Charting the Unknown: Interpreting LHC Data from the Energy Frontier

Aug 11, 2016

Tim Cohen
University of Oregon

with
N. Arkani-Hamed,
A. Hook,
H.D. Kim,
R.T. D’Agnolo,
D. Pinner

CERN Theory Institute
Charting the Unknown:
Interpreting LHC Data from the Energy Frontier
Aug 11, 2016

arXiv:1607.06821
Top partner limits constrain natural scenarios.
NATURALNESS
Gravity sees all degrees of freedom.

\[ M_{pl}^2(\mu) = M_{pl}^2(0) - N \frac{\mu^2}{96 \pi^2} \]

\[ \Lambda_{UV} \sim \frac{M_{pl}(0)}{\sqrt{N}} \]

For simplicity:
Only variation away from our Standard Model is Higgs mass parameter.

\[-\Lambda_{UV}^2 \lesssim (m_{H}^2)_{i} \lesssim \Lambda_{UV}^2\]
$N$ COPIES

$v = 0$

$v_{us} = 246 \text{ GeV}$

$v > v_{us}$

$\Lambda_{UV}^2$

$m_H^2$

$-\Lambda_{UV}^2$
Not a multiverse.
No anthropics!

\( v = 0 \)

\( v_{us} = 246 \text{ GeV} \)

\( v > v_{us} \)
But why is there energy density in only our sector?!?
OUTLINE

General Mechanism

Two Simple Models

Signatures!

Completing the Story

Outlook
GENERAL MECHANISM
<table>
<thead>
<tr>
<th>$m_H^2 &gt; 0$</th>
<th>$m_H^2 &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massless photon</td>
<td></td>
</tr>
<tr>
<td>$W^\pm, Z^0$ masses</td>
<td></td>
</tr>
<tr>
<td>$\sim \Lambda_{\text{QCD}}$</td>
<td></td>
</tr>
<tr>
<td>Fermion masses</td>
<td></td>
</tr>
<tr>
<td>$\sim y_f \frac{\Lambda_{\text{QCD}}^3}{m_H^2}$</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{sphaleron}} &lt; \Lambda_{\text{QCD}}$: no baryon relic density</td>
<td></td>
</tr>
<tr>
<td>No baryon relic density</td>
<td></td>
</tr>
</tbody>
</table>

- Massless photon
- $W^\pm, Z^0$, and fermion masses $\sim \nu$
- Neutrino masses:
  - Majorana mass $\sim \nu^2$
  - Dirac mass $\sim \nu$
S reheats the Universe after inflation.

Couples universally to all copies.
MODEL REQUIREMENTS

i) The reheaton is a gauge singlet;

ii) Parametrically lighter than the naturalness cutoff, $\Lambda_H/\sqrt{N}$;

iii) Couplings are most relevant ones possible that involve Higgs bosons of each sector.
COUPLE $S$ TO $H + X$

$m^2_H > 0$

$m^2_H < 0$

Increasing $m^2_H$

Increasing $\nu$

$\Delta \sim m_S$

$\Delta \sim m_S$

$\Gamma \sim \frac{m_S^5}{m^4_H}$

$\Gamma \sim \frac{\nu^2 m_S^3}{\nu^4}$
Even spacing for Higgs mass squared parameters:

\[
(m_H^2)_i = i \times (m_H^2)_{us}
\]

So that \( v_i \sim \sqrt{i} \).
MASSLESS DOF

Energy density in additional relativistic degrees of freedom.

\[ N_{\text{eff}} \sim \frac{\sum_{i \neq \text{us}} \rho_i}{\rho_{\text{us}}} \sim \frac{\sum_{i \neq \text{us}} \Gamma_i}{\Gamma_{\text{us}}} \sim \log N \]

Relic density of additional neutrinos.

\[ \Omega_{\nu} h^2 \sim \begin{cases} \frac{\sum_{i \neq \text{us}} v_i \rho_i^{3/4}}{v_{\text{us}} \rho_{\text{us}}^{3/4}} \sim N^{3/4} & \text{Dirac} \\ \frac{\sum_{i \neq \text{us}} v_i^2 \rho_i^{3/4}}{v_{\text{us}}^2 \rho_{\text{us}}^{3/4}} \sim N^{5/4} & \text{Majorana} \end{cases} \]
MASSIVE DOF

THERMAL FREEZE-OUT

Heaviest sector that thermalizes

\[
\Omega h^2 = \frac{s_0}{\rho_c} \sum_{i=-1}^{-N_d} m_i Y_{i}^{fo} + ... = a (N_d)^p + ...
\]

Model dependence

Naively, \( a \sim \Omega^{us} h^2 \), and \( p > 0 \).

Neglect contribution from reheaton decays (relevant at large \( N \)).

Neglect freeze-in.
Full hierarchy problem

\[ \nu_{us} \sim \frac{\Lambda_{UV}}{\sqrt{N}} \quad \text{and} \quad \Lambda_{UV} \sim \frac{M_{Pl}}{\sqrt{N}} \]

\[ N \sim \frac{M_{Pl}}{\nu_{us}} \simeq 10^{16} \quad \text{and} \quad \Lambda_{UV} \sim 10^{10} \text{ GeV} \]
HOW MANY COPIES?

Little hierarchy problem

\[ v_{us} \sim \frac{\Lambda_{SUSY}}{\sqrt{N}} \quad \text{and} \quad \Lambda_{UV} \sim \frac{M_{Pl}}{\sqrt{N}} \]

\[ \Lambda_{UV} \sim M_{GUT} \]

\[ N \sim 10^4 \]

\[ \Lambda_{SUSY} \sim 10 \text{ TeV} \]
HOW MANY COPIES?

Little hierarchy problem

\[ v_{us} \sim \frac{\Lambda_{SUSY}}{\sqrt{N}} \quad \text{and} \quad \Lambda_{UV} \sim \frac{M_{Pl}}{\sqrt{N}} \]

\[ \Lambda_{UV} \sim M_{GUT} \]

\[ N \sim 10^4 \]

\[ \Lambda_{SUSY} \sim 10 \text{ TeV} \]

Tons of signatures at future colliders!
HOW MANY COPIES?

Full hierarchy problem (again)

All new degrees of freedom

\[ N_{\text{total}} \quad \text{and} \quad N_{\text{reheat}} \]

Couple to reheation

\[ \nu_{us} \sim \frac{\Lambda_{\text{UV}}}{\sqrt{N_{\text{reheat}}}} \quad \text{and} \quad \Lambda_{\text{UV}} \sim \frac{M_{\text{Pl}}}{\sqrt{N_{\text{total}}}} \]

with \( N_{\text{total}} \gg N_{\text{reheat}} \)

For this scenario:

\[ N \rightarrow N_{\text{reheat}} \]
TWO SIMPLE MODELS
**NEUTRINO REHEATON**

\[ \mathcal{L} = m_S S S^c + \lambda \sum_i S H_i L_i \]

- **Case 1:** $m_H^2 > 0$
  - Particle Flow: $S \rightarrow H \rightarrow L$
  - Width: $\Gamma \sim m_S$
  - \( \Gamma \sim \frac{m_S^5}{m_H^4} \)

- **Case 2:** $m_H^2 < 0$
  - Particle Flow: $S \rightarrow H \rightarrow L$
  - Width: $\Gamma \sim m_S$
  - \( \Gamma \sim \frac{m_S^5}{v^4} \)

Increasing $m_H^2$

Increasing $\nu$

*Tim Cohen [University of Oregon]*
NEUTRINO REHEATON

SHI, N=10^4

Next sector
3-body to 2-body

BR_{us}

Z_{us}^0

W_{us}^{\pm}

m_s(GeV)
TOY SCENARIO

Parametrize distribution of Higgs masses:

\[
(m_{H}^{2})_{i} = -\frac{\Lambda_{H}^{2}}{N}(2i + r)
\]

\[
(m_{H}^{2})_{us} = -r \times \frac{\Lambda_{H}^{2}}{N} \approx -(88 \text{ GeV})^{2}
\]

\[
r \text{ parametrizes tuning.}
\]

\[
1/r
\]

“us” “us” +1
Reheaton mass is technically natural.

Critical that reheaton mass be $\mathcal{O}(m_{W_{\text{us}}})$.

Analogous to $\mu$-problem in the MSSM.
SCALAR REHEATON

\[ \mathcal{L} = \frac{1}{2} m_\phi \phi^2 + a \phi \sum_i |H_i|^2 \]

\[ m_H^2 > 0 \]

Increasing \( m_H^2 \)

Increasing \( \phi \)

\[ \phi \]

\[ H \]

\[ H^\dagger \]

\[ \Gamma \sim \frac{a^2}{m_\phi} \]

\[ \phi \]

\[ h \]

\[ b \]

\[ \Gamma \sim y_b^2 a^2 \frac{m_\phi^3}{v^4} \]

\[ \phi \]

\[ h \]

\[ c \]

\[ \Gamma \sim y_c^2 a^2 \frac{m_\phi^3}{v^4} \]

\[ \langle H \rangle \]

\[ \langle H \rangle \]

\[ \langle H \rangle \]

\[ \langle H \rangle \]

\[ \langle H \rangle \]

TIM COHEN [UNIVERSITY OF OREGON]
The left panel is for the SCALAR REHEATON with additional constraints discussed for the first few sectors, while the right panel is for the model with $\mu = 1 \text{ MeV}$. The diagrams that lead to these decays are shown in Fig. 4, and the energy density deposited in each sector is normalized to the energy density in our sector.
SIGNATURES!
(AND CONSTRAINTS)
NEUTRINO OVERCLOSURE

\[ \mathcal{L} = m_S S S^c + \lambda \sum_i S H_i L_i \]

Freeze-in abundance from:
\[ \nu_{us} \nu_{us} \rightarrow \nu_{us} \nu_i \]

Also, mixing with neutrino impacts their masses.

Hard to go beyond \( N \sim 10^3 \).
\[ N_{\text{eff}} \]

\[ \Delta N_{\text{eff}}, \phi, N = 10^4 \]

\[ \mathcal{L} = \frac{1}{2} m_\phi \phi^2 + a \phi \sum_i |H_i|^2 \]

\[ CMB \text{ Stage IV: future constraint on } N_{\text{eff}} \lesssim 0.02. \]

Also constrain \( \sum m_{\nu_i} \) to SM value.

Wu, et al. [arXiv:1402.4108]
ELECTRON (AND PROTON) OVERCLOSURE

Scalar model: \[ \mathcal{L} = \frac{1}{2} m_\phi \phi^2 + a \phi \sum_i |H_i|^2 \]

Estimate thermal electron density.

\[ \Omega^\phi_e h^2 = \sum_{i=1}^{N_{th}} \frac{m^i_e n^i_e}{\rho^0_c} \simeq \left( \frac{m^u_e T_{0u}}{\rho^0_c} \right)^3 \frac{N_{th}^{5/2}}{M_{pl} v_{u} \alpha^2} \]

Requiring

\[ \Omega^\phi_e h^2 \leq 0.1 \times \Omega_{DM} h^2 \implies N_\phi \lesssim 10^5 \]

Proton (symmetric) abundance subdominant.
GETTING TO $N = 10^{16}$

**Ultra-safe model:** add vector like-lepton.

$$\left( L, L^c, E, E^c, N, N^c \right)$$

with

$$\mathcal{L} \supset \text{mass terms} + \text{Yukawa terms} + \lambda HLS + \mu_E E e^c$$

![Diagram of particle interactions]

$$\Gamma \sim \frac{m_S^9}{v^8}$$
POWERS AT SMALL SCALES

\[ v = 0 \]
\[ v_{us} = 246 \text{ GeV} \]
\[ \nu > v_{us} \]

Potentially observable imprint on small scale power spectrum of cosmological perturbations.
MIXING BETWEEN SECTORS

Kinetic mixing: \( \epsilon_i F_{\mu\nu} F^H_{\mu\nu} \).

Energy loss in stars \( \Rightarrow \sqrt{\sum_i \epsilon_i^2} \lesssim 10^{-14} \)

Neutral state mixing: \( \epsilon_i^n \nu_i^+ \bar{\sigma}^\mu D_{\mu\nu} \).

Neutrino production rate from neutral current bremsstrahlung

\( \Rightarrow \sqrt{\sum_i (\epsilon_i^n)^2} \lesssim 10^{-4} \)

Charged state mixing: \( \epsilon_i^c G_F \left( \nu_{i}^{+}\bar{\sigma}^\mu e^c \right) \left( p^+ \bar{\sigma}_\mu n \right) \).

SN1987a charged current neutrino production

\( \Rightarrow \sqrt{\sum_i (\epsilon_i^c)^2} \lesssim 10^{-5} \)
COMPLETING THE STORY
REHEAT TEMPERATURE

\[ T_{rh} \sim \sqrt{\Gamma_{\text{reheaton}} M_{pl}} \]

Set by size of reheaton - Higgs coupling.

Constrained to be \( \lesssim m_{Wus} \).

\[ T \sim |m_H| \] in other sectors changes predictions.

Leads to larger reheaton branching ratios into \( i \neq us \).

[Tension can be alleviated by preheating.]
Low reheat temperature: not all standard mechanisms work.

**One option**

Primordial lepton asymmetry. Only converted to baryons for sectors with $T > T_{\text{sphaleron}} \sim m_W$. 
Assume only breaking of $\mathbb{Z}_2$ is from $m_H^2$, common axion to all sectors.

Same effective $\theta_{CP}$ for all sectors.
Axion gets contribution to mass from every $\Lambda_{QCD}$.
Larger $m_\alpha$ as function of $f$. 
DARK MATTER

Many options
Thermal relic (neutralino in SUSY scenario?)
Relics from other sectors
Axion
Superpartner of reheaton

...
Observable in HL-LHC, tera-Z, 100 TeV pp??
Very challenging.

Observability in tension with low reheat temp.
Likely only possible for small $N$.

Potentially see rate change by sending more energy through propagator to access more sectors!
OUTLOOK
Dynamically realizing $N$

Extra dimension (deconstruction)

Large number of DOF’s
Novel solution to big/little hierarchy problem.

Many simple models exist.

Success relies on cosmology.

Constrained by $N_{\text{eff}}$, neutrino, electron, and proton over closure.

If strong CP solved by axion, expect it to be heavier.

If $N \lesssim 10^4$, spectacular signatures at LHC or future colliders.

Observe “steps” in primordial power spectrum.