Problem Set for Hadron Collider Physics 2015
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Problem Set 7

**Your solutions have to be handed in by 10:10 am on Tuesday, June 30$^{th}$ 2015. Please drop them into the mailbox number 1 on the ground floor of the Gustav-Mie building!**

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1. **Search for the Higgs boson in the di-photon decay channel**

   The process $pp \to H \to \gamma\gamma$ was very import for the discovery of the Higgs boson at the LHC.

   Under the usual location

   `http://portal.uni-freiburg.de/jakobs/Lehre/ss-15/hadron-collider`,

   you can find the starting analysis scripts together with two root files. The first one `ggFHgamgam.root` contains simulated events of Higgs bosons produced in gluon fusion at $\sqrt{s} = 8\,\text{TeV}$. The file `gamgam.root` contains events of the di-photon continuum, also at $\sqrt{s} = 8\,\text{TeV}$, which we consider as a background process.

   (a) Select events containing at least 2 photons with $|\eta| < 2.37$. The leading photon, i.e., the photon with the highest transverse momentum in the event, is required to have a $p_T > 40\,\text{GeV}$, the sub-leading photon to have a $p_T > 30\,\text{GeV}$. Plot the distributions of the transverse momenta of the leading and sub-leading photon for signal and background. **[2 points]**

   (b) Plot the invariant mass of the di-photon pair $m_{\gamma\gamma}$. Normalize both histograms to the number of expected events and stack them on top of each other.

   Assume an integrated luminosity of $L = 20\,\text{fb}^{-1}$. The signal cross section is given by $\sigma(pp \to H) = 19.2\,\text{pb}$ and the branching ratio of the Higgs boson to two photons is $BR(H \to \gamma\gamma) = 0.0023$.

   Getting the correct cross section of the background process $pp \to \gamma\gamma$ is a bit more involved. For simplicity, just assume that the provided sample has $\sigma(pp \to \gamma\gamma) = 9\,\text{pb}$. **[2 points]**

   (c) Choose a mass range of the $m_{\gamma\gamma}$ distribution and compute the ratio of expected signal events $s$ to the number of expected background events $b$.

   To quantify the significance of the signal you can use the *Asimov significance* $Z_0^A$. It is given by the following formula:

   $$Z_0^A = \sqrt{2 \cdot [(s+b)\,\ln(1+s/b) - s]}.$$

   Try to optimize the mass range with respect to the significance. What is the best Asimov significance that you achieve and for which region of $m_{\gamma\gamma}$? **[3 points]**

   Please hand in the resulting distributions together with appropriate explanations.

2. **Top-quark decay**

The muon decay width $\Gamma_\mu$ can be very roughly estimated using dimensional arguments. The Feynman diagram involves two weak vertices, which means the width will be proportional to $G_\mathrm{F}^2$ ($G_\mathrm{F}$ being the Fermi constant).

(a) Based ONLY on dimensional arguments, write down an expression for $\Gamma_\mu$ as a function of $G_\mathrm{F}$ and the muon mass $m_\mu$. **[2 points]**

Note that the estimate is quite wrong, as in the exact calculation there is a large, dimensionless factor $1/192\pi^3$ which is involved in the expression.

With similar arguments, one can compute the width $\Gamma_t$ of a top quark decaying into $Wb$.

(b) Why is the $t \to Wb$ decay in practice the only decay channel of the top quark? **[1 point]**

(c) Based ONLY on dimensional arguments, write down an expression for $\Gamma_t$ as a function of $G_\mathrm{F}$ and the top-quark mass $m_t$. **[2 points]**

(d) The result of the exact LO calculation is that a factor $1/8\pi\sqrt{2}$ has to multiply the expression obtained at the previous point. Write down the numerical estimate for $\Gamma_t$. **[1 point]**