HOMAGE TO MARTINUS VELTMAN AND THE STANDARD MODEL*

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LEP established the Standard Model as a renormalizable quantum field theory with unprecedented precision. I take a personal and incomplete look back to that time and the impact Tini Veltman had on this exciting endeavour.

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The Standard Model of Particle Physics describes the visible matter in our Universe, the elementary particles, in a beautiful way, along with their interactions. It evolved through a combined effort by thousands of theorists and experimentalists over more than five decades. Its progress, both experimental and theoretical, spans the working lifetimes of many particle physicists: the Standard Model has determined the course of their scientific lives. More than thirty Nobel prizes acknowledge the individual and collaborative efforts that have contributed decisively to the establishment of this fantastic scientific edifice.

This special volume of *Acta Physica Polonica B* celebrates the contribution of one of those Nobel laureates, Martinus, 'Tini', Veltman. Over the years, I had the pleasure to meet Tini from time to time, first as a young physicist at a physics school in the mid-70s, and most recently at the Lindau Nobel Laureate meeting in 2019. I always admired his sharp reasoning, his clear and outspoken opinions, and not forgetting his wry sense of humour.

Since other contributions to this volume describe Tini's many achievements in and for theoretical particle physics in detail, I will give just a short and incomplete snapshot of his accomplishments that I consider most essential for the research at CERN. First and foremost, of course, comes his

* Contribution to the special volume of *Acta Physica Polonica B* commemorating Martinus Veltman.

pioneering work with Gerard 't Hooft that established the renormalizability of the electroweak theory, work for which they received the Nobel Prize 1999. The citation refers to ' ... the quantum structure of electroweak interactions ... ' but their work enabled a complete picture of the renormalizability of Yang–Mills theories to be derived, thereby bringing in QCD as an integral part of the Standard Model.

Tini's development of a computer program, a general-purpose symbolic manipulation program, paved the way for the calculation of Feynman diagrams, essential for precision calculations of Standard Model processes. I cannot resist quoting from his Nobel lecture in 1999 [1]: "I called the program SCHOONSCHIP, among others to annoy everybody not Dutch. The name means "clean ship", and it is a Dutch naval expression referring to clearing up completely a messy situation." Considering the many terms to be handled in such calculations, it certainly did.

I also want to mention his work on higher-order electroweak corrections, in particular the work on the ρ parameter, the square of the ratio of the charged vector-boson mass to the neutral vector-boson mass, with a correction related to weak mixing. This parameter has become an important part of today's physics, because it is the most sensitive to radiative effects of heavy particles, quarks or Higgs.

These ground-breaking efforts allowed particle physicists, theorists as well as experimentalists, to embark on precision calculations and precision tests of the Standard Model. The right machine for the experiments became the electron–positron collider, LEP.

Before discussing LEP, however, let me go back to the years before LEP started, to the electron–positron collider PETRA at DESY. The charge asymmetry in $e^+ + e^- \to \mu^+ + \mu^-$ was first established at the beginning of the 80s at PETRA in a statistically significant way at a centre-of-mass energy of 34 GeV, see, for example, [2] and references therein. There was excellent agreement with the prediction of the electroweak theory, which includes the $\gamma - Z$ interference. This measurement allowed tight constraints on the mass of the Z to be obtained shortly before its observation at the SPS. Figure 1, displaying the muon charge asymmetry over the energy range from PEP/PETRA to TRISTAN and LEP I (90 GeV), beautifully shows the effect from heavy particles not yet producible directly.

During the years 1976 to 1980, Tini Veltman was a member of the Scientific Policy Committee (SPC) of CERN. These were decisive years in the preparation for the approval of LEP, which came in 1981 during the mandate of Herwig Schopper. During that time, the parameters of the collider were intensively discussed, and Tini was a strong advocate of the highest possible (and affordable) energy of the collider, to allow precision tests of the Standard Model at, and well beyond, the W-pair production threshold.

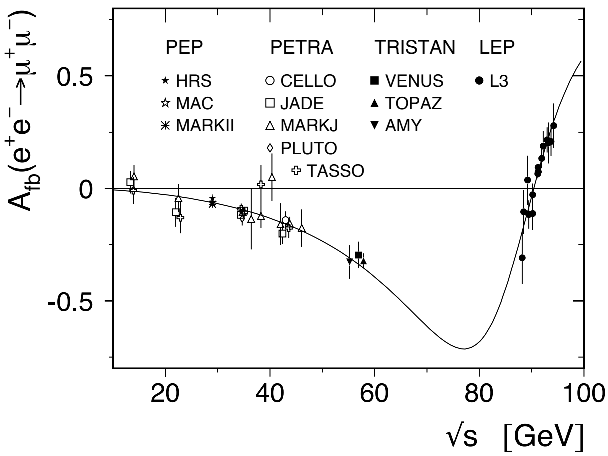

Fig. 1. Forward–backward charge asymmetry for $e^+ + e^- \to \mu^+ + \mu^-$. Away from the resonance the interference term dominates (Ref. [3], reused with permission from the author).

With LEP starting to deliver data in 1989, a new era in high-energy physics began. The analysis of the data delivered in the machine's 11 years of running at energies up to 209 GeV allowed stringent tests of Standard Model predictions, in some cases even to the sub-permille level, as summarized in the publication on precision electroweak measurements on the Z-resonance [4].

This publication is remarkable not only from the point of view of the wealth of scientific results it contains, but also from the collaborative aspect. It presents combinations of published results from all four LEP experiments at CERN and from SLD at SLAC, signed by more than 2500 authors. It sent a strong message that progress in science comes not only through competition, but also through cooperation.

Two results should serve as examples of the precision achieved through this combined effort:

— the mass of the Z-resonance was determined to $m_Z = 91.1875 \pm 0.0021$ GeV,

— and the number of light neutrinos, and therefore the number of generations, to $n_\nu = 2.9840 \pm 0.0082$ GeV.

The results from the measurements at LEP energies above the Z-resonance (LEP II) can be found in the publication on electroweak measurements at W-boson-pair energies [5], which presents the combination of results from the four LEP experiments, again a remarkable collaborative achievement.

To give just one example: at LEP II the mass of the W-boson was determined to an accuracy of 0.4‰ as $m_W = 80.376 \pm 0.033$ GeV.

W-pair production at LEP II energies allowed the self-coupling of the gauge bosons to be investigated. The measured production cross section as a function of the centre-of-mass energy is displayed in figure 2 compared to the Standard Model prediction and to two theoretical calculations under the assumption of bosons carrying no weak charge. The destructive interference of the amplitudes of the different production mechanisms for W-pairs leads to the finite value of the cross section at very high energies. This is another triumph for the Standard Model, and proof of the crucial impact of gauge symmetries.

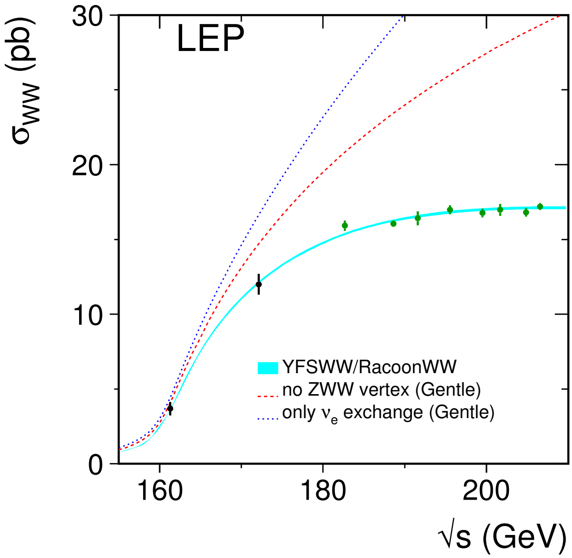

Fig. 2. Measurements of the W-pair production cross section at LEP II (Ref. [5], copyright CERN, License: CC-BY-3.0).

The precision data also allowed us to look beyond the energy regime of LEP. Through radiative corrections evaluated in the framework of the Standard Model, the Z-resonance data were also used to predict the masses of heavier particles not producible at LEP. Tini Veltman [6] realised that the observable effect to study was the ρ parameter and, in particular, its deviation from 1, which varies in proportion to the top-quark mass squared [7]. In his Nobel lecture, he stated: "This was the first instance in particle physics of a radiative correction becoming larger as the mass of the virtual particles increases, our first window to the very-high-energy region" [1].

Figure 3 gives a good example for this statement: it shows that the indirect determinations of the mass of the top quark, m_t, from electroweak data at LEP agree well with the measured values from the Tevatron. It is impressive to note that even before the discovery of the top quark in 1995, the then available set of electroweak precision data allowed the mass of the top quark to be predicted correctly as later verified by its direct measurement.

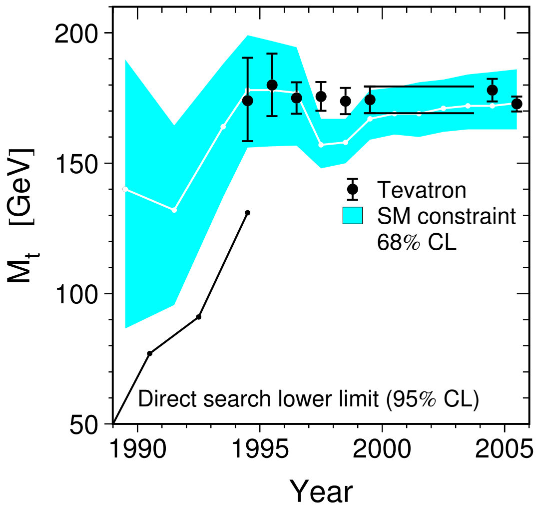

Fig. 3. Comparison of direct and indirect determinations of the mass of the top quark, m_t, as a function of time (Ref. [4], copyright CERN, reused with permission).

Radiative corrections also make it possible to predict the mass range for the Higgs-boson. However, the ρ parameter depends only logarithmically on the Higgs mass [8], thus allowing much less accuracy in the prediction. Figure 4 shows the probability of finding a Higgs boson of a certain mass value, as derived from the radiative corrections. The mass of this boson is found to be less than 285 GeV at 95% C.L. The yellow area is excluded through direct search results at LEP I, yielding a lower limit for the mass of 114 GeV.

LEP determined the masses of the top quark and the Higgs boson without a single top or Higgs being produced at the collider. Precision measurements can determine deviations from predictions and give hints to new physics. Such results have pointed out the direction to go for future experiments and will continue to do so.

Taking all measurements together, one can without hesitation state that LEP established the Standard Model as a renormalizable quantum field theory with unprecedented precision. The Nobel Prize to Veltman and 't Hooft in 1999 was a natural consequence.

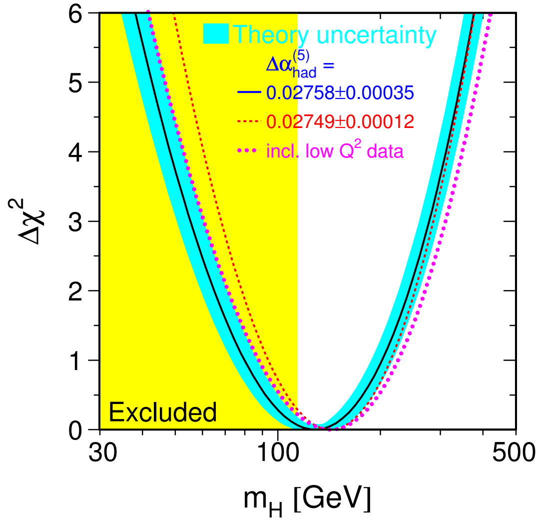

Fig. 4. Probability of finding a Higgs boson of a certain mass value, as derived from the radiative corrections. For details see [4] (copyright CERN, reused with permission).

This short contribution also needs to pay tribute to the strong interaction, QCD. LEP allowed a plethora of precision measurements in this area. In addition it triggered an interest in reanalysing data from lower energy electron–positron colliders, in this specific case, the reanalysis of data from the JADE experiment at PETRA [9] for the determination of the running of the strong coupling constant α_S. Figure 5 shows the LEP measurements of α_S, in the energy range from $M = 1.78$ GeV to $E_{\text{cm}} = 206$ GeV, together

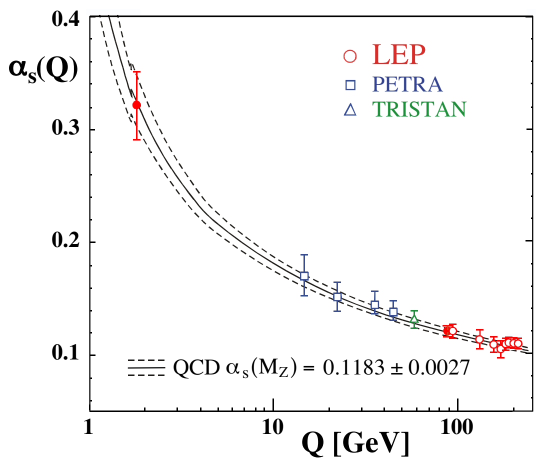

Fig. 5. Measurements of α_S in the energy range from $M = 1.78$ GeV to $E_{\text{cm}} = 206$ GeV (Ref. [10], reused with permission from the author).

with earlier results from the TRISTAN collider, and with results from a "LEP-style" reanalysis of PETRA data at lower c.m. energies. For details see [10]. Besides the scientific result, there is a message that data taken are precious and all efforts should be made to preserve them for eventual reanalysis.

All the results at LEP, and not only there, were only achievable through collaborative efforts on the experimental side, and through close cooperation between experimentalists and theorists. I would like to stress at this point that Tini Veltman liked to talk with experimentalists. He liked to confront theory and experiment. He had "a considerable fondness for experimental physics" and was "a deep believer in the importance of experiments for the progress of physics" as he stated in his biographical, published by the Nobel Foundation [11].

At the end of this short reminiscence of the Standard Model and Tini Veltman let me come back to that Lindau Nobel Laureate meeting in 2019, where I had the pleasure and the privilege to chair Tini's Agora talk. The title was 'The Future of Particle Physics' and he started it with his famous humour by confessing that "The title of my talk . . . has no relation whatsoever to the content of the talk", and he went on to embark on a journey through the evolution of particle physics spanning several decades, giving rise to a lively discussion with the attendees. The journey of course included the Higgs boson, discovered at the LHC at CERN in 2012. Although

Fig. 6. Martinus Veltman during his Agora Talk at # LINO19. Copyright: Patrick Kunkel/Lindau Nobel Laureate Meeting.

introduced in a different context, it also comes as a consequence of Veltman and 't Hooft's work, and to quote Tini: "That particle solved all the problems. I can tell you it was a great day ... when we knew this was the truth, that this was the way the world was made and not just fantasy in our heads" [12]. In other words: The pieces of the Standard Model puzzle finally fell into their appropriate place after much effort over more than five decades.

The story of the Standard Model tells us the obvious: progress in particle physics is made through the combined efforts of many people, it is not only due to one single scientist. But it also tells us that people like Tini Veltman are instrumental for the development of science. Thank you Tini.

REFERENCES

[1] Martinus J.G. Veltman — Nobel Lecture, https://www.nobelprize.org/prizes/physics/1999/veltman/lecture/

[2] B. Naroska, «Charge Asymmetries in e^+e^- Interactions at PETRA and PEP», DESY-86-051, contribution to 21st Rencontres de Moriond, 1986: Perspectives in Electroweak Interactions and Unified Theories, pp. 83–96.

[3] U. Uwer, «Messung der Myonpaarproduktion auf der Z-Resonanz», Ph.D. Thesis, Rheinisch-Westfälische Technische Hochschule Aachen.

[4] ALEPH, DELPHI, L3, OPAL, SLD collaborations, LEP Electroweak Working Group, SLD Electroweak and Heavy Flavour groups, «Precision electroweak measurements on the Z resonance», *Phys. Rep.* **427**, 257 (2006), CERN-PH-EP/2005-041

[5] ALEPH, DELPHI, L3, OPAL collaborations, LEP Electroweak Working Group, «Electroweak measurements in electron–positron collisions at W-boson-pair energies at LEP», *Phys. Rep.* **532**, 119 (2013), CERN-PH-EP/2013-022

[6] D.A. Ross, M.J.G. Veltman, «Neutral Currents in Neutrino Experiments», *Nucl. Phys. B* **95**, 135 (1975).

[7] M.J.G. Veltman, «Limit on Mass Differences in the Weinberg Model», *Nucl. Phys. B* **123**, 89 (1977).

[8] M.J.G. Veltman, «Second Threshold in Weak Interactions», *Acta Phys. Pol. B* **8**, 457 (1977).

[9] JADE Collaboration (P.A. Movilla Fernandez *et al.*), «A study of event shapes and determinations of α_s using data of e^+e^- annihilations at $\sqrt{s} = 22$ GeV to 44 GeV», *Eur. Phys. J. C* **1**, 461 (1998).

[10] S. Bethke, «QCD studies at LEP», *Phys. Rep.* **403-404**, 203 (2004), MPP-2004-66

[11] https://www.nobelprize.org/prizes/physics/1999/veltman/biographical/

[12] See B. Skuse's report at: https://www.lindau-nobel.org/de/blog-agora-talk-with-martinus-veltman-hiding-infinities/