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On the origins and the historical roots of the Higgs boson research from a bibliometric perspective

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Abstract. The subject of our present paper is the analysis of the origins or historical roots of the Higgs boson research from a bibliometric perspective, using a segmented regression analysis in combination with a method named reference publication year spectroscopy (RPYS). Our analysis is based on the references cited in the Higgs boson publications published since 1974. The objective of our analysis consists of identifying specific individual publications in the Higgs boson research context to which the scientific community frequently had referred to. We are interested in seminal works which contributed to a high extent to the discovery of the Higgs boson. Our results show that researchers in the Higgs boson field preferably refer to more recently published papers —particularly papers published since the beginning of the sixties. For example, our analysis reveals seven major contributions which appeared within the sixties: Englert and Brout (1964), Higgs (1964, 2 papers), and Guralnik *et al.* (1964) on the Higgs mechanism as well as Glashow (1961), Weinberg (1967), and Salam (1968) on the unification of weak and electromagnetic interaction. Even if the Nobel Prize award highlights the outstanding importance of the work of Peter Higgs and Francois Englert, bibliometrics offer the additional possibility of getting hints to other publications in this research field (especially to historical publications), which are of vital importance from the expert point of view.

1 Introduction

On 4 July 2012 the European Organization for Nuclear Research (CERN) announced the observation of a heavy particle around 126 MeV which is supposed to be consistent with the long-sought Higgs boson [1]. The magazine *Science* dedicated several articles to this discovery calling it “the breakthrough of the year” [2]. Even in public newspapers the event was published as the discovery of “God’s particle”, a name which referred to the title of a book by the Nobel Prize winner Leon Lederman [3]. In March 2013, the detection of the Higgs boson was confirmed by CERN [4]. In October 2013, Peter Higgs and Francois Englert were awarded the Nobel Prize for Physics for their contributions to the standard model of elementary particle physics and the prediction of the boson named after Higgs.

Since the beginning of the 20th century, when Rutherford developed his first atom model, the theory of fundamental particles and their interactions has been a hot topic in physics. One important breakthrough was the development of the unified electromagnetic and weak interaction. Among other ideas, this was based on the concept of broken symmetries and a mechanism for the provision of mass to the otherwise massless vector bosons of the weak interaction, the so-called Higgs mechanism. In 1964, papers on the subject of symmetry breaking and the possibility to create masses for gauge bosons of the weak interaction had been published independently by three research groups (Englert and Brout [5]; Higgs [6,7]; Guralnik, Hagen, and Kibble [8]). According to Close [9], only Higgs “drew attention to the

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consequential existence of a massive scalar particle, which now bears his name" (p. 141). The other researchers did not mention this boson since "it was obvious" (p. 164). Later, the corresponding field, the mechanism, and the boson were named after Peter Higgs. A few years later, Weinberg [10] and Salam [11] showed that the electromagnetic and weak interactions could be combined into a single theory of the electroweak interaction based on the breakthrough of the Higgs mechanism. At this time they were not aware that Glashow [12] had already developed a theory to solve this problem.

Subject of our present study is the research history of the Higgs boson from a bibliometric perspective. Bibliometric analyses are usually intended to measure the impact of research and they are based on a publication set comprising the publications of a researcher, a research institution, or a journal. Research performance can be measured by analyzing citation counts of the publications of such sets. Recently, it has been proposed to reverse the perspective of this classic citation analysis from a forward view on the overall citation impact of publications to a backward view on the major contributions to a specific research field [13]. In the latter case the cited references within the publications of a given research field are analyzed in order to determine the importance (the relative "weight") of specific papers, authors, and journals within that field and to quantify their significance.

In a previous analysis, Marx *et al.* [14] have proposed a method to detect the origins or historical roots of research fields by using this backward view of a cited reference analysis. In analogy to classic spectroscopy which shows physical phenomena as peaks in a spectrum, the new method has been named reference publication year spectroscopy (RPYS). RPYS implies to analyze the publication years of the references cited within the body of publications of a specific research field. Major contributions (single frequently referenced publications) appear as prominent peaks in the time series regarding the frequency of the cited references as a function of their publication years. As a rule, these few publications are the origins or historical roots of the research field in question.

In this study we identify the origins or historical roots of the Higgs boson research from the perspective of the cited references within the publications of this research field using the segmented regression analysis in the RPYS for the first time. We discuss the results of the RPYS against the backdrop of literature reviews on this field as written, for example, by Close [9] and Bleck-Neuhaus [15].

2 Physical background of Higgs Boson research

Nature consists of two different types of particles: fermions ("matter") and bosons ("radiation"). Fermions have to occupy different quantum states with the consequence that it is not possible to have two fermions with exactly identical quantum numbers. Examples of fermions are electrons, protons, and neutrons. Bosons, on the other hand, are not subject to such a restriction and they may occupy identical quantum states. The photon ("light") is a boson with zero mass and it is responsible for the electromagnetic interaction. In the second half of the 20th century, the standard model evolved as the fundamental model of elementary particle physics. It describes three of the four fundamental forces of nature, *i.e.* electromagnetic, weak, and strong interactions together with the corresponding subatomic particles. So far, gravitation could not be included in this description.

In the standard model the fundamental particles are divided into the three families of fermions (6 leptons and 6 quarks) and the bosons responsible for the electromagnetic (photon), the weak ($W^{\pm}/Z^0$ bosons), and the strong nuclear interactions (gluons). Under local transformations, these physical interactions are invariant, hence the corresponding field theories are gauge-invariant and the carriers of these interactions are called gauge bosons. Since these gauge bosons all have spin 1, they are classified as vector bosons, *e.g.* the photon is a massless gauge vector boson. The Higgs boson on the other side has a spin of 0 and is therefore classified as a scalar boson. The $W^{\pm}/Z^0$ bosons are originally massless but they obtain a mass through the (scalar) Higgs boson which interacts with all fundamental particles through the universal Higgs field. The addition of the Higgs boson is required to remove the infinities in the field equations by enabling the formulation of a renormalizable quantum field theory for the electroweak interaction. As a result, the standard model and the Higgs boson are inextricably intertwined. Therefore, it is clear that the detection of the Higgs boson in 2012 was an important milestone for the experimental verification of the standard model ("the breakthrough of the year" [2]).

3 Methods

3.1 Data

Our analysis is based on the search and retrieval in the database SCISEARCH accessible via STN International. SCISEARCH (the Thomson Reuters Science Citation Index) is a multidisciplinary database covering the publications from core scientific journals together with all the references cited therein. The SCISEARCH database in combination with the search functionalities of STN International enables sophisticated cited reference analyses.

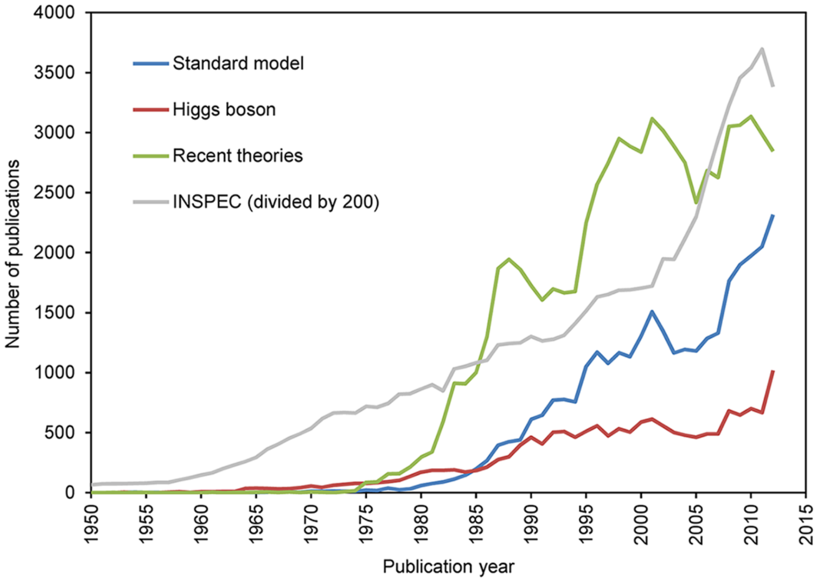

Fig. 1. Time series of publications dealing with the standard model ($n = 32\,654$), the Higgs boson ($n = 16\,545$), related theories (string theory, super symmetry, super gravity, and grand unified theory; $n = 71\,989$), and the total number of publications in the database INSPEC ($n = 14\,293\,823$).

The Higgs boson publications analyzed here were published between 1974 and August 2013 (08-08-2013). SCISEARCH covers no literature prior to 1974. However, for the present study no coverage of former publication years is needed due to the fact that relevant investigation on the Higgs boson which can be searched by corresponding search terms began approximately in the mid1970s. This starting point can be identified with the help of the INSPEC database, which has an excellent coverage of physics literature since 1900 and is also accessible via STN International.

Figure 1 shows the time series of the publications dealing with the standard model (blue), the Higgs boson (red), and related theoretical approaches (string theory, super symmetry, super gravity, and grand unified theory) in summary (green) between 1950 and 2012. The total number of publications in the INSPEC database (grey, divided by a factor of 200) is also included to show the time series of the overall physics literature. It is clearly visible that until the end of the 1970s the number of publications for the standard model, the Higgs boson, and the related theoretical approaches is rather small or even zero. From the late seventies on, the quantity of literature is rising constantly.

In order to reveal the origins or historical roots of the Higgs boson research, we performed a RPYS analysis of the Higgs boson publications covered by SCISEARCH. Even if the publications covered in SCISEARCH are limited to the year 1974, the references cited in the publications are not limited with regard to the reference publication year (RPY). Based on the cited references, we are able to detect those historical publications of outstanding importance for the Higgs boson investigation (and thus figuring as references in publications dealing with the Higgs boson).

The first step of our RPYS was a search for the relevant Higgs boson publications. At the date of searching (08-08-2013), the search for the term "higgs boson(s)" within the titles and abstracts yielded 7 623 papers published since 1974. The second step of the analysis was the extraction of all references cited by the 7 623 Higgs boson publications (altogether 136 403 cited references). Out of the complete set of cited references, the sub-set of 84 678 references belonging to the RPY time period 1900–1990 was analyzed in depth. The pre-1900 references are much less numerous, much more erroneous, and also much less important here. The past-1990 references refer to more current works which are less important from a historical perspective.

For the RPYS it was necessary to clean the dataset (cited references downloaded from SCISEARCH) with regard to variations of one and the same reference. The references included in citation databases are marginally standardized. In particular, the names of the cited journals may appear written out or may be cited in many possible abbreviations. Furthermore, many references are erroneous (*e.g.* incorrect with regard to the numerical data: volume, starting page, and publication year) [16]. The decisive publication of Abdus Salam (1968) [11] in the Higgs boson research published in the *Proceedings of the Nobel Symposium* is a good example: After collecting all the varying references of this publication, the number of cited references increased from 261 of the most referenced variant to 481 of all variants.

3.2 Statistical procedure

In the RPYS of this study, the annual numbers of cited references in the Higgs boson literature were evaluated statistically by regression analysis. To determine different segments of the growth development of cited references

Table 1. Results of the segmented regression analysis with five segments (1900–1990). The variance explained by the model amounts to $R^2 = 0.99$ or 99%; overall, the model parameters differ statistically significantly from zero according to the F-test: $F(9, 81) = 3\,233.4$, $p < 0.05$.

Parameter	Estimate	Standard error	95% confidence interval	Growth rate % per RPY
Breakpoint				
a_1	1916.3	1.08	[1914.2; 1918.5]	
a_2	1935.9	0.55	[1934.8; 1937.0]	
a_3	1943.3	0.47	[1942.3; 1944.2]	
a_4	1948.8	0.99	[1946.8; 1950.8]	
Growth constant				
b_1	0.00	0.00	[0.00; 0.00]	0.0
b_2	0.14	0.01	[0.11; 0.16]	14.6
b_3	−0.28	0.04	[−0.36; −0.19]	−24.2
b_4	0.42	0.09	[0.25; 0.60]	52.8
b_5	0.13	0.00	[0.12; 0.14]	13.8

within the time series, we used a segmented regression analysis [17–21]. For the analysis, the number of cited references within a year was determined as dependent variable and logarithmized ($\ln(y)$). To eliminate short-term deviations in the time curve of the annual number of cited references, a moving average over five years was calculated. Within the single segments which could be identified by using regression analysis, the references with a high reference volume were fixed. We suppose that these publications are the origins or historical roots of the Higgs boson research field.

For the different segments within the growth development of the annual number of cited references we suppose a simple exponential growth model with $y(t) = y(0)\exp(b_1 t)$, where b_1 is the growth constant and t the RPY time. The percent growth rate is given as $(y(t) - y(0))/y(0)$ is $\exp(b_1) - 1$. We analyze these data with a linear regression model on the variable $\ln(y(t)) = b_0 + b_1 t + \varepsilon$, where $b_0 = \ln(y(0))$ and ε the residual component. The segmented regression identifies different segments each with individual regression coefficients, respectively, where both the breakpoint (RPY) a_k of the segments as well as the intercept b_0 and the growth constant b_1 of each segment are estimated. For example, the equation for two segments is ([17], p. 2):

$$\begin{aligned}&\text{IF year} < a_1,\ \text{THEN}\ \ln(y) = b_0 + {b_1}^*\ \text{year} + \varepsilon,\\&\text{ELSE}\ \ln(y) = b_0 + {b_1}^* a_1 + {b_2}^*\ (\text{year} - a_1) + \varepsilon\\&\varepsilon \sim N(\mathbf{0}, \mathbf{I}\sigma^2),\end{aligned} \tag{1}$$

where the residuals ε are multivariate normally distributed with a zero mean vector and a covariance matrix with identical variances σ^2 (homoscedasticity) and zero covariances (no autocorrelations of the residuals) overall and across the segments ([22], p. 222). These rather strong assumptions regarding time series data are justified by the fact that given the observed high proportion of explained variance ($R^2 = 0.99$), and vice versa, the low proportion of residual variance, heteroscedasticity or autocorrelation of the residuals are in our case of no importance. Whereas the total variance of $\ln(y)$ amounted to 7.19, the overall residual variance amounts to 0.078, and it varies across segments from minimal 0.01 (segment 4) to maximal 0.28 (segment 1). The model parameters are estimated by the least squares method (Gauss-Newton) under the restriction that the breakpoints $a_1, a_2, \ldots$ are ordered. In order to avoid local minima of the estimation procedure, a grid of different starting values for the parameters is used. The regression constant b_0 is erased to enhance the fit of the model. The statistical analyses are performed using the SAS procedure PROC NLIN [23].

3.3 Results

The results of the segmented regression analysis are shown in table 1. The five segments resulting from the breakpoints in table 1 are as follows: 1900-1915, 1916-1936, 1937-1942, 1943-1949, and 1950-1990. As the growth constants in table 1 show, we have two growth periods within the five segments (1916-1936 and 1950-1990) with a similar growth rate of 13 to 14% interrupted by a break in 1937-1949. This break is caused by the decline of scientific activity around the Second World War.

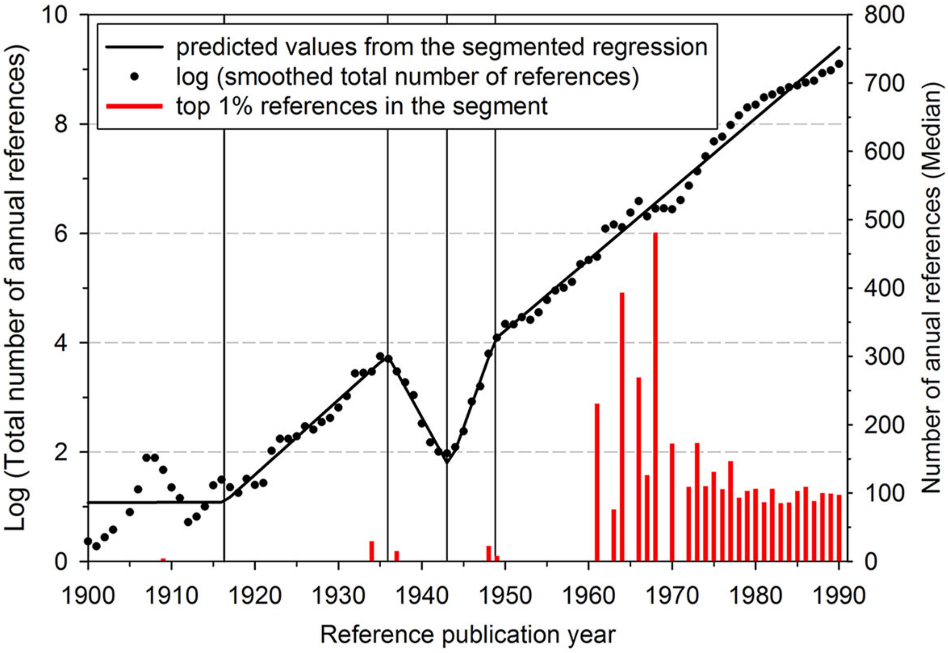

Fig. 2. Fitted segmented regression curve. The red bars show the average number of cited references (median) per RPY. The median of those cited references is shown which belong to the top 1% most frequently referenced publications within the five segments identified by regression analysis.

Figure 2 shows the fitted segmented regression curve. The exponential increase of the annual number of cited references in the five segments identified is the result of two concurrent phenomena. The first phenomenon is the growth of scientific literature: The scientific publications —especially in natural sciences— increased approximately by a factor of hundred throughout the 20th century [16]. In the first half of the 20th century the number of researchers in natural sciences was relatively small. Correspondingly, the number of ensuing publications was low, as reflected in the number of publications for these years [24]. The second phenomenon is named aging (obsolescence, replacement, or oblivion) which means that the interest for scientific papers decreases as time went by [25,26]. Scientists get especially back to publications of recent years and rarely cite publications which had been published many years ago.

Besides the fitted segmented regression curve, fig. 2 also shows the distribution of the (non-logarithmic) annual mean number of the references cited by the Higgs boson literature as a bar diagram. The median of those cited references is shown which belong to the top 1% most frequently referenced within the five segments identified by regression analysis. For the total period 1900 to 1990 it becomes apparent that the most frequently referenced publications can be found in the fifth segment (especially between 1960 and 1970).

Whereas the reference counts within the single segments are almost comparable, a comparison on cross segment basis is not possible. Due to the strong increase of the scientific literature, the counts *e.g.* of the references published before the Second World War are not comparable to those references published in the 1970s and 1980s. Another more important reason for the incomparableness is the fact that early publications are no longer explicitly indicated as references, but are taken as known by the reader —this phenomenon is called "obliteration by incorporation" [26]. Thus, table 2 shows the bibliographic data for those publications belonging to the top 1% most referenced publications *in its segment* being the basis for the calculation of the elevated bar score presented in fig. 2. Consequently, the concrete individual publications are listed to which the scientific community particularly often refers within the single segments. These publications are considered to be the origins or historical roots of the Higgs boson research. For the 5th segment only the 20 most frequently referenced publications from the total of 214 top 1% publications are shown in table 2. Appendix A lists all 214 publications.

Within the first four segments, covering the time period 1900-1949, we could identify four publications (no. 2, no. 3, no. 4, and no. 5 in table 2) with more than ten references within the Higgs boson literature: von Weizsäcker (1934, no. 2) [27], Williams (1934, no. 3) [28], Bloch (1937, no. 4) [29], and Landau (1948, no. 5) [30] with 38, 21, 15, and 37 references, respectively. These papers deal with "Radiation emitted in collisions with very fast electrons" (von Weizsäcker), with the "Nature of high energy particles" (Williams), with the "Radiation field of the electron" (Bloch), and with "The moment of a 2-photon system" (Landau), analyzing the possibility for the annihilation of slow electrons and positrons. Since all these papers have only a loose connection to the Higgs boson research, it seems that

Table 2. The top 1% most frequently referenced publications within the five segments identified by regression analysis (sorted according to RPY in ascending order within each segment). For the 5th segment only the 20 most frequently referenced publications from the total of 214 top 1% publications are shown (appendix A lists all 214 referenced publications).

No	REF	First author	RPY	Volume	Page	Journal/Book
1. Segment						
1	4	N. Nielsen	1909	90	123	Nova Acta Leopoldin
2. Segment						
2	38	C.F. Von Weizsacker	1934	88	612	Z. Phys.
3	21	E.J. Williams	1934	45	729	Phys. Rev.
3. Segment						
4	15	F. Bloch	1937	52	54	Phys. Rev.
4. Segment						
5	37	L.D. Landau	1948	60	207	Dokl. Akad. Nauk. SSSR
6	8	J. Schwinger	1948	73	416	Phys. Rev.
7	8	F.J. Dyson	1949	75	1736	Phys. Rev.
5. Segment						
8	380	S.L. Glashow	1961	22	579	Phys.
9	421	F. Englert	1964	13	321	Phys. Rev. Lett.
10	420	P.W. Higgs	1964	12	132	Phys. Lett. Nucl.
11	366	P.W. Higgs	1964	13	508	Phys. Rev. Lett.
12	361	G.S. Guralnik	1964	13	585	Phys. Rev. Lett.
13	269	P.W. Higgs	1966	145	1156	Phys. Rev.
14	536	S. Weinberg	1967	19	1264	Phys. Rev. Lett.
15	481	A. Salam	1968		367	Elementary Part.
16	270	S. Coleman	1973	7	1888	Phys. Rev. D
17	440	J. Ellis	1976	106	292	Nucl. Phys. B
18	479	B.W. Lee	1977	16	1519	Phys. Rev. D
19	252	S.L. Glashow	1977	15	1958	Phys. Rev. D
20	294	H.M. Georgi	1978	40	692	Phys. Rev. Lett.
21	342	G. Passarino	1979	160	151	Nucl. Phys. B
22	813	H.P. Nilles	1984	110	1	Phys. Rep.
23	917	H.E. Haber	1985	117	75	Phys. Rep.
24	257	M.S. Chanowitz	1985	261	379	Nucl. Phys. B
25	467	J.F. Gunion	1986	272	1	Nucl. Phys. B
26	314	J. Ellis	1989	39	844	Phys. Rev. D
27	983	J.F. Gunion	1990			Higgs Huntersguide

there are scarcely precursor publications in physics or mathematics published before the sixties which can be seen as direct historical roots of the Higgs boson research field. Even the classic papers of quantum physics do not appear extraordinarily frequently as cited references.

According to table 2 (and also fig. 2), researchers in the Higgs boson field fall back on publications published since the beginning of the sixties. Among these publications we have those publications by Englert and Brout (1964, no. 9) [5], Higgs (1964, no. 10 and 11) [6,7], and Guralnik *et al.* (1964, no. 12) [8] on the Higgs mechanism as well as the three papers by Glashow (1961, no. 8) [12], Weinberg (1967, no. 14) [10], and Salam (1968, no. 15) [11] on the electroweak interaction. According to Close ([9], p. 169 ff.), the situation in physics was as follows at that time: A quantum field theory of the electromagnetic field had been established and the photon was identified as the corresponding massless gauge vector boson. It was shown that the theory could be renormalized, *i.e.* all infinities disappeared with the right parameter choice. The scientists hoped to create also renormalizable field theories for the weak and strong interaction. However, the problem was that Nambu (1961, no. 154) [31] and Goldstone (1961) [32] had shown that a broken symmetry requires the existence of a massless boson (later called Goldstone boson). Such a massless boson could not be found in the experiments and it seemed that nature required only bosons with masses[1]. However, Englert and Brout (1964, no. 9) [5], Higgs (1964, no. 10 and 11) [6,7], and Guralnik *et al.* (1964, no. 12) [8] found a loophole in Goldstone's argument: when the local symmetry is broken, it is possible that massless gauge vector bosons gain mass through the interaction with a new field, later called the Higgs field. This result has been published independently several times within 4 months in the year 1964.

Although Englert and Brout (1964, no. 9) [5] were the first to describe the new field and the mechanism of symmetry breaking, Higgs (1964, no. 11) [7] was the only one to mention the creation of a massive scalar boson as a result of this process. Hence, his name has been associated with the field, the mechanism, and the boson. The paper by Guralnik *et al.*(1964, no. 12) [8], which was published shortly after the other papers had appeared in 1964, could include references to the other three papers. Together, the four papers contribute with 1568 out of 1979 references (79%) to the distinct peak in 1964 in fig. 2. The Higgs mechanism was further developed by Higgs (1966, no. 13) [33] and Kibble (1967, no. 78 in appendix A) [34]. Based on these ideas, Weinberg (1967, no. 14) [10] developed his model of the electro-weak interaction. The theory required two massive charged bosons (W^+ and W^-) and two neutral bosons —one massive (Z^0) plus the massless photon (γ). Independently of this publication, Glashow (1961, no. 8) [12] and Salam & Ward (1964) [35] came to the same results. Weinberg (1967, no. 14) [10] was able to estimate the masses of the $W^\pm$ and Z^0 vector bosons ([9], p. 285).

Weinberg (1967, no. 14) [10] also assumed that his model was renormalizable but he did not show this. He referenced Glashow (1961, no. 8) [12] as a predecessor to his own work but not Salam and Ward (1964) [35]. Salam (1968, no. 15) [11] had worked independently of the other authors on a unification of these two fundamental forces (electromagnetic and weak interaction). He presented his work at a conference in Sweden where it was published in the proceedings of the Nobel Symposium [11]. Glashow, Weinberg, and Salam shared the Nobel Prize for Physics in 1979 "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current" [36]. A prove for the renormalizability of the theory of electroweak interaction was given later by t'Hooft and Veltman (1972, no. 94 in appendix A) [37] for which they shared another Nobel Prize in 1999 "for elucidating the quantum structure of electroweak interactions in physics" [38].

Since 1976, further frequently referenced publications have been identified by the RPYS (see table 2). Two of these papers (Nilles, 1984, no. 22; Haber, 1985, no. 23) [39,40] are extensive reviews. This indicates that since the mid-eighties the Higgs boson theory has become a major research field which can serve as a basis for a literature summary in form of reviews. With regard to the relatively high reference counts of both reviews, it should be considered that reviews compared to classic articles are referenced above average [41]. The other papers in the table discuss the Higgs boson mass and the possibilities to detect them experimentally as well as the properties of the Higgs boson in a supersymmetric model. Ellis (1976, no. 17) [42] provides a phenomenological profile of the Higgs boson and discusses different possibilities to detect Higgs bosons depending on the possible mass ranges. Lee (1977, no. 18) [43] analyses the role of the Higgs boson mass for the weak interaction at very high energies within the Weinberg-Salam model and Gunion (1986, no. 25) [44] discusses "Higgs Bosons in Supersymmetric Models".

Finally, it should be noted that P.W. Anderson (1963) [45] was the first who discussed the possibility that photons could gain mass by entering a plasma or a superconductor ([9], p. 135 ff). In the theory of superconductivity there is no Goldstone boson present and the photon acts as if it has gained a mass. Anderson [45] concluded that Goldstone's argument might not be valid for all cases. However, the theory of superconductivity is a non-relativistic theory and part of solid state research while particle physics is founded on special relativity. Hence, Anderson's paper did not get enough attendance in the particle physics community (13 references in Higgs Boson research).

4 Discussion

Subject of our present paper is the analysis of the origins or historical roots of the Higgs boson research from a bibliometric perspective, using a segmented regression analysis in combination with the RPYS method. Our analysis is based on the references cited within the Higgs boson publications published since 1974. The objective of our analysis consists of identifying concrete individual publications in the Higgs boson research context to which the scientific community frequently had referred to. We were interested in seminal works which contributed to a high extent to the discovery of the Higgs boson. Even if the Nobel Prize award highlights the outstanding importance of the works of Peter Higgs and Francois Englert, bibliometrics offers the additional possibility of getting hints to other publications in this research field (especially to historical publications), which are of vital importance from the expert point of view.

The segmented regression analysis identified five time segments with two main periods (1916-1936 and 1950-1990) interrupted by a break in 1937-1949 caused by the Second World War. The decisive segment turned out to be the period

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[1] This is a possible reason why the paper by Goldstone (1961) is not listed among the most frequently referenced publications in table 2 and appendix A.

from 1950 to 1990. We identified four important publications, which appeared prior to 1950 and have been referenced more than ten times: von Weizsäcker (1934), Williams (1934), Bloch (1937), and Landau (1948) [27–30]. Beside these papers there are scarcely other precursor publications in physics or mathematics which have been important for the Higgs boson research community. Researchers in the Higgs boson field preferably refer to more recently published papers —particularly papers published since the beginning of the sixties. Our analysis revealed seven major contributions which appeared within the sixties: Englert and Brout (1964), Higgs (1964, 2 papers), and Guralnik *et al.* (1964) [5–8] on the Higgs mechanism as well as Glashow (1961), Weinberg (1967), and Salam (1968) [12,10,11] on the unification of weak and electromagnetic interaction. Since 1976, additional frequently referenced publications have been identified. Two papers (Nilles, 1984; Haber, 1985) [39,40] are extensive reviews. This indicates that in the mid-eighties the Higgs boson theory has become a major research field which can serve as a basis for a literature summary in the form of reviews. Three additional papers discuss the Higgs boson mass and the possibilities to detect them experimentally as well as the properties of the Higgs boson in a supersymmetric model.

As a result of this study, the historical publications which have been cited most frequently by Higgs boson researchers could be identified. However, we cannot act on the assumption that all important publications can be identified by RPYS. Intellectual influences are not always manifest in cited references. Therefore, experts in the field are needed to complete data and information where appropriate. The RPYS method reveals the historical publications potentially relevant for the evolution of a specific research field which could be taken into consideration when its history is reviewed. According to White and McCain [46] (p. 327), bibliometric methods like RPYS are *no substitute for extensive reading and fine-grained content analysis, if someone is truly interested in the intellectual history of a field.*

Appendix A.

The total of the 214 top 1% most frequently cited publications in the 5th segment sorted according to REF (number of cited references within the Higgs boson literature).

No	REF	First author	PY	Volume	Page	Journal/Book
1	983	J.F. Gunion	1990			Higgs Huntersguide
2	917	H.E. Haber	1985	117	75	Phys. Rep.
3	813	H.P. Nilles	1984	110	1	Phys. Rep.
4	536	S. Weinberg	1967	19	1264	Phys. Rev. Lett.
5	481	A. Salam	1968		367	Elementary Part.
6	479	B.W. Lee	1977	16	1519	Phys. Rev. D
7	467	J.F. Gunion	1986	272	1	Nucl. Phys. B
8	440	J. Ellis	1976	106	292	Nucl. Phys. B
9	421	F. Englert	1964	13	321	Phys. Rev. Lett.
10	420	P.W. Higgs	1964	12	132	Phys. Lett.
11	380	S.L. Glashow	1961	22	579	Nucl. Phys.
12	366	P.W. Higgs	1964	13	508	Phys. Rev. Lett.
13	361	G.S. Guralnik	1964	13	585	Phys. Rev. Lett.
14	342	G. Passarino	1979	160	151	Nucl. Phys. B
15	314	J. Ellis	1989	39	844	Phys. Rev. D
16	294	H.M. Georgi	1978	40	692	Phys. Rev. Lett.
17	270	S. Coleman	1973	7	1888	Phys. Rev. D
18	269	P.W. Higgs	1966	145	1156	Phys. Rev.
19	257	M.S. Chanowitz	1985	261	379	Nucl. Phys. B
20	252	S.L. Glashow	1977	15	1958	Phys. Rev. D
21	243	R.N. Mohapatra	1980	44	912	Phys. Rev. Lett.
22	239	M.E. Peskin	1990	65	964	Phys. Rev. Lett.
23	224	M. Sher	1989	179	273	Phys. Rep.

24	220	A.H. Chamseddine	1982	49	970	Phys. Rev. Lett.
25	217	M. Kobayashi	1973	49	652	Prog. Theor. Phys.
26	217	J.P. Derendinger	1984	237	307	Nucl. Phys. B
27	205	J. Ellis	1984	238	453	Nucl. Phys. B
28	202	E. Eichten	1984	56	579	Rev. Mod. Phys.
29	201	S. Dimopoulos	1981	193	150	Nucl. Phys. B
30	200	M. Drees	1989	4	3635	Int. J. Mod. Phys. A
31	199	J.M. Cornwall	1974	10	1145	Phys. Rev. D
32	197	L. Hall	1983	27	2359	Phys. Rev. D
33	196	R. Barbieri	1982	119	343	Phys. Lett. B
34	193	J.M. Frere	1983	222	11	Nucl. Phys. B
35	192	K. Inoue	1982	68	927	Prog. Theor. Phys.
36	191	B.W. Lee	1977	38	883	Phys. Rev. Lett.
37	184	M. Veltman	1977	8	475	Acta. Phys. Polon.
38	182	F. Wilczek	1977	39	1304	Phys. Rev. Let.
39	179	H.P. Nilles	1983	120	346	Phys. Lett. B
40	177	L. Alvarezgaume	1983	221	495	Nucl. Phys. B
41	177	J.F. Gunion	1986	278	449	Nucl. Phys. B
42	172	S. Glashow	1970	2	1285	Phys. Rev. D
43	169	L. Susskind	1979	20	2619	Phys. Rev. D
44	169	A. Sirlin	1980	22	971	Phys. Rev. D
45	168	J.C. Pati	1974	10	275	Phys. Rev. D
46	167	R.N. Cahn	1984	136	196	Phys. Lett. B
47	165	R. Barbieri	1988	306	63	Nucl. Phys. B
48	164	N. Cabibbo	1979	158	295	Nucl. Phys. B
49	164	W.A. Bardeen	1990	41	1647	Phys. Rev. D
50	161	E. Braaten	1980	22	715	Phys. Rev. D
51	156	P. Fayet	1975	90	104	Nucl. Phys. B
52	152	R. Barbieri	1988	11	1	Riv. Nuovo Cimento
53	148	P. Minkowski	1977	67	421	Phys. Lett. B
54	148	H. Goldberg	1983	50	1419	Phys. Rev. Lett.
55	148	A.B. Lahanas	1987	145	1	Phys. Rep.
56	147	H.E. Haber	1979	161	493	Nucl. Phys. B
57	145	M. Veltman	1977	123	89	Nucl. Phys. B
58	144	R.K. Ellis	1988	297	221	Nucl. Phys. B
59	142	V.A. Kuzmin	1985	155	36	Phys. Lett. B
60	140	M. Lindner	1986	31	295	Z Phys. C Part Field
61	139	R.N. Mohapatra	1981	23	165	Phys. Rev. D
62	138	G. Thooft	1979	153	365	Nucl. Phys. B
63	138	J. Schechter	1980	22	2227	Phys. Rev. D
64	137	R.D. Peccei	1977	38	1440	Phys. Rev. Lett.
65	137	S. Weinberg	1979	19	1277	Phys. Rev. D
66	137	W. Buchmuller	1986	268	621	Nucl. Phys. B
67	136	J.E. Kim	1984	138	150	Phys. Lett. B

68	136	J. Kublbeck	1990	60	165	Comput. Phys. Commun.
69	134	T. Appelquist	1980	22	200	Phys. Rev. D
70	134	E. Witten	1981	188	513	Nucl. Phys. B
71	134	V. Barger	1990	41	3421	Phys. Rev. D
72	132	T. Appelquist	1975	11	2856	Phys. Rev. D
73	131	G. Senjanovic	1975	12	1502	Phys. Rev. D
74	131	I.F. Ginzburg	1983	205	47	Nucl. Instrum. Methods
75	130	I.F. Ginzburg	1984	219	5	Nucl. Instrum. Methods A
76	129	T.D. Lee	1973	8	1226	Phys. Rev. D
77	128	M.A. Shifman	1979	30	711	Sov. J. Nucl. Phys.
78	126	T.W.B. Kibble	1967	155	1554	Phys. Rev.
79	126	G.F. Giudice	1988	206	480	Phys. Lett. B
80	125	R.N. Mohapatra	1975	11	566	Phys. Rev. D
81	125	N. Sakai	1981	11	153	Z. Phys. C Part. Field
82	121	S. Weinberg	1976	36	294	Phys. Rev. Lett.
83	121	S. Weinberg	1976	37	657	Phys. Rev. Lett.
84	121	S. Dawson	1985	249	42	Nucl. Phys. B
85	120	K. Hagiwara	1987	282	253	Nucl. Phys. B
86	117	M. Drees	1990	240	455	Phys. Lett. B
87	116	L. Ibanez	1982	110	215	Phys. Lett. B
88	113	D.A. Dicus	1973	7	3111	Phys. Rev. D
89	113	M.A. Shifman	1978	78	443	Phys. Lett. B
90	113	G.L. Kane	1984	148	367	Phys. Lett. B
91	112	A.I. Vainshtein	1979	30	711	Sov. J. Nucl. Phys.
92	111	J.L. Hewett	1989	183	193	Phys. Rep.
93	110	H. Georgi	1974	32	438	Phys. Rev. Lett.
94	109	G. Thooft	1972	44	189	Nucl. Phys. B
95	109	M. Bohm	1986	34	687	Fortschr. Phys.
96	108	A.C. Longhitano	1980	22	1166	Phys. Rev. D
97	108	I. Antoniadis	1990	246	377	Phys. Lett. B
98	108	W.F.L. Hollik	1990	38	165	Fortschr. Phys.
99	108	S. Weinberg	1990	42	860	Phys. Rev. D
100	107	G.P. Lepage	1978	27	192	J. Comput. Phys.
101	106	W.J. Marciano	1980	22	2695	Phys. Rev. D
102	106	K. Inoue	1982	67	1889	Prog. Theor. Phys.
103	105	W. Siegel	1979	84	193	Phys. Lett. B
104	104	B.L. Ioffe	1978	9	50	Sov. J. Part. Nucl.
105	103	M. Dugan	1985	255	413	Nucl. Phys. B
106	102	M. Fukugita	1986	174	45	Phys. Lett. B
107	102	T.P. Cheng	1987	35	3484	Phys. Rev. D
108	101	M. Gellmann	1979		315	Supergravity
109	101	A. Longhitano	1981	188	118	Nucl. Phys. B
110	101	V.A. Miransky	1989	221	177	Phys. Lett. B
111	100	J.F. Gunion	1988	299	231	Nucl. Phys. B
112	99	D.A. Dicus	1989	39	751	Phys. Rev. D
113	99	V.A. Miransky	1989	4	1043	Mod. Phys. Lett. A
114	99	S. Weinberg	1989	63	2333	Phys. Rev. Lett.
115	98	R.A. Flores	1983	148	95	Ann. Phys.-New York
116	98	M.S. Berger	1990	41	225	Phys. Rev. D
117	97	J.F. Gunion	1990	42	1673	Phys. Rev. D

118	96	P. Fayet	1977	69	489	Phys. Lett. B
119	96	S.L. Glashow	1978	18	1724	Phys. Rev. D
120	96	L. Alvarezgaume	1982	207	96	Nucl. Phys. B
121	95	G. Altarelli	1977	126	298	Nucl. Phys. B
122	94	L.E. Ibanez	1984	233	511	Nucl. Phys. B
123	94	J.F. Gunion	1987	294	621	Nucl. Phys. B
124	93	T. Yanagida	1979		95	P Worksh. UN Theor. B
125	93	T.P. Cheng	1980	22	2860	Phys. Rev. D
126	93	S.M. Barr	1990	65	21	Phys. Rev. Lett.
127	92	Z. Kunszt	1984	247	339	Nucl. Phys. B
128	92	S.G. Gorishny	1990	5	2703	Mod. Phys. Lett. A
129	90	S. Weinberg	1976	13	974	Phys. Rev. D
130	90	M.S. Chanowitz	1978	78	285	Phys. Lett. B
131	90	M.S. Chanowitz	1979	153	402	Nucl. Phys. B
132	90	M. Veltman	1981	12	437	Acta. Phys. Polb.
133	90	N. Gray	1990	48	673	Z. Phys. C
134	89	R.D. Peccei	1977	16	1791	Phys. Rev. D
135	89	D.R.T. Jones	1979	84	440	Phys. Lett. B
136	89	L. Girardello	1982	194	65	Nucl. Phys. B
137	88	E. Farhi	1981	74	277	Phys. Rep.
138	88	J.F. Gunion	1989	39	2701	Phys. Rev. D
139	86	S. Weinberg	1979	96	327	Physica A
140	86	A. Manohar	1984	234	189	Nucl. Phys. B
141	85	C.E. Vayonakis	1976	17	383	Lett. Nuovo Cimento
142	85	P. Fayet	1977	32	249	Phys. Rep. C
143	85	S. Dimopoulos	1981	24	1681	Phys. Rev. D
144	85	K. Aoki	1982	73	1	Prog. Theor. Phys. Suppl.
145	85	R. Dashen	1983	50	1897	Phys. Rev. Lett.
146	85	K. Inoue	1984	71	413	Prog. Theor. Phys.
147	85	D.B. Kaplan	1984	136	183	Phys. Lett. B
148	84	P. Nason	1988	303	607	Nucl. Phys. B
149	83	J.C. Collins	1985	250	199	Nucl. Phys. B
150	82	A.D. Linde	1976	23	64	JETP Lett.
151	82	C.T. Hill	1981	24	691	Phys. Rev. D
152	82	G. Altarelli	1987	287	205	Nucl. Phys. B
153	82	B. Holdom	1990	247	88	Phys. Lett. B
154	81	Y. Nambu	1961	122	345	Phys. Rev.
155	81	J. Wess	1974	70	39	Nucl. Phys. B
156	81	G.B. Gelmini	1981	99	411	Phys. Lett. B
157	81	H. Georgi	1985	262	463	Nucl. Phys. B
158	80	R.N. Mohapatra	1975	11	2558	Phys. Rev. D
159	80	M.E. Shaposhnikov	1987	287	757	Nucl. Phys. B
160	79	D.M. Capper	1980	167	479	Nucl. Phys. B
161	79	G. Lazarides	1981	181	287	Nucl. Phys. B
162	78	N.G. Deshpande	1978	18	2574	Phys. Rev. D
163	78	S. Dimopoulos	1979	155	237	Nucl. Phys. B
164	78	I. Bigi	1986	181	157	Phys. Lett. B
165	78	R.M. Barnett	1988	306	697	Nucl. Phys. B
166	77	A.D. Sakharov	1967	5	24	JETPJ. Am. Soc. Lett.
167	77	W.A. Bardeen	1978	18	3998	Phys. Rev. D

168	77	J. Ellis	1983	121	123	Phys. Lett. B
169	77	U. Amaldi	1987	36	1385	Phys. Rev. D
170	76	N. Cabibbo	1963	10	531	Phys. Rev. Lett.
171	76	L. Dolan	1974	9	3320	Phys. Rev. D
172	75	E. Eichten	1980	90	125	Phys. Lett. B
173	73	D.B. Kaplan	1984	136	187	Phys. Lett. B
174	73	J.F. Gunion	1989	40	1546	Phys. Rev. D
175	72	B. Pendleton	1981	98	291	Phys. Lett. B
176	72	J. Ellis	1983	128	248	Phys. Lett. B
177	72	W.Y. Keung	1984	30	248	Phys. Rev. D
178	72	W. Beenakker	1989	40	54	Phys. Rev. D
179	71	G.R. Farrar	1978	76	575	Phys. Lett. B
180	71	J. Fleischer	1981	23	2001	Phys. Rev. D
181	71	J. Polchinski	1983	125	393	Phys. Lett. B
182	71	T. Sjostrand	1987	43	367	Comput. Phys. Commun.
183	71	M. Lindner	1989	228	139	Phys. Lett. B
184	71	U. Baur	1990	339	38	Nucl. Phys. B
185	70	J. Ellis	1979	83	339	Phys. Lett. B
186	70	J.C. Collins	1981	193	381	Nucl. Phys. B
187	70	J. Ellis	1982	114	231	Phys. Lett. B
188	70	J. Gasser	1984	158	142	Ann. Phys.-New York
189	70	G. Vanoldenborgh	1990	46	425	Z. Phys. C Part. Field
190	69	C. Kounnas	1984	236	438	Nucl. Phys. B
191	69	L.E. Ibanez	1985	256	218	Nucl. Phys. B
192	69	R. Kleiss	1985	262	235	Nucl. Phys. B
193	69	J. Kuti	1988	61	678	Phys. Rev. Lett.
194	69	V.I. Telnov	1990	294	72	Nucl. Instrum. Methods A
195	68	F. Wilczek	1978	40	279	Phys. Rev. Lett.
196	68	M. Magg	1980	94	61	Phys. Lett. B
197	68	W. Buchmuller	1983	121	321	Phys. Lett. B
198	68	M.E. Machacek	1983	222	83	Nucl. Phys. B
199	68	E.W.N. Glover	1988	309	282	Nucl. Phys. B
200	68	A.C. Bawa	1990	47	75	Z. Phys. C Part. Field
201	67	C.D. Froggatt	1979	147	277	Nucl. Phys. B
202	67	A.I. Vainshtein	1980	23	429	Sov. Phys. Usp.
203	66	N. Sakai	1980	22	2220	Phys. Rev. D
204	66	S.P. Li	1984	140	339	Phys. Lett. B
205	66	G.J. Gounaris	1986	34	3257	Phys. Rev. D
206	66	M.B. Voloshin	1986	44	478	Sov. J. Nucl. Phys+
207	66	G. Gamberini	1990	331	331	Nucl. Phys. B
208	65	J. Ellis	1983	125	275	Phys. Lett. B
209	65	M.E. Machacek	1984	236	221	Nucl. Phys. B
210	65	J. Bagger	1990	41	264	Phys. Rev. D
211	64	R.N. Cahn	1979	82	113	Phys. Lett. B
212	64	K. Inoue	1983	70	330	Prog. Theor. Phys.
213	64	L.J. Hall	1984	231	419	Nucl. Phys. B
214	64	F.R. Klinkhamer	1984	30	2212	Phys. Rev. D

References

1. CERN, `http://press.web.cern.ch/press-releases/2012/07/cern-experiments-observe-particle-consistent-long-sought-higgs-boson` (2012).
2. A. Cho, Science **338**, 1524 (2012).
3. L. Lederman, D. Teresi, *The God particle: If the universe is the answer, what is the question?* (Houghton Mifflin, Boston, 1993).
4. CERN, `http://home.web.cern.ch/about/updates/2013/03/new-results-indicate-new-particle-higgs-boson` (2013).
5. F. Englert, R. Brout, Phys. Rev. Lett. **13**, 321 (1964) DOI: 10.1103/PhysRevLett.13.321.
6. P. Higgs, Phys. Lett. **12**, 132 (1964) DOI: 10.1016/0031-9163(64)91136-9.
7. P. Higgs, Phys. Rev. Lett. **13**, 508 (1964) DOI: 10.1103/PhysRevLett.13.508.
8. G.S. Guralnik, C.R. Hagen, T.W.B. Kibble, Phys. Rev. Lett. **13**, 585 (1964) DOI: 10.1103/PhysRevLett.13.585.
9. F. Close, *The Infinity Puzzle. How The Quest to Understand Quantum Field Theory Led to Extraordinary Science, High Politics, and The World's Most Expensive Experiment* (Oxford University Press, Oxford, 2011).
10. S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967) DOI: 10.1103/PhysRevLett.19.1264.
11. A. Salam, in *Elementary Particle Physics (Nobel Symposium No. 8)*, edited by N. Svartholm (Wiley-Interscience, London, 1968) pp. 367–377.
12. S.L. Glashow, Nucl. Phys. **22**, 579 (1961) DOI: 10.1016/0029-5582(61)90469-2.
13. L. Bornmann, W. Marx, J. Informetrics **7**, 84 (2013) DOI: 10.1016/j.joi.2012.09.003.
14. W. Marx, L. Bornmann, A. Barth, L. Leydesdorff, J. Assoc. Inf. Sci. Technol. **65**, 751 (2014) DOI: 10.1002/asi.23089.
15. J. Bleck-Neuhaus, *Elementare Teilchen: Von den Atomen über das Standard-Modell bis zum Higgs-Boson*, 2nd edition (Springer Spektrum, Heidelberg, 2013).
16. W. Marx, J. Assoc. Inf. Sci. Technol. **62**, 433 (2011) DOI: 10.1002/asi.21479.
17. E. Brusilovskiy, *The piecewise regression model as a response modeling tool*, in *Proceedings of the 17th Conference of North Eastern SAS User Group (NESUG) in Baltimore*, `www.nesug.org/proceedings/` (2004).
18. P.M. Lerman, J. R. Stat. Soc. Ser. C (Appl. Stat.) **29**, 77 (1980).
19. V.E. McGee, W.T. Carleton, J. Am. Stat. Ass. **65**, 1109 (1970) DOI: 10.2307/2284278.
20. U.H. Sauter, R. Mutz, B.D. Munro, Wood Fiber Sci. **31**, 416 (1999).
21. X. Shuai, Z. Zhou, R. Yost, J. Agr. Biol. Environ. Stat. **8**, 240 (2003) DOI: 10.1198/1085711031580.
22. N. Draper, H. Smith, *Applied Regression*, 3rd edition (Wiley, New York, 1998).
23. SAS Institute Inc. SAS/STAT 9.3 User's Guide (SAS Institute Inc. Cary, NC: 2011) p. 5146–5150.
24. W. Marx, L. Bornmann, M. Cardona, J. Assoc. Inf. Sci. Technol. **61**, 2061 (2010) DOI: 10.1002/asi.21377.
25. A.F.J. Van Raan, Scientometrics **47**, 347 (2000) DOI: 10.1023/A:1005647328460.
26. K.W. McCain, J. Assoc. Inf. Sci. Technol. **63**, 2129 (2012) DOI: 10.1002/asi.22719.
27. C.F. Von Weizsäcker, Z. Phys. **88**, 612 (1934) DOI 10.1007/BF01333110.
28. E.J. Williams, Phys. Rev. **45**, 729 (1934) DOI: 10.1103/PhysRev.45.729.
29. F. Bloch, Phys. Rev. **52**, 54 (1937) DOI: 10.1103/PhysRev.52.54.
30. L.D. Landau, Dokl. Akad. Nauk SSSR **60**, 207 (1948).
31. Y. Nambu, G. Jona-Lasinio, Phys. Rev. **122**, 345 (1961) DOI: 10.1103/PhysRev.122.345.
32. J. Goldstone, Il Nuovo Cimento **19**, 154 (1961) DOI: 10.1007/BF02812722.
33. P. Higgs, Phys. Rev. **145**, 1156 (1966) DOI: 10.1103/PhysRev.145.1156.
34. T.W.B. Kibble, Phys. Rev. **155**, 1554 (1967) DOI: 10.1103/PhysRev.155.1554.
35. A. Salam, J.C. Ward, Phys. Lett. **13**, 168 (1964) DOI: 10.1016/0031-9163(64)90711-5.
36. Nobel Lecture, *The Nobel Prize in Physics 1979*, `nobelprize.org`, Nobel Media AB 2013, Web 26 September 2013, `http://www.nobelprize.org/nobel_prizes/physics/laureates/1979/` (1979).
37. G. 't Hooft, M. Veltman, Nucl. Phys. B **44**, 189 (1972) DOI: 10.1016/0550-3213(72)90279-9.
38. Nobel Lecture, *The Nobel Prize in Physics 1999*. `nobelprize.org`, Nobel Media AB 2013, Web 26 September 2013, `http://www.nobelprize.org/nobel_prizes/physics/laureates/1999/` (1999).
39. H.P. Nilles, Phys. Rep. **110**, 1 (1984) DOI: 10.1016/0370-1573(84)90008-5.
40. H.E. Haber, Phys. Rep. **117**, 75 (1985) DOI: 10.1016/0370-1573(85)90051-1.
41. L. Bornmann, H.-D. Daniel, J. Document **64**, 45 (2008) DOI: 10.1108/00220410810844150.
42. J. Ellis, M.K. Gaillard, D.V. Nanopoulos, Nucl. Phys. B **106**, 292 (1976) DOI: 10.1016/0550-3213(76)90184-X.
43. B.W. Lee, C. Quigg, H.B. Thacker, Phys. Rev. D **16**, 1519 (1977) DOI: 10.1103/PhysRevD.16.1519.
44. J.F. Gunion, H.E. Haber, Nucl. Phys. B **272**, 1 (1986) DOI: 10.1016/0550-3213(86)90340-8.
45. P.W. Anderson, Phys. Rev. **130**, 439 (1963) DOI: 10.1103/PhysRev.130.439.
46. H.D. White, K. McCain, J. Assoc. Inf. Sci. Technol. **49**, 327 (1998) DOI: 10.1002/(SICI)1097-4571(19980401)49:4<327::AID-ASI4>3.0.CO;2-4.