Dominique Raynaud

Doctor in Sociology,
Habilitation in Epistemology and Sociology of Science
Associate Professor, Grenoble University,
Grenoble, France;
e-mail: dominique.raynaud@upmf-grenoble.fr

Collaborative Networks in Particle Physics: A Sociological Inquiry into the ATLAS and CMS Collaborations

The discovery of the Higgs boson is one of the most significant advances of particle physics in recent years. It led to the award of the Nobel Prize in Physics 2013 to Englert and Higgs for the theory explaining the origin of the particle mass. The Nobel Prize cannot conceal the fact that the results about the new particle have been achieved by the experimental physicists of the ATLAS and CMS collaborations, who are among the largest international collaboration of scientists in the world (2898 and 2932 physicists, respectively). This article is dedicated to the study of the organization and operation of the ATLAS and CMS international collaborations. The disparities between countries, structure of collaborative networks, physicists' cooperative vs. competitive preferences, and emerging properties of research work in large scientific collaborations are reviewed.

Keywords: ATLAS, CMS, Particle Physics, Scientific collaborative networks.

Introduction

As anticipated by Derek de Solla Price with the concept of "Big Science" (Price, 1963), a growing part of today science is taking place within large cosmopolitan collaborations — often composed of young researchers of all nationalities. This is the case in particle physics, where the size of collaborations now results in articles co-authored by thousands people. At first glance, the alphabetical lists of names appended to the papers gives an impression of "mass effect," which is hardly compatible with the very nature of the work done in these collaborations. The larger an organization, the more detailed the division of labor and internal structuring. This effect is not apparent in the lists of authors.

The ATLAS and CMS collaborations in particle physics have been selected as a subject matter because they provide favorable conditions for investigation:

1. The ATLAS and CMS collaborations have done research on the Higgs boson that has rewarded Englert and Higgs with the Nobel Prize in Physics 2013.

2. The findings were released in two twin articles of *Physics Letters B* (ATLAS, 2012; CMS, 2012).

3. These articles were signed by $N_A = 2932$ and $N_C = 2898$ authors, whose names are recorded in two lists representing 13 in 29 (ATLAS) and 17 in 32 (CMS) pages of text.

4. Until the release of the 2015 joint article by ATLAS and CMS (Aad G. et al., 2015), the ATLAS and CMS papers, with nearly 3,000 authors, held the record for the largest number of authors of a scientific article in the world.

5. The spirit of transparency that prevails at CERN makes it possible to investigate most documents from the CERN site (see *Appendix 1)*. They consist of scientific papers, preprints, notes and conferences reports, as well as technical notes, personnel statistics

and regulation documents. In particular, the Letters of Intent (CERN/LHCC/92–3; CERN/LHCC/92–4) and Memoranda of Understanding (ATLAS 2002; CMS 2002) define the framework in which the research on the Higgs boson was done.

6. The operating rules are clear and explicit: "All codes are written," and are basically the same for both collaborations.

7. Because the Tevatron at Fermilab closed on September 30, 2011, ATLAS and CMS are now the best instruments for doing research on high-energy particles. The lists of authors appended to the 2012 articles thus establish the *comprehensive* register of all experimental physicists who discovered the Higgs boson.

Plan. After introducing the subject *(1. Recent Advances in Particle Physics)*, we review the differences between the collaborations *(2. Frequency and Rank of the Laboratories)*. Then we correlate these data with socioeconomic variables of the countries providing the physicists to the twin experiments *(3. Size, Population and Wealth)*. Despite equivalent sizes, it appears that the two international collaborations are structured very differently *(4. Organizational Differences)*. Next, we examine the benefits that scientists can gain through a cooperative vs. competitive attitude *(5. Cooperation, Competition, and Strategic Edge)*. Emergent properties of large collaborations are also described.

1. Recent Advances in Particle Physics

The hypothesis of the Higgs field has been formulated to address a gap of "gauge theory" proposed by Glashow, Weinberg and Salam in the 1960s. This theory predicted the existence of a massless boson, whereas all bosons known at the time were massive bosons: 80 GeV for bosons $W^{\pm}$ and 91 GeV for the boson Z^0. The Higgs field confers mass to gauge particles, among which W and Z bosons, that acquire mass by interacting with the field. The particles that do not interact, such as photon, have a zero mass. Although it has been proposed to name it "BEH boson" (Brout, Englert, Higgs), "BEHHGK boson" (Brout, Englert, Higgs, Hagen, Guralnik, Kibble) or "scalar boson," most physicists continue to speak of the "Higgs boson." The detection of the Higgs boson only became realistic with the commissioning of the LHC (Large Hadron Collider) at CERN, which is to date the most powerful particle collider in the world, with some 1200 electromagnets, each weighting 34 metric tons, a current of 12,000 amperes and a magnetic field of 8.33 Tesla. The collision energy (7 TeV in 2012, 13 TeV in 2015) far exceeds the 100 to 200 GeV of the LEP and 1 TeV of the Tevatron, closed on 30 September 2011. The LHC was inaugurated on 10 September 2008, after fourteen years of construction. CMS (Compact Muon Solenoid) and ATLAS (A Toroidal LHC ApparatuS) are two twin detectors positioned on opposite sides of the LHC beamline. These instruments are now the only ones able to detect the Higgs boson. Signal detection (600 million collisions per second) produces a Po of data per second. Data are filtered (25 Po per year) and archived on the WLCG grid, a network of 200 computer centers distributed worldwide. Computing centers are divided into a cascade of levels: CERN computing center (Tier-0) stores and redirects the data with high speed dedicated connections to eleven sub-centers (Tier-1). These secondary centers perform preprocessing data before redistributing them to the centers responsible for physics analysis (Tier-2).

2. Frequency and Rank of the Laboratories

The authors' names of the twin articles on the Higgs boson released in *Physics Letters B* can be aggregated by laboratories or by countries.

1. Let us first aggregate the co-authors by country. For volumetric reasons, these rankings are given at the end of the article *(Appendices 2–3)*. Data indicate wide disparities in the contribution to the experiments: a few countries are enough to form half of the workforce of the collaborations.

In terms of number of researchers, CMS major contributing countries are the USA (958), Italy (291) and Germany (275), which together provide 52% of the staff of the collaboration. The first contributors to ATLAS are the USA (593), Germany (415), the UK (292) and Italy (223), which together provide 52% of the staff of the collaboration.

In terms of number of laboratories involved in the experiments, major CMS contributors are the USA (49) Italy (13) and Russia (7); major contributors to ATLAS are the USA (40), Japan (17), Germany (15), Great Britain (15) and Italy (13).

CERN physicists represent only 5% of the collaborations. This low number is because scientists only represent 3% of the staff, far behind the engineers (39%), technicians (35%), and administrative staff (17%). External scientists working at CERN outnumber the internal researchers. They were 9210 against 2544 in 2007; and 11025 against 2427 in 2010 (CERN, 2010: 44). The originality of large equipments such as the LHC detectors is to be placed at the disposal of physicists from around the world. This is why the articles on the Higgs boson are signed by international networks of co-authors.

2. Then aggregate the lists of authors by home institutions, and consider the laboratories with a staff above the upper quartile (Table 1).

Table 1

Laboratories participating in ATLAS and CMS above the upper quartile

Country	Laboratories	Workforce
	CMS Collaboration	
USA	Fermi National Accelerator Laboratory, Batavia	116
Germany	Inst für Experimentelle Kernphysik, Karlsruhe	93
Germany	DESY, Deutsche Elektronen-Synchrotron, Hamburg	73
Switzerland	Inst Particle Physics, ETH Zürich	68
GB	Imperial College, London	59
Italy	INFN Sezione di Pisa, Univ Pisa	46
Russia	Joint Institute for Nuclear Research, Dubna	42
USA	University of Florida, Gainesville	40
USA	California Inst Technology, Pasadena	39
Italy	INFN Sezione di Padova, Univ Padova	39
USA	Univ of Wisconsin, Madison	37
USA	Massachusetts Institute of Technology, Cambridge	35
France	Lab Leprince-Ringuet, Polytechnique/IN2P3, Palaiseau	35
GB	Rutheford Appleton Laboratory, Didcot	34
	ATLAS Collaboration	
Germany	Physikalisches Institut, Univ Bonn	58
USA	RHIC, Physics Dpt, Brookhaven Nat Laboratories	52

Netherlands	Nikhef Nat Institute Subatomic Physics, Univ Amsterdam	50
Germany	Fak Physik, Albert-Ludwigs-Universität, Freiburg	48
Germany	DESY, Deutsche Elektronen-Synchrotron, Hamburg	44
Germany	Max-Planck-Institut für Physik, München	42
France	LAL, CNRS/IN2P3, Univ Paris-Sud, Orsay	42
USA	Physics Division, Berkeley Nat Laboratories	40
Russia	Joint Institute for Nuclear Research, Dubna	40
France	DSM/IRFU, CEA Saclay, Gif-sur-Yvette	38
Spain	Instituto de Física Corpuscular, Barcelona	38
GB	Dept of Physics, Oxford University, Oxford	35
Italy	INFN Sezione di Roma I, Univ La Sapienza, Roma	35
Germany	Fachbereich C Physik, Bergische Univ, Wuppertal	35
Germany	Institut für Physik, Universität Mainz	34
China	Inst of High Energy Physics, Acad Sci, Beijing	33
Germany	II Physikalisches Inst, Georg-August-Univ, Göttingen	33
Germany	Fak Physik, Ludwig-Maximilians-Univ, München	32
Italia	INFN Sezione di Bologna, Univ Bologna	31

Fourteen laboratories provide more than a quarter of the total number of researchers of the CMS collaboration. The CMS collaboration is dominated by US laboratories, both by the one who is the leader (the Fermilab, 116 authors) and by the number of laboratories above the upper quartile (5 in 14). The ATLAS collaboration is dominated by German laboratories, both by the one who is the leader (the Physikalisches Institute in Bonn, 58 authors) and by the number of laboratories above the upper quartile (8 in 19). Among them, six laboratories were involved in the two parallel experiments on the Higgs boson.

The ranking of laboratories may be extended beyond the bottom quartile. Then appear all the laboratories that provide only a few researchers on the Higgs boson, such as the Yerevan Physics Institute (1) or the Institute of Single Crystals of Kharkov (1).

Now let us plot the frequency $P(k)$ of a laboratory with rank k against its rank k, that is, its size expressed in number of researchers, for CMS, ATLAS and ATLAS+CMS taken together. The data exhibit a very clear pattern: whatever the series, the y-axis frequency $P(k)$ correlates with the x-axis rank k of the laboratory (Figure 1*abc*).

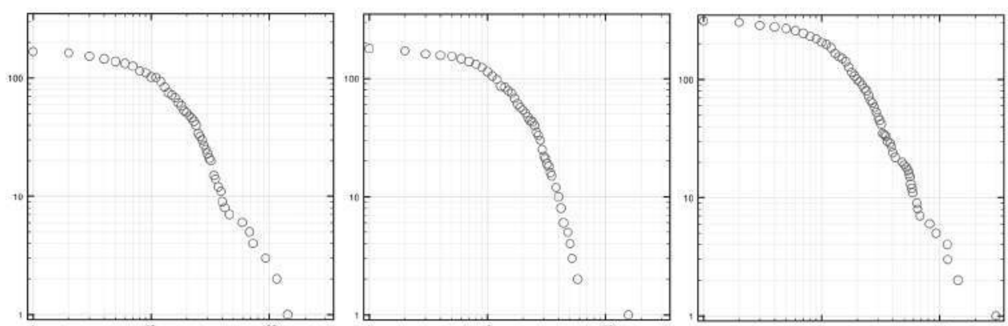

Fig. 1. Laboratory distribution by rank: (a) CMS (b) ATLAS (c) ATLAS+CMS

This result stands out for its novelty. This is indeed the first time that authors' data are numerous enough to reveal a link between the frequency and the rank of the laboratory. As a statistical distribution can be studied only if the sample is large, this observation results from growth in the number of authors in particle physics.

Given the propensity to interpret similar distributions as power laws in recent years, a protocol to compare different hypotheses to fit a probability distribution to a given empirical distribution has been proposed (Clauset, Shalizi and Newman, 2009). These are: the actual power law $P(x) \propto x^{-\alpha}$, power law with exponential cutoff $P(x) \propto x^{-\alpha}\, \mathrm{e}^{-\lambda x}$, exponential law $P(x) \propto \mathrm{e}^{-\lambda x}$, stretched exponential law in the form $P(x) \propto x^{\beta-1}\, \mathrm{e}^{\lambda x^{\beta}}$, and lognormal law $P(x) \propto \frac{1}{x} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right]$.

In the case at hand, we conducted tests using power-law-test in R (Shalizi, 2007). These tests reject the simple power law model with significant *p*-values, ranging from 10^{-13} to 10^{-80}. Such data, which deviate from the simple power law, are akin to power law with exponential cutoff. However as the tests do no apply for alternative hypotheses (e.g., the exponential vs. log-normal distribution), power law with exponential cutoff cannot be assert with certainty.[1]

3. Size, Population and Wealth

To find out if the countries participate in the ATLAS and CMS experiments at their own level of development, the number of the authors of the *Physics Letters B* twin articles have been compared to various socioeconomic variables. Once the countries are coded according to ISO 3166—1 (alpha-3), the numbers provided to the ATLAS and CMS experiments may be compared to the following variables: national population, wealth of the nation, Gini index, PISA results on scales science and mathematics, number of physics prizes obtained, and costs of maintenance and operation of the detectors broken down by country. Bivariate graphs and correlation coefficients were worked out. Similarities between the countries may be specified through a (multivariate) principal component analysis (PCA). We have used res.pca in R (Figures 2*ab*; for details see *Appendix 1: Methodology Note)*.

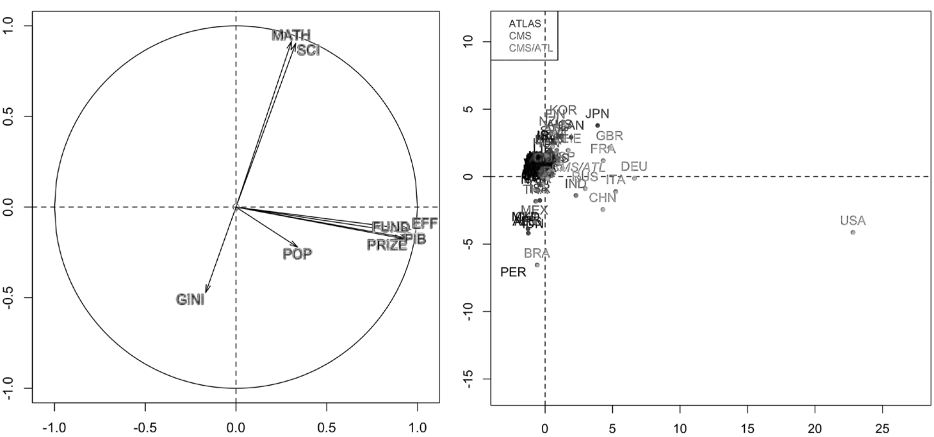

Fig. 2. PCA: (a) variables factor map, (b) countries factor map

[1] In any case, this result is consistent with the rule of thumb that an empirical distribution is a power law only if the data are aligned with three orders of magnitude, which is not the case here.

The correlation circle graph (Figure 2*a*) helps interpreting Figure 2*b*. The lower left sector includes unequal countries that little participate in experiments (e. g. Peru). The upper right sector hosts countries with high scientific performances (e. g. Korea, Finland). Around the mean one discerns a group of rich countries that earn numerous prizes and provide significant numbers to ATLAS and CMS.

This can be clarified by a hierarchical ascending classification (HCA) by using res.hcpc in R. The dendrogram, cut at the threshold $\alpha = 0.3$, produces seven classes:

Class 1. Rich and scientific countries, participating at the highest level in the ATLAS and CMS experiments comprise a singleton: the USA.

Class 2. Germany, Russia, Italy, Great Britain and France make up a group of rich countries heavily involved in high-energy physics.

Class 3. India and China are actively involved in experiments, at a level that is a little below that which would correspond to their population or wealth.

Class 4. This class includes the rich and scientific countries, such as Japan, Korea, Finland and Australia, which, however, have a lower contribution to high-energy physics.

Class 5. Next come countries, such as Spain, which moderately contribute to physics experiments, while having a scientific and economic level higher than the average.

Class 6. This class includes the countries about average.

Class 7. Finally come the poor or developing countries, such as Peru or Mexico, which contribute little or not at all to the ATLAS and CMS experiments.

Decorrelation of certain variables on the projection circle is very surprising (Figure 2*a*). The national workforce (EFF) provided to the experiments is unrelated to the Gini index (GINI) or PISA results concerning science and mathematics (SCI, MATH), and the national workforce depends little on the country's population (POP). By contrast, the other variables are highly correlated (Table 2):

Table 2

Correlation of variables

R	Variables	Interpretation
+0.992	EFF-FUND	Workforce highly correlates with M&O expenditures
+0.976	PRIZE-FUND	Countries with physics prizes spend more on M&O
+0.967	SCI–MATH	Science and mathematics performances are highly correlated
+0.960	EFF-PRIZE	Workforce correlates with the number of physics prizes
+0.844	PIB-PRIZE	Rich countries get more physics prizes
+0.844	PIB-FUND	Rich countries spend more on M&O
+0.840	EFF-PIB	Workforce correlates to the wealth of the country

The relationship between the number of physics prizes and the workforce provided to the experiments (+0.960), or between the mathematics and science performances (+0.967) are self-explanatory. Surprisingly, the closest bond is between the quota of physicists provided to ATLAS and CMS and country's M&O expenditures (+0.992). How is this to be interpreted? The *Memoranda of Understanding* (ATLAS, 2002; CMS, 2002) make it clear that the number of authors interact with the sharing rule of maintenance and operating costs for the central components of the detector (Category A):

> "The costs are to be shared amongst the Funding Agencies or Institutes in proportion to the number of their scientific staff holding PhD or equivalent qualifications who are entitled to be named as authors of scientific publications of the Collaboration" (ATLAS, 2002: 6).

Maintenance and operation expenditures are the missing link between the national GDP and number of authors who sign the articles. The more a country is wealthy, the more it can afford costs of maintenance and operation in ATLAS and CMS, and the more it is entitled to provide researchers to the collaborations that sign the articles. This is a payoff in kind, a rule that always operates for the benefit of the wealthiest contributor — i. e., in the case at hand, the USA.

4. Organizational Differences between the Collaborations

The twin articles on the Higgs boson mention the names of all the authors. The structure of the collaborations being known, their structural differences may be specified by network analysis. The network data were worked out using iGraph in R. Closeness and betweenness centralities appear to be the most discriminating indices.

Closeness centrality (Wasserman and Faust, 1994: 183—187) is the ability of a researcher to access other network researchers through the minimum number of steps. Mathematically, closeness centrality is the sum of all geodesic distances from *i* to other vertices — where the geodesic distance is the minimum number of edges to be scanned between vertices *i* and *j*. As the maximum value is (*g* — 1), the normalized index is written as:

$$C_{C_i} = \frac{(g-1)}{\sum_{j=1}^{g} d_{ij}} \qquad 0 \leqslant C_{C_i} \leqslant 1$$

The vertex of the graph linked to the other vertices by the shorter chain has the higher closeness centrality index.

Betweenness centrality (Wasserman and Faust, 1994: 188—191) expresses the ability of a researcher to intercept knowledge or resources flowing between the other researchers of the collaborative network. Mathematically, it is the probability $b_{jk}(i)$ of some vertex *i* to stand on the geodesic between *j* and *k*. As the betweenness centrality maximum is (*g* — 1) (*g* —2), the standardized index is:

$$C_{B_i} = \frac{\sum_{j=1}^{g}\sum_{k=1}^{g} B_{jk}(i)}{(g-1)(g-2)} \qquad 0 \leqslant C_{B_i} \leqslant 1$$

Below, the results are shown using the same LGL visualization.[2] Values above the bottom decile (N = 300) have been coloured to highlight the most salient differences (Figures 3—4).

ATLAS. The institutions with the highest values are the *nations* sitting at the Collaboration Board and large laboratories (closeness and betweenness). Individuals with the highest score are the members of the Brookhaven RHIC (closeness), CERN in Geneva and JINR in Dubna (betweenness).

[2] In both cases, we used the same LGL visualization to default: 150 iterations, 3000 changes by vertex in one iteration, cooling coefficient 1.5 (Csárdi et al 2014, 201). As closeness and betweenness results are very similar, we only show the graphs representing the closeness centrality index.

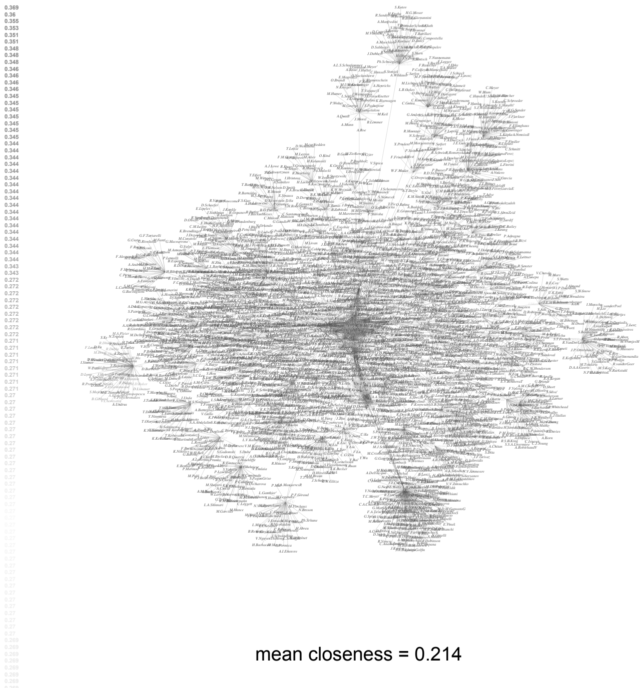

Fig. 3. Graph of the ATLAS collaboration network (closeness)

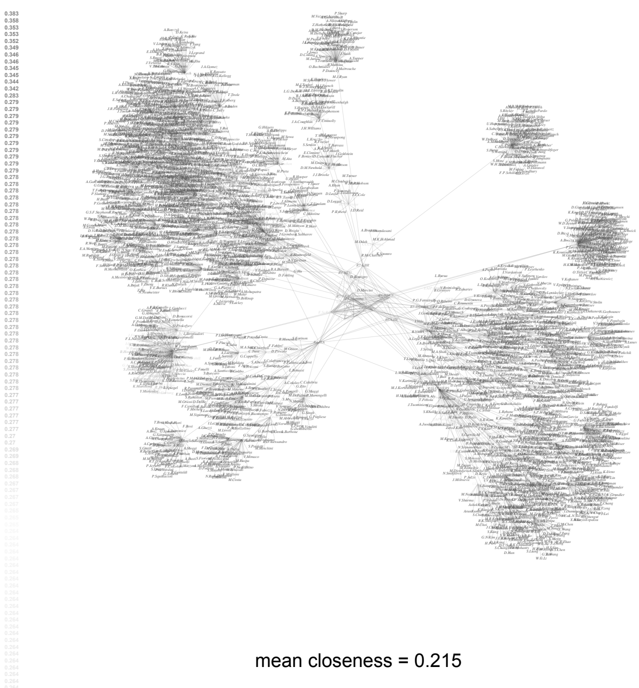

Fig. 4. Graph of the CMS collaboration network (closeness)

CMS. Institutions with the highest values are the "*regions*" serving on the Collaboration Board and large laboratories (closeness and betweenness). Individuals with the highest score are the members of the Fermilab in Batavia (closeness), HEPHY in Wien and HEP in Minsk (betweenness).

The fact that the same members have high closeness and betweenness scores indicates the key role they play in the collaborations. Visual inspection of the graphs shows organizational differences, which may be highlighted by representing only the core set of the two networks (Figures 5–6).

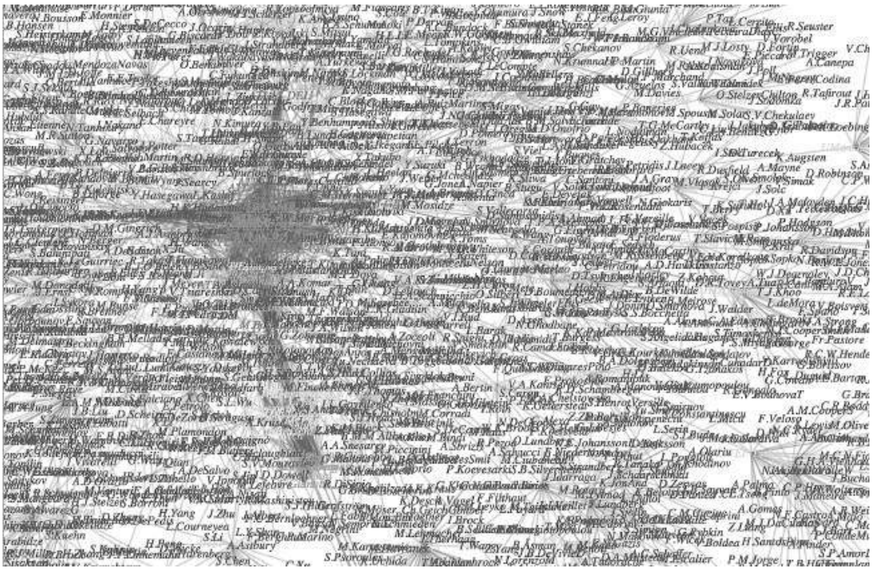

Fig. 5. The core set of ATLAS collaboration (closeness)

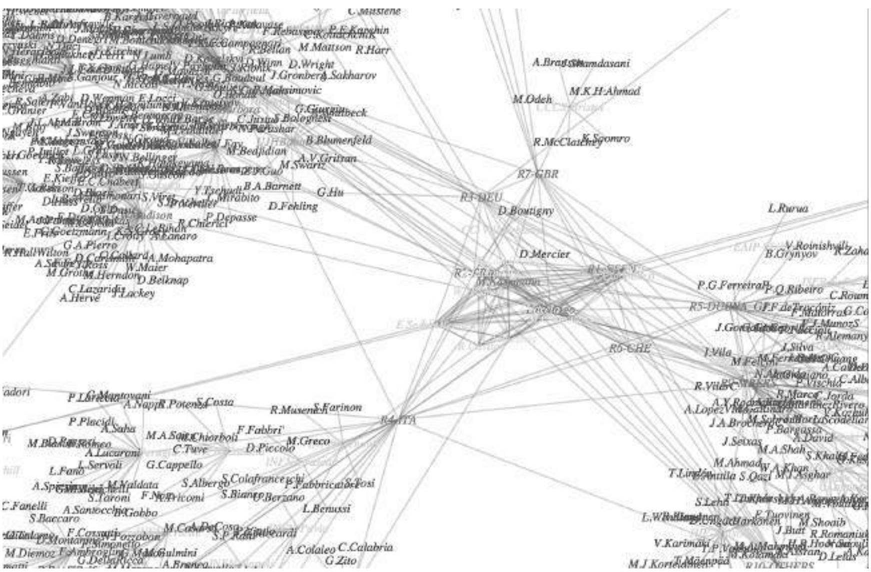

Fig. 6. The core set of CMS collaboration (closeness)

Due to the absence of the "*regions*" middle level in ATLAS, CMS organization appears more fragmented. This may have implications for research: CMS laboratories could enjoy greater *autonomy*; communication could be *slower* between the center and periphery; there could be a *loss* and *distortion* of information in exchanges. By contrast, ATLAS appears more unitary. *Belonging* to a common project could override local cultures; decisions could be more in the *dialogue*; communication between center and periphery could be *faster*; and there could be less loss of information. Further research should test these assumptions.

Obviously there is no indication of such organizational differences in the 3,000-author lists of each collaboration.

5. Cooperation, Competition and Strategic Edge

The line drawn between ATLAS and CMS experiments is a deliberate will, which stems from the observation that a result is more reliable when established by researchers who use different measuring devices and work separately.[3] Apart from methodological meetings (ATLAS, CMS, LHC Higgs Combination Group, 2011), the two experiments run separately. However, the way how the scientific work is progressing depends on the ability to anticipate the substance of future research. The way in which physicists are distributed in one or the other experiment provides further information about this facet of the scientific work. Laboratories involved *in both experiments* have a strategic edge over those who participate in one experiment. In straddling labs, researchers have direct information on the progress made by other collaboration. They may better anticipate the results and generate new hypotheses. Physicists have a more complete (by accessing data from both experiments) and immediate (by accessing data before publication) view on ongoing research. This causes an *asymmetry of information* between the laboratories invested in one or both collaborations.

Differential involvement of the nations can be studied by the staff of researchers provided to the one and the other experiment. These preferences can be presented on a graph, whose abscissae represent the share of the workforce provided to CMS (–1) and ATLAS (+1) and whose ordinates represent the number of researchers supplied by the country (Figure 7).

Some countries, such as Belgium, India and Korea only provide researchers to CMS (–1), others, such as Canada, Japan and the Netherlands, exclusively participate in ATLAS (+1). Between these extremes, there are 22 countries, some of which provide important staffs to the experiments. The biggest differences *in numbers* are caused by the USA (–365), very active in CMS; Great Britain (161) and Germany (140), most involved in ATLAS. In a word, CMS has an American color that contrasts with the European tone of ATLAS.

The propensity to select only one collaboration (less communication and thus competition between teams) vs. to distribute researchers between the collaborations (more communication and cooperation between teams) varies greatly according to nationality. If the measurement is limited to the 50 largest countries — because of low statistical significance of small countries choice — there is a sharp contrast between cooperative and competitive nations (Table 3).

[3] *Edward W.* Morley was the first scientist to consciously use this strategy in the determination of the atomic weight of oxygen (Morley, 1895). The concept of robustness was taken up again later (Wimsatt, 1981).

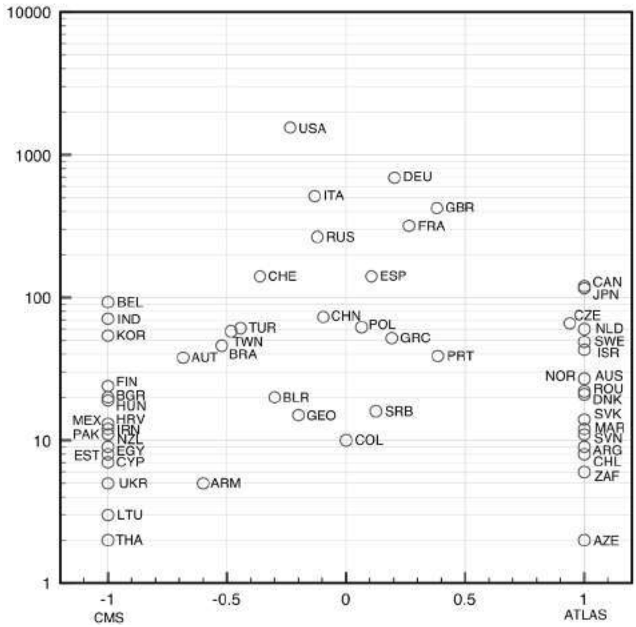

Fig. 7. Preference for the collaborations (*x*: ATLAS/CMS; *y*: workforce)

Table 3

Cooperation vs. competition between ATLAS and CMS collaborations

Countries	**CMS (*a*)**	**ATLAS (*b*)**	**CMS ∩ ATLAS (*c*)**	**(*a* + *b*)**	**(*c* / *a* + *b*)**
Russia	149	117	219	266	0,823
China	40	33	49	73	0,671
Italy	291	223	293	514	0,570
Czech Rep.	2	64	19	66	0,288
Turkey	44	17	17	61	0,279
Greece	21	31	13	52	0,250
France	117	201	69	318	0,217
Germany	275	415	119	690	0,172
GB	131	292	56	423	0,132
USA	958	593	180	1551	0,116
Spain	63	78	12	141	0,085
Others	—	—	—	—	0,000

Among the largest countries, Russia, China and Italy are characterized by their propensity to adopt the *cooperative model*. By providing people to both collaborations, these countries are better informed about the technical differences between the two experiments. But on the other hand, as their workforces are shared between the two collaborations, they cannot have significant influence on any of the collaborations.

The intensity of ATLAS-CMS exchanges within the *same laboratory* can be expressed by the number of constructible relationships among physicists. Let n be the number of physicists dedicated to CMS and let m be the number of physicists dedicated to ATLAS in a laboratory. The number of constructible relationships is then $R = n \cdot m$ (Table 4).

Table 4

ATLAS-CMS constructible relationships within the laboratories

Laboratory	n · m	R
DESY, Deutsches Elektronen-Synchrotron, Hamburg (Germany)	75 · 44	3 300
3rd quartile		
Joint Institute for Nuclear Research, Dubna (Russia)	42 · 40	1 680
University of Wisconsin, Madison (USA)	37 · 28	1 036
DSM/IRFU, CEA/Saclay, Gif-sur-Yvette (France)	26 · 38	988
2nd quartile		
INFN Sezione di Bologna, Università di Bologna (Italy)	28 · 31	868
Rutherford Appleton Laboratory, Didcot (GB)	34 · 22	748
INFN Sezione di Milano, Università di Milano (Italy)	24 · 31	744
INFN Sezione di Roma, Università La Sapienza (Italy)	19 · 37	703
1st quartile		
Institute of High Energy Physics, Beijing (China)	24 · 25	600
INFN Sezione di Pisa, Università di Pisa (Italy)	46 ·10	460
Institute for High Energy Physics, Protvino (Russia)	20 · 18	360
Lab Instrumentação Física Exp de Partículas, Lisboa (Portugal)	12 · 27	324
INFN Sezione di Napoli, Università Federico II (Italy)	11 · 20	220
The Ohio State University, Columbus (USA)	13 · 12	156
Moscow State University, Moscow (Russia)	25 · 6	150
The University of Iowa, Iowa City (USA)	27 · 5	135
Petersburg Nuclear Physics Institute, Gatchina (Russia)	13 · 9	117
Boston University, Boston (USA)	14 · 8	112
Institute for Theoretical and Experimental Physics, Moscow (Russia)	22 · 5	110
P. N. Lebedev Institute of Physics, Moscow (Russia)	8 · 11	88
INFN Laboratori Nazionali di Frascati, Frascati (Italy)	5 · 14	70
Vinca Institute of Nuclear Sciences, University of Belgrade (Serbia)	7 · 9	63
Bogazici University, Istanbul (Turkey)	7 · 9	63
INFN Sezione di Genova, Università di Genova (Italy)	5 · 12	60
Institute of High Energy Physics, Tbilisi State University (Georgia)	7 · 6	42
Massachusetts Institute of Technology, Cambridge (USA)	35 · 1	35
Charles University, Prague (Czech Rep.)	2 · 17	34
University of Athens, Athens (Greece)	3 · 10	30
Universidad Autónoma de Madrid (Spain)	3 · 9	27
E. Andronikashvili Institute of Physics, Acad Sci, Tbilisi (Georgia)	2 · 6	12
Nat Centre for High Energy Physics, Minsk (Belarus)	9 · 1	9
Istanbul Technical University, Istanbul (Turkey)	1 · 9	9
Centre de calcul IN2P3, CNRS/IN2P3, Villeurbanne (France)	2 · 3	6
Yerevan Physics Institute, Yerevan (Armenia)	4 · 1	4

Some caution is needed in interpreting Table 4. *R* estimates the constructible relationships in a laboratory where researchers work for both collaborations. This is an oversimplification: relationships are counted on complete graphs, when laboratories are not; and constructible relationships do not necessarily result in actual relations. The schema however remains informative, because the probability of a scientific relation depends on the number of constructible relationships. In a word: attention should be paid to the ordinal ranking that *R* provides, rather than to the value of this number.

This ranking highlights the DESY as the most conducive laboratory to the development of scientific relationships, since it alone holds one quarter of all the ATLAS-CMS exchanges. The addition of three other laboratories — the JINR of Dubna, the Physics Department of the University of Madison, and the DSM/IRFU of Gif-sur-Yvette — provide together half of all the internal relationships. ATLAS-CMS exchanges are concentrated in these centers, more than in any other place.

Conclusion

This article was intended to look into the structure of the ATLAS and CMS collaborations through the personal data of the twin articles on the Higgs boson released in *Physics Letters B* in September 2012. After introducing the subject (Section 1), we have investigated the major disparities between countries and laboratories, which are hidden by the "mass effect" imposed by the authors lists (Section 2). The laboratory distribution meets a rank-frequency law (most probably, a power law with exponential cutoff). This is the first time this property is described because a statistical law is detected only if the sample is large — a condition just fulfilled in particle physics. These data were compared with the socioeconomic variables of the countries providing physicists to the experiments (Section 3). Much to our surprise, the high correlation (+0.992) between the number of authors and the country's wealth is due to a rule for sharing the costs of maintenance and operation of the detectors. Other properties were studied, such as the difference between the center and periphery of the collaborative networks, and inner organization of the twin collaborations (Section 4). The propensity to adopt a competitive vs. cooperative model greatly varies across countries. This preference creates a contrast between Canada-Japan-India vs. Russia-Italy-China. However it appears that information asymmetry, created by the fact of having information on one or both collaborations, is beneficial at the scale of laboratories only (Section 5). Although invisible at first glance, all these properties are included in the lists of authors.

The operation of ATLAS and CMS collaborations help us understanding the new ways of thinking scientific work in some fields of science, primarily in particle physics, secondarily in biomedical research with the genome sequencing or double blinded random trials. All these research fields involve increasingly large human collaborations. That is why the ATLAS and CMS collaborations are forerunners of the way many fields of scientific research will operate in tomorrow's world. The increase in the number of authors leads to qualitatively new emerging phenomena, such as the growing organization of research teams and new signing practices, to which sociology of science should devote attention.

Appendix 1. Methodology Note

Apart from the two twin articles on the Higgs boson, which contain the key data (i. e., the two lists of co-authors), we have used framework data, which are mostly hosted on the CERN Document Server and TWiki:

- CERN Document Server: cds.cern.ch
- CERN Personnel Statistics: cds.cern.ch/collection/CERN%20Annual%20Personnel%20Statistics
- LHC Experiments: cds.cern.ch/collection/LHC%20Experiments
- ATLAS Higgs Results: twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
- CMS Higgs Results: twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Relevant information is also echoed on organizations and laboratories pages, e. g.:

- National Science Foundation: www.noao.edu/nsf
- JINR Physics: www.atlas-jinr.ru

The data set that was used for the Principal Component Analysis is as follows:

Population. — Data from the Population Reference Bureau:

www.prb.org/pdf12/2012-population-data-sheet_eng.pdf.

Wealth of the Nations. — Data from the World Bank:

data.worldbank.org/indicator/NY.GDP.MKTP.CD.

To find out whether a country contributes to a research program in relation to its wealth, the nominal GDP should be used rather than the domestic expenditures on R&D.

Gini Index. — Data from the World Bank:

data.worldbank.org/indicator/SI.POV.GINI.

Mathematics and science are positively correlated with each other (+0.967) and together negatively correlated with the Gini index (–0.702 science; –0.737, mathematics).

PISA Results. — Data from OECD:

www.oecd.org/edu/school/programmeforinternationalstudentassessmentpisa/33690591.pdf.

As PISA tests are carried out on 15 year old students, we have selected 2000 data, that correspond to a mean age of 15 + 12 = 27 year old researchers, at the date when the CMS and ATLAS twin articles were released. We have used data *mathematical literacy* (math) and *scientific literacy* (sci).

Physics Prizes. — No synthetic data exist on the subject. We selected the twenty most known physics prizes, recording, if any, the nationality of the institution awarding the prize. All prize winners in the last twenty years (1983–2012) were counted for the country where they exercised at the time when it was received. National prizes rewarding only citizens of the country have been excluded. The 12 remaining "international prizes" are the Boltzmann Medal, Elliott Cresson Medal, Dirac Medal, Fundamental Physics Prize, Harvey Prize, Lorentz Medal, Majorana Prize, Matteucci Medal, Albert A. Michelson Award, Max Planck Medal, Nobel Prize in Physics, and Wolf Prize in Physics. Finally the percentage of prizes received by country was calculated. The results are as follows: USA 154, Germany 33, Italy 27, France 25, Britain 20, Switzerland 13, Russia 18, Japan 7, the Netherlands 6, Canada 4, Austria 4, Israel 4, India 2, Belgium 2, Hong Kong 1, Palestine 1, Australia 1, and Ukraine 1.

Costs of Maintenance and Operation. — CERN Data:

cds.cern.ch/record/1537416 CERN-RRB-2013–053: 2012 ATLAS M&O budgets.

cds.cern.ch/record/1336102 CERN-RRB-2011–013: 2012 CMS M&O budgets.

Appendix 2. Members of the CMS Collaboration in 2012[4]

Countries	Labs	CMS Laboratories	Workforce	%
39	N=167	All laboratories	2898	100,00
USA	**N=49**	Total USA	**958**	33,06
		1 Fermi Nat Accelerator Lab, Batavia	116	
		2 University of Florida, Gainesville	40	
		3 California Inst Technology, Pasadena	39	
		4 Univ of Wisconsin, Madison	*37*	
		5 Massachusetts Institute of Technology, Cambridge	*35*	
		6 University of California, Davis	32	
		7 Purdue University, West Lafayette	32	
		8 University of California, San Diego, La Jolla	30	
		9 University of Illinois at Chicago, Chicago	27	
		10 The University of Iowa, Iowa City	*27*	
		11 Princeton University, Princeton	27	
		12 University of California, Santa Barbara	26	
		13 Cornell University, Ithaca	25	
		14 University of Notre Dame, Notre Dame	24	
		15 Rutgers, the State University of New Jersey, Piscataway	24	
		16 University of Maryland, College Park	23	
		17 University of Rochester, Rochester	22	
		18 University of California, Los Angeles	21	
		19 Brown University, Providence	20	
		20 University of Minnesota, Minneapolis	18	
		21 Texas A&M University, College Station	18	
		22 Florida State University, Tallahassee	17	
		23 University of Nebraska-Lincoln, Lincoln	16	
		24 Rice University, Houston	16	
		25 Vanderbilt University, Nashville	16	
		26 Boston University, Boston	*14*	
		27 University of Virginia, Charlottesville	14	
		28 Carnegie Mellon University, Pittsburgh	13	
		29 University of Colorado at Boulder, Boulder	13	
		30 The University of Kansas, Lawrence	13	
		31 Northeastern University, Boston	13	
		32 Northwestern University, Evanston	13	
		33 The Ohio State University, Columbus	*13*	
		34 Johns Hopkins University, Baltimore	11	
		35 Texas Tech University, Lubbock	11	
		36 State University of New York, Buffalo	9	

[4] Workforce in decreasing numbers. Laboratories taking part in both ATLAS and CMS experiments are written in *italics*. Since CERN is an international institution, it is not included in Switzerland. The secondary affiliations of the researchers have not been taken into account. Laboratories were members represent *half* the national contingent are coded (eg 1 Fermilab) in order to identify them on the graphs (Figs. 3–6).

		37 Kansas State University, Manhattan	9	
		38 University of Puerto Rico, Mayaguez	9	
		39 Wayne State University, Detroit	8	
		40 Florida International University, Miami	7	
		41 Florida Institute of Technology, Melbourne	7	
		42 University of Mississippi, Oxford	7	
		43 The Rockefeller University, New York	7	
		44 University of Tennessee, Knoxville	6	
		45 Lawrence Livermore National Laboratory, Livermore	4	
		46 Baylor University, Waco	4	
		47 The University of Alabama, Tuscaloosa	3	
		48 Purdue University Calumet, Hammond	2	
		49 Fairfield University, Fairfield	1	
ITA	**13**	Total Italy	**291**	10,04
		50 INFN Sezione di Pisa, Univ di Pisa	*46*	
		51 INFN Sezione di Padova, Univ di Padova	39	
		52 INFN Sezione di Bari, Univ di Bari	32	
		53 INFN Sezione di Bologna, Univ di Bologna	*28*	
		54 INFN Sezione di Milano, Univ di Milano	*24*	
		55 INFN Sezione di Torino, Univ di Torino	23	
		56 INFN Sezione di Roma I, Univ La Sapienza, Roma	*19*	
		57 INFN Sezione di Perugia, Univ di Perugia	17	
		58 INFN Sezione di Firenze, Univ di Firenze	15	
		59 INFN Sezione di Trieste, Univ di Trieste	12	
		60 INFN Sezione di Napoli, Univ Federico II, Napoli	*11*	
		61 INFN Sezione di Catania, Univ di Catania	9	
		62 INFN Sezione di Pavia, Univ di Pavia	*6*	
		63 INFN Laboratori Nazionali di Frascati	*5*	
		64 INFN Sezione di Genova, Univ di Genova	*5*	
DEU	**6**	Total Germany	**275**	9,49
		65 Inst für Experimentelle Kernphysik, Karlsruhe	93	
		66 DESY, Deutsche Elektronen-Synchrotron, Hamburg	*73*	
		67 University of Hamburg, Hamburg, Germany	32	
		68 RWTH Aachen Univ, III. Physikalisches Inst A, Aachen	30	
		69 RWTH Aachen Univ, I. Physikalisches Inst, Aachen	29	
		70 RWTH Aachen Univ, III. Physikalisches Inst B, Aachen	18	
RUS	**7**	Total Russian Federation	**149**	5,14
		71 *Joint Institute for Nuclear Research, Dubna*	*42*	
		72 Moscow State University, Moscow	*25*	
		73 Inst for Theor and Exp Physics, Moscow	*22*	
		74 Institute for High Energy Physics, Protvino	*20*	
		75 Institute for Nuclear Research, Moscow	19	
		76 *Petersburg Nuclear Physics Institute, Gatchina*	*13*	
		77 P. N. Lebedev Institute of Physics, Moscow	*8*	
CMS	*78*	*CERN-CMS, Geneva*	***143***	*4,93*
GBR	**5**	Total Great Britain	**131**	4,52

		79 Imperial College, London	59	
		80 Rutheford Appleton Laboratory, Didcot	*34*	
		81 University of Bristol, Bristol	20	
		82 Brunel University, Uxbridge	12	
		83 CCCS, University of the West of England, Bristol	6	
FRA	**5**	Total France	**117**	4,04
		84 Lab Leprince-Ringuet, Polytechnique/IN2P3, Palaiseau	35	
		85 Inst Phys Nucl, Univ Lyon 1, CNRS-IN2P3, Lyon	31	
		86 DSM/IRFU, CEA/Saclay, Gif-sur-Yvette	*26*	
		87 Institut Hubert Curien, CNRS/IN2P3, Strasbourg	23	
		88 Centre de Calcul, CNRS/IN2P3, Villeurbanne	*2*	
CHE	**3**	Total Switzerland	**96**	3,31
		89 Institute for Particle Physics, ETH Zurich	68	
		90 Paul Scherrer Institut, Villigen	16	
		91 Universität Zürich, Zürich	12	
BEL	**6**	Total Belgium	**93**	3,21
		92 Univ Catholique de Louvain, Louvain-la-Neuve	22	
		93 Universiteit Antwerpen, Antwerpen	18	
		94 Universiteit Ghent, Ghent	18	
		95 Université Libre de Bruxelles, Bruxelles	16	
		96 Vrije Universiteit Brussel, Brussel	15	
		97 Université de Mons, Mons	4	
IND	**6**	Total India	**71**	2,45
		98 Tata Institute of Fundamental Research, EHEP, Mumbai	15	
		99 Bhabha Atomic Research Centre, Mumbai	12	
		100 Panjab University, Chandigarh	12	
		101 University of Delhi, Delhi	12	
		102 Tata Institute of Fundamental Research, HECR, Mumbai	11	
		103 Saha Institute of Nuclear Physics, Kolkata	9	
ESP	**4**	Total Spain	**63**	2,17
		104 CIEMAT, Madrid	29	
		105 Inst de Física, CSIC, Univ de Cantabria, Santander	24	
		106 Universidad de Oviedo, Oviedo	7	
		107 Universidad Autónoma de Madrid, Madrid	*3*	
KOR	**6**	Total Korea	**54**	1,86
		108 Kyongpook National University, Daegu	17	
		109 Korea University, Seoul	13	
		110 Sungkyunkwan University, Suwon	10	
		111 University of Seoul, Seoul	9	
		112 Chonnam Univ, Inst for Elementary Particles, Kwangju	3	
		113 Kangwon National University, Chunchon	2	
TUR	**4**	Total Turkey	**44**	1,52
		114 Cukurova University, Adana	24	
		115 Middle East Technical University, Physics Dept, Ankara	12	
		116 Bogazici University, Istanbul	*7*	

		117 Istanbul Technical University, Istanbul	*1*	
TWN	**2**	Total Taiwan	**43**	1,48
		118 National Taiwan University, Taipei	28	
		119 National Central University, Chung-Li	15	
CHN	**2**	Total China	**40**	1,38
		120 Inst of High Energy Physics, Beijing	*24*	
		121 State Key Lab of Nucl Phys, University of Beijing	16	
BRA	**3**	Total Brazil	**35**	1,21
		122 Univ do Estado do Rio de Janeiro, Rio de Janeiro	17	
		123 Inst Física Teórica, Univ Estadual Paulista, São Paulo	12	
		124 Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro	6	
AUT	**1**	Total Austria	**32**	1,10
		125 Institüt für Hochenenergiephysik der OeAW, Wien	32	
POL	**3**	Total Poland	**29**	1,00
		126 Inst of Experimental Physics, University of Warsaw	14	
		127 National Centre for Nuclear Research, Swierk	13	
		128 Inst Electronic Systems, Warsaw Univ of Technology	2	
FIN	**3**	Total Finland	**28**	0,97
		129 Helsinki Institute of Physics, Helsinki	21	
		130 Lappeenranta University of Technology, Lappeenranta	4	
		131 Department of Physics, University of Helsinki, Helsinki	3	
GRC	**3**	Total Greece	**21**	0,72
		132 Inst Nuclear Physics Demokritos, Aghia Paraskevi	11	
		133 University of Ioánnina, Ioánnina	7	
		134 University of Athens, Athens	*3*	
BGR	**3**	Total Bulgaria	**20**	0,69
		135 Inst Nuclear Research and Nuclear Energy, Sofia	11	
		136 University of Sofia, Sofia	6	
		137 Inst System Engineering and Robotics, Sofia	3	
HUN	**3**	Total Hungary	**19**	0,65
		138 KFKI Inst for Particle and Nuclear Physics, Budapest	8	
		139 Institute of Nuclear Research ATOMKI, Debrecen	6	
		140 University of Debrecen, Debrecen	5	
MEX	**4**	Total Mexico	**13**	0,45
		141 Centro Invest y Estudios Avanzados del IPN, México	7	
		142 Universidad Autónoma de San Luis Potosí, San Luis Potosí	3	
		143 Universidad Iberoamericana, México	2	
		144 Benemerita Universidad Autonoma de Puebla, Puebla	1	
HRV	**3**	Total Croatia	**13**	0,45
		145 Institute Rudjer Boskovic, Zagreb	6	
		146 Technical University of Split, Split	5	
		147 University of Split, Split	2	
BLR	**2**	Total Belarus	**13**	0,45
		148 Nat Centre for Particle High Energy Physics, Minsk	*9*	
		149 Research Institute for Nuclear Problems, Minsk	4	

PRT	**1**	Total Portugal	**12**	0,41
		150 Lab Instrumentação e Física de Partículas, Lisboa	*12*	
IRN	**1**	Total Iran	**12**	0,41
		151 Inst Research in Fundamental Sciences (IPM), Tehran	12	
NZL	**2**	Total New Zeland	**11**	0,38
		152 University of Canterbury, Christchurch	9	
		153 University of Auckland, Auckland	2	
PAK	**1**	Total Pakistan	**11**	0,38
		154 Nat Centre Physics, Quaid-I-Azam University, Islamabad	11	
GEO	**2**	Total Georgia	**9**	0,31
		155 E. Andronikashvili Inst Physics, Acad Sciences, Tbilisi	*2*	
		156 Inst High Energy Physics, Tbilisi State University	*7*	
EGY	**1**	Total Egypt	**9**	0,31
		157 Academy of Sciences and Technology of Egypt, Cairo	9	
EST	**1**	Total Estonia	**8**	0,28
		158 Nat Inst Chemical Physics and Biophysics, Tallinn	8	
SRB	**1**	Total Serbia	**7**	0,24
		159 Vinca Inst of Nuclear Sciences, University of Belgrade	*7*	
CYP	**1**	Total Cyprus	**7**	0,24
		160 University of Cyprus, Nicosia	7	
UKR	**2**	Total Ukraine	**5**	0,17
		161 Kharkov Institute of Physics and Technology, Kharkov	4	
		162 Inst Single Crystals of Nat Academy of Science, Kharkov	1	
COL	**1**	Total Colombia	**5**	0,17
		163 Universidad de Los Andes, Bogotá	5	
ARM	**1**	Total Armenia	**4**	0,14
		164 Yerevan Physics Institute, Yerevan	*4*	
LTU	**1**	Total Lithuania	**3**	0,10
		165 Vilnius University, Vilnius	3	
CZE	**1**	Total Czech Republic	**2**	∈
		166 Charles University, Prague	*2*	
THA	**1**	Total Thailand	**2**	∈
		167 Chulalongkorn University, Bangkok	2	

Appendix 3. Members of the ATLAS Collaboration in 2012[5]

Countries	Labs	ATLAS Laboratories	Workforce	%
38	N=179	All laboratories	2932	100,00
USA	**N=40**	Total USA	**593**	20,22
		1 RHIC, Physics Dept, Brookhaven Lab, Upton	52	

[5] Same procedure as for CMS (see note 3).

		2 Physics Div, Berkeley Nat Laboratory, Berkeley	40	
		3 Dept of Physics, Univ of Wisconsin, Madison	*28*	
		4 SLAC National Accelerator Laboratory, Stanford	28	
		5 Dept of Physics, University of Michigan, Ann Arbor	28	
		6 Dept of Physics, Univ of Pennsylvania, Philadelphia	25	
		7 Enrico Fermi Institute, University of Chicago	24	
		8 Nevis Laboratory, Columbia University, Irvington	24	
		9 Dept of Physics, Michigan State Univ, East Lansing	21	
		10 High Energy Physics Div, Argonne Nat Lab, Argonne	20	
		11 Lab for Particle Physics, Harvard U, Cambridge	19	
		12 Dept of Physics & Astronomy, Univ of Stony Brook	19	
		13 Dept of Physics, University of Texas, Arlington	18	
		14 Dept of Physics & Astronomy, Univ California, Irvine	17	
		15 Dept of Physics, Yale University, New Haven	16	
		16 Dept of Physics, New York University, New York	14	
		17 Dept of Physics, University of Illinois, Urbana	14	
		18 Ohio State University, Columbus	*12*	
		19 Dept of Physics, Indiana University, Bloomington	12	
		20 Inst for Particle Physics, Univ California, Santa Cruz	12	
		21 Dept of Physics, University of Arizona, Tucson	11	
		22 Physics Dept, Southern Methodist Univ, Dallas	11	
		23 H. L. Dodge Dept of Physics, Univ Oklahoma, Norman	11	
		24 Dept of Physics, Iowa State Univ, Ames	10	
		25 Dept of Physics, University of Massachusetts, Amherst	10	
		26 Dept of Physics, University of Washington, Seattle	10	
		27 Center for High Energy Physics, Univ Oregon, Eugene	10	
		28 Dept of Physics, Brandeis University, Waltham	9	
		29 Dept of Physics, Duke University, Durham	9	
		30 Dept of Physics, Boston University, Boston	*8*	
		31 Dept of Physics & Astronomy, Univ Pittsburgh	8	
		32 Dept of Physics & Astronomy, Tufts Univ, Medford	8	
		33 Dept of Physics, Northern Illinois University, DeKalb	7	
		34 University of Iowa, Iowa City	*5*	
		35 Physics Dept, University of Texas at Dallas, Richardson	5	
		36 Dept of Physics, Hampton University, Hampton	5	
		37 Dept of Physics, Univ New Mexico, Albuquerque	5	
		38 Dept of Physics, Oklahoma State Univ, Stillwater	4	
		39 Physics Dept, SUNY Albany, Albany	3	
		40 Dept of Physics, MIT, Cambridge	*1*	
DEU	**15**	Total Germany	**415**	14,15
		41 Physikalisches Institut, University of Bonn	58	
		42 Fak Physik, Albert-Ludwigs-Universität, Freiburg	48	
		43 DESY, Deutsche Elektronen-Synchrotron, Hamburg	*44*	
		44 Max-Planck-Institut für Physik, München	42	
		45 Fachb C Physik, Bergische Universität, Wuppertal	35	
		46 Institut für Physik, Universität Mainz	34	

		47 II Physikalisches Inst, Georg-August-Univ, Göttingen	33	
		48 Fak Physik, Ludwig-Maximilians-Univ, München	32	
		49 Kirchhoff-Institut, Ruprecht-Karls-Univ, Heidelberg	29	
		50 Institut für Kernphysik, Technical University, Dresden	17	
		51 Dept of Physics, Humboldt University, Berlin	16	
		52 Fachb Physik, Universität Siegen, Siegen	12	
		53 Inst Exp Physik IV, Technische Universität, Dortmund	7	
		54 Fak Physik, Julius-Maximilians-Univ, Würzburg	6	
		55 II Physikalisches Inst, Justus-Liebig-Univ, Giessen	2	
GBR	**15**	Total Great Britain	**292**	9,96
		56 Dept of Physics, Oxford University, Oxford	35	
		57 SUPA, University of Glasgow	28	
		58 School of Physics, University of Manchester	26	
		59 School of Physics, University of Birmingham	25	
		60 Oliver Lodge Laboratory, University of Liverpool	25	
		61 Particle Physics Dept, Rutherford Appleton Lab, Didcot	*22*	
		62 Dept of Physics, University College London	22	
		63 Cavendish Laboratory, University of Cambridge	20	
		64 Dept of Physics, Holloway Univ London, Surrey	18	
		65 Physics Dept, Lancaster University	17	
		66 Dept of Physics, University of Sheffield	17	
		67 School of Physics, Queen Mary Univ, London	16	
		68 SUPA, University of Edinburgh	12	
		69 Dept of Physics, Univ of Sussex, Brighton	7	
		70 Dept of Physics, Univ of Warwick, Coventry	2	
ITA	**13**	Total Italy	**223**	7,69
		71 INFN Sezione di Roma I, Univ La Sapienza, Roma	*35*	
		72 INFN Sezione di Bologna, Univ Bologna	*31*	
		73 INFN Sezione di Milano, Univ Milano	*31*	
		74 INFN Sezione di Napoli, Univ Napoli	*20*	
		75 INFN Sezione di Roma Tre, Univ Roma Tre	15	
		76 INFN Laboratori Nazionali di Frascati, Frascati	*14*	
		77 INFN Sezione di Pavia, Univ Pavia	*13*	
		78 INFN Sezione di Genova, Univ Genova	*12*	
		79 INFN Gruppo Collegato di Cosenza, Arcavata di Rende	12	
		80 INFN Sezione di Roma Tor Vergata, Univ Roma II	11	
		81 INFN Sezione di Pisa, Lab E. Fermi, Univ Pisa	*10*	
		82 INFN Gruppo Collegato di Udine, Univ Udine	10	
		83 INFN Sezione di Lecce, Univ del Salento, Lecce	9	
FRA	**8**	Total France	**201**	6,85
		84 LAL, CNRS/IN2P3, Univ Paris-Sud, Orsay	42	
		85 DSM/IRFU, CEA Saclay, Gif-sur-Yvette	*38*	
		86 LAPP, CNRS/IN2P3, Univ Savoie, Annecy-le-Vieux	28	
		87 CPPM, CNRS/IN2P3, Univ Aix-Marseille	27	
		88 LPNHE, CNRS/IN2P3, Univ Paris 6 et 7	25	
		89 LPSC, CNRS/IN2P3, INPG, Univ Grenoble 1	21	

		90 LPC, CNRS/IN2P3, Clermont-Ferrand	17	
		91 Centre de Calcul de l'IN2P3, Villeurbanne	*3*	
	ATLAS	*92 CERN-ATLAS, Geneva*	***156***	*5,32*
CAN	**10**	Total Canada	**120**	4,09
		93 Dept of Physics, University of Toronto, Toronto	26	
		94 Dept of Physics & Astronomy, Univ Victoria	17	
		95 TRIUMF, Vancouver BC	16	
		96 Dept of Physics, McGill University, Montreal	15	
		97 Dept of Physics, Carleton University, Ottawa	12	
		98 Group of Particle Physics, University of Montreal	9	
		99 Dept of Physics, Simon Fraser University, Burnaby	9	
		100 Dept of Physics, University of Alberta, Edmonton	7	
		101 Dept of Physics, Univ British Columbia, Vancouver	7	
		102 Physics Dept, University of Regina	2	
RUS	**8**	Total Russian Federation	**117**	4,00
		103 Joint Institute for Nuclear Research, Dubna	*40*	
		104 State Institute for High Energy Physics, Protvino	*18*	
		105 Budker Institute of Nucl Physics, SB RAS, Novosibirsk	16	
		106 Moscow Engineering and Physics Institute, Moscow	12	
		107 P. N. Lebedev Inst of Physics, Acad Sciences, Moscow	*11*	
		108 Petersburg Nuclear Physics Institute, Gatchina	*9*	
		109 Skobeltsyn Inst Nuclear Physics, Moscow State Univ	*6*	
		110 Institute for Theor and Exp Physics, Moscow	*5*	
JPN	**17**	Total Japan	**116**	3,95
		111 Int Center Elementary Particle Physics, Univ Tokyo	30	
		112 KEK, High Energy Accelerator, Tsukuba	27	
		113 Graduate School of Science, Kobe Univ, Kobe	13	
		114 Graduate School of Science, Univ of Nagoya	8	
		115 Fac Pure and Applied Sciences, Univ Tsukuba	8	
		116 Graduate School of Science, Univ of Osaka	7	
		117 Dept of Physics, Tokyo Inst of Technology, Tokyo	6	
		118 Faculty of Science, Kyoto University, Kyoto	3	
		119 Dept of Physics, Kyushu University, Fukuoka	3	
		120 Graduate School of Science, Metropolitan Univ Tokyo	2	
		121 Waseda University, Tokyo	2	
		122 Dept of Physics, Shinshu University, Nagano	2	
		123 Fac Applied Inf Science, Inst Technology, Hiroshima	1	
		124 Kyoto University of Education, Kyoto	1	
		125 Nagasaki Institute of Applied Science, Nagasaki	1	
		126 Faculty of Science, Okayama University, Okayama	1	
		127 Ritsumeikan University, Kusatsu, Shiga	1	
ESP	**4**	Total Spain	**78**	2,69
		128 Instituto de Física Corpuscular, Barcelona	38	
		129 Institut de Física d'Altes Energies, Univ Aut Barcelona	29	
		130 Dept de Física Teorica C-15, Univ Aut Madrid	*9*	
		131 Dept de Física Teorica, CAPFE, Univ Granada	2	

CZE	**4**	Total Czech Republic	**64**	2,18
		132 Institute of Physics, Academy of Sciences, Prague	24	
		133 Czech Technical Univ, Prague	21	
		134 Fac Math and Physics, Charles Univ, Prague	*17*	
		135 Palacky University, RCPTM, Olomouc	2	
NLD	**2**	Total Netherlands	**60**	2,05
		136 Nikhef Nat Inst Subatomic Physics, Univ Amsterdam	50	
		137 Inst for Math, Part Physics, Radboud Univ, Nijmegen	10	
SWE	**4**	Total Sweden	**49**	1,67
		138 Dept of Physics, O. Klein Center, Univ Stockholm	25	
		139 Fysiska institutionen, Lunds Univ, Lund	12	
		140 Dept of Physics & Astronomy, Univ Uppsala	8	
		141 Physics Dept, Royal Inst of Technology, Stockholm	4	
CHE	**2**	Total Switzerland	**45**	1,56
		142 Section de Physique, Univ Genève	29	
		143 A. Einstein Center, Lab High Energy Physics, Bern	16	
ISR	**3**	Total Israel	**43**	1,47
		144 Dept Particle Physics, Weizmann Institute, Rehovot	19	
		145 R. B. Sackler School of Physics, Univ Tel Aviv	18	
		146 Dept of Physics, Technion Israel Inst Techn, Haifa	6	
CHN	**1**	Total China	**33**	1,12
		147 Inst of High Energy Physics, Acad Sci, Beijing	*33*	
POL	**2**	Total Poland	**33**	1,12
		148 Niewodniczanski Inst Nucl Physics, Acad Sci, Krakow	23	
		149 AGH Univ Science and Technology, Krakow	10	
GRC	**3**	Total Greece	**31**	1,06
		150 Physics Dept, Nat Tech Univ Athens, Zografou	14	
		151 Physics Dept, University of Athens	*10*	
		152 Dept of Physics, Aristotle Univ, Thessaloniki	7	
AUS	**3**	Total Australia	**27**	0,92
		153 School of Physics, University of Melbourne, Victoria	16	
		154 School of Physics, University of Sydney	9	
		155 School of Chemistry and Physics, Univ Adelaide	2	
NOR	**2**	Total Norway	**27**	0,92
		156 Dept of Physics, University of Oslo	15	
		157 Dept of Physics, University of Bergen	12	
PRT	**1**	Total Portugal	**27**	0,92
		158 Lab Instrumentação Física Exp de Partículas, Lisboa	*27*	
ROU	**1**	Total Romania	**22**	0,75
		159 Nat Inst of Physics and Nucl Engineering, Bucarest	22	
DNK	**1**	Total Denmark	**21**	0,72
		160 Niels Bohr Institute, University of Copenhagen	21	
TUR	**2**	Total Turkey	**17**	0,58
		161 Dept of Physics, Bogazici University, Istanbul	*9*	
		162 Dept of Physics, Ankara University, Ankara	8	
TWN	**1**	Total Taiwan	**15**	0,51

		163 Institute of Physics, Academia Sinica, Taipei	15	
SVK	**1**	Total Slovakia	**14**	0,48
		164 Fac Math Phy Inf, Comenius Univ, Bratislava	14	
MAR	**1**	Total Marocco	**12**	0,41
		165 Fac Sciences, Université Hassan II, Casablanca	12	
SVN	**1**	Total Slovenia	**11**	0,37
		166 Dept of Physics, Jozef Stefan Inst, Univ Ljubljana	11	
BRA	**1**	Total Brazil	**11**	0,37
		167 COPPE, Universidade Federal do Rio de Janeiro	11	
SRB	**1**	Total Serbia	**9**	0,31
		168 Vinca Institute; Inst of Physics, Univ Belgrade	*9*	
ARG	**2**	Total Argentina	**9**	0,30
		169 CONICET y Inst de Física, Univ de La Plata	5	
		170 Dept de Física, Univ Buenos Aires	4	
CHL	**1**	Total Chile	**8**	0,27
		171 Dept de Física, Univ Católica de Chile, Santiago	8	
BLR	**2**	Total Belarus	**7**	0,23
		172 B. I. Stepanov Inst of Physics, Acad of Sciences, Minsk	6	
		173 Nat Centre for Particle High Energy Physics, Minsk	*1*	
AUT	**1**	Total Austria	**6**	0,20
		174 Inst für Teilchenphysik, Leopold-Franzens-U, Innsbruck	6	
GEO	**1**	Total Georgia	**6**	0,20
		175 E. Andronikashvili Inst Physics, State Univ, Tbilisi	*6*	
ZAF	**1**	Total South Africa	**6**	0,20
		176 Dept of Physics, University of Johannesburg	6	
COL	**1**	Total Colombia	**5**	0,17
		177 Centro de Investigaciones, Univ A. Narino, Bogotá	5	
AZE	**1**	Total Azerbaijan	**2**	$\in$
		178 Inst of Physics, Azerb Acad of Sciences, Baku	2	
ARM	**1**	Total Armenia	**1**	$\in$
		179 Yerevan Physics Institute, Yerevan	*1*	

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