PROCEEDINGS OF SCIENCE

International Particle Physics Masterclasses

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An educational activity, the International Particle Physics Masterclasses, was developed by the International Particle Physics Outreach Group with the aim to bring the excitement of cutting-edge particle-physics research into the classroom. Thousands of pupils, every year since 2005, in many countries all over the world, are hosted in research centres or universities close to their schools and become “scientists for a day” as they are introduced to the mysteries of particle physics. In 2012, 10 000 students from 148 institutions in 31 countries participated in this popular event over a month period. The program of a typical day includes lectures that give insight to topics and methods of fundamental research followed by a “hands-on” session where the high-school students perform themselves measurements on real data from particle-physics experiments. The last two years data from the ALICE, ATLAS and CMS experiments at LHC were used. The performed measurements and the employed methodology are presented.

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1. Introduction

The International Particle Physics Outreach Group (IPPOG) [1] is a network of scientists, researchers, science educators and communication specialists engaged in informal science education and outreach for particle physics. Within the framework of IPPOG an educational project, called International Masterclasses (IMC), was developed with the aim to bring experimental data and research methods in the classroom. The main idea was to give high-school students, aged 15-18, the possibility to experience how scientists investigate nature by doing it themselves. The students and their teachers are invited to a university or research centre near their school for a day. There, students and teachers get acquainted with topics and methods of basic research and on the fundamental laws of matter and forces. The highlight of the day and the main idea of the Masterclass is to give them the possibility to perform measurements on real data from particle-physics experiments, as real scientists do. The project started in 2005 with the analysis of real data from the DELPHI and OPAL experiments at the LEP collider at CERN, inspired by similar activities that were taking place in the UK.

The experiments at the Large Hadron Collider (LHC) at CERN have already collected a large amount of data and started to produce and publish interesting new results. Naturally, the wish is to share this excitement with the general public and in particular with school children, the potentially future generations of scientists. Hence, for the past two years, the International Masterclasses featured a sample of these fresh LHC data from the ALICE, ATLAS and CMS experiments as detailed in [2, 3]. Educational material, methods and analysis tools have been developed to accommodate the new data. The emphasis varies from sharing the enthusiasm of our field to explaining to the teachers and young students how things really work through active participation and involvement in “do-it-yourself” measurements and searches.

A centrally organised event runs every year during the month of March. Institutes and universities all over the world host for a day a class of high-school students. A maximum of five institutes participate during the same day doing the same measurement and at the end of the day they join a video-conference to present and discuss their results. Depending on the time zone, the video-conference is coordinated and moderated either by CERN or Fermilab.

A typical day at each institute starts with introductory lectures on basic concepts of high-energy physics followed by a presentation of the relevant experiment. The aim is not to rigorously teach the students but to give them a flavour of the approach and methods of research. The Standard Model is briefly explained as our current understanding of the laws of nature and the remaining puzzles and open questions outlined. The physics observables scientists are looking for to complete the picture are discussed and the experiments designed to measure them are described. The students then visit a laboratory where some detector components for these experiments were constructed or when possible they visit the experiments themselves.

After a lunch break it is the time for the “hands-on” experience and the analysis of the LHC data. The students are brought into a computing room where computers have been setup for the specific measurement of the day. A brief explanation is given by the tutor on how to use the software and tools to perform the specific measurement. The tutor also performs a real-life demonstration as an example. The students are then asked to proceed by themselves and analyze larger data samples, two of them working together in each computer, supervised and helped by tutors.

Students quickly master real event-display programs, software tools and analysis methods. They mostly come with the results within the allocated time. At the end, the results obtained by each group are merged by the tutor to increase statistics. Even with this simple procedure students realise that this type of research is not an one person’s affair but requires collaborative effort. The tutor discusses the obtained results and their relevance to the physics questions exposed in the morning. The students prepare the final result of the classroom and a small presentation. They are then taken into a room with video-conferencing facilities and join a video-conference with CERN or Fermilab where all other participating institutes of the day also join to compare and further discuss the obtained results. They use the same facilities and tools as scientists of our international research collaborations do to participate in common meetings with participants spread all over the world. They share their presentations, combine their results, discuss them and draw common conclusions. The resulting combinations are then compared to recent results published by the collaborations.

Several measurements are proposed to the participating institutes. The different measurements available for each one of the LHC experiments are detailed below. However, the basic ideas and aim behind them are similar. The students are first exposed to the methods of identifying particles that cross the different detectors by exploiting the characteristic signals left by particles in various sub-detector elements; electrons, muons, photons and jets of particles can then be recognised. The students continue with selecting events based on specific signals. Using the different data samples, they measure different properties of some known particles, such as the W and Z weak gauge bosons and a number of hadrons (J/ψ, Y, Λ, K_s).

Using the CMS and ATLAS data, they also study complex particle properties, such as the quark-gluon structure of the proton, through the fraction of W^+ and W^- events, which they come to understand is not just the simple view of *uud* quarks. They also learn how the concept of invariant mass can be used to identify and measure masses and widths of short-lived particles. Furthermore, the invariant mass concept is applied to look for new particles.

Finally, they are given the ingredients and methods to search for a new state of matter, a deconfined state of quarks and gluons, called quark-gluon plasma, which within the Standard Model Big-Bang theory is believed to have existed at the very early stages of the universe.

2. Measurements

2.1 ATLAS

Two different Masterclass measurements, developed by the Universities of Dresden and Oslo [4], are proposed based on ATLAS data, the “Z-path” and “W-path”.

The “Z-path” [5] exploits the invariant mass concept as a tool for identifying known short-lived particles and to search for and discover new ones. An ATLAS data sample of 10 000 events comprises 9000 real events (dileptons from Z, J/ψ, Y, Drell-Yan, and other QCD and W data), and 1000 simulated dilepton Z’ particles at a mass of 1 TeV. The HYPATIA [6] event display software is used to inspect the events and identify particles. Each pair of students examines a subset of 50 mixed events. Based on this visual procedure, particles are identified, dilepton (e^+e^- or $\mu^+\mu^-$) events selected and invariant masses calculated. A web-based application [7] provides a plotting tool as well as a facility for upload and combination of results. A typical invariant mass spectrum resulting from the dilepton data analysis is shown in Figure 1. The students then discuss with the tutors the measured masses and widths of the known resonances, make a comparison between electrons and muons and compare with results published by ATLAS. Further investigating the invariant mass spectrum, they also “discover” a new particle with a mass around 1 TeV – this is the results of the simulated Z’. Such a new neutral gauge boson is supposed to mediate a hypothetical new weak interaction predicted by some theories beyond the Standard Model.

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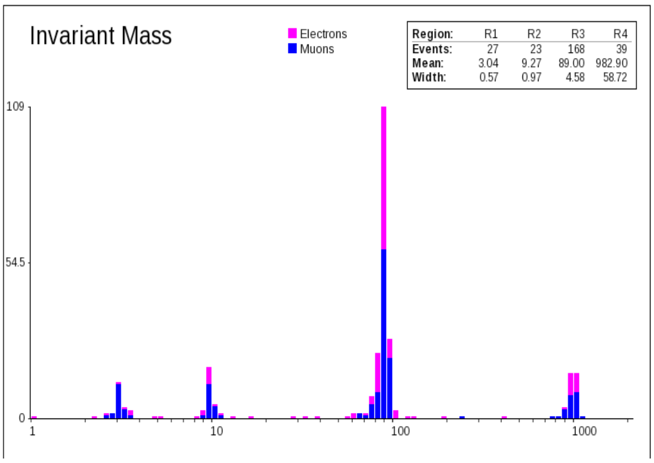

Figure 1. Invariant mass spectrum from ATLAS dilepton data as analysed by students, showing the J/ψ, Υ and Z resonances (from experimental data) as well as a simulated Z' peak at 1 TeV (from simulated data).

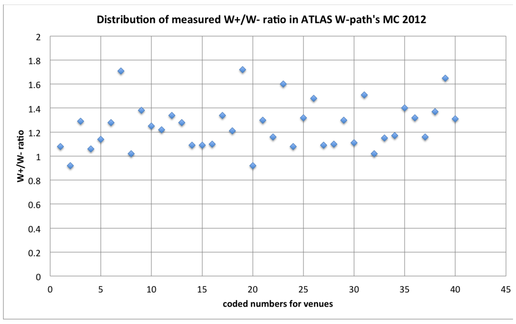

Figure 2. Studying the structure of the proton: the W^+/W^- ratio measured by the students is close to that expected for this data sample, and far from the prediction they made using the simple uud model of the proton.

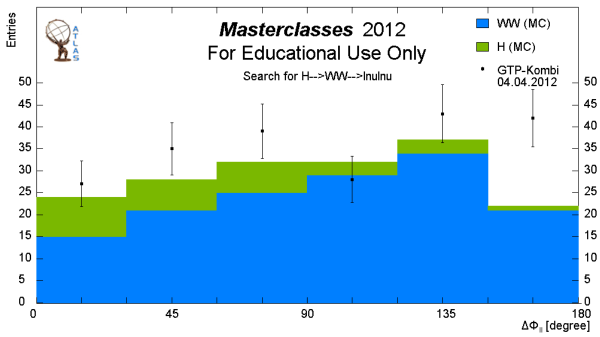

Figure 3. Distribution of the angle between the 2 leptons $\Delta\Phi_{ll}$ in the transverse plane for WW and H→WW events. "GTP-Kombi" corresponds to a combined measurement performed by a few groups of students.

The ATLAS "W-path" [8] makes use of a data sample of 6000 events, mainly consisting of W→ lν events with a high transverse momentum electron or muon and some missing transverse energy/momentum. Some background events (QCD jets, Z, top) and 250 simulated H→WW are added. The event display program MINERVA [9] is used to identify W bosons. The students measure the fractions of W^+ and W^- events and they plot the ration W^+/W^- as shown in Figure 2. This is then compared to the prediction they make using the simple uud model of the proton. They also measure the angle between leptons from 2 W-bosons in the transverse plane. The combined measurement of several groups is shown in Figure 3. To document their measurements students make use of online spreadsheets [10] from which summary tables and histograms are then extracted. The data sample made available for student analyses has a W^+/W^- ratio of 1.56±0.17, very close to the published ATLAS result of 1.52±0.07.

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2.2 CMS

The measurements based on CMS data have mainly been developed by QuarkNet [11], I2U2 [12] and the CMS Education and Outreach team. In the 2012 version of the CMS Masterclass [13], students are asked to study W and Z boson candidates using the purely web-based event display software iSpy-online [14]. Students examine and manipulate events in three dimensions to determine lepton flavour (e or μ), candidacy (*W*, *Z*, or “zoo”) and charge (W^+ or W^-). They then find W^+/W^- and e/μ ratios, as well as reconstructing the Z-mass. They find that many of their *Z* candidates were, in fact, other, lower mass particles: J/ψ and Υ. The recording of events and calculations are done using an EditGrid web-based spreadsheet. An example of the measurement is shown in Figure 4. The charge determination using the event display is shown on the left and the resulting invariant mass distribution on the right. Students were able to determine that an event contains the decay of a W with 95% efficiency. Of the correctly-identified events they were able to determine the charge (from electron or muon) for 92% of the events (if not, they marked them as "W candidate" with no charge specified). And for those events where they were able to determine the charge, they were able to determine it correctly with 96% efficiency. This high efficiency leads to the students finding a W^+/W^- ratio that is very close to the value in the data, that is in turn very close to the published value (1.43).

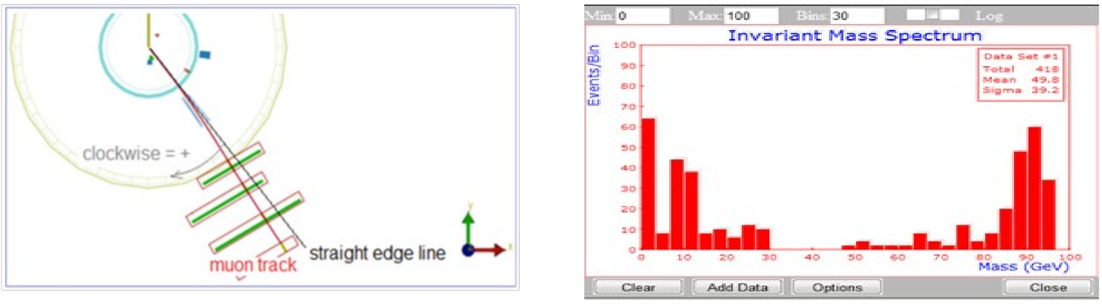

Figure 4. Charge determination and invariant mass (right plot).

2.3 ALICE

ALICE is the heavy-ion dedicated experiment at LHC. Its main goal is to search and characterize the properties of a deconfined state of quarks and gluons, called quark-gluon plasma. Such as state of matter is expected to be produced above certain critical conditions of temperature and density, which are reached and exceeded in collisions of lead ions at the LHC.

Contrary to the discovery of a new particle, one has to investigate several observables to draw conclusions about the creation of the QGP and its properties. In addition, one has to compare such observables to results from elementary proton-proton collisions, which are used as a baseline measurement. One of the first predicted signatures of the QGP was enhanced production of “strange” particles relative to the one in pp collisions. On the other hand, at the high energies of LHC hard probes like jets become available. It is predicted that highly energetic jets of particles are attenuated when they cross the hot and dense medium produced in heavy-ion collisions, thereby providing information about its properties.

Two measurements have been developed by ALICE based on the “strangeness enhancement” [15] and “jet quenching” [16] studies. The first one relies on the measurement of strange particles in Pb-Pb collisions and their comparison to results from pp collisions. The later relies on the measurement of the transverse momentum spectra of unidentified particles in Pb-Pb and pp collisions. Both observables are also studied as function of centrality, which characterises the degree of overlap of the two colliding nuclei. Head-on collisions provide most favourable conditions for the creation of QGP while the most peripheral collisions are similar to pp collisions.

In the 2012 version of the ALICE Masterclass the students are first given small pp and Pb-Pb data samples for visual inspection. By manipulating interactively the events in 3D they better appreciate the differences between pp and Pb-Pb events which are much more complex and of much higher multiplicity. They also get acquainted with the concepts of tracking and particle identification, learning that particles bend in a magnetic field and the information one can extract from this. Strange particles decay after flying for some distance in the detectors leaving a characteristic decay pattern, known as V_0 or cascade, which the students learn how to identify.

While the standard ALICE event display environment can be used, a simplified version of it has been developed which is independent on any other software of ALICE and is based on ROOT [17] only. It inherits however its powerful properties that allows, in addition to the visual inspection of the events, different other functions like filling of histograms and tables within the same environment [18]. Figure 5 shows a snapshot of the “strangeness enhancement” analysis tool, which contains V_0 and cascade decay finders, and allows the calculation of invariant masses as well as the filling of histograms. In addition to the visual inspection of individual events, it also implements methods to analyse large statistics samples of pp and Pb-Pb events. A fitting procedure is implemented that allows students to choose the limits for the fit, fit separately the background and the peak of the signal and subtract them to obtain the number of strange particles. The results obtained from the analysis of pp data samples are finally compared to Monte-Carlo predictions as well as to published results. For the next edition of the measurement Pb-Pb data of different centralities will be analysed. The goal is, by comparing results from proton collisions and from lead collisions, to observe strangeness enhancement as a telltale signal of the production of the quark-gluon plasma.

The “jet quenching” measurement implements the analysis of large statistics Pb-Pb samples of different centralities via a macro and produces the transverse momentum spectra of unidentified particles for different centralities. Those, properly normalised, are divided by the pp spectrum. The resulting spectrum, see Figure 6, known as nuclear modification factor, R_{AA}, which quantifies the suppression, is compared with published results. For the most central events the huge observed suppression, by a factor five, suggests that particles traverse a very dense medium like the hot and dense quark-gluon plasma.

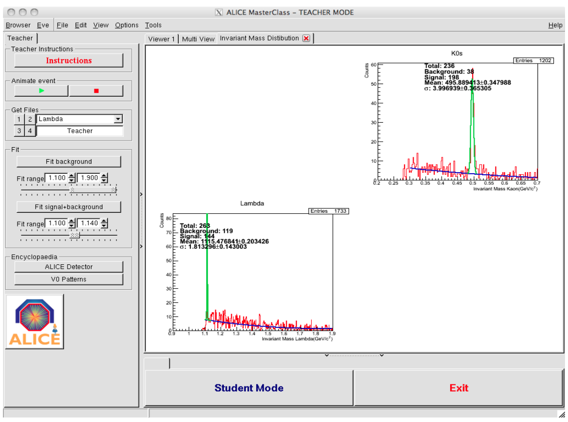

Figure 5. Invariant mass plot for K_s and Λ.

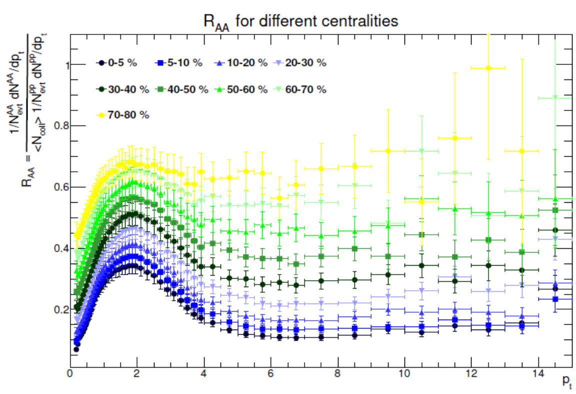

Figure 6. R_{AA} of charged particles for different centralities.

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3. Statistics

The 2012 IPPOG Masterclasses [19] featured an overall increase in participation compared to 2011, when LHC measurements were first introduced, also, resulting in an increase in the number of days that they were performed. Table 1 presents details on the number of countries, institutes and students that participated as well as the number of classes, video-conferences and moderators that assisted the video-conferences. Table 2 presents the break-down of the specific performed measurements.

Table 1. IMC statistics in 2011 and 2012. VC stands for video-conferences at CERN or Fermilab led by moderators.

	Days	Countries	Institutes	Students	Moderators	VC	Classes
2011	19	26	99	9000	15	23	116
2012	21	31	148	10000	21	36	143

Table 2. IMC Statistics on LHC measurements. In addition, 31 institutes followed the 2012 US program; 13 did the ATLAS Z-measurement and 18 the CMS W&Z measurement.

	ALICE	ATLAS W	ATLAS Z	CMS
2011	10	49	31	26
2012	13	42	53	35

In order to assess the whole event surveys are conducted immediately after the Masterclasses. They allow evaluating different aspects and provide information on topics to be improved, introduced or simplified. In general, the results of the 2012 surveys concluded that the IPPOG Masterclasses have been a great success. They also show that interest in participating is growing and students, teachers and moderators enjoy the event. Students expand their views, learn many things and have an increased interest in basic research after the Masterclasses. However, there is still room for improvement. The surveys show that the theory is sometimes found rather difficult to grasp. On the other hand some hands-on measurements have the tendency to be too easy and repetitive. Some students ask for more challenges and to be updated on the research front. They want to “take part in discoveries”.

4. Prospects

The map in Figure 7 gives a visual impression of the countries that participated in the international Masterclasses 2012 and their spread all over the world. At least 8 more countries have shown interest to join the 2013 IMC and will be added to the 2012 map below: Australia, Cyprus, Georgia, India, Turkey, Romania, Egypt, Palestine.

In addition to the centrally organised event in March, “on-demand” Masterclasses are also organised, when and where it suits, for events such as the “teacher’s day”, “women’s day”, to mention few examples. In addition, tutors, visit schools with the material needed for the Masterclasses in laptops and perform the measurements in the student’s classroom.

Every year, all measurements are being updated and improved incorporating new material and expanding the scope. In order to facilitate the work of tutors, but also the students, continuous effort is invested in improving the existing tools. In order to lessen the overhead of the practical issues related to the tools and documentation the aim is to present to the level that it is possible uniform packages for all measurements. Therefore, work is ongoing with the aim to converge towards common tools for plotting, uploading, combining the results and looping over large samples of data. Furthermore, the documentation is also becoming more detailed and systematized in a uniform way for all measurements.

Figure 7. Countries that participate in the International Masterclasses 2012.

Regarding the data samples, they are also updated and enriched every year. The LHC experiments have recognized the success and potential of the International Masterclasses and have recently approved the release of larger and more exotic data samples. The ATLAS Z-path is extended to apply the invariant mass technique to cover current research highlights: $H \rightarrow ZZ \rightarrow llll$, $H \rightarrow \gamma\gamma$. The ATLAS W-path will make use of real WW events. The ATLAS collaboration allows IMC to use $1fb^{-1}$ of data to cover these Higgs “searches”. The CMS collaboration makes available several Higgs candidates in the mass region of interest in various decay channels for “treasure hunt” activities. In the coming ALICE measurements, heavy-ion collision data will be used more extensively.

The IPPOG web site hosts a collection of resources [20]. They provide guidelines and material for particle physicist that wish to get involved in this activity or wish to develop their own initiatives. The included material can be used for developing further Masterclass activities based on the samples of LHC data and associated tools. New ideas and concepts are highly welcome.

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