Scientometrics (2019) 119:437–480
https://doi.org/10.1007/s11192-019-03030-1

How latecomers catch up to leaders in high-energy physics as Big Science: transition from national system to international collaboration

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Received: 19 September 2018 / Published online: 23 February 2019

Abstract

This study describes the increase of research productivity of latecomer countries (latecomers) in the high-energy physics (HEP) community by research strategies based on a national system and international collaboration (IC). The INSPIRE system, a bibliographic database for HEP researchers was used to obtain the number of publications and citations as indicators of research productivity. Our bibliometric estimates highlight two main results. First, latecomers' national systems of public research institutes play a major role, and initially produced a large proportion of the research output, but this influence declined as IC increased. Second, IC greatly increased both the quantity and quality (number of citations) of research output in all latecomers. In most countries, the IC strategy has shown a strong correlation with the research output. The findings highlight the importance of a national research-support system and development of IC as strategies for new states that are entering the HEP field, and provide comparison of the two strategies. Further bibliometric research, such as examination of the strategic patterns of the leading countries will broaden the understanding of the national units of the HEP academic community.

Keywords High energy physics · Big science · Latecomers · National policy · Public research institutes · International collaboration

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Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11192-019-03030-1) contains supplementary material, which is available to authorized users.

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Introduction

In the field of research policy, studies on latecomer countries have focused on applied research and technology accumulation. However, in basic research, especially in Big Science such as high energy physics (HEP), the catch-up strategies of the latecomers have not been well studied. HEP is a basic field of research in science, but at the same time it is one of the Big Sciences, in that research funds, manpower, facilities and international collaboration (IC) can be huge (Braun et al. 1992; Martin and Irvine 1981; Meadows 2012; Autio et al. 2004; Vuola and Hameri 2006). Some studies about catch-up strategies of latecomers have been conducted, but have focused on economic output, and have revealed that latecomers can have difficulty in responding to economic and social demands just by following the traditional linear model of innovation that the advanced countries (first-movers) followed when they initiated research in the field (Choung and Hwang 2013; Goldemberg 1998). However, few studies have considered the strategic patterns of latecomers that are trying to augment the academic output of their HEP research.

In most countries, universities are primarily responsible for conducting HEP, due to its basic scientific nature. The universities are representative of the public sector, which has traditionally been responsible for basic research in all areas of science (Jung and Lee 2014; Nelson 1959). This tendency was particularly strong when HEP was being developed around theoretical physics before the particle accelerator became larger in its size and cost as an experimental device.

Public research institutes (PRIs) are also part of the public sector. They are clearly separated from universities, and function as important *knowledge infrastructure* (Wong et al. 2015; Mathews and Hu 2007; Potì and Reale 2000; Smith 1997). PRIs have different labels (e.g., government research institutes; national laboratories) in different nations (Hallonsten and Heinze 2012; Doel 2003), but are all mission-oriented organizations and have large-scale projects, and are thus distinct from universities.

Public HEP research institutes around the world vary in form. Some are operated as joint-use facilities by several universities, and thereby blur the distinction between universities and PRIs. Among first-mover countries, Ko Enerugi Kasokuki Kenkyu Kiko (KEK) in Japan is an example of this type; the Brookhaven National Laboratory (BNL) in the United States also began in this form (Amaldi 2015). Among latecomers, the University of Chile and the Institute of Physics of the National Autonomous University of Mexico (IFUNAM) are the main examples. Although they belong to universities, they can be classified as PRIs because their accelerators are run for national use, and because they are corporations in law, or are public facilities funded by governments. Operation of very high-energy accelerators requires large financial resources, so public research institutes are commonly of a form in which the government may actively intervene. In particular, these high-energy accelerators have been considered to be a major factor to explain the development of the first-movers. This will be described in the next section.

Few studies have examined PRIs in the field of HEP. Some of these have observed that PRIs have been actively engaged in research activities such as international joint projects (Martin and Irvine 1984b, c) or operating accelerator facilities for experimental physicists in a region (Bonaccorsi 2007; Martin and Irvine 1984a).

Brief history of PRIs, accelerator facilities, and publications in HEP

The global academic community of HEP has continued to develop. Particle accelerators are major experimental devices for HEP. The first one was developed in 1932, and their numbers and performance have been rapidly increased. The first accelerator was constructed for £1000 (~€70,000 in 2015) (https://www.measuringworth.com/calculators/exchange/, followed by conversion of US$ to €) and the development period was only 3 years. Currently, the Large Hadron Collider (LHC) of the European Organization for Nuclear Research (CERN) is the largest; it cost about € 5×10^9, and the construction period has grown to about 25 years (Amaldi 2015). This huge cost in time and money has led most countries to found the PRIs to house and operate such expensive large-scale facilities or to enter IC to gain access to them.

Along the increase in the number of countries establishing such institutes which house and operate particle accelerators, the number of researchers and publications has also increased sharply. Talented researchers have constantly flowed into the field and revitalized the community, and this process led to great discoveries such as the Higgs particle and Nobel prizes.

Significant particle accelerators (A.1 in online appendix) have been developed by leading countries or research institutes who entered HEP academia in the early years and have been steadily performing. Other accelerators have been developed by companies (for materials research), and hospitals (for medical use); these and low-energy devices from universities cannot provide enough energy for HEP research, and are not considered here. As of 2016, more than 40,000 HEP papers have been published (A.1 in online appendix); 90% of them have been contributed by the top 40 countries, including first-movers and latecomers (A.1 in online appendix).

Particle accelerators have evolved from the initial Cockcroft–Walton accelerator to the Cyclotron, the Synchrotron, the Linear accelerator, the Synchro-cyclotron and the Collider (Amaldi 2015). This evolution has increased the probability of concentrating a bunch of dispersed particles at a single point, and the kinetic energy that can be imparted to particle beams. The Particle Collider is a modern form of the accelerator; its development began in the 1960s, and allowed the maximum beam energy to be increased to 1 GeV (Moritz 2001; Irvine and Martin 1985), which today is recognized as a high-energy region (Panofsky 1997).

Several colliders were built in the early 1960s. AdA of the Italian public research institute INFN at Frascati (operational since 1961), VEP-1 at Novosibirsk in Russia (since 1964), and CBX (since 1962) of the US Princeton–Stanford collaboration allowed HEP research into new energy realms (Richter 2014).

Many major countries have a national system of PRIs that operate particle accelerators. European CERN, US Fermilab, Stanford Linear Accelerator Center (SLAC), BNL, Italian INFN, German Electron Synchrotron (DESY), Japanese KEK and Russian Institute for High Energy Physics (IHEP) and Russian Joint Institute for Nuclear Research (JINR) are representative. However, some old, established laboratories have undergone changes in organizational missions in response to the emergence of world-class high energy facilities such as the TEVATRON in Fermilab and the Large Electron–Positron Collider (LEP) and LHC of CERN. These laboratories have secured the institutional persistence of PRIs and have moved away from classical HEP research by making strategic changes to provide services as Synchrotron Radiation facilities (SR), that instead satisfy the research demands of users from other fields of science, such as materials and medicine (Hallonsten and Heinze 2012, 2013, 2015; Westfall 2012).

International collaboration

Studies on IC in science and technology have been reported since the 1960s, and many researchers have observed that IC has increased significantly in all areas of science (Glänzel and Schubert 2004; Wagner 2005). This trend is common to both advanced countries (core) and latecomers (periphery). IC is a global system that brings greater advantages to the core group than to the periphery (Leydesdorff and Wagner 2008). IC has induced increases in both quantity and quality of HEP research (Persson et al. 2004; Narin 1991).

IC has benefitted HEP (Kim 2005; Braun et al. 1992) by diluting the economic burden of establishing and operating expensive research facilities (Wagner 2005; Luukkonen et al. 1992), by enabling specialization of operating complex instrumentation and facilities, and by fostering professionalization of all procedures from research planning, experimentation (theories and experiments), publishing, and management (Katz and Martin 1997).

The IC has also fostered the growth of HEP. Today most of the internationally-collaborative research publications that have the largest number of researchers are derived from CERN LHC experiments (Adams 2012). The proportion of scientific papers that have resulted from IC is increasing in all countries, including latecomers (Kim 2005; Collazo-Reyes et al. 2010). This growth is being driven by HEP large collaborations (HEPLCs) with huge accelerator facilities (Manganote et al. 2016); for example, the recent discovery of the Higgs particle at LHC, has spawned an explosive increase in the number of publications throughout the HEP community. These giant experiments have affected the research strategies of the players in HEP.

This paper describes the increase in the academic productivity of latecomers in the field of HEP, and provides an explanation for latecomers' patterns of strategic responses that support the achievement by entering IC, and improving national systems such as the PRIs. We analyzed the increase in the quantity and quality of latecomers' research publications that were produced in HEPLCs rather than by simple collaboration between individuals and compared these parameters to those of papers produced by the national system of PRIs.

Although the latecomers have in common that they increase their research capacity by combining PRIs and IC, the proportions of these components differ among countries and over time. In particular, the intensified ICs pivoting around CERN since the mid-2000s are changing the pattern of research strategies of latecomers' progress. We will document such variations.

This paper is organized as follows. In the "Data and method" section, the "Data source and its reliability" subsection introduces the HEP bibliometric database, INSPIRE. The "National system, IC and bibliometric output" subsection describes the data of publications and citations as research output and reviews the method of obtaining the data of national systems and ICs as explanatory variables. "The latecomers" section provides definitions and research outcomes of latecomers. The "Results" section presents the research output of latecomers, individually and together. The "National system (PRIs) and research output" and "IC and research output" subsections respectively, present analyses of how PRIs and IC strategy patterns affect research output. The "Variation along the countries and time period" subsection documents the evolution of strategic patterns across individual countries and over time from the 1960s to the recent 2010s. The "Discussion" section presents an evaluation of the results of the analysis, and an examination of the theoretical implications of the pattern variations of the national system, accelerator infrastructure, and IC strategies.

Data and method

Data source and its reliability

Although, as representative databases for bibliometric method in all areas of science, there are Web of Science (WoS) of Clarivate Analytics and Scopus service provided by Reed Elsevier (Archambault et al. 2009), but for high energy physics, a database called *INSPIRE* (http://inspirehep.net) has successfully settled and helped numerous bibliometricians who studied the field (Sánchez et al. 2018; Perović et al. 2016; Collazo-Reyes et al. 2004, 2010). INSPIRE evolved from the Stanford Public Information REtrieval System in High Energy Physics (SPIRES-HEP) database developed by Stanford University, and has become a web interface by adding the information technologies that CERN, DESY, Fermilab and SLAC had. For data sources, based on the initial Stanford data, the INSPIRE has worked with HEP Publishers who provided data of refereed journals, with e-print provider arXiv, with NASA-ADS which is one of the leading institutions in the field of astrophysical research, and with the Particle Data Groups (PDG) that provide raw data for particle physics. INSPIRE provides a customized bibliometric analysis of peer-reviewed journal articles. It is increasing its power by providing a variety of tools such as a function that can exclude self-citations. INSPIRE data are well documented from the early records of HEP history, so the database is helpful for researchers in other fields such as history and science policy because it enables them to see the historical flow of HEP. INSPIRE also includes data from non-English journals, which have increased in number over time. INSPIRE meets the statistic conditions for normality and for time-series datasets (Jarque Bera test) (Bai and Ng 2001).

National system, IC and bibliometric output

Productivity in HEP is quantified by the number of refereed articles, and the quality of the work is quantified by the number of citations or the impact factor (Martin and Irvine 1983, 1984a, b, c; Irvine and Martin 1985). To measure research quality, various measurement tools such as impact factor (Nederhof 2006) and h-index (Hirsch 2005; Bar-ilan 2008) have been developed, but they focus on comparing individual competencies or the excellence of journals, rather than on national units. However, several recent studies on the HEP research output at the level of macroscopic units such as nations are based on the publications and simple citation measurements (Manganote et al. 2016; Hassan et al. 2016; Gupta and Dhawan 2009; Collazo-Reyes et al. 2004; Godbole 2002; Rovira et al. 2000; Six and Bustamante 1996; Czerwon 1990).

Measurements here consider only refereed journal articles. Proceedings and conference papers were excluded because they tend to be published as peer-reviewed articles later; book chapters were excluded because they tend to be based on the contents of journal articles. The time period of analysis was limited to records until the year 2016, because all INSPIRE publications records are updated in real time, so recent publications are subject to frequent changes, and because the age of a publication strongly affects the number of citations that it can amass.

The INSPIRE system has about 1,238,000 records, of which 667,000 are refereed journal articles. INSPIRE provides the basic search formula for all types (e.g., time period, institutes) of refereed journal articles. Using China in 1965 as an example the search code is

$$\text{find tc p and cc CN and jy 1965,} \tag{1}$$

where *tc* p is a type code of publications, denoting refereed journal articles here, *cc* is a country code and *jy* is the year of publication. The formula draws articles from the refereed journals (*tc* p), published by an author belonging to a Chinese institute (*cc* CN) in 1965 (*jy* 1965). Since the INSPIRE nationality is based on the authors' affiliations (http://inspirehep.net/info/hep/search-tips), so the record is given to the country where the institute is located. For citations, 5-year aggregated records were utilized. The citation search formula for China in the 5-year period, from 1965 to 1970 is

$$\text{find tc p and cc CN and cx: } 50+ \text{ and } d \text{ } 1965 \rightarrow 1970; \tag{2}$$

The formula draws articles cited more than 50 excluding self-citation (*cx*: 50+) from the refereed journals (*tc* p), published by an author belonging to a Chinese institute (*cc* CN) during 1965–1970 period (*d* 1965→1970). We have excluded the self-citations because of the concern that the multi-authorship characteristics in HEP could be a strong factor in the increase of citations, and because the huge number of authors in papers produced by the recent LHC experiment, in particular, could cause a bias in comparison with papers from the past (Aksnes 2003).

We have considered the major PRIs that make up the national systems of 13 latecomers (Table 1). These PRIs can be categorized as those that operate particle accelerator facilities, those that are internationally collaborative, or as general PRIs. For most of these countries, we selected the institutes that contribute >1% of the total number of publications in each country for the entire period (until 2016). For China, Spain, and South Korea, which produce many more publications than other countries, all institutes that published >100 articles were considered.

For international collaborative institutes such as the astronomical observatories operated by ESO in Chile, they are marked as *international* separately due to the double counting of publications from national system and IC. A more specific description of each country's PRIs is provided in the following "Result" sections.

The publication data of these PRIs is based on the institutional information provided by the INSPIRE system. The basic search formula for refereed journal articles and 5-year aggregated citations of PRIs, with China as an example, is

$$\text{find tc p and cc CN and aff Beijing, Inst. High Energy Phys. (not aff other institutes followed by)} \tag{3}$$

$$\text{find tc p and cc CN and aff Beijing, Inst. High Energy Phys. (not aff other institutes followed by) and } d > 2016 \tag{4}$$

$$\begin{aligned}&\text{find tc p and cc CN and cx: } 50+ \text{ and } d \text{ } 1965 \rightarrow 1970 \text{ not aff Beijing, Inst. High Energy Phys.}\\&\text{not aff A not aff B} \ldots \text{(All the other institutes followed)}\end{aligned} \tag{5}$$

For the total number of publications, an institutional term is added to the basic formula (1), but a duplicate avoidance search (*not aff*) should be performed to prevent double counting between PRIs. The results are obtained by subtracting the number of journal articles (*tc* p) published after 2016 (*d*>2016) by the Chinese (*cc* CN) IHEP (*aff* Beijing, Inst. High

Table 1 Major PRIs of the latecomer countries

Country	Name of the PRIs	Year of foundation
Argentina	Cordoba Observatory	1871
	National Atomic Energy Commission, CNEA (Accelerator)	1953–1954
	Bariloche Atomic Center, CAB (Accelerator)	1955
	Balseiro Institute[a]	1955
	National Scientific and Technical Research Council, CONICET	1958
	Argentine Institute of Radio Astronomy at Villa Elisa	1962
	LIDAR division of Laser and Applications Research Center, CEILAP	1994
	Pierre Auger Observatory (International)	2004
Armenia	Yerevan Physics Institute (Accelerator)	1943
	National Academy of Sciences, NAS	1943
Chile	University of Chile, Faculty of Physics (Accelerator)	1842
	European Southern Observatory, ESO (International)	1962
	Cerro Tololo Inter-American Observatory, CTIO (International)	1965
	Las Campanas Observatory (International)	1969
	Gemini Observatory (International)	2000
	Scientific and Technological Centre of Valparaiso, CCTVal	2009
China	Purple Mountain Observatory, PMO	1928
	Yunnan Observatories	1938
	Institute of Physics	1950
	Peking University, PKU (Accelerator)	1952
	Institute of Modern Physics, IMP (Accelerator)	1957
	China Institute of Atomic Energy, CIAE (Accelerator)	1958
	Beijing Observatory	1958
	Shanghai Institute of Applied Physics, SINAP (Accelerator)	1959
	Shanghai Institute of Nuclear Research, SINR	1959
	Shanghai Astronomical Observatory, SHAO	1962
	Institute of High Energy Physics, IHEP (Accelerator)	1973
	Institute of Theoretical Physics, ITP	1978
	China Center of Advanced Science and Technology, CCAST	1986
	National Laboratory of Heavy Accelerator Lanzhou, HIRFL	1991
	National Synchrotron Radiation Laboratory, NSRL (Accelerator)	1991
	Kavli Institute for Theoretical Physics China, KITPC (International)	2006
	Theoretical Physics Center for Science Facilities, TPCSF	2007
	The Collaborative Innovation Center of Quantum Matter, CICQM	2012
Colombia	National Astronomical Observatory	1803
Finland	Tuorla Observatory (1991–2009)	1991
	Helsinki Institute of Physics, HIP (Accelerator)	1996
Greece	National Observatory of Athens	1842
	Academy of Athens	1926
	Institute of Nuclear and Particle Physics, INP (Accelerator)	1959
	Research Center for Astronomy and Applied Mathematics. RCAAM	1959
	Foundation for Research and Technology-Hellas, FORTH	1983

Table 1 (continued)

Country	Name of the PRIs	Year of foundation
Iran	Teheran Nuclear Research Center, TNRC (Accelerator)	1974
	Institute for Research in Fundamental Sciences, IPM	1989
	Institute for Advanced Studies in Basic Sciences, IASBS	1991
	Research Institute for Astronomy & Astrophysics of Maragha, RIAAM	2002
Mexico	Institute of Physics of the UNAM, IFUNAM (Accelerator)	1939
	National Institute for Nuclear Research, ININ (Accelerator)	1956
	Center for Research and Advanced Studies of IPN, CINVESTAV	1961
	School of Physics and Mathematics of the IPN, ESFM	1961
	National Council of Science and Technology, Conacyt	1970
	National Institute of Astrophysics, Optics and Electronics, INAOE	1971
	CINVESTAV Merida branch	1980
	Computing Research Center of the IPN, CIC	1996
Portugal	Lisbon Astronomical Observatory (–1995)	1878
	Instituto Superior Técnico, IST (Accelerator)	1954
	Laboratory of Instrumentation and Experimental Particle Physics, LIP Lisbon	1986
	LIP, Coimbra	1986
South Korea	Korea Institute of Science and Technology Information, KISTI	1962
	Korea Astronomy and Space Science Institute, KASI	1974
	Pohang Accelerator Laboratory, PAL (Accelerator)	1988
	School of Physics of Korea Institute for Advanced Study, KIAS	1996
	The Center for High Energy Physics, CHEP	2000
	Institute for Basic Science, IBS	2011
Spain	Spanish National Research Council, CSIC at Madrid	1939
	CSIC at Catalunya	1942
	Canary Islands Astrophysics Institute, IAC	1974
	Institute of Astrophysics of Andalusia, IAA	1975
	Institute for the Structure of Matter, IEM	1976
	The Isaac Newton Group of Telescopes, ING (International)	1984
	Centre for Energy, Environment and Technology Research, CIEMAT	1986
	Laboratory for Space Astrophysics and Theoretical Physics, LAEFF of ESA (International)	1991
	Institute of mathematics and fundamental physics, IMAFF	1992
	Institute of Physics of Cantabria, IFCA	1995
	The Institute of Space Studies of Catalonia, IEEC	1996
	National Accelerator Center, CNA (Accelerator)	1998
	Catalan Institution for Research and Advanced Studies, ICREA	2001
	Institute for Theoretical Physics, IFT	2003
	Consortium for the Construction, Equipping and Exploitation of the Synchrotron Light Source, CELLS (Accelerator)	2003
	European Space Astronomy Centre, ESAC of ESA (International)	2004
	Basque Foundation for Science, IKERBASQUE	2007
	Institute of Space Sciences, ICE	2008

Table 1 (continued)

Country	Name of the PRIs	Year of foundation
Taiwan	Institute of Physics of Academia Sinica	1962
	National Synchrotron Radiation Research Center, NSRRC (Accelerator)	1994
	Physics division of National Center for Theoretical Sciences, NCTS at Hsinchu	1997
	Mathematics division of NCTS, NCTS at Taipei	1997
	Institute of Astronomy and Astrophysics, ASIAA	2010

The Balseiro Institute is an affiliate of the National Atomic Energy Commission of Argentina (CNEA); we eliminated double counting by subtracting publications of Balseiro from the number of CNEA publications when we calculated research output. This relation problem was solved in the same way for other institutions

Energy Phys.), from the total number of publications in the entire period by Chinese IHEP [(3)–(4)].[1] However, the citation is obtained by subtracting the results of a non-PRIs search from the formula (2), which is the basic citation search [(2)–(5)].[2] These steps yield the number of publications and citations published by each country (here, China) from their PRIs until 2016.

IC is defined as research output as a result of participation in HEPLCs. INSPIRE provides a 'Collaboration/Experiments' field for this search. The HEPLCs are about 1200 experiments in nine categories (http://inspirehep.net/info/Experiments/list). They include all major collaboration/experiments, such as LHC and LEP at CERN, Fermilab, KEK Japan, BNL, DESY Germany, SLAC, the Laser Interferometer Gravitational-Wave Observatory (LIGO) in astronomy, and LATTICE in theoretical physics.

The basic search formula for IC of China is

$$\text{find tc p and cc CN and exp FNAL* (not exp BEPC*)} \tag{6}$$

$$\text{find tc p and cc CN and exp FNAL* (not exp BEPC*) and } d > 2016 \tag{7}$$

$$\begin{aligned}&\text{find tc p and cc CN and cx: 50 + and } d \text{ 1965} \rightarrow \text{1970 not exp BNL* not exp A not exp B} \ldots\\&\text{(All the other international collaborations followed)}\end{aligned} \tag{8}$$

Similarly, this is a method to subtract the journal articles (*tc* p) after 2016 ($d > 2016$) published by Chinese authors (*cc* CN) participating in Fermilab collaborations (*exp* FNAL*), from all publications [(6)–(7)]. However, a term must be added to exclude an experiment hosted by its own country, because such experiments are difficult to categorize into HEPLCs that have a low proportion of foreign researchers, unlike global experiments such as the ones of CERN in Switzerland. The Beijing Electron–Positron Collider (BEPC) experiment of China is the only significant case of this type among the latecomers (*not exp* BEPC*). The citation data for IC are obtained by subtracting the publications of HEPLCs

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[1] Because the whole period search of INSPIRE is much faster than the partial period search (*d* 1960→2016), time was saved by subtracting the result of partial period search after 2016 ($d > 2016$) from the whole period search.

[2] In this case, the PRIs are searched as 'a lump', so double counting does not occur. On the contrary, formula (3) searches for each institute, double counting can occur, so another term should be added to exclude subordinate (or superordinate) institutes.

in which China did not join (non-IC publications), from the 5-year aggregated records in formula (2) [(2)–(8)].

These commands can obtain the number of publications and citations published by each country (here, China) from their IC until 2016.

The latecomers

The term ‘latecomers’ has no generally accepted definition. Manganote et al. (2016) and De Almeida and Guimarães (2013) define the leaders in research output growth ranking in recent years as ‘emergent’ scientific countries. Godbole (2002) uses the rankings of publications and average numbers of citations for 21 years from 1980–2000 to identify countries that have developed relatively quickly. Leydesdorff and Wagner (2008) identify latecomers by using a core-periphery framework in interaction networks. Choung and Hwang (2013) define latecomers in combination with the economic concept of newly industrializing economies.

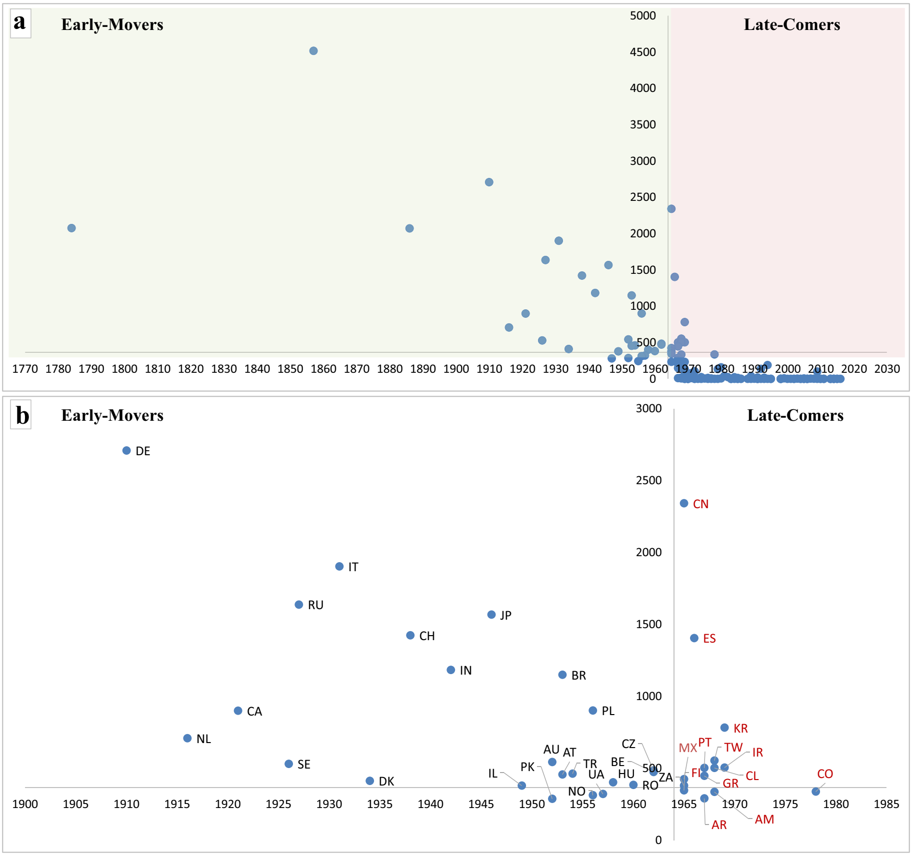

Fig. 1 Identification of latecomers. **a** All data. First quadrant (pink): latecomers; second quadrant (green): first-movers. Total number of publications decreases as debut date increases, so most latecoming and minor countries are concentrated in the fourth quadrant. **b** Enlargement of the chart to enable identification of countries. (Color figure online)

According to the existing studies, latecomers in HEP can be defined by their research productivity, based on the ranking of publications and citations for a specific period of time, as indicators of quantity and quality respectively. The time span depends on the subfield of science, but is related to the development history of the particle accelerator as an experimental device, and to the time of first research publication (Fig. 1).

Particle colliders began to be constructed in the 1960s (Richter 2014; Shiltsev 2013; Panofsky 1997; Six and Bustamante 1996), along with the first boom of publishing in the HEP field (A.1 in online appendix). Until then, the pioneers in the HEP academia were the leading scientific powers such as the United States, UK, Italy, Germany, the Soviet Union, France, and Japan, which remain advanced countries leading the field as of 2016.[3] Therefore, the countries that made their academic debuts after the 1960s should be examined. We classified countries on two axes (Fig. 1): the time of debut (x-axis) and current share of publications in academia (y-axis), with latecomers defined as countries whose debuts were after the 1960s, out of the 40 nations that contribute 90% of world HEP publications. The first-movers are both a pioneer and a major contributor to the academia, and the latecomers are a group of countries that have accepted their breakthroughs and carried out active catch-ups (Sabatier and Chollet 2017).

As of 2016, the number of HEP publications was 41,473; of these, the top 40 countries accounted for 90%.[4] The 13 countries that made their debut in international HEP after the 1960s are Argentina, Armenia, Chile, China, Colombia, Finland, Greece, Iran, Mexico, Portugal, South Korea, Spain, and Taiwan (Fig. 3).[5] These countries have the following in common: (a) they first entered HEP academia by publishing for two or three consecutive years after 1965, (b) they have contributed a significant part of world publications as of 2016, (c) and they show consistent increases in growth and scale from 1965 to 2016.

Results

Research output

As a group, the 13 latecomers showed an exponential rise in both the number of publications and citations over the entire period. All countries except Colombia, began to present their research results to the academic community in the late 1960s or at in 1970. The largest increase in the number of publications occurred in 2011–2012, with average growth of >20%, with 1200 and 1500 publications more than the previous year, respectively.

The next largest growth was during 2004–2005 period, in which the growth was 23% (700 publications more than the year before) and 16% (600 more) respectively. The greatest decreases were in 2013 (−7.6%, −610 papers), 1999 (−6.5%, −143) and 2008 (−1.5%, −79) (Fig. 2).

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[3] The advanced group is 13 countries (USA, Germany, UK, France, Italy, USSR/Russia, Japan, Switzerland, India, Brazil, Poland, Canada, Denmark).

[4] This figure includes double counting. The number of publications worldwide has been added to the total number of publications in each country, and double counting has been allowed to confirm its share of the top 40 countries.

[5] Although Taiwan is technically not accepted as a nation state, we follow the nationality of INSPIRE system which is based on internet country codes.

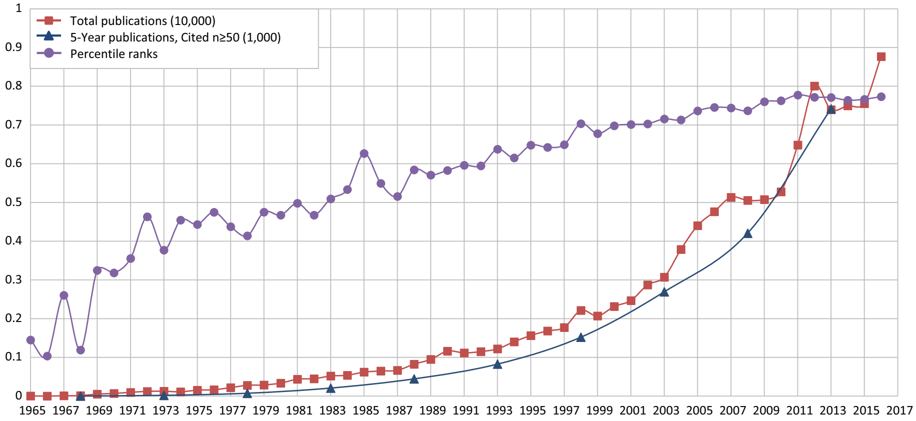

Fig. 2 The total number of publications, 5-year aggregated highly-cited publications, and percentile ranks of latecomers. The total number of publications (red) shows decline and stagnation during 2008–2010 and 2013–2015. In contrast, the citation count shows an almost continuous exponential increase. As a convergent oscillation for ranking curve (De Solla Price 1986), it has recently been stabilized at about the level of top 20–25%. (Color figure online)

The results of 5-year aggregated citations also show quantitative expansion. The number of publications cited $n > 50$ times follow an exponential rise curve with a smoother shape than the total publications (Fig. 2). The number of publications cited $n > 15$ times increased exponentially in all sections, except $n \geq 500$ and $n \geq 1000$ (Table 2).

To rank publications, a *simple ranking* that does not reflect newly participated countries in the HEP academic community, must be distinguished from a *Percentile ranks*. The number of countries that are participating in HEP has increased steadily, so simple ranking does not reveal the relative rise of latecomers among all nations. For instance, the average ranking of latecomers in the *simple ranking* has shown almost no change, from 26.5th in 1965 through fluctuations to 25.6th in 2016, whereas percentile rank shows that the latecomers have risen from the bottom 10% (<15th percentile) level to the top 20%. The ranking curve of latecomers as a whole (Fig. 2), has followed a relatively logistic pattern with the top 20% as a ceiling.

The time trends in number of publications and number of highly-cited ($n \geq 50$) of latecomers generally show basic exponential growth (A.2 in online appendix); this trend is a characteristic of "a sort of adolescent stage" in HEP history (De Solla Price 1986). Future study should examine whether the advanced countries also showed this pattern, or whether exponential growth has begun to slow to a logistic form. The ranking trends for each country also show logistic curves, with convergent oscillation near the 20–30% level in general (except China). This trend suggests that the advanced countries are maintaining their first-mover advantage.

National system (PRIs) and research output

The PRIs of latecomers contribute about 41% of overall research productivity (Table 3). This is a very large proportion as a single player, and confirms that PRIs are important contributors to HEP growth in these countries. The PRIs as a national system have 45,979

Table 2 Publications, highly-cited publications, and percentile ranks of latecomers. Percentile ranks: average of latecomers' percentile ranks of publications in the world in a given year

	Publications	Citations ($n \geq 15$)	$n \geq 30$	$n \geq 50$	$n \geq 100$	$n \geq 250$	$n \geq 500$	$n \geq 1000$	$n \geq 5000$	$n \geq 10{,}000$	Percentile ranks
1965	5	2	1								14.5
1966	2										10.3
1967	9										26.0
1968	14	21	9	2	1						11.9
1969	51										32.5
1970	69										31.8
1971	98										35.6
1972	122										46.3
1973	127	69	33	20	8	3	2				37.7
1974	111										45.5
1975	154										44.3
1976	165										51.9
1977	220										43.8
1978	279	196	114	74	32	9	3				41.4
1979	288										47.5
1980	336										46.7
1981	437										49.8
1982	450										46.7
1983	519	495	311	208	100	35	8	3			51.0
1984	539										53.3
1985	621										62.7
1986	648										54.9
1987	667										51.6
1988	825	1061	662	445	176	48	13	6			58.4
1989	948										57.1
1990	1162										58.3

Table 2 (continued)

	Publications	Citations ($n \geq 15$)	$n \geq 30$	$n \geq 50$	$n \geq 100$	$n \geq 250$	$n \geq 500$	$n \geq 1000$	$n \geq 5000$	$n \geq 10{,}000$	Percentile ranks
1991	1117										59.6
1992	1149										59.5
1993	1220	2074	1310	826	298	66	21	12			63.8
1994	1404										61.5
1995	1565										64.8
1996	1684										64.2
1997	1772										64.9
1998	2214	4059	2447	1521	628	151	40	15	5	4	70.4
1999	2071										67.8
2000	2315										69.8
2001	2468										70.2
2002	2872										70.3
2003	3072	7407	4452	2693	1142	274	92	21	4		71.6
2004	3789										71.3
2005	4403										73.6
2006	4763										74.6
2007	5133										74.4
2008	5054	11,475	6987	4207	1699	475	144	65	17		73.7
2009	5077										76.0
2010	5276										76.3
2011	6483										77.8
2012	8006										77.2
2013	7396	18,944	12,251	7417	2993	683	162	76	42		77.1
2014	7496										76.4
2015	7555										76.7

e.g. Percentile rank of China, Finland, Greece, Mexico, and Taiwan is 14.5% respectively in 1965, and the resulting percentile rank is, on average, 14.5%

Table 3 Numbers and proportion of publications contributed by PRIs and accelerator facilities for each country

Country	Total	PRIs		Accelerator PRIs	
		Sum	Ratio (%)	Sum	Ratio (% of PRIs)
Sum	112,987	45,979	40.7	9643	21.0
Argentina	4622	1429	30.9	731	51.2
Armenia	3571	3158	88.4	3139	99.4
Chile	4711	1341	28.5	228	17.0
China	29,481	15,072	51.1	365	2.4
Colombia	2226	26	1.2		0.0
Finland	5522	2634	47.7	2509	95.3
Greece	6677	2097	31.4	1622	77.3
Iran	4413	2089	47.3	26	1.2
Mexico	6757	3470	51.4	844	24.3
Portugal	5643	1732	30.7	64	3.7
South Korea	10,716	2701	25.2	57	2.1
Spain	22,270	7158	32.1	21	0.3
Taiwan	6378	3072	48.2	37	1.2

publications, which for 41% of the total 112,987, and the PRIs operating accelerator facilities have published 9643 papers which account for ~8% of all latecomers' publications and about one-fifth of the total output of the PRIs.

PRIs definitely contribute a large part of the quantity of publications from each latecomer, but not to the overall quality, as quantified by number of citations (Table 4). The latter is relatively overshadowed by the increase in the quality of IC research, which will be examined in a later section.

PRIs steadily contributed 20–30% of publications that have been cited > 15 times, before 2001–2005 period, and strengthened the research capabilities of latecomers by increasing the share to 50%. The effect of PRIs on the trend of ranking is not easy to identify as shown in Fig. 2. However, when compared with data of the accelerator facilities by modifying the Fig. 2 (Panofsky 1997), PRIs appear to have some effect (Fig. 3).

Latecomers built many facilities with maximum beam energy > 1 GeV during the periods of about 1985–1995 and 2007–2013. The accelerator facilities and their agency seem to have had some influence on the research productivity, but statistical research and case studies should be conducted to determine whether any clear correlation exists.

Detailed examination of country-specific research output was based on the list of PRIs (Table 1), and the list of particle accelerators and the PRIs that operate them (Table 5). Argentina has two PRIs that are operating particle accelerator facilities or equipment, but the country has no 'high energy' accelerator with beam energy > 1 GeV (Moritz 2001; Irvine and Martin 1985).

Argentine PRIs produced 1429 publications (Table 3), which account for 30.9% of the national total. About half of them (731) were published by CAB and CNEA, which are accelerator PRIs. Argentina had its highest publication growth rate of 200% in 1971, and with the highest absolute increase in number of publications in 2011–2012. Further research is needed to confirm whether the growth in 1971 was affected by CAB's accelerator, but research quantity and quality have not increased significantly since TANDAR began operation in 1985. The PRIs have produced 10–20% of the most-highly-cited publications

Table 4 The PRIs' share of highly-cited publications in latecomers (5 years)

	Number of citations								
	$n \geq 15$	$n \geq 30$	$n \geq 50$	$n \geq 100$	$n \geq 250$	$n \geq 500$	$n \geq 1000$	$n \geq 5000$	$n \geq 10{,}000$
1961–65 Total PRIs citations ratio	2	1							
	1	0							
	0.500	0.000							
1966–70 Total PRIs citations ratio	21	9	2	1					
	7	3	2	0					
	0.333	0.333	1.000	0.000					
1971–75 Total PRIs citations ratio	69	33	20	8	3	2			
	19	8	4	1	0	0			
	0.275	0.242	0.200	0.125	0.000	0.000			
1976–80 Total PRIs citations ratio	196	114	74	32	9	3			
	65	33	17	11	4	2			
	0.332	0.289	0.230	0.344	0.444	0.667			
1981–85 Total PRIs citations ratio	495	311	208	100	35	8	3		
	113	69	48	27	13	4	1		
	0.228	0.222	0.231	0.270	0.371	0.500	0.333		
1986–90 Total PRIs citations ratio	1061	662	445	176	48	13	6		
	317	214	143	48	15	3	3		
	0.299	0.323	0.321	0.273	0.313	0.231	0.500		
1991–95 Total PRIs citations ratio	2074	1310	826	298	66	21	12		
	727	483	311	111	23	8	6		
	0.351	0.369	0.377	0.372	0.348	0.381	0.500		
1996–2000 Total PRIs citations ratio	4059	2447	1521	628	151	40	15	5	4
	1329	790	486	209	49	13	7	3	3
	0.327	0.323	0.320	0.333	0.325	0.325	0.467	0.600	0.750

Table 4 (continued)

	Number of citations								
	$n \geq 15$	$n \geq 30$	$n \geq 50$	$n \geq 100$	$n \geq 250$	$n \geq 500$	$n \geq 1000$	$n \geq 5000$	$n \geq 10{,}000$
2001–05 Total PRIs citations ratio	7407	4452	2693	1142	274	92	21	4	
	2909	1737	1036	452	120	48	9	2	
	0.393	0.390	0.385	0.396	0.438	0.522	0.429	0.500	
2006–10 Total PRIs citations ratio	11,754	6987	4207	1699	475	144	65	17	
	4987	3001	1859	799	250	78	34	8	
	0.424	0.430	0.442	0.470	0.526	0.542	0.523	0.471	
2011–15 Total PRIs citations ratio	18,944	12,251	7417	2993	683	162	76	42	
	9988	6872	4301	1763	405	94	41	23	
	0.527	0.561	0.580	0.589	0.593	0.580	0.539	0.548	

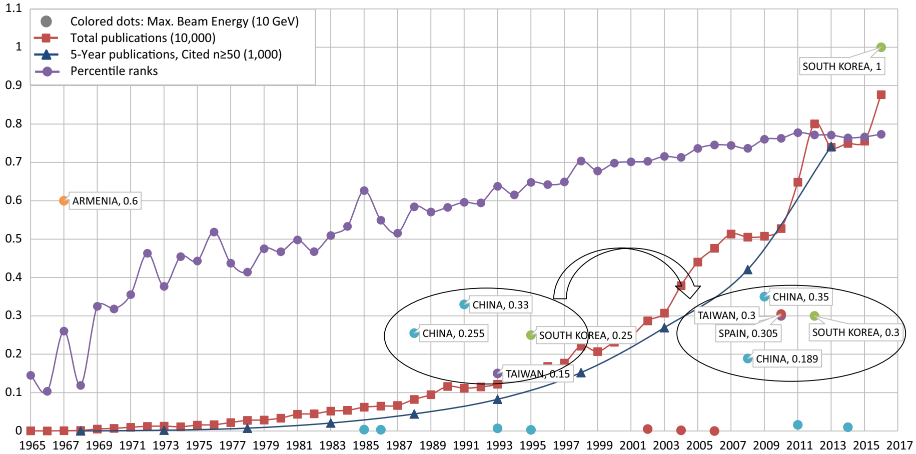

Fig. 3 Maximum beam energy of major colliders and Latecomers' research output. Colored dots: sum of the energies of the accelerators that have maximum beam energy > 1 GeV and that began operating in that year. The Armenian accelerator built in 1967 (6 GeV) is excluded, because no relevant records were identified; the Korean accelerator built in 2016 (10 GeV) is excluded because it is a laser-based accelerator, rather than a typical collider. (Color figure online)

(number of citations, $n \geq 15$) since the 1990s (A.3 in online appendix), although this rate has varied over time.

In Armenia, the Yerevan Physics Institute has operated the 6 GeV HEP accelerator 'ARUS' since 1967. However, despite having had a state-of-the-art facility at a fairly high energy of 6 GeV since an early time, little is known about how the facility has been operated and upgraded, how it is used currently, and how this has led to research output. The case of Armenia is peculiar because it was part of the USSR, which is among the 'Early-movers', and this makes a relevant difference from the other 'latecomers'. The PRIs of Armenia have published 3158 journal articles, which is about 88.4% of the total; this is the highest rate among the 13 latecomer countries. The high proportion of these PRIs is also evident in citations: PRIs have accounted for > 90% of all sections of citations (A.3 in online appendix).

Chile is distinctive by its high proportion of astronomical facilities.[6] The four observatories (The European Southern Observatory, CTIO, Las Campanas Observatory, and Gemini Observatory) are also international PRIs. These PRIs published a total of 1341 publications, which account for 28.5% of the total. However, the PRIs' contributions are of high quality. With the exception of the periods 1986–1990 and 2011–2015, > 40% of the highly-cited Chilean articles were from PRIs.

China has a large number of PRIs (Table 1); most of them belong to the Chinese Academy of Sciences (CAS), which is a research council system that can be compared to the National Center for Scientific Research (CNRS) in France and the Helmholtz Association in Germany. China also has many accelerator resources (Table 5); those with energy facilities > 1 GeV are the Beijing Electron Positron Collider (BEPC) of IHEP, the Beijing

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[6] The 'astronomy' category of INSPIRE does not cover all sub-disciplines of astronomy, but only major experiments related to HEP, specifically those related to the dark-matter search and dark energy studies.

Table 5 Major particle accelerator equipment/facilities and their operating institutes, with foundation year of institute, first operation year of the accelerator

Country	Organization/major accelerators	Year of foundation	Year of first operation	Type/particles	(Max) Beam energy (GeV)
Argentina	CAB	1955			
	Linac at CAB		1970	Linac/Electron	0.025
	CNEA (TANDAR Laboratory)	1953–1954			
	Tandem Accelerator		1985	Electrostatic/Ion	0.02
Armenia	Yerevan Physics Institute[b]	1943			
	ARUS		1967	SR[a]/Eelectron	6
Chile	University of Chile	1842			
	22 in. Cyclotron		1962	Cyclotron/Proton	0.01
	KN3750		1998	Electrostatic/Ion	0.0037
China	IMP	1957			
	1.5 m Heavy-Ion Cyclotron		1963	Cyclotron/Ion	0.1
	HIRFL[c]		1988	SR[a]/Ion	1
	CIAE	1958			
	V2		1958	Electrostatic/Proton	0.0025
	30 MeV Linac		1964	Linac/Electron	0.03
	HI-13		1986	Electrostatic/Proton	0.013
	CYCIAE-30		1995	Cyclotron/Proton	0.03
	CYCIAE-100		2014	Cyclotron/Proton	0.1
	IHEP	1973			
	BPL		1985	Linac/Proton	0.035
	BEPC-I		1988	Collider/Electron	1.55
	BSRF		1991	SR[a]/Eelectron	2.5
	BFEL		1993	FEL/Electron	0.03
	BEPC-II		2008	Collider/Electron	1.89
	CSNS		2017	SR[a]/Ion	1.6

Table 5 (continued)

Country	Organization/major accelerators	Year of foundation	Year of first operation	Type/particles	(Max) Beam energy (GeV)
	NSRL	1991			
	HLS		1991	SR[a]/Electron	0.8
	SINAP	1959			
	1.2 m Proton Cyclotron		1964	Cyclotron/Proton	< 0.03
	6 MV Tandem Accelerator		1993	Electrostatic/Proton, Ion	0.012
	SSRF		2009	SR/Electron	3.5
	SDUV-FEL		2011	FEL/Electron	0.16
	PKU School of Physics	1952			
	4.5 MV Van de Graaff		1986	Electrostatic/Proton, Ion	< 0.02
Colombia					
Finland	HIP	1996			
	3 MeV Van de Graaff		1959	Electrostatic/Protron	0.003
	5 MV Van de Graaff		1982	Electrostatic/Proton, Ion	< 0.01
	JYFL	1965			
	MC20 mini-cyclotron		1975	Cyclotoron/Proton	0.02
	K130 Cyclotron		1993	Cyclotron/Proton	< 0.065
	1.7 MV Pelletron		2007	Linac/Ion	< 0.015
	MCC30/15 Cyclotron		2010	Cyclotron/Proton, Deuteron	< 0.03
Greece	INP	1959			
	Golfo		1963	Electrostatic/Proton, Ion	< 0.001
	T 11/25 Van de Graaff		1975	Electrostatic/Proton, Ion	< 0.04
Iran	AEOI TNRC	1974			
	3 MeV Van de Graaff		1974?	Electrostatic/Proton	0.003
	AEOI YRPC	1998			
	Rhodotron TT200		1998	Cyclotron/Electron	0.01

Table 5 (continued)

Country	Organization/major accelerators	Year of foundation	Year of first operation	Type/particles	(Max) Beam energy (GeV)
	AEOI NRCAM	1991			
	Cyclone 30		1995	Cyclotron/Proton, Deuteron	0.03
Mexico	UNAM	1939			
	2 MV Van de Graaff		1953	Electrostatic/Ion	< 0.0025
	700 keV Van de Graaff		1973	Electrostatic/	0.00007
	5.5 MV CN Van de Graaff		1986	Electrostatic/Ion	< 0.02
	3 MV Pelletron		1995	Electrostatic/Ion	< 0.01
	ININ	1956			
	6 MV EN-Tandem		?	Electrostatic/Proton	0.012
	2 MV Tandetron		2000	Electrostatic/Proton, Ion	0.004
Portugal	IST/ITN	1954			
	2 MeV Van de Graaff		1960	Electrostatic/	0.002
	0.6 MeV Cockroft–Walton		1960	Electrostatic/	0.0006
	2.5 MV Van de Graaff		1999	Electrostatic/Proton	< 0.0025
	3 MV Tandem Accelerator		2006	Electrostatic/	0.006
South Korea	PAL	1988			
	Pohang Light Source-I		1995	SR[a]/Eelectron	2.5
	Pohang Light Source-II		2012	SR[a]/Eelectron	3
	PAL-XFEL		2016	FEL/Electron	10
Spain	CELLS	2003			
	ALBA Synchrotron		2010	SR[a]/Eelectron	3
	CMAM	2003			
	5 MV Tandetron		2002	Electrostatic/Ion	< 0.05

Table 5 (continued)

Country	Organization/major accelerators	Year of foundation	Year of first operation	Type/particles	(Max) Beam energy (GeV)
	CNA	1998			
	3 MV Van de Graaff		1998	Electrostatic/Proton, Ion	0.006
	Cyclrotron 18/9		2004	Cyclotron/Proton	< 0.018
	1 MV Tandetron		2006	Electrostatic/Ion	< 0.001
Taiwan	NSRRC	1983			
	TLS		1993	SR[a]/Eelectron	1.5
	TPS 3.0 GeV		2014	SR[a]/Eelectron	3

[a] Synchrotron radiation facility

[b] Renamed to Alikhanyan National Laboratory in 2011

[c] In 2008, upgraded to HIRFL-CSR

[d] From 2010 to 2014 upgraded to HIRFL-CSR

Synchrotron Radiation Facility (BSRF), the China Spallation Neutron Source (CSNS), the Heavy Ion Research Facility in Lanzhou (HIRFL) of IMP, and the Shanghai Synchrotron Radiation Facility (SSRP) of SINAP.

China began establishing major laboratories relatively early (1950s), and made its debut in the international academic community in the 1960s, when the first accelerators in IMP and CIAE were built. However, during the 1960s and 1970s, the country's HEP activities in the international arena highly contracted as a result of the deterioration of Sino-Soviet relations and the Cultural Revolution (Zhang and Fang 2016). This stagnation is noticeable compared to other countries in A.2.

The PRIs in China have published 15,072 articles (51.1% of Chinese publications), which became an important part of the rise in the average publication rate of latecomers. China is one of the countries with the highest proportion of national systems, along with Armenia and Mexico, and for this reason, China returned to the international field of HEP showing the highest publications growth in history (214% in 1978), after the social change through 1960s to 1970s. From ITP in 1978 to CICQM in 2012, many PRIs and particle accelerators (BEPC, HIRFL, HLS and so on) were built during this period (Zhang and Fang 2016), and this building boom contributed to the overall growth in the number of publications. The publications are also of high quality; although highly-cited publications by PRIs first appeared in the late 1970s, their share of these publications has been > 50% since then. This share grew rapidly to 80–90% in the mid-1980s to mid-1990s and has since declined, but has remained > 50% in recent years. Such achievements, in a part, can be seen as a result of independent capacity building by the Chinese HEP academy. For example, the number of publications increased rapidly in the late 1970s, especially in 1978, with about 50 of the 70 publications of that year written in Chinese. This increase of journals is an indirect aspect of China's independence in HEP academia.

Colombia is a rather exceptional case. In Colombia, the major research agents are universities, and the four major universities (Department of Physics of University of Los Andes, Antonio Narino University, National University of Colombia, and University of Antioquia) produce the most research output. These four accounted for about 96% (2148) of the total publications in Colombia. The only PRI in Colombia is the National Astronomical Observatory in the field of astronomy, and no accelerator facilities exist (Moreno 2014), so they made minimal contributions to quantity and quality of publications. Colombia has made many advances by international cooperation, which will be addressed in the next section (Masperi 2000).

In Finland, the HIP which is a representative PRI, was first established at Helsinki University in 1964 as its predecessor the Research Institute for Theoretical Physics (TFT), but did not begin to produce research output in earnest until 1996, when it was reorganized into the current HIP. The University of Jyvaskyla Institute of Physics (JYFL), another representative institute other than HIP, has been excluded from the PRIs list because the INSPIRE system does not provide data of JYFL separately from the entire data of Jyvaskyla University. The Tuorla Observatory first operated as an independent institute, but was incorporated into the Department of Physics and Astronomy at the University of Turku in 2009. These PRIs in Finland have published 2634 articles, which account for 47.7% of Finnish publications, with HIPs contributing 95%. Although the particle accelerators owned by HIP and JYFL are not high-energy facilities, their high output of research is attributed to the fact that the Finnish research tradition has focused on theoretical physics. Of the papers published in the years in which productivity increased the most which are 1969 (about triple increase, 6→20 articles) and 1990 (about double, 53→101 articles) most of the papers reported theoretical physics research.

In Greece, the PRIs have published 2097 articles (31.4% of publications); the INP of the National Centre of Scientific Research (DEMOKRITOS), the only institute in Greece that has a particle accelerator, is largely responsible for 77% of the all PRIs. The quality of the papers from PRIs has increased to account for about 57% of the total publications from 1976–1980 to 1991–1995, when the number of highly-cited publications began to increase, but has since declined to about 35% in recent years.

In Iran, PRIs have published 2089 journal articles (47.3% of publications). The research output largely declined during the Iranian Revolution and the Iran–Iraq War in the late 1970s–1985, but began to recover and has increased since the 1990s. The IPM and IASBS were built during that period and have contributed to the growth of research output up to now. Iranian PRIs have greatly contributed to growth in quality by producing more than 80% of the highly-cited publications for the entire period, except for 2006–2010.

In Mexico, based on the pioneering endeavors of two PRIs IFUNAM and ININ since 1930s, many PRIs are currently controlled by the National Polytechnic Institute (IPN), which is a representative research association like the CAS of China. Representative organizations among them are CINVESTAV, ESFM, and CIC. They produced a total of 3.470 publications (51.4% of the total). The publication growth was highest in 1974–1975 and 1981, after PRIs such as Conacyt, INAOE, CINVESTAV-Merida, and CIC were successively established in the 1970s, and began contributing to the growth. Of the most highly-cited publications, PRIs account for > 50–60%, and therefore make a significant contribution to the quality of Mexican output.

In Portugal, PRIs have published 1732 articles (30.7% of total publications). The output of research in Portugal grew significantly in the late 1980s, and the establishment of PRIs such as LIP Lisbon and Coimbra contributed to the growth. However, the publications were of relatively low quality, and the proportion of highly-cited publications was < 30%, except in 2011–2015. This is because the research strategy of Portuguese PRIs such as LIP focused primarily on IC, especially the collaborative project with CERN.

In South Korea, the resources of high-energy accelerator facilities (> 1 GeV) of Korean PRIs are relatively abundant compared to other latecomers. The PAL has Pohang Light Source-I and XFEL accelerators, which started operations in 1995 and 2016 respectively, and the Pohang Light Source-I was upgraded to Pohang Light Source-II in 2012. All PRIs have published 2701 journal articles (25.2% of the total) of South Korea. However, PAL contributed only 2% of the PRIs' total publications to HEP. This low contribution suggests that the accelerator facilities of PAL were used as an SR facility for other fields of research such as materials, rather than for classical HEP research. This alternative usage seems to be related to the tendency of *institutionally transforming* the accelerator facilities into more user-centered services in many countries, as global accelerator facilities become ultra-high-energy and ultra-expensive, like the LHC (Hallonsten and Heinze 2012, 2013).

South Korea's publication growth grew fastest during the 1980s and early 1990s, and many PRIs that had been erected in the 1970s contributed to this growth. However, the quality of the publications has been very low for a long time (< 1% share of the total highly-cited publications until 1995), but has increased greatly in recent years (nearly 50% in 2011–2015). The increase to 10% during the 2000s was a dramatic development that identified the importance of PRIs as key research entities in Korea today.

Spain is a research giant that ranks alongside China in the number of PRIs. CELL operates the ALBA accelerator, which is an SR facility that has 3-GeV beam energy, and there are PRIs in astronomy such as ESAC, led by ESA. As in China, Spain operates a research council system that has many PRIs under its jurisdiction; CSIC is the largest research council in Spain. CSIC is managed by the Ministry of Economy and Competitiveness and

Secretary of State for Research, Development and Innovation. IAC, IAA, ICE, IMAFF, are PRIs under the umbrella of CSIC, they make major contributions of Spanish HEP.

These PRIs have published 7158 articles (32.1% of the total Spanish publications). PRIs have been established continuously, from IAC in 1974 to ICE in 2008, and have contributed to constant and balanced growth in both quantity and quality. The contributions of the PRIs to Spanish HEP were initially of low quality, but it increased in the mid-2000s, and accounted for > 50% of the highly-cited publications during the period 2011–2015.

Taiwan has a relatively large number of high-energy accelerator facilities compared to the size of its research output. Typical facilities are the Taiwan Light Source (TLS), which has a beam energy of 1.5 GeV, and the Taiwan Photon Source (TPS) that has a beam energy of 3 GeV. However, these accelerators are SR facilities, and make a low contribution to research output in HEP.

Taiwan has few PRIs, but the National Science Council operates, similar to the case of China and Spain, and Academia Sinica and NCTS were founded and operated under the umbrella of the NSC. The PRIs of Taiwan have published 3072 journal articles (48.2% of total publications), and most of Taiwan's highly-cited publications.

IC and research output

Another important factor in the research output of latecomers is the increase of collaborative research in HEPLCs. ICs accounted for 25.6% of the total of 112,983 by latecomers. However, this figure only considers HEPLCs that are registered in INSPIRE; the figure could be much larger if individual small-scale collaborations between researchers were included. In addition, the output of ICs has tended to increase significantly in recent years, and its importance is greater than the simple figure of 25% shown here (Table 6).

HEPLCs account for 90% of publications (Table 7). When the HEPLCs divided into experimental categories, the Collider Experiments have accounted for 25,725 journal articles (89% of publications). Collider experiments are collaborative studies that use major collider facilities around the world, and it consists of subfields such as proton collision ($p–\bar{p}$, p–p); electron–positron collision ($e^-–e^+$); electron–proton collision (e–p); heavy-flavor factory; heavy ion; and detector development. The major organizations that perform HEPLCs are BNL, CERN, DESY, FNAL, KEK, and SLAC. Astronomy experiments (4.1%) and cosmic ray experiments (3.3%) are the second and third most productive categories.

Among the HEPLCs, CERN LHC accounts for 50.5% of all publications, followed by FNAL (18%), another CERN experiment LEP (4.5%), KEK (4%), BNL (3.5%), and SLAC (2.5%). LIGO, Major Atmospheric Gamma Imaging Cherenkov Telescopes (MAGIC), and VIRGO experiments of astronomy follow them in contribution proportion. The LHC experiment has the highest share among all CERN projects. In addition, as a single experiment, the LHC project accounts for the largest portion (51%) of all publications by ICs. It is bringing about a revolutionary change in IC in human history. In IC, the proportion of experiments that use large accelerators is very high.

The share of HEPLCs vary among countries (Table 6, Fig. 4), and China, Iran, Argentina, Spain, and Chile have a lower share than the average of latecomers; i.e., these countries show relatively independent research tendency. In particular, China and Iran have very strong tendencies to independent research. Colombia, Armenia, Taiwan, and Greece show a strategic pattern that relied heavily on overseas HEPLCs.

Table 6 Proportions of publications by ICs in latecomer countries, and the shares of each experimental category

	Latecomer countries													Overall IC
	AR	AM	CL	CN	CO	FI	GR	IR	MX	PT	KR	ES	TW	
Publications	4622	3571	4711	29,481	2225	5521	6677	4413	6756	5643	10,716	22,269	6378	112,983
IC ratio (%)	21.0	47.7	24.5	14.2	74.3	31.1	36.7	14.3	26.2	29.0	31.9	22.4	41.5	25.6
Total IC	971	1702	1153	4180	1653	1718	2453	631	1772	1634	3421	4988	2645	28,921
Collider	911	1552	896	3748	1648	1494	2401	624	1635	1434	2992	3957	2433	25,725
Fixed target		73	22	26		2	25	1	2	39	75	75	2	342
Neutrino (flavor)	5	7	13	80	2	13	10	2	8	3	155	168	30	496
Dark matter search				51			1		1	44	3	23	2	125
Cosmic ray	23	70	23	99	2	115	11	1	106	82	47	345	40	964
Other rare-process/exotic							1					1		2
Accelerator test facility				7				1		3	1			12
Astronomy	32		199	158	1	88	4	2	20	29	144	371	138	1185
Theory collaboration				11		6					4	48		69

Table 7 Top 90% HEPLCs

Categories	Collaborations/ experiments	Number of publications	Ratio (%)	Acc ratio (%)
Collider experiment	CERN-LHC	14,606	50.5	50.5
	FNAL	5170	17.9	68.4
	CERN-LEP	1287	4.5	72.8
	KEK	1148	4.0	76.8
	BNL	1022	3.5	80.3
	DESY	955	3.3	83.6
	SLAC	734	2.5	86.2
	CERN-NA	365	1.3	87.4
Astronomical (astronomy)	LIGO	299	1.0	88.5
Astronomical (cosmic ray)	MAGIC	241	0.8	89.3
Astronomical (astronomy)	VIRGO	219	0.8	90.1

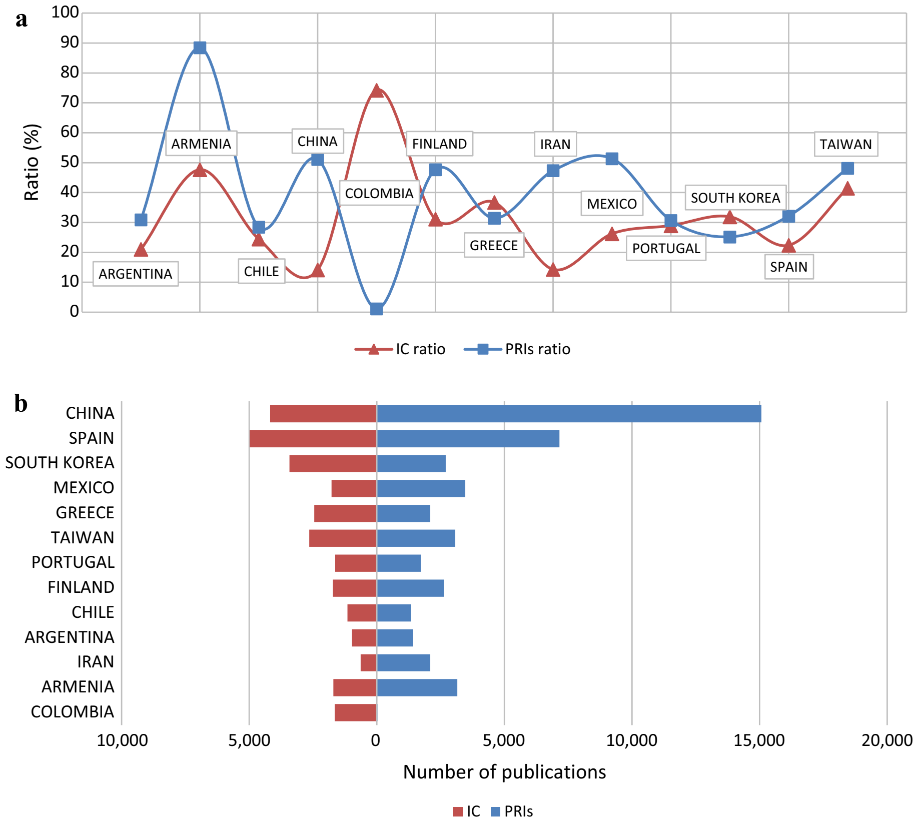

Fig. 4 **a** The list of proportion of research output by National System and IC by country. **b** Number of publications from ICs or PRIs (x-axis). (Color figure online)

The proportion of HEPLCs among citations has increased significantly since the 1980s. In 1980, for instance, Finland began to publish highly-cited articles as a result of participation in the Particle Data Group, and Greece achieved the same increase by participating in the Aachen–Bonn–CERN–Democritos–London–Oxford–Saclay Collaboration. All highly-cited articles ($n \geq 15$) from Greece published in 1980 were the result of IC in HEPLCs or small collaborations between researchers, and most of these papers used large infrastructure such as the Intersecting Storage Rings (ISR) at CERN.

In addition, IC has contributed more highly-cited publications, and this pattern has strengthened over time (Table 8). For example, during 1981–1985, the share of IC in highly-cited publications increased from 16.4% ($n \geq 15$), 21.9% ($n \geq 30$), 22.1% ($n \geq 50$), 26% ($n \geq 100$), 28.6% ($n \geq 250$), 37.5% ($n \geq 500$), to 66.7% ($n \geq 1000$). This proportion has also increased continually over time, from about 5% in 1966–1970, 11.6% (1971–75), 12.2% (1976–80), 16.4% (1981–85), 33.3% (1086–90), 32.3% (1091–95), 37.6% (2006–10), to 66.1% in (2011–15).[7] This observation concurs with previous studies that high-quality research across the scientific fields is a result of IC (Persson et al. 2004; Narin 1991). IC has a particularly strong correlation with citation data; more details are given in the country-by-country analysis below.

In Latin American countries, IC accounted for 971 (21%) of journal articles in Argentina, 1153 (24.5%) in Chile, 1772 (26.2%) in Mexico, 1653 (74.3%) in Colombia. Colombia is the country with the highest proportion of IC among the latecomers, and is in sharp contrast with China and Iran (Table 8).

These Latin American countries have been closely associated with IC from the very beginning, as domestic HEP community has begun to organize primarily to participate in the Fermilab collaboration (Masperi 2000). Argentina began to produce its first research output as a result of the D0 Collaboration in 1996, the detector of the FNAL Accelerator 'Tevatron'; the total publication count increased significantly in 2005 and 2008, and since 2010, research output from the CERN ATLAS experiment has increased significantly, and reached a peak during 2011–12 period (A.2 in online appendix).

Chile has been producing research output from the FNAL D0 experiment since 2007, the CERN-LHC ATLAS experiment since 2009, and the Dark Energy Survey (DES) experiment since 2013. The number of articles published as a result of the D0 and LHC experiments increased significantly in 2012, and accounted for 56% of total publications.

Mexico has been producing research output from the FNAL D0 experiment since 1996, from the Collider Detector at Fermilab (CDF) experiment since 2004, from CERN-LHC ALICE, Compact Muon Solenoid (CMS) and ATLAS experiments since 2002 (Sánchez et al. 2018), from the DESY H1 experiment since 2006, and from the Pierre Auger experiment for cosmic rays study since 2006. The share of IC in Mexican HEP has grown significantly since 2008, and has contributed $> 40\%$ of total publications every year since 2011, with a peak of $> 80\%$ in 2012.

Colombia has been producing research output from FNAL D0 experiment since 1995, from the CDF experiment since 2004, and from the CERN-LHC CMS and ATLAS experiments since 2008. The HEPLCs have steadily accounted for a large proportion of overall research production, and increased particularly in 2008 and 2010–2012. Most latecomers, not only in Latin America, showed a large growth in the period 2010–2012; this increase occurred because of the increase in IC, particularly by the CERN LHC experiment.

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[7] Although the share declined in 1996–2000 and 2001–2005 period, it was still similar or even increased in the section of the super-highly cited publications such as $n \geq 250$.

Table 8 The IC's share of highly cited publications for 5 years

	Number of citations								
	$n \geq 15$	$n \geq 30$	$n \geq 50$	$n \geq 100$	$n \geq 250$	$n \geq 500$	$n \geq 1000$	$n \geq 5000$	$n \geq 10{,}000$
1961–65 Total IC citations ratio	2	1							
	0	0							
	0	0							
1966–70 Total IC citations ratio	21	9	2	1					
	1	1	0	0					
	0.048	0.111	0.000	0.000					
1971–75 Total IC citations ratio	69	33	20	8	3	2			
	8	4	4	3	1	1			
	0.116	0.121	0.200	0.375	0.333	0.500			
1976–80 Total IC citations ratio	196	114	74	32	9	3			
	24	18	10	5	3	1			
	0.122	0.158	0.135	0.156	0.333	0.333			
1981–85 Total IC citations ratio	495	311	208	100	35	8	3		
	81	68	46	26	10	3	2		
	0.164	0.219	0.221	0.260	0.286	0.375	0.667		
1986–90 Total IC citations ratio	1061	662	445	176	48	13	6		
	353	289	213	82	29	8	6		
	0.333	0.437	0.479	0.466	0.604	0.615	1.000		
1991–95 Total IC citations ratio	2074	1310	826	298	66	21	12		
	670	545	359	118	22	10	10		
	0.323	0.416	0.435	0.396	0.333	0.476	0.833		
1996–2000 Total IC citations ratio	4059	2447	1521	628	151	40	15	5	4
	890	587	378	172	51	17	11	5	4
	0.219	0.240	0.249	0.274	0.338	0.425	0.733	1.000	1.000

Table 8 (continued)

	Number of citations								
	$n \geq 15$	$n \geq 30$	$n \geq 50$	$n \geq 100$	$n \geq 250$	$n \geq 500$	$n \geq 1000$	$n \geq 5000$	$n \geq 10{,}000$
2001–05 Total IC citations ratio	7407	4452	2693	1142	274	92	21	4	
	1509	1085	757	382	125	54	16	3	
	0.204	0.244	0.281	0.335	0.456	0.587	0.762	0.750	
2006–10 Total IC citations ratio	11,754	6987	4207	1699	475	144	65	17	
	4421	2957	2001	955	352	113	57	17	
	0.376	0.423	0.476	0.562	0.741	0.785	0.877	1.000	
2011–15 Total IC citations ratio	18,944	12,251	7417	2993	683	162	76	42	
	12,524	9266	5988	2547	608	139	65	42	
	0.661	0.756	0.807	0.851	0.890	0.858	0.855	1.000	

Citations of papers produced by Latin American countries have shown a similar pattern of increase (A.3 in online appendix). Highly-cited publications produced as a result of IC were rare until 1990, and Argentina has made a significant increase since 2006–2010 when it began participating in the FNAL D0 experiment, and Chile has made a significant increase since 2006–2010 when it began participating in the FNAL D0, CDF, and CERN-LHC ATLAS experiments. During 2011–2015, work on these projects accounted for as much as 70% of all highly-cited publications and > 80% of those cited > 100 times.

In Mexico, the timing of the increase in citations also generally coincides with the onset of participation in the FNAL D0 experiment (Collazo-Reyes et al. 2004). The years 2006–2010 (14%→47%) and 2011–2015 (47%→82%) showed particularly large increases in the proportion of the citations; during these periods Mexico began to participate respectively in CERN-LHC CMS, DESY H1, Pierre Auger cosmic ray experiments, and LHC ATLAS.

In Colombia, the share of highly-cited publications that were produced as a result of IC started to increase in 1991–1995 when collaborations with Fermilab, including the D0 experiment, began. The share has grown greatly since the mid-2000s when CDF, ATLAS, and CMS experiments began, and currently accounts for > 90% of highly-cited publications.

Armenia showed a similar pattern to those of Latin American countries. It had the second-highest proportion (about 42%) of IC (first is Colombia). The major HEPLCs in which Armenia participated were DESY HERMES (first article produced in 1998), Jefferson Lab (1998), CMS hadron calorimeter experiment (2001), ALICE (2004), CMS (2007), and ATLAS (2008). The LHC experiment has resulted in a significant increase in research output since 2010 (80% of the total increase in peak periods 2011–2012 and 2015–2016). No highly-cited publications occurred until 1990, but the proportion of papers that were highly cited grew significantly from 1996–2000 when major ICs began. This proportion has grown rapidly since 2006, and contributed to 97% of highly-cited publications as of 2011–2015; this was the highest share in the world. In Armenia, IC has made a significant contribution to the quantity of research output, and the quality of the output has depended strongly on IC.

Iran produced only 631 journal articles (14.3% of total) as a result of IC; this is the second lowest share among latecomers, after China. The largest part of these IC papers results from the LHC-CMS experiment, which has produced significant growth since 2010. Although the share of IC is only about 20% each year, it has shown its importance by contributing 53% and 63% of the increase in 2010 and 2011 when the number of publications increased the most. Iran has suffered from a significant setback due to domestic political turbulence, and began to increase citations by IC only after 2006. However, the proportion of highly-cited publications greatly increased to 60% during 2011–2015, as a result of participation in the LHC CMS project.

Portugal has produced 1634 journal articles (29% of total) as a result of IC, and has participated in CERN-LEP, LHC, and Pierre Auger cosmic rays experiments as major HELPLCs. Since joining CERN in 1986, Portugal has begun to produce collaborative research output as a result of the Detector with Lepton, Photon and Hadron Identification (DELPHI) experiment of LEP accelerator since 1989, and as a result of CMS, ATLAS and AUGER experiments since 2007. In particular, the share of IC in total publications and annual growth has increased significantly as a result of the LHC experiment. Portugal also saw a meaningful increase in citations as a result of IC from 1986 to 1990 period when the LEP experiment began. The proportion of highly-cited publications as a result of HEPLCs increased significantly during 2011–2015, to 63% of the total.

Taiwan has produced 2645 journal articles (41.5% of total) as a result of IC; this is the third highest proportion after Colombia and Armenia. The major HEPLCs that Taiwan participated in, and the year in which the country published its first article, are the CERN-LEP L3 detector experiment (1989), FNAL D0 and CDF (1994), KEK AMY and Belle experiments (1995), and CERN CMS, ATLAS, BNL PHOBOS, Pioneering High Energy Nuclear Interaction Experiment at RHIC (PHENIX) and Solenoidal Tracker (STAR) experiments (2007). The share of IC increased steadily to a peak at about 60% in 2012; the LHC experiment was a strong factor in this increase. Taiwan began to increase its share of qualitative output as a result of IC by starting participation in CERN-LEP experiments during 1986–1990, and then this output grew in 2006–2010 and 2011–2015.

China has the lowest share of IC (14.2% of total) among latecomers (Table 6); this result indicates that China has a very 'independent' research climate. Since first research output from the collaboration with Fermilab in 1980, it has begun to publish journal articles as a result of FNAL CDF (in 1989) and D0 (1990), CERN-LEP ALEPH and L3 (1996), KEK AMY and Belle (1996), BNL PHENIX (1994), PHOBOS (2000), STAR (2001), SLAC BaBar (2001), CERN-LHC ALICE (2004), CMS (2007), LHC beauty (2008), ATLAS (2010), DESY HERMES (2005), VIRGO (2003), and LIGO (2010).

The proportion of IC in China is small, so its only quantitative peculiarity is that it has made a contribution to the relatively large growth in 2012. However, the proportion of highly-cited publications that resulted from IC has increased sharply (22%→52%) since 1986–1990 when it began in earnest to participate in HEPLCs. IC still accounts for 47% of publications, and the number of citations of these papers is increasing; this trend confirms that IC has increased the quality of the output.

Greece has produced 2453 journal articles (36.7%) as a result of IC. The major HEPLCs in which Greece participated, and the first published article from it, are Fermilab (in 1983), CERN-LEP ALEPH and DELPHI (1989), DESY-Hadron Elektron Ring Anlage (HERA) ZEUS (2002) and H1 (2006), FNAL MINOS (2006), CDF (2008), D0 (2009), CERN-LHC CMS (2005), and ATLAS, ALICE (2008). In 1990, one of the years during which the growth rate in publications was highest, the LEP experiment accounted for > 70% of the increase; and during 2011–2012 in which the increase in publications was largest, the LHC experiment was also the main factor. The period 1981–1985, during which the share of IC in highly cited publications increased significantly, is largely consistent with the time when Greece initiated its FNAL collaboration. However, the share of FNAL experiment is small, and thus it seems to have produced research output in small experiments rather than large experiments, as with the major HEPLCs. Since then, IC accounted for > 70% of the highly-cited publications during 2011–2015.

South Korea has produced 3421 journal articles (32% of total) as a result of IC. This percentage is consistent with an earlier report (Adams 2013) that the share of IC in Korea is about 30% in all fields of science, and it is a figure that slightly exceeds the overall average of 27–29% in physics (Kim 2005). Since first research output from the collaboration with Fermilab in 1980, it has begun to publish journal articles as a result of major HEPLCs of FNAL-TEVATRON D0 (in 1995), CDF (1999), KEK AMY (1988), Belle (1996), SUPER-KAMIOKANDE (1998), DESY ZEUS (1993), BNL PHENIX (1994) STAR (2006), Chinese IHEP-BEPC Beijing Spectrometer (BES) (1998), BESIII (2010), Jefferson lab CEBAF Large Acceptance Spectrometer (CLAS) (2004), CERN-LHC CMS and ATLAS (2006), and LIGO (2011). IC contributed to 51% and 63% respectively of the year-over-year increase in the number of papers in 2007 and 2011, when publications increased the most. The proportion of highly-cited publications produced as a result of IC began to increase with the participation in Fermilab and KEK collaborations, and since 2006 this influence has expanded to 60% as a result of experiments at CERN, FNAL, KEK, JLAB, DESY, and BEPC.

In Spain, 4.939 publications (22.4% of total) were a result of IC. Since collaborating with Fermilab early on, Spain began to participate in and publish journal articles as a result of DESY Two Arm Spectrometer Solenoid (TASSO) (in 1985) and ZEUS (1992), CERN-LEP ALEPH, L3, DELPHI (1989), FNAL CDF (1999), D0 (2004), DESY HERMES (2012), SLAC BaBar (2003), LHC CMS (2000), ATLAS (2003), ALICE (2006), LHCb (2009), and KEK Belle (2003). In particular, Spain has conducted active IC in the field of astronomy, and began to publish articles as a result of LIGO (in 2005), VIRGO (2008), Pierre Auger cosmic rays experiment (2006), FERMI-LAT (2009), ESA-PLANCK (2013), and DES (2015).

In Spain, the greatest increases in the total number of publications were in 2011–2012 (largely attributed to CERN LHC) and 2016 (mostly astronomical experiments). As a result, 98% (2011), 63% (2012), and 81% (2016) of the year-on-year growth were produced by IC. The increase in the proportion of citations that resulted from IC coincides with the period during which Spain actively participated in major HEPLCs. The share of IC in highly-cited publications has increased since 1976–1980, after which cooperative research with Fermilab began to yield output. The increase in IC share during 1986–1990 (33%) was due to the LEP and DESY TASSO experiments, and the increase of the 2011–2015 period was a result of the LHC experiment.

Finland has 1718 (31%) of publications as a result of IC. Finnish authors published papers as a result of IC with LEP DELPHI experiment (in 1989), LHC CMS (2002), ALICE in (2004), TOTal Elastic and diffractive cross section Measurement (TOTEM) (2006), FNAL CDF (2003), D0 (2008), BNL PHENIX (2008), MAGIC (2006) and PLANCK (2013). These collaborations contributed mostly to the growth rates in 2016 and 2011, the years in which the increase in publications was largest, and in the 2010s results from IC account for >50% of publications. The proportion of IC in Finland is currently 31%, but recent trends suggest that the importance will increase.

Finland, among latecomers, was the earliest country to produce excellent research output as a result of IC. Specifically, the number of highly-cited publications produced by IC was much higher than by other latecomers (A.4 in online appendix), even before 1989 when the FNAL DELPHI experiment began to produce research output. The early start by Finland was a result of research output from small ICs that are not listed in Table 9. In addition, as in other countries, the quality of the papers increased significantly during 2011–2015 as consequences of participation in the LHC experiment, and in a group of astoparticle physics experiments; the share of highly-cited papers was close to 77%.

To summarize, IC had an important influence on the research output of latecomers. IC has contributed to both the quantity and quality of production, and its importance is growing. Therefore, the momentum for this growth is expected to continue. IC has a particularly strong correlation with the quality of the research: since latecomers began participating in major HEPLCs, the number of publication and the proportion of highly-cited publications that result from IC have both increased significantly.

Variation along countries and time periods

As research output as a result of IC has greatly increased in recent years, the strategic patterns of latecomers have also changed over time (Table 10). The number of publications by

Table 9 Major HEPLCs, onsets, and their specific experiments in each latecomers country

Institute and country	Collaboration or experiment/(Year of publications)			
Fermi National Lab	General[a]	TEVATRON		
Spain	Since 1976	CDF (1999~)	D0 (2004~)	
China	1980	CDF (1989~)	D0 (1999~)	
South Korea	1980	D0 (1995~)	CDF (1999~)	
Greece	1983	MINOS (2006~)	CDF (2008~)	CDF/D0 (2009~)
Mexico	1992	D0 (1996~)	CDF (2004~)	
Taiwan	1992	CDF (1994~)	D0 (2003~)	
Colombia	1993	D0 (1996~)	CDF (2004~)	
Chile	1994	D0 (2007~)	CDF (2010~)	
Argentina	None	D0 (1996~)	DAMIC (2016~)	
Finland	None	CDF (2003~)	D0 (2008~)	
SLAC, Stanford	General[a]	PEP-II Collider		
China	Since 1984	BaBar (2001~)		
Spain	None	BaBar (2003~)		
DESY, Germany	General[a]	PETRA	HERA	
China	Since 1985		HERMES (2005~)	ZEUS (2012~)
Spain	None	TASSO (1985~)	ZEUS (1992~)	HERMES (2012~)
South Korea	None		ZEUS (1993~)	
Armenia	None		HERMES (1998~)	H1 (2006~)
Greece	None		ZEUS (2002~)	H1 (2006~)
Mexico	None			H1 (2006~)
CERN, Geneva	General[a]	LEP		
China	Since 1986	ALEPH, L3 (1989~)		
Spain	1986	ALEPH, L3, DELPHI (1989~)		
Finland	None	DELPHI (1989~)		
Greece	None	ALEPH, DELPHI (1989~)		

Table 9 (continued)

Institute and country	Collaboration or experiment/(Year of publications)				
Fermi National Lab	General[a]	TEVATRON			
Portugal	None	DELPHI (1989~)			
Taiwan	None	L3 (1989~)			
KEK, Japan	General[a]	TRISTAN	KEKB Collider		
South Korea	None	AMY (1988~)	Belle (1996~)		
China	None	AMY (1989~)	Belle (1996~)		
Taiwan	None	AMY (1995~)	Belle (1996~)		
Spain	None		Belle (2013~)		
Brookhaven National Lab	General[a]	Relativistic Heavy Ion Collider (RHIC)			
China	Since 1990	PHENIX (1994~)	PHOBOS (2000~)	STAR (2001~)	
South Korea	None	PHENIX (1994~)	STAR (2006~)		
Taiwan	None	PHOBOS (2000~)	PHENIX (2001~)	STAR (2016~)	
Finland	None	PHENIX (2008~)			
CERN, Geneva	General[a]	LHC			
Spain	Since 1996	CMS (2000~)	ATLAS (2003~)	ALICE (2006~)	LHCb (2009)
Greece	1997	CMS (2005~)	ATLAS, ALICE (2008~)		
Portugal	1998	CMS, ATLAS (2007~)			
Taiwan	2000	CMS (2007~)	ATLAS (2008~)		
Armenia	None	CMS (2001~)[b]	ALICE (2004~)	CMS (2007~)	ATLAS (2008~)
Finland	None	CMS (2002~)	ALICE (2004~)	TOTEM (2006~)	
Mexico	None	ALICE (2002~)	CMS (2007~)	ATLAS (2012~)	
South Korea	2002	CMS, ALICE (2006~)			
China	None	ALICE (2004~)	CMS (2007~)	LHCb (2008)	ATLAS (2010~)
Iran	2006	CMS (2007~)			

Table 9 (continued)

Institute and country	Collaboration or experiment/(Year of publications)			
Fermi National Lab	General[a]	TEVATRON		
Argentina	None	ATLAS (2008~)		
Colombia	None	CMS, ATLAS (2008~)		
Chile	None	ATLAS (2009~)		
Jefferson Lab	General[a]	Hall B		
Armenia	Since 1998	ATLAS (2003~)		
South Korea	1998	ATLAS (2004~)		
IHEP, Beijing	General[a]	BEPC Collider		
South Korea	None	BES (1998~)		BESIII (2010~)
University of Tokyo	General[a]	Kamioka Observatory		
South Korea	None	Super Kamiokande (1998~)		
Pierre Auger Observatory	General[a]	Pierre Auger Cosmic Rays experiments		
Spain	Since 1998	Auger (2006~)		
Mexico	None	Auger (2006~)		
Portugal	None	Auger (2007~)		
La Palma Observatory	General[a]	MAGIC Telescopes		
Spain	None	MAGIC (1999~)		
Finland	None	MAGIC (2006~)		
LIGO-VIRGO Collaboration	General[a]	LIGO-VIRGO Collaboration		
China	Since 2001	VIRGO (2003~)	LIGO (2010~)	LIGO-VIRGO (2011~)
Spain	None	LIGO (2005~)	LIGO-VIRGO (2008~)	
South Korea	None	LIGO-VIRGO (2011~)		
NASA, US	General[a]	Fermi Gamma-ray Space Telescope		
Spain	None	FERMI-LAT (2009~)		
Cerro Tololo Observatory	General[a]	BLANCO Telescope		

Table 9 (continued)

Institute and country	Collaboration or experiment/(Year of publications)	
Fermi National Lab	General[a]	TEVATRON
Chile	None	DES (2013~)
Spain	None	DES (2015~)
European Space Agency	General[a]	PLANCK Space Telescope
Finland	None	PLANCK (2013~)
Spain	None	PLANCK (2013~)

[a] Neither a major experiments nor a big accelerator based experiments

[b] CMS hadron calorimeter experiment (HCAL)

Table 10 Growth and reduction of publications from National System and IC of latecomers in principal years

Country	1998	1999	2003	2004	2005	2007	2008	2009	2010	2011	2012	2013
IC total	220	173	267	380	654	810	1104	1195	1403	2340	3565	2947
Argentina	6	5	5	6	23	24	52	47	41	102	145	78
Armenia	6	6	5	5	16	27	44	56	76	151	261	206
Chile	7	1	4	3	1	7	7	31	36	130	202	118
China	34	25	63	104	146	142	175	163	184	272	436	402
Colombia	6	6	3	8	23	19	51	33	58	134	248	194
Finland	4	1	8	12	37	60	68	94	101	148	189	172
Greece	33	26	29	35	24	48	53	108	130	210	327	274
Iran		1			1	5	6	3	36	74	97	90
Mexico	7	6	11	20	43	33	75	82	107	182	276	238
Portugal	1	6	3	10	3	24	43	35	70	135	250	193
Korea	35	30	58	76	121	174	214	202	207	252	306	279
Spain	51	41	50	53	140	166	201	241	225	341	520	466
Taiwan	30	19	28	48	76	81	115	100	132	209	308	237
NL total	611	604	1002	1232	1407	1590	1291	1131	1213	1317	1379	1353
Argentina	35	29	42	55	53	40	62	47	56	62	84	79
Armenia	31	29	35	30	25	35	26	25	26	32	25	29
Chile	20	12	76	84	139	155	29	9	16	33	25	52
China	249	222	340	455	519	526	481	466	442	446	502	448
Colombia									2	6	5	5
Finland	18	39	60	68	76	99	80	61	59	70	60	67
Greece	28	22	45	51	56	65	50	42	51	63	55	30
Iran	40	34	64	55	61	54	61	74	87	78	91	103
Mexico	60	59	93	102	107	84	60	47	49	64	60	65
Portugal	3	6	10	30	19	25	12	12	24	17	20	13
Korea	18	54	41	57	51	70	77	65	64	94	89	86
Spain	85	77	154	192	218	328	261	208	244	251	280	289
Taiwan	24	21	42	53	83	109	92	75	93	101	83	87

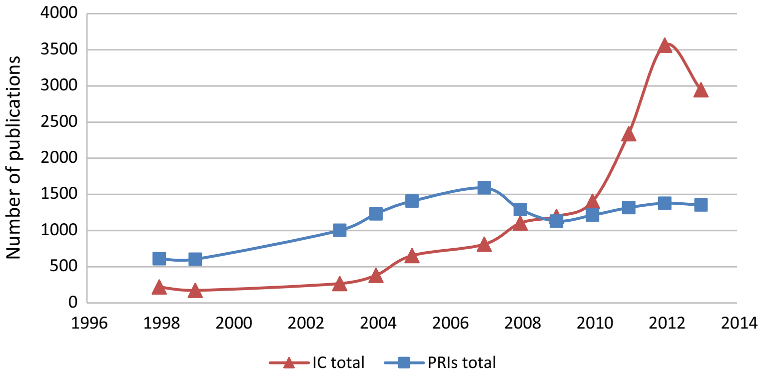

Fig. 5 Latecomers' trends of publications from National System and IC in principal years. The patterns of National System and IC are clearly different

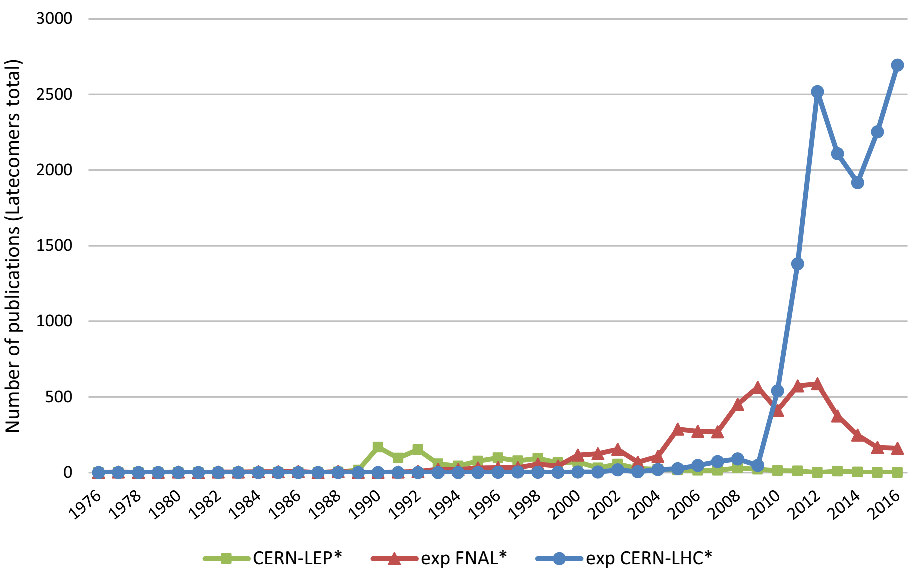

Fig. 6 Major International collaborations and experiments

latecomers increased most in 2004–2005, 2007, and 2011–2012, and declined the most in 2008 and 2013. In contrast, the number of publication from PRIs peaked in 2007 and has been stagnant since then. The number of publications produced as a result of IC gradually caught up with the volume of publications produced as a result of PRIs, and exceeded them in 2009 (Fig. 5).

The number of citations of papers varied in a similar way. PRIs (A.3 in online appendix) have traditionally contributed more high-impact publications than ICs did (A.4 in online appendix), but the difference declined and in 2011–2015 the contribution by IC exceeded the proportion by PRIs. The impact of papers published as a result of IC during 1986–1990 was due to the influence of CERN LEP. Since then, the impact of papers published as a result of IC remained relatively constant until the end of 2004, then TEVATRON D0 and CDF experiments began to produce research output in 2005, so the share of IC in highly-cited publications began to increase. The increase was strongly affected by the FNAL TEVATRON experiment that peaked in 2010, and the CERN LHC experiment that has increased steeply since 2010. CERN LEP, FNAL TEVATRON, and CERN LHC have sequentially led international collaborative research (Fig. 6) in both the quantity and quality of production.

In conclusion, the latecomers are divided into a group that maintained an ‘independent’ research climate with emphasis on the national system (China and Iran), and a ‘cooperative’ group that emphasizes IC (e.g., Colombia and Armenia). Chronologically, research by latecomers has evolved from a pattern of domestic-oriented research strategies (before the mid-2000s) to a pattern that relies heavily on IC (late 2000s, especially after 2010–2012, when the CERN LHC experiment began to produce output). Most latecomers are now pursuing strategies to produce a large number of high-quality research publications by getting deeply involved in the international high-energy accelerator system.

Discussion

Latecomers show a linear or exponential rise curve in all three indicators: (1) total number of publications, (2) proportion in highly-cited publications, and (3) percentile ranks. Various forms of PRIs of National System, such as having accelerator facilities as the main experimental equipment, or being operated jointly by the international community, have fostered such a growth, especially quantitatively. Specifically, the National System accounts for about 41% of publications by latecomers.

However, the causal relationship between the National System and the quality of output is unclear. PRIs contributed only 20–30% of highly-cited publications, and although this share has recently increased to 50%, it differs significantly among countries. Further investigation is required to find out whether the difference is related to the language in which the papers were published. In addition, the proportion of highly-cited papers by PRIs did not show an increase as the section of citation gets higher (e.g., from $n \geq 15$ to 100), whereas the proportion of highly-cited papers by IC did.

The influence of accelerator facilities (Irvine and Martin 1985; Panofsky 1997; Moritz 2001), as a research infrastructure which was an important factor for the growth of the first-movers, also has a limited ability to explain the growth of the latecomers. For example, in Colombia, the number of publications and rankings continue to rise, although the country has no special high-energy accelerator facility, whereas in Iran, one of the PRIs (i.e., IPM), has traditional strengths in non-experimental fields such as theoretical physics and mathematics and has contributed to the progress of HEP.

Only China, South Korea, Spain, and Taiwan among the latecomers have built high-energy accelerator facilities in the 2010s, and these account for most of the sum of latecomers' maximum beam energies, so the high rate of publication growth by the other nine countries is not easy to explain. Previously-established accelerator facilities may have contributed to the current productivity. However, the percentile rank has shown increases and decreases, it cannot be used to estimate the trends. In addition, during the 23 years between the 1988–1995 and 2008–2012 periods in which many facilities were constructed, the research output of latecomers greatly increased but the level of maximum beam energy did not change significantly (Fig. 3). Because most of these facilities built during the period of 2008–2012 were upgrades of facilities that had been originally built for SR, they may have little direct correlation with high-energy physics research (Hallonsten and Heinze 2012, 2013).

However, the conclusion that the accelerator infrastructure is not important may not be valid. Instead, the emergence of a series of global super-accelerators, from CERN LEP in 1980–1990, FNAL TEVATRON in mid-1990s–2000s, and CERN LHC in 2010s, has attracted a large number of users and researchers from around the world, so IC may be the strategic response of latecomers to gain use of these facilities.

If this is the case, then the on-going construction of large accelerator facilities by some latecomers is hard to explain. The reason may be that the motivation is to build capacity (Leach 1973) or to strengthen international competitiveness and reduce the emigration of highly-trained young people (Moreno 2014). Furthermore, an infrastructure for various research fields may function as a national platform institution (Da Silva 1996). In summary, the reason for investment in accelerator facilities in latecomers is generally to strengthen scientific competitiveness and cultivate human resources by constructing infrastructure.

This inference suggests that these forms of National System have only a partial effect on the research productivity of latecomers. Latecomers have certainly caught up with the first-movers by means of the National System, but each country has a different situation. Some PRIs such as IHEP in China and IPM in Iran function as focal points in their national HEP community, whereas others have a small share, such as Colombia and Chile. Over time, in addition, the HEP research strategy of latecomers is gradually evolving to increased reliance on IC.

The IC is a more obvious factor for the development of latecomers. The pattern of participating IC is a strategic action that increases both the quantity and quality of production, as a result of participation in HEPLCs. IC began to increase as early as the 1980s, but the rapid growth in the quantity of output began in the mid and late 2000s, primarily as a result of the overwhelming productivity of CERN LHC.

IC during this period has also made a significant contribution to qualitative growth. The share of IC in highly-cited publications by latecomers surged to 66% in 2011–2015, and the papers produced by IC were cited consistently more often than papers that were not produced by IC (A.4 in online appendix). This trend has been noted previously (Wagner and Leydesdorff 2005; Persson et al. 2004; Katz and Hicks 1997; Narin 1991).

To explain the cause of strong correlation between IC and the quality of the publication, several studies have evaluated the need to collaborate in *experimental* fields (Wagner-Döbler 2001), the specialization of research fields and countries (core-periphery structure), and on the development of methods of communication. However, collaboration may be due to the nature of the global academic community as a *self-organizing system* in which such pro-IC acts may lead to benefits to a researcher, such as increased reputation and requests for further research (Wagner and Leydesdorff 2005); however, they did not consider HEP directly, so to consider the theoretical implications of IC in the HEP field, this explanation should be reviewed in more detail, but that analysis is beyond the scope of this study.

Conclusion

The 13 latecomer countries that we examined have strengthened their research capabilities in HEP, a fundamental and a Big Science, by developing a National System of PRIs, and by active participation in IC, and have also been coping with ever-increasing demand for experimental facilities. Besides universities, which are traditionally well known as subjects of fundamental science, PRIs are important components of a National System.

The three types of PRIs (Normal, Accelerator, International) are the main components of the national system and generally function as a focal point for strengthening HEP capabilities in each country. In particular, in latecomers that have accelerator facilities, which compose the infrastructure that has been considered important factor HEP first-movers, PRIs tend to operate these facilities, and this control was a factor in the increase in research output. However, the contribution of accelerator facilities to HEP research output is only a fraction of the overall PRIs, and in some cases, countries without such facilities have achieved significant growth in HEP productivity. Therefore, the historically well-organized National System of PRIs seems to be a more important factor in the increase of national research productivity than the possession of high-energy accelerator facilities.

However, the influence of the establishment of the PRIs and accelerator facilities on the quantity and quality of output has varied among countries and over time, and has gradually become less important than IC. Therefore, PRIs have only a partial influence on productivity, whereas IC has had a clear positive influence among countries, over time, and in the number of citations.

Quantitative output by PRIs increased linearly over the survey period, but the output of IC has increased exponentially since the 2000s. IC has a more universal positive effect on research quality than PRIs do, and the CERN LHC as a single experiment has been a key factor in the rapid growth of all citation sectors in all latecomers since the late 2000s. This single input has increased the power of IC to explain research productivity.

We conclude that the latecomers are divided into a group that maintains 'independent' research climate with a great emphasis on the national system (China, Iran), and a 'cooperative' group that emphasized IC (e.g., Colombia, Armenia) (Table 6). Chronologically, HEP research has evolved from a pattern of domestic-oriented research strategies prior to the mid-2000s to a strategic pattern that relies heavily on IC in the late 2000s, especially after 2010–2012. Most latecomers are now pursuing strategies to derive good quantity and quality of research output by getting deeply involved in the international high-energy accelerator system (Fig. 5).

This study has described the National System and IC as common characteristics of latecomers in the HEP community. It has presented an examination of the differences in strategic patterns among the latecomers from a cross-section and time-series perspective, with the intent of contributing to the understanding of science and technology policies and bibliometric studies in HEP as a basic science and as a Big Science. Further studies based on reliable bibliometric data of various topics such as the strategic patterns of first-movers, the contributions of universities as another traditional component of the National System, and the share of other important fields like theoretical physics and astronomy, will deepen understanding of the quantity and quality of research in Big Science at the national level.

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