Particle Physics FYS4560

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Project 1

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Item 1 – SM and beyond: Allowed, forbidden and discovery processes

1. **State whether the following processes are allowed or not.**
   1. Classify them according to the underlying interaction and draw the corresponding Feynman graphs.
   2. For each particle decay, indicate the lifetime and the branching ratio.
   3. What conservation laws, invariance principles, or other mechanisms account for the suppressing or forbidding of some processes.
   4. Why are processes 3, 4, 8, 10, 11, 14 and 18 of particular importance? Justify and tell more.

1. $e^+e^- \to q\bar{q}gg$	2. $gg \to e^+e^-$	3. $e^+e^- \to \tilde{l}^+\tilde{l}^-$
4. $p\bar{p} \to l^+l^-X$	5. $\tau^+ \to \mu^+\nu_e\bar{\nu}_\tau$	6. $K^-p \to \Omega^-K^+K^0$
7. $\nu_e e^- \to \nu_e e^-\gamma$	8. $pp \to l^+l^-l^+l^-X$	9. $e^+e^- \to HH\gamma$
10. $q\bar{q} \to W^+W^-Z$	11. $e^+e^- \to ZZZ$	12. $e^+e^- \to H \to gg$
13. $e^+e^- \to \nu\bar{\nu}\gamma\gamma$	14. $gg \to t\bar{t}HH$	15. $e^+e^- \to \Upsilon(3s) \to B^0\bar{B}^0$
16. $q\bar{q} \to gge^+e^-$	17. $gg \to H \to Z\gamma$	18. $ep \to J/\psi + X$
19. $D^0 \leftrightarrow \bar{D}^0$	20. $e^+e^- \to Z^0t\bar{t}$	

Item 2 – Let us see with the LHC

1. **The two peculiar event displays below (Figure 1 and Figure 2) stem both from Lead-Lead heavy ion collisions recorded by the ATLAS detector at the LHC.**
    1. Briefly describe the two events with emphasis on their peculiarities.
    2. *Light-by-light scattering*: Write lowest-order possible Feynman diagrams of the following two processes
    3. Compare the properties of photons and of gluons. Infer the main differences between the electromagnetic (QED) and strong (QCD) coupling constants a_{EM} and a_S. Describe asymptotic freedom and colour confinement.
    4. *Jet quenching*: What is quark-gluon plasma and what are the two necessary conditions to produce it experimentally? Discuss one experimental signature of such a new state of matter that includes jets.

Pb-pb collision events recorded by ATLAS

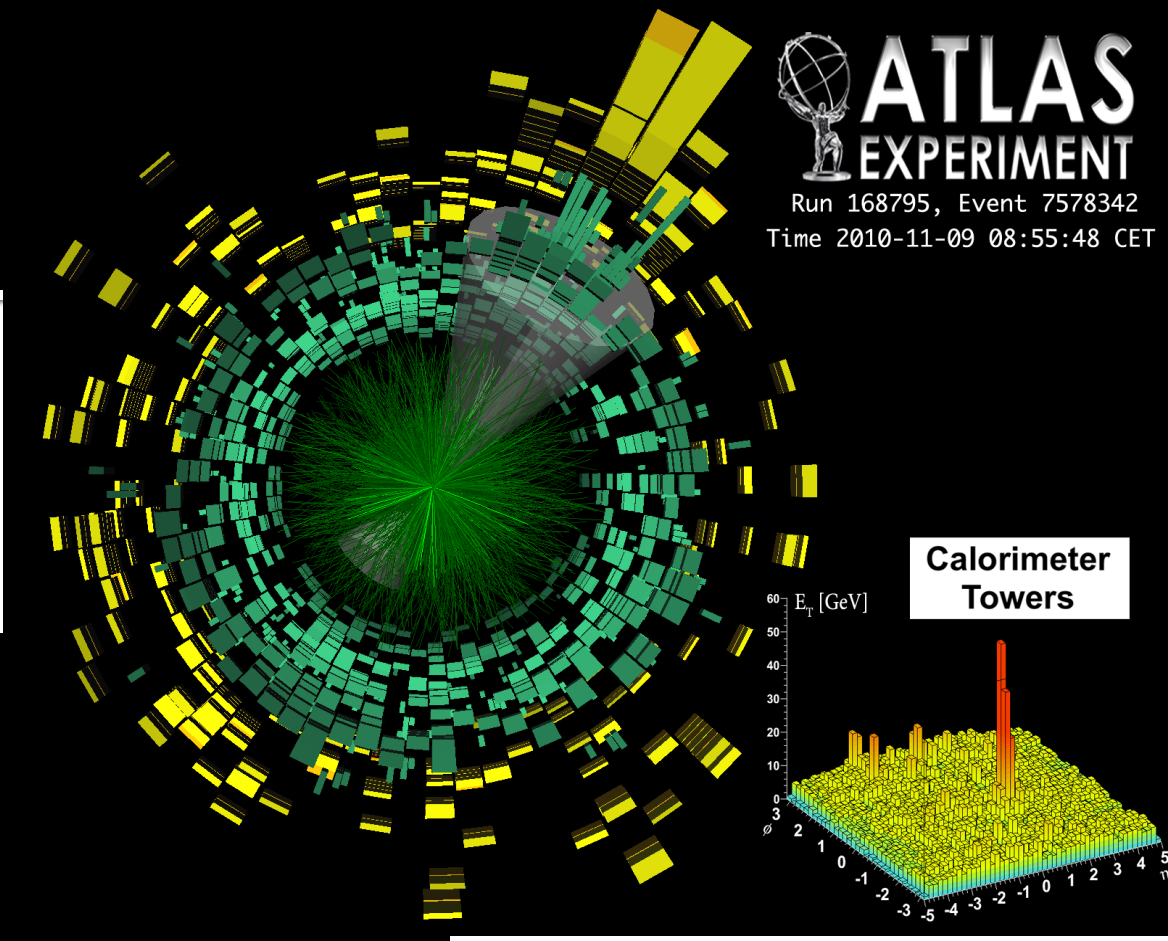


Figure 1

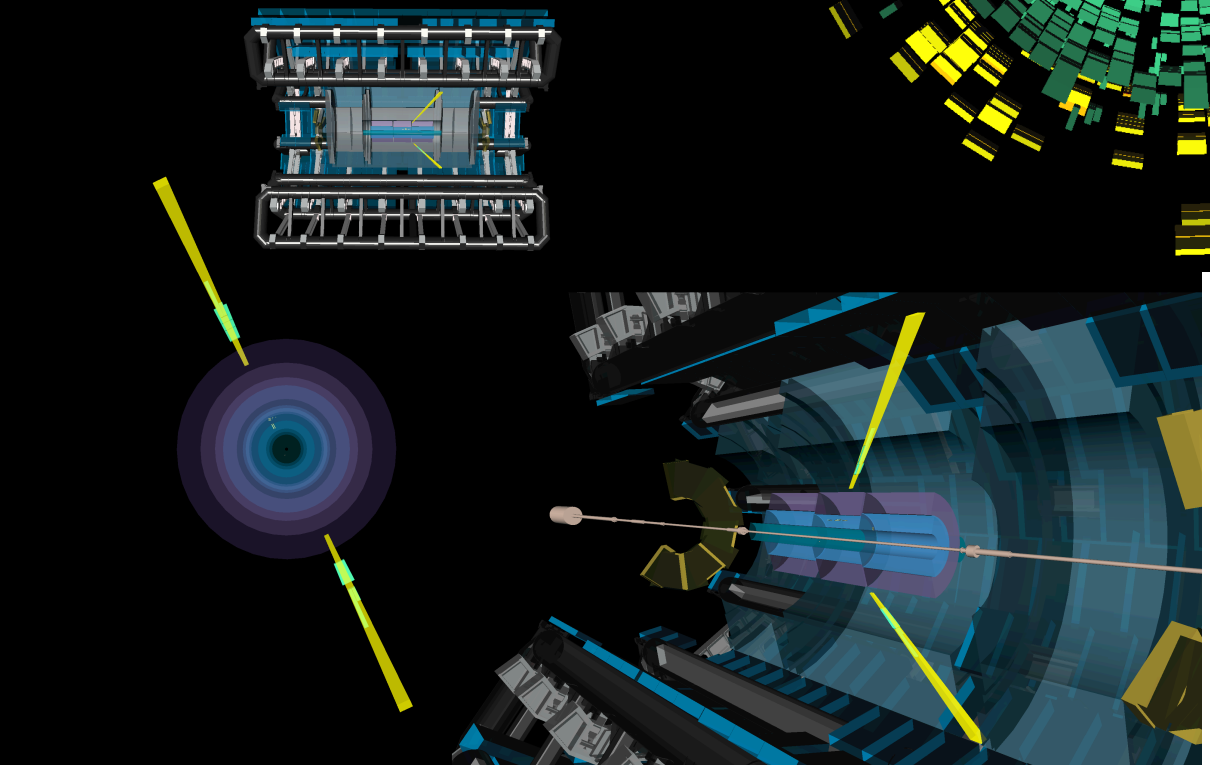


Figure 2

Item 3 – New physics

1. **New physics**
   1. Which of the following reactions are allowed in or are beyond the Standard Model (SM) and why?

$$\left.\begin{aligned} p &\rightarrow \pi^0 + e^+ \\ p &\rightarrow \pi^+ + \bar{\nu}_e \end{aligned}\right\} \quad (1)$$

$$e^+e^- \rightarrow \tilde{l}^+\tilde{l}^- \rightarrow l^+\chi^0 l^-\chi^0 \quad (2)$$

$$nn \rightarrow pp + e^-e^-\bar{\upsilon}_e\bar{\upsilon}_e \quad (3)$$

$$nn \rightarrow pp + e^-e^- \quad (4)$$

   2. Discuss possible new physics scenarios that would predict the beyond-SM processes.
   3. Write down the Feynman diagrams for each of the processes above. What would be the corresponding experimental signatures?

Item 4 – CKM Mass matrix, Top and bottom quarks

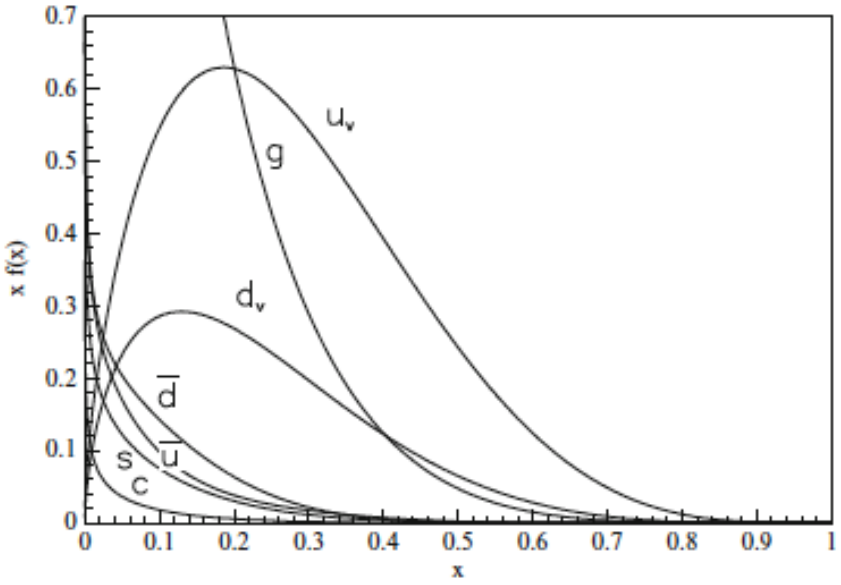
1. Start by introducing the CKM matrix and the role of the W boson
   1. Which of the matrix elements are related to B-Bbar mixings
   2. How are these measured experimentally.
2. Consider B-meson decays
   1. Draw the Feynman diagrams of the following decays

$$B^- \to D^0 K^{*-} \quad ; \quad B^- \to D^0 \rho^-$$

   2. Estimate the ratios of the two decay widths $\dfrac{\Gamma\left(B^- \to D^0 K^{*-}\right)}{\Gamma\left(B^- \to D^0 \rho^-\right)}$
3. Discuss top-quark production in electron-positron, proton-proton and proton-antiproton collisions
   1. Consider single top and top-anti-top and give the corresponding Feynman graphs?
   2. How does the top-quark decay and why?

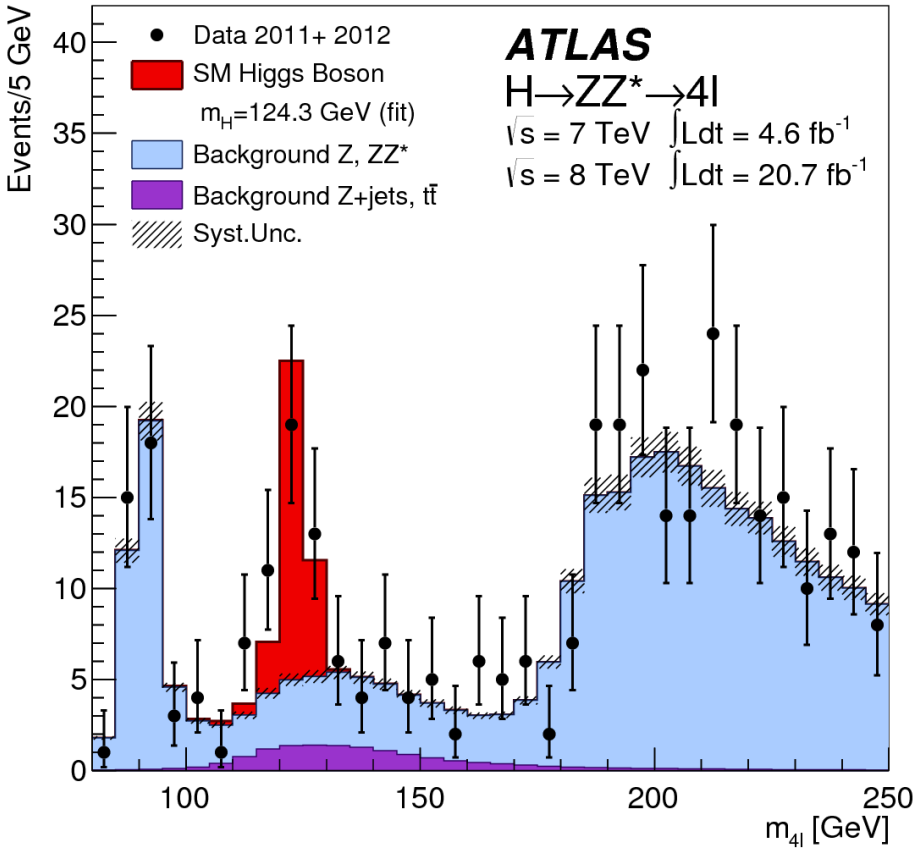
Item 5 – the Higgs boson

1. How can the ***Higgs boson*** be produced in e^+e^- and in proton-proton collisions? Give two main Feynman diagrams for each case.
2. Assuming a Higgs boson of mass 125 GeV is produced through the Higgs-strahlung process,
    1. what is the centre of mass energy threshold for creating both the Z and Higgs bosons at rest?
    2. What would be (approximately) the threshold in the case of proton-antiproton collisions? Make simple assumptions on the parton distribution functions in the proton/antiproton after commenting on the Figure



Item 5 – Higgs boson discovery

1. ***Higgs discovery***
    1. Explain how the ATLAS and CMS experiments at the LHC discovered the Higgs boson in its decays to pairs of gauge bosons (gg and ZZ*).
    2. Study the distribution of the invariant mass of 4 leptons measured by ATLAS in the Figure.
    3. Which processes contribute to the Higgs signal and to the Standard Model backgrounds? Draw Feynman diagrams. Discuss in particular the Z and ZZ* blue contributions.



Item 6 – Gauge theories

1. Discuss the classification of particles in the SM
    1. How are the SM symmetries behind related to conservation laws.
    2. Discuss the classification of particles in Grand Unified Theories
1. Define the gauge principle and apply it to Quantum Chromo-Dynamics, QCD
    1. Go through all steps in detail – as you have done for QED
    2. Derive the QCD Lagrangian
2. Make a detailed comparison of QCD and QED *(no need to repeat what was in Item 1 above)*
    1. Conceptually
    2. Experimentally
3. Deduce the Electroweak Lagrangian based on QED and QCD formulation
    1. Ignore the gauge boson masses
    2. Where are the complications?