DRAFT # CALCULATE DIMUON MASSES **DRAFT**

SHORT NOTES

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/c^2)

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..

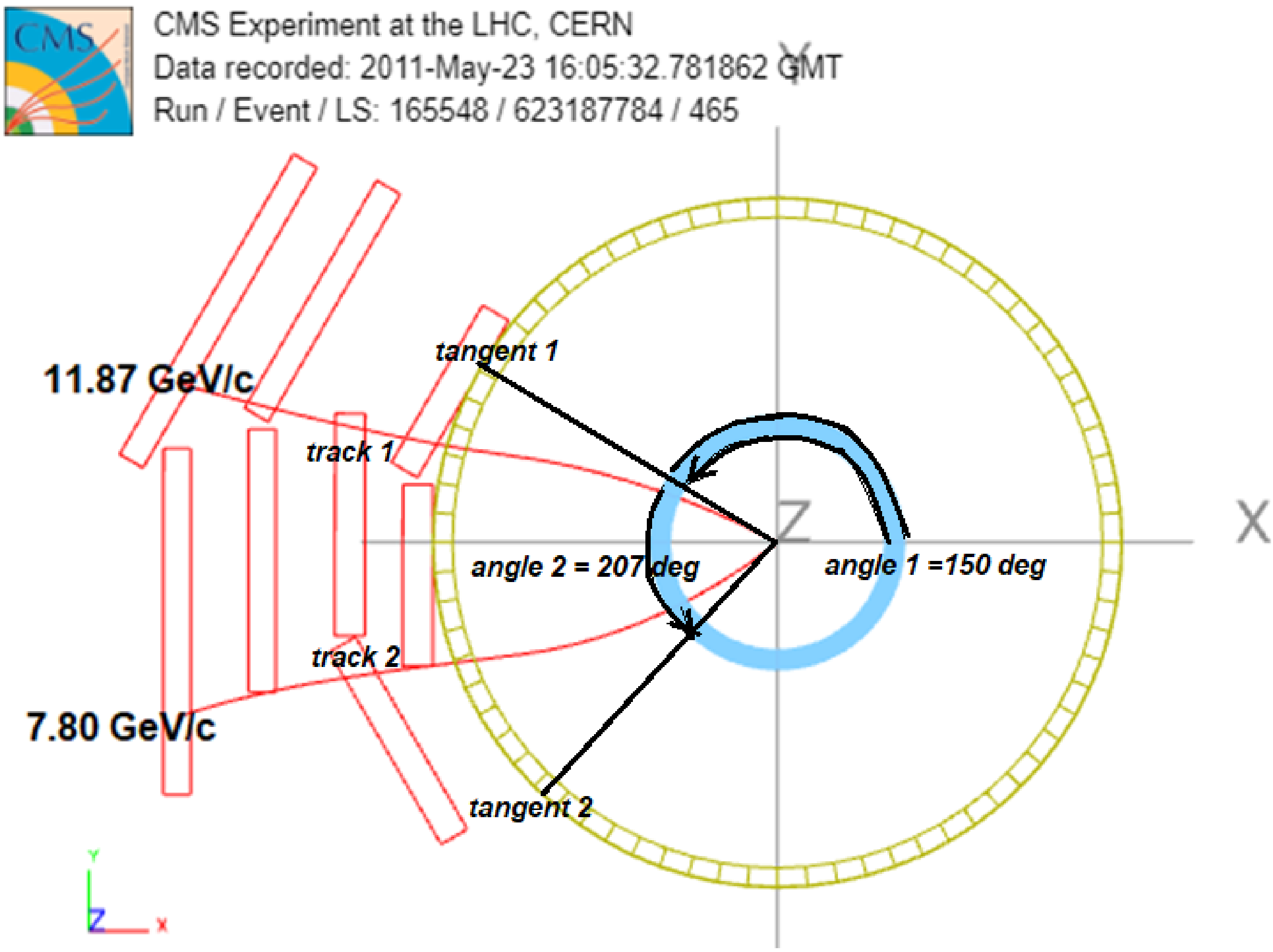
Each of these events shows the decay into two muons. The detector can only "see" the muons. These are shown on these events as tracks. The parent particles are J/Ψ and Υ (J/Psi and Upsilon) mesons, so the students should get two mass bands.an important part of the discussion will be resolving the two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

SAMPLE CALCULATION OF AN EVENT



If p in GeV/c >> muon mass in GeV/c^2, then E = p (almost).

First we add the energies:

$$E = E_1 + E_2 = 11.87 \text{ GeV} + 7.8 \text{ GeV} = 19.67 \text{ GeV}.$$

For muon 1, we find p_{x1} and p_{y1} using trig:

$$p_{x1} = p_1 \cos \theta_1 = (11.87 \text{ GeV/c}) \cos 150^o = -10.28 \text{ GeV/c}$$

$$p_{y1} = p_1 \sin \theta_1 = (11.87 \text{ GeV/c}) \sin 150^o = 5.94 \text{ GeV/c}.$$

We do the same for muon 2:

$$p_{x2} = p_2 \cos \theta_2 = (7.8 \text{ GeV/c}) \cos 207^o = -6.95 \text{ GeV/c}$$

$p_{y2} = p_2 \sin \theta_2 = (7.8 \text{ GeV/c}) \sin 207^o = -3.54 \text{ GeV/c}.$

Now we use $E^2 = p^2c^2 + m^2c^4$:

$E^2 = [(p_{x1} + p_{x2})^2 + (p_{y1} + p_{y2})^2]c^2 + m^2c^4$

$(19.67 \text{ GeV})^2 = [(-10.28 \text{ GeV/c}^2 – 6.95 \text{ GeV/c}^2)^2 + (5.94 \text{ GeV/c}^2 – 3.54 \text{ GeV/c}^2)^2] c^2 + m^2c^4$

$386.91 \text{ GeV}^2 = [302.59 \text{ GeV}^2/c^2] c^2 + m^2c^4$

Rearrange and cancel c^2:

$386.91 \text{ GeV}^2 – 302.59 \text{ GeV}^2 = m^2c^4$

$m^2c^4 = 84.32 \text{ GeV}^2$

$m^2 = 84.32 \text{ GeV}^2/c^4$

Take the square root:

$m = 9.18 \text{ GeV/c}^2$.

Pro tip: You can ignore all the c's – do not even write them – until the end.

Table version of above:

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 HISTOGRAM OF RESULTS