CMS J/ψ–PATH MASTERCLASS
TEACHER NOTES

NOTE: This activity is designed to help teachers and their students participate in a masterclass held at a university or lab, in partnership with a particle physicist.

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.

The J/ψ masterclass, done in the classroom, can be an alternative to this model while retaining its most important features. With the J/ψ-path, a teacher with sufficient background knowledge may elect to run this masterclass at their own high school. In this version of a masterclass, we encourage teachers 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
4. Analyzing and interpreting data
5. Using mathematics and computational thinking
6. Constructing explanations
7. Engaging in argument from evidence
8. 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

- Physicists must identify and subtract "noisy" background events in order to identify the "signal."
- Particle physicists use conservation laws to discover characteristics 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 muon 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. Explain why some small peaks do not represent particles. Discuss differentiating signals and background noise.
5. 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, Histograms and Probability* 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 *Calculate the Top Quark* or *Calculate the Z Mass* 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: https://web.quarknet.org/mc/cms/
- 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 when students have access to a physicist while analyzing data, either in the classroom or in a university lab. Version 2 includes instructions when the physicist is only available through videoconferencing during the discussion and interpretation of the results.

<u>Version 1 – At a university or lab with physicist(s) present</u>: In this version, you partner with a particle physicist (mentor) at a university or lab in order to conduct a masterclass for your 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 and include an orientation in which 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 be the responsibility of the mentor and the videoconference moderator.

Implementation details can be found in the QuarkNet Masterclass Library; see above. We encourage you to use the Classroom Preparation and CMS sections of the Library. CMS Masterclass Documentation is linked in the CMS section of the Library and you understand the mechanics of the CMS masterclass.

<u>Version 2 – At a high school without a physicist present</u>: You are an experienced masterclass teacher with sufficient knowledge to run a masterclass at your own high school without access to a physicist. In this version, you are responsible for facilitating the on-site discussion of results with students. We encourage you to include a videoconference with a physicist and/or students from other schools who are performing the same analysis.

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

- *<u>Graphs</u>:* 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 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 because 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. There are so many background events present that it may be very difficult to identify a clearly defined peak in the histogram.*
- *<u>Analysis during Videoconference</u>:* You may want to build these same graphs combining results with other schools that are 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. We encourage you to use the Classroom Preparation and CMS sections of the Library. CMS Masterclass Documentation is linked in the CMS section of the Library and helps you understand the mechanics of the CMS masterclass.

ASSESSMENT

Upon completion of the masterclass experience, you 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.
4. Explain why keeping lower ratings increases the noise in your histogram.
5. Describe how eliminating all the noise eliminates some of the signal.