A- General questions: You are expected to answer to most of these questions. You should provide the correct answer to at least 4 out of the 6 questions to get the maximal mark of 12.

1) Indicate two observations that the Standard Model of particle physics cannot account for?
Dark matter, matter-antimatter asymmetry in the universe, number of families, neutrino mass….
2) Cosmological and astrophysical observations have provided evidences of the existence of dark matter. Briefly describe two of them.
   a- Dynamics of galaxies in the Coma cluster : viral theorem vs luminous mass
   b- Rotation curves of spirals galaxies
   c- Gravitational lensing effect
   d- CMB
3) Expansion and Redshift — Explain how the observation of galaxy redshifts provides evidence for the expansion of the Universe. What does it mean when we say that "space itself is expanding" rather than galaxies simply moving through space?
When we observe light from distant galaxies, we see that it is redshifted — its wavelength has been stretched. This means that the space between us and those galaxies has expanded. Saying "space itself is expanding" means that galaxies are not just moving through space, but rather, the fabric of space is stretching, increasing the distance between galaxies over time. This was first observed by Hubble in 1929-1931.
4) For a given beam energy, why colliders have larger potential than fixed targets experiments. What limits the LHC to a beam energy of 7 TeV ?
The center of mass energy of a collider (2E) is much larger than the center of mass energy of a fixed target experiments (sqrt(2mE))
The LHC beam energy is limited by the maximal magnetic field provided by the supraconducting magnets to bend the beam.
5) Question on statistic with counting experiment:
Expected background: 100 events (perfectly known)
Simulation of signal: 50 events for 10 fb cross section
Observation 130 events
   a) What is the measured cross section and the integrated luminosity used ?
   *(130-100/50)*10 = 6fb and 50/10 = 5fb-1*
   b) What is the statistical error of his measured cross section?
   10*sqrt(130)/50
   c) What is the statistical significance ? Would you call it a discovery ?
   30/sqrt(130) = 2.6 sigma
6) If you would need to design an analysis to search for di-Higgs production, which are the two main channels you would choose and why?

Channel	Pros	Cons	Key Feature
bb¯bb¯	Highest branching ratio (largest yield)	Large QCD multijet background	Large statistics, requires powerful background rejection
bb¯γγ	Clean diphoton peak, good S/B ratio	Small branching fraction, limited statistics	Good mass resolution, clean final state

Other channels like bb¯τ+τ−bb¯τ+τ−, bb¯WW∗bb¯WW∗, or γγWW∗γγWW∗ are also studied but typically have either lower branching fractions or more challenging backgrounds

7) Describe the different sources of neutrinos (natural and artificial) and discuss the advantages *and disadvantages of artificial sources with respect to natural ones*

large number of neutrinos come from natural sourecs of neutrinos such as the Sun and the Earth Atmosphere. Neutrinos are also produced in artificial sources, such as the reactors and the particle accelerators.
The main advantage of these artificial sources is that one can tune the distance and the neutrino energies to maximize the oscillation probability that depends on the mass squared differences Dm2, the baseline L and the energy E.
In the case of reactor neutrinos the energy is defined and we can only choose the baseline L.
In the case of accelerators, both L and E can be tuned.

8) Why we need to look at upgoing muons to identify astrophysical neutrinos? We can use this strategy for whatevever neutrino energy?
Downgoing channel dominated by background of muons coming from extensive air shower. Earth propagation enhances probability of neutrino interactions. Still, Earth starts to be opaque to neutrinos at the highest energies (above 10^16 eV)

B- Topical questions: You should provide the correct answer to at least 2 out of the 4 questions to get the maximal mark of 8.

1) What are the experimental signatures that allow for the observation of a WIMP signal? Briefly describe them.
3.a Multi-target detection
3.b Annual modulation
3.c Directionality

2) Cosmic Timeline and Observational Evidence — List three major events in the history of the Universe and describe how we are able to obtain observational evidence for each of them

a) *Big Bang / Primordial Nucleosynthesis: We detect light elements like helium and deuterium in the Universe, matching predictions from early Universe nuclear reactions.*

b) Recombination (≈380,000 years later): The Cosmic Microwave Background (CMB) is the afterglow of this event, when the Universe became transparent.

c) Galaxy Formation: We observe galaxies at different ages (redshifts), showing how structures evolved over billions of years.

3) Can you summarize how experiments are searching for CP violation and mass ordering in neutrino oscillations and how to solve the degeneracies between these two parameters?

In Long Baseline experimets we can search for CP violation and mass ordering by comparing the appearance probability of electron neutrinos and electron anti-neutrinos. The appearance probability depends on two unknown parameters, the CP violation phase and the mass ordering.The degeneracy can be solved by going to higher energies (and hence longer baseline to keep a constant L/E) where the matter effects are larger and allow to disentangle the two solutions. Another option is to use information from experiments that are only sensitive to mass ordering, as for example JUNO and ORCA.

4) What do we gain using multi-messenger approach and you cite three of them? What is the difference between leptonic and hadronic processes in gamma-ray production, and why are neutrinos important to distinguish them? How is this related to cosmic rays?

Each messenger is associated with different physical processes and can escape from regions opaque to others. Multiple signatures/detection are needed to confirm unambiguously the source of violent events in the universe.

Cosmic rays, neutrinos, photons, gravitational waves

Leptonic processes involve high-energy electrons producing gamma rays via inverse Compton scattering or bremsstrahlung, without neutrino emission. Hadronic processes involve high-energy protons (cosmic rays) interacting with gas or photons, producing pions:

Neutral pions decay into gamma rays.

Charged pions decay into neutrinos.

Detecting neutrinos confirms a hadronic origin and proves that the source is accelerating cosmic rays, making them essential messengers in identifying cosmic-ray sources.