

Scientometric indicators for Brazilian research on High Energy Physics, 1983-2013

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ABSTRACT

This article presents an analysis of Brazilian research on High Energy Physics (HEP) indexed by Web of Science (WoS) from 1983 to 2013. Scientometric indicators for output, collaboration and impact were used to characterize the field under study. The results show that the Brazilian articles account for 3% of total HEP research worldwide and that the sharp rise in the scientific activity between 2009 and 2013 may have resulted from the consolidation of graduate programs, the increase of the funding and of the international collaboration as well as the implementation of the Rede Nacional de Física de Altas Energias (RENAFAE) in 2008. Our results also indicate that the collaboration patterns in terms of the authors, the institutions and the countries confirm the presence of Brazil in multinational Big Science experiments, which may also explain the prevalence of foreign citing documents, emphasizing the international prestige and visibility of the output of Brazilian scientists. We concluded that the scientometric indicators suggested scientific maturity in the Brazilian HEP community due to its long history of experimental research.

INTRODUCTION

High Energy Physics (HEP) is considered one of the most internationalized and collaborative scientific knowledge areas (Mele et al. 2006). Since the 1950s, large experiments with particle accelerators have involved scientists from several countries. The small number of laboratories, operational costs of research and interdisciplinarity are factors that strengthen ties between nations. The prevalence of multiauthor publications on HEP is the result of a strong culture of communication and scientific exchange.

This collective effort generates information on particle interaction and the formation of the universe, in addition to knowledge transferred to areas such as Medicine (the development of CT scans and radiation therapy for cancer diagnosis and treatment), Information & Communication Technology (creation of the World Wide Web), Engineering (improving the quality of thermal insulation for electrical equipment), the Environment (renewable energy production) (Santoro and Novaes 2003; Lefevre 2007).

In 2008, Brazil began to work towards becoming an Associate Member of the European Organization for Nuclear Research (CERN). Despite not being formally affiliated with the institution, collaboration by Brazilian HEP is significant and long-standing. In terms of number of researchers, students and engineers, Brazil has the second largest participation among non-member countries, second only to Canada. Concomitantly, Brazilian researchers in the field participate in major international projects in partnership with National Laboratories such as the Fermi National Accelerator Laboratory (Fermilab) and Brookhaven National Laboratory (BNL) in the United States, and Pierre Auger in Argentina (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior [CAPES] 2013).

It is known that joining CERN alone is not enough to ensure a quality leap in HEP research in Brazil; significant investment in infrastructure, the creation of new laboratories and training of human resources are also needed (Lépine-Szily et al. 2011). It should be noted

that no specific scientometric study on Brazilian HEP was found in the existing literature. Therefore, this paper identifies the peculiarities of research in the field, national and international co-participation, and research visibility through citations. Moreover, it can be used as a source of information for decision-making in relation to granting new funding and graduate scholarships.

This paper presents an analysis of the characteristics of the scientific output, the collaboration and impact of Brazilian HEP. The analysis is based on articles published in journals indexed under the Web of Science Category (WC) 'Physics, Particles & Fields' between 1983 and 2013.

OVERVIEW OF HEP RESEARCH IN BRAZIL

Research on high-energy cosmic rays in Brazilian HEP and collaboration between scientists have been systematic since the 1930s, especially with the creation of the first universities in São Paulo and Rio de Janeiro and the arrival of foreign physicists, including the Italian Gleb Wataghin and the German Bernard Gross (Schwartzman 2001; Motoyama 2004). The participation of César Lattes in the discovery of meson π in 1947 and the creation of the physics research center, Centro Brasileiro de Pesquisas Físicas (CBPF), in 1949, contributed to the consolidation of HEP as a thematic area of research. The establishment of the two governmental grant agencies, Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and CAPES, in 1951, boosted the development of national science and of Physics in particular. The creation of federal and state universities in the 1960s (and more intensely in subsequent decades) propelled the development of human resources. The high education system consolidated and in the second half of the 1960s, graduate programs were established in the country (Sociedade Brasileira de Física [SBF] 1987; Schwartzman 2001; Vieira and Videira 2007; Shellard 2011). The first program with an HEP research line was

offered by the CBPF in 1962 (Sistema Nacional de Pós-Graduação [SNPG] 2015). The most recent assessment of graduate programs conducted by CAPES revealed the rapid development of teaching in the area. Among the 32 graduate HEP programs graded in the Avaliação Trienal, 11 were regarded as having an international profile and deemed outstanding, receiving the highest grades (CAPES 2013).

The participation in the large collaborations in HEP requires specific planning related not only to the visits to the international laboratories but also to the selection of experiments in which the scientists from Brazil can participate. Then, in 2008, the Ministério de Ciência e Tecnologia (MCT) set up the Rede Nacional de Física de Altas Energias (RENAFAE). Its main objectives are to study particles and their interactions, coordinate activities related to major international collaborations and devise a project for the development of instrumentation and software (Centro Brasileiro de Pesquisas Físicas [CBPF] 2011; Shellard 2011). In the scientific community, the creation of RENAFEA is believed to be responsible for a major boost in HEP research in Brazil, given that the number of publications and research groups registered in the CNPq directory have since increased considerably. While the rise in the number of graduate programs has been less pronounced, consolidation and expansion of programs with HEP research lines are thought to have occurred. According to the CBPF (2011), RENAFEA has played a key role in the articulation of Brazilian collaborations in international projects, including experiments conducted at CERN and the Pierre Auger Observatory.

SCIENTOMETRIC STUDIES ON HEP

Previous studies by national and international researchers analyzed different aspects of HEP scientific output, collaborations and impact. Although HEP is the focus of analysis in foreign research, studies in Brazil provide an indirect overview of the field, such as the investigations

by Vanz (unpublished data), who observed the formation of large groups (teamwork) in the field due to the high cost of research and the complexity of experiments; and Duarte (2008), who stated that scientific and technological development in HEP should be based on international collaboration and Brazilian participation in CERN.

A number of international studies also stand out. Braun et al. (1992) compared the patterns of international co-authorship in the subfields of physics, underscoring, in HEP, the role of multinational laboratories in building partnerships. These studies highlight the similarities and differences between HEP and other collaborative associations. For instance, Kretschmer and Rousseau (2001) found that, in fields such as HEP, Lotka's law is annulled by intense collaboration. Also, Chompalov et al. (2002) reported 53 multi-institutional collaborations in Physics, observing that HEP is more participatory and consensual in terms of decision-making. Complementary to Chompalov et al. (2002), Newman (2001a, 2001b, 2001c, 2004) examined the structure of scientific collaboration networks in different fields and noted that HEP exhibits a high level of clustering. Krause et al. (2007) studied the geographical distribution of authors who published articles in major HEP journals in 2005-2006 and found that the United States and CERN Members States are the most productive and collaborative countries. Lehmann et al. (2003) demonstrated the homogeneity of the HEP citing network consisting of scientific publications indexed in SPIRES database. Likewise, Collazo-Reyes and Luna-Morales (2002) analyzed the scientific output and growth of Mexican HEP between 1971 and 2000, underscoring the maturity of the scientific community at the local level. Calero (unpublished data) found high rates the scientific output, international collaboration and impact of Spanish HEP from articles indexed in the Science Citation Index (SCI) and arXiv between 2000 and 2005. Mele et al. (2006) considered the HEP preprints submitted in 2005 in the arXiv repository and observed that the scientific output later published in peer review journals is highly concentrated in six titles.

Corresponding to Mele et al. (2006), Aman (unpublished data) described the scholarly communication system using articles from core HEP journals indexed by Scopus, emphasizing that only three of the six publications centralizes 50% of HEP literature. Finally, Collazo-Reyes et al. (2004) observed publication and citing patterns in the Mexican Particle Physics community in SPIRES between 1971 and 2000, recognizing the communication models typical of a Big Science field.

MATERIALS AND METHODS

In December 2014, data were collected and Brazilian HEP articles for the 1983-2013 period were downloaded from the SCI of the multidisciplinary Web of Science (WoS) database. After importing 6,350 bibliographic records, the information was organized into a single file (.txt). We used the List of Authorities from the Grupo de Pesquisa Comunicação Científica of the Universidade Federal do Rio Grande do Sul (UFRGS) and the CNPq Plataforma Lattes to standardize the names of authors, institutions and countries. For impact analysis, data from 41,152 citing documents were imported using the WoS tool Create Citation Report.

The variables analyzed were Published Year (PY), Web of Science Category (WC), Source (SO), Author (AU), Author Address (C1) and Total Times Cited Count (Z9). General and specific scientometric indicators were used to characterize Brazilian HEP. *Output Indicators*: Total Publication (TP), Growth Rate (GR). *Collaboration Indicators*: International Collaboration (ICO), National Collaboration (NCO), Not Collaboration (NotC), Average Author Per Publication (AAPP), Average Institution Per Publication (AIPP), Average Country Per Publication (ACOPP). *Impact Indicators*: Publication Cited (PC), Total Citation (TC), H Index, Maximum Citation (MaxC), Average Citation Per Publication (ACPP). International co-authorship is the percentage of articles with authors from more than one country. With regard to data processing, software programs Bibexcel (descriptive analysis), Pajek

(collaboration networks), Philcarto (thematic mapping), SPSS 18.0 (multivariate analysis) and Microsoft Excel 2007 were used. Salton's Cosine was employed as similarity measure to examine the strength of the ties between Brazil and coauthoring countries, using the formula proposed by Luukkonen et al. (1993).

The thirty-one-year period studied (1983-2013) was aimed at ensuring greater reliability of scientometric indicators by using an extensive time period to analyze the evolution of scientific production in Brazilian HEP. In line with the strategy used by other researchers, such as Kretschmer and Rousseau (2001), Vanz (unpublished data) and Calero (unpublished data), this study employed total counts, that is, an article/citation for each author, institution or country.

RESULTS AND DISCUSSION

CHARACTERIZATION OF BRAZILIAN HEP RESEARCH

The Brazilian HEP contribution to the global output indexed in the WoS WC (Advanced Search) Physics, Particles & Fields for the 1983-2013 period was analyzed and compared with other countries. Brazilian articles accounted for 3% of the total investigated. The most productive country is the United States (29.78%), followed by Germany (13.60%), Italy (11.77%), the United Kingdom (9.10%) and Russia (8.96%). Brazil occupies the fourteenth position in terms of participation. In order to identify if this position can potentially change in the next years, the growth of Brazilian and international publications was examined. Fig. 1 shows the Brazilian growth (left vertical axis) with the total global production (right axis). While the global production shows an inverse parabolic growth ($R^2 = 0.979$), the Brazilian production increases much faster by an exponential growth ($R^2 = 0.9131$).

Our results show that the average publications growth in this period in Brazil, 14.27%, is larger than that of world publications, 3.78%. Since we analyze a more recent period of time, the average recorded here is higher than the 10.7% reported by Almeida and Guimarães (2013) for Brazilian scientific output from 1980 to 2010 period, the 6.4% found by Calero (unpublished data) for Spanish Particle Physics output indexed in the SCI between 2000 and 2005, and the 12.5% observed by Vanz (unpublished data) for Brazilian Physics articles published between 2004 and 2006. This recent exceptional growth, between 2009 and 2013, coincides with the establishment of RENAFAE. It is important to note that the increase in the number of national journals indexed in WoS from 2007 to 2008 and the resulting rise in Brazilian scientific production (Leta 2012; Vargas et al., 2014) did not affect HEP, since a negative growth rate was observed in 2008 (-18.91%). The creation of new CNPq research groups, the consolidation and expansion of graduate programs, greater financial resources and the key coordinating role of RENAFAE for Brazilian collaboration in international experiments may have been determining factors for the increase in the volume of papers in these years and, consequently, development in the field.

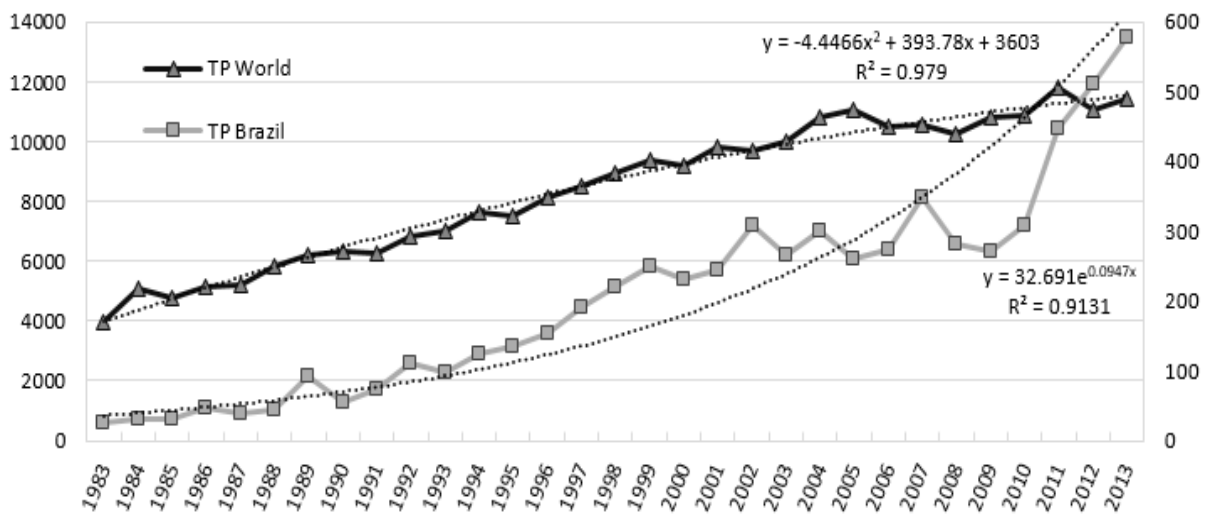


Figure 1 - Growth dynamics of Brazilian and international HEP publications, 1983-2013. The right axis is for the TP Brazil and the left axis for the TP World.

The Table I illustrates the year-on-year output, collaboration and impact data. The table shows for each year: the total number of publications (TP), the percentual growth rate between the number of publications in one year compared with the number in the previous year (GR), the number of publications in international collaboration (ICO), the number of publications in national collaboration (NCO), the number of publications without collaboration (NotC), the number of publications that received any citation (PC), the total number of citations (TC), the average number of citations per publication (ACPP).

TABLE I
Annual evolution of Brazilian HEP scientific activity, 1983-2013.

Year	Output		Institutional Collaboration ^a			Impact		
	TP	GR (%)	ICO	NCO	NotC	PC	TC	ACPP
1983	25	..	2	0	7	23	598	23.92
1984	32	28.00	2	3	10	27	382	11.93
1985	30	-6.25	3	3	10	29	279	9.30
1986	47	56.66	9	3	12	43	466	9.91
1987	39	-17.02	6	2	14	35	336	8.61
1988	44	12.82	9	1	9	42	858	19.50
1989	93	111.36	13	5	31	81	679	7.30
1990	54	-41.93	11	7	11	44	791	14.64
1991	73	35.18	17	1	27	60	863	11.82
1992	112	53.42	36	2	29	98	2,194	19.58
1993	97	-13.39	19	4	37	88	1,744	17.97
1994	123	26.80	39	9	38	102	1,499	12.18
1995	135	9.75	54	9	40	117	2,054	15.21
1996	153	13.33	50	10	43	141	2,891	18.89
1997	190	24.18	59	9	68	175	2,511	13.21
1998	221	16.31	121	29	71	198	3,072	13.90
1999	251	13.57	113	44	94	221	3,077	12.25
2000	231	-7.96	109	49	73	209	4,017	17.38
2001	244	5.62	114	42	88	221	3,587	14.70
2002	308	26.22	136	60	112	273	4,220	13.70
2003	265	-13.96	120	65	80	239	4,496	16.96
2004	300	13.20	115	77	108	255	4,978	16.59
2005	260	-13.33	117	64	79	224	3,542	13.62
2006	274	5.38	123	63	88	243	4,222	15.40
2007	349	27.37	132	93	124	295	3,983	11.41
2008	283	-18.91	114	81	88	267	4,021	14.20
2009	271	-4.24	122	63	86	241	2,978	10.98
2010	309	14.02	145	71	93	281	4,062	13.14

2011	448	44.98	256	92	100	383	4,246	9.47
2012	512	14.28	334	88	90	465	4,136	8.07
2013	577	12.69	388	81	108	446	2,030	3.51
..	6,350	14.27	2,888	1,130	1,868	5,566	78,812	12.41

TP *total publication*, GR *growth rate*, ICO *international collaboration*, NCO *national collaboration*, NotC *not collaboration*, PC *publication cited*, TC *total citation*, ACPP *average citation per publication*. ^a Within the 6,350 documents analyzed, 5,886 (92.70%) contained information in the C1 field in WoS.

A significant difference was observed in the number of published articles in the study period. In 1983, WoS indexed journals published only 25 papers by Brazilian researchers. In 2013, output reached its peak at 577 publications. A significant increase in scientific activity of Brazilian HEP was seen over the period.

Brazilian HEP scientific output indexed in WoS from 1983 to 2013 amounts to 6,350 articles, accounting for an average of 205 publications per year. The set of Brazilian HEP articles studied received 78,812 citations from 41,152 documents, representing an average of 12.41 citations per paper. In terms of visibility, significant internationalization of research in the field seems to have contributed to the high rate of articles with at least one citation (87.65%). According to Lehmann et al. (2003), a smaller number of minimally cited HEP articles would be expected, due to the operational cost of experiments, strict research controls and the large number of co-authors.

It is interesting to notice that the most cited article (484 citations), 'Properties and performance of the prototype instrument for the Pierre Auger Observatory', it was not for an experiment at CERN, but for building up an instrument for the the detection and study of cosmic rays in a large apparatus built in Argentina. The paper was published in 2004 by the Auger Collaboration in the journal Nucl. Instrum. Meth. A. This particular project was very important to Brazil because due to the location of the instruments, the technical support largely came from Brazilian companies.

Then we analyzed if the increase in citations in Brazilian HEP total publication partially resulted from the growth of international collaborations. Fig. 2 shows the number of

papers in international collaboration (ICO) at the left axis and the total number of citations (TC) at the right axis from 1983 up to 2008. Although the number of citations decreased in 2012-2013 because papers published in this period have not yet been incorporated by the scientific community and referenced in further studies (Meadows 1999), the expansion of International Collaboration contributed in some measure to the increased visibility of research by Brazilian scientists. In the Fig. 2 both the total number of citations and the number of papers in international collaborations are moderately correlated. Computing the Person correlation measurement namely:

$$r = \frac{\sum_{i=1}^n (x_i - \langle x \rangle)(y_i - \langle y \rangle)}{\sqrt{\sum_{i=1}^n (x_i - \langle x \rangle)^2} \sqrt{\sum_{i=1}^n (y_i - \langle y \rangle)^2}}$$

where x_i and y_i are the measures of total number of citations and total number of publications in international collaborations in each year and $\langle x \rangle$ and $\langle y \rangle$ are the average number along the period. Systems that show low correlation have r close to zero while systems in which the correlation is high the value is close to 1. In the case of TC and ICO $r=0.62$ what suggests moderate correlation.

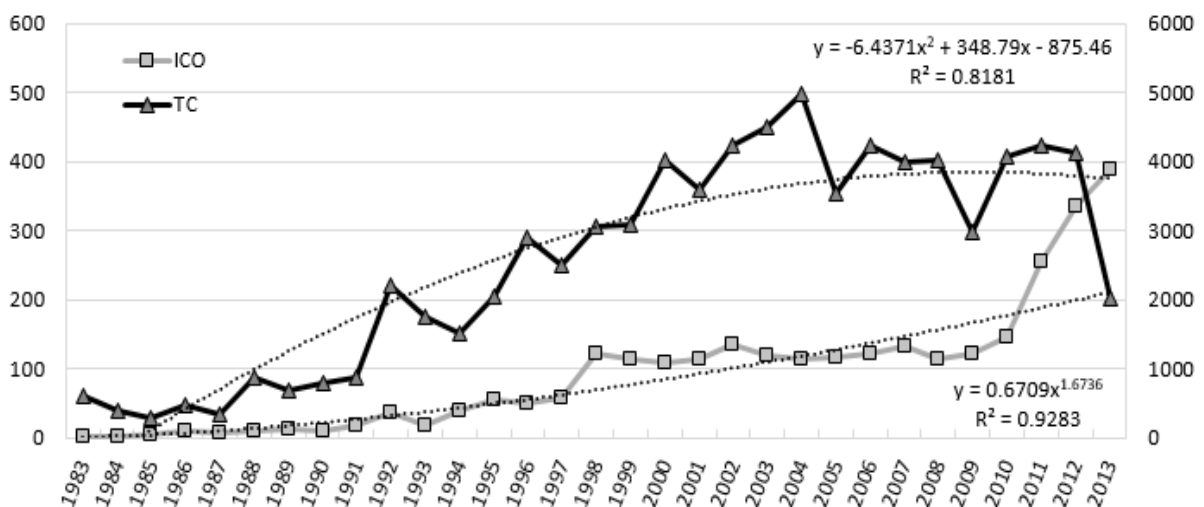


Figure 2 - International collaboration and citation patterns of Brazilian HEP, 1983-2013. The left axis is for the international collaboration (ICO), while the right axis is for the total number of citations (TC).

Brazilian HEP articles were analyzed by theme using the WC field in order to determine the distribution of publications per subject for the journals used and relate this to patterns of collaboration and citations received. The Table II shows for each sub domain in the high energy physics the total number of publications, the percentage of the total number of publications, the average number of authors per publication, the average number of institutions per publication, the average number of countries per publication, the total number of citations, the average number of citations per publication in each specified sub domain of HEP. It should be noted that the same document can be classified into more than one category, and as such, the sum of identified occurrences does not match the total number of articles in scientific production.

TABLE II
Thematic areas in the scientific output of Brazilian HEP, 1983-2013.

Sub domain	Output		Collaboration			Impact	
	TP	%	AAPP	AIPP	ACOPP	TC	ACPP
Astronomy & Astrophysics	3,003	45.63	98.13	12.50	3.66	43,987	14.64
Physics, Nuclear	1,228	18.66	5.05	2.40	1.58	6,529	5.31
Physics, Multidisciplinary	556	8.45	4.14	2.03	1.40	5,654	10.16
Nuclear Science & Technology	442	6.72	30.12	6.82	3.14	5,654	12.79
Instruments & Instrumentation	435	6.61	30.57	6.92	3.14	5,650	12.98
Spectroscopy	435	6.61	30.57	6.92	3.14	5,650	12.98
Physics, Mathematical	410	6.23	2.74	1.86	1.31	2,124	5.18
Computer Science, Theory & Methods	42	0.64	3	1.73	1.26	214	5.09
Meteorology & Atmospheric Sciences	7	0.11	7.42	2.85	2.42	41	5.85
Geosciences, Multidisciplinary	7	0.11	7.42	2.85	2.42	41	5.85
Engineering, Aerospace	7	0.11	7.42	2.85	2.42	41	5.85
Physics, Fluids & Plasmas	6	0.09	2.33	2	2	0	0
Materials Science, Multidisciplinary	1	0.01	3	3	3	0	0
Physics, Applied	1	0.01	3	3	3	0	0
Physics, Condensed Matter	1	0.01	3	3	3	0	0

TP total number of publication, percentage of the publications, AAPP average number of authors per publication, AIPP average number of institutions per publication, ACOPP average number of countries per publication, TC total number of citations, ACPP average number of citations per publication in each specified sub domain of HEP.

Despite the multidisciplinary and complexity of Brazilian HEP research, since Brazilian articles were also indexed by journals for other fields, the distribution publications

per WC in the period covered was low compared with the totality of subject categories of WoS. This indicator shows that the field studied often concentrates research results within a limited number of specialized journals. The concentration of the publications in the sub domain of Astronomy & Astrophysics and Nuclear Physics in Brazilian publications stems not only from their significant influence on HEP in the historical context, but also from the interest in subjects such as dark matter, neutrinos, The Big Bang, astroparticles, heavy-ion collisions, reactions on stars, and decays. The highest contribution and impact rates for the period were observed in the most productive WC and in technical areas strongly linked to detection methods and control of nuclear reactions (Nuclear Science & Technology), detectors and accelerators (Instruments & Instrumentation) as well as measurements of quantum numbers of particles (Spectroscopy). With only one article, the WCs Materials Science, Multidisciplinary; Physics, Applied and Physics, Condensed Matter showed low representativeness in the set of documents examined. As such, these three categories showed low AAPP, AIPP, ACOPP and ACPP.

Another aspect is the selection of the journals in which the publications appear. The Table III illustrates for each different journal (the home country of the journal is also specified) the total number of publication, the percentage of the number of publications, the average number of authors per publication, the average number of institutions per publication, the average number of countries per publication, the total number of citations, the H index, and the average number of citations per publication. The 6,350 Brazilian HEP articles indexed in WoS for the 1983-2013 period are published in 35 international English-language journals. The fact that the first PhDs in Physics and Astronomy were trained abroad is one of the reasons for the preference for English-language journals as a communication channel for research results (CAPES 2013). Among the 15 foreign journals that were most used by researchers, the titles published in Europe (Germany, England, the Netherlands, Italy) and in

the USA, responsible for publishing 85.20% of the articles (Table III), stood out. The absence of articles in journals published in Brazil confirms the strong internationalization of the field under study. In addition, Table III shows collaboration and impact indicators generated in order to establish the co-authorship and citation patterns of the publication sources preferred by Brazilian HEP scientists.

TABLE III
Fifteen main journals for Brazilian HEP scientific output, 1983-2013.

Journal (country)	Output		Collaboration			Impact		
	TP	%	AAPP	AIPP	ACOPP	TC	H Index	ACPP
Phys. Rev. D (USA)	2,259	35.57	124.23	14.93	4.15	35,640	70	15.77
J. High Energy Phys (ITA)	505	7.95	694.75	56.67	12.99	6,281	39	12.41
Eur. Phys. J. C (DEU)	449	7.07	619.09	56.48	13.98	6,019	34	13.40
Nucl. Instr. Meth. A (NLD)	435	6.85	30.57	6.92	3.14	5,650	34	12.98
Int. J. Mod. Phys. A (SIN)	382	6.02	2.46	1.82	1.34	1,733	19	4.53
Mod. Phys. Lett. A (SIN)	354	5.57	2.74	1.89	1.30	1,841	20	5.20
Class. Quantum Grav (GBR)	342	5.39	5.30	2.23	1.45	3,485	28	10.19
Nucl. Phys. B (NLD)	297	4.68	51.96	6.44	2.69	6,354	42	21.53
J. Phys. G (GBR)	232	3.65	12.02	3.49	1.95	1,780	21	7.67
Gen. Relat. Gravit (USA)	187	2.94	2.28	1.69	1.32	2,060	22	11.01
J. Cosmo. Astro. Phys (GBR)	140	2.20	27.88	6.45	2.68	1,305	17	9.32
Int. J. Mod. Phys. E (SIN)	133	2.09	4.35	2.33	1.53	317	9	2.38
Astropart. Phys (NLD)	67	1.06	117.26	22.19	6.04	1,455	20	21.71
Eur. Phys. J. A (DEU)	66	1.04	7.92	3.92	2.50	542	12	8.21
Int. J. Quantum Inf (USA)	24	0.38	2.79	1.58	1.08	146	7	6.08

TP total number of publication, percentage of the number of publications, AAPP average number of authors per publication, AIPP average number of institutions per publication, ACOPP average number of countries per publication, TC total number of citations, H index, ACPP average number of citations per publication in each different journal with the specified home country of the journal.

In terms of productivity, the importance of the most traditional HEP journals, such as Physical Review D, Journal of High Energy Physics, European Physical Journal C and Nuclear Physics B, was noted. As reported by Calero (unpublished data) and Aman (unpublished data), our results show a high concentration of publications in a few journals with a high Impact Factor in the field of Particle Physics, with 70% of articles published in six journals. This is lower than 83% reported by Mele et al. (2006) for the international HEP scientific output in 2005. The arrangement of articles by quartile revealed that the three most

productive journals fall under Q1. The level of excellence achieved by Brazilian HEP is supported by the number of top-rated graduate programs according to the 2013 CAPES Avaliação Trienal. The indicators in Table III show highly varied collaboration and impact patterns among different journals. The highest rates recorded were for the journals J. High Energy Phys. (AAPP, AIPP), Eur. Phys. J. C (ACOPP) and Astropart. Phys. (ACPP). Our results also confirm the correlation between H index and citations (Hirsch, 2005) as proposed by Hirsch.

Even though HEP is built in collaborations, the individuals play a relevant role. The Table IV shows the list of more productive Brazilian authors on HEP including their total number of publications, the total number of citations, the number of citations of their paper with the maximum number of citations, the average number of citations per publication. The most productive Brazilian scientist for the period was Maria Elena Pol, a female PhD in Physics from the Pontifícia Universidade Católica of Rio de Janeiro, with 316 articles. She is currently Head Researcher II for CBPF, with experience in the field of experimental HEP and especially in the standard model of electroweak interactions, data processing software, physics of detectors, and particle identification. She is also a member of CERN's Compact Muon Solenoid (CMS) research group.

TABLE IV
Twenty most productive Brazilian HEP authors, 1983-2013.

Author (institution)	Output	Impact			
	TP	TC	H Index	MaxC	ACPP
Pol M. E. (CBPF)	316	6,503	39	413	20.57
Mundim L. (UERJ)	282	5,255	34	413	18.63
Begalli M. (UERJ)	243	6,097	39	413	25.09
Alves G. A. (CBPF)	241	4,808	34	413	19.95
Novaes S. F. (UNESP)	235	4,204	33	413	17.88
Gandelman M. (UFRJ)	228	4,220	32	317	18.59
Carvalho W. (UERJ)	219	4,436	33	413	20.25
Amato S. (UFRJ)	219	4,008	32	317	18.30
Gregores E. M. (UNESP)	217	3,846	30	413	17.72
Santoro A. (UERJ)	215	3,941	33	413	18.33
Mercadante P. G. (UNESP)	215	3,050	28	153	14.18
Sznajder A. (UERJ)	202	3,585	29	413	17.74
de Paula L. (UFRJ)	177	2,466	26	104	13.93
da Silva W. L. P. (UERJ)	165	2,516	26	413	15.24
Nogima H. (UERJ)	161	2,487	25	484	15.44
Lopes J. H. (UFRJ)	159	2,066	23	104	12.99
Oguri V. (UERJ)	156	3,324	29	413	21.30
Rangel M. S. (UFRJ)	156	2,383	25	153	15.27
do Vale M. A. B. (UFRJ)	151	1,852	21	302	12.26
Marechal B. (UFRJ)	150	3,491	31	317	23.27

TP total number of publication, TC total number of citations, H index, MaxC maximum number of citations, ACPP average number of citations per publication for each specific author.

The 20 most productive Brazilian authors are experimental and they are affiliated to public institutions in the states of Rio de Janeiro and São Paulo: Universidade do Estado do Rio de Janeiro (UERJ), Universidade Federal do Rio de Janeiro (UFRJ), Universidade Estadual Paulista Júlio de Mesquita Filho (UNESP) and Centro Brasileiro de Pesquisas Físicas (CBPF). The distribution of the number of articles per author between 1983 and 2013 shows that 7,674 (29.87%) published only one paper. The rate obtained is almost 30% lower than the 60% predicted by Lotka's inverse square model, as shown in other HEP studies (Kretschmer and Rousseau 2001).

The productivity and impact of the group of scientists were estimated using the H Index. In terms of individual productivity, the good performance of Brazilian HEP is related to the active participation in CNPq research groups and international collaboration with

CERN in Switzerland as well as Fermilab and Brookhaven in the United States. As a co-author in the most cited HEP article (484 citations), Hélio Nogima (UERJ) had the highest MaxC, while researchers Marcia Begalli (UERJ) and Bernard Marechal (UFRJ) had the highest ACPP for the period.

Since the HEP is a very cooperative field the analysis of the geographic distribution of the publications is relevant to understand how much the field percolated in the country. The Table V shows the total number of publications, the percentage of the number of publications, the total number of citations, the average number of citations per publication for the different states in Brazil. The table indicates that the federal and state institutions (predominantly universities) lead the ranking of the most productive institutions in Brazilian HEP. The leading role of institutions from the states of São Paulo and Rio de Janeiro is evident, accounting for almost 76% of the articles produced. Leta and Cruz (2003) explain that the quantitative differential of graduate students, scientists and organizations involved in the activity and a greater research tradition are among the main factors responsible for the leading position of these states in Brazilian science. On the other hand, the regional concentration of technical and scientific production is a peculiarity of peripheral countries where the decentralization of science is very costly. Although Southeastern states were most cited, the highest ACPP in the period under study corresponded to Mato Grosso (Mid-west). Its partnership with institutions in more productive regions may have influenced this result.

TABLE V
Distribution per state of Brazilian HEP scientific output, 1983-2013.

State	Output		Impact		State distribution of TP
	TP	%	TC	ACPP	
São Paulo	3,616	37.89	39,537	10.93	
Rio de Janeiro	3,591	37.63	31,422	8.75	
Minas Gerais	504	5.28	3,196	6.34	
Paraíba	445	4.66	4,321	9.71	
Rio Grande do Sul	303	3.17	1,879	6.20	
Espírito Santo	194	2.03	1,688	8.70	
Distrito Federal	165	1.73	2,463	14.92	
Bahia	146	1.53	2,473	16.93	
Paraná	134	1.40	1,031	7.69	
Rio Grande do Norte	85	0.89	1,291	15.18	
Ceará	77	0.81	482	6.25	
Pará	76	0.80	492	6.47	
Santa Catarina	61	0.64	573	9.39	
Maranhão	43	0.45	593	13.79	
Pernambuco	35	0.37	231	6.60	
Goiás	14	0.15	86	6.14	
Sergipe	14	0.15	54	3.85	
Roraima	11	0.12	41	3.72	
Alagoas	10	0.10	79	7.90	
Tocantins	9	0.09	80	8.88	
Amapá	3	0.03	5	1.66	
Mato Grosso	3	0.03	84	28.00	
Piauí	3	0.03	5	1.66	
Acre	1	0.01	0	0.00	
Mato Grosso do Sul	1	0.01	0	0.00	

TP total number of publication, percentage of number of publications, TC total number of citations, ACPP average number of citations per publication for the different states in Brazil. The map is in the right panel.

In order to understand how the HEP network percolates within each state of Brazil, the productivity of the different institutions was analyzed. The Table VI illustrates the total number of publication, the percentage of the number of publications, the total number of citations, the H index, the number of citations of the paper with maximum number of citations, the average number of citations per publication for the different institutions. Universidade de São Paulo (USP) is the most productive institution in HEP between 1983 and 2013. Its influence on Brazilian science is the result of its focus as a research university and

the substantial funding it receives from the state research support agency FAPESP (Leta 2011).

TABLE VI
Twenty most productive institutions in Brazilian HEP, 1983-2013.

Institution	Output		Impact			
	TP	%	TC	H Index	MaxC	ACPP
Univ. São Paulo (USP)	1,436	14.96	19,697	58	484	13.71
Centro Brasileiro de Pesquisas Físicas (CBPF)	1,165	12.13	18,395	55	484	15.78
Univ. Est. Paulista Júlio de Mesquita Filho (UNESP)	944	9.83	13,997	51	413	14.82
Univ. Fed. Rio de Janeiro (UFRJ)	908	9.46	13,082	49	317	14.40
Univ. Estado Rio de Janeiro (UERJ)	707	7.36	11,244	44	413	15.90
Univ. Estadual Campinas (UNICAMP)	491	5.11	7,707	43	484	15.69
Univ. Fed. Paraíba (UFPB)	366	3.81	4,142	31	151	11.31
Univ. Fed. ABC (UFABC)	361	3.76	5,211	32	261	14.43
Pontifícia Univ. Católica Rio de Janeiro (PUC-Rio)	283	2.95	5,917	39	317	20.90
Univ. Fed. Juiz de Fora (UFJF)	227	2.36	2,028	22	86	8.93
Univ. Fed. Fluminense (UFF)	166	1.73	2,331	21	484	14.04
Univ. Fed. Espírito Santo (UFES)	158	1.65	1,694	23	71	10.72
Univ. Fed. Rio Grande Sul (UFRGS)	148	1.54	1,253	19	79	8.46
Univ. Fed. São João del-Rei (UFSJ)	127	1.32	1,010	15	51	7.95
Centro Nacional de Energia Nuclear (CNEN)	111	1.16	570	12	45	5.13
Univ. Brasília (UnB)	108	1.12	955	16	85	8.84
Instituto Nacional de Pesquisas Espaciais (INPE)	92	0.96	308	11	42	7.33
Centro Técnico Aeroespacial (CTA)	90	0.94	1,111	18	125	12.34
Observatório Nacional (ON)	81	0.84	1,251	19	109	15.44
Univ. Fed. Rio Grande Norte (UFRN)	77	0.80	1,277	19	116	16.58

TP total number of publication, percentage of the number of publications, TC total number of citations, H index, MaxC maximum number of citations, ACPP average number of citations per publication for the different institutions.

Centro Brasileiro de Pesquisas Físicas holds the second place in the productivity ranking. Since its inception in 1949, the national center has worked in a variety of research fields, including cosmology and relativity, high energy and cosmic rays, nuclear physics and astrophysics, fields and particles, etc. CBPF has carried out several projects in collaboration with universities and national and international research institutes, in addition to participating in a number of HEP projects with the CERN and Fermilab laboratories since 1980. In 2000, the center began effective participation in the Pierre Auger Observatory Project, which involves around 20 countries (CBPF 2011). The highest ACPP corresponds to Pontifícia

Universidade Católica do Rio de Janeiro, the only private university among the most productive institutions.

SCIENTIFIC COLLABORATION LEVELS

In the previous subsection the year by year temporal evolution of the number of publications (Table I), of the distribution in different sub fields (Table II) and of the distribution in different journals (Table III) were presented. Since changes occur in a much larger scale than the year by year an analysis over the decades was performed. Table VII shows the evolution per decade of the 6,350 articles, as well as the average number of authors, institutions and countries per article and the rate of collaboration in Brazilian HEP. This table shows that the strong presence of Brazilian researchers in international collaborations between 2010 and 2013 justified the increase in the averages in this last period and explains the continuous increase in the average number of authors per article. Comparatively, the average of 155.89 authors for the 1983-2013 period is higher than the 8.96 presented by Newman (2001a, 2001b, 2004a), the 24.8 reported by Krause et al. (2007) for HEP publications in SPIRES between 1995-1999 and 2005-2006, respectively, and the 62 recorded by Calero (unpublished data) for Spanish Particle Physics articles indexed in SCI between 2000 and 2005. Only 11.39% of the articles were written by a single author and 68.26% presented co-authorship between two or more entities. Based on the share of articles with ≥ 4 countries (37.26%), the existence of large networks was confirmed. Experiments with accelerators and particle detectors require the joint use of facilities, e participation by experts from different areas, and economic contributions from several countries (Bordons and Gómez 2000; Vanz and Stumpf 2010).

TABLE VII
Summary of the main collaboration results for Brazilian HEP, 1983-2013.

Period	Average Per Publication			% Collaboration		
	Authors	Institutions	Countries	Authors	Institutions	International
1983-1992	9.55	3.74	2.29	85.79	45.76	36.61
1993-2002	36.49	6.38	2.98	86.53	61.90	46.70
2003-2013	237.37	22.91	5.92	90.07	72.87	51.00
1983-2013	155.89	17.05	4.87	88.61	68.26	49.07

Another interesting effect is the correlation between productivity and connectivity. The number of citations is directly correlated with the number of authors and with the number of countries involved in the paper (Jones et al. 2008; Ale Ebrahim et al. 2013). This also applies for the HEP in Brazil. The five most productive institutions in Brazilian HEP are also the most connected in the inter-institutional collaborative network. The level of clustering demonstrates the significant concentration of research within a small number of institutions, most notably universities. With regard to co-authorship, the presence of specialized centers with a tradition in Nuclear Physics and High Energy Physics is noted, such as Centre National de la Recherche Scientifique (CNRS) and Commissariat à L'énergie Atomique (CEA) in France, Istituto Nazionale di Fisica Nucleare (INFN) in Italy, and the Joint Institute for Nuclear Research (JINR) and Institute for High Energy Physics (IHEP) in Russia. The role of American (Fermilab) and European (CERN) experimental laboratories in establishing institutional partnerships is clear, as is the importance of INFN in terms of funding and productivity (Mele et al. 2006; Adams and King 2009). The predominance of foreign institutions in the network confirms the internationalization of research and Brazil's presence in the multinational groups DØ (Fermilab), CMS and DELPHI (CERN).

The international collaborative network for Brazilian HEP displays strength as to its structure. Absolute indicators show that the United States (6.10%) is Brazil's main partner in terms of co-authoring for the 1983-2013 period, followed by Russia (4.56%), and CERN Member States with a long history in experimental research: France (4.34%), Germany

(4.32%), UK (4.19%), and Italy (4.18%). The low presence of the USA in HEP articles implies a decline in Brazil's scientific dependence and the consolidation of ties with other partners, mostly in Europe.

The intensity of inter-country collaboration was classified according to criteria adopted by Leta et al. (2006): strong relationship (Salton's Cosine ≥ 2.5); medium relationship (Salton's Cosine ≥ 1 and < 2.5); weak relationship (Salton's Cosine < 1). Relative indicators show that neighboring Colombia (20.6) is Brazil's main co-author (Table VIII). Geographical proximity encourages the establishment of partnerships (Katz 1994), especially in a country as Brazil, where geographical distance is a decisive factor in collaboration (Sidone et al. 2016). In the field of HEP, the analysis of collaborative strength indicates decentralization and diversification for Brazil's collaborations, with a strong presence of East European countries such as the Czech Republic (16.7), Serbia (16.1), Georgia (14.8) and Belarus (13.8).

TABLE VIII
Main countries collaborating with Brazil in HEP, 1983-2013.

Country	Absolute indicators		Country	Relative indicators	
	TP	Share (%)		TP	Salton Cosine
USA	1,399	6.10	Colombia	441	20.6
Russia	1,042	4.56	Czech Rep.	635	16.7
France	994	4.34	Serbia	294	16.1
Germany	991	4.32	Georgia	304	14.8
United Kingdom	961	4.19	Belarus	295	13.8
Italy	959	4.18	Portugal	565	13.6
Spain	818	3.57	Ecuador	117	13.2
Poland	704	3.07	Armenia	361	12.9
Switzerland	693	3.02	Slovenia	327	12.4
China	660	2.88	Greece	508	11.5
Czech Rep.	635	2.77	Lithuania	142	11.5
Netherlands	623	2.72	Poland	704	11.1
Portugal	565	2.47	Austria	460	10.9
Greece	508	2.22	Romania	347	10.9
Sweden	482	2.10	Netherlands	623	10.6
Austria	460	2.01	Estonia	141	10.4
Colombia	441	1.92	Mexico	424	10.2
Mexico	424	1.85	Spain	818	10.2
India	420	1.83	Norway	325	10.1
Belgium	391	1.71	Argentina	346	20.6

TP *total number of publication.*

ORIGIN OF CITING DOCUMENTS

Results of the impact of HEP research were presented and discussed in previous analyses, and citations were characterized in relation to time evolution (Table I), the fields (Table II), the publishing journals (Table III), the author productivity (Table IV) and the institution productivity (Table V, Table VI). Within the 41,152 citing documents analyzed, 39,555 (96.11%) contained information in the C1 field in WoS (Table IX). The number of international citing articles for Brazilian HEP production was 34,721 (87.78%). Citations from documents produced by authors affiliated with foreign institutions, including studies in collaboration with Brazil, are considered international. On the other hand, national citations correspond to publications produced exclusively by researchers affiliated with Brazilian institutions. Among the international documents, 30,327 (76.67%) originate from articles published by foreign authors, while 4,394 (11.11%) are from papers produced through foreign collaboration with Brazil. In addition, national HEP scientists accounted for 4,834 (12.22%) citing documents published in the 1983-2015 period. The high number of researchers affiliated with foreign institutions in citing documents underscores the internationalization of research and low self-citation in the field under study.

TABLE IX
Summary of the main results for Brazilian HEP citations, 1983-2013.

Period	Citing documents					
	Nat	%	Nat&Int	%	Int	%
1983-1993	117	14.63	99	12.38	584	73.00
1994-2004	1,660	15.44	1,290	12.00	7,801	72.56
2005-2015	3,057	10.92	3,005	10.73	21,942	78.35
1983-2015	4,834	12.22	4,394	11.11	30,327	76.67

Nat *National*, Nat&Int *National and International*, Int *International*.

Figure 3 shows the global influence of Brazilian HEP research. Brazil's main partners (and the most productive ones in High Energy Physics) between 1983 and 2013 also lead the

ranking of citing countries. The United States tops the list of 112 citing nations, with 10.25% of the documents published, followed by CERN Member States such as Germany (6.14%), Italy (4.99%), and UK (4.45%).

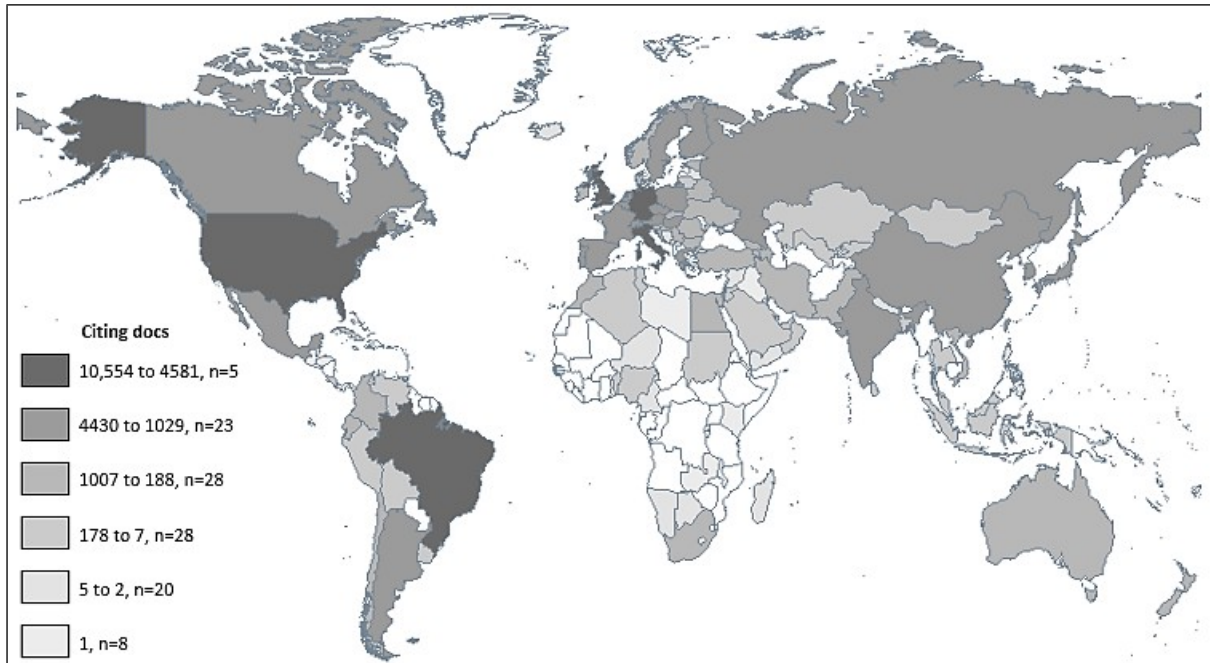


Figure 3 - Geographical distribution of citing documents for Brazilian HEP, 1983-2013.

CONCLUSION

The contribution of Brazilian HEP to global output indexed in the WoS WC Physics, Particles & Fields from 1983-2013 accounts for 3% of the total investigated. The national average annual growth rate for publications is higher than the global average, but more inconsistent, with a sharp increase in domestic production between 2009 and 2013. The creation of new CNPq groups, the consolidation of graduate programs, the establishment of RENAF AE, and increased funding and international collaborations may have been key factors in this growth in these years, as well as development in the field. Astronomy & Astrophysics and Physics, Nuclear are the most representative fields in Brazilian articles. This suggests that having the

infraestructure of graduate programs and regular funding through RENAFAE might be the ingredient for the growth.

The most productive authors are affiliated with institutions in the Rio de Janeiro-São Paulo axis and belong to the experimental subfield. The data show a concentration of scientific activity in public institutions (predominantly universities). USP, Brazil's largest university, leads the ranking in terms of productivity and citations received. The theoretical subfield stood out for articles written by a single author. This result indicates that the growth in science was driven by the infraestructure and money since both regions in addition to the RENAFAE funds also have strong financial support from their state.

Scientists' preference for publishing in English-language foreign journals, associated with collaboration patterns in terms of authors, institutions and countries, indicated the presence of Brazil in multinational Big Science experiments and the internationalization of Brazilian HEP. Absolute indicators demonstrate that the USA, Russia and France are the country's main partners. Relative indicators show decentralization and diversification in national collaborations. The high number of foreign researchers in citing documents underscores the global prestige and visibility of local production. The results of the analytical characterization suggest a maturation process in the Brazilian HEP community as a result of its long history in experimental research. Indeed, the status of Associate Member of CERN may boost Brazil's credibility in long-term projects, consolidate areas of expertise on instrumentation and data analysis tools (software programs), and enhance the influence of the country's science in the international arena. The scenario of highly internationalized HEP participation of Brazil follows the international trend in which productivity and impact are associated with large and multicultural groups.

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RESUMO

Este artigo apresenta uma análise da pesquisa brasileira em Física de Altas Energias (FAE) indexada pela Web of Science (WoS) no período de 1983-2013. Indicadores cientométricos de output, colaboração e impacto foram utilizados na caracterização do campo abordado. Os resultados mostram que os artigos brasileiros representam 3% do total da pesquisa em FAE mundial e que a forte aceleração da atividade científica entre 2009 e 2013 pode ter sido consequência da consolidação dos programas de pós-graduação, da ampliação do financiamento e colaborações internacionais e da instituição da Rede Nacional de Física de Altas Energias (RENAFAE) em 2008. Os resultados também indicam que o padrão de colaboração de autores, instituições e países confirmaram a presença do Brasil nos experimentos multinacionais da Big Science, o que também pode explicar a prevalência de documentos citantes estrangeiros, ressaltando o prestígio e a visibilidade da produção dos cientistas brasileiros no âmbito internacional em decorrência da sua longa trajetória na pesquisa experimental.

Palavras-chave: Brasil, Cientometria, Colaboração científica, Física de Altas Energias, Impacto, Produção científica.

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