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Evaluation of the OPERA Collaboration and the Faster than Light Neutrino Anomaly

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Abstract On 22 September 2011 the OPERA collaboration published a paper which communicated their results concerning the measurement of the neutrino velocity, which appeared to have exceeded the speed of light. If confirmed, this would imply a huge anomaly for the theory of relativity and physics in general. It took until July 2012 for the OPERA collaboration to figure out this was due to an internal error in the experimental set-up. It made spokesperson Antonio Ereditato and physics coordinator Dario Autiero eventually resign. In the meanwhile there was a lot of attention from both scientists as the media, however the OPERA collaboration is yet to be properly evaluated. This paper aims at evaluating the scientific practice of the OPERA collaboration by considering the following two questions. How did the OPERA collaboration address this apparent anomaly and have the OPERA scientists performed as professional scientists should or not?

Keywords Scientific explanation · OPERA collaboration · Evaluation of scientific practice · Scientific communication

1 Introduction

On 22 September 2011 the OPERA collaboration published a paper on the *arXiv* where they state that they have measured a neutrino (ν) velocity which appears to exceed the speed of light c [Adam et al(2011a)].[1] Up until that day we had not been able to measure a phenomenon in physics with which it was

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[1] The arXiv is a collection of electronic preprints of scientific papers which are free accessible. The papers stem from various fields, physics, mathematics, computer science, statistics, quantitative biology and quantitative finance. Those who are interested can take a look at `http://arxiv.org/`.

possible to exceed c. In other words, this would imply the first serious anomaly for the theory of relativity and physics in general.

This result was received with a lot of attention from the media [Brown, K. and Khan, A.(2011), Brumfield, G.(2011), Hooker, B.(2011), Matson, J.(2011)]. The physics community was also aware of the result, but remained a skeptical approach. One of the reasons for this is that previous experiments in which the neutrino velocity was determined had always been in accordance with the theory of relativity.

It took until July 2012 for the OPERA collaboration to conclude that their measurements resulted from an error in the experimental set-up. Spokesperson Antonio Ereditato and physics coordinator Dario Autiero resigned after the publication of their error, which seems to imply a certain form of unprofessionalism.

This paper consists out of two goals. The first one is to determine how the OPERA collaboration addressed the apparent anomaly. This will be illustrated by giving a brief sketch of the complexity of the experiment in section 3 after which I will analyze their working papers and communications to the press in section 4. Second I will try to answer the question whether the OPERA collaboration can be called unprofessional or not. This will be done by evaluating their scientific practice in a systematic way. This will be done in section 5. However, in order to be able to get a full grip on the subject I will start with some necessary background information.

2 Background Information

I will first give a short introduction in the theories of physics which are needed to understand the experiment. I will start with the theory of relativity.

One of the postulates of Einstein's special theory of relativity reads that there is a finite speed of information, which in fact is the speed of light c; this quantity has in vacuum the approximate value of 3×10^8 m/s. Particles who are massless will move with the speed of light. Particles who are not will move at a speed $v < c$. In other words, it is not possible the exceed the speed of light.

In physics we distinguish four different fundamental forces: the gravitational force, the electromagnetic force, the strong interaction and the weak interaction. The neutrino can be seen as a signature of the weak interaction. It belongs to the family of leptons, of which neutrinos are the uncharged ones. The charged leptons are the electrons (e), muons (μ) and tauons (τ), which all carry a negative charge. Accordingly, neutrinos can have three different flavors: the electron-neutrino (ν_e), the muon-neutrino (ν_μ) and the tau-neutrino (ν_τ).

Neutrinos can perhaps be seen as one of the fundamental particles in physics of which we still know the least. Within the Standard Model (SM), the established model in particle physics which describes subatomic particles and their interactions, neutrinos are massless. This would imply according to the theory of relativity that they move at the speed of light.

However, in more recent experiments physicists have registered certain phenomena which would imply that neutrinos do have a mass, albeit still a very small mass. One of these phenomena are the so-called *neutrino-oscillations*: neutrinos are able to oscillate between different flavors or in other words, one is able to measure neutrinos which appear to have a different flavor later on. This is however only possible when neutrinos do have a mass.

This is where the OPERA experiment becomes important. The original goal of the OPERA experiment was to perform a direct measurement of the $\nu_\mu \rightarrow \nu_\tau$ oscillation. The measurement of the neutrino velocity was initially an additional goal, meant as a confirmation and fine-tuning of previous results. These results carry the following information. In 1979 Kalbfleish et al. were able to measure the maximum deviation of the velocity of movement of a neutrino v_ν compared to c: $(v-c)/c < 4\times10^{-5}$ [Kalbleish et al(1979)Kalbleish, Bagett, Fowler, and Alspector]. The neutrinos coming from the SN1987A supernova yielded a maximum deviation of $|v-c|/c < 2\times10^{-9}$ [Longo(1987)]. The MINOS collaboration reported in 2007 a measurement of $(v-c)/c = (5.1 \pm 2.9) \times 10^5$ [Adamson et al(2007)]; in other words, all these results are in agreement with the theory of relativity.

As stated, the OPERA collaboration reported a different result. They found a six times statistical deviation of the neutrino velocity compared to c, namely that $(v-c)/c = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^5$ [Adam et al(2011a)]. This would imply a serious anomaly for the theory of relativity.

3 Complexity of Experiment

One should not underestimate the complexity of contemporary scientific experiments. It is an idealized image that contemporary scientists are both theorists as well as experimentalists. This romantic image of science no longer holds. Setting up and designing experiments and the technology that goes along with it calls for a whole different kind of expertise than research in theoretical sciences does. Communication between the two fields can therefore be cumbersome, a topic which perhaps should be given more attention in the philosophy of science.

However, this section is not intended as a discussion of this topic. I do would like to give an overview of the complexity of the experimental set-up of the OPERA experiment in order to illustrate that various errors can be concealed at different levels of the experiment and that it therefore can take up a lot of time to expose them. I will highlight various topics in the same sequence as the OPERA collaboration builds up its papers discussing the neutrino velocity measurement, see [Adam et al(2011a), Adam et al(2011b), Adam et al(2012a)] and [Adam et al(2012b)].[2]

[2] The final design of the theoretical experimental set-up from which it was built can be found in [Acquafredda et al(2009)].

3.1 Experimental Set-Up

The OPERA detector and the CNGS neutrino beam. The neutrinos are produced at the CERN Super Proton Synchrotron (SPS) at Genève. In the synchrotron protons are accelerated up to high speeds and lead to carbon targets, after which they will decay into kaons and pions.[3] The positively charged pions and kaons are energy-selected and lead to the laboratory at Gran Sasso. These particles will decay in muons and muon-neutrinos in a 1000 m long vacuum pipe after which the muons will be filtered out. This results in the CERN Neutrino beam to Gran Sasso (*CNGS neutrino beam*).[4] The majority of the beam now consists out of muon-neutrinos.[5] These neutrino's are detected by the OPERA detector which is able not only to locate neutrino interactions in its target, but also to measure the arrival of time of neutrinos.

Principle of the neutrino time of flight measurement. In order to measure the neutrino velocity, one needs te measure the time of flight of neutrinos (TOF_ν) and compare it to the time of flight assuming the speed of light (TOF_c), which results in the deviation $\delta t = TOF_c - TOF_\nu$. One is not able to measure TOF_ν at the single interaction level because it is not clear which proton will result in the production of a neutrino. However by measuring time distributions of protons for each sample of which neutrino interactions are observed in the detector at CERN one can obtain the probability density function (PDF) of the time of emission of the neutrinos at CERN. These distributions can then be compared to the time distributions at OPERA. The timing measurements were performed by GPS receivers and Cesium (Cs) atomic clocks at both ends of the CNGS beam. These are needed in order te be able to have an accurate relative time tagging.

The OPERA collaboration calculated side-effects in order to check whether their were deviations and if so, if they needed to compensate for them. For example the reference point for the baseline measurement at CERN is 743.4 m upstream of the target. This results in a negligible correction of 0.007 ns [Adam et al(2012b), p. 6]. Another example is a difference between the time base of the CERN and OPERA GPS receivers, which was measured to be $(2.3 \pm 0.9.)$ ns.[6]

Measurement of the neutrino baseline. Another important feature in the determination of δt is accurate knowledge of the neutrino baseline between the CERN and Gran Sasso facilities. As we need to use relativity theory, these coordinates need to be known within the same global geodesy reference frame. Special attention has been made to relative distances in the experimental set-ups at both CERN and OPERA. The determination of the total

[3] Kaons and pions belong to the *meson* family, which are constituted by two quarks.

[4] A more thorough elaboration concerning the construction of the CNGS beam can be found in [Acquafredda et al(2009), section 2].

[5] There is a 2.1% contamination with muon-antineutrinos ($\bar{\nu_\mu}$'s), and contaminations of less than 1% with electron-neutrinos and electron-antineutrinos; see [Adam et al(2012b), p. 3 - 4].

[6] See [Feldmann et al(2011)] for a full report on this compensation.

distance results in a distance of 730534.61 ± 0.20 m.[7] *"The 20 cm uncertainty is dominated by the 8.3 km underground link between the outdoor GPS benchmarks and the benchmark at the OPERA detector"*[Adam et al(2012b), p. 9]. There has also been a correction for tidal effects. The GPS receivers are able to continuously monitor tiny movements of the Earth's crust.

Neutrino event timing. One cannot simply start a stopwatch at CERN and stop it when a neutrino arrives at OPERA. Several instruments are needed to capture various travel times and interactions between particles. Furthermore, these instruments need to communicate with each other. For example, the CERN timing chain is characterized by three delays, the OPERA timing chain is even more complex. One also needs to take into account the rotation of the Earth around its axis, the so-called *Sagnac effect.* Therefore the timing of the several neutrino events is far from an easy mission.

3.2 Data

The following two topics consider the experimental set-up at a different level. No longer will I speak of the experimental set-up, measurements, communication between devices and side-effects scientists have to deal with, but now I will consider the data scientists have gathered after performing their experiment. Two steps have to be considered in dealing with data. Firstly, data needs to be filtered in a proper way, and secondly it needs to be analyzed.

Data selection. Some data is contaminated with effects OPERA scientists would like to exclude from their experimental set-up. These numbers have to be left out ot the analysis. Other data has to be sorted in different categories. A classification algorithm has been developed in order to do so.[8] In total 15223 neutrino interactions have been analyzed. They do not include 5% of the preselected events, these are classified as 'noise'.

Data analysis. Data has to be analyzed in order to be able to make justified conclusions. Firstly this means the right corrections have to be actually carried out; a number of these corrections have already been mentioned in the previous section. Secondly, one has to apply the right statistics for the various components of the experiment. For example one has to perform a maximum likelihood procedure for the proton extractions at CERN. Another example is the comparison of the proton PDF and the neutrino time distributions to show that they are statistically equivalent. Thirdly, one needs to consider systematic effects. An example in the OPERA set-up is the check whether there are density variations at the target of the detectors the particles collided with and whether this yields an effect. The effect is negligible [Adam et al(2012b), p. 24].

[7] See [Colosimo et al(2011)] for a full report.

[8] See [Bertolin and Tran(2009)] for a full report.

4 Communication by the OPERA collaboration

This section will consider the way in which the results were communicated. In the first subsection I will consider the four versions of the paper *"Measurement of the neutrino velocity with the OPERA detector in the CNGS beam"* which they have published on the arXiv and of which the final version is published in *JHEP* (*Journal of High Energy Physics*); I will do this in chronological order. All versions largely have the same outline as presented in section 3. In the second subsection I will briefly highlight some comments made in press releases considering this experiment. This will be used in order to be able to properly evaluate the scientific practice of the OPERA collaboration, which will be done in section 5.

4.1 OPERA Timeline

4.1.1 version 1

The first communication about their results dates from 22 September 2011 [Adam et al(2011a)]. After summing results from previous experiments considering measurements of the neutrino velocity, it deals with the entire experimental set-up and data selection and analysis of the OPERA experiment. In the section 'final results' they communicate their experimental results. They state that they were able to measure $(v - c)/c$ one order of magnitude better than previous measurements. They find that $\delta t = TOF_\nu - TOF_c = (60.7 \pm 6.9 \text{ (stat.)} \pm 7.4 \text{ (sys.)})$ ns and that $(v - c)/c = (2.48 \pm 0.28 \text{ (stat.)} \pm 0.30 \text{ (sys.)}) \times 10^5$ [Adam et al(2011a), p. 22]. In other words, these results yield a significant statistical deviation from the upper limit c. This would imply a serious anomaly for the theory of relativity. However, the OPERA collaboration does not speak of an anomaly; they call it an *"early arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum"* [Adam et al(2011a), p. 19].

Already this early on the OPERA scientists performed an additional test in order to check the energy dependence of their results. They split their data in two bins of nearly equal statistics for all their internal events. They find for the low- and high-energy bins respectively that $\delta t = (54.7 \pm 18.4 \text{ (stat.)} ^{+7.3}_{-6.9} \text{ (sys.)})$ ns and $\delta t = (68.1 \pm 19.1 \text{ (stat.)} ^{+7.3}_{-6.9} \text{ (sys.)})$ ns, from which they conclude that they are not able to find clues towards a possible energy dependence.

The OPERA collaboration conclude their work with the following sentence:

"In conclusion, despite the large significance of the measurement reported here and the robustness of the analysis, the potentially great impact of the result motivates the continuation of our studies in order to investigate possible still uknown systematic effects that could explain the observed anomaly. We deliberately do not attempt any theoretical or pheomenological interpretation of the results" [Adam et al(2011a), p. 22].

4.1.2 version 2

The second publication appears 17 November 2011 [Adam et al(2011b)]. In the meanwhile the OPERA collaboration was able to improve the CNGS timing system and the OPERA detector. However, the new found result is still not in agreement with the theory of relativity: $\delta t = (57.8 \pm 7.8 \text{ (stat.) } ^{+8.3}_{-5.9}\text{(sys.)})$ ns. In order to be more accurate, the OPERA collaboration performed an alternative analysis in which they now calculated a maximum likelihood function built by associating each neutrino interaction to its waveform instead of the global PDF. Spitefully, this has lead to a compatible value of $\delta t = (54.5 \pm 5.0 \text{ (stat.) } ^{+9.6}_{-7.2} \text{ (sys.)})$ ns [Adam et al(2011b), p. 25].

They performed an additional test in order to exclude possible systematic and statistical biases because of the use of proton waveforms as PDF for the distribution of neutrino arrival times within the two extractions. Again they find a compatible result of $\delta t = (62.1 \pm 3.7)$ ns. This makes them end with exactly the same sentence as written in the previous paragraph.

4.1.3 version 3/4

The third and fourth publication only differ one day in publication date, as they don't differ much from each other, they will be discussed together (see [Adam et al(2012a)] for the third version and [Adam et al(2012b)] for the fourth). Version four appeared on the arXiv on 12 July 2012. The OPERA scientists state that they have found the following result: $\delta t = (6.5 \pm 7.4 \text{ (stat.) } ^{+8.3}_{-8.0} \text{ (sys.)})$ ns, which gives $(v - c)/c = 2.7 \pm 3.1\text{(stat.)}^{+3.4}_{-3.3}\text{(sys.)} \times 10^{-6}$ [Adam et al(2012b), p. 30].

An alternative analysis in which the likelihood function is built by associating each neutrino interaction to its waveform instead of using the global PDF gives a value of $\delta t = (3.5 \pm 5.6 \text{ (stat.) } ^{+9.4}_{-9.1} \text{ (sys.)})$ ns. The search for an energy dependence yields a null effect. An additional test to exclude possible systematic and statistical biases because of the use of the proton waveforms as PDF for the distributions of the neutrino arrival times within the two extractions leads also to compatible results: $\delta t = -1.9 \pm 3.7$ ns (TT-distribution) and $\delta t = -0.8 \pm 3.5$ ns (RPC).[9]

These results leads the OPERA collaboration to conclude the following:

"After several months of additional studies, with the new results reported in this paper, the OPERA Collaboration has completed the scrutiny of the originally reported neutrino velocity anomaly by identifying its instrumental sources and coming to a coherent interpretation scheme"[Adam et al(2012b), p. 30].

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9 The additional tests made use of the data registered by the Target Tracker (TT) on the one hand and the Resistive Plate Chambers (RPC) on the other, which results in two values. See for more information [Adam et al(2012b), section 9].

4.1.4 Final Paper and Further Results

In 2012 they published this version in the *JHEP* [Adam et al(2012)]. In 2013 there appeared a follow-up in which they were able to measure the neutrino velocity with even higher accuracy [Adam et al(2013)]. In this way we can conclude the OPERA collaboration eventually accomplished their two premised goals of establishing the $\nu_\mu \rightarrow \nu_\tau$ channel and measuring the neutrino velocity with high accuracy.

4.2 Communication to the Press

Another way in which the OPERA collaboration communicated their results to the media was by means of press releases alongside the papers discussed in subsection 4.1.[10] I will briefly highlight some interesting quotations from the original press release which will be used in section 5 to evaluate the scientific practice of the OPERA collaboration.

According to the original press release, the OPERA collaboration communicated their results in order to invoke a broader scrutiny of their results. *"When an experiment finds an apparently unbelievable result and can find no artefact of the measurement to account for it, it's normal procedure to invite broader scrutiny, and this is exactly what the OPERA collaboration is doing, it's good scientific practice,"* as CERN Research Director Sergio Bertolucci stated. Spokesperson Ereditato makes a similar comment: *"After many months of studies and cross checks we have not found any instrumental effect that could explain the result of the measurement. While OPERA researchers will continue their studies, we are also looking forward to independent measurements to fully assess the nature of this observation."*

However, both also make statements in which they speak of a possible impact on physics. Bertolucci states the following: *"If this measurement is confirmed, it might change our view of physics, but we need to be sure that there are no other, more mundane, explanations. That will require independent measurements."* Spokesperson Ereditato makes a similar statement: *"The potential impact on science is too large to draw immediate conclusions or attempt physics interpretations. My first reaction is that the neutrino is still surprising us with its mysteries."*

Already in February 2012 one can read that the OPERA has distinguished two effects who might have had their impact on their results, however one would lead to an overestimate of the result, the other one the an underestimate. The press release states the OPERA collaboration has informed its funding agencies and host laboratories of these effects.

In June 2012 it is communicated that the OPERA measurements are in agreement with those of other experiments which have also measured the neu-

[10] A summary of these releases by CERN can be found here: `http://press.web.cern.ch/press-releases/2011/09/opera-experiment-reports-anomaly-flight-time-neutrinos-cern-gran-sasso`

trino velocity (Borexino [Sanchez et al(2012)], ICARUS [Antonello et al(2012)] and LVD [Agafonova et al(2012)]). Bertolucci states that *"[a]lthough this result isn't as exciting as some would have liked, it is what we all expected deep down. The story captured the public imagination, and has given people the opportunity to see the scientific method in action an unexpected result was put up for scrutiny, thoroughly investigated and resolved in part thanks to collaboration between normally competing experiments. That's how science moves forward."*

This information will be used in order to evaluate the scientific practice of the OPERA collaboration. However, I will first briefly illustrate how the effects mentioned above resulted in the erroneous results made by the OPERA collaboration.

4.3 Explanation of the Apparent Anomaly

One can distinguish two errors which the OPERA scientists did not know prior to the first two publications. The first is a *time shift* due to an improper connection of an optical cable. This reduces the amount of light received by the optical/electrical receiver of the Master Clock, which makes the Master Clock giving a pulse with a delay. This makes neutrinos appear to have traveled in less time than they actually have which results in apparent fast neutrinos.

However, there also seemed to be a *time drift* in the other direction. This was due to an incorrect calibration of the Master Clock. Intuitively one could argue that both effects would cancel each other out. The time drift was however not big enough to compensate for the time shift. After additional tests and simulations, the OPERA collaboration was able to explain what went wrong and how these effects resulted in erroneous measurements.

5 Evaluation of Scientific Practice

The evaluation of the scientific practice of the OPERA collaboration will happen by means of section 3.7 in the work *"Scientific Explanation"* by Weber, Van Bouwel and De Vreese [Weber, E. and Van Bouwel, J. and De Vreese, L.(2013)]. They consider five clusters of evaluative questions, each centered around a different theme. The first cluster centers around 'explanation-seeking questions', the second around the 'format' in which the explanation is given, the third deals with the 'ontological level', the fourth with the 'level of abstraction' and the fifth and last considers the use of 'irrelevant criteria'.

5.1 EQ1: Explanation-Seeking Questions and Epistemic Interests

This topic considers the questions asked by a scientific practice. Not every question that can be asked is equally interesting. Two questions from the cluster which are especially important to evaluate the OPERA practice are the following:

- *"What are the interesting explanation-seeking questions about this phenomenon?"*
- *"Do scientists in this discipline ask interesting explanation-seeking questions?"*[11]

A first guideline in a search for interesting explanation-seeking questions is the following. Weber et al. suggest to search for mutually exclusive properties P and P^*. The guideline suggests then that: *"Suppose that object x has property P at time t. Then the question "Why does x have property P, rather than the ideal property P^*?" is an interesting explanation-seeking question"*[Weber, E. and Van Bouwel, J. and De Vreese, L.(2013), p. 63]. If we let property P be the ability to travel faster than the speed of light, the obvious interesting explanation-seeking question becomes the following contrastive question: *"Why do the OPERA neutrinos appear to have moved faster than c while neutrinos in previous experiments appear to have c as an upper limit and in this way are in agreement with the well-established theory of relativity?"*[12] This is perhaps the most interesting question that can be asked about the experiment.

It is remarkable that the OPERA collaboration does not ask a single question in all four versions of their paper about their measurement of the neutrino velocity. Regarding their conclusions they wrote in the different versions of their paper, they do seem to realize that they have encountered a phenomenon which is extraordinary. That is why we may conclude they are aware of the interesting explanation-seeking question concerning their results. Especially as they speak in the final sentence of their final paper of completing *"the scrutiny of the originally reported neutrino velocity anomaly"*, they finally explicitly address their original result as an anomaly. It is only then that it is explicitly clear they did try to answer the former explanation-seeking question. The fact this is evident so late on in the research might imply a first hint of unprofessionalism.

5.2 EQ2: The Appropriate Format of an Explanation

The second cluster deals with the different formats explanations can have. The most suitable evaluative question to ask in this case is the following:

- *"Do scientists in this discipline give answers that have an appropriate format?"*

[11] As we are evaluating the OPERA collaboration, I will interpret in the following sections "scientists in this discipline" as "scientists of the OPERA collaboration".

[12] Weber et al. call this an I'-type question, as it invokes an ideal state considering two objects who are not the same but belong to the same category, see[Weber, E. and Van Bouwel, J. and De Vreese, L.(2013), p. 64].

The OPERA collaboration gives a very thorough description of their experimental set-up and the way they selected and processed their data. They also seem to consider a great account of systematic effects and motivate approximations and steps in their analysis thoroughly or by referring to other more extensive reports. They use an etiological account for interactions betweens particles and interactions between particles and detectors.[13]

All four versions have the same format. They are all papers published on the arXiv, but it goes further than that. They all have the same outline, and large parts of the paper are identically the same. Only version 1 differs from the others as it discusses its results under the section ‘data-analysis’, after which the paper ends with the section ‘conclusions’. The other versions have a separate section called ‘(final) results’ followed by a section which discusses an additional test called ‘test with a short-bunch wide-spacing beam’ after which the section ‘conclusions’ follows. It is odd that the section in version 2 is called ‘final results’ instead of ‘results’. This seems to indicate that the collaboration has reached some kind of end point in their research process.

It seems troublesome that they use the same outline and the same parts of text in different versions of the paper. It is hard to spot the differences and one must actually search to find the explanation for the apparent anomaly. Because they only address the apparent anomaly properly in the final section in the final version of the paper, one gets only in the end the feeling that they are fully committed on exposing the reasons for their results. One might actually perceive that they want to hide their errors, which is something that should never happen. As they are fully aware of the meaning and impact of their results, they should add a straightforward and brief explanation which addresses the causes.

When analyzing some of their communications to the press, we can conclude that they did not speak of an anomaly but are aware of the controversy of their results. The invoked scrutiny is at place. However, the ‘what-if-our-results-are-established scenarios’ in section 4.2 are not, especially not when communicating with the media. This should only be put forward when the results are *effectively* established.

Furthermore, when some time later on the phenomenon is attributed to instrumental errors, even though the OPERA collaboration made sure the effect could not come from instrumental effects, it is only justified that your scientific practice is being questioned. It would be unfair to call them unprofessional purely based on this part of the communication, but one might understand why others would.

Another feature which wasn’t discussed yet, is the question why the OPERA collaboration did not wait any longer to publish their results as they don’t have a competing collaboration. For example, in the search for the Higgs-Boson there are two competing collaborations who carry out the task, the ATLAS collaboration and the CMS collaboration. This has been done in order to prac-

[13] See [Weber, E. and Van Bouwel, J. and De Vreese, L.(2013), p. 48-49] for a more detailed discussion considering the etiological account.

tice science in an efficient manner, as the scientific enterprise is built around the *priority rule*; only the first who achieves a result is credited.[14] However, this is not the case for the OPERA collaboration. In this way, there was no need to publish fast and they could have carried out their research a bit more in all peace and quiet.

5.3 EQ3: Explanations and Levels of Reality

The third cluster of evaluation considers different levels of reality where the explanation can be situated. We can evaluate the OPERA collaboration by means of the following question:

– *"Do scientists in this discipline consider explanations at different levels of reality and do they make justified decisions about the level to be used?"*

One can say that the OPERA collaboration has put a lot of effort in the proper application of various theories and methods. For example, they carried out an additional test considering the energy dependence of neutrinos; in the second version of their paper they associated each neutrino to its waveform instead of the global PDF, which is a lot more accurate. However, one may get the feeling that they did not put enough effort in screening and making sure the experimental hardware works in the way they think it works.

It took them until the last versions to come up with the proper explanation, published ten months after the firs appearance of the paper. Malfunctioning hardware appears quite unprofessional after having performed additional checks and making sure you applied your theory right, even more when you stated you could not attribute any instrumental malfunctioning to the explaining of the results.

5.4 EQ4: Abstraction and Amount of Detail in Explanations

This cluster deals with the amount of information included in the explanation. Which information is causally relevant and which information can be excluded? The question to evaluate the OPERA collaboration is the following:

– *"Is the level of detail of the explanation adequate?"*

According to Weber et al., an explanation is adequate if it contains information which makes a difference. The description of the experimental set-up and statistical data-analysis is elaborate, but not overly detailed. They deal cautiously with the amount of details and often refer to additional notes or other literature for those who want to know more about a certain feature of which the motivation is not essential to the experiment.

[14] For a schematic overview of the priority rule, see for example [Strevens(2003), p. 56 - 58].

However, as already earlier stated, the explanation of the apparent anomaly should be a lot more clearer when reading their final paper. They should have addressed the causation more properly and perhaps include a distinct section in which they elaborate on their explanation. They did however test the time shift and drift thoroughly, and were able to explain their previous results afterwards.

The last cluster of evaluation (EQ5) deals with irrelevant premises. As the OPERA collaboration did not use any, it is clear that this cluster of evaluation does not have to be used.

6 Conclusion

How do we evaluate the practice of the OPERA collaboration? Scientific experiments are nowadays very complex. A large number of scientists have to cooperate in the hope to accomplish in this case two goals: determination of the first oscillation in the $\nu_\mu \rightarrow \nu_\tau$ channel and the measurement of the neutrino velocity with an higher accuracy than previous experiments were able. And in the end the OPERA collaboration managed to accomplish then.

They have built a complex experimental set-up which was able to do the task and performed a very thorough statistical analysis, for which they should be credited. They were open about their results and invoked broader scrutiny at a time they were distraught about the follow-up of their work.

Based on EQ1 it is clear the OPERA collaboration realizes what the interesting explanation-seeking question is concerning their results. However, considering EQ2, they should have addressed the anomaly in their papers more properly. One really has to search for the explanation to this question; a distinct section or perhaps even a paper dealing solely with the explanation would be at place. There was also no need for hurrying in publishing their results as they had no competitors. Analyzing the press releases they spoke with proper care about their results, however they did speak of possible consequences when their results would be established, which is unprofessional.

Even more, we also can state they acted unprofessional based on EQ3. Eventually it was clear the anomaly was caused by two internal errors in the experimental set-up. Theories and methods are open for other scientists as well to evaluate and sometimes adjust or redefine, but the experimental set-up is not. When it then becomes clear the phenomenon is nevertheless due to errors in the internal business of the OPERA collaboration only a long time after they have invoked a broader scrutiny, it is justified to call the OPERA collaboration unprofessional. When invoking broader scrutiny other scientists need to be sure the experimental set-up operates the way it was communicated it operates. Otherwise no scientist is able to perform proper science.

In the end we might say that it is still science who triumphs, as the apparent anomaly did get its proper explanation and we furthermore were able to solve yet another puzzle in the area of experimental subatomic particle physics.

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