Beyond Standard Model Theory

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BSM Theory before LHC

- partners of the top (partners of gauge bosons)
- Higgs
- low-energy SUSY
- compositeness
- extra-dimensions
- Naturalness
Main actors related to naturalness: \textbf{stops} and \textbf{gluinos}

- They control the corrections to the Higgs mass and the amount of tuning

\[
\delta m_H^2 \sim \frac{3y_t^2}{8\pi^2} m_t^2 \log(\Lambda/m_{\tilde{t}})
\]

\[
\delta m_H^2 \sim \frac{\alpha s y_t^2}{\pi^3} m_{\tilde{g}}^2 \log^2(\Lambda/m_{\tilde{g}})
\]

- Current exclusions

\[m_{\tilde{t}} \gtrsim 1 \text{ TeV}\quad m_{\tilde{g}} \gtrsim 2 \text{ TeV}\]

imply a minimal tuning

\[\frac{1}{\Delta} \equiv \frac{m_H^2}{\delta m_H^2} \sim \text{few\%}\]
Main actors related to naturalness: fermionic top partners

- They control the generation of the Higgs potential

\[ \delta m^2_H \sim \frac{3}{16\pi^2} y_t g_* m_*^2 \]

- Current exclusions

\[ m_{X_{5/3}, T, B} \geq 1.3 \text{ TeV} \]

imply a minimal tuning

\[ \frac{1}{\Delta} \equiv \frac{m^2_H}{\delta m^2_H} \sim \text{few} \% \]
A Change of Attitude

LHC results stimulated a healthy change of attitude in the particle theory community

- explore alternative theory paradigms (eg. alternatives to classical naturalness)
- abandon unmotivated prejudices (eg. minimality)
- enlarge the set of signatures to look for at colliders
- theory work closer to experiments (eg. working on strategies for data analysis, proposing new experiments)
- look for BSM physics in non-colliders experiments (eg. table-top, cosmological tests, …)
BSM Theory after LHC Run II

- Naturalness
  - fermionic partners
  - massive vectors
  - axions
  - dark photons
  - neutral naturalness
  - low-energy SUSY
  - compositeness
  - extra-dimensions

- Modified Naturalness
  - extended Higgs sectors
  - phase transitions
  - gravitational waves
  - long-lived particles
  - landscape
  - UV-naturalness

- Un-Naturalness
BSM Theory after LHC Run II

Naturalness
- stops
- gluinos
- neutral naturalness
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Modified Naturalness
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- massive vectors
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- phase transitions
- relaxion
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Un-Naturalness
Is Theory still important?

Theory continues to play an important role in BSM exploration

- **naturalness** is still an important question to answer (although maybe no more the strongest guideline)

- **models** are useful to explore signatures and provide a framework for searches

- theory is needed to devise effective *model-independent search strategies* (blind search likely to miss crucial observables to look at)

- theory is needed for an *interpretation* of the experimental results
Naturalness and Predictivity
Naturalness is a very deep question: what we want to know is whether the value of the Higgs mass can be explained by the UV theory.

- in the presence of high tuning, even measuring with very good precision the fundamental parameters, we can not determine the Higgs mass

loss of predictivity
Naturalness and Predictivity

Two opposite possibilities

**Full Predictivity**

Higgs mass and EW scale linked to *new dynamics at the TeV*

*New symmetry* ensures stability of Higgs potential
(SUSY, spont. broken global symmetry,...)

Main signatures:
*partners of top quark*
(stops, fermionic top partners,...)

- low-energy SUSY (eg. MSSM)
- composite Higgs

**No Predictivity**

Higgs mass as a *free parameter*, can only be measured experimentally but not explained

*No specific* (low-energy) signatures

- landscape & anthropic
- UV-naturalness (no high-energy thresholds destabilize Higgs mass)
Naturalness and Predictivity

Two opposite possibilities … and a third way in between

**Full Predictivity**
- Higgs mass and EW scale linked to new dynamics
- New symmetry ensures stability of Higgs potential
- Main signatures: partners of top quark (stops, fermionic top partners)
  - low-energy SUSY
  - composite Higgs

**Semi-Predictivity**
- Higgs mass determined dynamically, only overall size explained but not exact value
- New axion-like particle
  - relaxion

**No Predictivity**
- Higgs mass as a free parameter, can only be measured experimentally but not explained
- No specific (low-energy) signatures
  - landscape & anthropic
  - UV-naturalness (no high-energy thresholds destabilize Higgs mass)
Modifying classical scenarios

Classical scenarios “rescued” by modified (typically non-minimal) constructions

Example:  **Maximally symmetric composite Higgs**  

- standard symmetry pattern
  \[
  \text{SO}(5)_L \times \text{SO}(5)_R \rightarrow \text{SO}(4)
  \]

- maximal symmetry pattern
  \[
  \text{SO}(5)_L \times \text{SO}(5)_R \rightarrow \text{SO}'(5)
  \]

- maximal symmetry reduces radiative contributions to Higgs mass term
- minimal tuning can be realized  (analogy with old little Higgs idea)
- top partners can have larger masses ($\sim$ few TeV) with acceptable amount of tuning
Elusive new-physics

Strong collider constraints come from the fact that top partners are charged under QCD and therefore easily detectable.

What if partners are neutral under QCD?

→ **Neutral naturalness** models implement this idea through symmetries

**The Twin Higgs construction**

• discrete $Z_2$ symmetry ensures stability of Higgs mass (thanks to enhanced $SU(4)$ symmetry in Higgs mass term)

$$V(H, H') \sim \frac{\Lambda^2}{16\pi^2} y_t^2 (|H|^2 + |H'|^2)$$

• top partners are neutral under ordinary QCD, more difficult to be produced at colliders

• many implementations of this idea in different frameworks
Higgs mass is dynamically selected through a backreaction mechanism

[i] rolling relaxion field controls Higgs mass

[ii] when Higgs VEV turns on a backreaction potential is induced

[iii] evolution of relaxion is stopped

❖ vacuum is not uniquely selected: range of vacua possible
  ‣ quantum corrections do not allow to determine stopping vacuum
  ‣ many vacua with similar properties
  ‣ UV parameters determine only overall size of Higgs mass

[ Graham, Kaplan, Rajendran ’15]
Many open questions:

- source of friction (needed to dissipate kinetic energy)
  (inflation? particle production? …)

- origin of relaxion field
  (difficulties in identifying with QCD axion, new dark sector needed)

- complete implementation still missing

Interesting phenomenology:

- new physics not necessarily at the TeV scale

- relaxion field typically light and very weakly coupled
  (difficult to test at colliders)

- non-collider searches typically necessary to test models
  (table-top axion experiments, cosmological consequences,….)
Beyond Naturalness
BSM is not just naturalness

Many open questions imply physics beyond the Standard Model

- dark matter
- neutrino masses
- inflation
- baryogenesis
- strong CP problem
- hierarchy problem

Energy scale [TeV]

Only naturalness (assuming full predictivity) seems to point towards a sharp range close to LHC energy…

… but different kinds of new physics can show up at other experiments and even (accidentally) at LHC
EW baryogenesis and Higgs sector

Interesting way to realize baryogenesis is via a strong \textit{EW phase transition}

- modification/extension of Higgs sector
  (SM EW phase transition is cross over $\rightarrow$ not enough breaking of thermal equilibrium)

- new sources of CP violation \hspace{1em} (too weak in SM)

Example: \textbf{Higgs sector extended with additional singlet}

- a two-step transition can give a strong 1st-order EW phase transition

- in the presence of additional CP violation baryogenesis can be achieved

\[\text{[Anderson, Hall '92; Choi, Volkas '93; Espinosa, Quiros '93; Profumo, Ramsey-Musolf, Shaughnessy '07, ...]}\]
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- a two-step transition can give a strong 1st-order EW phase transition
- in the presence of additional CP violation, baryogenesis can be achieved

- can be probed at (future) colliders looking for the additional singlet

Example: Higgs sector extended with additional singlet

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![Graph showing production cross-sections at hadron colliders for various modes of singlet production with $H_S=2$.](image)

Fig. 5: Production cross-sections at hadron colliders for various modes of singlet production with $HS=2$. These calculations were computed at LO with MadGraph5.

- $\sqrt{s} = 100$ TeV
  - can be probed at future colliders looking for the additional singlet

...
EW baryogenesis and Higgs sector

Interesting way to realize baryogenesis is via a strong EW phase transition

- modification/extension of Higgs sector
  (SM EW phase transition is cross over → not enough breaking of thermal equilibrium)

- new sources of CP violation

Example:

- a two-step EW phase transition
  - in the first stage, a strong 1st-order EW phase transition
  - in the second stage, a first-order phase transition

- can be probed at (future) colliders looking for the additional singlet

- possible tests through gravitational waves
A viable flavor structure is an essential ingredient for all BSM scenarios

- many flavor puzzles still open
- high precision in new flavor data gives strong indirect tests for NP

Recent development: Improved bound on electron EDM

\[ |d_e| < 9.4 \cdot 10^{-29} \, \text{e cm} \quad \rightarrow \quad |d_e| < 1.1 \cdot 10^{-29} \, \text{e cm} \quad \rightarrow \quad |d_e| \lesssim 0.3 \cdot 10^{-30} \, \text{e cm} \]
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\]

- can test NP in the 10 TeV range even through two-loop effects

- relevant implications also for EW baryogenesis models
Model-Independent Approaches
Model-independent approaches try to look for New Physics in a virtually unbiased way.

Advantages:

- only relies on SM (+ minimal set of additional assumptions)
- can look for wider range (virtually any) NP model
- might discover unthought-for NP

Possible approaches:

- precision measurements (through Effective Field Theory formalism)
- anomaly detection
Even if NP is too heavy to be produced directly we can still look for deviations from SM in low-energy observables!

- NP parametrized in a model-independent way through extension of SM with higher-dimensional operators:

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_{i}^{\text{dim}-6} + \sum_i \frac{d_i}{\Lambda^4} \mathcal{O}_{i}^{\text{dim}-8} + \cdots \]

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Precision program effective also at hadron colliders (including LHC)

- new physics effects grow with energy

\[ \frac{\Delta \mathcal{O}}{\mathcal{O}} \sim \frac{E^2}{\Lambda^2} \]

  - big boost with collider energy
  - steady improvement with luminosity
Simplest example:  

**Oblique parameters in di-lepton Drell-Yan**

[ Farina, GP, Pappadopulo, Ruderman, Torre, Wulzer '16 ]

\[ \Delta \mathcal{L} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 - \frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2 \]

- LHC improves the LEP bounds by one order of magnitude

Precision Measurements

\[ \text{DY are already competitive with LEP constraints.} \]
Simplest example: Oblique parameters in di-lepton Drell-Yan

\[ \Delta \mathcal{L} = - \frac{W}{4m_W^2} (D_\rho W^a_{\mu\nu})^2 - \frac{Y}{4m_W^2} (\partial_\rho B_{\mu\nu})^2 \]

- LHC improves the LEP bounds by one order of magnitude
- can complement direct searches (eg. heavy resonances or difficult signals)
Anomaly Detection

Search for **departures** from a given **reference model** (in our case the SM) with no need to specify alternative theory

- ideally sensitive to *any* new-physics model

*machine learning* used to compare experimental data with reference model

- limitation: can not be used for exclusion  (negative results are not informative)
Anomaly Detection

Still at an early-development level, but many interesting directions…

- CWoLa Hunting  [Collins, Howe, Nachman '18]
- Novelty Detection  [Hajer et al. ’18; Pierini et al. in progress]
- Distribution Comparison  [D’Agnolo, Wulzer ‘18]
- Non-QCD jets  [Aguilar-Saavedra et al ’17; Heimel et al. ’18]
- Gaussian Mixture pdf  [Kuusela et al.’11]
- Nearest-Neighbours pdf  [De Simone, Jacques ‘18]
Conclusions
Conclusions

Last years saw explosion of research directions in BSM physics

**Naturalness** remains an important question and fruitful guideline…

- (minimal) classical scenarios under pressure
- several alternatives are being explored

… but a **broader search program** is clearly necessary

- many open questions in SM
- new search strategies at colliders (eg. model independent approach)
- beyond-collider probes