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FOLLOWING IN TINI'S GIANT FOOTSTEPS[*] [**]

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This paper describes my personal appreciation of some of Tini Veltman's great research achievements and how my own research career has followed the pathways he opened. Among the topics where he has been the most influential have been the pursuit and study of the Higgs boson and the calculation of radiative corrections that enabled the masses of the top quark and the Higgs boson to be predicted ahead of their discoveries. The search for physics beyond the Standard Model may require a complementary approach, such as the search for non-renormalizable interactions via the Standard Model Effective Field Theory.

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1. Introduction

It is an honour to have been offered the opportunity to contribute to this memorial volume celebrating Martinus (Tini, as he was generally known) Veltman, particularly because he was one of my scientific heroes. In addition to his personal scientific research, he played a central role in putting Dutch theoretical particle physics on the international map (think Gerard 't Hooft, Bernard De Wit, Peter van Nieuwenhuizen and many others), pioneered the development of computer algebra with his SCHOONSCHIP programme, and was a key early supporter of the LEP accelerator. Moreover, beneath his occasionally idiosyncratic and outspoken exterior lurked a fiercely independent thinker with empathy for young theorists whose work he appreciated, as well as for the experimentalists whose work he encouraged.

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2. Renormalization

Tini's main scientific achievement was of course the demonstration (together with 't Hooft) how spontaneously-broken non-Abelian gauge theories could be renormalized [1–4], and my main scientific contacts with Tini resulted from my own research work pursuing corollaries of that work. It is worth remembering that Tini's most consequential work was done somewhat in the wilderness, struggling tirelessly with a problem that most theorists disregarded: "sweeping an odd corner of weak interactions" as he reported being told by Sidney Coleman [5]. For one thing, quantum field theory, in general, was unfashionable for much of the 1960s, as causality, analyticity and the S-matrix held sway. For another, very few theorists could see the interest in non-Abelian gauge theories. Significant progress had been made by Feynman, DeWitt, Faddeev and Popov in formulating massless non-Abelian theories at the quantum level, but nobody understood how to renormalize them if the gauge bosons were massive, and obtain sensible, finite results.

Many suggested that massive gauge vector bosons were the likely mediators of the weak interactions, once the $\mathrm{V}-\mathrm{A}$ structure of their effective four-fermion interaction was established experimentally. Among the proposals was Glashow's proposal in 1961 [6] of the $\mathrm{SU}(2)\times\mathrm{U}(1)$ structure of the electroweak sector of the Standard Model, in which he simply postulated masses for such bosons without concerning himself with their origins, nor the renormalizability of his model. Some years later, in 1967, Salam [7] and Weinberg [8] revived his model with the suggestion that their masses might arise from spontaneous symmetry breaking, using the mechanism that had been proposed back in 1964 by Higgs [9], Englert and Brout [10], and Kibble [11]. They did not attempt to prove that the Standard Model was renormalizable, though apparently, Weinberg suspected that it might be, and set a student to trying (unsuccessfully) to prove it. The numbers of citations of these papers were minuscule until the papers of Tini and 't Hooft showed how to renormalize and obtain finite results from spontaneously-broken gauge theories.

3. The Higgs boson

These papers triggered a tsunami of theoretical interest, joined by experimental interest following the discovery of neutral currents in 1973 [12] and charmonium in 1974 [13]. Mainstream efforts started targeting the discovery of the massive electroweak gauge bosons, but that was not the priority for Mary Gaillard, Dimitri Nanopoulos and myself. We reasoned that the key element in the whole theoretical edifice of the Standard Model was the Higgs–Englert–Brout mechanism for spontaneous gauge symmetry breaking, and the existence of the physical scalar boson predicted by Higgs [9] (who had also considered several of its physical properties [14]). This was why we set out to write our paper on the phenomenological profile of the Higgs boson [15]. Since we were aware that we were out on what was considered by most senior theorists in those days to be quite a hypothetical limb, we ended our paper by saying (tongues somewhat in cheek) that "we [did] not want to encourage big experimental searches for the Higgs boson".

However, Tini was supportive of our efforts. I remember giving a talk on Higgs phenomenology at a gauge theory workshop at the École Normale in Paris in early 1976 about our paper. The reception was generally tepid, but Tini was very positive about it. There had been only a handful of papers before ours on signatures of the Higgs boson, and nobody had a clue what its mass might be. Tini had already worked on this problem [16], arguing that a very small Higgs mass would be incompatible with cosmology, and this problem continued to be one of his principal theoretical interests in the following years [5]. In particular, he was one of the first to point out that a massive Higgs boson would necessarily be strongly-interacting, and to argue that this imposed a qualitative upper limit on its mass of a few hundred GeV [17], at which stage it would become strongly-interacting and some low-mass bound states might emerge[1].

The renormalizability of the Standard Model is a joint effort of all its particles: remove any of them and uncontrollable infinities appear. This is reflected in the growths of their quantum loop contributions to physical quantities as their masses increase, which may be either quadratic or logarithmic. Tini was a pioneer in exploring these renormalization effects, and how they would affect physical observables. He considered these questions in [17], showing that quadratic dependences on heavy-particle masses are the general rule, but the one-loop effects of the Higgs boson in the Standard Model increase only logarithmically with its mass, because of the screening effects of a custodial symmetry in the Higgs sector (see [20] for a later discussion). Tini went on to discuss the quadratic mass dependences of one-loop corrections to vector boson masses in [21] imposed an upper limit of several hundred GeV on mass differences within a fermion multiplet.

These pioneering papers were followed by a stream of calculations of one-loop corrections to various specific electroweak processes, paying particular attention to their sensitivities to the Higgs mass. These included the violation of μ–e universality in lepton–hadron interactions [22] (very topical at the moment! [23, 24]); the processes $e^+e^- \to \mu^+\mu^-$ [25] (with Giampiero Passarino) and $e^+e^- \to W^+W^-$ [26] (with Michel Lemoine); vector–boson masses [27]; and low-energy processes [28] (with Martin Green). Somewhat later, Tini made a heroic calculation of two-loop corrections to the ratio of

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[1] The upper limit on the Higgs mass was also discussed in [18, 19].

W and Z masses (the ρ parameter) [29] (with Jochum van der Bij), showing that they are quadratically sensitive to the Higgs mass. On this basis, Tini and Jochum argued that perturbation theory would breakdown for a Higgs mass > 3 TeV. These pioneering calculations played key roles in the subsequent predictions of the top and Higgs masses on the basis of high-precision LEP data, as discussed below.

Tini was also one of the first to worry about the quadratic divergences in the quantum corrections to the Higgs mass, considering the possibility of cancellations between fermion and boson loops [30]. In particular, he considered the possibility of cancelling the top-quark contribution with those of the massive vector and Higgs bosons in the Standard Model, and also mentioned the possibility of supersymmetry. However, he was never strongly enamoured of it, although it is the most systematic realization of his idea. (It remains to be seen whether Nature likes it!)

In parallel to his theoretical work during this period, Tini was a member of the CERN Scientific Policy Committee, where he was an enthusiastic advocate of the construction of LEP. This project grew out of a paper written by Burt Richter while he was on sabbatical at CERN in the academic year 1975/6 [31], in which he analysed the possible scaling up of circular e^+e^- colliders from the few GeV of those operating at the time to a machine with beams of energy ~ 100 GeV each. Mary Gaillard and I were tasked with writing the theoretical section of the first LEP physics study, which was published in 1976 [32]. In addition to precise experiments at the Z peak and measurements of W^+W^- production, we highlighted the importance of searching for the Higgs boson, *e.g.*, via its production in association with a Z boson. Tini supported strongly this physics programme, and pushed for LEP to have the largest size compatible with CERN's cramped geographical surroundings, so as to reach the highest centre-of-mass energy possible. This foresight also maximized the real estate available for the later construction of the LHC, where the Higgs boson was finally discovered.

4. Radiative corrections

During the 1980s, there was a sustained theoretical campaign to make and refine calculations of quantum corrections to many physical quantities that were to be measured at LEP. These made manifest the top and Higgs mass dependences that had been foreshadowed by Tini in his pioneering calculations. These theoretical contributions were gathered and reviewed in a series of CERN reports [33–36], where they were presented in an experimentalist-friendly way.

Meanwhile, many low-energy experiments were providing a growing array of constraints on the electroweak sector of the Standard Model, particularly on the neutral-current interactions. Towards the end of the 1980s, they were sufficiently precise to be sensitive to quantum loop corrections, and in 1987 it became possible [37, 38] to constrain the top-quark mass through the quadratic quantum effects that Tini had pointed out. We found an upper limit on its mass similar to the value that was subsequently measured experimentally [39]. We also pointed out that it would also be possible to establish a lower bound on m_t once the Z mass was measured accurately [40], which was done by the CDF experiment at Fermilab, SLC and LEP in 1989. However, these data were not yet accurate enough to provide any useful information about the mass of the Higgs boson [41], whose effects were suppressed by Tini's screening theorem.

During the following few years, LEP (and SLC) produced many more high-precision electroweak measurements, and the net around the top-quark mass drew tighter, enabling it to be estimated with $\sim 10\%$ accuracy [42]. The plethora of LEP measurements also provided the first indications on the possible mass of the Higgs boson, indicating that it probably weighed < 300 GeV [43]. The first direct evidence for the top quark came in 1994 [44], and in 1995 it became strong enough to claim discovery [45]. The measured mass was quite consistent with the indirect estimate based on Tini's loop corrections. Moreover, the combination of the direct measurement with the high-precision electroweak data made it possible to refine the estimate of the Higgs mass [46].

The Nobel Physics Prize was awarded to Tini and Gerard 't Hooft in 1999. To quote the Nobel citation: "They showed that the non-Abelian quantum field theories could make sense and provided a method for computing quantum corrections in these theories . . . the mass of the top quark could be predicted, using high precision data from the accelerator LEP . . . several years before it was discovered".

The story did not end there. The direct search for the Higgs boson had evolved from a minority interest [15], supported enthusiastically by Tini, into a central theme of the LEP experimental programme [32, 35, 36]. However, searches at LEP were ultimately unsuccessful, constraining its mass to be > 114 GeV [47]. The torch was then passed to Fermilab, where unsuccessful searches excluded a range of masses around 160 GeV [48]. A global analysis of the combined direct and indirect information of the mass of the Higgs boson in 2011 quoted the 68% mass range $m_H = 120^{+12}_{-5}$ GeV [49]. Finally, in 2012 the Higgs boson was discovered, with a mass of 125 GeV and an uncertainty < 200 MeV [50]. This provided the final experimental vindication of Tini's proof of the renormalizability of spontaneously-broken gauge theory, his obsession with the Higgs boson, and his calculations of quantum loop corrections.

5. What next?

And the story continues. On the one hand, high-energy measurements at the LHC continue obstinately to agree with the Standard Model, in particular those of the production mechanisms and decays of the Higgs boson. On the other hand, every term in its effective Lagrangian

$$\mathcal{L} \ni \; yH\bar{\psi}\psi + \mu^2|H|^2 - \lambda|H|^4 - V_0 + \ldots \tag{1}$$

poses a theoretical mystery. The pattern of Yukawa couplings y is the flavour problem of the Standard Model, to which recent LHCb measurements [23] have added. While the Higgs can be responsible for the masses and mixings of fundamental matter fermions, it does not explain their magnitudes. The magnitude of the mass term μ raises the notorious naturalness/hierarchy problem: why is it not of the same order of magnitude as the quantum loop corrections that Tini strove to cancel? The magnitude of the quartic coupling λ corresponding to the measured values of the Higgs vacuum expectation value (v.e.v.) and m_h is so small that it is probably driven negative at high renormalization scales by radiative corrections due to the top quark [51], in which case the present electroweak vacuum would not be stable, and how the Higgs evolved to reach its observed v.e.v. would pose a cosmological puzzle [52]. The constant term V_0 corresponds to the cosmological constant (a.k.a. dark energy). It is measured to be $\mathcal{O}(\mathrm{meV})^3$, which is far smaller, *e.g.*, than the difference in the vacuum energy between the local maximum of the Higgs potential at the origin and its present-day value after sinking into its v.e.v. [53], or the shift induced by non-perturbative QCD effects[2]. Finally, there could be additional terms represented by the $\ldots$, of higher order in the Higgs and other Standard Model fields. These would not be renormalizable in the same sense as the Standard Model, as proved by Tini and 't Hooft, but they could appear as terms in a low-energy effective field theory when massive particles in some renormalizable extension of the Standard Model are integrated out.

The possibilities for such terms are taken into account systematically by the Standard Model Effective Field Theory (SMEFT) [54], which includes all operators of dimensions $d \geq 5$ that are invariant under the Standard Model gauge group and composed of Standard Model fields with their conventional quantum numbers

$$\mathcal{L}_{\mathrm{SMEFT}} = \sum_{i:d\geq 5} \frac{C_i}{\Lambda_i^{d-4}} \mathcal{O}_i \,, \tag{2}$$

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[2] I remember having inconclusive discussions about the magnitude of the cosmological constant with Tini in early 1976. To my mind, the problem is not that it exists, but that it is so small.

where the Λ_i are mass scales characteristic of the new physics generating the operators $\mathcal{O}_i$ with coefficients C_i. The operators of dimension 5 in the SMEFT can generate neutrino masses, but are not of interest to us here. There are in general 2499 operators of dimension 6, many of which could in principle contribute to cross sections measured at the LHC and are constrained by LHC measurements, as well as measurements of Higgs decays and high-precision electroweak measurements at LEP and elsewhere. If we could discover SMEFT interactions with dimension $\geq$ 6 and disentangle their structure, we would have clues to physics beyond the Standard Model, just as the V $-$ A structure of the weak interactions led us towards Tini's giant footsteps.

We have recently performed a global analysis of the constraints on dimension-6 operators provided by all the available data, making simplifying assumptions about their flavour structure, specifically that operators including fermions have flavour-universal coefficients, apart possibly from those involving the top quark [55]. Switching on individually the 34 dimension-6 operators in a top-specific scenario with $\mathrm{SU}(2)^2 \times \mathrm{SU}(3)^3$ symmetry, we see in Fig. 1 that the operator scales range between a few hundred GeV and $\sim$ 20 TeV if their coefficients $C_i = 1$.

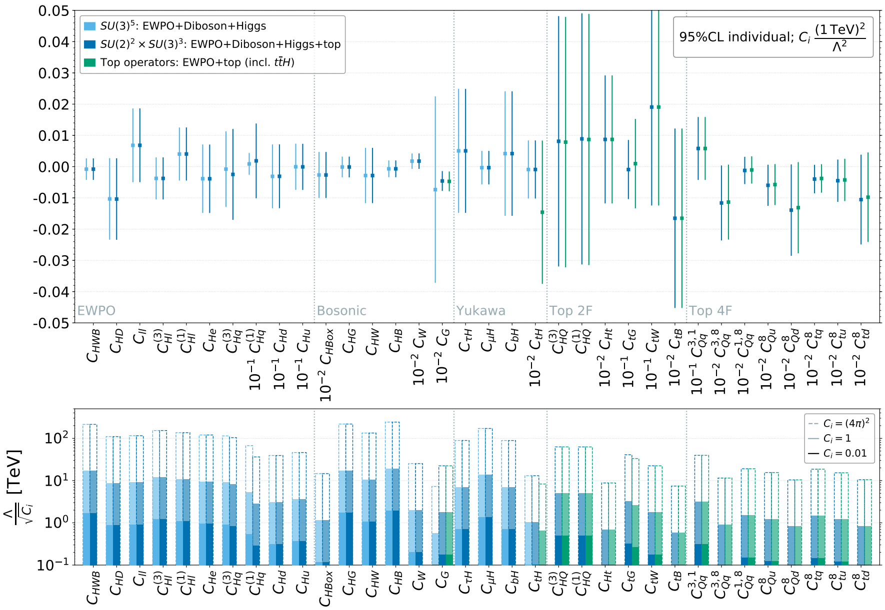

Fig. 1. Results from a global fit [55] to the electroweak, diboson, Higgs and top data in a top-specific scenario with $\mathrm{SU}(2)^2 \times \mathrm{SU}(3)^3$ symmetry [55]. The two panels show results for fits to 34 individual dimension-6 operators, showing the 95% C.L. ranges for the operator coefficients C_i normalising all the new physics scales Λ_i to 1 TeV, and the ranges for the scales Λ_i for different universal values of the C_i.

Searching for possible indications of new physics beyond the Standard Model, we have considered all the single-field extensions of the Standard Model catalogued in [56], and the corresponding mass limits (in TeV) at the 95% C.L. and upper limits on couplings assuming masses of 1 TeV are shown in Fig. 2. As shown also, there are no significant pulls in the fit that might indicate the presence of some new physics.

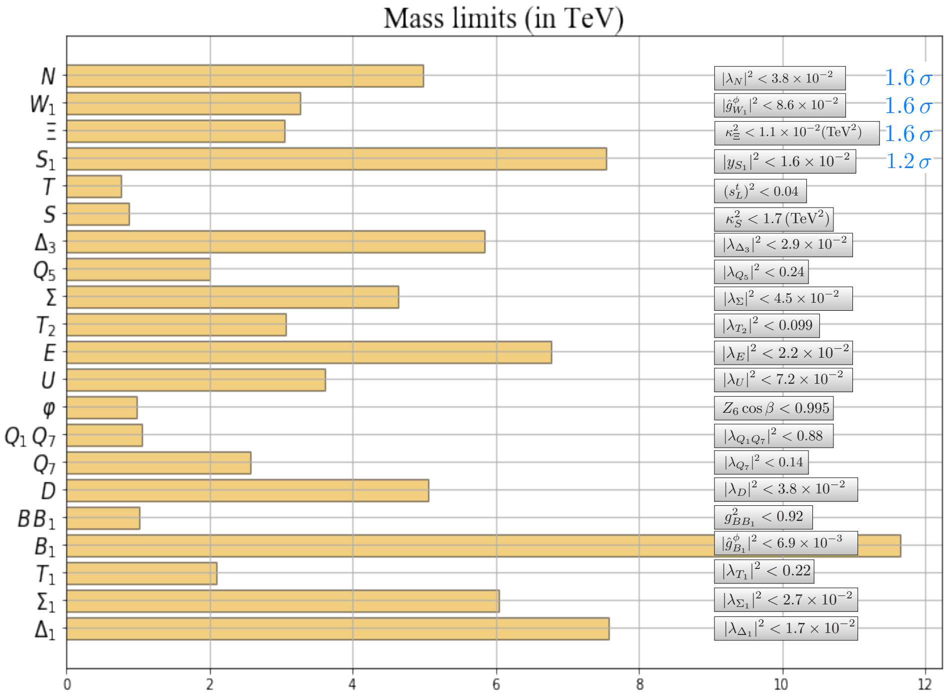

Fig. 2. The yellow bars show the mass limits (in TeV) at the 95% C.L. for the single-field extensions of the Standard Model catalogued in [55], setting the corresponding couplings to unity. The grey boxes contain the coupling limits obtained when setting the mass to 1 TeV, and the numbers in light blue are the pulls in the fit that exceed 1-σ.

These results indicate that there is a non-trivial hierarchy of mass scales between the particles of the Standard Model and whatever might appear at higher energies. As mentioned earlier, Tini was concerned about the quadratic divergence in the mass of the Higgs boson that appears in the Standard Model, and speculated how to cancel it. One possibility that has attracted much attention over the years is supersymmetry (though Tini did not pursue it). Since the Standard Model is renormalizable by itself, and supersymmetry is an add-on, its contributions to low-energy measurements via loop diagrams do not grow with the supersymmetry mass scale, and are difficult to constrain via precision measurements. Indeed, global analyses of LEP and LHC data using either exact calculations of supersymmetric radiative corrections [57] or the SMEFT approach are quite consistent with the lightest supersymmetric particles, such as the lighter stop squark, weighing just a few hundred GeV [55], as seen in Fig. 3.

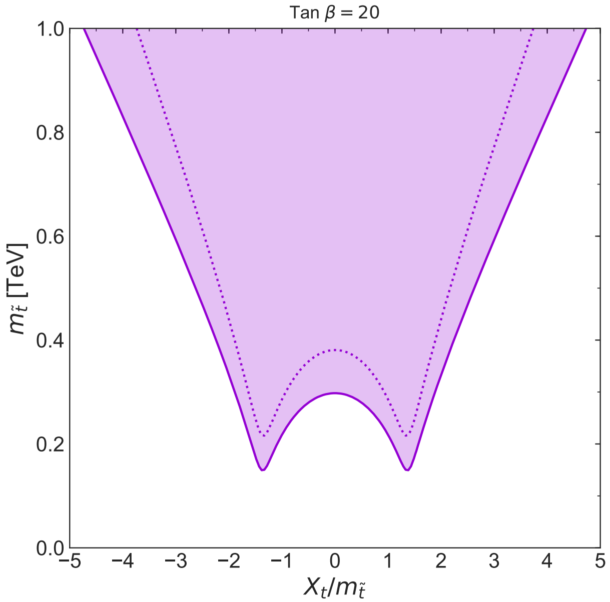

Fig. 3. Limits found in the global fit [55] on the mass of the lighter stop squark, $m_{\tilde{t}}$, and the stop mixing parameter, $\frac{X_t}{m_{\tilde{t}}}$, for one value of the ratio of supersymmetric Higgs vacuum expectation values, $\tan\beta = 20$.

In general, supersymmetric particles may contribute to several SMEFT coefficients, and the same holds for many other possible extensions of the Standard Model. Accordingly, we performed [55] a general survey of all possible extensions that contribute to 2, 3, 4 or 5 SMEFT coefficients, as seen in Fig. 4, which shows the distributions of pulls found in three categories of SMEFT operators: those that include only operators that affect $t\bar{t}$ production (blue), those that do not include operators that affect $t\bar{t}$ production (orange), and the rest (green). So far, we see no significant evidence for possible physics beyond the Standard Model.

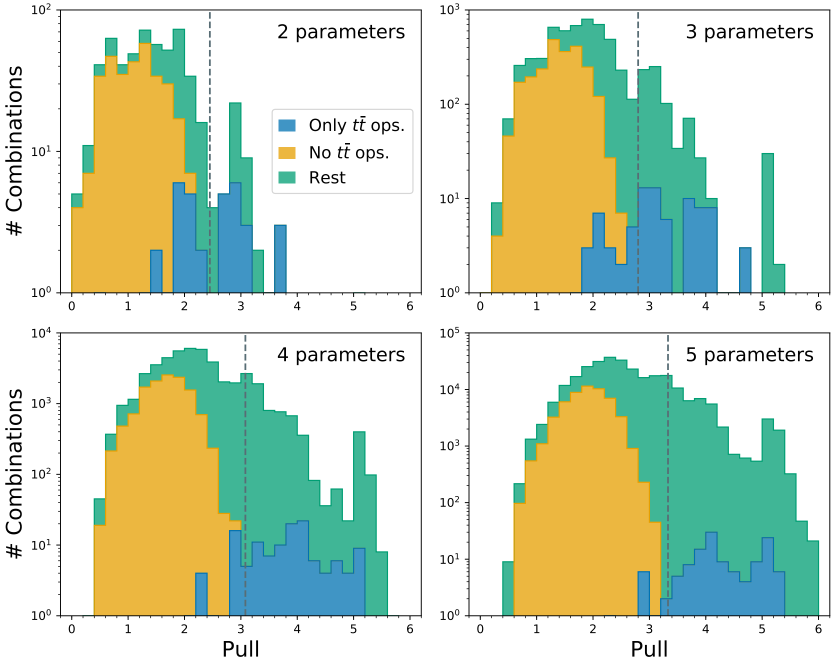

Fig. 4. The distributions of pulls found [55] in global fits to 2 (upper left), 3 (upper right), 4 (lower left) and 5 (lower right) parameter subsets of operators, which have been split into three categories: those including only operators that affect $t\bar{t}$ production (blue), those without any operators that affect $t\bar{t}$ production (orange), and the rest (green). The dashed vertical lines mark the ranges for the pull distributions expected at the 95% confidence level.

6. Reflections

What would Tini make of the current situation in particle physics? On the one hand, he would be justifiably proud of the robust successes of the Standard Model that did so much to place on a firm footing. On the other hand, some of the problems that concerned him remain unresolved, notably the quadratic instability in the mass of the Higgs boson and the magnitude of the dark energy (cosmological constant). What would he think of the experimental anomalies involving muons that have been strengthened recently [23, 24]? My suspicion is that he would not yet be convinced, if only because they do not have any obvious bearing on his theoretical preoccupations. My hunch is that Tini would continue to focus his energies on the manifold problems associated with the Higgs boson that he did so much to promote to theoretical respectability and experimental reality.

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