quiver Gauge Theory

Symmetry breaking = Bound state formation:



$$\mathrm{ch}(F_0) \;=\; 3\,\mathrm{ch}(F_{10}) - \sum_{i=1,2,3} \mathrm{ch}(F_i) - \mathrm{ch}(\tilde{F}_{11})$$

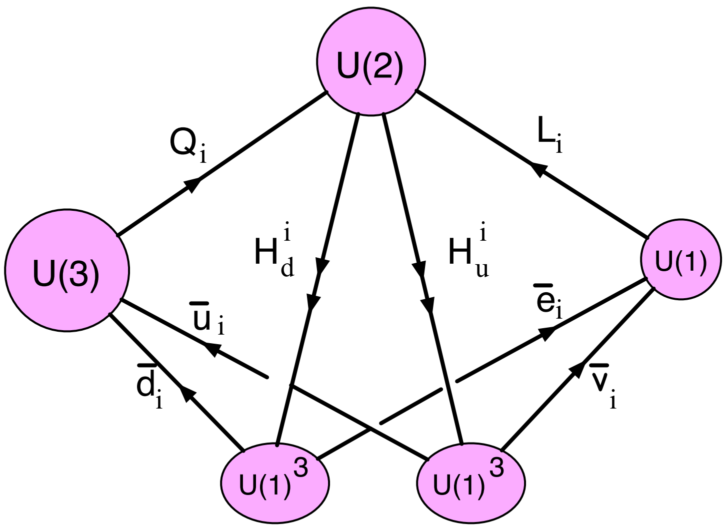
The new bound state basis of fractional branes spans the full homology of the del Pezzo 8 surface, except for two generators: α_1, α_2



Interpretation:

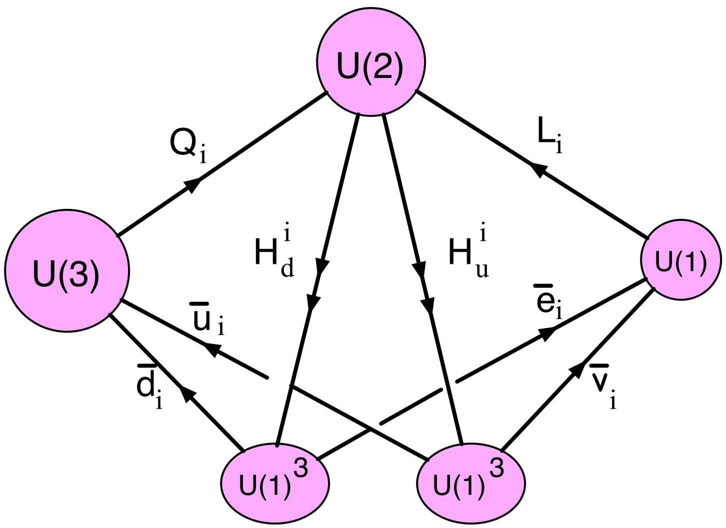
The symmetry breaking is triggered by blow-up of the two 2-cycles α_1, α_2.

This blow-up mode exists, provided the shape of dP_8 develops a A_2 singularity.



New Quiver: MQSSM

+ extra $U(1)$'s



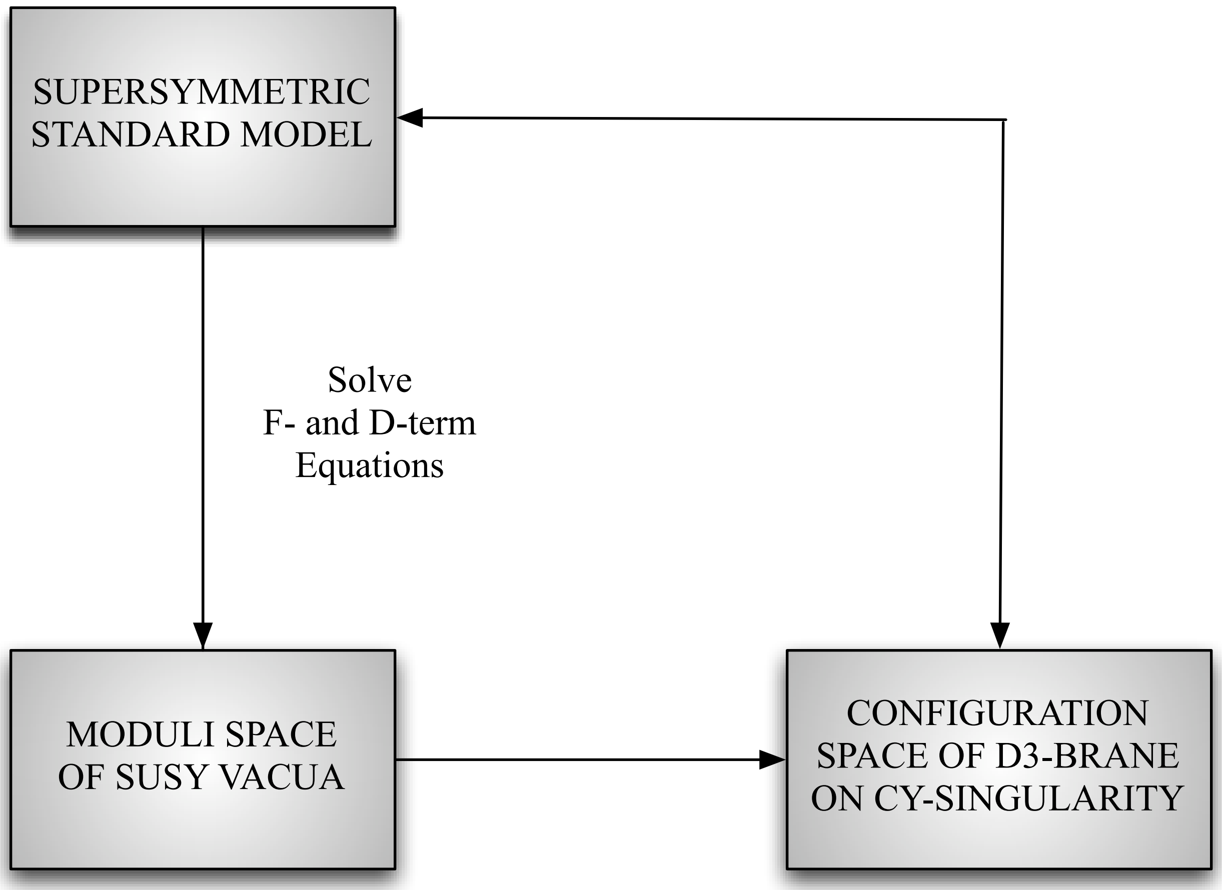
New Quiver: MQSSM

+ extra $U(1)$'s

Bottom-Up Philosophy: Open String Phenomenology

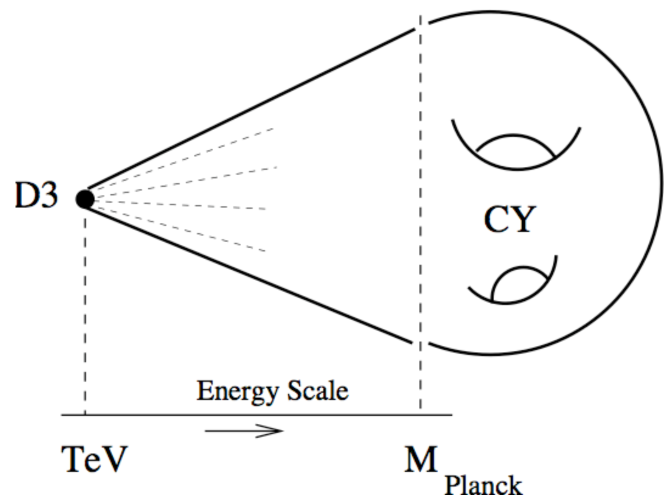
- Take decoupling limit from gravity and closed string moduli.
- Couplings and expectation values dialed by local geometry.
- Postpone issue of string compactification and the landscape.
- Geometric unification: one single D3-brane?

Uniqueness:

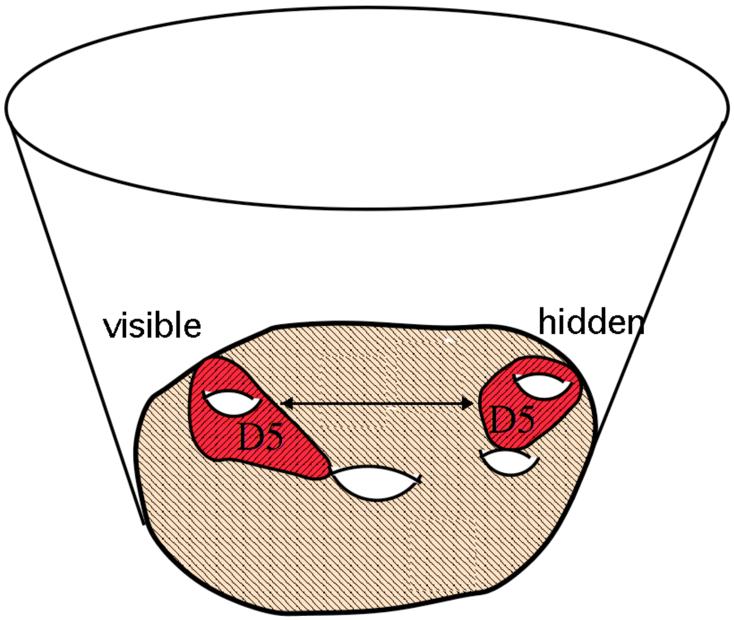

SUPERSYMMETRIC
STANDARD MODEL
Solve
F- and D-term
Equations
MODULI SPACE
OF SUSY VACUA
CONFIGURATION
SPACE OF D3-BRANE
ON CY-SINGULARITY

Embedding in full string compactification:

- Moduli stabilization
- Tadpole cancellation
- Decoupling of $U(1)$'s



SUSY breaking:



Gauge or Gravity Mediation?

Depends on distance between branes, relative to string scale.

Provocative Question:

Is open string phenomenology useful?

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Provocative Question:

Is open string phenomenology useful?

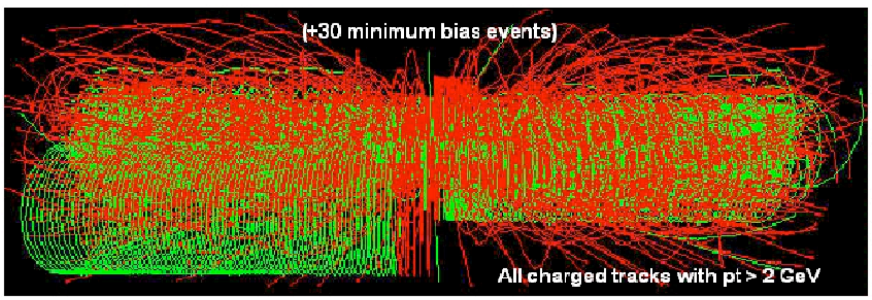
Provocative Answer:

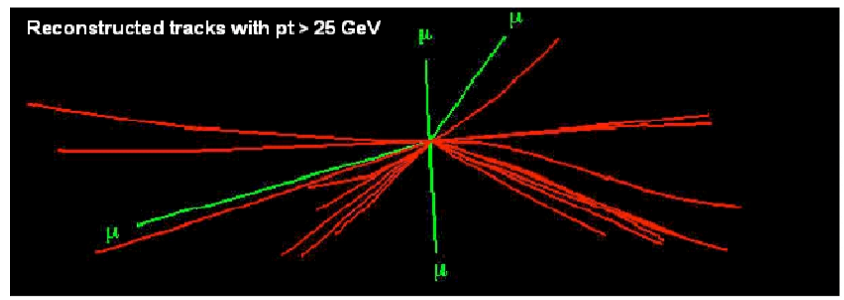
Via open string phenomenology, we may identify:

closed string in the near-horizon geometry of the D3-brane	=	QCD string defined via the $1/N$ expansion

LHC

CERN, 9/10 February, 2005





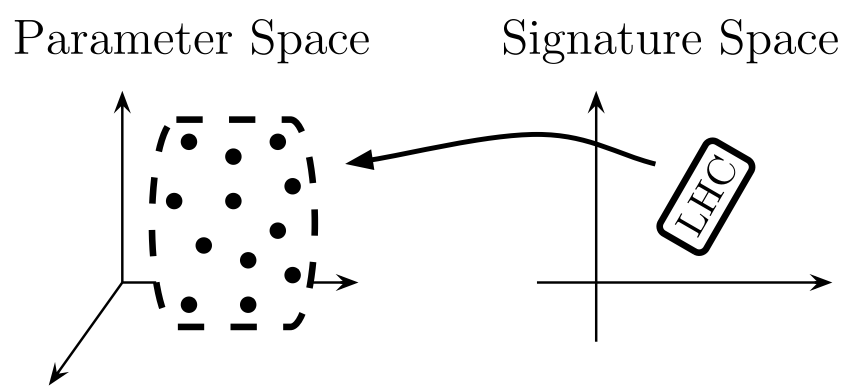
Organizers:

Ignatios Antoniadis (Cern)
Nima Arkani-Hamed (Harvard)
Savas Dimopoulos (Stanford)
Gian Giudice (Cern)

Gordy Kane (Michigan)
Steve Mrenna (Fermilab)
Matt Strassler (Univ. of Washington)
Herman Verlinde (Princeton)

Challenge:

Extract the theory
from
inclusive signatures



What is the LHC Olympics?

A set of activities to help theorists prepare for the advent of LHC data:

- A webpage with instructions on how to use simulation and analysis tools.
- A data challenge, based on of 3 “black boxes” with simulated data sets.
- A series of workshops with theorists, experimentalists, experts in MC.

What is inside of a black box?

- Based on unknown theoretical model except to creators.
- List of "interesting events" selected by "triggers"
- Event = final state of "objects" particles, jets, missing energy.
- Object = row of numbers

event	object	η	ϕ	P_T	M_{jet} / $Q_{particle}$	b-tag?	isolated?

- Signal only! No SM background!

How are the black boxes generated?

- Matrix elements are calculated. Pythia.
- Decay of unstable particles and jet formation. Pythia.
- Simulation of detector PGS — jet reconstruction, lepton identification

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How to read the black box data?

Make your own plots!

Root, for experts   Chameleon, for beginners

Generate your own white boxes!