The QuarkNet CMS masterclass: bringing the LHC to students

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Abstract

QuarkNet is an educational program which brings high school teachers and their students into the particle physics research community. The program supports research experiences and professional development workshops and provides inquiry-oriented investigations, some using real experimental data.

The CMS experiment at the LHC has released several thousand proton-proton collision events for use in education and outreach. QuarkNet, in collaboration with CMS, has developed a physics masterclass and e-Lab based on this data.

A masterclass is a day-long educational workshop where high school students travel to nearby universities and research laboratories. There they learn from LHC physicists about the basics of particle physics and detectors. They then perform a simple measurement using LHC data, and share their results with other students around the world via videoconference.

Since 2011 thousands of students from over 25 countries have participated in the CMS masterclass as organized by QuarkNet and the International Particle Physics Outreach Group (IPPOG). We describe here the masterclass exercise: the physics, the online event display and database preparation behind it, the measurement the students undertake, their results and experiences, and future plans for the exercise.

Keywords: CMS, masterclass, QuarkNet, IPPOG, LHC, physics education

1. Introduction

QuarkNet [1] is an program that brings high-school teachers and students into the particle physics research community by supporting research experiences and professional development workshops, providing access to physics data and to analysis tools, by creating opportunities for use of these data, and by building and fostering communities that use data for engaged learning about science. QuarkNet is organized into centers at universities and laboratories comprising one or more physicists acting as mentors to up to ten high-school teachers. All are assisted by QuarkNet staff.

CMS (Compact Muon Solenoid) [2] is one of two general-purpose experiments at the Large Hadron Collider (LHC) at CERN, comprising nearly 3000 physicists and around 800 engineers from over 40 countries. Since 2010, CMS has collected around 28 fb⁻¹ of proton-proton collision data at center-of-mass energies up to 8 TeV as well as data from proton-lead and lead-lead collisions. Analysis of these data have produced over 300 published papers describing searches for SUSY and exotica, measurements of QCD, electroweak, top, forward, heavy-ion, and B physics, as well as discovery of the Higgs boson [3].

In recognition of the importance of education and outreach in particle physics, the CMS experiment has allowed the release of selected data to the public. The datasets for education and outreach contain information at the level of four-vectors and are released in human-readable, text-based formats. QuarkNet, in collaboration with CMS, has developed a physics masterclass.
using these data. An LHC masterclass is an activity where high-school students travel to nearby universities and research laboratories, listen to lectures about particle physics and the experiments built with which to study it, analyze real LHC data, and interact with other groups of students participating in the activity in other locations via videoconference.

The masterclasses are organized under the auspices of IPPOG [4]. In 2014, from February to April, there were 69 CMS masterclasses in 26 countries in 12 languages [5]. In the map seen in Figure 1, one can see the locations of CMS masterclasses in 2014. This contribution describes the QuarkNet CMS masterclass exercise, its results and plans for the future.

2. Masterclass

2.1. Input data

The data released by CMS for education and outreach forms the core of the QuarkNet CMS masterclass exercise. Specifically, the data are:

- 2000 events each of $\psi \rightarrow \mu\mu$, $\psi \rightarrow ee$
- 2000 events of $\Upsilon \rightarrow ee$
- 500 events each of $Z \rightarrow \mu\mu, Z \rightarrow ee$
- 1000 events each of $W \rightarrow \mu\nu, W \rightarrow e\nu$
- 100,000 events each of di-muons and di-electrons in the energy range 2-110 GeV
- 13 Higgs candidate events: 10 $\gamma\gamma$, 1 2e2$\mu$, 1 4e, and 1 4$\mu$ in the mass range 120-130 GeV

More information can be found from the CMS website [6]. An additional sample of 2000 $\Upsilon \rightarrow ee$ events, 100,000 di-jet events in the energy range 2-110 GeV, and 6 Higgs candidate events (2 $b\bar{b}$, 2 $\tau\tau$, 2 WW in the mass range 120-130 GeV) are in preparation. The data described above is separated into thirty separate datasets, each with 100 events containing samples from the $W$, $Z$, and di-muon events; one four-lepton and two di-photon Higgs candidates are included in each set. The $W^+/W^-$ and $W/Z$ ratios in each of the thirty datasets were set to those measured by CMS [7]. The ratio of electrons to muons for each channel was set to one.

2.2. Typical masterclass exercise

A full-day masterclass, taking place at a nearby university or laboratory begins with a presentation given by the moderator, typically a particle physicist from CMS. The presentation covers particle physics the CMS detector and how physicists use the detector to study the Standard Model and beyond. The students then go to a computer room where the data analysis portion of the masterclass takes place. The students work in groups of typically two or three and each group views in a browser-based event display [8] one of the thirty samples of 100 events. An example event in the display can be seen in Figure 2.

The students then attempt to determine from information available in the display if the current event is a $W$ or a $Z$ event. For example, in the event shown in Figure 2, a student might infer, from the presence of one electron along with a significant amount of missing transverse energy, that this event is a $W$ candidate where the $W$ decays into an electron and a neutrino. If a $W$ and with either an electron or muon, the students then attempt to determine the charge of the lepton. This can be estimated by visually determining the direction of the curvature of the particle track in the magnetic field. If a $Z$ candidate, or a similar-looking event, the student marks
In regards to the invariant mass spectrum, the students are not told beforehand that there are any other particles in the dataset that could decay into two leptons besides the $Z$. The presence of other peaks not at the mass of the $Z$ (such as the $J/\psi$ and the $\Upsilon$) initiates further discussion. The event as either one decaying into a di-electron or a di-muon.

All of this analysis is recorded into a spreadsheet prepared for each dataset with an entry for each event, as seen in Figure 3. The students continue until they have examined all 100 events or until time (typically 60 to 90 minutes) has run out.

### 2.3. Masterclass results and discussion

At the end the students will have obtained several results such as a determination of the ratio of electrons to muons, a determination of the $W^+/W^-$ ratio, and for events with two leptons, an invariant mass spectrum. Example results for one group in 2014 can be seen in Figure 4.

For all of the masterclasses in 2014, students correctly identified an event as a $Z$ candidate (i.e. an event containing two leptons) 92% of the time, correctly identified an electron 90% of the time and a muon 93% of the time, and correctly identified an event as a $W$ event 91% of the time. When the students correctly identified an event as $W$ to $\mu\nu$ ($W$ to $e\nu$), they correctly identified the charge 84% (81%) of the time; 11% (16%) of these events were assigned no charge. Shown in Figure 5 are the number of events each student group was able to analyze. When students are able to examine all 100 events, the distribution of results for the $W^+/W^-$ ratio can be seen in Figure 6. The dark vertical line indicates the result measured by CMS [7].

At the end of the data analysis, the students discuss their results with the moderator and with other masterclasses at other locations via videoconference using Vidyo [9]. A recorded videoconference discussion can be found on the CERN Document Server [10]. Topics discussed include the source of the "unexpected" peaks in the invariant mass distribution, the result of the $W^+/W^-$ ratio and its comparison with the CMS result, and what the measurement means with regards to the structure of the proton.

### 3. Conclusions and future plans

Since 2011, the CMS masterclass as developed and organized by QuarkNet and IPPOG has been a success in terms of the growth of the number of masterclasses and countries from which the students participate. The masterclass exercise has been improved and refined and...
this contribution has described the recent status and success.

We plan to build upon this success by continuing to improve the data analysis tools, to expand the number of masterclass events further around the world, and to develop new exercises as the LHC continues to provide more collision data to the CMS experiment. An upcoming large release of CMS data to the public [11] will provide a great opportunity for development and extension of the successful efforts to use real particle physics data in an educational setting.

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