The status of fine-tuning arguments in the CEPC era

Andrew Fowlie

Xi'an Jiaotong-Liverpool University
andrew.fowlie@xjtlu.edu.cn
andrewfowlie.github.io

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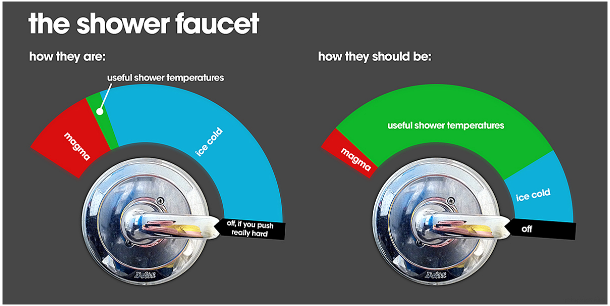
Partially based on work with Gonzalo Herrera [2406.03533]

Background

Fine-tuning in everyday life



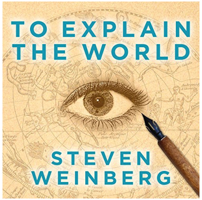
We know that showers that require **fine-tuning** are bad showers!

Background

Fine-tuning in physics

In high-energy physics, a theory is considered **fine-tuned or unnatural** if small variations in its parameters result in dramatic changes in its predictions. For reviews, see ref. [1–3]

> ***Fine-tuning in a scientific theory is like a cry of distress from nature***, *complaining that something needs to be better explained*

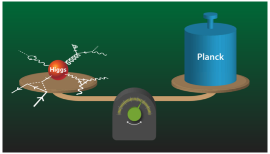


Background

Hierarchy problem

Higgs mass parameter must be **fine-tuned.** This is the hierarchy problem [4–8]

$$m^2 \simeq {m_0}^2 + M_{\mathrm{UV}}^2$$



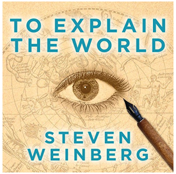
Require **fine-tuning** of bare mass and loop correction $\sim M_{\mathrm{UV}}^2$ such that $m^2 \lll M_{\mathrm{UV}}^2$

Decades searching for solutions — e.g. supersymmetry [9–11], large extra dimensions [12] and technicolor [4] — that canceled UV corrections or eliminated any UV scales

Background

Cosmological constant

Cosmological constant requires **fine-tuning** — $\rho \lesssim 10^{-121}$ but corrections from known physics are at least 60 orders of magnitude greater [13]

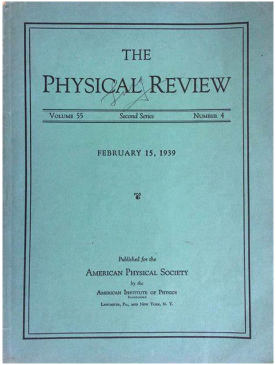


***This level of fine-tuning is intolerable**, and theorists have been working hard to find a better way to explain why the amount of dark energy is so much smaller than that suggested by our calculations*

Background

History of fine-tuning

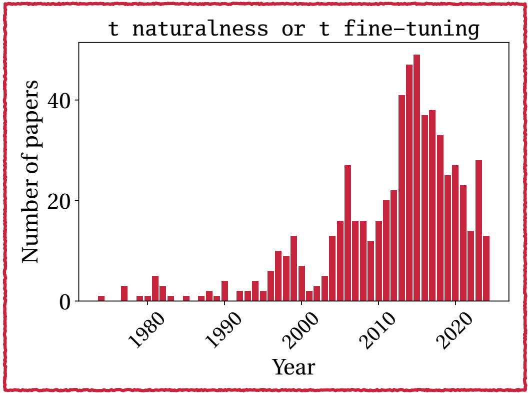
- **1934** — Weisskopf's calculation of electron self-energy [14]
- **1938** — Dirac's large numbers hypothesis [15]
- **1973** — Wilson understanding of effective field theory [16]
- **1974** — Gaillard and Lee predict charm quark mass [17]
- **1988** — Weinberg makes anthropic argument [18]



Background

Popularity of fine-tuning — data from INSPIRE

- **1974** — first hit by Georgi [19]
- **1979** — ’t Hooft [20]
- **1987** — Barbieri-Giudice measure [21]
- **2000** — fine-tuning at LEP [22]
- **2006** — pre-LHC forecasts
- **2010 onward** — LHC-era



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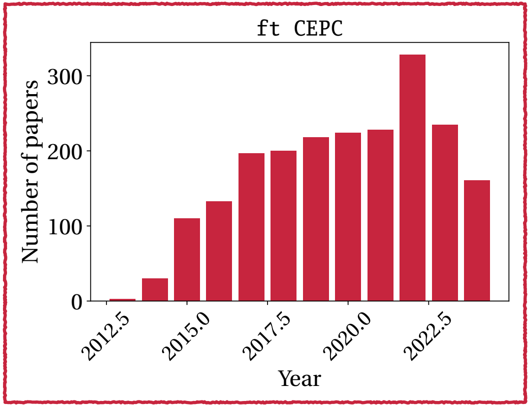


Background

Measures of fine-tuning

Fine-tuning of electroweak scale usually quantified by sensitivity measure [21, 23], e.g. Barbieri-Giudice (BG)

$$\Delta_{\mathrm{BG}} = \left| \frac{\mathrm{d} \ln M_Z}{\mathrm{d} \ln a_i} \right| = \left| \frac{a_i}{M_Z} \frac{\mathrm{d} M_Z}{\mathrm{d} a_i} \right|$$

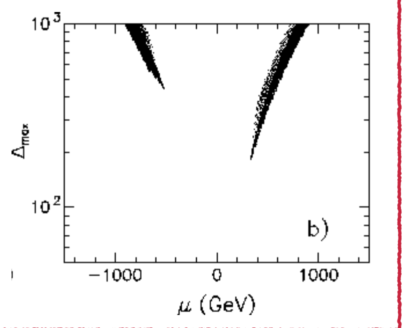
We could combine them by maximizing across parameters or summing in quadrature.

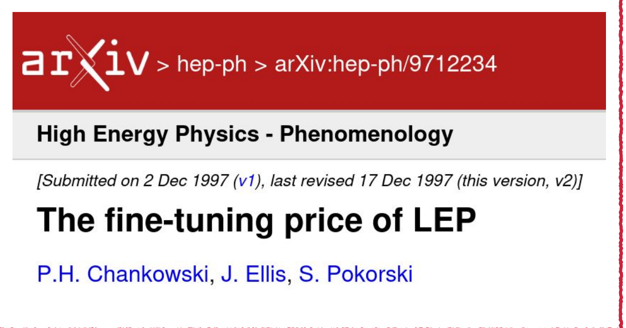
Why though? What's the connection between these measures and plausible models?

Background

Fine-tuning at LEP

Fine-tuning price of LEP [22, 24–26] — allowed points show $\Delta_{BG} \gtrsim 100$

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High Energy Physics - Phenomenology

[Submitted on 2 Dec 1997 (v1), last revised 17 Dec 1997 (this version, v2)]

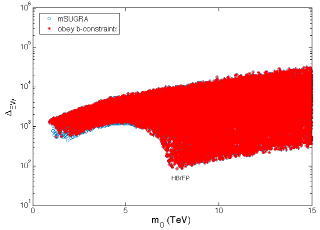
The fine-tuning price of LEP

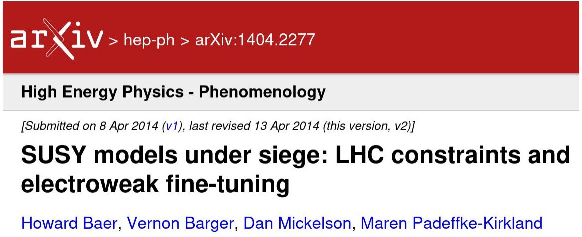
P.H. Chankowski, J. Ellis, S. Pokorski

Background

Fine-tuning at the LHC

Fine-tuning price of the LHC [27, 28] — allowed points show $\Delta_{BG} \gtrsim 1000$, except in focus-point region





There are, thus, now criticisms and doubts about fine-tuning [29]

Recent developments

Statistical interpretation

Fine-tuning connected to probability of cancellations [30–35] and statistical inference [36–47]

Plausibility is updated by data via Bayes' theorem

$$p(A \mid B) = \frac{p(B \mid A)}{p(B)} \cdot p(A)$$

Contrasts with frequentist probability — frequency with which repeatable event occur in repeat trials [48]

Recent developments

Bayes factor

We want to find which model is most plausible in light of data. The relative plausibility is called the posterior odds [49, 50]

$$\frac{p(M_b \mid D)}{p(M_a \mid D)} = \frac{p(D \mid M_b)}{p(D \mid M_a)} \times \frac{p(M_b)}{p(M_a)}$$

Posterior odds = Bayes factor × Prior odds

The Bayes factor updates the prior odds to the posterior odds. This requires more than one model

Recent developments

Bayes factor surface [56]

The Bayes factor surface shows the change in plausibility of a model as a function of that model's parameters relative to a reference model

$$B(\theta) = \frac{p(D \,|\, M, \theta)}{p(D \,|\, M_0)}$$

This is **a new way to understand the impact of experimental measurements**; see ref. [51–55] for recent related works in other contexts

Recent developments

Information theory

The Kullback-Leibler (KL) divergence between the prior and the posterior [57]

$$D_{\mathrm{KL}} \equiv \int p(\phi \,|\, M_Z) \ln \left[\frac{p(\phi \,|\, M_Z)}{\pi(\phi)} \right] \mathrm{d}\phi$$

This is a measure of the **extra information required about a parameter to fit the *Z* mass** [58]

Recent developments

Equivalence [59]

- Model of new physics with parameters θ, e.g. SUSY
- **Exchange one model parameter for the Z mass**, e.g. μ-parameter
- Reference model with M_Z as an input parameter

We found a link between the BG measure, statistics, and information theory

$$B(\theta) = e^{\triangle D_{\text{KL}}} = \Delta_{\text{BG}}$$

Bayes factor surface = Relative information = BG measure

... for the parameter that was exchanged for the Z mass

Recent developments

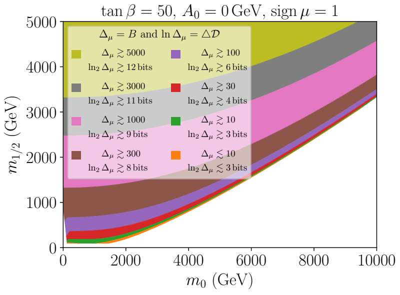
Interpretations of BG measure

- **Statistical** — the BG measure shows the Bayes factor surface versus an untuned model — *measures the change in plausibility of a model relative to an untuned model in light of the Z mass measurement*

- **Information-theoretic** — the BG measure shows the compression versus an untuned model — *measures the exponential of the extra information, measured in nats, relative to an untuned model that you must supply about a parameter in order to fit the Z mass*

Example

CMSSM/mSUGRA



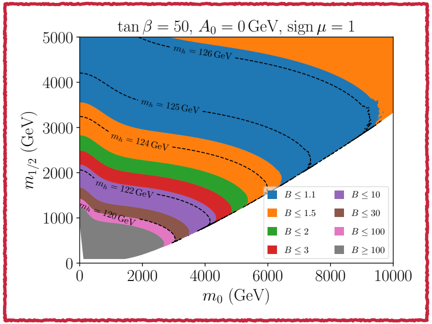
The traditional BG measure is equivalent to

- Bayes factor surface relative to untuned model — *CMSSM points disfavored by more than factor 300*
- Extra information that must be specified about a parameter — *at least 6 extra bits of information required about the μ-parameter*

... everywhere except in the narrow focus point strip where $\Delta_{BG} \leq 10$

Example

CMSSM/mSUGRA



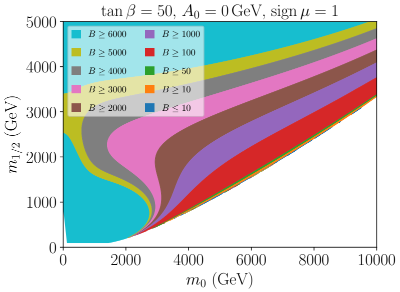
The Bayes factor surface for the $m_h \simeq 125$ GeV Higgs mass measurement

- Computed relative to a reference model — *model that predicts $m_h = 125$ GeV with no tuning*
- Requires $m_0 \gg$ TeV and $m_{1/2} \gg$ TeV — *except in narrow focus-point*

How can we combine the Higgs mass measurement with the BG measure?

Example

CMSSM/mSUGRA



Bayes factor surfaces from *Z* and Higgs mass measurements can be multipied

- The *Z* and Higgs mass measurements select narrow focus-point strip — *disfavoured, but only by $B \leq 10$*
- … and rule out other choices — *disfavored by at least $B > 100$*

The BG measure should not be thought of as a χ^2, but as a Bayes factor

Relevance

Today & at the LHC

Predictions from naturalness continue to guide searches for new physics

- Searches for light stops e.g. [60, 61]
- Searches for light higgsino-like neutralinos and charginos & compressed spectra e.g. [62–64]

Novel strategies for hidden naturalness

- Compressed spectra
- R-parity violation
- Blind spots & secluded sectors

Relevance

CEPC era

- Fine-tuning a major motivation for CEPC and SppS in CDR [65]
- Neutral naturalness probed through ZZh precision — *reach 3 TeV in twin Higgs and 1 TeV in folded SUSY models [65]*
- Exploration of **higgsino world** at CEPC [66] — *possible through* $ee \to WW$ *to exclude* $\mu \lesssim 210$ *GeV at* $\sqrt{s} = 240$ *GeV*
- Higgsino or bino-like direct production [67] — *reach limit* $\sqrt{s}/2$
- Indirect constraints from precision Higgs in combination with other limits [68, 69]

Conclusions

- Doubts raised about fine-tuning — arbitrariness, lack of logical foundation & negative results from LEP and LHC
- There are, however, precise interpretations of the fine-tuning measure

  — **Statistical** — *measures the change in plausibility of a model relative to an untuned model in light of the Z mass measurement*

  — **Information-theoretic** — *measures the extra information that you must supply about a parameter in order to fit the Z mass*

- Fine-tuning thus a legitimate guide for new physics
- Motivating search strategies at the LHC and **should play role at CEPC**

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