DRAFT # CALCULATE DIMUON MASSES **DRAFT**

TEACHER NOTES

DESCRIPTION

In process…

STANDARDS (subject to revision)

Next Generation Science Standards

Science Practices

1. Asking questions
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
PS3.B: Conservation of Energy and Energy Transfer

Crosscutting Concepts

1. Patterns.
3. Scale, proportion, and quantity.
4. Systems and system models.

Common Core Literacy Standards

Reading

9-12.7 Translate quantitative or technical information . . .

Common Core Mathematics Standards

MP2. Reason abstractly and quantitatively
MP6. Attend to precision.

IB Physics Topic 1: Measurement and Uncertainty

1.2.6 Describe and give examples of random and systematic errors.
1.3.1 Distinguish between vector and scalar quantities.
1.3.2 Combine and resolve vectors.

IB Physics Topic 2: Mechanics

2.3.6 Use the principle of conservation of energy to compare an initial state to a final state.
2.4.3 Use conservation of linear momentum to compare an initial state to a final state.

IB Physics Topic 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

IB Physics Additional Higher Level Option Topic A.4: Relativistic Mechanics

A.4.6 Use MeV c^{-2} or as GeV c^{-2} the unit of mass and MeV c^{-1} or GeV c^{-1} as the unit of momentum.
A.4.7 Describe the laws of conservation of momentum and conservation of energy within special relativity
A.4.10 Solve problems involving relativistic energy and momentum conservation in collisions and particle decays

ENDURING UNDERSTANDINGS

- Particle physicists use conservation of energy and momentum to measure the mass of fundamental particles.
- TBD

LEARNING OBJECTIVES

Students will be able to:

- Apply momentum conservation to real-life situations.
- Calculate the invariant mass of a decay particle.
- Use energy conservation to determine the mass of an object undergoing decay.

PRIOR KNOWLEDGE

Students must be able to:

- Differentiate mass, energy and momentum units as used by particle physicists (Energy-eV, Momentum–eV/c, mass–eV/c2)

BACKGROUND MATERIAL

These event displays are authentic data. However, most high school students think of data as numbers, perhaps columns of numbers. Use the event displays to prompt a discussion of data forms and the fact that they can use this authentic data to calculate invariant masses of particles which decayed into muons of with relatively low energies for the products of LHC collisions (most less than 20 GeV).

RESOURCES/MATERIALS

The links below provide useful background material.
Detectors at the LHC:

- https://alice.cern/
- https://atlas.cern/
- https://cms.cern/
- https://lhcb-public.web.cern.ch/

Histograms, useful units:

- http://quarknet.fnal.gov/toolkits/new/histograms.html
- http://quarknet.fnal.gov/toolkits/ati/whatgevs.html
- http://en.wikipedia.org/wiki/Full_width_at_half_maximum

IMPLEMENTATION

Students use printed event images, ruler and protractor to analyze the data. This activity requires averaging many independent calculations of the invariant mass determined from the eight events. Students analyze CMS events chosen because the decay products had little momentumin the direction of the beam. This makes resolving vector components a fairly simple matter of adding two vectors in two dimensions. Students will use a protractor to measure momentum direction, resolve momentum components and add these to determine the mass of the parent particles which each decayed into two muons..

Each of these events shows the decay into two muons. The detector can only "see" the muons. These are shown on these events as tracks. The parent particles are J/Ψ and Υ (J/Psi and Upsilon) mesons, so the students should get two mass bands.an important part of the discussion will be resolving the two bands to indicate the present f two particles rather than one.

You can use this activity to reinforce the addition of vectors or to explore the conservation of momentum and energy. The students may have difficulty in two different areas: resolving and adding vectors and determining mass from the vector sum. It is important to stress that these are authentic events and that the “answer” is the result of their analysis. Nature doesn’t provide an answer key. Students can share their results publicly by entering their mass values into a table on the board.

You can also use this activity to introduce calibration. In early runs, CMS used the determination of the J/Ψ and Υ masses (as well as the Z mass) as a confirmation that the detector was behaving as expected. If the values from new data differed from early results, their detector had problems.

The events are currently available at https://quarknet.org/sites/default/files/dimuon_events.pdf.

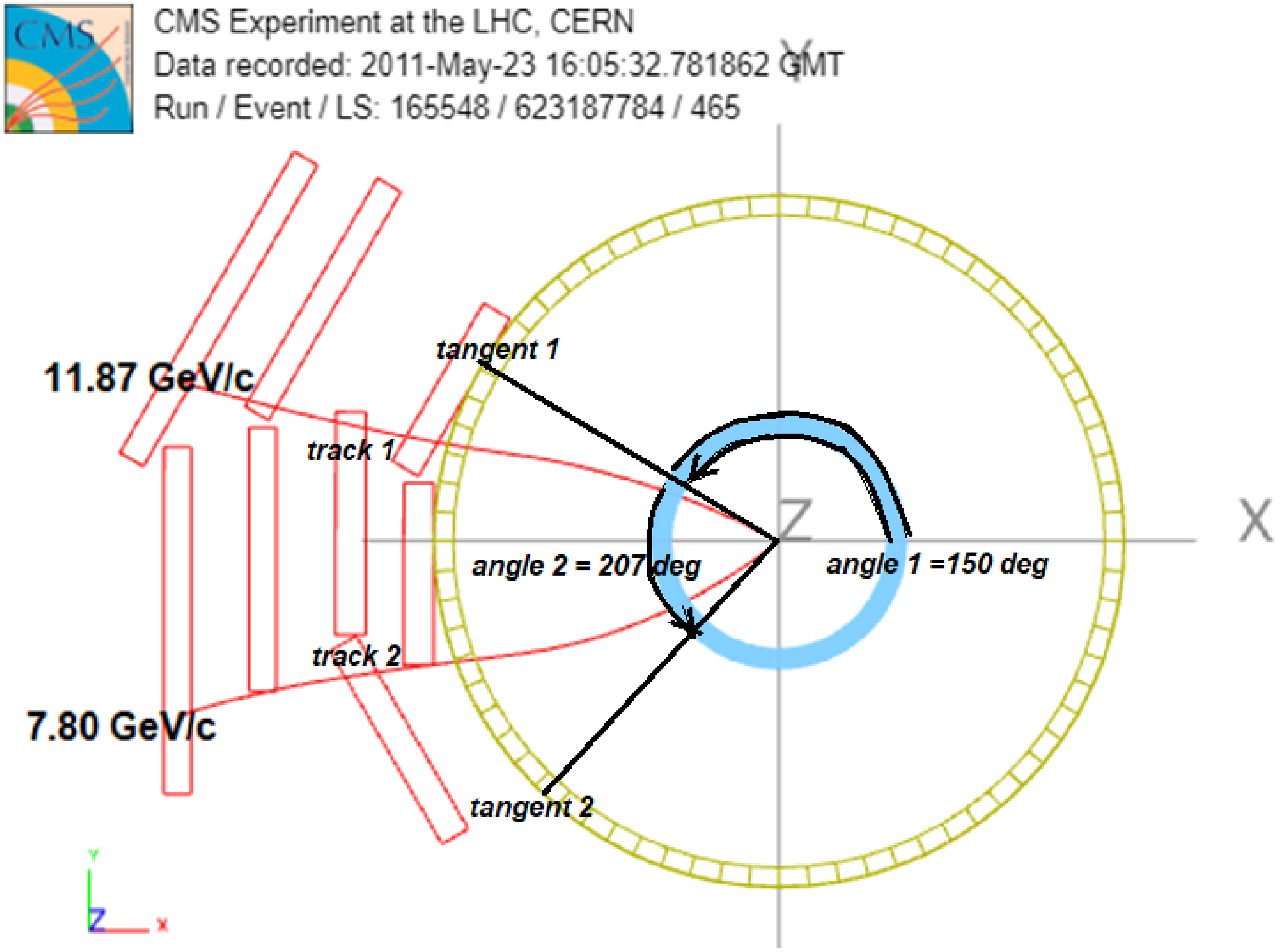
ASSESSMENT

- Interpretation
  - Check for the following: correct identification of the two peaks and the particle masses; indication that the width of the peak represents the uncertainty in the value of the mass.
  - Did the analysis indicate that the detector is well calibrated? That is, did the mass plot yield a result in agreement with accepted values for the J/Ψ and Υ masses? (3.1 and 9.46 GeV/c^2)

- Discussion
  Divide the class into groups. Each group presents their findings to the class with open discussion of the claims, evidence and reasoning provided by each group. Questions addressed during the discussion include:
    - How many types of particle is represented?
    - What are their approximate masses?
    - What are the ranges of J/Ψ and Υ masses sampled in your data?
- Written report
  A written report should stress *claims*, *evidence*, and *reasoning*:
  What claims can scientists make based on these results?
    - *Examples: mass, discovery, uncertainty.*
  - What is the evidence for and against the validity of the claims?
    - *Examples: signal-to-background, width.*
  - Explain the reasoning linking the evidence to the validity of the claim.
    - *Example:* the *J/Ψ signal is large compared to background, with a width narrowcompared to the height of the peak.*

Provide the evidence for these claims, and the reasoning behind them over to the shift manager in your *Shift Report*. The link to the *Shift Report* is on the front page of the activity.

SAMPLE CALCULATION OF AN EVENT



Detector	CMS						
Run No.	165548						
Event No.	623187784		*sum these three quantities vertically*				
	p (GeV/c)	**muon mass (GeV/c^2)**	**E (GeV)**	**angle (0-360 deg)**	**px = p cos (ang)**	**py = p sin (ang)**	**Z mass (GeV/c^2)**
1	11.87	0.106	11.87	150	-10.28	5.94	
2	7.8	0.106	7.8	207	-6.95	-3.54	
1+2			19.67		-17.23	2.39	
squared →	302.59		386.91		296.86	5.73	9.18
	sum of squares		*square of sum*		*square of sum*	*square of sum*	*sqrt(E^2 - p^2)*
	i.e. px^2 + py^2		i.e. (E1+E2)^2				

SAMPLE RESULTS