**CMS J/ψ–path MASTERCLASS**

**TEACHER NOTES**

**DESCRIPTION**

Each year about 13,000 high school students in 50 countries come to one of about 200 nearby universities or research centers for one day in order to unravel mysteries of particle physics. Lectures from active scientists give insight in topics and methods of basic research on matter and forces at the fundamental level, enabling the students to perform measurements on authentic data from particle physics experiments. At the end of each day, as in an international research collaboration, the participants join in a videoconference for discussion and combination of their results.

As an alternative to holding the J/ψ Masterclass at a university or lab, a teacher with sufficient background knowledge may elect to run this masterclass at their own high school. In this version of a masterclass, teachers are encouraged to include a videoconference in which students connect with a physicist and/or students from other schools to discuss results.

**STANDARDS ADDRESSED**

*Next Generation Science Standards*

Science and Engineering Practices

1. Asking questions
2. Developing and using models
3. Analyzing and interpreting data
4. Using mathematics and computational thinking
5. Constructing explanations
6. Engaging in argument from evidence
7. Obtaining, evaluating, and communicating information

Disciplinary Core Ideas – Physical Science

PS1.A: Structure and Properties of Matter

PS2.B: Types of Interactions  
PS2.C: Stability and Instability in Physical Systems

PS3.B: Conservation of Energy and Energy Transfer

PS3.C: Relationship between Energy and Forces

Crosscutting Concepts

1. Patterns
2. Cause and effect: Mechanism and explanation
3. Scale, proportion, and quantity
4. Systems and System Models

7. Stability and Change

*Common Core Literacy Standards*

Reading

9-12.4 Determine the meaning of symbols, key terms . . .

9-12.7 Translate quantitative or technical information . . .

*Common Core Mathematics Standards*

MP2. Reason abstractly and quantitatively.

MP6. Attend to precision.

*IB Physics Standard 1: Measurement and Uncertainty*

1.2.6 Describe and give examples of random and systematic errors.

## 1.2.8 Explain how the effects of random errors may be reduced.

## 1.2.11 Determine the uncertainties in results.

*IB Physics Standard 7: The Structure of Matter*

Aim 4: Particle physics involves the analysis and evaluation of very large amounts of data.

Standard 7.3.4: Apply the Einstein mass-energy equivalence relationship.

**Enduring Understandings**

* Claims are made based on data that comprise the evidence for the claim. These data provide indirect evidence to study phenomena that cannot be directly observed.
* Particle physicists use conservation laws to discover characteristics, such as mass and charge, of fundamental particles that cannot be observed directly.

**LEARNING OBJECTIVES**

Students will be able to:

1. Describe the particle properties that are detected by each major component of the CMS detector.
2. Rate each event as a likely J/ψ event by determining the charge of each muons and the quality of the muon tracks.
3. Build a series of mass histograms based on the ratings to determine if there is a peak that may represent the presence of a particle.
4. Describe how the shape of a peak on the histogram gives an indication of the uncertainty in the reported mass for each particle identified.

**PRIOR KNOWLEDGE**

Students must be able to:

* Describe a claim and indirect evidence based on an activity such as Rolling with Rutherford found in the Data Portfolio.
* Identify the peak in a histogram and explain what it means based on an experiment such as Dice and Histograms found in the Data Portfolio.
* Describe how quarks combine to form mesons and baryons based on an activity such as Quark Workbench found in the Data Portfolio.
* Apply conservation rules to measurements to provide evidence for unobserved particles based on an activity such as Top Quark or Z Mass calculation found in the Data Portfolio.

In order to address this prior knowledge before the masterclass day, teachers may use the classroom preparation resources found in the **QuarkNet Masterclass Library**: go online to <https://quarknet.org>, then select MASTERCLASSES from the top menu bar and then select LHC PROJECT MAP.

**BACKGROUND MATERIAL**

* The LHC from *CERN in 3 minutes:* <https://www.youtube.com/watch?v=PHP13tTjidA>
* Information on the CMS experiment at CERN: <https://home.cern/about/experiments/cms>
* Additional background information can be found in the QuarkNet Masterclass Library: [see above]

**RESOURCES**

* CMS Masterclass website: <http://cms.physicsmasterclasses.org/cms.html>
* Additional resources can be found in the QuarkNet Masterclass Library: [see above].

**IMPLEMENTATION**

There are two ways to implement this activity. Version 1 includes instructions for cases where the students have access to a physicist while analyzing data, either in the classroom or in a university lab. Version 2 includes instructions for cases where the physicist is only available through video conferencing during the discussion and interpretation of the results.

Version 1 – At a university or lab with physicist(s) present: In this version, a teacher partners with a particle physicist (mentor) at a university or lab in order to conduct a masterclass for their students. The masterclass institute itself is usually one day in length, and often takes place at the university or lab where the mentor is based. The most successful masterclasses involve advanced planning among the teachers and mentors involved, and include an orientation in which the teachers and mentors become familiar with the masterclass process, structures, data analysis, and classroom preparation expectations that allow students to maximize their masterclass experience. In this version, much of the post-analysis discussion of results with the students will primarily the responsibility of the mentor and the videoconference moderator.

Implementation details can be found in the QuarkNet Masterclass Library: [see above]. Teachers are particularly encouraged to use the Classroom Preparation and CMS sections of the Library. CMS Masterclass Documentation is linked in the CMS section of the Library and is particularly helpful for understanding the mechanics of the CMS masterclass.

Version 2 – At a high school without a physicist present: In this version, an experienced masterclass teacher with sufficient knowledge runs a masterclass at his/her own high school without access to a physicist. In this version of the masterclass, the teacher is responsible for facilitating the on-site discussion of results with students. The teacher is encouraged to include a videoconference connecting with a physicist and/or students from other schools who are performing the same analysis.

In facilitating the discussion of results with students, teachers may want to include the following graphs, questions, and points of discussion. Other methods of interpreting the data may arise from the discussion.

* *Graphs:* Students should build several mass histograms: one histogram containing events rated as a 3, another histogram containing events rated at a 2 or 3, and another containing events rated as a 1, 2, or 3.
  + *What do you notice when comparing the three histograms?*Assuming all events are analyzed, and that students did a good job of rating events, potential responses to this question may include:
    - *The histogram with events labeled as a 3 contains the fewest events, has the most pronounced peak, and contains the least background. The clear peak at ~3.1 GeV clearly indicates the mass of the J/ψ (~3.1 GeV).*
    - *The histogram with events labeled as a 2 or 3 contains more events and has a less pronounced peak as the additional background events somewhat mask the peak near 3.1 GeV.*
    - *The histogram containing events labeled as a 1, 2, or 3 contains the most events. At this point, there are so many background events present that it may be very difficult to identify a clearly defined peak in the histogram.*
* *Analysis during Videoconference:* The teacher may want to also build these same graphs combining results with other schools that may be participating in the analysis. If additional data were also collected by students who did a good job of rating events, the peaks will likely be more pronounced in all cases, emphasizing the importance of large data sets in statistical analyses.

Other implementation details can be found in the QuarkNet Masterclass Library: [see above]. Teachers are particularly encouraged to use the Classroom Preparation and CMS sections of the Library. CMS Masterclass Documentation is linked in the CMS section of the Library and is particularly helpful for understanding the mechanics of the CMS masterclass.

**ASSESSMENT**

Upon completion of the masterclass experience, teachers may have students provide answers to each of the following through discussion, and/or video, and/or written responses on paper.

1. Describe the particle properties that are detected by each major component of the CMS detector.
2. Identify the presence of a particle and an estimate of the particle mass given a sample mass histogram.
3. Describe how the shape of a peak on the histogram gives an indication of the uncertainty in the reported mass for each particle identified.