Lecture : Introduction to Elementary Particle Physics
DESY Summer Student Program
Joachim Meyer DESY

TEST : Did I learn the essentials ?

With Answers !

1. Leptons of 2 GeV total energy scatter on protons at rest. How big is the invariant mass of the lepton-proton system in case the lepton is a a) neutrino, b) electron, c) τ - lepton
   answer : $M^2 = (P_l + P_p)^2 = M_l^2 + M_p^2 + 2E_l M_p$. *For* ν *und e the term* M_l^2 *can be neglected.*

2. What was the crucial experiment to demonstrate that one has to differentiate between ν_e and ν_μ ?
   answer: First neutrino experiment at accelerators (Brookhaven, 1962) : Scatter neutrinos from muonic pion decays ($\pi \to \mu\nu$) *on matter. Only the processes* $\nu N \to \mu X$ *were observed , not the processes* $\nu N \to eX$.

3. What conservation laws are violated in weak interactions compared to electromagnetic interactions ?
   answer: Parity, C- parity and CP-invariance. In charged current weak interactions (CC) also the flavors (strangeness, charm, bottom, top).

4. How does the π^+ decay ? Why does it decay so rarely into $\pi^+ \to e^+\nu_e$?
   answer :with 99.99% in $\pi^+ \to \mu^+\nu$. *Due to angular momentum conservation the charged lepton has to be produced with the wrong helicity. This is suppressed by the factor* $(1 - \beta_l)$.

5. How do the charged lepton spectra differ in the decays of π^+ and μ^+ ?
   answer: $\pi^+ \to \mu^+\nu$ *is a two body decay : sharp energy.* $\mu^+ \to e^+\nu_e\overline{\nu_\mu}$ *is a three body decay with a continuum* β*-decay spectrum*

6. Which data show that quarks come in 3 degrees of freedom (color) ?
   answer: The decay rates (leptonically/hadronically) of τ *und W demand a factor 3*

7. How does the W decay ? Quantitative relation between the leptonic and hadronic decay channels.
   Antwort: W decays in $e\nu_e, \mu\nu_\mu, \tau\nu_\tau$, *ud und cs. It thus follows that the*

relation $e : \mu : \tau :$ hadrons is 1: 1: 1: 6 (Lepton universality and color).

8. What does *lepton universality* mean ? Examples.
   answer:Couplings to the leptons of the three generations are equal. E.g. the three leptonic W decays or the two leptonic τ decays are of equal strength.

9. How do we know that there are just 3 generations of fundamental fermions ?
   answer: The width of the Z depends on the kinematically possible decay channels. Assuming that $m_{\nu_4} < m_Z/2$ a decay $Z \to \nu_4\overline{\nu_4}$ would give a further contribution to the width. Experimental measurements of the total Z - widths do not allow such a contribution.

10. What limits the maximal reachable energy of proton accelerators and that of electron accelerators ?
    answer: For a given radius the energy E_p is limited by the achievable strength of the magnetic dipole fields, whereas E_e is limited by the energy losses due to synchrotron radiation.

11. What distance (in vacuum) does a π^+ , π^-, π^0 of 140 GeV reach on average before decaying ?
    answer: $x = \gamma c\tau$, $\gamma = E/m = 1000$. $x_{\pi^\pm} = 7.8Km, x_{\pi^0} = 25\mu m$

12. How can one experimentally distinguish between $\gamma, e^+, \pi^+, \mu^+, \tau^+$?
    answer : γ*: em shower, no track .* e^+ *: em shower with track.*
    π^+ *: hadronic shower with track,* μ^+ *: no shower, penetrating track.*
    τ^+ *: very short track, decay, secondary vertex*

13. What was the experimental evidence for 'strange quarks' ?
    answer: V-particles, produced in pairs by strong interaction, but weakly decaying (long lifetime). The neutral strange particles (Λ, K_0) decay in pairs of charged particles.

14. What was the experimental evidence for 'charmed quarks' ?
    answer: Discovery of the $J/\Psi = c\overline{c}$. Massive strongly decaying new particle with very long lifetime, since decay into charmed mesons kinematically impossible.

15. What was the experimental evidence for 'top quarks' ?
    answer: Produced in proton-antiproton collisions at 1.8 TeV. Top decays to W and b-quark. Signature of this very rare processes : Leptonic W-decay and secondary vertices from b-decays.

16. What was the experimental evidence for τ ?
answer : Observation of $e^+e^- \rightarrow e^+\mu^-$ events with unbalanced kinematics. . Explained by $e^+e^- \rightarrow \tau^+\tau^-$ with e and μ decays of the τ

17. How does the τ^- decay ?
answer : $\tau^- \rightarrow e^-\overline{\nu_e}\nu_\tau$, $\tau^- \rightarrow \mu^-\overline{\nu_\mu}\nu_\tau$, $\tau^- \rightarrow$ hadrons ν_τ

18. What is the quark composition of the Δ^{++}? How does it decay ? Via which interaction ? What life time ?
answer : $\Delta^{++} = uuu \rightarrow p\pi^+$, Strong interaction, $\tau = 10^{-25} sec$

19. What is the quark composition of the lightest strange Baryon ? How does it decay ? Via which interaction ? What life time ?
answer: $\Lambda = uds \rightarrow N\pi$. Weak interaction , $\tau = 2.6 * 10^{-10} sec$

20. What type of neutrino is dominantly produced in a) the sun, b) at a reactor, c) at accelerators ?
answer: Sun $pp \rightarrow de^+\nu_e$. Reactor Beta decay $n \rightarrow pe^-\overline{\nu_e}$. Accelerators $\pi \rightarrow \mu\nu_\mu$

21. How can one produce a pure ν_μ beam with only minimal Anti-ν_μ admixture ?
answer : Sign selection of the pions. π^+ produce ν_μ, π^- produce $\overline{\nu_\mu}$

22. How did one discover the existence of weak neutral currents ?
answer: $\nu_\mu e^- \rightarrow \nu_\mu e^-$ und $\nu_\mu N \rightarrow \nu_\mu X$.

23. Give some examples for parity violation in weak interactions.
answer : Neutrinos only lefthanded, antineutrinos only righthanded. Wu-Experiment (Decay of polarised Co^{60}, angular asymmetry of decay electrons), pion decay, muon decay.

24. Under which conditions are neutral particles their own antiparticles ? Give examples and counter examples.
answer : In case all 'charge like' quantum numbers are zero. (γ, π^0). Not Neutron, K^0.

25. The J/Ψ particle ('HEP-November revolution 1974') was found at a mass of 3.1 GeV at the SPEAR e^+e^- storage ring. At slightly higher masses one discovered the Ψ' and Ψ'' particles. Why is the width of the Ψ'' so much larger (factor 100) than that of the Ψ' ?
answer: The Ψ'' can decay into charmed mesons $\Psi'' \rightarrow D^+D^-$ (dominating strong decay). For J/Ψ und Ψ' this mode is kinematically forbidden.

26. How is it possible to separate in lepton-proton scattering experiments the scattering on quarks from the scattering on antiquarks ?
answer : Via Charged Current Neutrino scattering. Quarks interact lefthanded and antiquarks righthanded.

27. How is it possible to separate in lepton-proton scattering experiments the scattering on u-quarks from the scattering on d-quarks ?
answer : Via Charged Current Neutrino scattering :
$\nu_\mu d \to \mu^- u$, $\overline{\nu_\mu} u \to \mu^+ d$

28. Which data prove that the quarks have charges 1/3 and 2/3 ?
answer : Compare Elektron-Proton scattering with CC-Neutrino-Proton-scattering. Photons couple to charge quadratic (4/9 , 1/9) . W couple universell (1) to u and d quarks.

29. Draw all (relevant) Feynman diagrams for the following leptonic reactions
$e^+e^- \to e^+e^-$ *answer : spacelike and timelike diagram*
$e^+e^- \to \tau^+\tau^-$ *answer : only timelike (annihilation) diagram*
$\nu_\mu e^- \to \nu_\mu e^-$ *answer: Only NC diagram (Z-exchange)*
$\nu_e e^- \to \nu_e e^-$ *answer : NC (Z-exchange) und CC (W-exchange) diagram*

30. Why does the electron have a mass of 0.5109989 MeV ?
answer : In case you know the answer, please tell me.