Disorder at the LHC

Matthew Low

Fermilab

in progress with

Raffaele Tito D'Agnolo

Outline

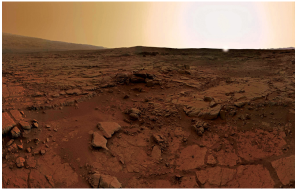
- Motivate framework of large N and randomness
- Review large N
- Review randomness
- Toy model with a few particles
- Scalar model with more particles

Motivation (Experimental)

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

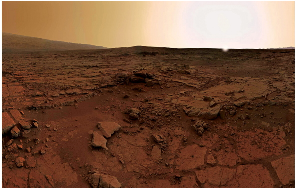
Motivation (Experimental)

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

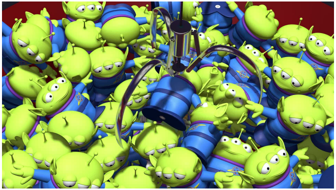


Motivation (Experimental)

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



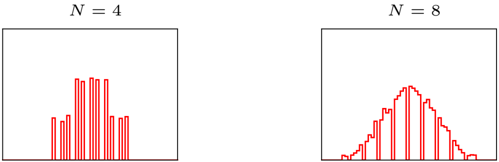
  - *Possibility 2:* There are too many new particles.



Motivation (Theoretical)

- Perhaps UV theory has a structure that makes low energy parameters appear to be random
  - *e.g.* Consider a parameter x which is a sum:

$$x = \pm x_1 \pm x_2 \pm \ldots \pm x_N$$

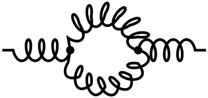


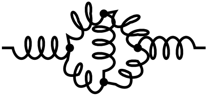
  - With a few terms distribution looks normal-like

- Large N is a powerful tool for these types of theories

Large N Review

- Consider an SU(N) gauge theory with gauge coupling g ('t Hooft, 1974)
  - $N^2 - 1$ gluons (and optionally N quarks)
  - In $N \to \infty$ limit there is a new expansion

 $\sim g^2 N$

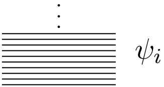
 $\sim g^4 N^2$

  - Expand in 't Hooft coupling $(g^2 N)$
    - (i) $g \lesssim 1/\sqrt{N}$
    - (ii) $g^2 N \lesssim \mathcal{O}(1)$
- Applicable to other theories (See e.g. Cohen, D'Agnolo, ML, *1808.02031*)

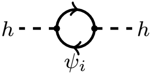
$$\mathcal{L} \supset \lambda \phi_\alpha^2 |H|^2 \qquad\qquad (\lambda N) \lesssim \mathcal{O}(1)$$

Large N Review

- Consider N new states $(i = 1, \ldots, N)$

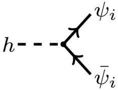


- With interaction $\mathcal{L} \supset yh\bar{\psi}_i\psi_i$
- 't Hooft coupling: y^2N
  - Loop corrections



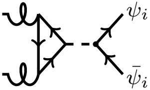
$\Delta \sim y^2N$

  - Decay widths



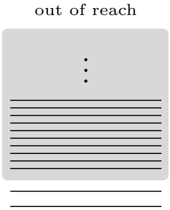
$\Gamma \sim y^2N$

  - Cross sections



$\sigma \sim y^2N$

Large N



- Perhaps only the bottom of the spectrum is accessible

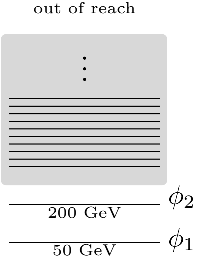
$$\sigma \sim N_{\text{LHC}} y^2 \sim \frac{N_{\text{LHC}}}{N}(y^2 N)$$

- Contribution to widths also reduced

$$\Gamma \sim \frac{N_{\text{LHC}}}{N}(y^2 N)$$

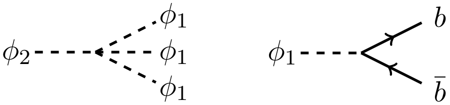
- ’t Hooft coupling remains $y^2 N$, only observables suppressed

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



$$\mathcal{L}_{\text{int}} \supset \lambda \phi_i^4 + \omega \phi_i^2 |H|^2 + a\phi_i |H|^2$$

- Take $\omega \ll \lambda$, then primary decays are:



- Would have final states:

$$\phi_1\phi_1 \to (b\bar{b})(b\bar{b})$$

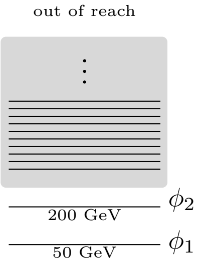
$$\phi_1\phi_2 \to (b\bar{b})(b\bar{b}b\bar{b}b\bar{b})$$

$$\phi_2\phi_2 \to (b\bar{b}b\bar{b}b\bar{b})(b\bar{b}b\bar{b}b\bar{b})$$

- What is a good trigger for this toy model?

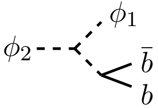
Toy Model

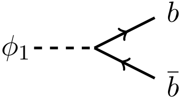
- Consider a toy model with two (accessible) real scalars ϕ_1 and ϕ_2



$$\mathcal{L}_{\text{int}} \supset \lambda\phi_i^4 + \omega\phi_i^2|H|^2 + a\phi_i|H|^2$$

- Take different limit $\lambda \ll \omega$, then:





- Would have final states:

$$\phi_1\phi_1 \to (b\bar{b})(b\bar{b})$$

$$\phi_1\phi_2 \to (b\bar{b})(b\bar{b}b\bar{b})$$

$$\phi_2\phi_2 \to (b\bar{b}b\bar{b})(b\bar{b}b\bar{b})$$

- What is a good trigger for this toy model?

Disorder

- At low energies parameters could look random
- Interesting collective behavior is possible
  - *e.g.* Anderson localization (Craig and Sutherland, *1710.01354*) mimics features of clockwork

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

- Even less structure is possible
  - Consider a mass matrix with random values

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

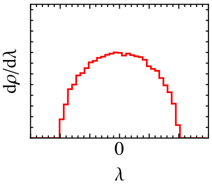
  - What does the spectrum look like?

Disorder

- Random mass matrices are described by the Gaussian Orthogonal Ensemble
  - Matrix has real values and is symmetric (real scalars)
  - Each entry is drawn from a Gaussian distribution

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

  - Spectrum is $\lambda = \{65.6, 31.2, -15.8, -13.9\}$
  - In large N limit the eigenvalue spectrum is predicted

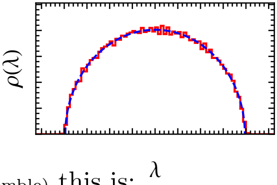


Disorder

- Wigner Semicircle Distribution
  - Ubiquitous distribution in random matrix theory

$$\rho_W(\lambda) = \frac{1}{2\pi}\sqrt{4-\lambda^2}$$

(for $\mu = 0$, $\sigma = 1$)



  - In the large N limit (for the orthogonal ensemble) this is:

$$\rho(\lambda) = \frac{1}{2\pi N\sigma^2}\sqrt{4N\sigma^2-\lambda^2}$$

$(-2\sqrt{N}\sigma, 2\sqrt{N}\sigma)$

(spectral edges)

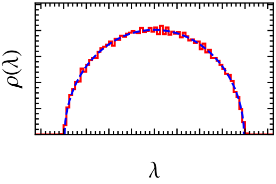
  - Matrix entries drawn from $\mathcal{N}(0,\sigma)$
  - Same distribution for some other mass matrices

Disorder

- Model building with the semicircle
  - Ubiquitous distribution in random matrix theory

$$\rho_W(\lambda) = \frac{1}{2\pi}\sqrt{4-\lambda^2}$$

(for $\mu = 0$, $\sigma = 1$)



  - Distribution is centered around $\lambda = 0$
  - Adding a non-zero mean $\mathcal{N}(\mu, \sigma)$ does not modify distribution

$$\rho(\lambda) \to \rho(\lambda) \qquad\qquad \lambda_N \to N\mu$$

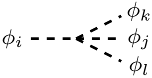
  - Distribution is shifted by adding a diagonal contribution to matrix

Model

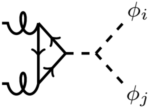
- Consider N real scalars with interactions

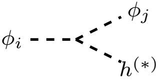
$$\mathcal{L} \supset -\frac{1}{2} m_{ij}^2 \phi_i \phi_j - \lambda_{ijkl} \phi_i \phi_j \phi_k \phi_l - \lambda_{ij}^H |H|^2 \phi_i \phi_j$$

  - m_{ij}^2 generates spectrum
  - $\lambda_{ijkl} \sim 1/N$ introduces scalar-scalar interactions



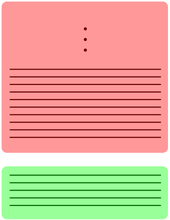
  - $\lambda_{ij}^H \sim 1/N$ allows production and decays through a Higgs





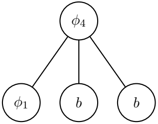
  - Z_2 forbids other terms

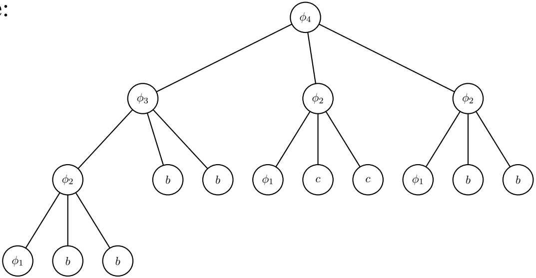
Model



- **Heavy** states lead to cascade decays
  - Many low p_T final state particles
- **Light** states have short decay chains
  - Little visible and little missing energy

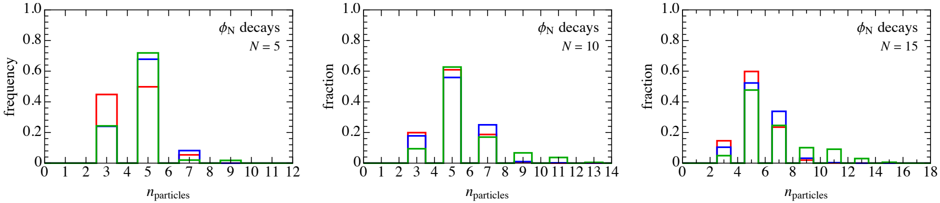
- Cascades might look like:





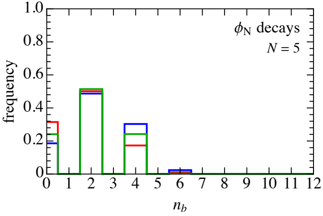
Model

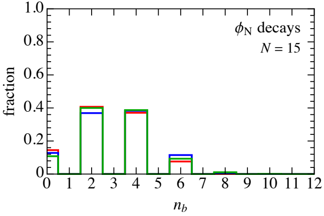
- Study decay of ϕ_N (heaviest state)
  - Masses between 100 GeV and 600 GeV
  - Cascades into ϕ_1's and SM particles
  - Multiplicity depends on spectrum details
    - Red is spaced
    - Blue has a few compressions
    - Green is very compressed



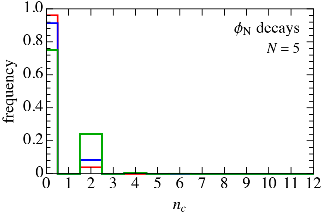
Model

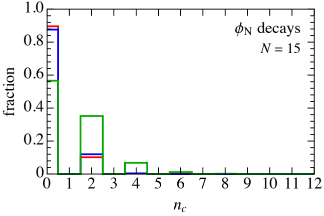
- Most commonly have pairs of b's in decays





- Not necessarily all b's





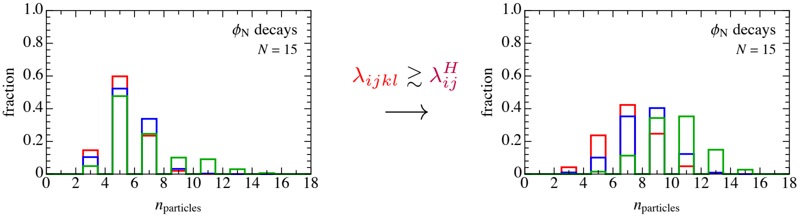
Model

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

- When $\lambda_{ijkl} \approx \lambda_{ij}^H$ most decays proceed through Higgs
- Branching ratios of ϕ_N determined by phase space
- Barring additional structure, cascades are prompt and not too long

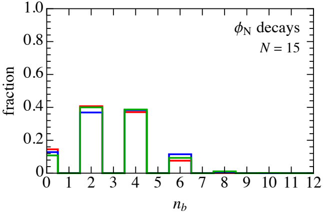
  e.g. *1807.06642* (Goudelis, Mohan, Sengupta) uses clockwork and has similar cascades but with displacements to ϕ_1

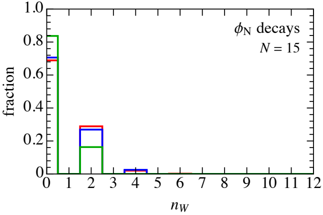
- If $\lambda_{ijkl} \gtrsim \lambda_{ij}^H$ then decays among scalars are more common



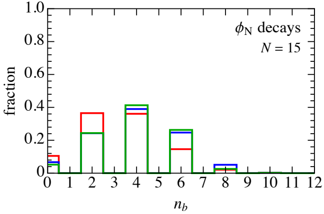
Model

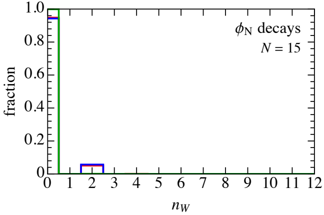
$\lambda_{ijkl} \approx \lambda_{ij}^{H}$





$\lambda_{ijkl} \gtrsim \lambda_{ij}^{H}$





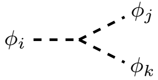
Modifications

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

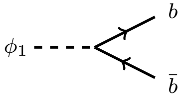
- Can also consider Z_2-breaking interactions

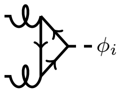
$$\mathcal{L} \supset -a_{ijk} \phi_i \phi_j \phi_k - a_i^H |H|^2 \phi_i$$

- a_{ijk} favors scalar cascades



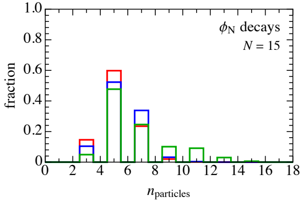
- a_i^H lets ϕ_1 decay *and* allows single production





Outlook

- Disorder is a tool for low energy model building
- Results in high multiplicity, low p_T, b-rich final states



- Resonances may not be reconstructable
- Modifications to model permit more resonant structure
- What triggers are needed for these topologies?