Exercise – 7 : 4-Vector notation

a) Start with the expression for a Lorentz transformation along the x^1 axis. Write down the *inverse* transformation (i.e. express (x^0, x^1) in $(x^{0\prime}, x^{1\prime})$)

b) Use the chain rule to express the derivatives $\partial/\partial x^{0\prime}$ and $\partial/\partial x^{1\prime}$ in $\partial/\partial x^0$ and $\partial/\partial x^1$

c) Use the result to show that $(\partial/\partial x^0, -\partial/\partial x^1)$ transforms in the same way as (x^0, x^1)

d) In other words the derivative four-vectors transform inversely to the coordinate four-vectors:

$\partial^\mu = \left(\frac{1}{c}\frac{\partial}{\partial t}, -\vec{\nabla}\right)$ and $\partial_\mu = \left(\frac{1}{c}\frac{\partial}{\partial t}, \vec{\nabla}\right)$

Note the difference w.r.t. the minus sign!

Exercise – 8: Kinematics: Z-boson production

- The Z-boson particle is a carrier of the weak force. It has a mass of 91.1 GeV. It can be produced experimentally by annihilation of an electron and a positron. The mass of an electron, as well as that of a positron, is 0.511 MeV.
  a) Draw the Feynman interaction diagram for this process.
  b) Assume that an electron and a positron are accelerated in opposite directions and collide head-on to produce a Z-boson in the lab frame. Calculate the minimal beam energy required for the electron and the positron in order to produce a Z-boson.
  c) Assume that a beam of positron particles is shot on a target containing electrons. Calculate the beam energy required for the positron beam in order to produce Z-bosons.
  d) This experiment was carried out in the 1990's. Which method do you think was used? Why?

“Quick” Exercises 9, 10, 11

9. [Griffiths exercise 2.2] “Crossing lightsabers”
    - Draw the lowest-order Feynman diagram representing Delbruck scattering: $\gamma + \gamma \rightarrow \gamma + \gamma$
    - This has no classical analogue. Explain why.
10. [Griffiths exercise 2.4]
    - Determine the invariant mass of the virtual photon in each of the lowest-order Feynman diagrams for Bhabha scattering
11. [Griffiths exercise 2.7]
    - Examine the processes in Griffiths exercise 2.7 and state which one is possible or impossible, and why / with which interaction.

    Hint: draw the corresponding Feynman diagrams if needed.

Exercise – 12: Penguins

- One of the flagship analyses of the LHCb experiment is the decay $B_s^0 \rightarrow J/\psi\phi$.
  It is used for the analysis of CP violation.
  - Draw the lowest order (tree) Feynman diagram of the process. $(B_s^0 = (\bar{b}s), J/\psi = (c\bar{c}), \phi = (s\ \bar{s}))$. Hint: it consists of an 'internal' $W \rightarrow cs$ transition.
    Why would this diagram be called 'colour suppressed'?
  - I addition to the tree diagram, there is a famous 'loop' contribution, called a *penguin* diagram. Here, the b transforms into an s due to the emission and re-absorption of a W and a quark, while this quark radiates off a gluon that turns into a $c\bar{c}$. Draw this diagram. Try to twist and turn the diagram such that it may look as a penguin?
  - Ask for the funny story behind this name
  - Which flavour can this internal quark have? Which option has the largest probability?
  - The precision of LHCb is such that these penguin contributions are becoming a nuisance. Based in the vertices and CKM elements, can you guess how much weaker the penguin diagram is with respect to the tree?