Elementary Particle Physics I

Exercise Set 1: Electron-Proton Scattering at HERA

Information on the lectures and exercises may be found on the web at

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http://www-zeus.physik.uni-bonn.de/~paul/tp.html
http://www-zeus.physik.uni-bonn.de/~critten/eti/ss2000/html/title.html
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1 Discussion Exercises

1.1 ep-Streuung an HERA

The storage-ring facility HERA (Hadron-Elektron-Ring-Anlage) at the DESY (Deutsches Elektronen-SYnchrotron) in Hamburg, which has a circumference of 6336 m, brings electrons or positrons of energy $E_{\mathrm{e}} = 27.5$ GeV to collision with protons of energy $E_{\mathrm{p}} = 820$ GeV. One of the primary goals of this research is to study the internal structure of the proton. Calculate the momenta of the beam particles and determine the accuracy of the approximation $E = |\vec{p}|$.

The proton beam current is about 160 mA. What is the total energy stored in the beam? Calculate the speed of of a truck weighing 7500 kg which carries the same amount of kinetic energy.

1.2 Schwerpunktsenergie

Since the electron and proton beam momenta are not equal, the Lorentz frame of the center-of-mass system is boosted in the laboratory Lorentz frame. Calculate this boost transformation and determine the center-of-mass energy E_{CM}^{ep}. Use the flight direction of the proton beam to define the z-axis. Give a simple interpretation of this center-of-mass energy.
Reminder:

$$\begin{pmatrix} E^* \\ p_x^* \\ p_y^* \\ p_z^* \end{pmatrix} = \begin{pmatrix} \gamma & 0 & 0 & -\gamma\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\gamma\beta & 0 & 0 & \gamma \end{pmatrix} \begin{pmatrix} E^{lab} \\ p_x^{lab} \\ p_y^{lab} \\ p_z^{lab} \end{pmatrix} \tag{1}$$

with $\gamma = \frac{1}{\sqrt{1-\beta^2}}$.

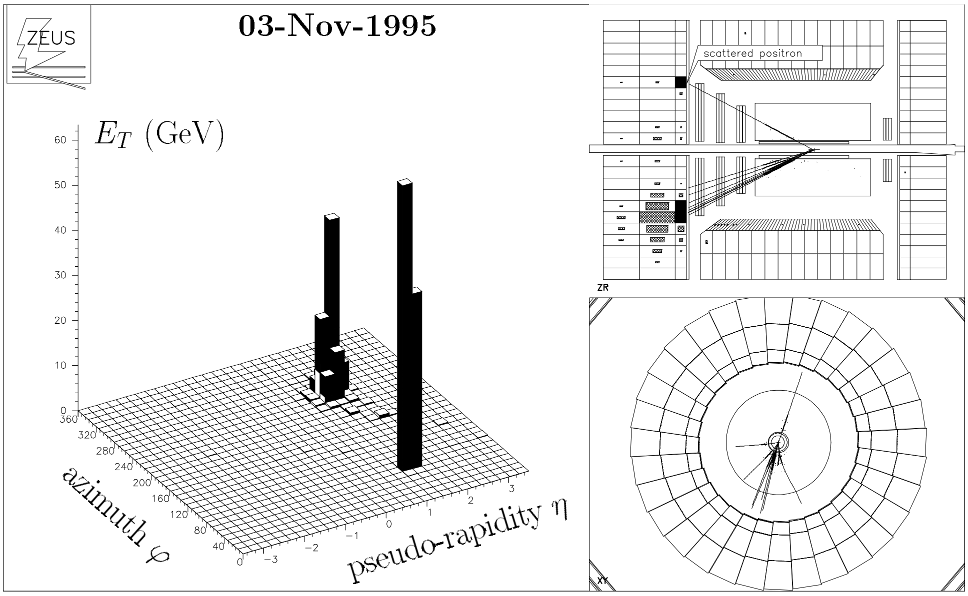

Abbildung 1: A scattering event in the ZEUS detector. The protons enter the detector from the right and interact with the positrons at the point where the observed final-state charged-particle trajectories originate. In this particular example, the electron energy was measure to be $E_{e'} = 220$ GeV, scattered through an angle of $\theta_{e'} = 27.8°$. The energy of the jet was measured to be $E_{Jet} = 235$ GeV.

1.3 Discussion of a positron-proton scattering event

The positron-proton collisions at HERA are recorded by the large, multi-purpose detectors H1 and ZEUS. Figure 1 shows an example of such an *ep* scattering event. Which detector components are necessary for the investigation of the final state and what conclusions can one draw concerning this event.

Describe the observed final state. Would you interpret the energy depositions in the calorimeter shown in the lower half of the picture as resulting from the parts of the proton which did not participate in the hard scattering subprocess?

We have now known for about thirty years that the proton is a composite particle made up of electrically charged quarks and electrically neutral gluons. Sketch the above scattering process as the scattering of an electron on a quark.

1.4 The Variable x

Let's define the variable x to represent the fraction of the proton momentum carried by the interacting constituent quark. What relationship does the *ep* center-of-mass energy bear to that of the *eq* system? Estimate the value of x exhibited in this event by using the observed energies of the final-state positron and of the jet. Identify some sources of differences between the value thus calculated and the actual momentum fraction carried by the quark.

Under the assumption of energy and momentum conservation, one can also calculate x using the energy and scattering angle of the electron. Alternatively, one can also use the angle of the electron and the angle of the jet. Give some of the advantages and disadvantages of these reconstruction methods.

1.5 Resolving Power

The resolving power Δx in such a scattering process at HERA may be calculated using the Heisenberg uncertainty relation:

$$\Delta x \approx \frac{\hbar}{\Delta p} = \frac{1}{\Delta p}. \tag{2}$$

What value of Δp should be used here? Convince yourself that Δx is a Lorentz-boost-invariant quantity. What is the maximum resolving power which can be obtained for HERA kinematics?

1.6 Allowed/Forbidden Processes

Of the following processes, which are kinematically or dynamically forbidden? In the case the the process is dynamically forbidden, which quantum number conservation laws are violated? For the processes which are allowed, which of the four fundamental forces of nature mediate the reaction?

1. $p + \overline{p} \to \pi^+ + \pi^0$
2. $e^+ + e^- \to \mu^- + \tau^+$
3. $\Sigma^0 \to \Lambda + \pi^0$
4. $\Sigma^- \to n + \pi^-$
5. $e^+ + e^- \to \mu^+ + \mu^-$
6. $\mu^- \to e^- + \overline{\nu}_e$
7. $\Delta^+ \to p + \pi^0$
8. $\overline{\nu}_e + p \to n + e^+$
9. $e^- + p \to \nu_e + \pi^0$
10. $p + p \to \Sigma^+ + n + K^0 + \pi^+ + \pi^0$
11. $p \to e^+ + \gamma$

2 Homework Exercises

2.1 Discussion Exercises 1.1 - 1.5 (5 Punkte)

Solve the exercises 1.1 - 1.5, which were discussed during the exercise session.

2.2 Allowed/Forbidden Processes (5 Punkte)

As in the discussion exercise.

1. $p + p \to p + p + p + \overline{p}$
2. $n + n \to \pi^+ + \pi^- + \pi^0$
3. $\pi^+ + n \to \pi^- + p$
4. $K^- \to \pi^- + \pi^0$
5. $\Sigma^+ + n \to \Sigma^- + p$
6. $\Sigma^0 \to \Lambda + \gamma$
7. $\Xi^- \to \Lambda + \pi^-$
8. $\Xi^0 \to p + \pi^-$
9. $\pi^- + p \to \Lambda + K^0$
10. $\pi^0 \to \gamma + \gamma$
11. $\Sigma^- \to n + e^- + \overline{\nu}_e$