Some Perspectives on the Standard Model

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Minimal dynamical symmetry breaking of the standard model

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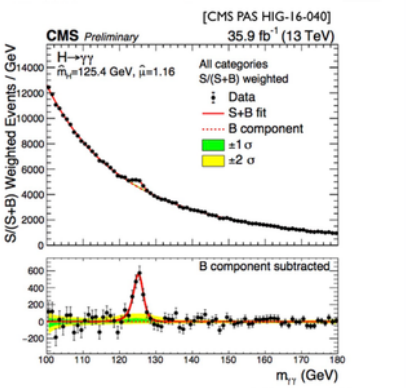
(Received 21 July 1989; revised manuscript received 2 November 1989)

We formulate the dynamical symmetry breaking of the standard model by a top-quark condensate in analogy with BCS theory. The low-energy effective Lagrangian is the usual standard model with supplemental relationships connecting masses of the top quark, W boson, and Higgs boson which now appears as a $\bar{t}\,t$ bound state. Precise predictions for m_t and m_H are obtained by abstracting the compositeness condition for the Higgs boson to boundary conditions on the renormalization-group equations for the full standard model at high energy.

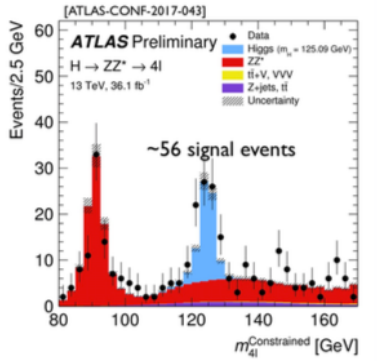
- Special role of top quark in electroweak symmetry breaking.
- Composite Higgs boson.
- Great idea − not chosen by nature.

- LHC Discovery of a light Higgs boson completes Standard Model

Behaving like a Higgs boson

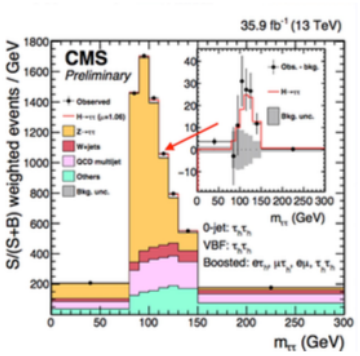


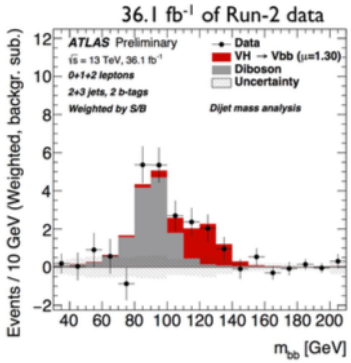
$\mu = 1.16^{+0.15}_{-0.14} = 1.16^{+0.11}_{-0.10}(\text{stat})^{+0.09}_{-0.08}(\text{exp})^{+0.06}_{-0.05}(\text{theo})$



$\mu = 1.28^{+0.18}_{-0.17}(\text{stat.})^{+0.08}_{-0.06}(\text{exp.})^{+0.08}_{-0.06}(\text{th.})$

Higgs gauge boson coupling well established.

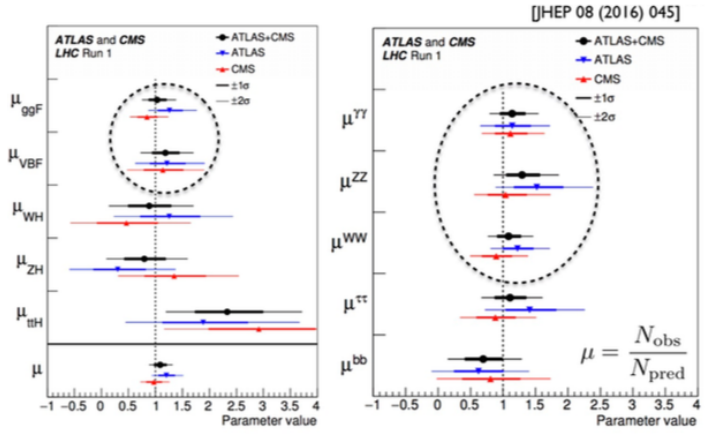




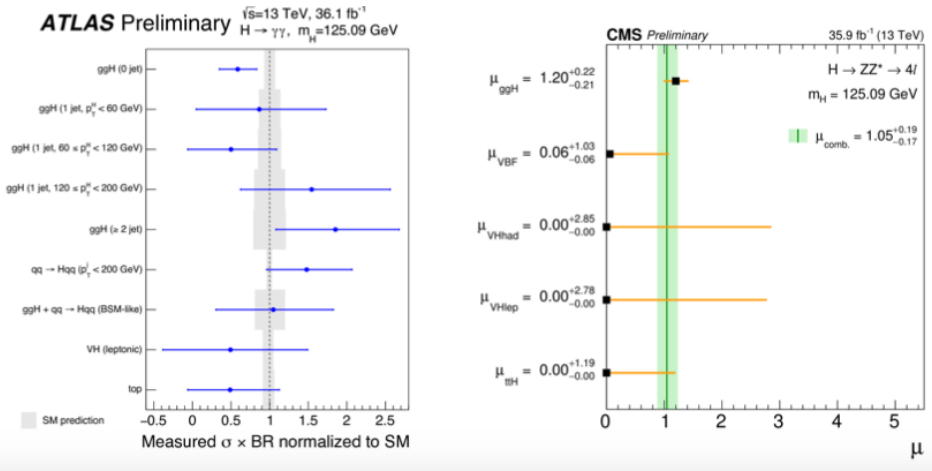
Started to see Higgs fermion coupling as well.

LP2017

Roughly agree with Standard Model



Agree to about 10-20%



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- Too light for composite state.
- Too heavy for vanilla SUSY.

- Elementary Higgs boson – a Theorist's nightmare
  - Big hierarchy problem – $V_{ew}/M_{planck} \sim 10^{-18}$.
  - Little hierarchy problem – $m_{top}/E_{LHC} \sim 10^{-2}$.
  - Yukawa hierarchy – $m_{electron}/m_{top} \sim 10^{-8}$, $m_{neutrino}/m_{top} \sim 10^{-14}$.
  - Strong CP Problem – theta angle $< 10^{-10}$.
  - Baryon asymmetry – baryon/photon $\sim 10^{-9}$.
  - Grand Unification.
  - Dark Matter.
  - Dark Energy, Inflation.
  - Quantum gravity.

- Focus on the physics of the Standard Model

On Naturalness in the Standard Model

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A talk presented at the 1995 Ontake
Summer Institute, Ontake Mountain, Japan
August 27-September 2, 1995

ABSTRACT

The question of the naturality of the Standard Model of the electroweak interactions is discussed. In the context of perturbation theory, the classical scale invariance of the theory implies naturalness condition on the Higgs mass counterterms and a possible explanation of the electroweak scale.

- Classical Standard Model and Scale Symmetry

$$L = \bar{q}\gamma Dq + \bar{l}\,\gamma Dl + [DH]^2$$

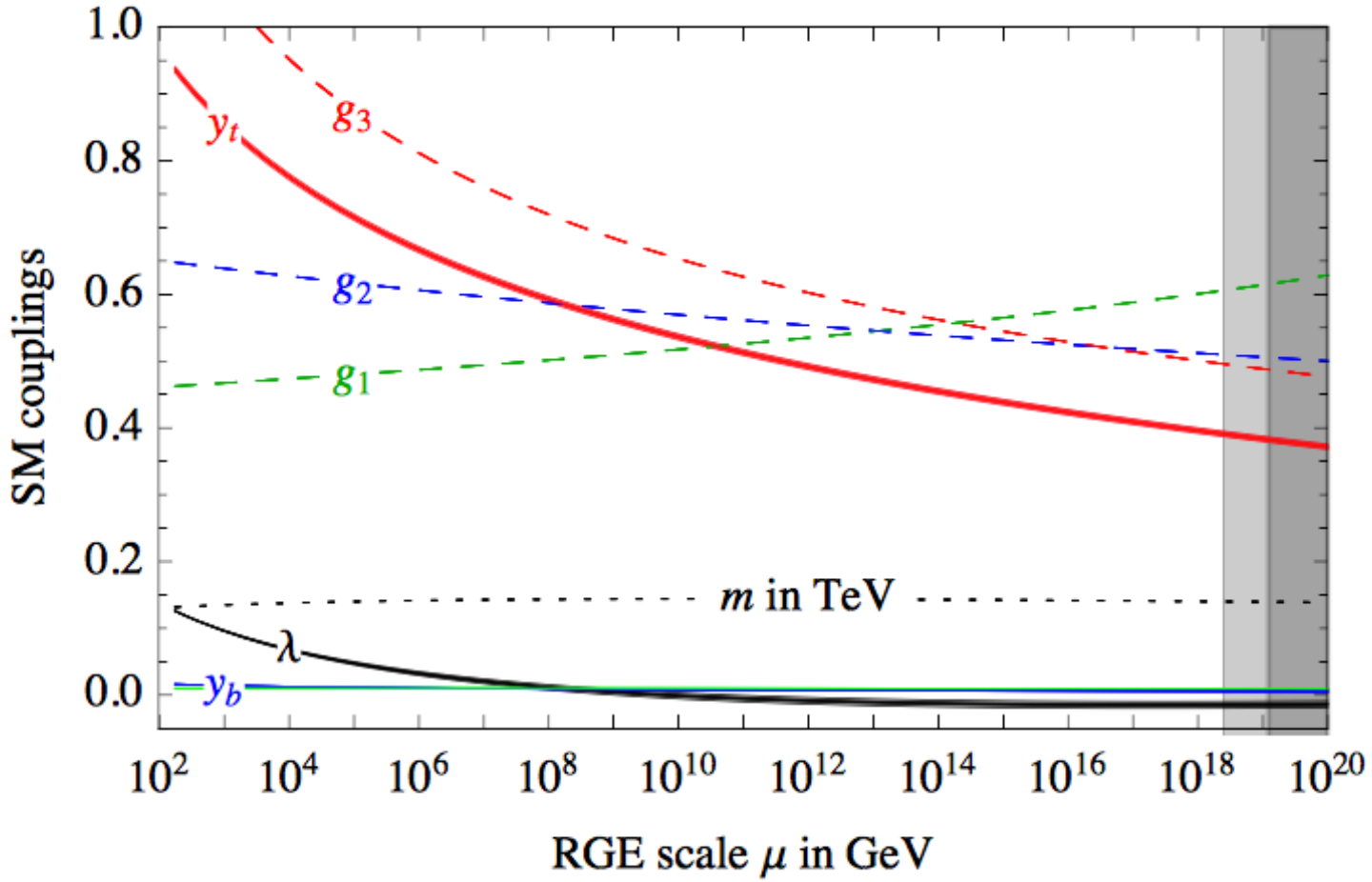
$$-\bar{q}_L G_u H u_R - \bar{q}_L G_d \tilde{H} u_R - \bar{l}_L G_l \tilde{H} l_R - \bar{l}_L G_\nu H \nu_R$$

  - Includes SM gauge interactions and Yukawa couplings for quarks, leptons and right-handed neutrinos.
  - Classical shift symmetry allows Higgs VeV, V_{ew}.
  - All particles, except the Higgs, have masses ~ V_{ew}*couplings.
  - Higgs is massless – a dilaton.
  - No scale theory, V_{ew} arbitrary – a dynamical scale.
  - Addition of Higgs potential breaks scale symmetry, Higgs is massive.

- Quantum Standard Model

  - Renormalization of Higgs Potential generates a single fundamental dimensional scale, V_{ew}.
  - All masses, including the Higgs boson mass, are ~ V_{ew}*couplings.
  - Coupling constants are renormalized and run with scale.
  - But - does dimensional transmutation generate new physical scales from the running couplings?
  - Coupling evolution is determined from beta-functions of the SM.
  - Explore by evolving couplings from their values at the physical electroweak scale by varying the effective electroweak scale - corresponds to varying the fundamental dimensional scale, V_{ew}, for a fixed theory.

• Ultraviolet running of the Standard Model couplings



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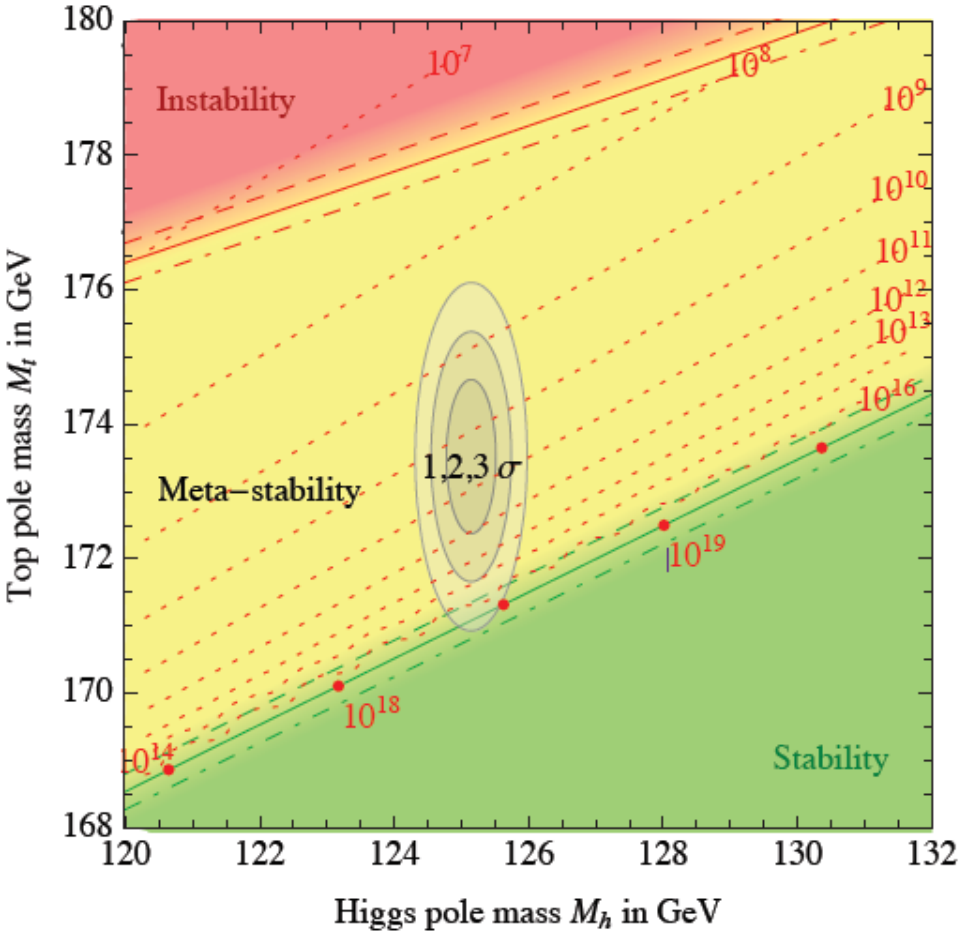
- Observe possible metastability of the Higgs coupling



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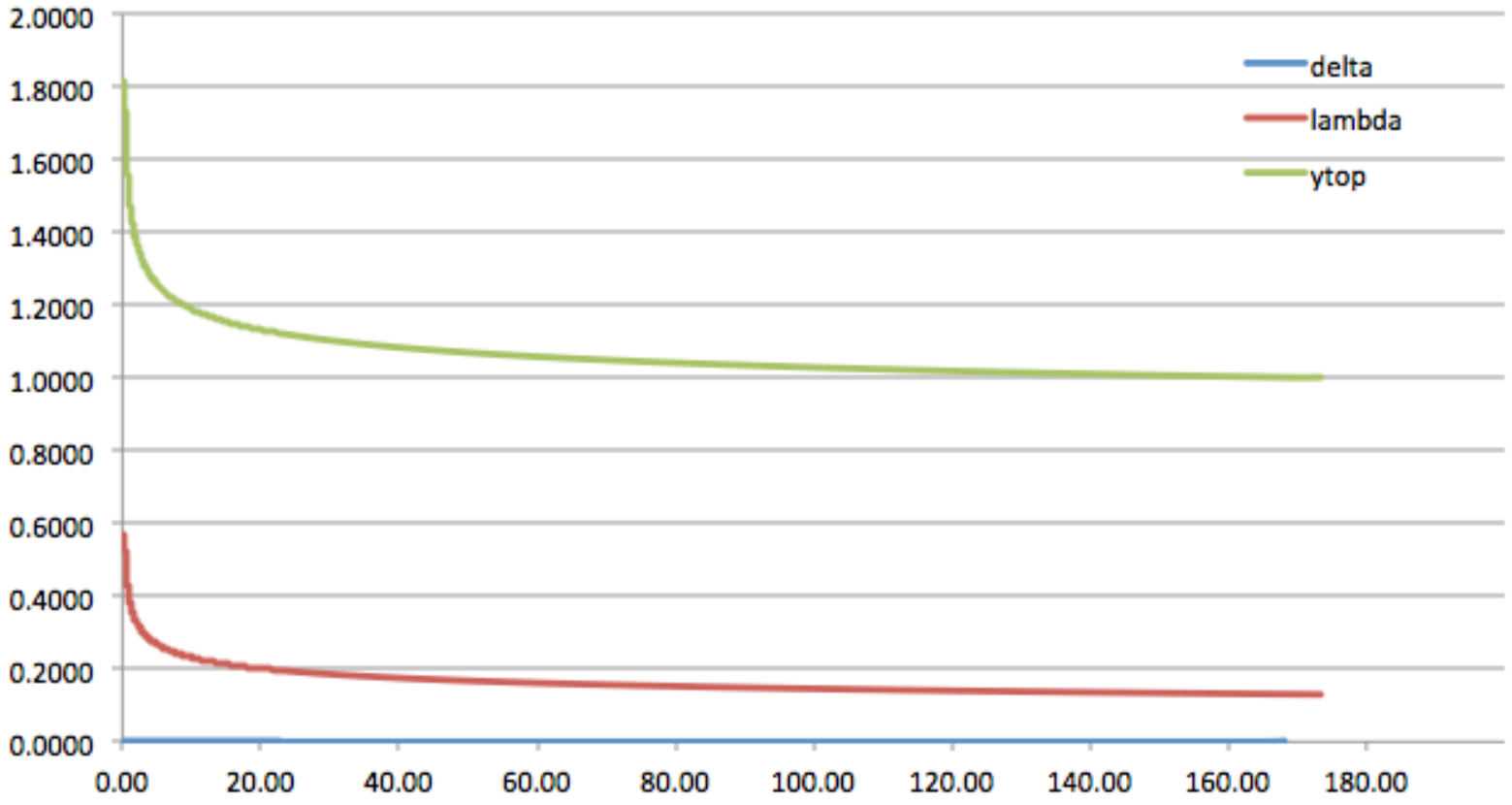
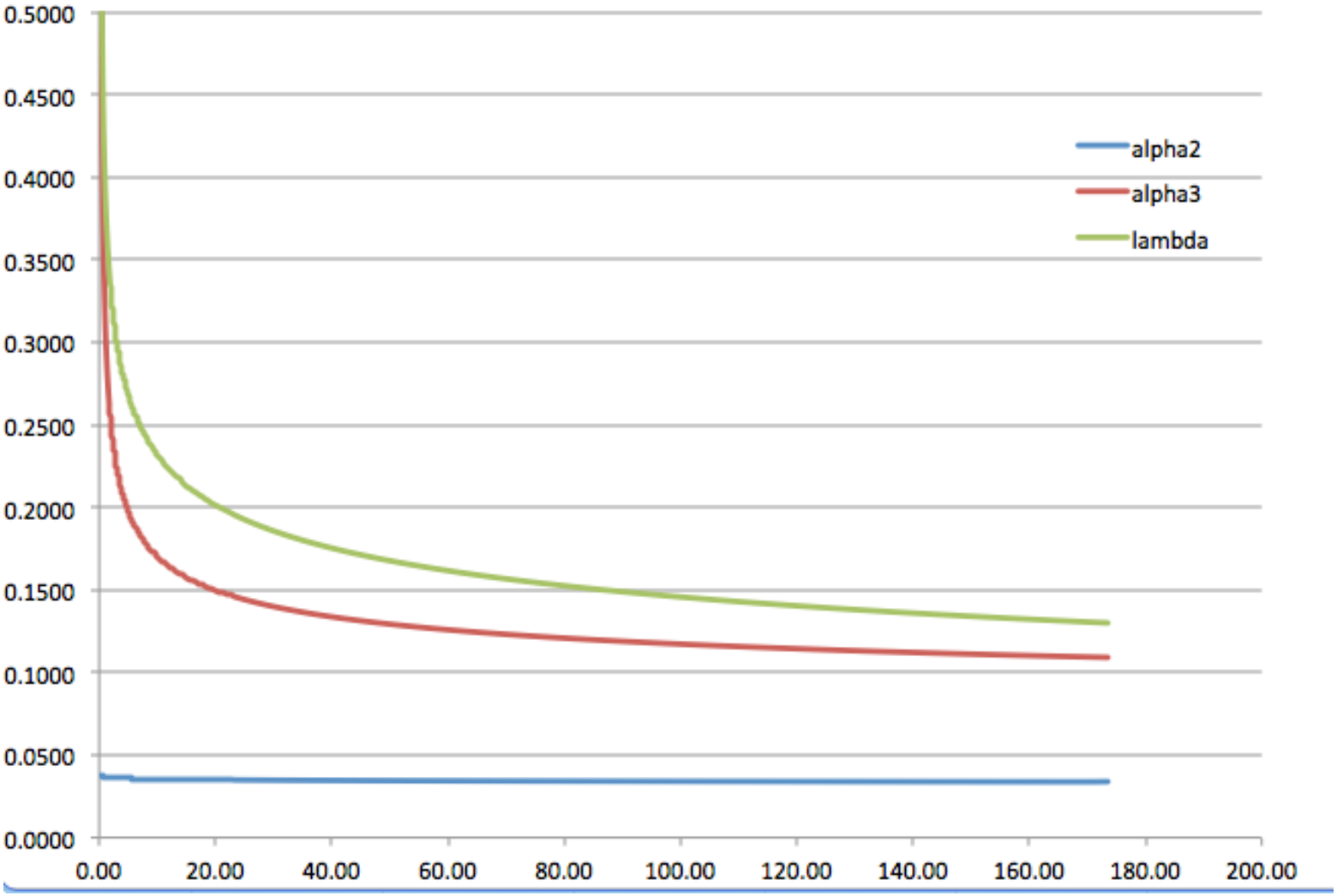
- Remarkably smooth ultraviolet running of all couplings.
- All couplings decreasing in UV except smallest U(1) coupling.
- Conspiracy of beta-functions.
  - Higgs coupling – top loops dominate boson loops.
  - Top Yukawa – gauge boson corrections dominate Yukawa.
  - QCD coupling – boson loops dominate fermion loops.
  - SU(2) coupling – boson loops dominate fermion loops.
  - U(1) coupling – small, growing slowly below Planck scale.

• Infared running of the top Yukawa and Higgs couplings



• No apparent new strong scale above the QCD scale.

- Infrared running of the gauge and top couplings



- Summary

  - No indication of new physical scales within the pure Standard Model – except for infrared scales such as QCD.

  - Metastability may be an indicator of new physics or missing degrees of freedom coupled to the Higgs boson.

  - Dark Matter, flavor structure, or other physics may require embedding the SM in a more complete theory which could have additional issues for the hierarchy problem, etc, that are not visible in the Standard Model physics.

  - Neutrino masses may require new physics if the seesaw model is correct with new Majorana mass scales.

  - perhaps BHL ideas could apply to the generation of the physics of the Majorana mass scale instead of the electroweak scale.

Happy Birthday Manfred

Best Wishes

Marge and Bill