FCC-ee: Detector constrains on Invisible width of the Higgs and and dark matter in Higgs portal models

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Outline

- prospects for $H \rightarrow inv$ discovery/constraint at FCC-ee
- repeat first the analysis done for TLEP
- recompute for FCC-ee luminosity proposal
- comparison of two detector Simulations
  - CMS and ILD using Delphes fast-simulation
- interpretation in the Higgs Portal model and compare with HL-LHC and future DM experiment
Motivations

- Constraining $H \rightarrow inv$ down 1% is very important
  - indirect constrains from fitting the others BR
    - Total Higgs width: needed to understand possible BSM decays in a model-independent way.
  - direct constraints
    - if Higgs of shell, limits on light DM ($m_{DM} < m_{h/2}$)

- New Physics (NP) is likely to be near the electroweak scale
  - co-responsible for generating it is a candidate to stabilize it
  - NP is likely to interact with the newly discovered h boson
    - higgs as Dark Matter (DM) Portal, where DM is supposed to carry no charges in the Standard Model gauge interactions
FCC-ee: Higgs factory

- FCC-ee at 240 GeV is very suitable for that!
  - FCC-ee 3rd run
    - $\sqrt{s} = 240$ GeV
    - $L = 3.5$ ab$^{-1}$/yr
    - $7.0 \cdot 10^5$ ZH events/yr
  - Reconstructed peak at $m_{\text{miss}} = m_H$ independent of $H$ decay mode!
  - Inclusive measurement of $Z$H production
    - Tagging events under the peak allows determination of individual BRs
  - Missing mass distribution may also be used to search for invisible decays
    - $B(H \rightarrow \text{inv}) = \Gamma_{\text{inv}}/(\Gamma_{\text{SM}} + \Gamma_{\text{inv}})$

\[
M_{\text{miss}} = \sqrt{(\sqrt{s} - E_Z)^2 - |\vec{p}_Z|^2}
\]
**H→inv**

### H→inv

- Generation with Pythia8 of signal and backgrounds (WW, ZZ, ...)
- CMS-like and ILD-like detectors in Delphes 3.2.0 standalone simulation
- Vetoes and event selection:
  - No jets with PT > 20 GeV detected
  - 2μ OR 2e with opposite charge and PT > 10 GeV
  - 1 max reconstructed2 with PT > 10 GeV. If present, it is assumed to be FSR
  - to reduce ZZ
    - Angle between leptons in the laboratory frame Δθll > 100 deg
    - Longitudinal momentum of the lepton pair < 50 GeV
  - to avoid Radiative return
    - angle between the plane containing the lepton momenta and the beam axis θaco > 10 deg
    - Transverse momentum of the lepton pair PllT > 10 GeV
  - to kill WW:
    - mll in M² ± 4 GeV

### Final efficiency

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>HZ</td>
<td>74%</td>
</tr>
<tr>
<td>WW</td>
<td>3.5%</td>
</tr>
<tr>
<td>ZZ</td>
<td>36%</td>
</tr>
</tbody>
</table>

**HZ, ZZ**

$$\sigma \sim 13\text{pb}^{-1}$$

**WW**

$$\sigma \sim 370\text{pb}^{-1}$$
Comparison with LEP3, CMS

- LEP3 studies used CMS full simulation for 500 fb$^{-1}$

very similar number of expected events and performance
- differences attributed to fast vs full simulation
CMS vs ILD

CMS
- $B_Z=3.8T$
- $R_B=1.29m$, $L_B=3.0m$
- acceptance up to $\theta = 85.3$ deg
- Tracker: silicon pixels and strips
- calorimetry LHC optimized

ILD
- $B_Z=3.5T$
- $R_B=1.8m$, $L_B=2.4m$
- acceptance up to $\theta = 84.8$ deg
- Tracker: TPC and silicon
- calorimetry optimized for e+e-collision
CMS vs ILD (2)

ILD o(10) better for both muons and electron resolution

- Resolution CMS $e^\pm$ energy
- Resolution CMS $\mu^\pm$ momentum ($|\eta|$ dependent)
- Resolution ILD $e^\pm$ energy
- Resolution ILD $\mu^\pm$ momentum ($|\eta|<1$)
- Resolution ILD $\mu^\pm$ momentum ($1<|\eta|<2.4$)

Relative resolution [per cent]

<table>
<thead>
<tr>
<th>Energy or $P_T$ [GeV]</th>
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<tbody>
<tr>
<td>10</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>50</td>
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<tr>
<td>60</td>
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<td>70</td>
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<tr>
<td>80</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>100</td>
</tr>
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</table>

CMS
- Tracking eff.: 95% for $P_T>100$ MeV and $|\eta|<2.5$
- Reconstruction eff.: 85 – 95% ($e,\mu$ and $\gamma$) for $P_T>10$ GeV

ILD
- Tracking eff.: 99% for $P_T>100$ MeV and $|\eta|<2.4$
- Reconstruction eff.: 99% ($e,\mu$ and $\gamma$) for $P_T>10$ GeV
CMS vs ILD

- effect on $M_{\text{miss}}$ after inclusion of beam energy spread (0.12% on total C.M. Energy)

\[
\frac{\Delta M}{M} \sim \frac{\Delta \sqrt{s}}{\sqrt{s}} \oplus \frac{\Delta P}{P}
\]

- ILD better tracking allows to have smaller width
  - but despite 10 better $p^T$ resolution for ILD like detector we have ~4 better resolution in $M_{\text{miss}}$
  - beam energy precision is a limiting factor for ILC, at least for better Higgs physics
Constraint H→inv, CMS-like detector

- analytical fit with background templates
  - in “reality” we will use data for ZZ(ZZ→4l) and WW (→eμνν)
- Using s+b dataset and b only dataset, details in backup
- Tagging Z→ll, from the missing mass we get for 1 y of FCC

\[
BR_{lim95\%} = 0.92 \pm (0.30)_{stat} \pm (0.02)_{sys} \%, \quad BR_{5\sigma} = 2.5 \pm (0.2)_{stat} \pm (0.1)_{sys} \%, \quad 68\% \, CL
\]
Constraint $H \to \text{inv}$, ILD-like detector

- Repeating the same for ILD detector
- Tagging $Z \to ll$, from the missing mass we get for 1 y of FCC

$$BR_{\text{lim}95\%} = 0.63 \pm (0.20)_{\text{stat}} \pm (0.02)_{\text{sys}} \%, \quad 68\% \text{ CL}$$

$$BR_{5\sigma} = 1.7 \pm (0.1)_{\text{stat}} \pm (0.01)_{\text{sys}} \%, \quad 68\% \text{ CL}$$
Comparison with LHC/HL-LHC

- CMS now and future

**CMS-PAS-HIG-15-012**

\[ H \rightarrow \text{invisible} \lesssim 34\% \text{ (LHC)} \]

- ATLAS has (of course!) comparable performance, so HL-LHC would give \( H \rightarrow \text{inv} \) \( \text{BR}_{\text{limit}}^{95\%} \approx 5\% \)


<table>
<thead>
<tr>
<th>L (fb⁻¹)</th>
<th>γγ</th>
<th>WW</th>
<th>ZZ</th>
<th>bb</th>
<th>ττ</th>
<th>Zγ</th>
<th>μμ</th>
<th>inv.</th>
</tr>
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<td>300</td>
<td>[6, 12]</td>
<td>[6, 11]</td>
<td>[7, 11]</td>
<td>[11, 14]</td>
<td>[8, 14]</td>
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<td>[40, 42]</td>
<td>[17, 28]</td>
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<tr>
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<td>[4, 8]</td>
<td>[4, 7]</td>
<td>[4, 7]</td>
<td>[5, 7]</td>
<td>[5, 8]</td>
<td>[20, 24]</td>
<td>[20, 24]</td>
<td>[6, 17]</td>
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Interpretation in Hidden Sector

- at colliders:
  - If the DM candidate has a mass below $m_{H/2}$, the invisible Higgs boson decay width, $\Gamma_{\text{inv}}$, can be directly translated to the spin-independent DM-nucleon elastic cross section
    - for scalar (S), vector (V), and fermionic (f) DM
    - scalar interpretation is the only one does not assume other mechanisms at higher mass
    - equivalent to say $m_{\text{med}} = 125$ GeV in DM searches

- In direct detection experiments:
  - the elastic interaction between DM and nuclei exchanged through the Higgs boson results in nuclear recoil which can be reinterpreted in terms of DM mass, $M_\chi$, and DM-nucleon cross section.

\[ \sigma_{\chi-N} \]

\[ 10^{-1} \quad 10^{-2} \quad 10^{-3} \quad 10^{-4} \quad 10^{-5} \quad 10^{-6} \quad 10^{-7} \quad 10^{-8} \quad 10^{-9} \quad 10^{-10} \quad 10^{-11} \quad 10^{-12} \]

\[ 10^1 \quad 10^2 \quad 10^3 \]

\[ \text{DM Mass } M_\chi \text{ [GeV]} \]

\[ \text{DM-nucleon cross section } \sigma_{\chi-N} \text{ [pb]} \]

\[ \text{Combination of VBF and } ZH, H \rightarrow \text{invisible} \]
\[ \sqrt{s} = 8.0 \text{ TeV}, L = 18.9-19.7 \text{ fb}^{-1} \text{ (VBF+ZH)} \]
\[ \sqrt{s} = 7.0 \text{ TeV}, L = 4.9 \text{ fb}^{-1} \text{ (ZH)} \]

\[ B(H \rightarrow \text{inv}) < 0.51 @ 90\% \text{ CL} \]
\[ m_\chi = 125 \text{ GeV} \]

\[ \text{CMS} \]

\[ \text{Eur. Phys. J. C 74 (2014) 2980} \]
with 1y of FCC-ee we get an improvement of 2 order of magnitude wrt current LHC
FCC-ee vs future direct DM detector experiments

- Comparing FCC-ee (1y) with projections on underground direct DM detection experiment

FCC-ee (1y) will be very competitive at lower DM masses

Conclusions

- FCC-ee very well suited for constraining the H→inv width
- With FCC-ee, 1 y of data taking we can easily reach precision around .6%
  - BR limit 95% CL of 0.6% with ILD-like detector!
  - This would improve 2! order of magnitude current constraint on the DM--nucleon cross section in the Higgs portal model and allow FCC-ee to remain competitive with projections of future direct detectors

- We compared CMS and ILD-like performances
  - ILD-like detector allow to achieve better resolution
  - but beam energy resolution starts to be a limiting factor, at least for this measurement
BACKUP
Angular/kinematical cuts
### Statistical analysis

**Discovery significance:**
- $s+b$ dataset, $s$ from fixed BR
- $\sigma = \sqrt{-2 \log \frac{L_b}{L_{s+b}}}$

**Limit on BR(95% cl):**
- $b$ only dataset
- $0.95 \equiv \int_{0}^{N^*_S} L(s + b|N_S) dN_S$

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**Figure 3:** Left: discovery significance as a function of the 5\(\sigma\) Bayesian procedure, integrating the product function. An upper limit is derived from these fits, as shown in Fig. 4. An upper limit from simulation, posteriori is computed with a Bayesian procedure, integrating the product function.

**Figure 4:** Significance from simulation, $\int_{Ldt=500 fb^{-1}} Ldt=500 fb^{-1}$

**Figure 5:** Likelihood scan

**Figure 6:** Posterior distribution, $pdf_{post} = L \times pdf_{prior}$

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*Thursday, April 14, 16*