Higgs-Phenomenology

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Exercise Sheet 3

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Exercise 3: Tau Decays and Collinear Approximation

With a branching fraction of about 6%, the decay of the Higgs boson into τ leptons is an important channel at the LHC. The τ will then further decay. In this exercise we consider only the leptonic decay channels, where a τ decays into an electron or muon plus the corresponding neutrinos, so that in total the decay chain might look like

$$H \to \tau^+\tau^- \to e^+\nu_e\bar{\nu}_\tau\mu^-\bar{\nu}_\mu\nu_\tau \,.$$

The neutrinos pose a challenge for reconstructing the invariant mass of the τ pair, which should peak at the Higgs boson mass. They escape the detector, and only the vectorial sum of their transverse components can be reconstructed as missing transverse momentum

$$\vec{p}_{T,\text{miss}} = \vec{p}_{T,\nu_e} + \vec{p}_{T,\bar{\nu}_\tau} + \vec{p}_{T,\bar{\nu}_\mu} + \vec{p}_{T,\nu_\tau} \,.$$

Show that the invariant mass $m_{\tau\tau}$ can still be reconstructed from the measured quantities in the collinear approximation. These are the four-momenta of the positron and muon, which we take as massless, as well as $\vec{p}_{T,\text{miss}}$. The collinear approximation assumes that the lepton goes into the same direction as its τ mother particle,

$$\vec{p}_{e^+} = x_1\vec{p}_{\tau^+} \qquad \vec{p}_{\mu^-} = x_2\vec{p}_{\tau^-} \,, \qquad x_{1,2} \in [0;1] \,.$$

Use momentum conservation and find two equations to determine x_1 and x_2.

Exercise 4: Fat Jets

When the Higgs boson has a large transverse momentum, the resulting decay products, for example a pair of bottom quarks, will be fairly collinear. In a significant fraction of the events then their distance will be smaller than the jet clustering radius, and both get

combined into a single jet. Relevant observables are

$$\begin{aligned} &\text{rapidity} && y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right), \\ &R \text{ separation between two particles} && R = \sqrt{(\Delta y)^2 + (\Delta\varphi)^2}\,. \end{aligned}$$

Write a small program to test the approximation given in the lecture for some exemplary values:
If the minimal jet separation has the value $R_{jj} = \frac{3M_H}{p_{T,H}}$, then in about 75% of the events the R separation of the two bottom quarks is smaller, and they get combined into a single jet.
Start in the rest frame of the Higgs boson and generate an isotropic decay into two bottom quarks. Then transform into the lab frame, where the Higgs boson has transverse momentum $p_{T,H}$. Without loss of generality, you can assume that the Higgs boson goes into the x-direction. There, calculate the R separation of the two bottom quarks and compare with R_{jj}.

Exercise 5: Recoil Measurement

For electron-positron colliders, the energy of the incoming leptons is known precisely. This allows us to do the so-called recoil measurements. In ZH production, only the decay products of the Z boson are observed and hence the Z four-momentum fully measured. Show that with this information, the mass of the Higgs boson can be reconstructed. What is its value in terms of the known quantities?