BSM theory review

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What is BSM?

Nobody really knows...
See, however Nikitenko's talk for an excess of events in a ~ 28 GeV dimuon mass region observed in the 8 TeV data.
What is BSM?

We can start by looking at experimental facts not addressed by SM...
**Need for BSM (experiment)**

- Dark Matter

**mono-X searches@ LHC**

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**Spin-independent DM-nucleon cross section vs \( m_{\text{DM}} \)**

![Graph showing spin-independent DM-nucleon cross section vs DM Mass [GeV]](image)

- DM Simplified Model Exclusions
- **ATLAS** Preliminary July 2017

**Spin-dependent DM-proton cross section vs \( m_{\text{DM}} \)**

![Graph showing spin-dependent DM-proton cross section vs DM Mass [GeV]](image)

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Under the model assumptions:

- **collider searches**
  - are sensitive at low DM (<~5 GeV)
  - have ~3 orders of magnitude better sensitivity for \( \sigma_{\text{SD}} \) (DM-nucleon)

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**DM Mass [GeV]**

- DM Simplified Model Exclusions
- **ATLAS** Preliminary July 2017

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**ATLAS Exotics Summary**

**CMS Dark Matter Summary**
Need for BSM (experiment)

- Neutrino masses

\[ \frac{(HL)^2}{\Lambda_L} \quad \Lambda_L \sim 10^{14} \text{ GeV} \]

Seesaw

Type-I (RH neutrino)  Type-II (scalar triplet)  Type-III (fermion triplet)

LHC

Lepton number violating signals at the LHC
### Need for BSM (experiment)

- Neutrino masses

\[
\mathcal{L} = \mathcal{L}_{\text{SM}} + |D_{\mu}T|^2 - M^2 |T|^2 + \frac{1}{2} \left( \lambda_L LLLT + M\lambda_H HHT^* + \text{h.c.} \right)
\]

\[
\frac{(HL)^2}{\Lambda_L} \quad \Lambda_L \sim 10^{14} \text{ GeV}
\]

\[
m_\nu = \frac{\lambda_L \lambda_H v^2}{M}
\]

\[pp \to T^{++}T^{--} \rightarrow \begin{cases} 
\ell_1 \ell_2 \bar{\ell}_1 \bar{\ell}_2 & \propto \lambda_L^4 \\
W^+W^+W^-W^- & \propto \lambda_H^4 \\
\ell_1 \ell_2 W^+W^+ & \propto \lambda_L^2 \lambda_H^2 
\end{cases}
\]

Production controlled by electroweak couplings

![Feynman diagrams and production cross-sections](image)
Need for BSM (experiment)

- Matter-antimatter asymmetry
- muon g-2
- ....
Need for BSM (theory)

- Higgs potential metastability

Running of the Quartic Coupling, Metastability

Need to measure Higgs, top mass and quartic coupling

Could this be a guiding principle?
Intriguing results from LHCb and Belle experiment with anomalies in B and D meson systems

\[ R(D^{(*)}) = \frac{Br(B \rightarrow D^{(*)}\tau\nu)}{Br(B \rightarrow D^{(*)}l\nu)} \]

• Flavour problem

Talks later today by Capriotti, Mihara, Kamenik

Need for BSM (theory)
Need for BSM (theory)

- Strong CP problem

\[ L_{QCD} = \bar{q}(i\gamma_\mu D_\mu - m_q)q - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\theta}{32\pi^2} \tilde{F}_{\mu\nu} F^{\mu\nu} \]

Experimentally (neutron EDM) : \( \theta < 10^{-10} \)

why is it so un-naturally small?

Most popular solution: AXION

Peccei Quinn 77

Axion can be also DM candidate!
Promote the $\theta$-term to a field “a”:

$$L_{axion} = \frac{1}{2} \partial_\mu a \partial^\mu a + \frac{a}{32\pi^2 f_a} \tilde{F}_{\mu\nu} F^{\mu\nu}$$

$$\theta_{eff} \rightarrow \theta + \frac{<a>}{f_a}$$

The field “a” has a potential just like Higgs and it is minimised for

$$\theta_{eff} = 0$$

It is a dynamical solution independent of the value of the original value of the $\theta$-term.
Need for BSM (theory)

- Gauge hierarchy problem (naturalness). Dominant guiding principle for BSM model building

The only dimensionful (quadratically divergent) parameter in the SM:

\[ m^2 H^2 \]

Small value of this parameter in the SM (compared to, say, Planck scale) is un-natural due to huge fine-tuning
Need for BSM (theory)

- Cosmological constant problem
- Gravity (gravity waves) see talk by N. Leroy
- Proton decay
- ...

Not the main LHC focus…
Scale of the new physics

High scale?

• Proton Decay \( \frac{u^de}{M_{NP}^2} \quad M_{NP} \sim 10^{16} \text{ GeV} \)

• Neutrino mass \( \frac{(HL)^2}{\Lambda_L} \quad \Lambda_L \sim 10^{14} \text{ GeV} \)

Low scale?

• CC problem \( M_{NP} \sim 10^{-3} \text{ eV} \)

• Naturalness \( M_{NP} \sim 1 \text{ TeV} \)
How do we actually build models?
Two approaches to BSM

• UV guides/predicts IR (strings, GUTs, naturalness)

• IR constraints UV (experiments drive theory)
Naturalness principle

Small value for the coupling is natural if it is associated to the symmetry

- the fermion mass parameters are protected by chiral symmetry

- Un-naturalness (apparent fine-tuning of the parameter) may signal new physics

- the rho meson (QCD) to cutoff the EM contribution to the charged pion mass

\[
M_{\pi^\pm}^2 - M_{\pi^0}^2 = \frac{3\alpha}{4\pi} M^2 \rho \frac{F_\rho}{f_\pi^2} \ln \frac{F_\rho^2}{F_\rho^2 - f_\pi^2}
\]

\[
\Lambda_{NP}^2 < \frac{\delta M^2}{\alpha}
\]
The only dimensionful (quadratically divergent) parameter in the SM:

\[ m^2 H^2 \]

Small value of this parameter in the SM (compared to, say, Planck scale) is un-natural due to huge fine-tuning.

In a cutoff scheme, with cutoff \( \Lambda \)

\[
m^2 = m_0^2 \left( 1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2} \right) - f_2(\lambda, g_i) \Lambda^2
\]

- \( m_0 \) is bare mass parameter
- \( m \) is renormalised (measured) mass parameter

• new physics at the TeV scale to cancel the UV sensitivity of the Higgs mass?
Approaches to Higgs naturalness

Single vacuum solutions

1. Symmetry (SUSY, conformality)
2. Form-factor (Composite Higgs/TC)
3. Low UV scale (extra-dimensions, RS, . . .)

Many vacua solutions (recent developments)

1. Antropic multiverse
2. NNnaturalness with many SM copies
3. Relaxion and cosmological scanning
Single vacuum solutions:

\[ m^2 = m_0^2 (1 + f_1(\lambda, g_i) \log \frac{\Lambda^2}{m_0^2}) - f_2(\lambda, g_i) \Lambda^2 \]

- **SM tuning**: no predictions for the BSM physics
- **SUSY**: \( f_2 = 0 \) by supersymmetry
- **Tuning via conformal symmetry**: \( m_0 = 0, \, \Lambda \) is dropped
- **Composite Higgs/TC**: Higgs is not fundamental
Many vacua solutions:

nNaturalness

Some sectors are accidentally tuned at the 1/N level:

$$|m_H^2|_{\text{min}} \sim \Lambda_H^2 / N.$$  

Need to change dramatically the cosmological history and hierarchy problem is rephrased into question on how to reheat only sectors with fine-tuned Higgs mass. For this “reheaton” field is introduced which decays predominantly to small Higgs mass sector
Many vacua solutions:

relaxion mechanism in a nutshell

\[ m^2 H^2 \]

- Higgs mass-squared promoted to a field
- The field evolves in time in the early universe and scans a vast range of Higgs mass
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking stops the time-evolution of the dynamical system

Example of self-organised criticality when the dynamical evolution of a system is stopped at a critical point due to back-reaction
Relaxion mechanism

Minimal model: \( \text{SM} + \text{QCD axion} + \text{inflaton} \)

\[
(-M^2 + g\phi)|h|^2 + V(g\phi) + \frac{1}{32\pi^2} \frac{\phi}{f} \tilde{G}^{\mu\nu} G_{\mu\nu}
\]

Below QCD scale:

\[
(-M^2 + g\phi)|h|^2 + (gM^2\phi + g^2\phi^2 + \cdots) + \Lambda^4 \cos(\phi/f) \quad \Lambda^4 \sim f_\pi^2 m_\pi^2
\]

- During inflation axion slow-rolls and scans Higgs mass
- Once mass gets negative, Higgs obtains a vev
- Axion potential barriers (linear in the vev) grow and stop scanning

\[
m_\pi^2 \sim m_q f_\pi \sim y_q < h > f_\pi \quad \rightarrow \quad y_q f_\pi^3 < h > \cos \frac{\phi}{f}
\]
Relaxion mechanism

\[ (-M^2 + g\phi)|h|^2 + (gM^2\phi + g^2\phi^2 + \cdots) + \Lambda^4 \cos(\phi/f) \]

Rolling stops when slopes match:

\[ gM^2 \sim \frac{m_W^2 f^2}{f} \]

slow-roll

\[ <h> \neq 0 \]

\[ <h> = 0 \]

axion is oscillations around minima

FIG. 1: Here is a characterization of the axion's potential in the region where the barriers begin to become important. This is the one-dimensional slice in the field space after the Higgs is integrated out, effectively setting it to its minimum. To the left, the Higgs vev is essentially zero, and is \( O(m_W) \) when the barriers become visible. The density of barriers are greatly reduced for clarity.
Conclusions

• No NP from the LHC so far
• However, new ideas continue to emerge in theoretical community
• A lot of new physics is still to be tested!
The topics to be discussed include:

1. DM (Theory, Observations, Detection)
2. Structures in the Universe
3. New observational probes of the Universe
4. Multimessenger cosmology (Gravitational waves, Cosmic rays, Neutrinos)
5. Unknown physics in the Universe