Publication patterns in HEP computing

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Abstract. An overview of the evolution of computing-oriented publications in high energy physics following the start of operation of LHC. Quantitative analyses are illustrated, which document the production of scholarly papers on computing-related topics by high energy physics experiments and core tools projects, and the citations they receive. Several scientometric indicators are analyzed to characterize the role of computing in high energy physics literature. Distinctive features of software-oriented and hardware-oriented scholarly publications are highlighted. Current patterns and trends are compared to the situation in previous generations' experiments.

1. Introduction
Publications in scholarly journals establish the body of knowledge deriving from scientific research; they also play a fundamental role in the career path of scientists and in the evaluation criteria of funding agencies.

A previous scientometric study [1] highlighted that software-oriented publications are underrepresented with respect to hardware-oriented ones in the field of high energy physics (HEP). The results of that analysis showed that the relative difference between the production of scholarly literature in these areas had increased in the context of the experiments at LHC (Large Hadron Collider) with respect to the previous generation’s experiments at LEP (Large Electron-Positron collider). The analysis in [1] was performed prior to the start of operation of LHC.

The scientometric analysis summarized in this paper, which reflects a presentation on this topic at the CHEP (Computing in High Energy Physics) 2012 conference, reviews the publication patterns in HEP computing in greater detail, with special emphasis on their evolution since the beginning of LHC operation.

2. Scope of the study
The study summarized in this paper provides a quantitative overview of publication patterns in high energy physics over the past thirty years, with emphasis on software-oriented publications.

The scientometric analysis is focused on a set of topics that are representative software R&D (research and development) in the context of HEP. The selection is far from exhaustive of the wide variety of research activities in experimental high energy physics, rather it intends to highlight some distinctive features of the literary production in the field.
The analysis concerns a representative sample of general software tools, which respond to common needs of the HEP experimental community, and a sample of HEP experiments of the current and past generation. Two widely used general software tools, Geant4 [2, 3] and ROOT [4, 5] are the object of a detailed scientometric analysis. More limited investigations concern the publications associated with other software tools contributing to the general computing infrastructure of LHC experiments, such as the LHC Computing Grid. The four major experiments at LEP, the ALICE, ATLAS, CMS, LHCb and TOTEM experiment at LHC, and the BaBar experiment at the SLAC B-factory are included in the scientometric analysis.

The sample subject to evaluation consists of regular publications in established peer reviewed journals. Contributions to conference proceedings, books, institutional reports, items in preprint archives, white papers posted on web sites and software manuals are not considered. Some journals (e.g. Nuclear Instruments and Methods, NIM) also publish conference proceedings, usually in dedicated issues: these articles have been identified and excluded from the analysis.

The examined scientometric indicators include the number of publications produced by the various subjects under study, their time distribution, the journals where they are published and their citation patterns.

3. Data sources and analysis methods
The main source for the scientometric analysis reported in this paper is Thomson-Reuters’ Web of Science [6], which is considered the most authoritative reference for bibliometric information in the academic environment. The authors’ institutional subscription gives access to a subset of it, the “Science Citation Index Expanded” database; it does not include the “Conference Proceedings Citation Index”. The database covers the period from 1970 to date.

The access to a subset of the Web of Science generates an apparent mismatch between the total number of citations associated with a paper, which includes entries from the “Conference Proceedings Citation Index”, and the actual number of citations available for analysis, which is limited to publications in journals belonging to the “Science Citation Index Expanded”. A further complication for scientometric analysis is due to the incorrect classification of some publications listed in the “Science Citation Index Expanded” as “Conference proceedings”: this label is arbitrarily attributed by Thomson-Reuters to some regular articles in journals that never publish conference proceedings (e.g. IEEE Transactions on Nuclear Science, TNS). Conversely, some entries in the “Science Citation Index Expanded” that are not labeled as “Conference proceedings”, appear in journals (e.g. Nuclear Instruments and Methods) as contributions to conference proceedings. These errors in the Web of Science have been manually corrected in the analysis whenever possible: for instance, all papers published in IEEE Transactions on Nuclear Science are considered in the analysis as regular journal publications, irrespective of Thomson-Reuters’ classification of some of them as conference proceedings, and papers published in Nuclear Instruments and Methods A issues dedicated to conference proceedings have been removed from the analysis, even if they are not identified as “Conference proceedings” in the Web of Science.

Other sources have been used to cross-check and complement the information derived form the Web of Science: the web sites of the publishers of technological journals relevant to HEP and CERN Document System (CDS). The comparison of the data retrieved from these sources has highlighted some omissions and inconsistencies in the data sample retrieved from Thomson-Reuters’ Web of Science: for instance, some papers published by LHC experiments, which are listed in the CDS database, do not appear in the Web of Science, and the number of citations of a paper reported in the publisher’s web site is in some cases inconsistent with that reported by the Web of Science.

The publications by HEP experiments are distinguished into physics papers (i.e. publications of experimental results representing the object of the experiment) and technological papers (i.e.
publications about the instruments and methods that contribute to produce the experimental results). Technological publications are further identified as hardware-oriented, software oriented or dealing with data acquisition (DAQ) and trigger. This classification implies some degree of subjectivity, which has been mitigated by performing cross-checks over the selections performed by individual analysts. It is worthwhile to note that the classification of publications is part of the regular professional practice of the authors of this paper, either as members of the Editorial Board of a core journal in nuclear technology or as responsible of the library of a major HEP laboratory.

The attribution of a paper to a given category is based on a variety of criteria. In some cases the title of a paper or the journal where it is published unambiguously identify its topic: for instance, papers published in Physical Review D are all classified as physics papers. For most papers, the record in the Web of Science, which also includes the abstract, provides sufficient information to identify the scope of the paper and to classify it in one of the above mentioned categories. In cases where the attribution is not evident based on the information in the Web of Science, the full text of the paper was evaluated.

Complementary analyses based on the Web of Science and on publishers’ web sites data, performed independently by different analysts, confirmed the robustness of the classification. Based on detailed cross checks over selected samples, the uncertainty in the results reported in this paper, which derives from intrinsic inconsistencies in the Web of Science and from subjective classification of papers, can be estimated of the order of a few percent. This level of uncertainty does not affect critically the conclusions of this study.

The analysis reported in the following sections covers three decades of scientific literature (1982-2011); it is limited to papers published until the end of 2011 to ensure the reproducibility of results based on the Web of Science. Unless differently stated, the number of citations reflects the status in the Web of Science as on 14 May 2012, i.e. one week prior to the beginning of the CHEP 2012 conference.

4. General software tools
Two software tools used by LHC experiments for simulation and data analysis have been evaluated: Geant4 and ROOT.

Geant4 is documented in two reference publications [2, 3], which are brought to the attention of the experimental community in the Geant4 web page. These papers have collected respectively 2934 and 574 citations (including citations from conference proceedings indexed by the Web of Science); reference [2] has crossed the threshold of 3000 citations shortly after the CHEP conference (3037 citations by 18 June 2012). Reference [2] is the most cited publication in the "Nuclear Science and Technology" category over the period considered in this scientometric study. Excluding the Review of Particle Properties, it is the most cited paper produced by CERN and by INFN.

The time distribution shown in figure 1 shows that citation to the more recent reference [3], published in 2006, is omitted by most publications that cite the earlier one [2], published in 2003.

Although the development of Geant4 was originally motivated by the requirements of LHC experiments, the source of the citations to its reference paper [2] shows the widely multidisciplinary character of its use in the scientific community. Figure 2 lists the journals contributing the largest number of citations to [2]: it includes physics journals with various scope (high energy physics, nuclear physics, astroparticle physics), nuclear technology journals, medical physics and radiation protection journals, and a regional journal (published by a national physics society).

One can observe in figure 3 that only a relatively small number of citations to [2] are associated with LHC collaborations at this stage of their life-cycle. It is worthwhile to note that only
Figure 1. Number of citations collected by Geant4 reference papers [2, 3] as a function of time.

Figure 2. Journals citing Geant4 reference [2]; the colour codes in the plots are associated with the scope of the journals (physics: violet, nuclear technology: green, medical physics: orange, radiation protection: light brown, regional: blue. The journals listed in the histogram contribute approximately 75% of the total number of citations to [2].
approximately 20% of the citations to [2] listed in the Web of Science are formally associated with a collaboration (identified as "Group Authors"); the vast majority of publications citing [2] appear as the product of individual research groups, rather than of formal experimental organizations. Figure 3 lists the collaborations that contribute the largest number of citations; they correspond to approximately 75% of the citations associated with collaborations in the Web of Science.

ROOT is documented in two reference publications [4, 5], published in 1997 and 2009. The earlier one is a contribution to a workshop proceedings, while the later one is a regular journal publication. These papers have collected respectively 540 and 27 citations (including citations from conference proceedings indexed by the Web of Science).

The time distribution shown in figure 4 shows a similar pattern as in figure 1: the citation to the more recent reference is omitted by most publications that cite the earlier one.

The citations to ROOT earlier reference [4] have a multidisciplinary character, as is visible in figure 5, although the relative contribution from various domains appears different for Geant4 and ROOT. The distribution of the domains of the citations listed in figures 2 and 5 is summarized in table 4: citations to Geant4 appear equally distributed between physics and nuclear technology journals, while nuclear technology journals are the most relevant source of citations to ROOT; also, the fraction of citations from medical physics and radiation protections journals is significantly larger for Geant4 than for ROOT. It is worthwhile to remind the reader that table 4, similarly to figures 2 and 5, reflects the major sources of citations, amounting to approximately 75% of total citations collected by Geant4 and ROOT main references.

5. Publications by HEP experiments
The number of publications produced by the HEP experiments considered in this study is plotted in figure 6. The plot distinguishes papers belonging to various categories: physics,
Figure 4. Number of citations collected by ROOT reference papers [4, 5] as a function of time.

Figure 5. Journals citing ROOT reference [4]; the colour codes in the plots are associated with the scope of the journals (physics: violet, nuclear technology: green, medical physics: orange, radiation protection: light brown, computing: grey. The journals listed in the histogram contribute approximately 75% of the total number of citations to [4].
Table 1. Source of citations to Geant4 and ROOT main reference papers.

<table>
<thead>
<tr>
<th>Journal categories</th>
<th>Geant4 (%)</th>
<th>ROOT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear technology</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Physics</td>
<td>30</td>
<td>18</td>
</tr>
<tr>
<td>Medical physics and radiation protection</td>
<td>14</td>
<td>6</td>
</tr>
</tbody>
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Figure 6. Papers published by the HEP experiments considered in this study, distinguishing the contribution of various categories to the total count.

Hardware, software, DAQ-trigger and general. Physics papers are the dominant component for the experiment that terminated the data-taking phase and are close to the end of their lifecycle, while they represent a small fraction of the publications by LHC experiments, which are in the early stage of their run. The last category includes papers describing the whole detector, or the performance of some subsystems, which involve hardware and software aspects.

Software related papers appear to be a small fraction of publications for all the experiments: this trend is evident in figure 7, which shows the apportioning of technological papers across the three categories of hardware, software and DAQ-trigger. The relatively smaller presence of software publications in the production of LHC experiments is confirmed in a more detailed analysis performed over the papers published since the start of LHC operation in 2008 in two representative nuclear technology journals, NIM A and TNS, shown in figure 8.

The time distribution of the publications produced by the experiments considered in this study is shown in figure . The horizontal scale of the plots takes as a reference the year when LEP (1989), BaBar (1998) and LHC (2008) started running. Figure shows both the total count of papers produced per year, and the number of published papers per collaboration member along the lifecycle of the experiments. The number of collaboration members is subject to variation over the lifetime of an experiment, a constant number is assumed in this study, due to the difficulty of ascertaining the number of collaboration members as a function of time for all
Figure 7. Technological papers published by the HEP experiments considered in this study: fraction of hardware, software and DAQ-trigger publications.

Figure 8. Technological papers published by the HEP experiments considered in this study in TNS (left) and NIM A (right) since 2008: hardware, software and DAQ-trigger publications. The bins identified as LHC correspond to papers related to LHC, but not specifically associated with any of the LHC experiments.

The number of hardware, software and DAQ-trigger publications appears approximately constant of the three generations of HEP experiments considered in this study, when it is scaled to the collaboration size, as shown in figure 11. The ratio of hardware to software publications, shown in figure 12, is also approximately constant across the experiments: hardware papers outnumber software ones by approximately a factor four. This result differs from that reported in [1], which depicted an earlier stage of the lifecycle of LHC experiments, preceding the start of LHC operation. The difference could be also partly explained by evolutions in the Web of
Figure 9. Papers published by the HEP experiments considered in this study as a function of operation year: total count (left) and number of published papers per collaboration member (right). Years are counted with reference to the start of run of LEP (1989), BaBar (1999) and LHC (2008).

Figure 10. Size of the experimental collaborations considered in this study.

Science since the publication of [1], namely the move of a large number of conference papers to a dedicated database, which excludes them from the analysis reported here.

Figure 13 illustrates the distribution of papers published by HEP experiments in physics and technological journals. The histogram involves the journals collecting the largest number of publications by the experiments considered in this study. One can observe in figure 14 that the relative importance of some journals has evolved over the years in the field: among technological journals, TNS has increased its popularity in the HEP domain in the last decade, while JINST (Journal of Instrumentation) is growing rapidly.
Figure 11. Number of hardware, software and DAQ-trigger papers published by HEP experiments, scaled by the number of collaboration members.

Figure 12. Ratio of hardware to software papers for a sample of HEP experiments.

The distribution of the number of citations collected by various categories of HEP experimental papers is shown in figure 15: physics papers receive a larger number of citations than technological papers. The fraction of physics papers that are not cited amounts to 4%, while it is much larger for technological papers: 17% for hardware, 25% for software and 27% for DAQ-trigger publications within the data sample examined in this study. Physics papers include a larger number of references than technological papers, as it appears in figure 16: the different citation habits in these two domains are prone to affect the citation patterns shown in 15.

The citations to the physics papers of the HEP experiments considered in this study come almost entirely from journals specialized in high energy physics or closely related fields, such
Figure 13. Journals where the HEP experiments considered in this study published their papers.

Figure 14. Journals where HEP experiments published their papers: in years 1982-1999 (left) and 2000-2011 (right)
as nuclear physics and astroparticle physics: the journals contributing more than 90% of the citations to physics papers published by representative LEP experiments (ALEPH and DELPHI) and LHC experiments (ATLAS and CMS) are listed in figure 17. Technological papers published by HEP experiments are cited by high energy and nuclear physics journals, by nuclear technology journals and by review journals, as is illustrated in 18. Differently from what observed for the general software tools examined in section 4, the papers published by HEP experiments do not appear to collect a significant number of citations from other disciplines, such as medical physics and radiation protection.

A large fraction of the citations collected by LHC technological publications consists of self-citations (i.e. the citing papers include at least one of the authors of the cited work): this pattern is illustrated in figures 19 and 20 for the two journals collecting the largest number of technological publications by LHC experiments, NIM A and TNS.

The most cited publications produced by HEP experiments are in most cases the respective reference papers describing the whole detector: these papers are usually cited by the papers reporting the physics results of the experiment. In the data sample examined in this study,
excluding LHC experiments, the number of citations collected by the most cited paper varies from 309 for the DELPHI experiment to 859 for the BaBar experiment; the citation statistics is not yet meaningful for LHC experiments, that are at an early stage of their physics production.

6. Publications related to the LHC Computing Grid

Grid computing is an essential component of the operation of LHC experiments: a large effort has been invested in the past decade to develop the grid computing infrastructure and several application tools used by LHC experiments within a project known as “LHC Computing Grid” (LCG).

A search for publications associated with LCG in the Web of Science results in a small sample, consisting of less than 20 papers. Grid computing has represented a large fraction of the scientific program of the CHEP conference for the past decade, in addition to dedicated conferences. The small sample of journal publications related to LCG retrieved in the Web of Science suggests that only a limited fraction of conference presentations in this field evolves into
Figure 17. Sources of citations to physics papers published by representative LEP experiments (left) and LHC experiments (right); the histograms include more than 90% of the citations received by the physics papers of the selected experiments.

Figure 18. Sources of citations to technological papers published by representative LEP experiments (left) and LHC experiments (right); the histograms include more than 90% of the citations received by the technological papers of the selected experiments.
Due to the small sample size, a statistical analysis of LCG publications does not appear meaningful.

Conclusions
The scientometric analysis reported in this paper provides a quantitative overview of publication patterns in HEP experiments, covering the last three decades.

The analysis has confirmed the general trend observed in a previous study: software related papers are largely underrepresented with respect to hardware papers in the high energy physics experimental environment. The ratio of hardware to software papers is approximately constant over the experiments of the LEP and LHC generations.

Figure 19. Number of self-citations (left) and outside citations (right) to papers published by LHC experiments in NIM A since 2008: a citation is considered a self-citation when the citing paper includes at least one of the authors of the cited work, otherwise it is considered an outside citation. The bins identified as LHC correspond to papers related to LHC, but not specifically associated with any of the LHC experiments.

Figure 20. Number of self-citations (left) and outside citations (right) to papers published by LHC experiments in TNS since 2008: a citation is considered a self-citation when the citing paper includes at least one of the authors of the cited work, otherwise it is considered an outside citation. The bins identified as LHC correspond to papers related to LHC, but not specifically associated with any of the LHC experiments.
Software papers collect in average fewer citations than hardware papers (and physics papers); they also cite fewer references in their bibliography.

The analysis of citations to papers published by HEP experiments shows that both physics and technological papers collect the largest number of citations within the HEP environment; a small fraction of citations comes from closely related fields, such as nuclear and astroparticle physics.

General software tools motivated by the requirements of HEP experiments, such as Geant4 and ROOT, exhibit different patterns. The earlier Geant4 reference [2] has received more than 3000 citations at the time of writing this paper: it is a landmark paper in Thomson-Reuters Nuclear Science and Technology category, and the most cited publication for major institutions such as CERN and INFN. The analysis of the citations collected by these software tools shows the multidisciplinary character of these tools, which appear to be used in a variety of experimental fields not limited to HEP. Geant4 is cited by a large number of physics papers, which confirm its significant role in the production of physics results by HEP experiments in the LHC era.

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References