Exercise to the Lecture Astroparticle Physics
KIT, Wintersemester 2022/23

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Lectures	Thur. 11:30 + Wed 14:00 (every 14 days), Phys-HS Nr. 3
Exercises	Wed 14:00 (alternating with lecture), Phys-HS Nr. 3
ILIAS	`https://ilias.studium.kit.edu/goto.php?target=crs_1902412&client_id=produktiv`

Information about the exercise

- Wed 14:00 - 15:30, Phys-HS Nr. 3
- 7 Dates: 02.11., 16.11., 30.11, 14.12., 11.01., 25.01., 08.02.
- Criteria for exercise ECTS
  - Attendance in the exercise
  - Presentation of a solution to at least one (sub-)problem on the board
  - Solution of at least 60 % of the exercises of each block (two blocks: Sheet 1-3, and 4-7)
- Handout of the sheets will be each Thursday the week before the exercise *only on Ilias*.
  Please sign up here:
  `https://ilias.studium.kit.edu/goto.php?target=crs_1902412&client_id=produktiv`
- Contact: `anton.huber@kit.edu`, `neven.kovac@kit.edu`, `hiu-sze.wu@kit.edu`

Sheet 1 – Due 02.11.2022

1) LHC vs. the Universe

Cosmic accelerators such as active galactic nuclei (AGN) have the ability to accelerate particles to energies of up to 10^{20} eV = 100 EeV. The Large Hadron Collider in Geneva is the most powerful human-made particle accelerator and is able to reach proton energies of $7 \cdot 10^{12}$ eV = 7 TeV.
In the lecture *modern experimental physics III - particles and hadrons* (assuming you studied at KIT) you learned how to calculate the invariant mass (aka. center of mass energy) $\sqrt{s}$ for different accelerating processes.

(a) Derive the invariant mass for two cases: i) for a collider (both particles have the same mass) and ii) for a fixed-target-experiment (different masses). *Hint:* use the relativistic energy and momentum conservation (invariance of the quadratic four-momentum). In order to check the plausibility of your derivation, calculate the invariant mass of two colliding protons at LHC and check the literature if your answer is correct.

(b) Calculate the invariant mass of a cosmic proton with an energy of $E = 10^{19}$ eV that collides with a resting proton in the earth's atmosphere. How much energy would a cosmic proton require to reach the same invariant mass of 14 TeV as the LHC?

(c) Name one cosmic process (other than AGNs) that could cause such high energetic protons and one terrestrial experiment that is able to detect them. Describe both roughly in a couple of sentences.

2) Proton-Photon-Scattering

The cosmic microwave background (CMB) radiation is an isotropic, electro magnetic radiation that is present in the entire Universe. The corresponding photons were generated approximately 300.000 years after the Big Band during the recombination epoch. The intensity of the CMB photons shows a perfect black body spectrum due to the thermal equilibrium that was present before the recombination. At the time of the decoupling, the temperature of the CMB photons was 3000 K. As a consequence of the expansion of the Universe the temperature of the CMB reduced to it's today value of 3 K.
High energetic cosmic protons can scatter inelastically with CMB photons in the following process: $\gamma + \mathrm{p} \rightarrow \Delta^{+} \rightarrow \mathrm{X} + \mathrm{Y}$.

(a) Name two different allowed combinations for the particles X and Y. Pay attention to the different conservations that are given by the Standard Model of Particle Physics (SM).

(b) What is the minimum energy that is required for the process $\gamma + \mathrm{p} \rightarrow \Delta^{+}$?[1]

(c) This effect is the so-called *GZK-Cutoff*. Why does it (naturally) limit the maximal energy of cosmic protons? In order to answer this question, calculate the mean free path λ for a cross section of the pγ-process $\sigma_{\mathrm{p}\gamma} = 120\,\mu\mathrm{b}$. *Hint: Look up the mean photon density of the CMB.*

(d) In addition to protons there are other particles that act as cosmic rays, for example iron. How does the GZK-threshold energy changes for different elements?

(e) The Pierre-Auger-Observatory measured (a small number) of ultra high energy cosmic rays caused by primary particles with energies higher than the *GZK-Cutoff*. How is that possible?

[1] Due to simplifications in our calculation (e.g. a fixed photon energy), the value you get is probably higher than the typical values you find in literature. Don't be confused.