Signals for Light Landscape Scalars

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in progress with

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Hierarchy Problems

- The two relevant questions:

$$\frac{\Lambda^{1/4}}{M_{\text{Pl}}} \ll 1, \qquad \frac{v}{M_{\text{Pl}}} \ll 1,$$

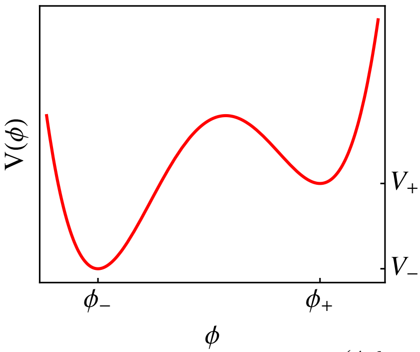
- Given a landscape can be solved anthropically.
  - Cosmological constant (CC) explained by *structure principle*.
  - Hierarchy problem explained by *atomic principle*.
- Provided we live in a "friendly neighborhood" of the landscape.
  - Super-renormalizable couplings are scanned.
  - Renormalizable couplings are not scanned.

(Weinberg, 1987)

(Arkani-Hamed, Dimopoulos, Kachru, hep-th/0501082)

Field Theory Landscape

- A field theory landscape of scalars can be friendly.
  - Consider N scalars ϕ_i (where $i = 1, \ldots, N$).
  - Each has a potential $V(\phi_i)$.



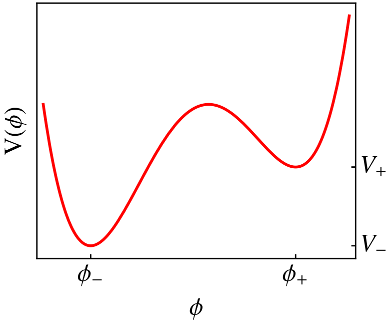
- Have 2^N metastable vacua.
- Can be long-lived

$$\Gamma \sim M_*^4 e^{-27\pi^2 \frac{\sigma^4}{p^3}}$$

- (with scales given by M_*)

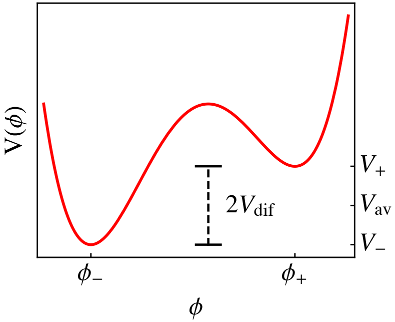
(Arkani-Hamed, Dimopoulos, Kachru, hep-th/0501082)

Field Theory Landscape



- Label two minima ϕ_+, ϕ_-
- Take $V_+ = V(\phi_+)$, $V_- = V(\phi_-)$
- Average and difference: $V_{\rm av}$, $V_{\rm dif}$
- These vacua are:

$$V_\eta = V_{\rm av} + \eta V_{\rm dif}, \qquad (\eta = \pm 1)$$



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$$V_\eta = V_{\rm av} + \eta V_{\rm dif}, \qquad (\eta = \pm 1)$$

- Include all N scalars: $\{\eta_i\}$

$$V_{\{\eta_i\}} = N\bar{V}_{\rm av} + \sum_i \eta_i V_{{\rm dif},i}, \qquad \bar{V}_{\rm av} = \frac{1}{N}\sum_i V_{{\rm av},i}$$

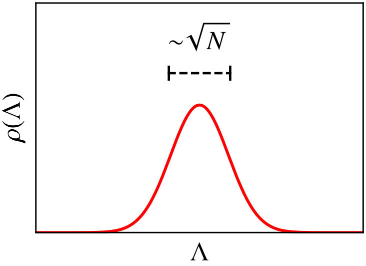
- At large N, distribution of vacua is Gaussian.

Field Theory Landscape

- With cutoff M_*, would like $\Lambda \sim 2^{-N} M_*^4$
- Vacuum distribution:

$$\rho(\Lambda) = \sum_{\{\eta_i\}} \delta(\Lambda - V_{\{\eta_i\}})$$

- Vacuum energy densely scans range $\sim \sqrt{N} V_{\text{dif}}$.



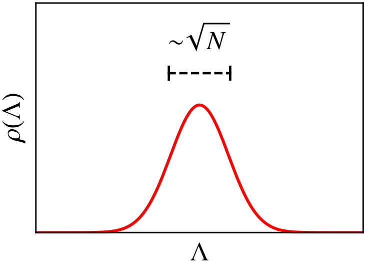
Field Theory Landscape

- With cutoff M_*, would like $\Lambda \sim 2^{-N} M_*^4$
- Vacuum distribution:

$$\rho(\Lambda) = \frac{2^N}{\sqrt{2\pi N} V_{\rm dif}} e^{-\frac{(\Lambda - N\bar{V}_{\rm av})^2}{2NV_{\rm dif}^2}}$$

$$\text{mean} = N\bar{V}_{\rm av}$$
$$\text{width} = \sqrt{N} V_{\rm dif}$$

- Vacuum energy densely scans range $\sim \sqrt{N} V_{\rm dif}$.



Field Theory Landscape

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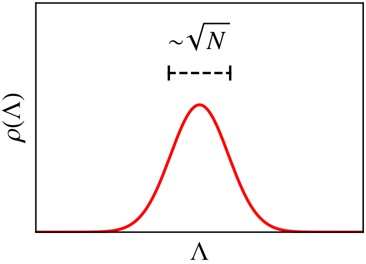


- Naively, $\bar{V}_{\text{av}} \sim M_*^4 \quad \rightarrow \quad \text{mean} \sim N$.
- Generically, parameter does not scan much.
- (1) Tuning allows super-relevant couplings to be small.
- or, (2) Set $\bar{V}_{\text{av}} \sim 0$ by symmetry.

Field Theory Landscape

- (1) Naively, have $\bar{V}_{\text{av}} \sim M_*^4$, $V_{\text{dif}} \sim M_*^4$.

$$\rho(\Lambda = 0) \sim \frac{2^N}{V_{\text{dif}}} e^{-\frac{N^2(\bar{V}_{\text{av}})^2}{2N(V_{\text{dif}})^2}}$$

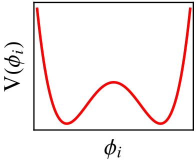
$$\sim \frac{1}{V_{\text{dif}}} \left(2e^{-\frac{(\bar{V}_{\text{av}})^2}{2(V_{\text{dif}})^2}} \right)^N$$

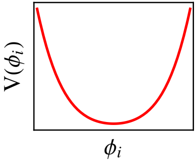
- (2) Take the superpotential:

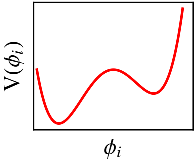
$$W = \lambda\phi^3 - \mu^2\phi$$

  - Two supersymmetric minima: W_+, W_-.
  - Have $W_+ = -W_-$ since odd in ϕ.
  - $W_{\text{av}} = 0$.

Light Scalars







- Can connect the CC and the Higgs using *light* scalars.
- Let $V(\phi_i)$ be Z_2-symmetric.
  - EW unbroken leaves $V(\phi_i)$ unperturbed.

    $\rightarrow$ Cannot scan for CC.
  - Large VEV leads to only 1 minimum.

    $\rightarrow$ Cannot scan for CC.
  - Smaller VEV has 2 minima.

    $\rightarrow$ Can scan for CC.

Light Scalars

- Superpotential and soft terms

$$W = \mu H_u H_d + \frac{\lambda_i}{\sqrt{N}} \phi_i H_u H_d + \frac{\kappa_i}{\sqrt{N}} \phi_i^3$$

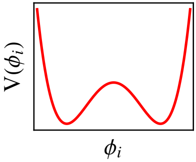
$$V_{\text{soft}} = -m_\phi^2 |\phi_i|^2 + \left(\frac{a_\phi}{\sqrt{N}} \phi_i H_u H_d + \text{h.c.} \right)$$

- Relevant part of potential is

$$V(\phi_i) = \frac{\kappa_i^2}{N} |\phi_i|^4 - m_\phi^2 |\phi_i|^2 + \frac{\lambda_i^2}{N} |\phi_i|^2 (|H_u|^2 + |H_d|^2)$$

$$+ \frac{a_\phi}{\sqrt{N}} \phi_i H_u H_d + \frac{\lambda_i \mu}{\sqrt{N}} \phi_i (|H_u|^2 + |H_d|^2) + \text{h.c.} + \dots$$

Light Scalars

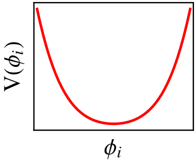


- EW unbroken

$$V(\phi_i) = \frac{\kappa_i^2}{N}|\phi_i|^4 - m_\phi^2|\phi_i|^2$$

- EW broken

$$V(\phi_i) = \frac{\kappa_i^2}{N}|\phi_i|^4 - \left(m_\phi^2 - \frac{\lambda_i^2 v^2}{N}\right)|\phi_i|^2 + \frac{v^2}{\sqrt{N}}\phi_i\left(a_\phi s_\beta c_\beta + \lambda_i \mu\right) + \text{h.c.}$$

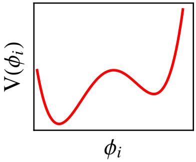


If $m_\phi^2 - \dfrac{\lambda_i^2 v^2}{N} < 0$ quadratic term flips sign.

Light Scalars

- EW broken

$$V(\phi_i) = \frac{\kappa_i^2}{N}|\phi_i|^4 - \left(m_\phi^2 - \frac{\lambda_i^2 v^2}{N}\right)|\phi_i|^2 + \frac{v^2}{\sqrt{N}}\phi_i\left(a_\phi s_\beta c_\beta + \lambda_i \mu\right) + \text{h.c.}$$



$$(i) \quad m_\phi^2 - \frac{\lambda_i^2 v^2}{N} > 0$$

$$(ii) \quad a_\phi^2 \lesssim v^2 \lesssim \frac{m_\phi^3}{a_\phi}$$

- Allows CC to be scanned.

Light Scalars

- Can include cross-couplings:

$$W = \mu H_u H_d + \frac{\lambda_i}{\sqrt{N}}\phi_i H_u H_d + \frac{J_{ijk}}{\sqrt{N}}\phi_i\phi_j\phi_k$$

- Leads to new quartic vertices

$$V = \frac{J_{abc}J_{ade}}{N}\phi_b\phi_c\phi_d^*\phi_e^* + \frac{\kappa_a J_{abc}}{N}\phi_a^2\phi_b^*\phi_c^* + \dots$$

Phenomenology

- Higgs can decay to pairs of scalars.
- Scalars decay via mixing with the Higgs.

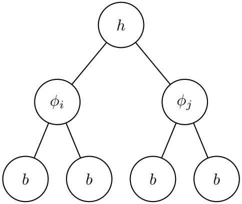
$$\text{mixing} \sim \frac{a_\phi v}{\sqrt{N}}$$

- Cascade decays that end in $\bar{b}b$, $\bar{c}c$, ...
- Have two cases:
  - (1) small cross-couplings:

$$p_T(b) \sim \frac{m_h}{4}$$

$$(p_1 + p_2 + p_3 + p_4)^2 \text{ fixed}$$

$$(p_1 + p_2)^2, (p_3 + p_4)^2 \text{ vary}$$



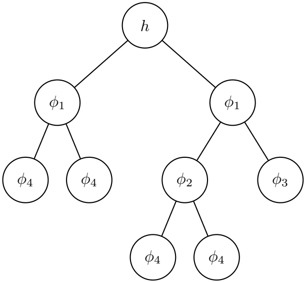
Phenomenology

- Higgs can decay to pairs of scalars.
- Scalars decay via mixing with the Higgs.

$$\text{mixing} \sim \frac{a_\phi v}{\sqrt{N}}$$

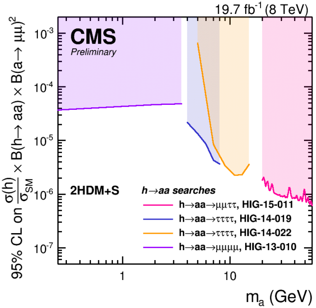
- Cascade decays that end in $\bar{b}b$, $\bar{c}c$, ...
- Have two cases:
  - (2) sizable cross-couplings:

$$p_T(b) \sim \frac{m_h}{N}$$
$$(\sum_i p_i)^2 \text{ fixed}$$
$$(p_i + p_j)^2 \text{ vary}$$



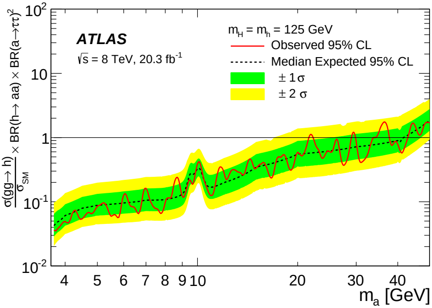
Phenomenology

- Searches for exotic Higgs decays
  - CMS (HIG-15-011): $h \to (\mu\mu)(\tau\tau)$, $h \to (\tau\tau)(\tau\tau)$, $h \to (\mu\mu)(\mu\mu)$.
  - Utilizes $(p_1 + p_2)^2 = (p_3 + p_4)^2$.
  - $p_T(\mu_1) > 18$ GeV, $p_T(\mu_2) > 9$ GeV.



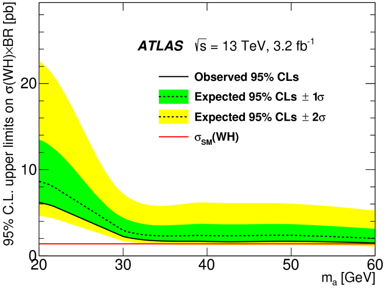
Phenomenology

- Searches for exotic Higgs decays
  - ATLAS (HIGG-2014-02): $h \to (\tau\tau)(\tau\tau)$.
  - Does not utilize $(p_1 + p_2)^2 = (p_3 + p_4)^2$.
  - $p_T(\mu_1) > 18$ GeV, $p_T(\mu_2) > 8$ GeV.



Phenomenology

- Searches for exotic Higgs decays
  - ATLAS (HIGG-2016-01): $h \to (b\bar{b})(b\bar{b})$.
  - Utilizes $(p_1 + p_2)^2 = (p_3 + p_4)^2$.
  - $p_T(b) > 20$ GeV.

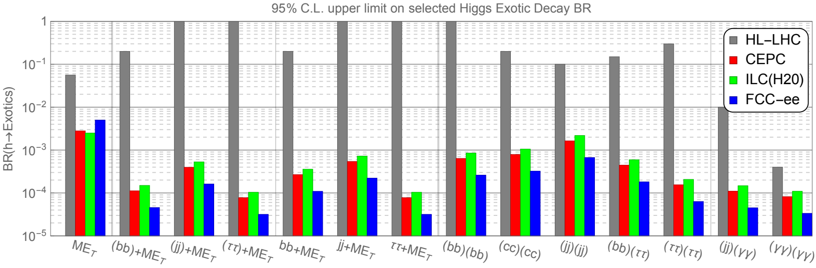


Phenomenology

- Reach from future (e^+e^-) colliders.

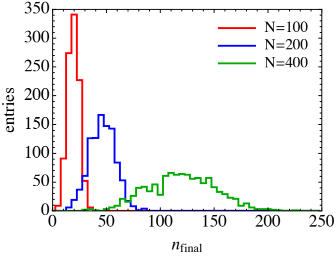
(Curtin et al., 1312.4992)

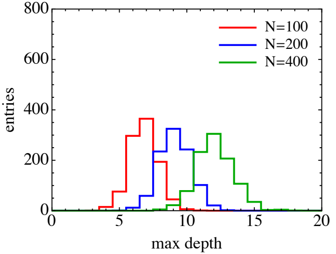
(Liu, Wang, Zhang, 1612.09284)

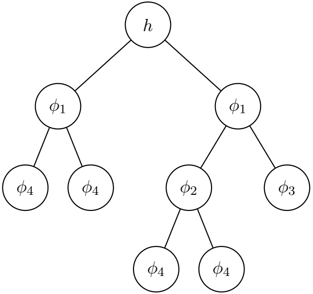


Phenomenology

- Large variations among cascade decays.







- Difficult signal at hadron collider.
- Better suited for a lepton collider.

Summary

- Can correlate CC and Higgs with a landscape of light scalars.
- Predict many light scalars couplings to the Higgs.
- Expect cascade decays with many resonance masses.
- Interesting signal for future lepton colliders.