Outreach Modules for a New Particle Search Using the ATLAS Forward Proton Detector and Higgs Boson Physics - Summer Student Report

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Abstract

We present two modules as part of the Czech Particle Physics Project (CPPP). These are intended as learning tools in masterclasses aimed at high-school students (aged 15 to 18). The first module is dedicated to the detection of an Axion-Like-Particle (ALP) using the ATLAS Forward Proton (AFP) detector. The second module focuses on the reconstruction of the Higgs boson mass using the Higgs boson golden channel with four leptons in the final state. The modules can be accessed at the following link: http://cern.ch/cppp.

Introduction

Outreach is an important part of CERN's mission. An audience that is particularly important consists of high-school students who might be interested in pursuing further studies in Science, Technology, Engineering and Mathematics (STEM) fields. In this summer project we developed a set of online material that can be used in masterclasses to teach high-school students (15 to 18 years old) about particle physics at CERN. These tools are part of the wider Czech Particle Physics Project.

Two modules were developed during the summer. Both have two main components: an introduction page which explains the basic physics involved and a simulation which allows students to learn about physics research interactively. The first module takes students through the process of finding an Axion-Like Particle (ALP) using the ATLAS-Forward Proton (AFP) detector. The second one shows students how to determine the mass of the Higgs boson by studying the so-called golden channel ($H \to ZZ \to 4e$).

In this report, we will explain how these modules are intended to be used and how the simulations function.

1 Czech Particle Physics Project

The Czech Particle Physics Project (CPPP) is a larger outreach project which includes the work done this summer. The CPPP has a home page which lets the user easily access different modules. At the moment, it contains the ALP and Higgs boson golden channel modules as well as a module that allows users to search a database of publications with automated update and categorisation related to the experimental Higgs boson research[1]. The CPPP is expected to be expanded and new modules can easily be added to the home page in the provided structure.

2 Finding an ALP using the AFP detector

2.1 ALP and AFP

Axion-Like-Particles (ALP) are potential dark matter candidates that are predicted by some extensions of the Standard Model [3]. These new particles could be detected with the ATLAS detector at CERN. The ATLAS Forward Proton (AFP) detector is used to enhance the sensitivity for a discovery. The AFP detector is located at either sides of the ATLAS main detector (Figure 1), and it is able to detect protons that come from the central pp interaction point being deviated from the axis of the beampipe. Two incoming protons could pass closely by each other instead of colliding in which case they will interact through their respective electromagnetic fields and be deflected. This will produce a pair of photons. If ALPs exist the photons could scatter through an ALP ($\gamma\gamma \to ALP \to \gamma\gamma$), and the photons are detected in the central detector whereas the scattered protons could be detected in the AFP detector. These are the signal events. There are also diphoton events without an ALP being involved which are called background events. They can be removed largely by calculating the energy loss from the diphoton system and the deflected protons. If the scattering happened through an ALP the calculated energy loss should match. This criterion allows to increase the ratio of signal-to-background events and thus isolate the signal better. The fact that the information of an additional detector

[1] Developed by Peter Zacik for his Bachelor's thesis [1], which followed a feasibility study described in the Bachelors's thesis by Martin Kupka [2].

allows to enhance the sensitivity to find a new particle is an important aspect in teaching the high-school students.

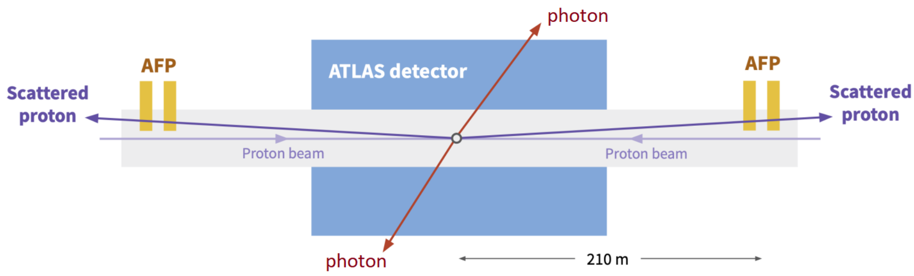

Figure 1: Diagram of the AFP detector, with sensors on both sides of the ATLAS central detector.

2.2 Introduction page

Before getting access to the simulation, the students read through an introduction page which has five sections. The first section introduces CERN and the LHC. The second section focuses on ATLAS and specifically the AFP detector. The third section explains what ALPs are and how the AFP detector can help to discover them. The final section explains to the student the basics of the interactive event display.

This introductory page contains all the information the student needs to appreciate the simulation. It should also stimulate further reading about CERN, LHC and the ATLAS detector. The introduction is kept short as too detailed information could be detrimental to the learning process. Links to other CERN pages are given for the students who wish to learn more. It is important to keep the level for high-school students to be able to understand the material on this page. Once the students have read the introduction, they can access the simulation by clicking a button at the bottom of the page.

2.3 User experience

The interactive event display is shown in Figure 2. The main components of this page are:

1. Control panel: allows the user to interact with the simulation
2. Event counters: counter for the total number of events fired and counter for auto-fired events
3. Inner ATLAS central detector
4. ATLAS central detector side view with AFP on either side: animation of the protons being fired
5. Energy loss matching histograms: the energy loss calculated from the AFP in red and from the central detector in green
6. Invariant mass histograms: left histogram for all events, right histogram only for events where the energy loss matched (as decided by the user, or automatically in auto-fire mode)
7. Access to admin page: password protected

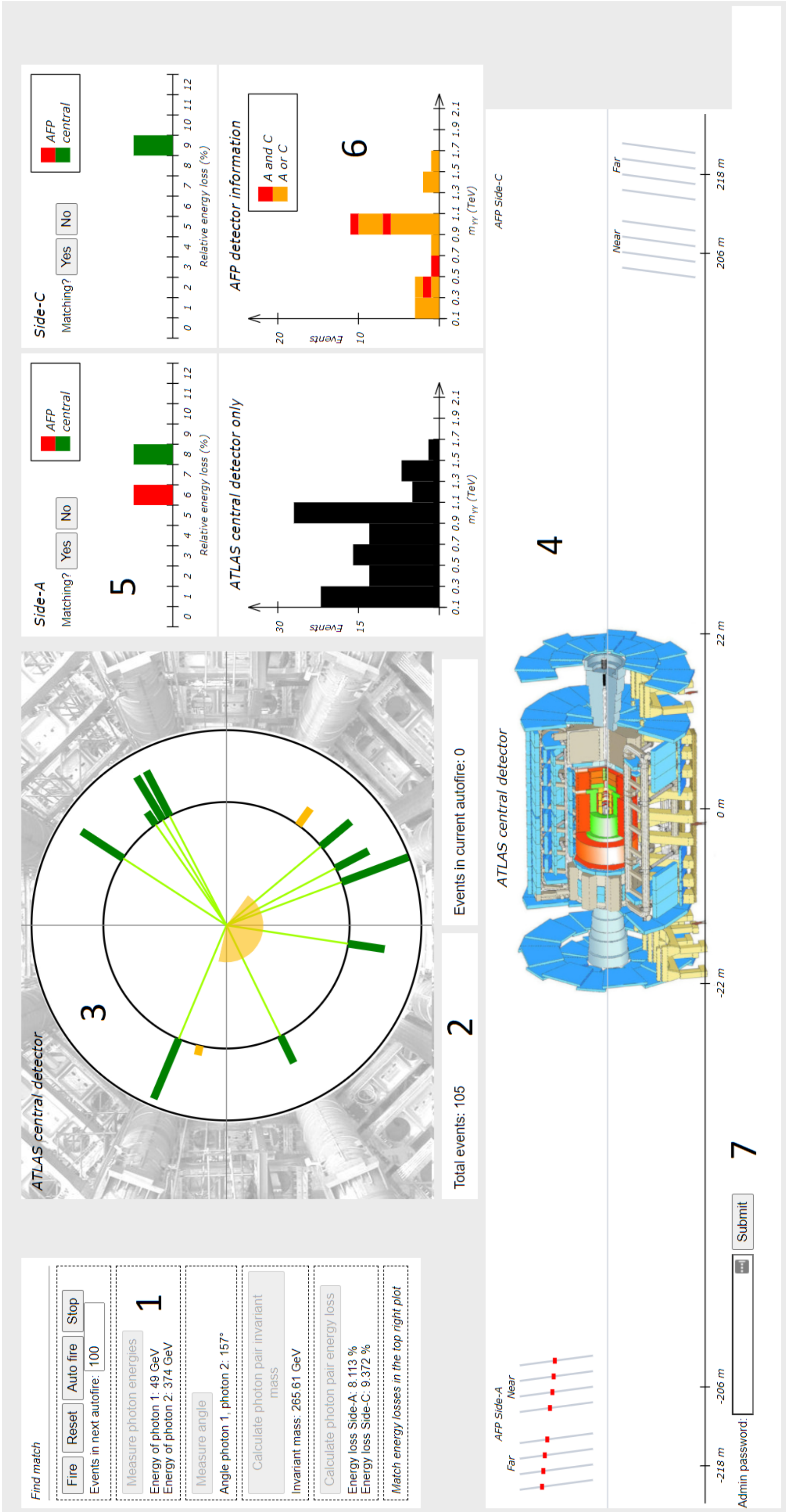

Figure 2: Screenshot of the ALP simulation page.

Once the user loads the simulation page, a succession of post-it notes on the screen will guide them through the steps needed to run the simulation. These steps are:

1. Fire protons on either side of the central detector by pressing the fire button.
2. After the collision, identify the photons in the central detector by finding particles that left no tracks (no electric charge), click on the corresponding energy deposits.
3. Measure the angle between the photons.
4. Calculate the diphoton invariant mass by clicking the appropriate button.
5. Find the energy loss in the AFP detector using a histogram.
6. Check if the energy loss of side A and C match with the diphoton mass.
7. If there is a match the event is added into a separate histogram.

After going through this process manually at least five times, the user unlocks the auto-fire feature. This allows the user to generate a large number of events automatically. In general, around 100 events are needed to see a clear signal in the data.

Once the user has gone through a full auto-fire, a quiz pops-up which asks the user to locate the signal. If this is done correctly an explanation is given and the user is free to continue to play with the simulation, If a wrong answer is given, the user is encouraged to continue firing more events and collect more statistics.

2.4 Simulation

The diphoton events are either signal or background. The signal events are stored in a JSON file. These events were simulated using a Monte-Carlo simulation and are realistic. The background events are generated using random number generators. On top of the diphoton events, some charged particles are added using a random number generator. The only condition placed on these particles is that their energy deposits in the central detector do not overlap with any of the photons. This ensures that the user is always able to select the two photons.

The signal events always have matching energy loss. The background events can have accidental matching energy loss. So matching the energy loss will not remove the background completely. With about 100 events the signal will be clearly visible. This is shown in Figure 2 where 105 events were fired and one can observe a clear peak in the right histogram where the energy losses have been matched.

2.5 Admin page

The website has a password protected admin page. This page allows an administrator to modify the parameters of the simulation. Any changes done on this page are sent to the server and are applied globally so anyone on the website will have the new parameters. The parameters are stored in a JSON file. Another JSON file contains default parameters that should give the optimal user experience and can be recovered through a single button on the admin page. A possible extension of the project could be that individual user groups can define their own Admin settings.

The settings that can be changed on this page are: the signal probability, the single or double tag probabilities (whether or not a deflected proton is detected by both sides of the AFP detector), the number of events before unlocking the auto-fire feature and the speed of the auto-fire. One can also disable the tutorial and the end quiz.

3 Higgs boson module

3.1 Higgs boson golden channel

The Higgs boson golden channel is one of the research modes of the Higgs boson [4]. In this channel, the Higgs boson decays to a pair of Z bosons (real or virtual). Each Z boson then decays to a pair of light leptons (electron or muon). The Feynman diagram for this process is shown in Figure 3. The signal for the Higgs boson is four leptons with an invariant mass equal to the Higgs boson mass. The main background to this signal is the production of di-Z bosons directly from the proton collision decaying to leptons. For simplicity, the module focuses only on the di-electron final state.

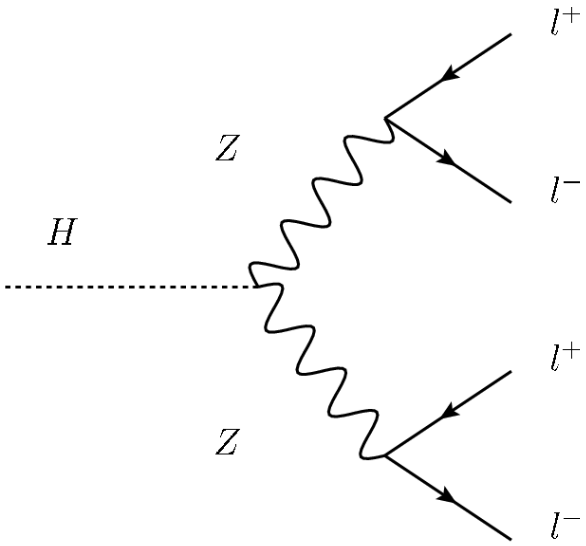

Figure 3: Feynman diagram for the Higgs boson golden channel. The l stands for electrons or muons.

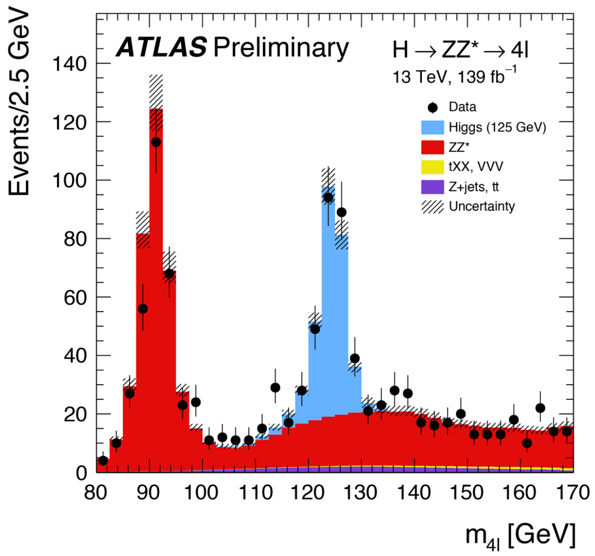

Figure 4: Distribution of 4-lepton invariant mass in ATLAS data [4].

This process has been observed with the ATLAS detector. The resulting plot is shown in Figure 4 [4]. The signal in blue peaks at the Higgs boson mass (125 GeV). The background in red covers a wide range of energies and it peaks at the Z boson mass around 91 GeV. In this module, the students learn how to identify the four leptons by applying a selection on the lepton transverse momentum, and thus they will reproduce the ATLAS distribution with the Z and Higgs boson mass peaks.

3.2 Introduction page

The first two sections of the introduction page are identical to the previous module with the exception that there is no mention of the AFP detector. The third section covers how to reconstruct the invariant mass of a particle from its decay product. The fourth section explains the Higgs boson golden channel process. The final section explains to the student the basics of the interactive event display.

3.3 User experience

The interactive event display for the second module is shown in Figure 7. The user experience is similar to the first module. The student can press the fire button to fire two protons. The event is displayed in the inner ATLAS detector. The student then has to choose a cut-off value for the transverse momentum (p_t) of the particles. This cut should be such that only the four particles with the highest p_t are kept. An example of such a cut is shown in Figures 5 and 6. Then, one can select the four particles to calculate their energy to find the invariant mass of the event. This mass is added to a histogram where the mass peaks appear with sufficient statistics.

In this simulation the p_t cut can be adjusted for each event. However, as made clear in the introduction page, this is a simplification for the students, usually in the actual analysis, a fixed selection cut is set for all events, and a statistical analysis follows.

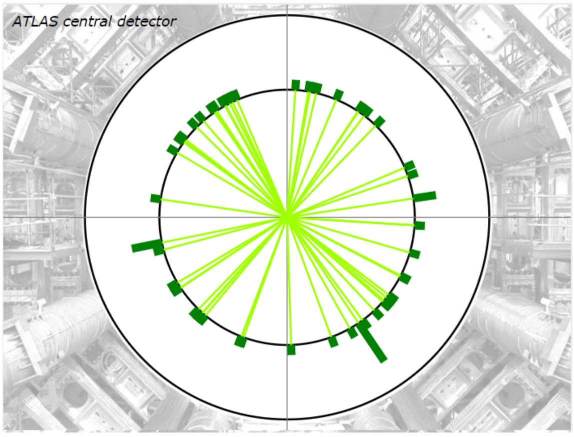

Figure 5: Inner ATLAS detector before applying a p_t cut.

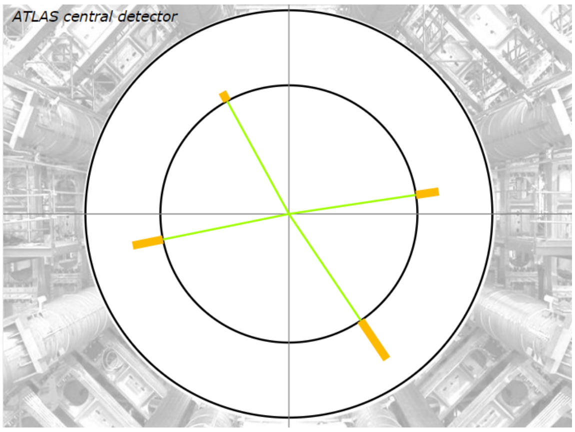

Figure 6: Inner ATLAS detector after a p_t cut is applied.

After five events, the student can use the auto-fire feature to increase statistics. After a few hundred events, the student should clearly observe the distribution from Figure 4. This distribution is shown in Figure 7.

Similarly to the first module, post-it notes are used to explain how the simulation works and a quiz pops-up after an auto-fire to check if the student is able to locate the Higgs boson mass peak. If not, they are encouraged to continue generating more events and increase the statistics until the mass peak becomes visible.

3.4 Simulation

The signal and di-Z background have been generated using Madgraph, this is to ensure that the events look realistic. In particular the momentum balance of the events is realistic. The invariant mass is picked from the distribution shown in Figure 4 by approximating the published distribution. This is to ensure that the student reproduces a realistic invariant mass distribution. On top of the signal and di-Z background, a background of particles with low transverse momentum is added. These are the particles the student should remove using the p_t cut. These particles are generated using a random number generator.

The hosting, deployment and maintenance of the webpage on the CERN server is addressed in an internal ATLAS note [5].

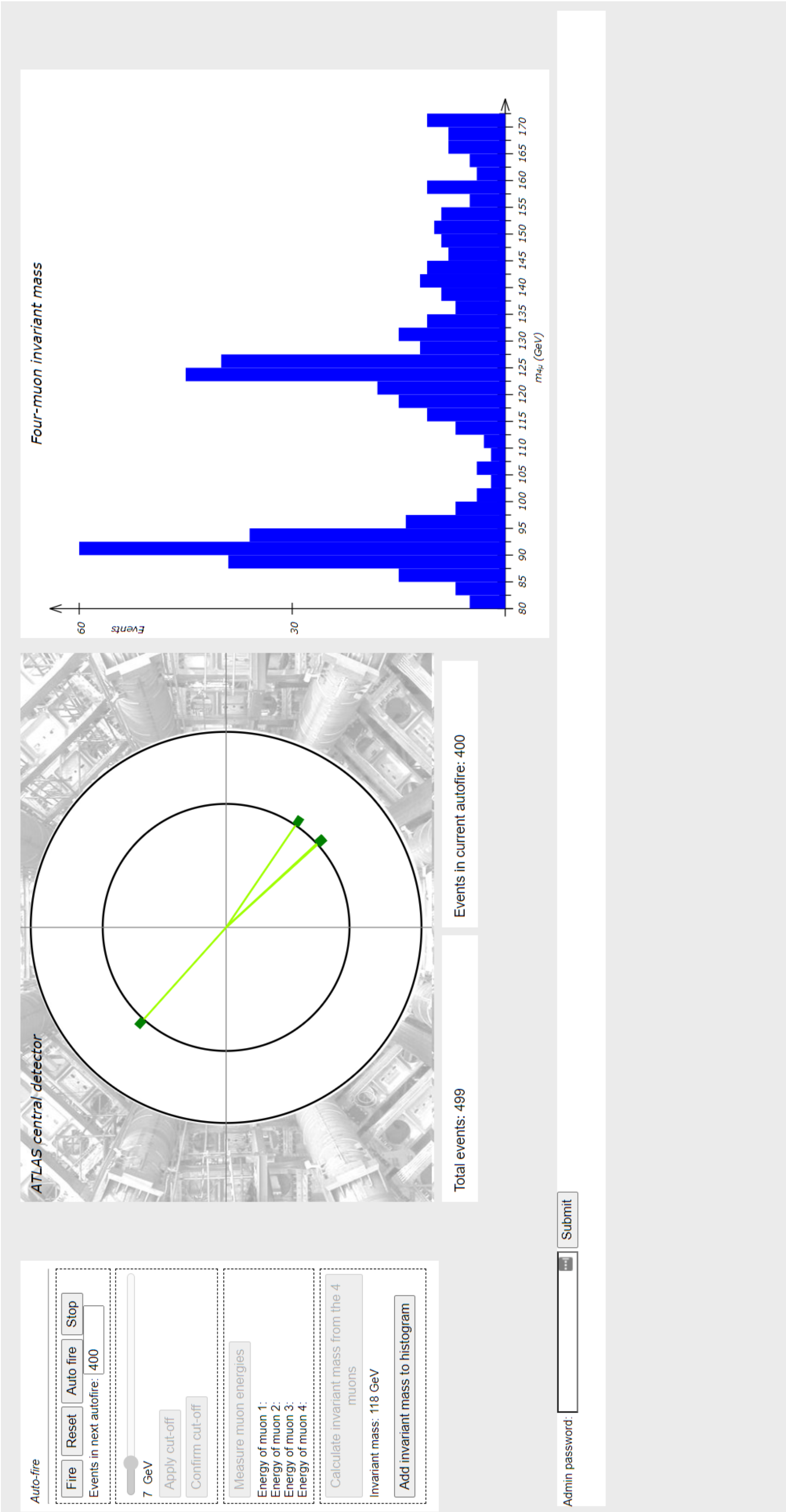

Figure 7: Screenshot of the Higgs boson golden channel simulation page.

4 Conclusions

Two new outreach modules were developed and implemented for the Czech Particle Physics project. They are available at http://cern.ch/cppp. They are ready to serve students, teachers, and the interested public. Learning goals are:

- sensibilizing school student for the fun with science, technology, engineering and mathematics,
- awakening interest in CERN, LHC and ATLAS physics,
- understanding basic concepts in particle physics,
- acquiring initial knowledge about elementary particles and how to detect them,
- becoming aware that additional detectors help to separate signal and background events,
- motivating the understanding that increasing data statistics leads to new observations and discoveries.

Feedback on the developed modules is very welcome and will be used in future updates of the modules. Future modules on related fields of research as well as modules on other research directions can be efficiently created and maintained using the structural setup in this project.

Acknowledgements

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References

1. Zacik, P. *Implementation of a Portal Dedicated to Higgs Bosons for Experts and the General Public* Presented 15 Jun 2021 (May 2021). `https://cds.cern.ch/record/2774895`.
2. Kupka, M. *Feasibility Study of Portal to Provide Knowledge about Higgs Boson to General Public and Experts* Presented 23 Jun 2020 (June 2020). `https://cds.cern.ch/record/2722144`.
3. Du, N. *et al.* Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment. *Phys. Rev. Lett.* **120,** 151301. `https://link.aps.org/doi/10.1103/PhysRevLett.120.151301` (15 Apr. 2018).
4. ATLAS Collaboration. Measurement of inclusive and differential cross sections in the $H \rightarrow ZZ^* \rightarrow 4l$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. *Journal of High Energy Physics* **2017.** ISSN: 1029-8479. `http://dx.doi.org/10.1007/JHEP10(2017)132` (Oct. 2017).
5. Vauterin, A. and Sopczak, A. *Outreach Modules for a New Particle Search Using the ATLAS Forward Proton Detector and Higgs Boson Physics - Summer Student Project* tech. rep. ATL-COM-OREACH-2021-019 (CERN, Geneva, Oct. 2021). `https://cds.cern.ch/record/2788941`.