DARK MATTER

Problem set 4: Higgs-portal dark matter

Jun.-Prof. Susanne Westhoff
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LHC bounds on invisible Higgs decays

Fig. 5 (right) where the 95%CL upper limits on the VBF production cross section times the invisible Higgs branching fraction, normalized to the SM VBF rate, is shown as a function of the mass $M_H$, assuming a SM Higgs–like state; the full $p_s = 8 \text{ TeV}$ has been used. The observed (expected) limit for $M_H = 125 \text{ GeV}$ is $B(H \rightarrow \text{inv}) = 0.63 (0.48)$ at 95%CL in VBF only; when combined with the $ZH$ channel, again at $p_s = 8 \text{ TeV}$, the limits become $B(H \rightarrow \text{inv}) = 0.55 (0.41)$.

A promising search for invisible decays is the monojet channel [57,221,222]. In the ggF mode, an additional jet can be emitted at NLO leading to $gg \rightarrow Hj$ final states and, because the QCD corrections are large, $(H+1j)$ is not considered small (<223–225). The NNLO corrections [226–229], besides significantly increasing the $H+0j$ and $H+1j$ rates, lead to $H+2j$ events that also occur in VBF and VH with $Vjj$. Hence, if the Higgs is coupled to invisible particles, it may recoil against hard QCD radiation, leading to monojets or dijets. Already in Ref. [57], it has been shown that the monojet signature carries a good potential to constrain the Higgs invisible decay branching ratio. In a model independent fashion, constraints can be placed on the process $R_{ggF} = \frac{(gg \rightarrow Hj)}{\sigma_{gg} \cdot B(H \rightarrow \text{inv})}$, even if the Higgs couplings to fermions and gauge bosons are not SM–like. $\Delta f, \Delta V = 1$.

Combined VBF-tag $Z(ll)H$-tag $V(qq')H$-tag $ggH$-tag

CMS

- Observed
- Median expected
- 68% expected
- 95% expected

$35.9 \text{ fb}^{-1} (13 \text{ TeV})$

95% CL upper limit on $\alpha \times B(H \rightarrow \text{inv})/\sigma_{SM}$

Combined VBF-tag Z(ll)H-tag V(qq')H-tag ggH-tag
LHC bounds on Higgs couplings

The total decay width of the Higgs boson, where all channels contribute, is then modified by the amount (which explicitly gives the branching ratios for the various channels)

\[ H \rightarrow \gamma \rightarrow \gamma + 0.57 H \rightarrow t + 0.22 b + 0.2 W + 0.06 t + 0.0023 c + 0.0016 (Z) + 0.00022 \mu + 0.0001 s. \]

These couplings modifiers, as determined by ATLAS only, CMS only and by the combined results of the two collaborations are shown in the left–hand side of Fig. 3 for the RunI LHC. All channels in the production and in the decays have been included, using the expressions eqs. (25-27) for the various contributions and, hence, assuming the absence of additional non–standard particles in the loops. All couplings were left free with some minimal assumptions. The 1 and 2 intervals for the error bars are indicated. As can be seen, some couplings like \( \kappa_W \), \( \kappa_Z \) are measured with an accuracy of about 10% which is in line with the previous discussion (since the cross sections and decay signal strengths are proportional to \( \kappa^2 X \), their error is hence twice the one that affects the reduced couplings).

In the right–hand side of Fig. 3, negative 68% and 95% confidence level (CL) log–likelihood contours are displayed in the \((\kappa_f, \kappa_V)\) plane for the combined RunI ATLAS and CMS measurements in various channels and their combination (in black) with no assumption on the sign of the couplings. Two other quadrants, symmetric with respect to the point (0,0), are not shown. For the upper quadrant, the SM expectation falls in the middle of the combined measurement which sets strong constraints on \( |\kappa_f| \) and \( |\kappa_V| \).
Higgs decay branching ratios

At hadron colliders such as the LHC, the special mass value $M_H = 125 \, \text{GeV}$ allows to observe the SM Higgs particle in many redundant production channels and to detect it in a variety of decay modes [15–23, 203]. It is this mass value that enabled the very detailed studies of the Higgs properties, which have been performed by the ATLAS and CMS collaborations already in the first LHC run with $p_s = 7$ and $8 \, \text{TeV}$ center of mass energies [7]. The analytical elements that allow to describe the Higgs boson decays and production mechanisms at hadron colliders have been relegated to Appendices B1 and B2, respectively, and we simply summarize the main features here.

Considering first the decay modes, for $M_H = 125 \, \text{GeV}$, the Higgs mainly decays into $b\bar{b}$ pairs but the channels with $WW^* \rightarrow 4\ell$ and $ZZ^* \rightarrow 4\ell$ final states, before allowing the gauge bosons to decay leptonically ($\ell = e, \mu$), are also significant. The $H \rightarrow \tau^+\tau^-$ channel (as well as the $gg$ and $c\bar{c}$ decays that are not detectable at the LHC) is also of significance, while the clean loop induced $H \rightarrow W^-\gamma$ mode can be easily detected albeit its small rates. The very rare $H \rightarrow Z\mu^+\mu^-$ channels should be accessible at the LHC but only with a much larger data sample [185–187]. These features are illustrated in the left–hand side of Fig. 1 where the decay branching fractions of a SM–like Higgs are displayed for the mass range $M_H = 120–130 \, \text{GeV}$. For this purpose, we have used the program $HDECAY$ [204–206] which calculates the partial widths and the branching ratios of all Higgs decays (in the SM but also in some of its extensions like the 2HDM and the MSSM as will be seen later in this review) including all relevant higher order effects.
3.3 The Higgs Portal in $\ell + E_T + t\bar{t}$

Finally, we consider the sensitivity of searches for the Higgs Portal in the $t\bar{t} + E_T$ channel. This channel sets a promising limit on invisible Higgs decays at $p_s = 14$ TeV, suggesting it may potentially be interesting in future Higgs Portal searches at the LHC and beyond.

The dominant backgrounds in this channel are expected to be $t\bar{t} +$ jets and $W +$ jets. To improve statistics, we separately simulate semi-leptonic and di-leptonic decays for the $t\bar{t}$ background matched up to two additional jets, while we simulate leptonic $Wjj$ matched up to two additional jets. To extract the sensitivity in this channel, we first apply the following requirements:

- $n_{\text{jet}} \leq 4$\text{,}$\,\,|\eta_j| < 2$
- $E_T > 300$ GeV\text{(3.7)}
- Exactly one isolated $e^\pm/\mu^\pm$ with $P_{T} > 10$ GeV
- At least one $b$-tag among the leading four jets
- The transverse mass between the lepton and $E_T$ is constrained to $m_T > 200$ GeV
- $M_{W\ell > 200}$ GeV\text{(70)}

### 4 Results and Discussion

![Graph of 95% exclusion](image.png)

**Figure 6**: Left: 95% exclusion reach in all three channels at $p_s = 14$ TeV determined from $S/p_S + B = 1.96$, neglecting systematic errors. Right: 5 discovery reach in the VBF and monojet channels at $p_s = 14$ TeV determined from $S/p_B = 5$, again neglecting systematic errors.

We have performed a simple cut and count analysis following the cut flows for the searches outlined in Sections 3.1, 3.2, and 3.3. For $p_s = 14$ TeV we assume an integrated luminosity.
Literature
