Disorder at the LHC

Matthew Low

Institute for Advanced Study

in progress with

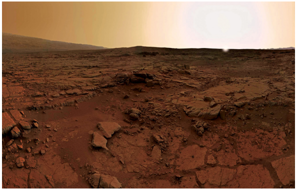
Raffaele Tito D'Agnolo

Motivation

- Why haven't we seen anything at the LHC?

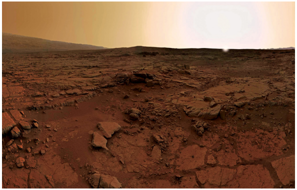
Motivation

- Why haven't we seen anything at the LHC?
  - *Possibility 1:* There is nothing to see.

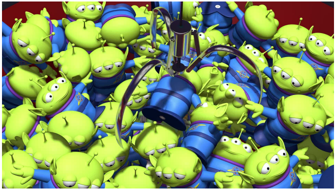


Motivation

- Why haven't we seen anything at the LHC?
  - *Possibility 1:* There is nothing to see.

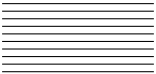


  - *Possibility 2:* There are too many new particles.



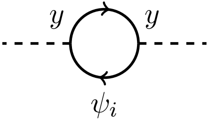
Large N

- Consider N new states



ψ_i

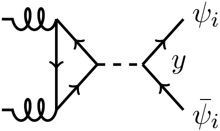
- With $\mathcal{L}_{\text{int}} = hy\bar{\psi}_i\psi_i$



- For perturbativity

$$y \sim \frac{1}{\sqrt{N}}$$

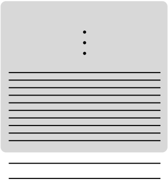
- Production rate can still be sizable



$$\sigma_{\text{tot}} \sim \sum_{i=1}^{N} y^2\sigma_h \sim (Ny^2)\sigma_h$$

Large N

out of reach



- Perhaps only the bottom of the spectrum is accessible

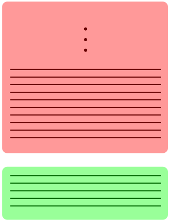
$$\sigma_{\text{acc}} \sim y^2 \sigma_h \sim \frac{1}{N} \sigma_h$$

- Contribution to invisible Higgs width reduced

$$\Gamma_{\text{inv}} \sim \frac{y^2}{y_b^2} \Gamma_{bb} \sim \frac{1}{N} \Gamma_{bb}$$

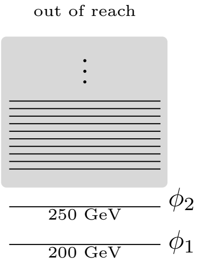
(given couplings among new sector)

- **Heavy** states lead to cascade decays
  - Many low p_T final state particles
  - Diffuse signal, hard for triggers
- **Light** states have short decay chains
  - Little visible and little missing energy
  - Hard to extract from backgrounds

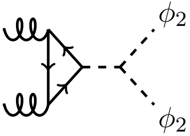


Toy Model

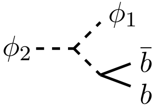
- Consider a toy model with two accessible real scalars ϕ_1 and ϕ_2



$$\mathcal{L}_{\text{int}} = (y_1\phi_1^2 + y_{12}\phi_1\phi_2 + y_2\phi_2^2)|H|^2$$



- Decays to ϕ_1 and offshell Higgs



- Have $pp \to \phi_2\phi_2 \to (\phi_1 b\bar{b})(\phi_1 b\bar{b})$

  $\to 4b + \not{E}_T$

Disorder

- Consider N real scalars $\phi_i, \quad i = 1, \ldots, N$

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu \phi_i \partial^\mu \phi_i - \frac{m_{ij}^2}{2}\phi_i\phi_j - \lambda_{ijkl}\phi_i\phi_j\phi_k\phi_l$$

- Let the mass term be randomly-determined

$$m^2 = \begin{pmatrix} m_{11}^2 & m_{12}^2 & \cdots & m_{1N}^2 \\ m_{21}^2 & m_{22}^2 & \cdots & m_{2N}^2 \\ \vdots & \vdots & \ddots & \\ m_{N1}^2 & m_{N2}^2 & & m_{NN}^2 \end{pmatrix}$$

- *Example 1:* $m_{ij}^2 = 0$ for $i \neq j$.

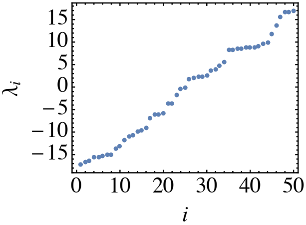
$$m^2 = \begin{pmatrix} m_1^2 & 0 & \cdots & 0 \\ 0 & m_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \\ 0 & 0 & & m_N^2 \end{pmatrix}$$

Disorder

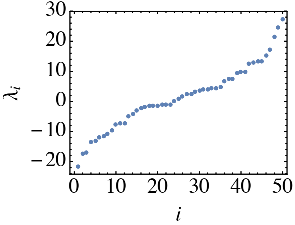
- *Example 1:* $m^2_{ij} = 0$ for $i \neq j$.

$$m^2 = \begin{pmatrix} m_1^2 & 0 & \cdots & 0 \\ 0 & m_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \\ 0 & 0 & & m_N^2 \end{pmatrix}$$

- From $Unif(\mu = 0, \sigma = 10)$



- From $Gaus(\mu = 0, \sigma = 10)$



- Spectrum can be shifted by non-zero mean μ

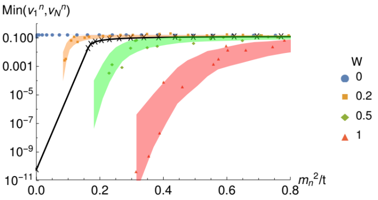
Disorder

(Craig and Sutherland, 1710.01354)

- *Example 2:* Anderson localization
  - Nearest neighbor structure to mass matrix
  - Randomness in diagonal terms, ϵ_i

$$m^2 = \begin{pmatrix} \epsilon_0 + t & -t & 0 & \cdots & & 0 \\ -t & \epsilon_1 + 2t & -t & \cdots & & 0 \\ 0 & -t & \epsilon_2 + 2t & \cdots & & 0 \\ \vdots & \vdots & \vdots & \ddots & & \vdots \\ & & & & \epsilon_{N-1} + 2t & -t \\ 0 & 0 & 0 & \cdots & -t & \epsilon_N + t \end{pmatrix}$$

  - Mass spectrum



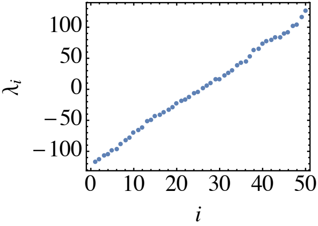
Disorder

- *Example 3:* Fully-populated m_{ij}^2 drawn from $Gaus(\mu = 0, \sigma)$

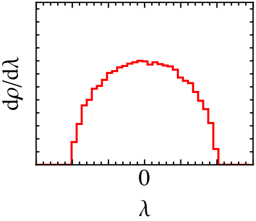
$$m^2 = \begin{pmatrix} 29.9 & 19.2 & 3.5 & -1.3 \\ 19.2 & 27.6 & -31.5 & -14.7 \\ 3.5 & -31.5 & 19.1 & 14.4 \\ -1.3 & -14.7 & 14.4 & -9.6 \end{pmatrix}$$

$$\lambda = 65.6, 31.2, -15.8, -13.9$$

- Eigenvalue distribution



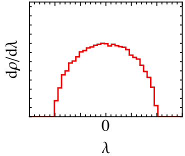
- Probability density



- In large N limit, distribution goes to Wigner semicircle

Disorder

- Wigner semicircle distribution
  - Distributions has endpoints at $\pm\sqrt{2N}\sigma$
  - Non-zero μ does not shift spectrum

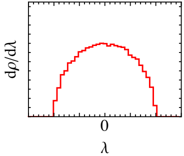


$$\lambda_N \sim N\mu$$

$$\lambda_i \in (-\sqrt{2N}\sigma, \sqrt{2N}\sigma) \qquad i = 1, \ldots, N-1$$

Disorder

- Wigner semicircle distribution
  - Distributions has endpoints at $\pm\sqrt{2N}\sigma$
  - Non-zero μ does not shift spectrum



$$\lambda_N \sim N\mu$$

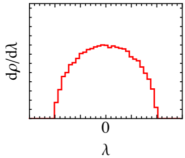
$$\lambda_i \in (-\sqrt{2N}\sigma, \sqrt{2N}\sigma) \qquad i = 1, \ldots, N-1$$

  - Consider $\mu \gg \sigma$, matrix is approximately constant

$$\lambda_N \approx N\mu \qquad \text{trace} = \sum \lambda_i = N\mu$$

$$\lambda_i \approx 0 \qquad i = 1, \ldots, N-1$$

Disorder



- Wigner semicircle distribution
  - Distributions has endpoints at $\pm\sqrt{2N}\sigma$
  - Non-zero μ does not shift spectrum

$$\lambda_N \sim N\mu$$

$$\lambda_i \in (-\sqrt{2N}\sigma, \sqrt{2N}\sigma) \qquad i = 1, \ldots, N-1$$

  - Consider $\mu \gg \sigma$, matrix is approximately constant

$$\lambda_N \approx N\mu \qquad \text{trace} = \sum \lambda_i = N\mu$$

$$\lambda_i \approx 0 \qquad i = 1, \ldots, N-1$$

  - Wigner distribution still holds for general μ and σ
    - A model with σ and μ independent could yield light states

Model

- Possible portals (assuming no light mediators)

$$\phi|H|^2 \qquad \phi^2|H|^2 \qquad LH\psi$$

- We use the following model

$$\mathcal{L} \supset -\frac{1}{2}m_{ij}^2\phi_i\phi_j - \lambda_{ijkl}\phi_i\phi_j\phi_k\phi_l - \lambda_{Hij}|H|^2\phi_i\phi_j$$

- For simplicity, for all scalars, take

$$\lambda_{ijkl} = \frac{1}{N} \qquad \lambda_{Hij} = \frac{1}{N}$$

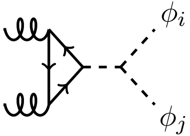
- For simplicity, take masses uniformly distributed
- Lightest scalar, ϕ_1, is stable

Model

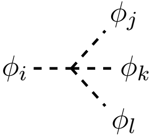
- We use the following model

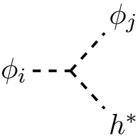
$$\mathcal{L} \supset -\frac{1}{2} m_{ij}^2 \phi_i \phi_j - \lambda_{ijkl} \phi_i \phi_j \phi_k \phi_l - \lambda_{Hij} |H|^2 \phi_i \phi_j$$

- Production from gluon fusion



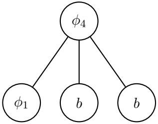
- Decays within scalar sector and via offshell Higgs

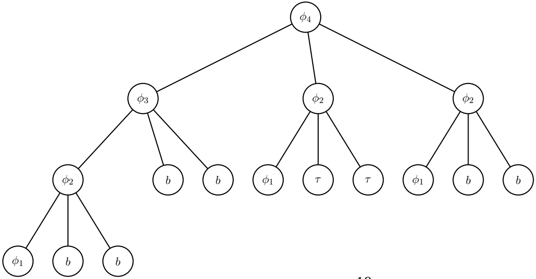




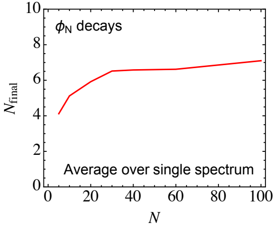
Model

- When heavy scalars are produced, they cascade down through the scalar sector



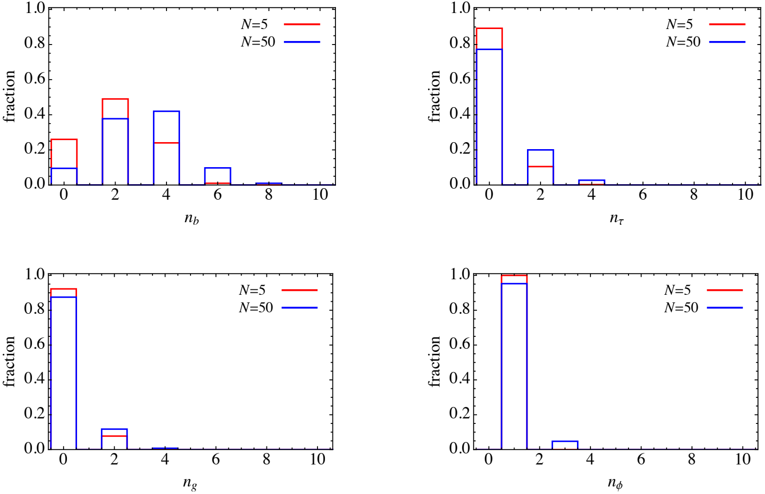


- Maximum height of tree $\sim \log N$
- Maximum final state particles $\sim N$
- In practice, spectrum-dependent



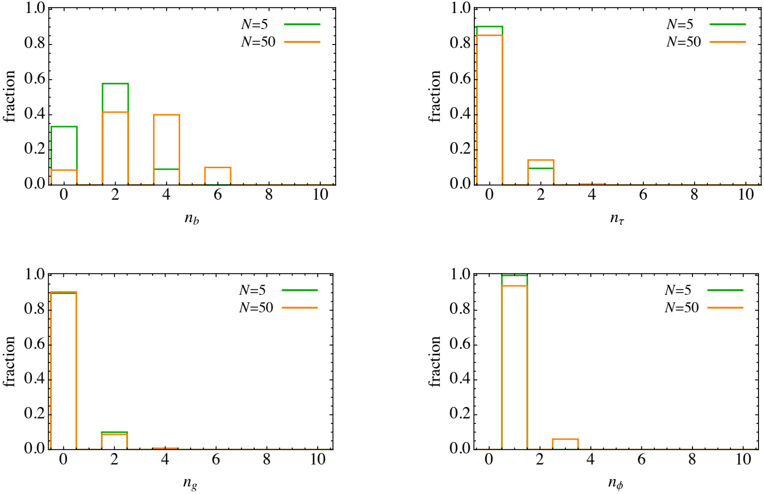
Model

- Number of particles in ϕ_N decay (spectrum A)



Model

- Number of particles in ϕ_N decay (spectrum B)



Outlook

- New sectors are plausible new physics scenarios
- Have a large N number of new particles does not mean it is necessarily easy to observe
- Can disorder answer any other interesting questions in model building?