Theoretical high energy physics in Latin America from 1990 to 2012: a statistical study

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Abstract We present a statistical overview of the publications in theoretical high energy physics (HEP), which emerged in Latin America (LA) in the period from 1990 to 2012. Our study captures the eight Latin American nations, which are dominant in this field of research: Brazil, Mexico, Argentina, Chile, Colombia, Venezuela, Uruguay and Cuba. As an intercontinental benchmark, we compare them with India, Canada, South Korea, Belgium and South Africa. We consider the productivity of research papers in specialized high-impact journals, and the corresponding numbers of citations. The goal is to document the efforts in LA to catch up with the most wealthy countries, in a field of research without direct practical benefits. The restriction to theoretical HEP excludes large international collaborations, which enables a fair evaluation of national achievements. We further investigate how these records are correlated with three socio-economic indices: the Gross Domestic Product (GDP), the Human Development Index (HDI) and the Education Index (EI). Despite some progress, there remains a backlog of LA compared to the dominant countries, which cannot be explained solely by economic deficiency. In general, a detailed correlation between the socio-economic and scientific evolution is not obvious.

Keywords Latin America · Theoretical high energy physics · Bibliometrics · Socioeconomic indicators

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Outline

For centuries, the universities in Latin America (LA) were entirely dedicated to higher education; only since the middle of the 20th century they also act as research centers. This was also the beginning of graduate programs in physics. Half a century later, in the year 2000, LA had a total population close to 500 millions, and about 10,000 active researchers in physics (Morán-López 2000). This embraces some 800 active researchers in High Energy Physics (HEP)—including Ph.D. students—with a majority of about 650 researchers working in theoretical HEP (Masperi 2000).

Our study sets in four decades after a LA research community in physics (beyond individuals) was established. More precisely, this work deals with research papers in theoretical HEP from LA, in the period from 1990 and 2012. HEP is a specific field of science which does not focus on immediate practical applications. The motivations for this line of research is rather cultural and pedagogical, whereas technological benefits are only conceivable on a longer time-scale.

As a distinction from the previous bibliometric literature, our restriction to theory excludes large international collaborations, where national contributions are hard to quantify, and which could therefore significantly distort the statistics of publications and citations.

We present statistical data for the productivity of the eight dominant countries regarding the number of publications, the Impact Factor (IF) of the journals where they appeared, and the citations that they received. In order to interpret these data, we compare them to five intercontinental countries, and we search for correlations with the economic and social development.

“Criteria for the statistical data” section explains our selection criteria for the data that enter our statistics. “Ranking by nations” section presents the record for each country under consideration, with respect to the number of publications, the IF of the corresponding journals, and the number of citations to these articles. “Correlations with socio-economic indices” section confronts these results with three well-established socio-economic indices. “Conclusions” section is devoted to our conclusions, and an appendix gives an explicit list of particularly top-cited and groundbreaking papers.

Criteria for the statistical data

This section explains how the entries to our statistics were selected. We consider peer-reviewed publications\(^1\) that are documented in the Web of Science—formerly known as the Web of Knowledge—(Web of Science, n.d.), which is widely accepted as a reliable data base of the scientific literature. A paper is counted for the productivity of a country if at least one author indicates a working address in that country. (We are not concerned with the authors’ citizenships.) Hence some publications count for several countries, although relatively few papers emerge from international collaborations within LA; a study of all

\(^1\) In HEP also preprints play an important rôle, more than in other fields, in particular due to the data bases arXiv and INSPIRE (formerly SPIRES). For instance in 2015 a total of 10 126 preprints were submitted to the arXiv; 6415 of them were later published in peer-reviewed journals, unlike proceeding contributions (about 20%) and others (Alvarez and Caregnato 2017). In INSPIRE-HEP we capture contributions to hep-ph (48%), hep-th (40%) and hep-lat (4%), but not to hep-ex (8%).
scientific papers (Russell et al. 2007) found that this fraction was always below 4% from 1975 to 2004 (most frequent were collaborations between Argentina and Brazil).

Our selection rule is sensible only as long as the number of authors of an article is modest. Large international collaborations—such as the four LHC collaborations at CERN, with thousands of members—may be very productive, but their papers would confuse the interpretability of such a statistics: very few collaboration members in one country could contribute $\mathcal{O}(100)$ papers per year, but as a very small group among thousands of authors; that could drastically overestimate the importance of their contribution.

Since the 1990s—when experimental HEP gained new momentum—some LA countries got strongly involved in “Big Science” projects (large international experimental collaborations), which boosted the HEP community and enhanced its overall HEP productivity [to some extent, this process had already started in the 1980s (Masperi 2000)]. The case of Mexico is analyzed in Collazo-Reyes and Luna-Morales (2002), Collazo-Reyes et al. (2004), which describe the participation in research centers like CERN, DESY, SLAC, Fermilab and BNL as a style of science, which was new in LA. The HEP challenges required a new working style, which later propagated into other sciences (Manganote et al. 2016). Collazo-Reyes et al. (2004) observed that experimental arXiv entries receive on average about 4.5 times more citation than theoretical ones, but that theoretical papers have a longer “citing life”, and that cross-citations between theory and experiment are rare. A number of papers by large collaborations are very highly cited, and including them would clearly distort our statistics. Manganote et al. (2016) document this effect in the case of Brazil: in the period 2010–14 its participation in large collaborations yielded just 8.3% of the HEP papers, but 33.2% of the citations. Hence this small fraction strongly affects the citation record (and therefore also the university rankings), if all HEP is combined. Collazo-Reyes et al. (2010) reported a similar phenomenon in Mexico. This confirms that experimental HEP may well have a misguiding effect on statistical studies. Theoretical HEP, however, is particularly appropriate for a clean analysis of national achievements (mathematics might be an alternative).

This motivates our restriction to papers in theoretical HEP, where the number of authors is usually small, so one can assume each of them to have contributed significantly. To the best of our knowledge, this is the first study of this kind. As a quantitative rule, our statistics only includes papers signed by less than 20 authors.

This cutoff tends to include (exclude) theoretical (experimental) research papers. Referring to HEP in general, Frandsen and Nicolaisen (2010) point out that there is more “hyper-authorship” (inclusion of passive authors) than in other disciplines. This obviously concerns experimental physics, which again justifies our focus on theory.2

We also had to be selective with the journals where the articles contribute to our statistics. Unfortunately we had to exclude interdisciplinary journals, like Physics Review Letters, Nature and Science, although they published some particularly important works in theoretical HEP. However, in the framework of our statistical study it would have been practically impossible to select the papers in these journals which refer to theoretical HEP.3 Therefore our data taking is limited to specialized journals, which are exclusively devoted

2 Birnholtz (2000), as well as Frandsen and Nicolaisen (2010) further observed that in about 3/4 of the HEP papers, the authors appear in alphabetic order. This quota is higher than in other disciplines, and it shows that in our study a consideration of first authors is not motivated.

3 Mele et al. (2006) observed in 2006 that a total of about 6000 HEP papers are published annually (including experimental HEP), 83% of them in just six journals. Five of them are specialized on HEP and therefore included in our Table 1 (Phys. Rev. D, Phys. Lett. B, Nucl. Phys. B, J. High Energy Phys., Eur. Phys. J. C), whereas Phys. Rev. Lett. is broadband, as we mentioned above.
to HEP, such that all their articles (that refer to theory) can be considered contributions to
the field that we consider.

Moreover, in order to restrict the data to articles of scientific importance, we only
considered high-impact journals. In this respect, our criterion was a 2-years IF $> 1$ in the
year 2012, according to the Journal Citation Reports (n.d.).

The application of these selection criteria led to a set of 14 international journals, which
do provide entries to our statistics. They are listed in Table 1, along with their IF; before
2010 it is averaged over periods of 5 years. Note that five of these journals came to
existence after 1990, which explains the empty slots in Table 1.

Based on these criteria, our study captures theoretical research papers in particle physics
and quantum field theory, and—following general conventions (INSPIRE, n.d.)—also in
cosmology and gravity (although the term “high energy” might be arguable in those cases).
On the other hand, for instance the extensive literature on condensed matter physics and
optics is not included. As we mentioned in “Outline” section, we consider subjects which
are rather far from practical applications, say in technology or industry, at least on a short
time-scale. Hence these fields of research can be considered as some kind of “luxury”. On
the other hand, they are relatively cheap, compared to experimental science. These char-
acteristics should be kept in mind in “Correlations with socio-economic indices” section,
when we are going to compare the national productivities with indices from economy and
development.

Table 1  List of the journals specialized on HEP, with their 2-years IF averaged over periods of 5 years, and in 2012. The latter is above 1 in all cases, which was our criterion for a high-impact journal, where the articles enter our statistics

| Journal                               | 1990–94 | 1995–9 | 2000–04 | 2005–09 | 2012 |
|---------------------------------------|---------|--------|---------|---------|------|
| J. Cosmol. Astropart. Phys.           | –       | –      | 7.914   | 6.374   | 6.036|
| J. High Energy Phys.                  | –       | –      | 6.454   | 5.678   | 5.618|
| J. Phys. G                            | 2.178   | 1.277  | 1.348   | 2.966   | 5.326|
| Eur. Phys. J. C                       | –       | –      | 4.766   | 3.453   | 5.247|
| Astropart. Phys.                      | –       | –      | 3.924   | 3.783   | 4.777|
| Phys. Rev. D                          | 2.734   | 3.702  | 4.462   | 4.883   | 4.691|
| Phys. Lett. B                         | 3.174   | 3.723  | 4.314   | 4.291   | 4.569|
| Nucl. Phys. B                         | 4.578   | 3.311  | 5.395   | 4.771   | 4.327|
| Class. Quantum Gravity                | 1.492   | 1.790  | 2.262   | 2.924   | 3.562|
| Adv. High Energy Phys.                | –       | –      | –       | –       | 3.500|
| Prog. Part. Nucl. Phys.               | 2.060   | 2.119  | 2.354   | 3.699   | 2.257|
| Int. J. Mod. Phys. A                  | 1.411   | 1.400  | 1.198   | 1.014   | 1.127|
| Mod. Phys. Lett. A                    | 1.306   | 1.070  | 1.251   | 1.335   | 1.110|
| Int. J. Theor. Phys.                  | 0.370   | 0.438  | 0.556   | 0.530   | 1.086|

4 To compute the IF of some year $Y$, one considers all articles published in one journal during the years $Y – 1$ and $Y – 2$. The IF is the average number of citations that these articles received in the course of the year $Y$ (Journal Citation Reports n.d.).

5 This concerns J. Cosmol. Astropart. Phys. (since 2003), J. High Energy Phys. (since 1997), Eur. Phys. J. C (since 1998), Astropart. Phys. (since 1992) and Adv. High Energy Phys. (since 2010).

6 According to Russell et al. (2007), between 10 and 15% of the LA physics papers deal with particles and fields.
Our search strategy in the Web of Science specified a country, publications in one of the journals in Table 1, research in “Physics Particles Fields”, and the restriction to less than 20 authors. This excludes most experimental works, but some of them adhere to this cutoff. To exclude them we eliminated the research areas “instrumentation” and “spectroscopy”, as well as some well-known experimental collaborations. Then we searched for specific terms in title, keywords and abstract, which could hint at experimental physics, like “measurement”, “beam”, “detection”, “instrumentation”, “spectrum”, “collision” and “eV” (the latter is also sensitive to “MeV”, “GeV” etc.). If such a suspicious term was detected, a look at title and abstract was necessary to decide whether the paper was experimental or theoretical.

To summarize: articles enter our statistics if they were published in one of the journals on Table 1, if they refer to theoretical physics, and if the number of authors is below 20. They count for a country if at least one author gives a working address there. Citations to these articles count in any paper which appears in the Web of Science, until (and including) the year 2012.

Ranking by nations

Overview

The left-hand side of Table 2 gives the total number of publications—according to the criteria specified in “Criteria for the statistical data” section—that emerged in the eight dominant LA countries. They can be divided into a leading group: Brazil, Mexico, Argentina and Chile, and a sub-leading group, consisting of Colombia, Venezuela, Uruguay and Cuba. All other countries in LA have a production rate below one typical active researcher, who publishes about two papers per year; this motivates our cutoff at this point.

The corresponding numbers for the five intercontinental countries under consideration are given on the right-hand side of Table 2. We see that their productivity is in the magnitude of the leading group in LA.

Regarding science and technology in general, a comparison between the leaders in LA and among the intercontinental countries in Table 2, Brazil and India, is discussed by Sikka (1997), which stresses certain similarities. A newer study of this kind, Gonzalez-Brambila et al. (2016), considers nine developing countries, including BRA, MEX, ARG, CHL, IND and ZAF. It applies methods (like the illustration with “radar charts”) of the classical global analysis by King (2004). Below we are going to comment on key observations by Gonzalez-Brambila et al. (2016).

From a global perspective, Mele (2009) reports that e.g. in the years 2005/6 the countries included in our studies produced the following fractions of the HEP papers worldwide: CAN 2.8%, BRA 2.7%, IND 2.7%, KOR 1.8%, MEX 0.8%, BEL 0.7%, ARG 0.6%, CHL 0.6%, while the rest is below 0.4%. This hierarchy is similar to Table 2; the most notable difference is that Canada and Brazil catch up with India. Explanations could be the inclusion of experimental HEP, and that co-authorship is counted on a pro-rata basis (assigning fraction of a country).

These results can be compared to the ranking by Morán-López (2000), which divides the LA countries into four groups, based on the number of Ph.Ds in physics and “overall scientific output”:

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7 This table also contains the official national acronyms, to be used in the following.
Table 2 The total number of publications, which fulfil the criteria of “Criteria for the statistical data” section, over the entire period from 1990 to 2012

| Country | Publication | rwf | Country | Publication | rwf |
|---------|-------------|-----|---------|-------------|-----|
| Brazil  | BRA 4650    | 3.68| India   | IND 6570    | 3.39|
| Mexico  | MEX 1924    | 3.33| Canada  | CAN 5452    | 4.03|
| Argentina| ARG 1387   | 3.73| South Korea| KOR 3491  | 4.23|
| Chile   | CHL 1034    | 4.23| Belgium  | BEL 1819    | 4.08|
|         |             |     | South Africa| ZAF 747    | 3.51|
| Colombia| COL 277     | 3.88|         |             |     |
| Venezuela| VEN 266    | 3.48|         |             |     |
| Uruguay | URY 100     | 3.63|         |             |     |
| Cuba    | CUB 77      | 3.72|         |             |     |

The gap in the left columns (which refers to LA) distinguishes the leading from the sub-leading group among these eight countries. The intercontinental countries (right columns) are comparable to the leading group in LA. The column “rwf” shows the average re-weighting factor by the journal IF, as described in “Re-weighting by the journal impact factor” section. We also display the official acronym for each country, to be used below.

Group 1: Brazil, Mexico, Argentina.
Group 2: Cuba, Chile, Venezuela, Colombia.
Group 3: Includes 11 countries, among them Uruguay.
Group 4: Rest, negligible in physics.

This is very similar to our groups in Table 2, but there Chile and Uruguay move one level up.

The time-lines which led to Table 2, i.e. the production in these countries during the period from 1990 to 2012, is illustrated in Fig. 1 [for the detailed numbers we refer to Urrutia Sánchez (2015)]. The general trend is that the productivity increases with time (up to short term fluctuations). For some—though not all—countries we observe a dip, in the period (roughly) between 2001 and 2004, to be interpreted in “Search for correlations in the time-evolution” section.

Re-weighting by the journal impact factor

A possible criticism of the overview in “Overview” section is that all articles are counted equally, if they refer to theoretical HEP and they were published in any of the journals of Table 1, which all had an IF > 1 in the year 2012. However, in the considered period the IFs of these journals vary from 0.370 to 7.914, so one could argue that these articles should be counted with different weights. Figure 2 shows the outcome of such a re-weighting, where each paper is multiplied with the IF of its journal in that year.

Regarding LA, the hierarchy among the eight dominant countries does not change, but the dominance of Brazil is further enhanced. In particular, the structure of a leading and a sub-leading group, composed of four countries each, persists. This distinction is not visible, however, if we just consider the mean re-weighting factor for each country, which is given
in the columns “rwf” of Table 2. If we include the intercontinental countries, we see that Chile, South Korea, Belgium and Canada tend to publish in high-impact journals (rwf \( > 4 \)), whereas the papers from South Africa, Venezuela, India and Mexico appeared in journals with relatively low IF.

Figure 3 shows how many papers from LA were published in each of the 14 journals of Table 1. There is a clear dominance by Phys. Rev. D in all countries, usually followed by
We recall, however, that five of these journals were founded after 1990, cf. footnote 5. For detailed numbers and the annual time.

**Fig. 2** Histograms of the total number of publications per country (to the left), and of the IF-re-weighted record (to the right).

**Fig. 3** Histogram for the number of publications from LA in the journals of Table 1. In each bin, the rectangle is divided into the contributions by the eight countries under consideration. Phys. Rev. D clearly dominates, followed by Phys. Lett. B.
evolution, we refer again to Urrutia Sánchez (2015), since a comparative study of the importance of various journals is not our goal.

Total number of citations

Yet another point of view is that one should directly re-weight each article with the number of citations to it, rather than using the IF of the journal. This amounts to a statistics of all citations received (at any time from 1990 to 2012) by all papers of one country. This sum, over all 23 years, is shown in Table 3. Within LA the striking dominance of Brazil persists (in particular the citation ratio Brazil/Mexico, 2.45, is very similar to the publication ratio, 2.42), while Argentina almost catches up with Mexico, and also Chile is moving closer.

We observe a marked distinction between these four leading nations and the sub-leading group, also with respect to the citations. Within the latter group, we notice that Venezuela is slightly superior to Colombia, in contrast to the hierarchy of Table 2.

Earlier statistics of the citations of LA articles from all sciences are given by Krauskopf et al. (1995) and Osareh and Wilson (1997). The latter refers to the period 1981–93, and arrives at the same hierarchy as the leading group as in Table 3 (which also coincides with Table 2): BRA, MEX, ARG, CHL.

Compared to Table 2, the intercontinental countries appear superior in this statistics. In particular, Canada achieved an impressive number of more than $10^5$ citations. The trend is that papers from LA are somewhat less quoted than the publications from these five countries; the overall average citation number per article in LA (intercontinental) is 12.30 (15.96).

In order to make this point more explicit, Table 3 also displays the mean number of citations per article for each country. The time-lines of citations are shown in Fig. 4. In general, the world-wide publication output tends to rise with time, which explains an

|            | citations | citations per article |            | citations | citations per article |
|------------|-----------|-----------------------|------------|-----------|-----------------------|
|            | Canada    | 105189                |            | South Korea | 50894                 |
| Brazil     | 53452     | 11.5                  | India      | 89100     | 13.6                  |
| Mexico     | 21797     | 11.3                  | South Korea | 50894     | 14.6                  |
| Argentina  | 19164     | 13.8                  | Belgium    | 32951     | 18.1                  |
| Chile      | 15284     | 14.8                  |            | South Africa | 10455                |
| Venezuela  | 4018      | 15.1                  |            |            |                       |
| Colombia   | 3476      | 12.5                  |            |            |                       |
| Uruguay    | 1628      | 16.3                  |            |            |                       |
| Cuba       | 713       | 9.3                   |            |            |                       |

Note, however, that Uruguay’s value is to a significant part due to one single publication, quoted as Ref. [2] in the appendix “Top-cited LA papers in theoretical HEP, published in specialized journals between 1990 and 2012, regarding citations until 2012”; otherwise it would have just 12.3 citations per article.
increasing number of citations until the end of the 20th century. The decrease after 2005 is simply due to the fact that newer papers had little time to be cited (before 2013).

The results of this section can be compared to the data on the webpage Journal & Country Rank (n.d.), which displays a ranking for LA (or other regions) in Nuclear Physics.

**Fig. 4** Time-lines of the citations received, from 1990 to 2012, for the countries under consideration. We show 3-years averages (plus the average of 2011 and 2012)
and HEP, since 1996. That ranking is based on the national H-index (Hirsch 2005). If we consult it for single years, we see that our dominant group is practically the same (as a difference we note that until 1999 ARG was second, before MEX). Among the following four countries, the annual ranking sometimes contains Ecuador, Peru and Puerto Rico, and otherwise countries which are present in our study. The summary of the period 1996–2016 is identical to our Table 2 up to position 6, followed by Cuba, Ecuador, Puerto Rico, Peru and Uruguay. These slight differences are apparently due to the inclusion of experimental HEP, and nuclear physics.8

In the appendix “Top-cited LA papers in theoretical HEP, published in specialized journals between 1990 and 2012, regarding citations until 2012” we add a list of the most cited LA papers which enter our statistics.

Publications per capita

Depending on the aspect of interest, one should rather refer to the scientific productivity of different countries relative to their population. In fact, the populations of the eight LA countries in our tables varies by orders of magnitude.9 Table 4 shows, country by country, the total number of papers, divided by the population (in millions) of that country, in the year when each paper was published. This table also includes the total number of citations per million of inhabitants in 2012.

We observed before that re-weighting by the IF, or by the citation numbers, hardly affects the hierarchy. The statistics per capita, however, does alter the picture significantly. Here the leader turns out to be Chile, followed by Argentina, and Uruguay rises from the sub-leading group to the third position. On the other hand, Brazil and Mexico lose three positions each, and Colombia slips down to the last position in this list for LA.

This matches the observation of Gonzalez-Brambila et al. (2016) that Chile has a particularly high number of publications and citations per researcher in science and technology. This observation is also consistent with data available from the public webpage Red de Indicadores de Ciencia y Tecnología – Iberoamericana e Interamericana (n.d.). As an interpretation, Gonzalez-Brambila et al. (2016) refer to Chile’s excellent collaboration with Europe, in particular related to the European Southern Observatory for ground-based astronomy, created by 16 nations in 1962, and located in northern Chile. However, our observation of an analogous trend in theoretical HEP suggests that this observatory alone is not sufficient to explain Chile’s extraordinary scientific efficiency.

From the intercontinental perspective, we now see an overwhelming record of the First World countries (Canada and Belgium), which might be expected in a field of research without immediate applications. South Korea is still ahead of all LA countries, whereas India—the leader in Table 2—is now below any of the eight LA nations in our tables.

The perspective of this subsection will be relevant for considerations in the “Correlations with socio-economic indices” section, in particular for the search of correlations with human development and education.

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8 Our study does include nuclear physics at the fundamental level of Quantum Chromodynamics, but not necessarily the (more traditional) effective approaches to nuclei, with external potentials etc.

9 From 1990 to 2012, the population (in millions) evolved as follows: Brazil 149–198, Mexico 83–115, Colombia 34–47, Argentina 32–41, Venezuela 19–30, Chile 13–17, Cuba 10.6–11.3, Uruguay 3.1–3.4.
Correlations with socio-economic indices

**Gross Domestic Product (GDP)**

The GDP is widely used as a measure for the economic performance of a country (The International Monetary Fund, n.d.). It represents the monetary value—in US dollars—of all final goods produced, and services provided, during 1 year.\(^\text{10}\) Three quantities can be used to estimate the GDP; theoretically the results should coincide.

- Total value of the domestic production and services, minus intermediate consumption.
- Sum of the incomes of all residents and enterprises. (Unpaid work is not captured.)
- Sum of all expenses for purchasing final goods and services, which emerge in the country under consideration.

The GDP is distinct from the Gross National Income (GNI), which considers the nationality of the owners of productive enterprises. In contrast, the GDP solely refers to the location of production.

Both the GDP and the GNI are purely economic indices. They do not account e.g. for the wealth distribution among the residents, the quality of health-care and education, or the environment-friendliness of the production. The following two subsections will refer to some of these complementary aspects, which are more directly linked to the quality of human life.

A study of the entire region of Latin America reports an increase of the GDP by 50.8\% in the period 2002–2007, along with an increase by 56.5\% of the Gross Domestic Expenditure for Research and Development (GERD) (Chinchilla-Rodrı´guez et al. 2015).\(^\text{11}\)

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\(^{10}\) This is not based on the currency exchange rate, but on the actual values of goods, i.e. it refers to purchasing power parity.

\(^{11}\) We do not have corresponding data specifically for HEP, let alone for theoretical HEP.
This corresponds to an increase of the GDP world fraction from 8.0 to 8.5\%; the GERD world fraction had a stronger relative growth, though at a lower level, from 2.8 to 3.5\%.

Gonzalez-Brambila et al. (2016) compare the world fraction of the GERD in a number of countries to their impact, measured by the citation share of papers in science and technology (averaged over 5 years). In 1993 Chile had a balanced record (its GERD share and citation share where both 0.1\%), whereas in ARG, BRA, IND, MEX, ZAF the citation share stayed behind the GERD share. This was still the case in 2009, except for ARG, which now attained a balanced record (0.3\% each), while in Chile the citation share became even stronger (0.2\% citation share with still just 0.1\% GERD share).

For earlier studies of the correlation between the GDP and the overall scientific output in LA we refer to Cardoza and Villegas (1996) and Lewison et al. (1993) (for the 1980s) and De Moya-Anegón and Herrero-Solana (1999) (for the period 1991–7). The latter reports an annual increase of the scientific production by 13\%, with a ranking very similar to our Table 2: BRA, MEX, ARG, CHL, VEN, COL, CUB, URU. In addition to the correlation with the GDP it considers the relation to the GERD, and to the number of researchers in each country.

Figure 5 refers to the two periods from 1990 to 2000, and from 2001 to 2012. In both cases, we show for each country in our study the total number of publications versus the GDP.
average GDP in this period. The data points do not follow any obvious function, hence the only fit that appears sensible is linear (although for instance India deviates strongly from these fits).\(^{12}\) It has been performed separately in and beyond LA, for both periods. We observe a stronger slope for the intercontinental countries, i.e. if we extrapolate the publications/GDP from LA to the region of the intercontinental data points, the extrapolated line tends to be lower (South Africa is the exception). This trend is enhanced in the later period.

**Human Development Index (HDI) and Education Index (EI)**

The HDI was developed since the 1990s; key protagonists were Mahbub ul Haq (from Pakistan) and Amartya Sen (from India). Obviously, notions like well-being and happiness are hard to parameterize and to measure statistically. However, a single index, which is more oriented towards the quality of human life than the GDP, is motivated by the purpose of shifting the attention of influential persons (such as politicians) from purely economic criteria towards a more social perspective.

The HDI is composed of three indices, which are related to health, education and income (Human Development Reports—United Nations Development Programme, n.d.). Before 2010 these three components were computed as follows:

- Life Expectancy Index \( \text{LEI} = \frac{\text{LE} - 25}{60} \), where \( \text{LE} \) is the life expectancy (in years).
- Education Index \( \text{EI} = \frac{1}{3} (2 \times \text{ALI} + \text{GEI}) \), where Adult Literacy Index \( \text{ALI} = \text{adult literacy, and the Gross Enrollment Index \( \text{GEI} = \text{school enrollment (both in fractions of 1).} \)} \)
- Income Index \( \text{II} = \ln \left( \frac{\text{GDPpc}}{100} \right) \ln 400 \), where GDPpc = GDP per capita.

This assumes an effectively maximal LEI and II of 1 for 85 years of life expectancy, and a GDPpc of 40,000 dollars. Finally the HDI is obtained as the geometric mean of these three indices: \( \text{HDI} = \left( \frac{\text{LEI} \times \text{EI} \times \text{II}}{1} \right)^{1/3} \). Compared to the arithmetic mean, it decreases the more the three components are distinct.

In 2010 the definitions of the EI and the II (but not of the LEI) were refined:

- \( \text{EI} = \frac{1}{2} (\text{MYSI} + \text{EYSI}) \), where \( \text{MYSI} = (\text{mean years of schooling of the populations above 24 years})/15, \text{and EYSI} = (\text{expected years of schooling of a 5-years old child})/18. \)
  (The denominator 18 corresponds to the usual duration of the education up to a master's degree.)
- \( \text{II} = \frac{\ln(\text{GNIpc}/100)}{\ln 750} \) where GNIpc = Gross National Income per capita, at purchasing power parity (cf. “Gross domestic product (GDP)” section).

Figure 6 compares the HDI to the number of publications per million of inhabitants and year. In addition, Fig. 7 refer exclusively to the EI, which can be viewed as the direct basis for scientific research.

As in Fig. 5, the plots in Figs. 6 and 7 are divided into two periods, and without any obvious fitting function, a linear interpolation seems to be again the only applicable fit. In both periods, and in both figures, the fits for the intercontinental countries have a stronger slope. This means that in those countries the given conditions—the HDI and EI—are converted into a higher production of physics papers that enter our statistics. The same qualitative feature was observed for the GDP in Fig. 5.

\(^{12}\) Explicit data about the fit quality of the plots in this section are given in Urrutia Sánchez (2015).
Search for correlations in the time-evolution

We proceed to a schematic overview of the time-line of the socio-economic indices, searching for trends, where a relation to the productivity of theoretical HEP papers is conceivable. Here we refer to properties, which would be called “intensive” in the terminology of thermodynamics, i.e. they do not depend on the size, or in our case the total population of a country. In particular, we consider the publication rate per million of inhabitants, which modifies the leading and sub-leading group, as Table 4 shows. Correspondingly, we now consider the GDP per capita (GDPpc), as well as HDI and EI, which are “intensive” as well. (In this terminology, the total number of publications or citations and the GDP would be denoted as “extensive” quantities).

The time-lines of these four intensive quantities are shown in Figs. 8, 9 and 10. In several countries we observe a marked economic recession in the period 2002–2003, but afterwards a significant growth. This feature is extreme in Argentina, where in 2002 the GDPpc collapsed down to 36% of its value in 2001. It seems obvious to relate this crises to

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**Fig. 6** The number of publications/(million of inhabitants × year) versus the average HDI, in the period 1990–2000 (plots above) and for the period 2001–2012 (plots below). We show data for the countries under consideration in LA (on the left) and beyond (on the right). For each of the two periods we include linear fits for the LA and for the intercontinental countries—although these fits have a rather poor quality. In both periods, the latter have a stronger slope: 0.72 vs. 1.19 in the first period, and 1.28 vs. 2.03 in the second period. This effect is due to Canada, Belgium and India, while the publication/HDI ratio for South Korea and South Africa is similar to LA. Within LA, Brazil and Chile have a high HEP productivity relative to their HDI, while the opposite holds for Cuba.
the subsequent period of stagnation (including slight recessions) of the HDI, EI and publications per capita, which lasted for about 5 years.

An analogous, but less extreme, economic crises around 2002, followed by significant growth, is observed in Uruguay and Venezuela, while in Brazil, Chile, Colombia, South Africa and South Korea the growth after 2003 coincides. In Uruguay a stagnation of the EI after 2002 could be a consequence of the economic crises, but no detailed correlation with the publication number is visible.13

Venezuela achieved a relevant improvement in its HDI and EI in the early 21st century, but the publication number did not follow this trend—on a long-term scale it is stable. Colombia improved its HDI and EI in this period (but it is still at a modest level), while its publication rate was slightly increased, but there are no correlated fluctuations.

We mentioned already that the economies of Brazil and Chile strongly expanded after 2003. In this period, the HDI and EI increased as well, but again there is no detailed correlation. Chile attained the strongest increase in publications per capita, so it clearly dominates in Latin America in this respect, although its EI is below Argentina and Cuba. In

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13 Here the annual publication number per capita fluctuates strongly. This can be explained by the relatively small population, so the HEP publications are written by very few individuals. For the same reason, the publication rate fluctuates strongly also in Cuba and Chile.
Brazil the publication rate per capita increased marginally, without really reflecting the strong boost in the GDPpc.

The Mexican economy followed a more continuous growth (except for the years 1995 and 2009), the same holds for the HDI, EI, and also the publication rate had a weak but mostly continuous trend up (except for fluctuations in 2001 and 2003). So all four indicators followed a similar behavior, but there is no evidence for a detailed correlation. The Cuban economy grew gradually in the 21st century, while the HDI and EI were strongly boosted (they decreased after 2009, but still at a high level). The publication number fluctuates strongly, with a long-term trend up. It would be a matter of speculation to relate the peak in 2009 to the maxima of the HDI and EI.

Beyond Latin America, South Korea exhibits a strong (though not always continuous) economic growth, which seems consistent with an improvement of the other three parameters under consideration. The evolution in India is trend-wise similar, but at a much lower level. In South Africa the GDPpc clearly increased after 2003, as in a number of Latin American countries. The publication number increased as well in this period, although the HDI does not follow this trend.

To summarize, a long-term trend up in all four parameters is manifest everywhere. Beyond this general pattern, a relation of the socio-economic circumstances and the publication rate seems obvious in the case of Argentina, and it might be plausible in Chile and South Korea, but in most cases such a detailed correlation cannot be observed.
Fig. 9 The time-line of the GDPpc (per capita, in units of 1000 dollars), the publication rate per million of inhabitants, the HDI and the EI of the sub-leading group of LA countries—with respect to the theoretical HEP productivity per capita—in the period 1990–2012. (Note that the scale for publication pc differs from Figs. 8, 10)

Fig. 10 The time-line of the GDPpc (per capita, in units of 1000 dollars), the publication rate per million of inhabitants, the HDI and the EI in three selected countries outside LA, in the period 1990–2012
Conclusions

We presented a statistical analysis of the activity in theoretical HEP in Latin America, in the period from 1990 to 2012. We considered the 8 dominant countries in LA, as well as 5 countries in other regions for comparison.

Regarding the number of publications and citations, the leading nations in LA are Brazil, Mexico, Argentina and Chile. If we consider this productivity relative to the population, the hierarchy reads: Chile, Argentina, Uruguay, Brazil.

As a generic trend, the productivity increases with time. More wealth of a country—measured in terms of its GDP—tends to increase its productivity in theoretical HEP, but the correlation does not follow any simple rule, nor detailed fluctuations in time. An obvious interpretation is that the activity in theoretical HEP significantly depends on the priorities in a country, even within science, and not only on its economic potential.\(^{14}\)

Nevertheless a linear fit of the national data for the number of publications vs. the GDP appears reasonable. The comparison shows a stronger slope in the intercontinental countries, in particular in the 21st century. Therefore, in order to explain the lower productivity in LA compared to the leading countries in Asia, Europe and North America, it is not sufficient to refer to the lower economic potential in LA. If the interpolation of the intercontinental countries is linearly extended to the GDPs in LA, the extrapolated productivity is still above the one observed in LA.

For instance, Morán-López (2000) refers to “poor economic conditions in most Latin American countries” as “one major reason” why this subcontinent is not as productive in physics as the “developed countries in the North”. This is certainly correct, but our study suggests that this reason alone is not a sufficient explanation.

The observation of a superior (linear) extrapolation of the HEP productivity outside LA persists similarly for the HDI, and in particular for the EI (as one of its components). Again a monotonous dependence can be seen, and a linear dependence is the best (reasonable) fit, but some countries deviate strongly from this interpolation.

As for the detailed time-evolution, there are in most cases no simple relations between the publication rate and socio-economic indices. An exception is the economic collapse of Argentina in 2002, which did affect theoretical HEP. In a few other countries, including Chile, a scientific boost due to an economic boom is conceivable. However, such an impact is not a generic rule (our discussion includes counter-examples), so in general the publication rate does not react in an obvious manner to the socio-economic development.

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\(^{14}\) Our ranking can be compared to a branch of science, which is devoted to practical benefits (in contrast to HEP), like public health. A study of publications in this field (Chinchilla-Rodríguez et al. 2015) identified 10 leading countries in LA, which coincide with the countries in our list, plus Peru and Puerto Rico. In this field, Brazil strongly dominates with a production 67.25% of all LA publications, followed by MEX, COL, CHL, CUB and ARG, i.e. particularly COL and CUB are stronger than in HEP. From an intrinsic perspective, relative to the population, the ranking changes more drastically: here Cuba is the leader, followed by Puerto Rico, BRA, CHL and URU. This illustrates differences in the national research priorities, like the Cuban focus on medical research.
Appendix: Famous Latin American publications in theoretical high energy physics

Top-cited LA papers in theoretical HEP, published in specialized journals between 1990 and 2012, regarding citations until 2012

We add a list of the eight most cited LA papers in our statistics (each of them can be assigned to exactly one LA country). Each of these eight papers has over 250 citations, which means that it is famous according to the terminology used in the online data base INSPIRE (n.d.), which is freely accessible and highly popular in HEP. However, our citation numbers added to this list are counted in the Web of Science, up to the end of 2012, as described in “Criteria for the statistical data” section.

1. M. Banados, M. Henneaux, C. Teitelboim and J. Zanelli, “Geometry of the (2+1) black hole”, Phys. Rev. D48 (1993) 1506 [Chile] 799 citations.
2. R. Gambini and J. Pullin, “Nonstandard optics from quantum space-time”, Phys. Rev. D59 (1999) 124021 [Uruguay] 413 citations.
3. F. Pisano and V. Pleitez, “An SU(3) x U(1) model for electroweak interactions”, Phys. Rev. D46 (1992) 410 [Brazil] 371 citations.
4. J. Frenkel and J.C. Taylor, “High Temperature Limit of Thermal QCD”, Nucl. Phys. B334 (1990) 199 [Brazil] 370 citations.
5. N. Berkovits, “Super-Poincaré covariant quantization of the superstring”, J. High Energy Phys. 0004 (2000) 018 [Brazil] 299 citations.
6. L.P. Chimento, A.S. Jakubi, D. Pavon and W. Zimdahl, “Interacting quintessence solution to the coincidence problem”, Phys. Rev. D67 (2003) 083513 [Argentina] 263 citations.
7. P.B. Arnold and O. Espinosa, “Effective potential and first order phase transitions: Beyond leading-order”, Phys. Rev. D47 (1993) 3546 [Chile] 258 citations.
8. G. Aldazabal, L.E. Ibáñez, F. Quevedo and A.M. Uranga, “D-branes at singularities: A bottom-up approach to the string embedding of the standard model”, J. High Energy Phys. 0008 (2000) 002 [Argentina] 254 citations.

Note that all authors of these top-cited papers are distinct. This list is dominated by the nations of the leading group with respect to the publication per capita, cf. Table 4.

Five among these top-cited papers involve co-authors in First World countries (there are no co-authors from other countries in the Third World). References [3] and [5] are all Brazilian, while in Ref. [1] all authors give a Chilean institute as their first address, but part of them add a second address in the First World.

Groundbreaking earlier publications

At last, we mention three groundbreaking highlights of earlier theoretical HEP in LA, i.e. these three papers truly entered the history of physics (cf. Masperi (2000)): the prediction of the geomagnetic effect on cosmic rays by M. Sandoval Vallarta (MEX) and G. Lemaître (Mateos and Minor 2013), the prediction of the Z-boson by J. Leite Lopes (BRA) (Leite Lopes 1999), and the invention of dimensional regularization by C. Bollini and J.J. Giambiagi (ARG) (Bietenholz and Prado 2014):
G. Lemaître and M. Sandoval Vallarta, Phys. Rev. 43 (1933) 87.
J. Leite Lopes, Phys. Rev. 190 (1958) 509.
C.G. Bollini and J.J. Giambiagi, Nuovo Cim. 12B (1972) 20; Phys. Lett. 40B (1972) 566.

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