A Bayesian Perspective on the Search for Low Energy Supersymmetry

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Model independent search vs guidance by models

One element in finding the balance between model independent approaches and model-guided search is the assessment of the epistemic significance of arguments in favor of specific theories/models.

- This is the topic of my talk.

Assessing the status of SUSY

- LHC offers mixed messages regarding the prospects of SUSY that are viewed differently by different actors:

➢ A majority of observers take SUSY (at any rate for energies far below the Planck scale) to have significantly lost credence:
  - Most of the parameter space for low energy SUSY has been ruled out.
  - A core prediction of (SUSY + naturalness) seems to have failed.

➢ Others (Giudice, Arkani-Hamed, Wells) take the data to mainly call into question standard views on naturalness arguments. They emphasize that
  - all other arguments in favor of SUSY remain intact.
  - the measured Higgs mass value increases credence in SUSY.
  - naturalness may either be retainable in split SUSY scenarios or may be replaced entirely by anthropic arguments.

The goal of this project

- Immediate goal: to clarify the structure of reasoning that leads to these divergent views on the same set of evidence.

- Wider goal: provide a framework for understanding credence in SUSY in general.

A Bayesian Perspective

If we look for an epistemic basis for assessing research strategies, it is natural to develop a probabilistic (Bayesian) account.

$$\frac{P(H|E)}{P(H)} = \frac{P(E|H)}{P(E)}$$

$$P(E) = \sum_{n=1}^{N} P(H_n)P(E|H_n) \quad \text{(the total probability)}$$

- The total probability covers all known as well as all unconceived alternatives (formally represented by a catch-all hypothesis).
- There is no precise way of specifying the probabilities of known, let alone unknown theories.

Bayesian Data Analysis vs. Bayesian Epistemology

➢ **Bayesian data analysis** aims at generating objectifiable results to the extent possible.

⇒It tries to avoid the use of subjective assessment of P(H) and P(E).

- The aim is to find generic priors.
- Often, two theories are compared to each other in order to cancel the effect of P(E).

(The goal is not fully achievable –see the significant role of prior assessments in current Bayesian analysis in cosmology.)

⇒Bayesian data analysis does not represent a full-fledged Bayesian epistemic perspective that models a scientist's actual credence in a hypothesis.

Bayesian Data Analysis vs. Bayesian Epistemology

- **Bayesian epistemology**, to the contrary, addresses the overall prospects of a theory's viability.

⇒One needs to take scientifically informed prior credences at face value.

⇒One needs to assess full P(E), accounting for the role of unconceived alternatives.

- As difficult as this may seem, this is the ONLY basis for assessing a theory's prospects at all.

! This does not just hold for the assessment of speculative hypotheses like low energy SUSY, but for assessing the predictive reliability of empirically well-confirmed hypotheses as well.

The full Bayesian analysis at work

$$P(H|E) = \frac{P(E|H)}{P(E)} P(H)$$

$$P(E) = \sum_{n=1}^{N} P(H_n) P(E|H_n)$$

In order to assess P(H|E), one needs to assess the total probability.

1: One needs to consider alternatives that provide the same predictions.

This can be done.

2: But one also needs to assess the unconceived alternatives that could do the job as well.

How can this work?

Meta-empirical assessment.

Why Supersymmetry? Data-Based Reasons

a) It makes the gauge couplings meet – given their measured values at the electroweak scale.
b) It provides a dark matter candidate.
c) It predicts a Higgs mass around the value where it was found.
d) It was hoped to be a means of rescuing naturalness in the face of separation of scales.

$$P(H|E) = \frac{P(E|H)}{P(E)} P(H)$$

$$P(E) = \sum_{n=1}^{N} P(H_n) P(E|H_n)$$

➢ P(E|H) > P(E) in all cases because H can be read as predicting E (or take back a "prediction").

❖ P((E|H) will not be not very high though, because

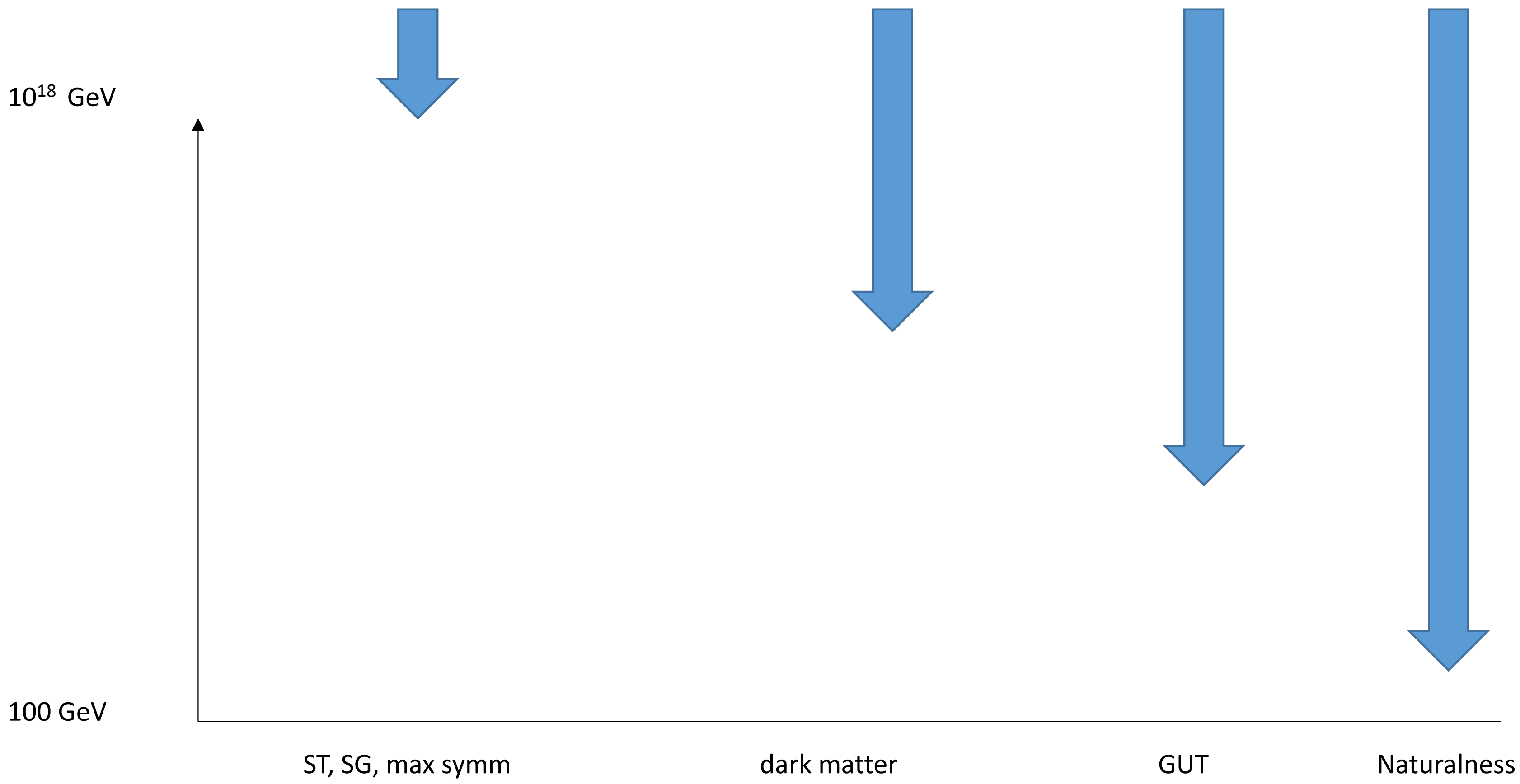
- the predictions are "soft".
- Known alternatives exist in all cases => only a weakened form of meta-empirical support.
  - In (d), before anthropic reasoning a weak no alternatives argument was considered by some observers.

Why Supersymmetry? Conceptual Reasons

a. It is a natural – and the maximal - extension of symmetry structure that binds together spatiotemporal and internal symmetries.
b. It naturally leads towards an inclusion of gravity in a gauge theory framework.
c. It is implied by string theory.

- Not based on empirical evidence for the theory.
- For c., meta-empirical theory assessment is endorsed by many string theorists. Since SUSY is implied by ST, this feeds down to SUSY.
- b. and a. may have intuitive force. But it is difficult to see a basis of meta-empirical theory assessment for them.

Reinforcement



SUSY sub-hypotheses to test

One might distinguish 3 sub-hypotheses on which to update:

(1) Low Energy (LE) SUSY: No SUSY partner is above 10 TeV.

(2) Mid Energy SUSY (ME) (inspired by split SUSY): Not LE-SUSY but at least one SUSY partner is below 1000 TeV.

(3) High Energy (HE) SUSY: No Superpartner is below 1000 TeV.

SUSY-related empirical evidence pre LHC:

E1(-) No compelling evidence for non-SM signals in low-energy experiments.

E2(+) Gauge couplings within tight locus in SUSY-RGE mapping to high scale but not in SM-RGE mapping to high scale

E3(+) Matter states (quarks, leptons and neutrinos) of the SM fit precisely within complete SU(5) multiplets, but bosonic states (vector bosons and Higgs boson) multiplets do not.

Favors GUT and therefore indirectly SUSY.

E4(+) Signal of proton decay into positron-pion not found by any experiment yet.

Rules out SM SU(5), but not SUSY SU(5), due to the latter's higher unification scale.

E5(-) Signal of proton decay into kaon-neutrino not found by any experiment yet.

Channel only for SUSY GUT.

E6(+) Cosmological data (e.g. galaxy rotation curves) suggests dark matter.

E7(+-) No evidence of particle detection in dark matter experiments.

SUSY-related empirical evidence LHC and beyond:

E8(+) Higgs boson was found at LHC with SUSY compatible mass.

MSSM: $m < 135$ GeV; more generally: $m<155$GeV

E9(-) No additional elementary particles discovered at the LHC.

E10 Some uncertain evidence for non-SM signal in g-2 experiment.

E11 Tevatron-data indicates a W-mass incompatible with the SM.

Some general points on the modeling of SUSY assessment:

- Whether there is a net increase or decrease of credence can depend on the priors.

$\Rightarrow$ One needs to model the basis for credence in SUSY in order to model the effect of the LHC data.

- Credence in SUSY cannot be understood without linking it to credences in GUT, dark matter, and, in the full picture, string theory.

$\Rightarrow$ One needs to model the credence in those theories in conjunction with SUSY.

- Updating credences relies (via calculating P(E)) on interpreting a parameter space as a probability space.

This involves uncertainties that reduce the strength of updating carried out on its basis.

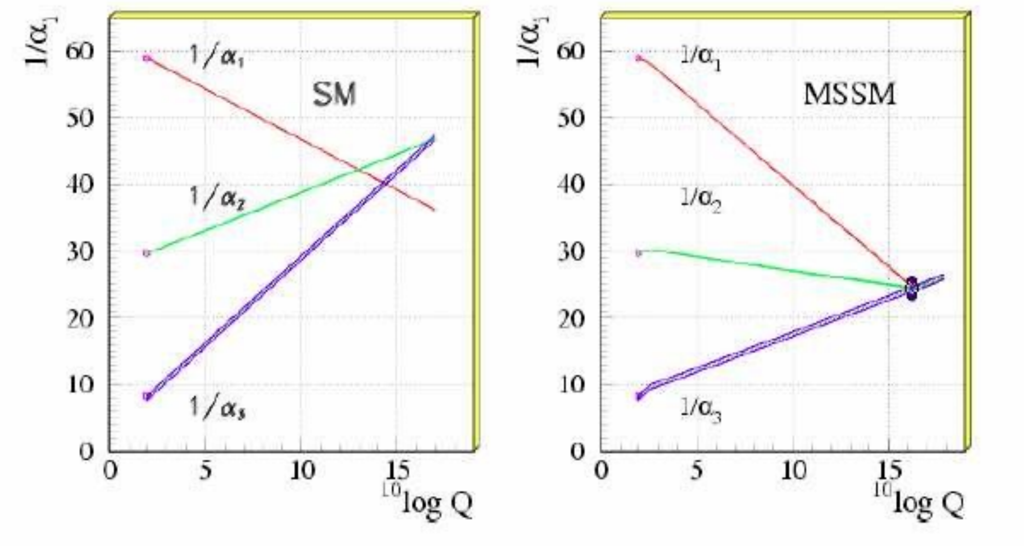
It is important to emphasize, however, that rejecting the decribed step blocks all epistemic import of empirical data.

SUSY and GUT

Representations

- Not even if anomaly freedom is required does it follow that matter particles fall into full GUT representations.
- If one treats matter content as a random pick, observation **E3** that they do will lead to $P(GUT| \mathbf{E3}) \gg P(GUT)$.

SUSY and GUT: meeting of gauge couplings



If one assumes an even probability distribution of gauge couplings, one can find:
P(couplings meet at least as well as in SM) = 0,0061
P(couplings meet about as well as in MSSM) = 0,00045

SUSY and GUT: meeting of gauge couplings

➢ The size of threshold corrections is not clear.

Based on the observed values of couplings, **E2**, one may test for three assumptions:

1. GUT + (threshold corrections are large $\{\Lambda_{23}<250\}$)
2. GUT + (threshold corrections are moderate $\{\Lambda_{23}<50\}$)
3. GUT + ((nearly) precise GUT $\{\Lambda_{23}<10\}$)

and consider the options (GUT+SUSY), (GUT+SM), (GUT+ else), (-GUT+expl), (-GUT+stat).

Results:

- P(-GUT+stat| **E2**) is close to zero for significant priors P(GUT) (informed by **E3**).
- Only the prior for unconceived explanation controls P(-GUT|**E2**).
- Precise GUT is boosted. If it starts from a prior similar to 1. and 2., it turns into the by far most probable option. If its prior is an order of magnitude smaller, it turns into an equal contender.
- SUSY gets boosted to an equal contender from one order of magnitude down.

The Impact of LHC: Higgs mass vs Naturalness

E8(+) Higgs boson was found at LHC with SUSY compatible mass

MSSM: m < 135 GeV; more generally: m<155GeV

The successful Higgs mass prediction of SUSY affects credence in correlation with the parameter spaces.

E9(-) No additional elementary particles discovered at the LHC.

Reducing parameter space for LE-SUSY decreases credence in correlation with its parameter space.

- Net effect depends on the balance between P(LE-SUSY) and P(ME-SUSY) (which also works for **E8**).
- LE-SUSY was “predicted” based on naturalness arguments.

? How strong does the naturalness argument favor LE-SUSY over ME-SUSY?

SUSY and Finetuning

The naturalness problem of the Higgs mass:

- The Higgs mass (100 GeV) is much lower than the Planck scale (10^{19} GeV).
- Heavy scalars would naturally pull the Higgs mass up to their mass scale through loop corrections. (=> Finetuning needed to get a low Higgs mass).
- Supersymmetry
  - would enforce a cancellation of quadratic terms.
  - Logarithmic terms would contribute proportionally to the difference between SM and SUSY mass terms.

⇒SUSY could solve the naturalness problem if SUSY masses are not much higher than the Higgs mass.

❖ The fact that SUSY has not been found pushes SUSY masses upwards and generates a FT problem even in the presence of SUSY.

Finetuning from a fully Bayesian perspective

- Let's assume:
  - Parameter v has values in the interval [0,1].
  - the measured value v is finetuned to a very small number (compared to naïve expectations from summing over many potentially large contributions).
  - H does not predict any value v.

=> The physicist's intuition says: a FT problem.

➢ In Bayesian terms, we have: $\frac{P(H|v)}{P(H)} = \frac{P(v|H)}{P(v)}$ $\quad P(v) = \sum_{n=1}^{N} P(H_n)P(v|H_n)$

➢ we have a FT problem if $P(H|v) \ll P(H)$.

➢ If the H_n–s don't favor any specific v on average, the P(v) is evenly distributed.

$\Rightarrow P(v|H) = P(v)$.

$\Rightarrow$ observing v does not generate a FT problem.

Finetuning from a fully Bayesian perspective:

A FT problem only arises if it is assumed *a priori* that there probably are credible theories that predict FT.

These theories then boost P(v) for finetuned v-s.

$\Rightarrow$ P(H|v)<<P(H) , which amounts to a FT problem.

$\Rightarrow$ FT generates a problem for the present theory only if one expects that credible future theories can explain it.

This has two important implications in the SUSY case.

P(v|H) becomes tricky.

- FT solutions can live at a scale different from the one where the FT problem arises.
  - Anthropic reasoning
  - Entirely different mechanisms?
- We always just assess the probability of a theory's viability at some scale.

$\Rightarrow$P(H) should be interpreted as addressing the viability at some scale rather than truth:
A theory that does not solve the FT can be a viable effective theory of a theory that does.

$\Rightarrow$P(v|H) must factor in the prospects of higher-scale theories that explain the FT.

$\Rightarrow$P(v|H) is higher than what it would be based on the direct predictions of H.

Severity of the FT problem decouples from severity of FT

⇒ The probability of higher-scale alternatives that can explain the FT cuts off the possible significance of a FT argument: No theory H can be discredited beyond the chance that FT can be explained by an unconceived alternative for which H is an effective theory.

⇒ In the absence of further low energy considerations, extreme FT is epistemically no more significant than moderate but significant FT.

⇒ What controls the strength of an argument of significant FT is not its magnitude but the confidence in ruling out alternatives that solve it at higher energies or in a different conceptual framework.

But the same argument also weakens moderate FT

The last point, however, opens up a basis for weakening the import of moderate FT as well:

- if one envisions mechanisms or conceptual ambiguities that might explain moderate but not huge FT, this may lead to a devaluation of moderate FT based on introducing a significant credence in those unconceived explanations.

⇒The differences between moderate and extreme FT then is decoupled from the numerical FT values and is fully controlled by the prior credences P(expl[moderateFT) and P(expl[extremeFT].

Conclusion

- Trustworthiness of GUT plays a core role in generating credence in LE- and ME-SUSY.

- Arguments favoring or disfavoring SUSY may seem stronger than they actually are when assessed in terms of comparing known low energy theories.
  - FT problems may look too powerful if they are judged in terms of the degree of FT.
  - Predictive success may look too significant if compared to the lack thereof in the considered alternative theory (such as the standard model).

- In the end, assessing a theory's prospects is a matter of evaluating prospects of related theories and all possible alternatives.
- Spelling this out does not decrease the differences in assessments but may make the roots of those differences more transparent.