Higgs and Dark Matter Phenomenology at Colliders

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Combined results for each experiment

- Huge international and intergenerational success!
- First observed in clean final states: photons, ZZ, WW
- Now more channels, e.g. taus
- In absence of other resonances Higgs is window to new physics
Results from Run 1: ‘The End of the Beginning’

Mass:

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS (new ZZ(4l) not used)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$125.5^{+0.2}<em>{-0.2}^{+0.5}</em>{-0.6}(\text{stat})$ GeV</td>
<td>$125.7^{+0.3}_{-0.3}(\text{stat})$ GeV</td>
</tr>
</tbody>
</table>

Spin

- Tested spin-1 and $O$- excluded with 1-CLs > 0.99%

CP

- Tested Spin-2 models excluded with 1-CLs > 0.95%

width

- Combine 4l and 2l2n decay channels.

**Observed (expected)** 95%CL limits: $\Gamma < 8.5(4.2) \times \Gamma_{\text{SM}}$

Couplings

- ATLAS
  - $\mu_{\gamma\gamma} = 1.57^{+0.33}_{-0.28}$
  - $\mu_{ZZ} = 1.44^{+0.40}_{-0.35}$
  - $\mu_{WW} = 1.00^{+0.32}_{-0.39}$
  - $\mu_{tt} = 1.4^{+0.5}_{-0.4}$
  - $\mu_{bb} = 0.2^{+0.7}_{-0.6}$

- CMS
  - $\mu_{\gamma\gamma} = 0.77^{+0.27}_{-0.27}$
  - $\mu_{ZZ} = 0.92^{+0.28}_{-0.28}$
  - $\mu_{WW} = 0.68^{+0.2}_{-0.2}$
  - $\mu_{tt} = 1.10^{+0.41}_{-0.41}$
  - $\mu_{bb} = 0.80^{+0.14}_{-0.14}$
Organisation

- YETI
- BUSSTEPP
- RAL
- S.Ex. Fellowships
- HXWG
- Joint Exp-Theory
- Postdocs

Workshops

- ITNs: MCNet, HiggsTools
- HEJ
- Sherpa
- Herwig++
- Jet substructure tools
- BlackHat
- VBFNLO

Interpretation

- Width
- Higgs couplings
- Portals
- Composite Higgs
- Simplified Models
- EFT vs non-EFT

Support

- VBFNLO
Higgs-bottom coupling

[Soper, MS ‘10]
[Soper, MS ‘11]

ct vs cg in H+jet

[Schlaffer, MS, Takeuchi, Walter, Wymant ‘14]
[Buschmann, Englert, Goncalves, Plehn, MS ‘14]
[Buschmann, Goncalves, Kutimalai, Krauss, Plehn, ‘14]

Higgs-top coupling

[Plehn, Salam, MS ‘09]
[Artoisenet, de Aquino, Maltoni, Mattelaer ‘09]

Higgs selfcoupling

[Dolan, Englert, MS ‘13 ‘14]
[Barr, Dolan, Englert, MS ‘14]
[Ferreira, Papaefstathiou, MS ‘14]
[Dolan, Englert, Greiner, MS ‘14]
[Englert, Krauss, MS, Thompson ‘14]

CP Higgs

[Andersen, Arnold, Zeppenfeld ‘10]
[Dolan, Harris, Jankowiak, MS ‘14]

Invisible Higgs

[Englert, Jaeckel, MS, Re ‘11]
[Englert, MS, Wymant ‘13]
[Bernacek, Plehn, Schichtel, Tattersall ‘14]

Off-shell Higgs (Width)

[Englert, McCullough, MS ‘15]
[Englert, MS ‘14]
[Englert, Soreq, MS ‘14]
Constraining the Higgs width at the LHC?

- alternative method using interference effects directly see [Dixon, Li '13]

Constraining the Higgs boson width with \( ZZ \) production at the LHC

Fabrizio Caola\(^1,\ast \) and Kirill Melnikov\(^1,\dagger \)

\(^1\)Department of Physics and Astronomy, Johns Hopkins University, Baltimore, USA

We point out that existing measurements of \( pp \rightarrow ZZ \) cross-section at the LHC in a broad range of \( ZZ \) invariant masses allow one to derive a model-independent upper bound on the Higgs boson width, thanks to strongly enhanced off-shell Higgs contribution. Using CMS data and considering events in the interval of \( ZZ \) invariant masses from 100 to 800 GeV, we find \( \Gamma_H \leq 38.8 \, \Gamma_H^{SM} \approx 163 \) MeV, at the 95\% confidence level. Restricting \( ZZ \) invariant masses to \( M_{ZZ} \geq 300 \) GeV range, we estimate that this bound can be improved to \( \Gamma_H \leq 21 \, \Gamma_H^{SM} \approx 88 \) MeV.

Measurement done in CMS-PAS-HIG-14-002 and presented at Moriond '14

By now ATLAS has performed same measurement
I. Count events in on-shell region

\[ \mu_{i,j} = \sigma_{H,i} \times BR_j \sim \frac{g_{ggH}g_{HZZ}}{\Gamma_H} \]

II. measure \( g_{ggH}^2 g_{HZZ}^2 \) in off-shell region

using angular correlations of 4l decay products

III. insert off-shell coupling measurement in on-shell signal strength to bound width

\[ \text{Obs.} / \text{exp.) @95\% C.L:} \]

\[ \Gamma_H < 4.2(8.5) \Gamma_H^{\text{SM}} \]

\[ \Gamma_H < 17.4 \ (35.3) \text{ MeV} \]

[Kauer, Passarino 2011]
Unfortunately, method has loop-holes:

- In SM couplings in on-shell and off-shell region intimately related

- Direct correlation of on-shell \( g_{gh}^2 g_{hZZ}^2 \) and off-shell \( g_{gh}^2(\sqrt{s}) g_{hZZ}^2(\sqrt{s}) \)

necessary ingredient for width measurement \( \rightarrow \) can be broken by BSM effects

\[
\mathcal{L}_\phi = |D_\mu \phi|^2 - \tilde{m}_\phi^2 |\phi|^2 - \lambda |\phi|^2 |H|^2 + \ldots.
\]

Example: Higgs-portal (toy) model

Scalar only charged under \( SU(3)_C \)

\[
m_\phi^2 = \tilde{m}_\phi^2 + \lambda v^2 \quad \text{free parameter}
\]

\[
g_{ggh}(m_h) > g_{ggh,SM} \rightarrow \Gamma > \Gamma_{SM} \quad \text{for } \mu \sim 1
\]

Despite increased on-shell coupling (and Higgs width) negligible contribution in off-shell region

\[
\begin{array}{|c|c|c|c|}
\hline
m_\phi & \mu (h \text{ peak}) & \Gamma_h/\Gamma_{SM}^{\text{SM}} & \sigma/\sigma_{\text{SM}} [m(4\ell) \geq 330 \text{ GeV}]^a \\
\hline
70 \text{ GeV} & \approx 1.0 & \approx 5 & -2\% \\
170 \text{ GeV} & \approx 1.0 & \approx 4.7 & +80\% \\
170 \text{ GeV} & \approx 1.0 & \approx 1.7 & +6\% \\
\hline
\end{array}
\]

\( ^a \)We impose the cut set used by CMS [17] without the MELA cut [34].

- Here only simplest toy model - thus question: WHEN IS WIDTH INTERPRETATION VALID
• Width interpretation ONLY interesting if model-independent
  
  Within a model width is fixed (not free parameter of theory), result of QFT
  
  Width measurement is result of global coupling fit.
  
• But for classes of models a width interpretation is valid: [Englert, Soreq, MS '14]

  Necessary condition: 
  
  \[ R(m_{\text{\textit{ZZ}}}^2) = \frac{g g H(m_{\text{\textit{ZZ}}}^2)/g g H_{\text{SM}}(m_{\text{\textit{ZZ}}}^2)}{g g H(m_H^2)/g g H_{\text{SM}}(m_H^2)} \approx 1 \]

  complex valued double ratio

  color triplet scalar

  \[ k_{\text{\textit{gg}}}(m_{\text{\textit{ZZ}}}^2)/k_{\text{\textit{gg}}}(m_{\text{\textit{H}}}^2) \]

  \[ m_{\text{\textit{ZZ}}} \text{[TeV]} \]

  \[ 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1.0 \]

  color triplet fermions

  effective GGHH coupling

  \[ k_{\text{\textit{gg}}}(m_{\text{\textit{ZZ}}}^2)/k_{\text{\textit{gg}}}(m_{\text{\textit{H}}}^2) \]

  \[ m_{\text{\textit{ZZ}}} \text{[TeV]} \]

  \[ 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1.0 \]
• Way to close loophole of Caola–Melnikov method by using WBF process:

Same tree-level coupling in production and decay

$T$ parameter links $WWH$ and $ZZH$

$$\mathcal{L}_{HD} = F_{HD} \left[ H^+ H - \frac{v^2}{4} \right] \cdot \text{tr} \left[ (D^\mu H)^+ (D^\mu H) \right]$$

assumed

$$hW^+_\mu W^-_\nu : \quad ig M_W g_{\mu \nu} \frac{v^2 F_{HD}}{2}$$

$$hZ^+ \mu Z^\nu : \quad ig \frac{M_W}{\cos^2 \theta_W} g_{\mu \nu} \frac{v^2 F_{HD}}{2}$$

• Use LEP as off-shell Higgs factory:

Why off-shell LHC coupling measurement?

LEP has already performed precise Higgs coupling measurements!

Use LEP coupling measurements and plug into LHC signal strength measurement
Higgs self-coupling measurements

\[ -\mathcal{L} = \frac{1}{2} m_h^2 h^2 + \sqrt{\frac{\eta}{2}} m_h h^3 + \frac{\eta}{4} h^4 \]
\[ - g m_V V^2 h - \frac{m_f}{v} f f h \]
\[ - \frac{\alpha_s}{12\pi} G_{\mu\nu}^a G^{a\mu\nu} \log(1 + h/v) \]
\[ = - \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} h + \frac{\alpha_s}{24\pi v^2} G_{\mu\nu}^a G^{a\mu\nu} h^2 + \ldots \]

Potential needs at least dihiggs production!
Higgs self-coupling in HH+X

\[ s = (p_{h,1} + p_{h,2})^2 = 4m_t^2 \]

Total cross section: [HXSWG]

\[ pp \rightarrow HH(\lambda = 1) = 33.86 \text{ fb} \]
\[ pp \rightarrow HH(\lambda = 0) = 71.01 \text{ fb} \]
\[ pp \rightarrow HH(\lambda = 2) = 15.85 \text{ fb} \]
<table>
<thead>
<tr>
<th>Decay</th>
<th>Issues</th>
<th>Expectation 3000 ifb</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>• Signal small&lt;br&gt;• BKG large &amp; difficult to assess&lt;br&gt;• Simple reconst.</td>
<td>$S/B \simeq 1/3$&lt;br&gt;$S/\sqrt{B} \simeq 2.5$</td>
<td>[Baur, Plehn, Rainwater]&lt;br&gt;[Yao 1308.6302]&lt;br&gt;[Baglio et al. JHEP 1304]&lt;br&gt;[Azatov et al. JHEP '15]</td>
</tr>
<tr>
<td>$b\bar{b}\tau^+\tau^-$</td>
<td>• tau rec tough&lt;br&gt;• largest bkg tt&lt;br&gt;• Boost+MT2 might help</td>
<td>differ a lot&lt;br&gt;$S/B \simeq 1/5$&lt;br&gt;$S/\sqrt{B} \simeq 5$</td>
<td>[Dolan, Englert, MS]&lt;br&gt;[Barr, Dolan, Englert, MS]&lt;br&gt;[Baglio et al. JHEP 1304]</td>
</tr>
<tr>
<td>$b\bar{b}W^+W^-$</td>
<td>• looks like tt&lt;br&gt;• Need semilep. W to rec. two $H$&lt;br&gt;• Boost + BDT proposed</td>
<td>differ a lot&lt;br&gt;best case: $S/B \simeq 1.5$&lt;br&gt;$S/\sqrt{B} \simeq 8.2$</td>
<td>[Dolan, Englert, MS]&lt;br&gt;[Baglio et al. JHEP 1304]&lt;br&gt;[Papaefstathiou, Yang, Zurita 1209.1489]</td>
</tr>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>• Trigger issue (high pT kill signal)&lt;br&gt;• 4b background large difficult with MC&lt;br&gt;• Subjets might help</td>
<td>$S/B \simeq 0.02$&lt;br&gt;$S/\sqrt{B} \leq 2.0$</td>
<td>[Dolan, Englert, MS]&lt;br&gt;[Ferreira de Lima, Papaefstathiou, MS]&lt;br&gt;[Wardrope et al, 1410.2794]</td>
</tr>
<tr>
<td>others</td>
<td>• Many taus/W not clear if 2 Higgs&lt;br&gt;• Zs, photons no rate</td>
<td></td>
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</tbody>
</table>
More jets more fun:

First to calculate HH+jet and HH+2jets beyond effective theory

keep mHH small \(\rightarrow\) retain sensitivity for high-pT Higgs

Additional jet can help to suppress backgrounds:

\[ H \bar{H} j \rightarrow b \bar{b} \tau^+ \tau^− j \quad S/B \sim 3/2 \]
\[ H \bar{H} \rightarrow b \bar{b} \tau^+ \tau^- \quad S/B \sim 1/2 \]

Unfortunately rate small

- Want to study VVHH
  Directly related to long. gauge boson scattering
  Though strongly modified in comp. Higgs models

- In SM fixed:
  \[ g_{WWhh} = e^2/(2s_w^2) \]
  \[ g_{ZZhh} = e^2/(2c_w^2s_w^2) \]

- Unfortunately gluon fusion dominating over WBF
  Usual WBF cuts, e.g. central jet vetos not applicable.

- WBF only measurable for large enhancement of SM coupling value
Higgs self-coupling in $ttHH$

Enhanced self-coupling can be measured in $tthh$

[Englert, Krauss, MS, Thompson ‘14]
Higgs/Scalars and their Dark Matter relation

Evidence for Dark Matter overwhelming:

- Spiral Galaxy rotation curves
- Gravitational lensing
- Acoustic peaks

Several ways to look for Dark Matter

Which way more sensitive depends mostly on nature of mediator
Effective theory approach:

- Parametrise interactions in terms of eff. operator
- Simplest way of capturing interactions

Used to be preferred choice of experiments to present results

- However, only valid if interaction not resolved

Going beyond:

- At colliders momentum transfer too large for EFT approach

Need simplified models

[Fox, Williams ‘12] [Buchmueller, Dolan, McCabe ‘13]

LHC-DM Forum
Dark matter could interact with SM via scalar mediator

- CP-even scalar, e.g. Higgs portal, or CP-odd scalar
- Dark Matter interacting via CP-odd scalar difficult to find
  - Direct detection interaction velocity suppressed
  - Difficult to produce at colliders, e.g. LEP
  - But might give visible signal in indirect detection
    “Coy Dark Matter” and can fit GC excess

[Boehm, Dolan, McCabe, MS, Wallace ’14]
Searching scalar DM-mediators in mono-jets

simplified model

\[ \mathcal{L}_{\text{pseudo-scalar}} \supset - \frac{1}{2} m_{\text{MED}}^2 P^2 - g_{\text{DM}} P \bar{\chi} \gamma^5 \chi - g_{\text{SM}}^t P \bar{\tau} \gamma^5 t - g_{\text{SM}}^b P \bar{b} \gamma^5 b \]

\[ \mathcal{L}_{\text{scalar}} \supset - \frac{1}{2} m_{\text{MED}}^2 S^2 - g_{\text{DM}} S \bar{\chi} \chi - g_{\text{SM}}^t S \bar{t} t - g_{\text{SM}}^b S \bar{b} b \]

4 relevant parameters for phenomenology

1. mediator mass \( m_{\text{MED}} \)
2. mediator width \( \Gamma_{\text{MED}} \)
3. dark matter mass \( m_{\text{DM}} \)
4. effective coupling parameter \( g_q \cdot g_{\chi} \)

[Buckley, Feld, Goncalves ’14]
[Harris, Khoze, MS, Williams ’14]
• For light Dark Matter and heavy mediators the LHC can provide complementary information to DD and ID experiments.

• A joint effort of all possible ways to look for (coy) Dark Matter is needed to maximize our chances to find it.
Summary

• Scalar sector most interesting for coming years, i.e. strong crosstalk between different experiments

• Higgs and Dark Matter Phenomenology hot topics for upcoming runs

• IPPP has many staff members involved in this line of research

• For a successful program close collaboration between experimentalists and theorists essential