Beyond Models

Workshop on model independence in physics
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Model independence

a personal perspective

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From the plan of the conference

The lack of new physics discoveries at the LHC has had many significant effects on the field of particle physics. It has led to the re-evaluation of guiding principles such as naturalness, a decrease in the popularity of prominent models, such as supersymmetry, and an increase in model independent (MI) search methods. These MI methods aim at reducing BSM model dependence in a variety of ways and may include using bottom-up EFTs, using signature-based, rather than model-based, searches, performing SM precision measurements, or using unsupervised deep learning to let experimental data speak for itself as much as possible. This hybrid workshop will bring together physicists and philosophers of science to explore various aspects of this shift towards model-independent strategies, the tools they employ, as well as the methodological and epistemic issues they bring. We may examine questions such as:

- **what is model independence? How independent from models can one be?**
- **how does one historically, or philosophically, characterise the methodological shift that is happening?**
- **have there been other time periods during which physicists pursued model independence? what relation does this bear to today?**
- **why pursue model independence? what are its benefits and limitations?**
- **in what various ways are physicists reducing dependence on models, modelling biases, and modelling assumptions?**
- **how do deep learning and AI searches fit with model independent strategies?**

I will focus on the items highlighted in dark blue …

In preparing the talk, I realized that I lack even the most basic knowledge of what is meant by “model” in the philosophical discussion, not to speak about knowledge of the status of the debate.

This will be manifest in my talk, where most observations will be at best naive or well known, at worse wrong. Still, I’m grateful for having been arm-twisted into thinking by myself about the subject and giving this talk about it…

What is model independence? How independent from models can one be?

Preliminary question: what defines a model? E.g., was **F**=m**a** a “model” when it was first introduced ?
I’ll come back to this point …

Physics builds on different *(non exclusive: what follows is very crude and sketchy…)* **categories**

- **principles** (eg minimum action, space and time invariance of physical laws, speed of light, uncertainty principle, invariance under general coordinate transformations, gauge invariance, …)
  - ➡theorems or mathematical consequences of the principles (eg conservation laws, Lorentz transformations, quantum mechanics, general relativity, …)
- **frameworks** (consistent with principles or with observations, they can host classes of models)
  - mathematical frameworks (lagrangian field theory, gauge theories, supersymmetry, string theory, …)
  - phenomenological frameworks (Big Bang cosmology, inflation, atomic and nuclear physics, electroweak symmetry breaking, …)
- **models** (they fill frameworks with content)
  - choice of a gauge group and representations
  - specific dynamics to address specific issues (eg axion couplings, inflation potentials, composite Higgs, …)
  - description of specific phenomena (eg dark matter, neutrino masses, CP violation)
- **theories**
  - mathematical consequences of the principles (eg special relativity, quantum mechanics, general relativity, …)
  - established models, self-contained in the description of a given phenomenological framework, can be elevated to the status of theory (eg QED, QCD)

- New physics can emerge in any of the first three above categories (principles, frameworks, models) … the “models” discussed at this workshop typically refer to objects living in the lowest tier of the above categories, they do not touch on principles or frameworks
- Model independence can at best be obtained in the context of a given phenomenological framework (some desired properties, or emerging properties, may not depend on the specific model)

Back to the preliminary question:

What is a model?

Cambridge Dictionary:

- something that a copy can be based on because it is an extremely good example of its type

Merriam Webster:

- a system of postulates, data, and inferences presented as a mathematical description of an entity or state of affairs
- a description or analogy used to help visualize something

Mac Dictionary:

- a simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions

The diversity of connotations given to the term “model” is probably consistent with the observation that we assign a different value to the concepts of “model for” and “model of” … the simple term “model” appears incomplete

I got struck by this observation when thinking to myself about what is a model. I thought it was a relevant point, and googled it up for curiosity… to my surprise, there is indeed a vast literature on the subject of model “for” vs “of” !!!
See eg https://link.springer.com/article/10.1007/s11191-017-9884-4 (although in a different context)

Examples

- CKM is a model **for** fermion mixing, in the sense of MAC dictionary's defintion* . Models **of** fermion mixing (*which is what theorists are after*) try to identify a dynamical framework from which CKM would emerge. As such, CKM can be seen as a *model-independent model* **of** fermion mixing.

- The situation is similar for the modeling of neutrino properties. The favourite model **for** these properties relies on mixing and masses, and is independent of specific hypotheses on the origin of the resulting PMNS mixing matrix, **of** which many different models have been proposed.

- Ultimately, due to their success, we do not consider CKM and PMNS as models any longer. But, epistemologically, they are themselves models, we do not consider them as theories since they cry for an explanation of their origin. In fact, the search for their ultimate origin is a key driver of modern research (and model building).

* a simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions

Is the Standard Model a model, a theory, or what ?

Several colleagues argue that, with the discovery of the Higgs, the SM must now be called Standard Theory

For the person on the street, **“theory”** sounds less robust, established and reliable than **“model”** (as in *“in theory you are right, **but** …”* or *“well, this is **your** theory…”*)…

Eg, from the Britannica Dictionary

Theory

1. an idea or set of ideas that is ***intended to explain*** facts or events
2. an idea that is suggested or presented as ***possibly true but that is not known or proven to be true***

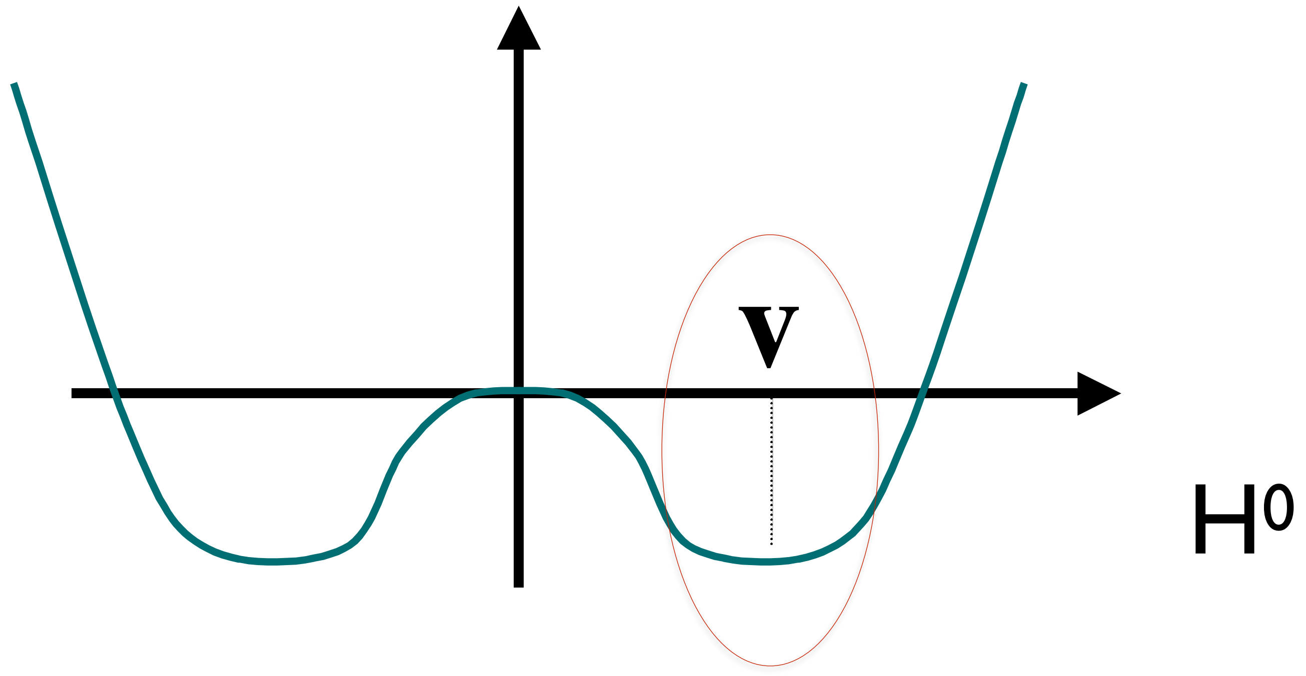
Model

a set of ideas and numbers that ***describe*** the past, present, or future state of something

So, I’d rather stick to **Model….** but there is a deeper reason why I believe the SM is, and will remain, a model.

More precisely, I would actually define the SM as **the theory <u>of</u>** weak interactions, but just **a model <u>for</u>** electroweak symmetry breaking

Is the Standard Model model independent?



$$V(H) = -\mu^2 |H|^2 + \lambda |H|^4$$

$$L_{eff} = L_0 + \sum_n \frac{c_n}{\Lambda^n} L_n$$

Where does this come from?

L_0: the Higgs potential is the minimal and universal form of the potential that provides the known ingredients of EW symmetry breaking (EWSB). As such, it is the reference model **for** EWSB, providing also its leading order description. All models **of** EWSB will contain L_0. The possible sets **{c_n L_n}** give different models **of** L_{eff} , parameterizing the deviations induced by BSM physics that should lie at the origin of EWSB itself

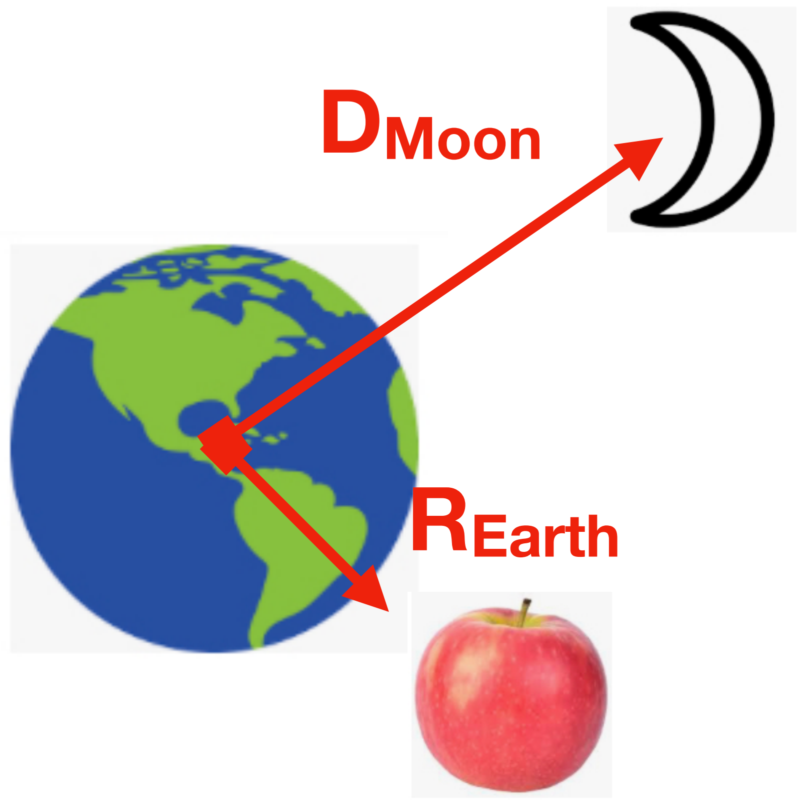
So in a sense the SM is model independent. Notice that the reason to look for a BSM origin is not the form of the potential itself (which is rather model independent), but the numerical value of the Higgs mass in the minimal SM version, which is “unnatural” in the context of the hierarchy problem, and calls for specific BSM scenarios of EWSB to justify it

Have there been other time periods during which physicists pursued model independence? what relation does this bear to today?

Newton's Gravity, a first "model independent" analysis

Starting intuition: same force is responsible for centripetal acceleration of celestial bodies and for free fall on Earth

Model-independent **parameterization**: $$g = -\frac{C}{D^n}$$ D=distance



Input **data**: $$g_{Moon} = \frac{4\pi^2 D_{Moon}}{[28 \text{ days}]^2} \qquad g_{Apple} = 9.8 \text{ m/s}^2$$

Data **fit**: $$\frac{g_{\text{Apple}}}{g_{\text{Moon}}} = \left(\frac{D_{\text{Moon}}}{R_{\text{Earth}}}\right)^n \Rightarrow \quad n = 2$$

Interpretation: **"Hypotheses non fingo" ….** the first model-independence Manifesto!

*I have not as yet been able to discover the reason for these properties of gravity from phenomena, and **I do not feign hypotheses**. For whatever is not deduced from the phenomena must be called a hypothesis; and hypotheses, whether metaphysical or physical, or based on occult qualities, or mechanical, have no place in experimental philosophy. In this philosophy particular propositions are inferred from the phenomena, and afterwards rendered general by induction. (I. Newton)*

Validation/generalization: C/R^2 implies Kepler laws

A model-independent analysis of Mercury's orbit anomaly

$$V_{eff}(M,R) = -G_N \frac{M}{R}\left[1 + \sum_{n\geq 1} \frac{v_n}{(MR)^n}\right]$$

- This could have been done before Einstein's **General Relativity**, as a GR EFT precursor
- The precise study of Mercury's perihelion precession would have given values of v_n coefficients consistent with General Relativity results.
- However out of this exercise we would not have recovered the full "non-perturbative" version of the underlying theory, or even predicted the deflection of light by the gravitational field.
- Even Eddington's experimental input may not have helped, as it's not obvious how to connect the EFT coefficients above to light's deflection in the gravitational field of the Sun
- Here the "new physics" is General Relativity, and uncovering the full theory required a quantum leap that seems to go beyond a basic model-independent approach to canonical observables and expansion parameters

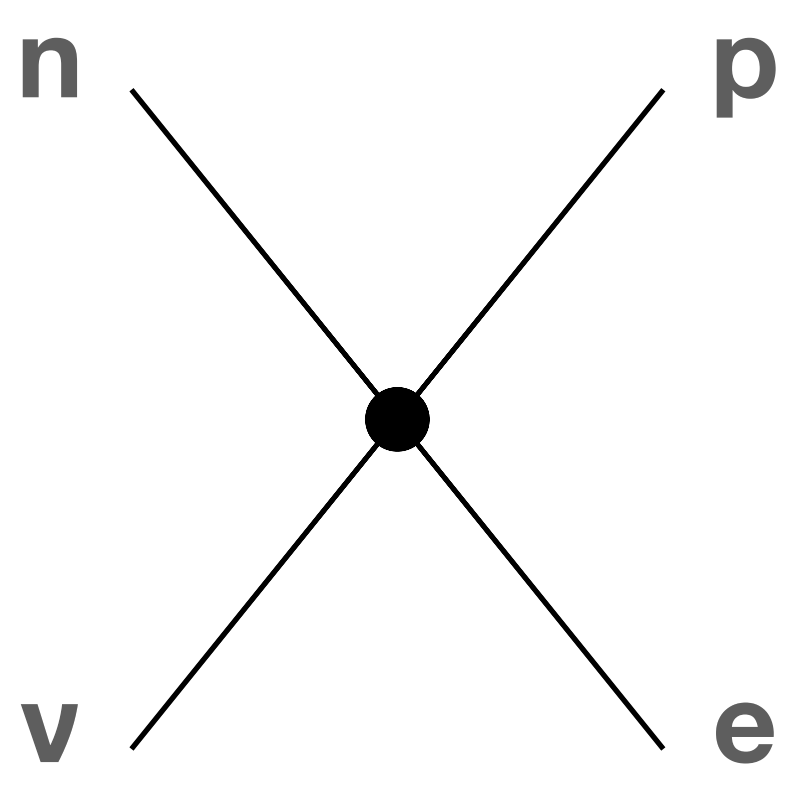
➡ ***an intrinsic limitation of the power of EFTs or model-independent searches for new physics?***

- **NB** In the analysis of the Sun-Mercury 2-body problem, the expansion in powers of 1/(MR) is equivalent to an expansion in powers of $(v/c)^2 \sim a/(MR)$ (where $a=GM^2$) ==> see today's non-relativistic EFTs

Fermi theory of weak interactions

$$L_{eff} \sim G_F \ \bar{\psi}_p L^\alpha \psi_n \ \bar{\psi}_e L_\alpha \psi_\nu \quad , \quad L = (S, P, V, A, T)$$

L= possible Lorentz nature of couplings, to be determined by comparison with data



- Possibly the most successful model-independent theory of the XX century, and the "model" *(→ Cambridge Dictionary *)* for today's "model independent" EFT approaches

* *something that a copy can be based on because it is an extremely good example of its type*

More possible examples of model-independent descriptions

- Thermodynamics
- Phase transitions

Homework, food for thought

- Can one formulate the historical evolution that led to the eventual discovery of quantum mechanics in terms of effective theories or model-independent approaches (Einstein’s photoelectric effect, Bohr quantization, …)?

How does one historically, or philosophically, characterise the methodological shift that is happening?

- The late 70’s - early 80’s witnessed the establishment of the SM (’79 Nobel prize, success of QCD, W/Z discovery, …) and the expansion of confidence in the gauge and symmetry paradigm (GUT’s and SUSY), with a flourishing of models for extensions of the SM and the identification of the ultimate theory. This was a cataclysmic philosophical shift, putting theory ahead of experiments.

- Experiments started focusing on tests of specific models, searching for proton decay, SUSY particles, preons, etc

- The **hierarchy problem** was identified as a serious conceptual limitation of the SM early on (’t Hooft ’79), but it exploded as a main driver of BSM speculation as the SM itself became more firmly established at LEP, shifting the focus towards the search of its **natural** solution

- A first example of model-independent exploration of the SM limitations emerged at LEP, driven by the powerful indirect sensitivity to new physics enabled by the accurate measurements, with the introduction of the S,T,U ($\varepsilon_{1,2,3}$) parameters (similar EFT approaches were in parallel pursued before that at low energy, eg in the study of c/b hadrons)

- But searches and analyses at the Tevatron, and in the the planning for LHC, remained focused on the direct search of new particles, thanks to the powerful energy and mass reach

- With the LHC approaching, it became clear that any discovery would have been a “model-independent” one: the observation of a new phenomenon was not going to single out at first a specific model, but at best to provide evidence for general properties (eg multijets or missing ET signatures). The task of identifying a specific model relied on the solution of the “inverse problem”, something more easily done with a structured model-independent approach, whereby many models at the same time could be tested against the features of the new data.

- This approach was particularly justified by the realization that the class of BSM scenarios discussed in the 90’s was too limited, and the explosion of new and phenomenologically diverse models to address naturalness (extra dimensions, Higgs-less theories, …)

- The concept of **simplified models** was thus introduced

- Simplified models and EFTs became the new paradigm. The former covering direct signals, accessible thanks to the huge LHC energy; the latter covering indirect signals, accessible through the new precision frontier

- As the first LHC data showed no evidence for new particles, the concept of re-interpretation was then developed, to allow the fast and effective translation of limits (on specific or on simplified models) to the continuously growing sets of BSM models appearing in the literature

Why pursue model independence? what are its benefits and limitations?

- More efficient use of data and of experimental resources: model-independent parameterizations of the results enabled the TH community to play a direct role in the interpretation and extension of results to the multitude of TH scenarios. The experiments could focus on canonical benchmark BSM scenarios, with re-interpretation enabling the generalization

- Broader and more educated TH participation, increasing the knowledge by the TH community of the experimental analysis environment (backgrounds, detector resolution, efficiencies, triggers)

- New experimental protocols to facilitate this exchange: dedicated use of data repositories (HEPdata), stand alone and public reusable mocks of the experimental analyses (Rivet), now evolved to the Open Data framework.

- Better representation and persistence of the record of the experimental results

➡ *Overall this led to an optimization of the exploitation of the LHC data*

On the interplay of model -independent and -dependent approaches

- In general, connecting simplified models and EFTs to concrete models remains necessary and must be done more. Among other benefits, this allows to establish correlations among different observables, suggesting more powerful analyses, putting the existing limits in context (eg determining the effectiveness of the reach of specific EFT operators in constraining relevant benchmark scenarios), thus strengthening and corroborating the outcome of model-independent studies.

- Re-interpretation tools allow to bridge between simplified and concrete models

- An often debated issue is whether precision (ie EFTs) can overcome energy reach and direct search. This is a critical question in the context of defining the strategy for future accelerators

- With EFT having become the new gospel, there is a (unjustified) tendency to assume that their indirect reach for a high energy scale Λ is an absolute probe of all possible new phenomena below Λ

$$L_{eff} = L_0 + \sum_n \frac{c_n}{\Lambda^n} L_n$$

In more detail…

$$L_{eff} = L_0 + \sum_n \frac{c_n}{\Lambda^n} L_n$$

- What is constrained by precision observables in EFT approaches are ratios of a coupling strength (the generic c_n above) and the scale of the new physics Λ:

$$c / \Lambda < 1/\Lambda_{max} \Longrightarrow \Lambda > c\, \Lambda_{max}$$

- If $c = O(1)$, $\Lambda \gtrsim \Lambda_{max}$, maximizing the energy reach for strongly-coupled BSM scenarios. For weakly coupled theories, or for loop-induced BSM effects, $c \ll 1$ and sets poorer limits on Λ

- Strong limits on forbidden decays, such as $K \rightarrow \mu e$ or $\mu \rightarrow e\gamma$, interpreted in the context of c=O(1), give limits in the range of several hundreds TeV … but in practice most models for, eg, $\mu \rightarrow e\gamma$, are constrained by data at the level of few hundred GeV

- LEP EW precision tests properly established the mass range for both the top quark and the Higgs boson, well above LEP's reach for their direct discovery. However, the same tests could not constrain the mass scale of SUSY particles above the direct production limits. SUSY particles could have been behind the corner, without leaving a trace in the EFT analysis, given the available precision

- EFT is the best tool to analyze and document in a model-independent way the outcome of precision measurements. But its use to establish constraints on high-mass phenomena, and to project the sensitivity to new physics, is strongly dependent on the concrete examples of new physics one is considering, and it cannot be used to set universal model-independent constraints on the scale of new physics

- This issue should enter more prominently in the discussions about the future of accelerator physics, where its neglect or consideration lead to different weights in the assessment of different strategies.