IPhO 2016

International Physics Olympiad Switzerland Liechtenstein

T-3: LHC – particle acceleration and particle identification

10 marks

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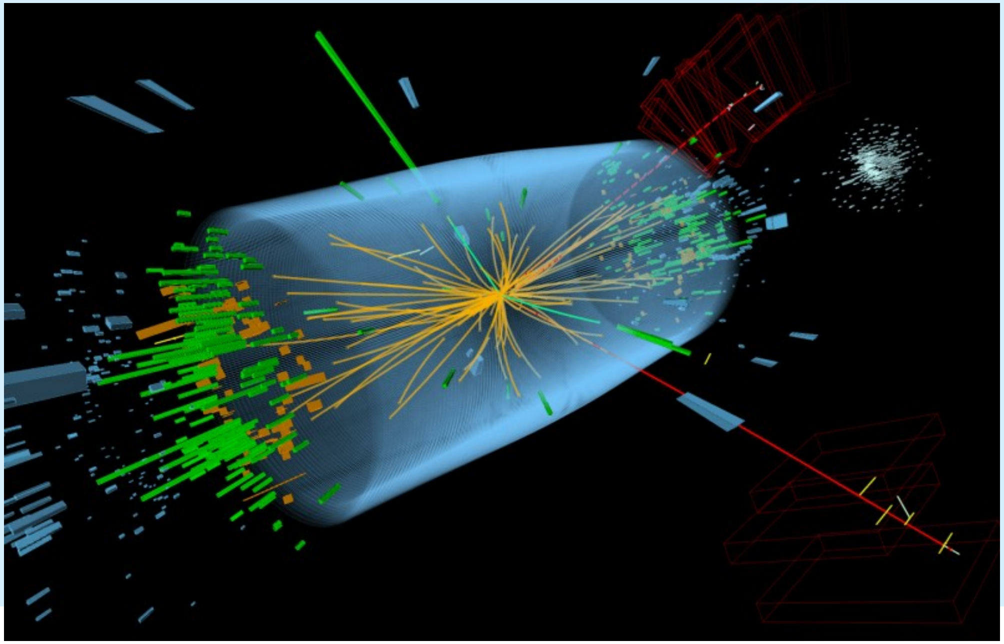
Motivation

LHC - the largest machine in the world – built to answer fundamental questions

- origin of mass: Higgs discovery 2012
- where has all the antimatter gone?
- search for new particles



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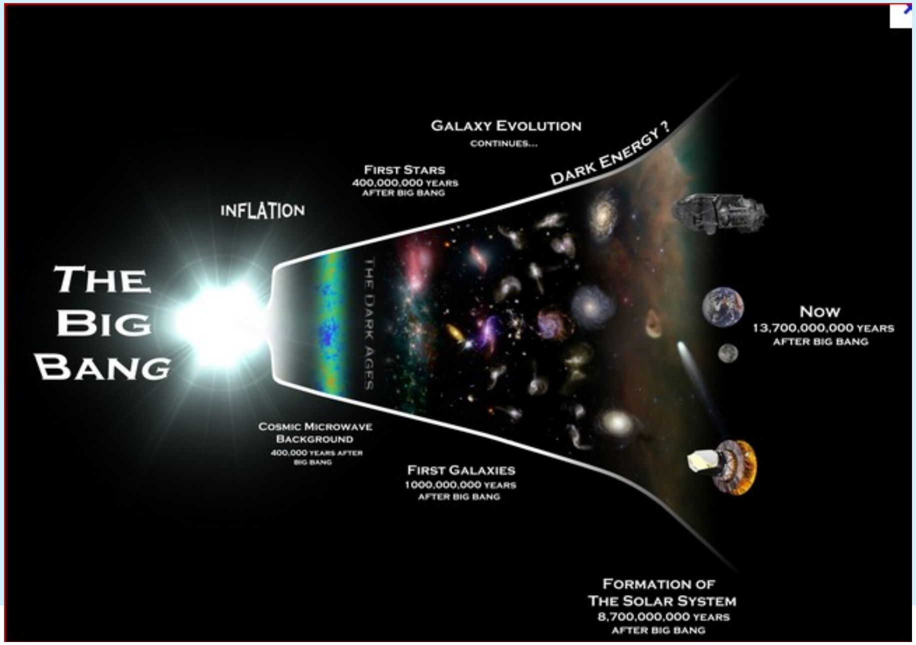

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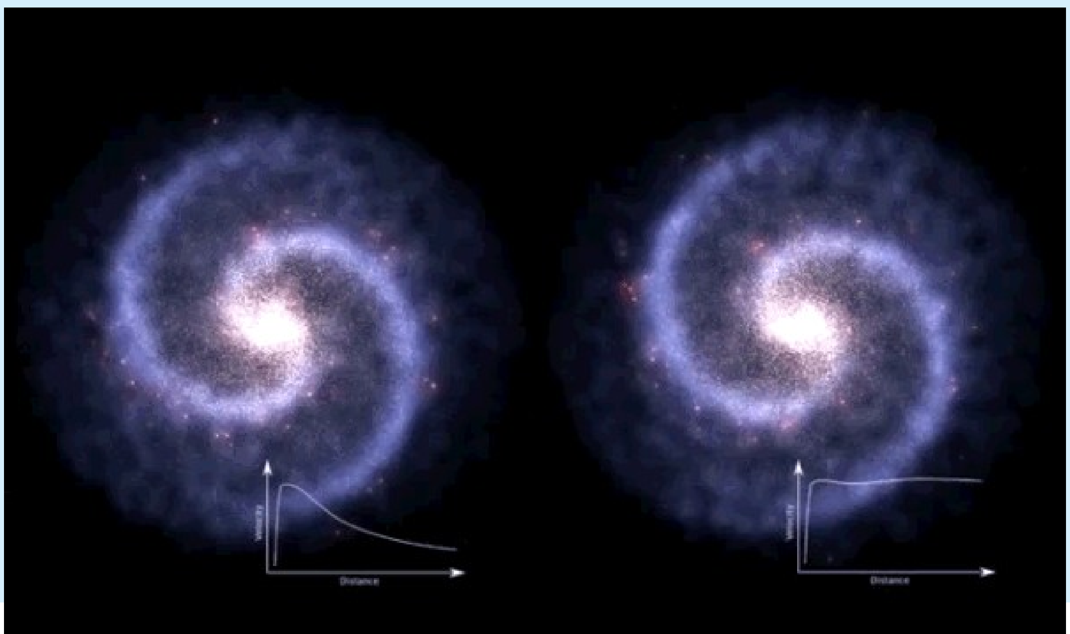


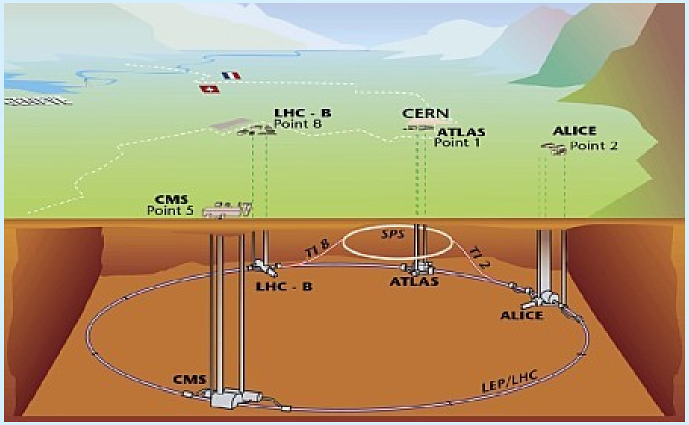
Objective

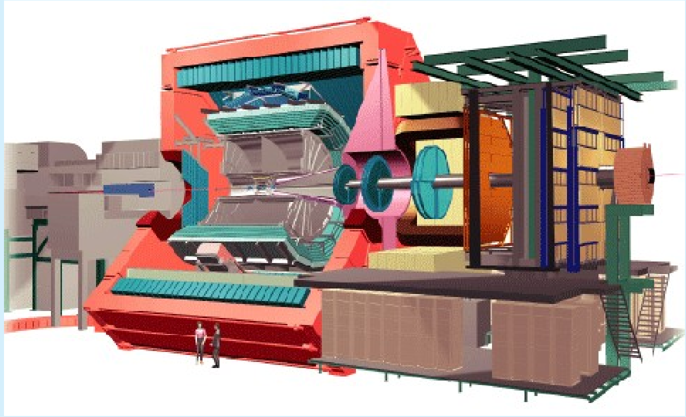
Task A: LHC acceleration (6.0 P)

- acceleration of protons and electrons
- magnetic flux density for dipole magnets
- radiated power
- linear acceleration

Task B: Particle Identification (4.0 P)

- Time-of-flight (ToF) detector
- 2-stage detector: momentum and ToF





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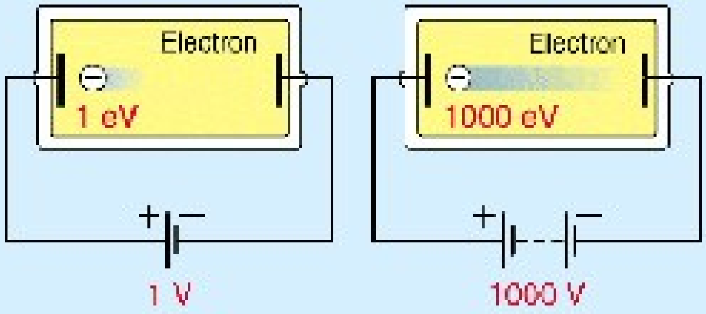
A word on units

particle physicists use convenient units for energy, momentum and masses:

energy: eV
mass: eV/c^2
momentum: eV/c



1 eV is the amount of energy gained (or lost) by a particle with elementary charge, e, moved through a potential difference of one volt

$1\ eV = 1.602\ 10^{-19}\ kg \cdot m^2/s^2$

students can of course also calculate the results in SI units

Task A: LHC acceleration of protons and electrons (A1, A2, A3)

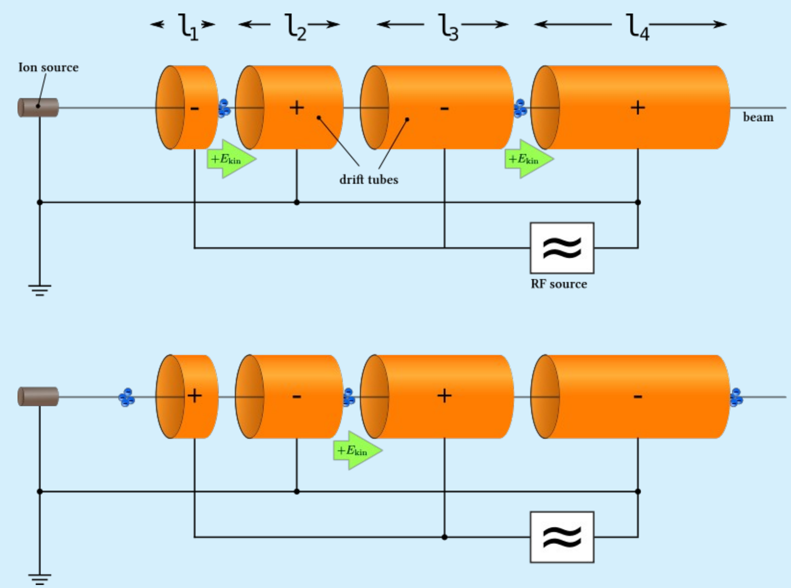
A design for a future experiment at CERN plans to use the protons from the LHC and to collide them with electrons with an energy of 60 GeV thus providing the cleanest high resolution microscope in the world.

- A1 : acceleration in electric field
  - expression for final velocity
  energy conservation → velocity

- A2 : relative velocity of electrons with an energy of 60 GeV - $v \approx c$

  approximation: $\sqrt{1+x} = 1 + \frac{1}{2} \cdot x$

  classical solution fails



Task A: LHC acceleration of protons and electrons (A1, A2, A3)

A design for a future experiment at CERN plans to use the protons from the LHC and to collide them with electrons with an energy of 60 GeV thus providing the cleanest high resolution microscope in the world.

- A1 : acceleration in electric field
  energy conservation → velocity
- A2 : relative velocity of electrons with an energy of 60 GeV - $v \approx c$
- A3 : magnetic flux density needed to keep protons on circular track (length L)
  Circular motion with Lorentz force
  express γ as energy of proton, neglecting rest energy
  with v ≈ c

$$B = \frac{2\pi \cdot E}{c \cdot e \cdot L}$$

Task A: radiated power (A4, A5)

- A4: dimensional analysis to calculate radiated power

  Ansatz: $$P_{rad} = const \cdot a^{\alpha} \cdot q^{\beta} \cdot c^{\gamma} \cdot \epsilon_0^{\delta} \rightarrow P_{rad} = \frac{const \cdot a^2 \cdot q^2}{c^3 \cdot \epsilon_0}$$

  a : acceleration [m/s^2]
  q : charge [C]
  c : speed of light [m/s]
  ε_0 : permittivity [C/(Vm)]

- A5 : total radiated power
  take formula from A4
  use relativistic energy to calculate

  $$\gamma = \frac{E}{m_p c^2} + 1$$

  → radiated power per proton
  → total radiated power

Installation of radiation detectors close to the magnets
https://www.liverpool.ac.uk/opac/projects/cern/

Task A: linear acceleration (A6)

A6 : determine the time a proton needs to pass through the accelerating field
→ several different solutions

A) *F=dp/dt → V·e/d=p/T → T=p·d/Ve*
final momentum from energy conservation

B) final momentum = γ·m·v
with v from A1 or energy conservation

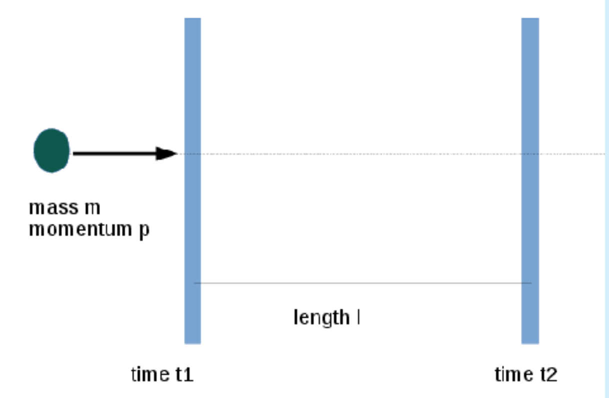
C) integration $T=\int dt=\int_0^d \frac{dx}{v}(t)$

D) differential equation

$$a=\ddot{s}=\frac{V\cdot e}{d\cdot m}\left(1-\frac{\dot{s}^2}{c^2}\right)^{\frac{3}{2}}$$

E) classical solution

Task B: Particle identification



Particle identification is necessary to interpret the interaction process – several specialised detectors for example measure the time-of-flight (TOF).

B1: expression for the mass

- express velocity as a function of momentum, flight time and length of the detector

$$m=\sqrt{\left(\frac{p\cdot t}{l}\right)^2-\left(\frac{p}{c}\right)^2} \qquad m=\frac{t\cdot p}{l}$$

relativistic p — non-relativistic (0 points, but B2-B4 will score)

B2 : flight distance that allows to separate kaons and pions

- calculate ToF difference for kaon and pion
- ToF difference > three times the time resolution → length

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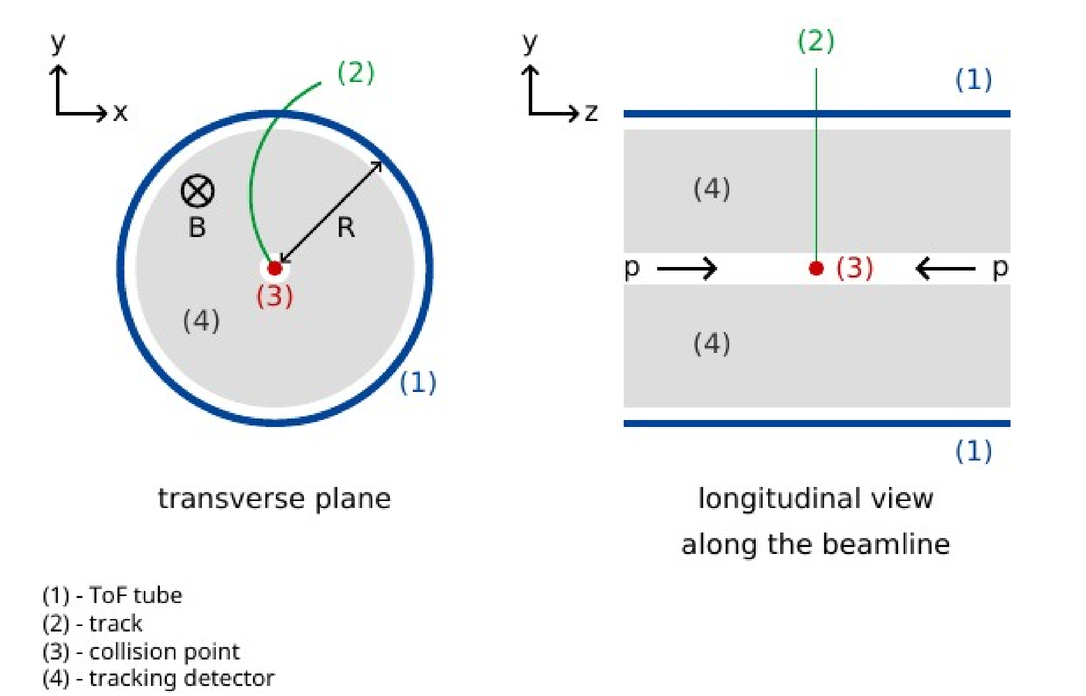
Task B: Particle identification cont.

Now take a realistic detector (ALICE) with a tracking chamber and a ToF detector.
The tracking chamber is in the magnetic field → radius of track allows determination of transverse momentum
ToF: collision time is known → only one ToF plane needed

Experimental setup :



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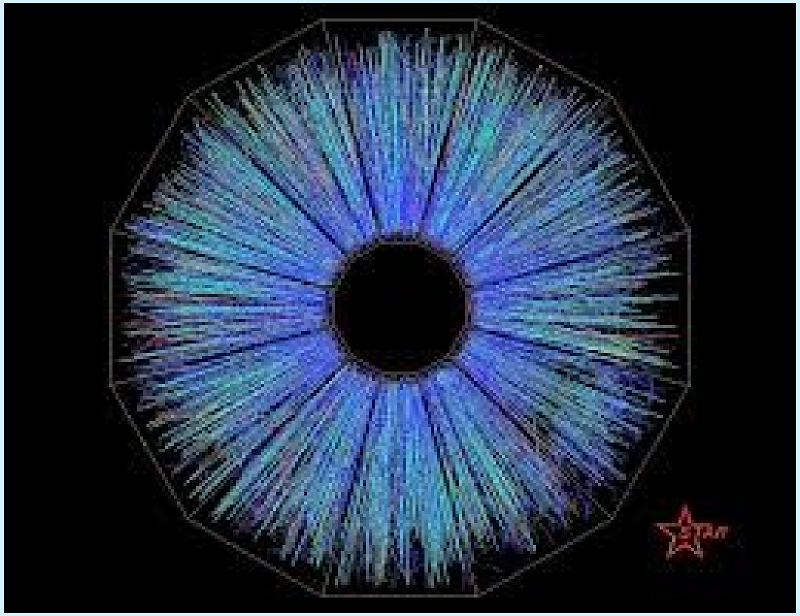
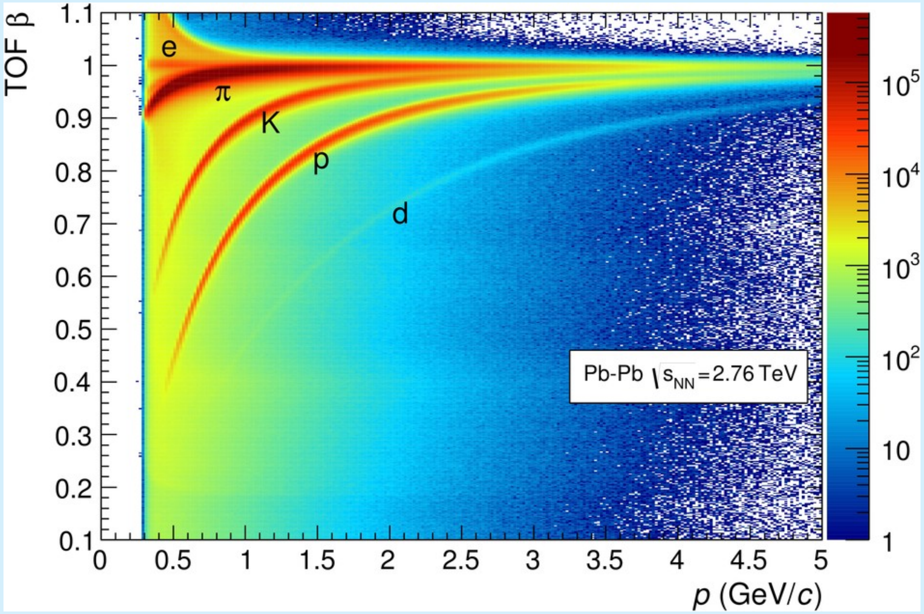
ALICE: investigate quark-gluon plasma
→ identify as many particles as possible

ALICE: typical event



velocity vs momentum



http://aliceinfo.cern.ch

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Task B: Particle identification: mass determination

B3 and B4 mass determination from measurement of momentum and ToF

- calculate track length in transverse plane (arc) $l=2r\ asin(R/2r)$
- Lorentz force in transverse plane → transverse momentum
- no longitudinal momentum → momentum=transverse momentum
- → determine mass with formula from B1

particle identification with four measurements of track radius and ToF

- use formula B3 and calculate mass in kg or MeV/c^2

Note: wrong (non-relativistic) solution in B1 still scores in B3, B4

Summary

Task A: LHC acceleration (6.0 P)

- acceleration of protons and electrons
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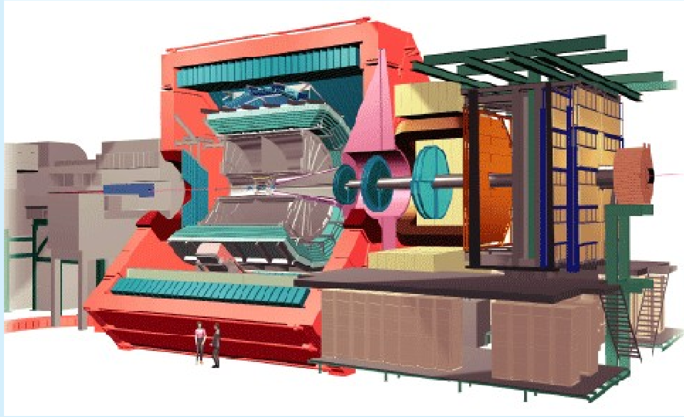


What the students are being tested for

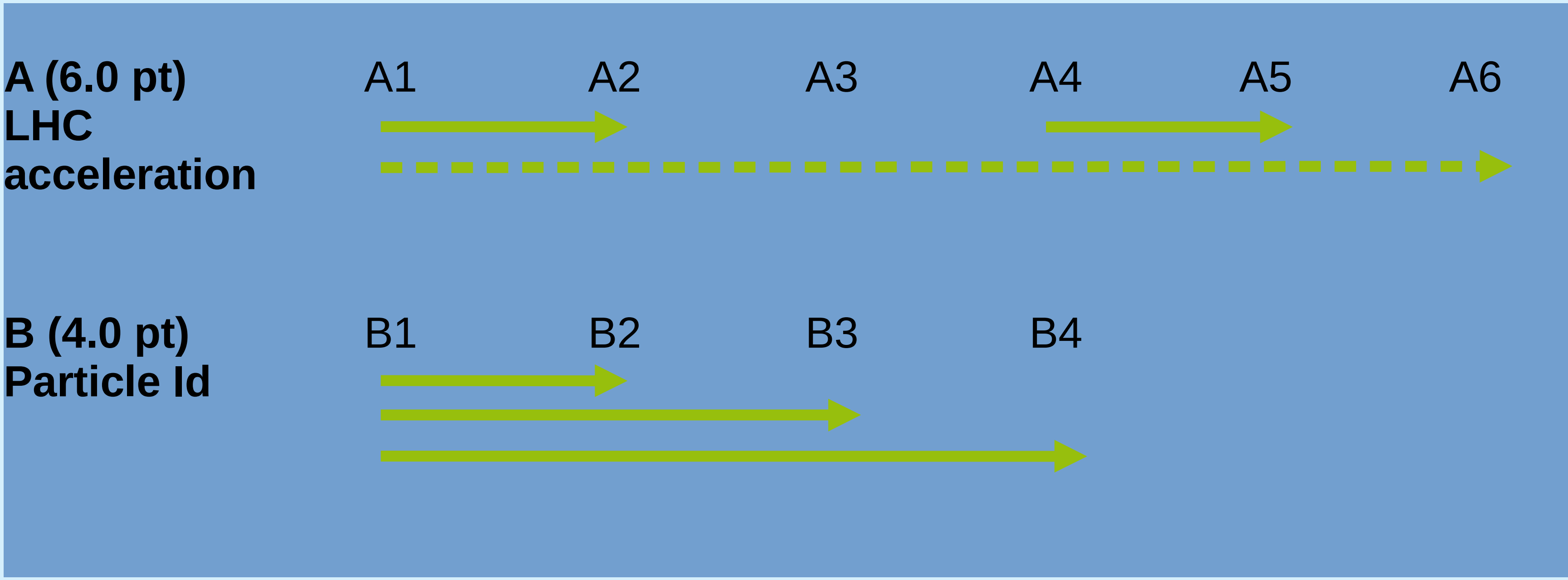
Knowledge

- *Circular motion (2.2.3)*
- *Centrifugal force (2.2.3)*
- *Momentum, energy and their conservation laws (2.2.3)*
- *Lorentz force (2.3.1)*
- *Lorentz transformations for the energy and momentum (2.5)*
- *Mass-energy equivalence (2.5)*
- *Relativistic equation of motion (2.5)*

Skills

- *Mathematical formulation of physical situations*
- *Linear approximations based on Taylor series (4.8)*
- *Dimensional analysis*

Modularity



Note1: Dependencies between sub-tasks are indicated by arrows.

Note2: Non relativistic solution in B1 still gives points in B2-B4