Future Perspectives --- Part 2

Higgs Days at Santander 2019
Theory meets Experiment
16.-20. September

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Based in part on discussions at the 2018 GGI Workshop “Beyond the Standard Model: Where do we go from here?”
Outline

1. The fate of naturalness

2. Do we really know the theory of fundamental particles and their interactions at the TeV scale?

3. Open questions in Higgs physics

4. The current status of particle physics

5. So, where do we go from here?
1. Has the idea of naturalness run its course?
Scalar fields portend an energy scale associated with new phenomena that are close at hand.
The situation is, however, entirely different for a particle with Bose statistics. Even the Coulombian part of the self-energy diverges to a first approximation as $W_{st} \sim e^2 h / (mc a^2)$ and requires a much larger critical length that is $a = (hc/e^2)^{-\frac{1}{4}} \cdot h / (mc)$, to keep it of the order of magnitude of $mc^2$. This may indicate that a theory of particles obeying Bose statistics must involve new features at this critical length, or at energies corresponding to this length; whereas a theory of particles obeying the exclusion principle is probably consistent down to much smaller lengths or up to much higher energies.
Weisskopf’s arguments imply that there should be new physics at the scale of $m_H/g \sim 1 \text{ TeV}$. But where is the new TeV-scale physics?
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*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATLAS SUSY Searches* - 95% CL Lower Limits
July 2019
$\sqrt{s} = 13$ TeV
Overview of CMS EXO results

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

January 2019
At what point do you lose interest in extending the new physics searches?

- Keep in mind that after Run 2, you will only have collected 5% of the total luminosity expected during the LHC lifetime.

- If you discover new physics consistent with explanations of the gauge hierarchy problem (why is $m_W/M_{PL} \sim 10^{-17}$?), the little hierarchy problem becomes much less pressing.
Final thoughts on naturalness

- The announcement of the death of naturalness may be premature.
- There is still room for theoretical innovations.
- However, in evaluating new approaches to naturalness, it is important to consider how one could test these ideas experimentally (i.e. what observable phenomenon would convince you that Nature has employed a natural theory for the dynamics of electroweak symmetry breaking?).
2. Do we really know the particle content of the TeV-scale effective theory?

- The fermion sector of the Standard Model (SM) consists of three generations of quarks and leptons.

- The scalar sector of the SM has a single Higgs boson. Why not multiple families of Higgs scalars?

- There are good reasons to think that the number of families of chiral fermions is limited to 3. But what about vector-like quarks and leptons?

- Flavor anomalies have revived interest in leptoquarks.
Are we really sure that the gauge group of the effective TeV-scale theory is SU(3) x SU(2) x U(1)? Are there new gauge bosons lurking in the region of 1—10 TeV? (How about with masses below $m_Z$?)

Of course, don’t forget about the dark sector, which I shall define as particles that are neutral with respect to SU(3) x SU(2) x U(1). Perhaps motivated by theories of dark matter, but could exist independently. Communication with the SM sector is possible through the various portals.

- The Higgs portal ($\Phi^+ \Phi$ is a SM singlet)
- U(1) gauge boson mixing ($F_{\mu \nu} F'_{\mu \nu}$)
- The neutrino portal ($L^+ \Phi N$)
3. Open questions in Higgs physics

- Is the Higgs boson observed at the LHC a solo act? Or are there additional fundamental scalars to be discovered near the energy scale of electroweak symmetry breaking (EWSB)?

- Is the Higgs boson and its cousins, if present, elementary scalars (when observed at length scales of order $\text{TeV}^{-1}$ or larger)? Or are they bound states of more elementary constituents?

- Do the couplings of the 125 GeV Higgs boson deviate from the predictions of the Standard Model? If yes, what does this suggest about the nature of new BSM physics?

- Is the Higgs sector a portal to new BSM physics (perhaps associated with the dynamics responsible for the origin of EWSB and/or the presence of a dark sector)?

- Do Higgs bosons play a relevant role in early universe cosmology?
Motivations for an extended Higgs sector

- The fermion and gauge boson sectors of the Standard Model (SM) are not of minimal form ("Who ordered that?"). So, why should the spin-0 (scalar) sector be minimal?

- Some extended Higgs sectors can provide a dark matter candidate.

- Extended Higgs sectors can modify the electroweak phase transition and facilitate baryogenesis.

- Extended Higgs sectors can enhance vacuum stability.

- Models of new physics beyond the SM often require additional scalar Higgs states. E.g., two Higgs doublets are required in the minimal supersymmetric extension of the SM (MSSM).
Is the electroweak vacuum of the SM stable?

The Higgs field of the SM has a local minimum at $<\Phi>$=246 GeV. However, it is possible that a second minimum develops at very large field values. For field values larger than the Planck scale, $M_{\text{PL}} = 10^{19}$ GeV (in units of $c=1$), calculations within the SM are not reliable, as gravitational effects can no longer be neglected.

However, below $M_{\text{PL}}$ one can reliably compute the shape of the scalar potential to determine whether our vacuum is stable.

(figure courtesy of A. Kusenko)
Detailed calculations by G. Degrassi, S. Di Vita, J. Elias-Miro, J.R. Espinosa, G.F. Giudice, G. Isidori and A. Strumia (2012)—see figure below on the left, and a more recent treatment by A.V. Bednyakov, B.A. Kniehl, A.F. Pikelner and O.L. Veretin (2015)—see figure below on the right, suggest that the electroweak vacuum is metastable, with a lower secondary minimum below $M_{\text{PL}}$.

However, for a slightly lower value of $m_t$ (compared to the central PDG value), stability up to $M_{\text{PL}}$ is recovered.
The popular press has taken notice ...
4. The current status of particle physics

With the discovery of the Higgs boson, we have entered a new era of particle physics.
- There is no longer a no-lose theorem to guarantee future discoveries.
- We are in a data-driven era—i.e., we depend on new data to guide future directions in BSM physics.
- The principle of naturalness, although not dead, is under tension.
- So how do we motivate the next generation of colliders?
In this data-driven era, one should remind what Galileo himself famously said:

Measure what can be measured and make measurable what cannot be measured.

And also:

Never fully trust quotes found on internet.

This slide courtesy of Marie-Helene Genest
5. So, where do we go from here?

- Explore the Higgs sector as thoroughly as possible (since, you have never seen anything like it before).
  - Experimental studies at present and future colliders
  - Implications for early universe cosmology

- Precision, precision, precision.

- Exploit the LHC to its maximum (it’s the only game in town at the energy frontier). Search for BSM physics in regions with significant SM backgrounds.

- Provide a roadmap for future energy-frontier facilities.