The DSSM: Electroweak Symmetry Breaking & Collider Phenomenology

Piyush Kumar
Columbia University

1108.3849[hep-ph]
Heckman, P.K.,Vafa, Wecht

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Plan of the Talk

- Motivation.
- Setup.
- Higgs Potential – EWSB and Mass scales.
- Precision Constraints.
- Potential Signals at Colliders.

Motivation

What/Where is the Higgs?

- LEP : SM-like Higgs $M_h > 114$ GeV
- MSSM the most popular extension of the SM.

$$M_h < \sim 135 \text{ GeV}$$

- $M_h^{\text{tree}} < M_Z$, Radiative corrections log sensitive to stop mass.

Together with requirement of EWSB, gives rise to O(0.1-1)% fine-tuning

→ **Little Hierarchy Problem**

- Extensions – such as NMSSM, help, but not completely solve it.

Various Proposals to increase the Higgs Mass

Luty et al ph/0006224; Harnik et al ph/0311349; Stancato et al 1002.1694; Fukushima et al 1012.5394; Craig et al 1106.2164, …

From a Theoretical point-of-view:

- MSSM just one particular field theory.
- Three basic inputs in a SUSY model:

  a) Kahler Potential, b) Superpotential, c) Soft Breaking terms.

- Many models in the literature with different choices for b) and c).

- In this work, we study what happens if the Kahler potential for the Higgs sector $K_{\text{Higgs}} \neq H^{\dagger} H$

Introducing the DSSM

(Delta-deformed Supersymmetric Standard Model)

- Two higgs doublets like the MSSM, but

a) Non-trivial scaling dim.

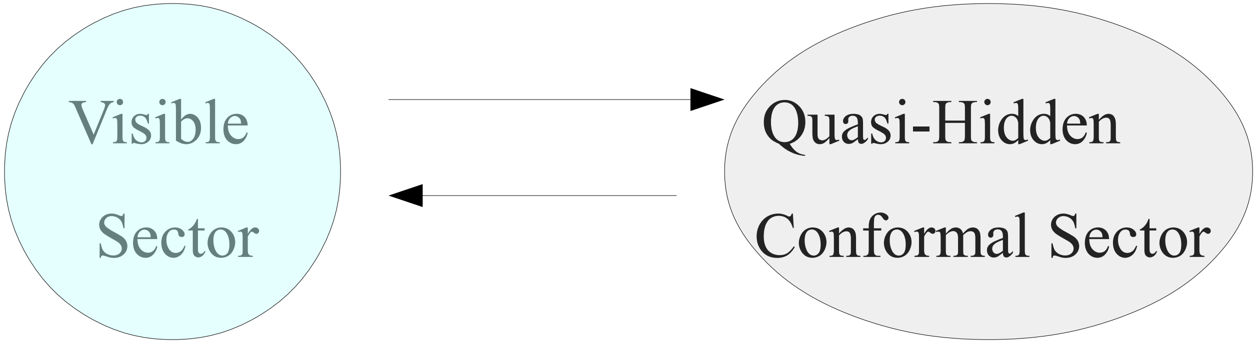
$$\Delta(H_u) = 1 + \delta_u; \;\; \Delta(H_d) = 1 + \delta_d$$

b) Kahler metric singular at the origin.

Can be motivated from Top-down constructions

– F-theory GUT models in string theory.

Basic Setup



Visible Sector

Quasi-Hidden Conformal Sector

- Visible Gauge symmetry – weakly gauged flavor symmetry in conformal sector (with a mass gap).
- States charged under both sectors.
- Higgs assumed to mix with the conformal sector.

Mixing Via: $\int d^2\theta \, (H_u O_u + H_d O_d)$

Also see

Stancato, Terning 0807.3961

Azatov, Galloway, Luty 1106.4815

Gherghetta, Pomarol 1107.4697

- Above coupling assumed to be relevant in the UV.

Higgs develops a non-trivial scaling dimension in the IR

Main Focus (Small δ regime)

- When $\delta = \Delta - 1 \ll 1$ but not zero, Higgs fields retain identity as elementary fields.
- Retain good features of the MSSM:
  - Perturbative Gauge Coupling Unification.

    Effect of charged states in conformal sector treated as threshold effects.

    [Heckman, Vafa, Wecht 1103.3287]
  - Large top yukawa coupling possible.

    Higher dim. Operator, but suppressed only by a small amount for small δ

    Example: H_uQU coefficient: $\left(\frac{10^3}{10^{16}}\right)^{\delta} \sim 0.74$ for $\delta \sim 0.01$

RG Flow and Mass Deformations

- Interaction between two sectors added at High scale (~ GUT scale)
  - These deformations trigger an RG flow to an interacting N=1 conformal fixed point. *[Heckman, Vafa, Wecht 1103.3287]*
  - Using "a-maximization", compute the scaling dimensions of fields in the IR. *[Intriligator, Wecht hep-th/0304128]* (δ small in many explicit examples)
- However, never quite reach the fixed point (F.P).
  - Close to the Fixed Point, assume

supersymmetry broken $\longrightarrow$ conformal symmetry also broken.

IR:

CFT Breaking Deformations:
via Higgs 2-point functions

$$\int d^2\theta\ (\mu H_u H_d) + B h_u h_d + h.c.$$

$$m_u^2||H_u||^2 + m_d^2||H_d||^2$$

$$\mu \propto \Lambda_{soft}^{3-\Delta_u-\Delta_d}$$

$$B \propto \Lambda_{soft}^{4-\Delta_u-\Delta_d}$$

$$m^2 \propto \Lambda_{soft}^2$$

Electroweak Symmetry Breaking

Characteristic vev scale:

$$\frac{v}{\sqrt{2}} \equiv \sqrt{v_u^{2/\Delta_u} + v_d^{2/\Delta_d}}$$

$$M_W \sim \frac{gv}{2}$$

Dimensionless ratio: $\tan\beta \equiv \frac{v_u^{1/\Delta_u}}{v_d^{1/\Delta_d}}$

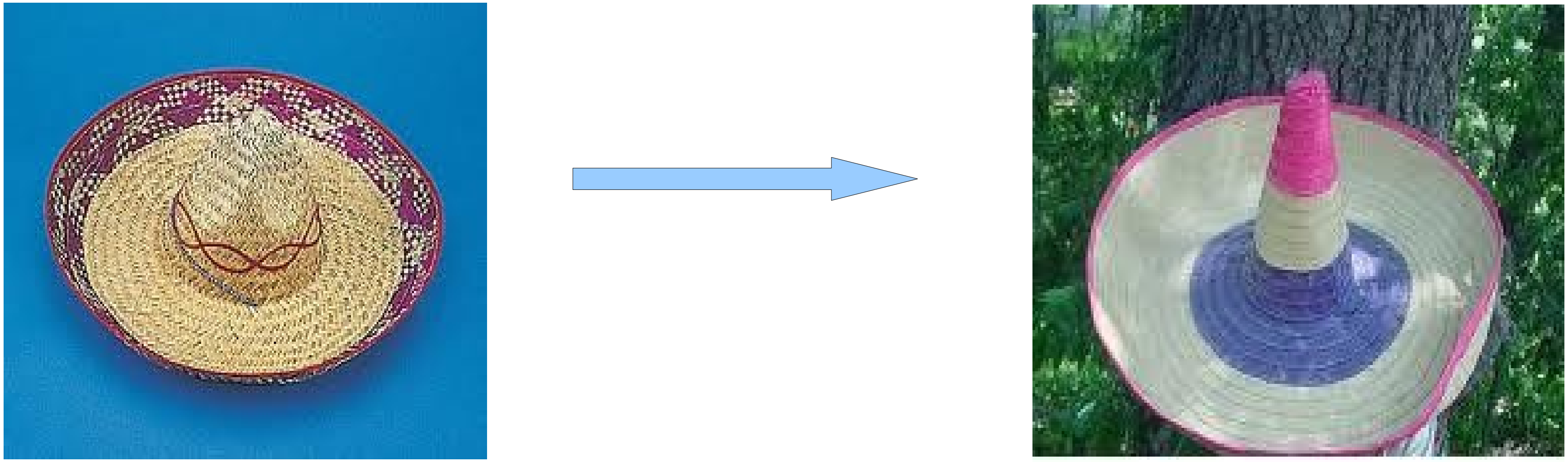
- **Higgs Potential very different from the MSSM (& the SM)**

“Squeezed” Mexican Hat

$K_{\text{higgs}} \sim (H^\dagger H)^{1/\Delta}$

$\delta \neq 0 \Rightarrow$ Scaling arguments fix V_{Higgs}

$$V_{Higgs}(v, \tan\beta) \simeq \overset{\text{soft masses}}{m^2v^2} - \overset{B\mu\text{-term}}{Bv^{2+2\delta}} + \overset{\mu\text{-term}}{|\mu|^2v^{2+4\delta}} + \overset{\text{negligible!}}{O(v^4)}$$



“Squeezed” Minimum near the Origin of Field Space $(v << \Lambda_{\text{soft}})$

$v \sim \Lambda_{soft} \times (\sqrt{q_0})^{1/\delta} \ll M_h$

($q_0 < 1$ for consistency)

Physical Mass Scales

$$\left.\begin{array}{l} M_W \sim \Lambda_{soft} \times g \times (\sqrt{q_0})^{1/\delta} \\ \\ M_h \sim \Lambda_{soft} \times \sqrt{\delta} \end{array}\right] \text{Hierarchy}$$

Can range from 114 GeV - 800 GeV

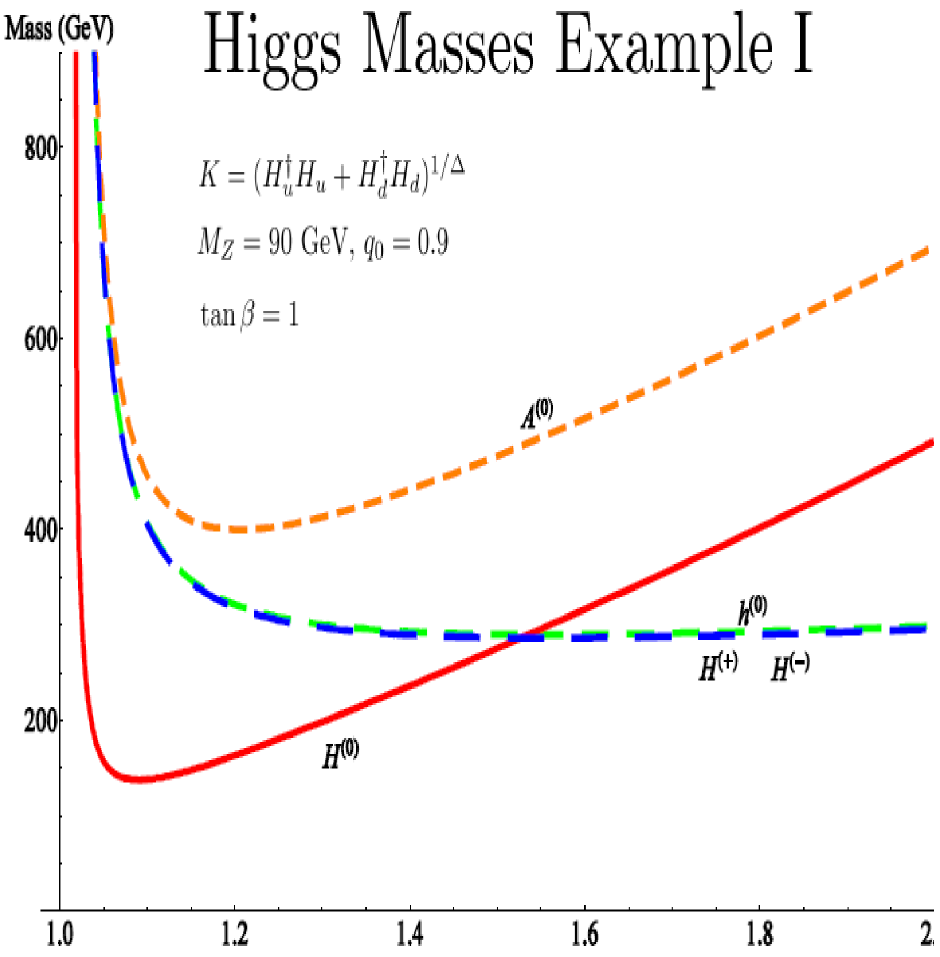
Singular Kähler potential $\Rightarrow$ Extra (not light) states

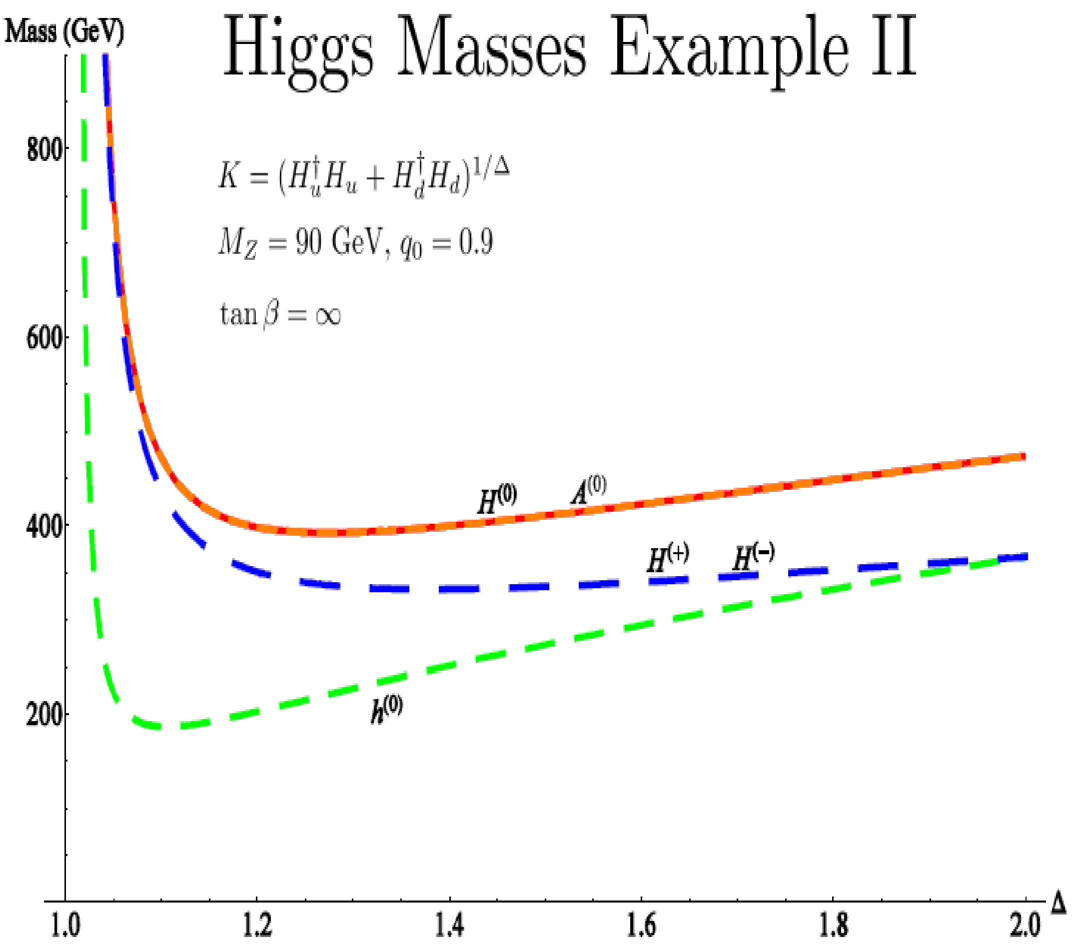
$$M_{extra} \sim 4\pi v \times \sqrt{\delta} \sim (3 \text{ TeV}) \times \sqrt{\delta}$$

Can range from $\sim$ 300 GeV - O(TeV) (Model Dependent)

M_h and M_Z/M_W are exponentially decoupled – very different from other cases where $M_h \sim M_z$ at tree level.

⇨ Manifestly solves the Little Hierarchy Problem


Higgs Masses Example I
Mass (GeV)
$K = (H_u^\dagger H_u + H_d^\dagger H_d)^{1/\Delta}$
$M_Z = 90$ GeV, $q_0 = 0.9$
$\tan\beta = 1$
$A^{(0)}$
$h^{(0)}$
$H^{(+)}$
$H^{(-)}$
$H^{(0)}$
800
600
400
200
1.0
1.2
1.4
1.6
1.8
2.


Higgs Masses Example II
Mass (GeV)
$K = (H_u^\dagger H_u + H_d^\dagger H_d)^{1/\Delta}$
$M_Z = 90$ GeV, $q_0 = 0.9$
$\tan\beta = \infty$
$H^{(0)}$
$A^{(0)}$
$H^{(+)}$
$H^{(-)}$
$h^{(0)}$
800
600
400
200
1.0
1.2
1.4
1.6
1.8
2.0
Δ

Weakly coupled limit

- In the weakly coupled limit, Higgs has dimension 1.
  - Use Coleman-Weinberg Kahler potential to determine the effective Higgs Potential.

$$K_{\log} = H^\dagger H \left(1 - \hat{\delta} \log \frac{H^\dagger H}{\Lambda_{(0)}^2}\right) \qquad \hat{\delta} \sim \delta$$

  - Minimizing the potential generically gives

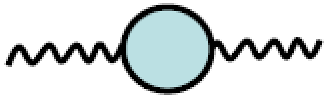
$$\delta \log \left(\frac{v^2}{\Lambda_{(0)}^2}\right) \simeq \left(\frac{B - |\mu|^2 - m^2}{|\mu|^2 - m^2}\right) = \mathcal{O}(1),$$

Hence, cannot trust the solution. K_Δ provides a completion of $K_{\log}$

DSSM does not reduce to the MSSM in the $\delta \longrightarrow 0$ limit.

Electroweak Precision

- Electroweak Precision measurements place important constraints on all models of EWSB.
- Correction to EW observables well encapsulated by "Oblique Parameters" (S, T,..) in many cases



– also true for these models.

- Deviations from SM reside essentially in gauge boson self energies.
- Well known that the SM alone prefers a light Higgs in the absence of new (or decoupling) physics.
- Here, Higgs can be naturally much heavier than the LEP bound:

→ negative contribution to T

(smaller) positive contribution to S.

Other Contributions to S & T

Can estimate these – precise computation not possible due to strong coupling

Argue that including all contributions can naturally give rise to S & T consistent with data.

- $$S = S_{IR} + S_{UV}$$
  $$T = T_{IR} + T_{UV}$$

UV : contributions from “New Physics” arising from the non-standard Kahler potential.

IR : coming from Higgs particles in loops similar to that for the usual 2 HDM.

[Haber, O'Neil 1011.6188]

$$S_{IR} \simeq S_{IR}^{\rm singlet} + S_{IR}^{\rm doublet} \; , \; T_{IR} \simeq T_{IR}^{\rm singlet} + T_{IR}^{\rm doublet}$$

Singlet: similar to that for the SM higgs.

$T_{IR} \sim \pm O(0.1 - 10)$ (Model Dependent) – *Haber et al 1011.6188*

$T_{UV} \sim \frac{\delta}{\alpha_{QED}} \sim O(1) - O(10)$ for $\delta \sim 0.01 - 0.1$ -- *From Kahler potential*

Need T_{IR} to cancel against T_{UV} to $O(0.1)$

For $\delta \sim 0.01$, requires $O(30\%)$ cancellation

For $\delta \sim 0.1$, requires $O(1\%)$ cancellation

when there is NO custodial SU(2)

$\delta \sim 0.01$ also better for unification and top quark mass...

Can also consider models with SU(2)$_R$

If tan β ≈ 1, Have approx. custodial SU(2) Extra suppression of T_{UV}

δ = 0.1 possible with no (minimal) tuning.

- S_{IR} small, but S_{UV} hard to compute.

  Technicolor Models – extrapolation from QCD sum rules typically give large positive contribution to S.

- Models considered here very different from QCD & SQCD

  – Naïve QCD sum rules don't apply.

  – Vector-like spectrum. Once CFT and EW symmetry broken, large vector-like masses possible reducing contribution to S_{UV}.

  – Operators with different EW representations exist in the CFT, the contributions to S from which can cancel each other in principle.

  - Dugan & Randall PLB 264 (1991) 154

  – Existence of Majorana masses for some states can give negative contributions which cancel positive contributions from other states.

- $S = S_{UV} + S_{IR}$ can naturally lie between -0.1 and 0.1 in large regions of parameter space.

Consequences for Collider Physics

Qualitatively, the DSSM predicts ∃ three sectors:

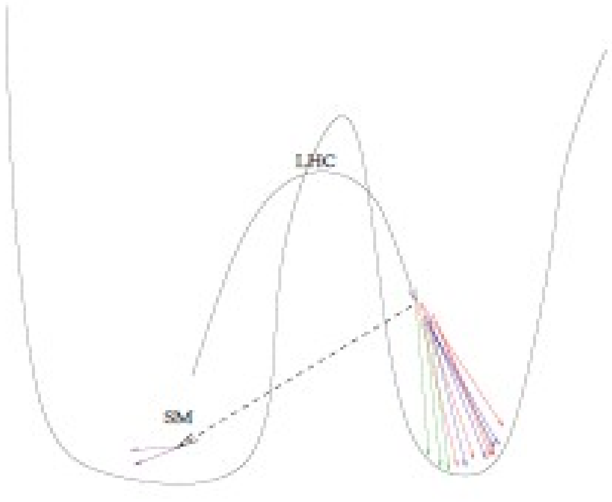
- Modified Higgs sector (compared to MSSM)
- Extra $SU(3)_C \times SU(2)_L \times U(1)_Y$ charged states
- Hidden sector singlets (which may be light)

Hence, Collider Phenomenology quite rich, but depends crucially on details of Hidden sector.

Only restrict to qualitative remarks

Collider Signatures

- Although detailed study needed, qualitatively looks similar to Hidden-Valley scenarios with a Mass Gap (Since CFT broken at TeV Scale).



Strassler, Zurek ph/0604261

Strassler ph/0801.0629

Han, Zurek, Strassler 0712.2041

- Focus on general features and constraints

Electroweak Sector

- Presence of electroweak states in hidden sector.
  - Can mix with the Higgs (when SM singlets get vevs)
  - These states could be produced and can decay to Higgs and long-lived states in hidden sector. For e.g. final states with Higgs.

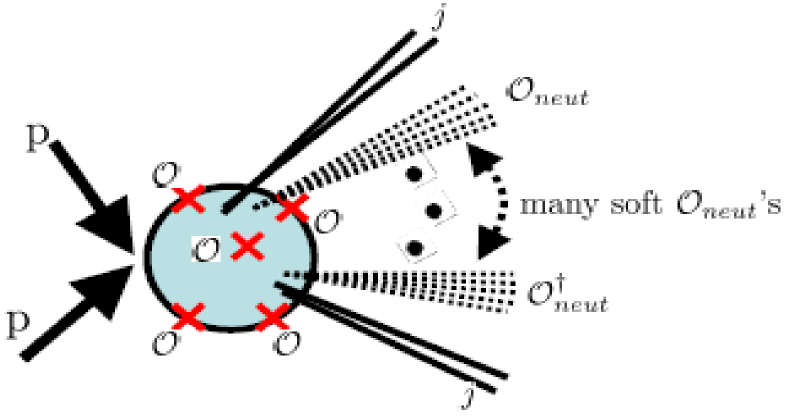
$$gg \longrightarrow \tilde{H}_{hid} \longrightarrow H\, S_{\text{hid}}$$

- Higgs Phenomenology also very rich & complicated
  - Just as in 2 HDM, H ⟶ {WW, ZZ, ff} different from SM.
  - Higgs can decay to hidden sector non-singlets as well as singlets.

    --- *Multiple cascades with many jets in final state.*
  - Higgs can decay to LSPs.
  - Production cross-section may also be different.
- Present bounds from LHC Higgs searches can be weakened.

Colored Sector

If light enough, extra colored states produced by LHC?



Standard Search – Jets + Missing energy (if R-odd)
– (Di)-Jets (if R-even) *CMS 1107.4771*

(See http://lhcnewphysics.org; Shelton,Spannowsky)

But typically require hard jets AND large missing energy

Here, many soft hidden states expected → high multiplicity of jets, many soft.
Missing energy may be small too.

Again, expect existing LHC bounds to be weakened

Conclusions

- DSSM is a novel & interesting class of models with Δ (H) > 1.
  - Consistent with gauge unification.
  - Predicts rich (but complex) phenomenology at the LHC
- Decouples M_H and M_Z. $M_H > M_Z$ naturally.

Future Directions

- Dynamical Supersymmetry Breaking.
- More detailed study of representative Signals of the Framework.

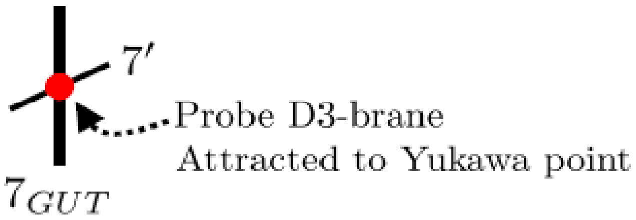
Backup Slides

Stringy Setup

JJH Vafa '10
JJH Tachikawa
Vafa Wecht '10
Cecotti, Cordova
JJH Vafa '10
JJH Rey '11
JJH Vafa Wecht '11

This occurs in actual string constructions

Example: D3-Brane probe of F-theory GUT:



In absence of introducing a mass scale, leads to SCFTs

Small excess dimension: $\delta \simeq O(0.01) - O(0.1)$

D3-brane probe theory very different from (conformal) SQCD.

Below, the CFT breaking scale $\longrightarrow$ strongly coupled U(1) gauge theory

Cartoon Plot for functions $V = -1.5|x|^2 + |x|^{2+2\delta}$. At $\delta = 0$, the non-zero minimum disappears.