Higgs Physics
End Game
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Saturday May 20, 2023 — Patrick Bryant — Mel Fest
Higgs Physics
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Starting in September

Saturday May 20, 2023 — Patrick Bryant — Mel Fest
Higgs Physics

• Observed ‘Higgs like’ boson in phenomenological sweet spot
  - A little lighter $\rightarrow$ bosonic decays suppressed
  - A little heavier $\rightarrow$ fermionic decays suppressed

observed $m_H=125$ GeV
So many fun things to measure!

- Observed four primary production modes and five decay modes
• So many fun things to measure!
  - Observed four primary production modes and decay modes

*Almost six!*
• So many fun things to measure!
  - Observed four primary production modes and five* decay modes
  - Very ‘Higgs like’
Higgs Physics

• Four parts of the Higgs mechanism to check:
  - Higgs self-coupling
  - Higgs total width
  - Higgs to invisible
  - Yukawa CP violation
Higgs Self-Coupling

- Standard HH measurements combined with all single H measurements
Higgs Self-Coupling

- $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$ remarkably competitive!

**ATLAS**

$\sqrt{s} = 13$ TeV, 126—139 fb$^{-1}$

$\sigma_{99\% + VBF}(HH) = 32.7$ fb

<table>
<thead>
<tr>
<th>Category</th>
<th>Obs.</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b\bar{b}\gamma\gamma$</td>
<td>4.2</td>
<td>5.7</td>
</tr>
<tr>
<td>$b\bar{b}\tau^+\tau^-$</td>
<td>4.7</td>
<td>3.9</td>
</tr>
<tr>
<td>$b\bar{b}b\bar{b}$</td>
<td>5.4</td>
<td>8.1</td>
</tr>
<tr>
<td>Combined</td>
<td>2.4</td>
<td>2.9</td>
</tr>
</tbody>
</table>
Higgs Self-Coupling

- Standard candles for $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$ are remarkably competitive!

\[
\frac{\sigma(pp \to ZZ \to b\bar{b}b\bar{b})}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 31
\]

\[
\frac{\sigma(pp \to ZH \to b\bar{b}b\bar{b})}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 7
\]

\[
\frac{\sigma(pp \to ZZ \to b\bar{b}\tau\tau)}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 63
\]

\[
\frac{\sigma(pp \to ZH \to b\bar{b}\tau\tau)}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 13^*
\]

\[
* (3.5[b\bar{b}\tau\tau] + 9.7[\tau\tau b\bar{b}])
\]
Combination with single H measurements mostly serves to constrain $\kappa_t$.
Higgs Width

• Any new couplings can change width, particularly BSM decay modes which may be hard to observe directly
  - Direct measurement is hopeless
  - Rely on ratio of off/on-shell cross section, some model dependence

\[
\frac{\sigma_{\text{off-shell}}^{gg\rightarrow H\rightarrow ZZ}}{\sigma_{\text{on-shell}}^{gg\rightarrow H\rightarrow ZZ}} \propto \frac{\Gamma_H m_H}{m_{ZZ}^2} \times f(\text{scale dependence of } HZZ \text{ and } ggH \text{ couplings})
\]
- Precision calculations of non-resonant ZZ cross section
- NLO QCD k-factors as function of $m_{ZZ}$ 1.5-2
- N3LO QCD norm k-factor 1.32
- Impressive to find $3\sigma$ evidence of an effect which is smaller than these k-factors
• Precision calculations of non-resonant ZZ cross section
- NLO QCD k-factors as function of $m_{ZZ}$ 1.5-2
- N3LO QCD norm k-factor 1.32
- Impressive to find $3\sigma$ evidence of an effect which is smaller than these k-factors

![Graph](HIGG-2018-32)

**ATLAS**

On + Off-shell combined
13 TeV, 139 fb$^{-1}$

- Obs-Stat. only: 1.1$^{+0.6}_{-0.5}$
- Obs-Sys: 1.1$^{+0.7}_{-0.6}$
- Exp-Stat. only: 1.0$^{+0.8}_{-0.9}$
- Exp-Sys: 1.0$^{+0.9}_{-0.9}$

$\Gamma_{H}/\Gamma_{H}^{SM}$
Combination of visible Higgs decays gives indirect and model dependent constraint on BSM Higgs to invisible BR.

- Direct search in VBF production gives strongest constraint
Another impressive measurement relying on large theory k-factors
- In this case double ratio of EW Z/W+jets vs $m_{jj}$
Yukawa CPV

- Tree level CP Violation is possible in Yukawa couplings
  - CPV in gauge couplings is suppressed by $\Lambda^{-2}$
  - $H \rightarrow \tau\tau$ is the only option at the LHC
Yukawa CPV

• Pure CP-odd hypothesis disfavored at $3.4\sigma$

- 10 different combinations of $\tau$ decay modes, 16 signal regions

\[
d\Gamma_{H \rightarrow \tau^+ \tau^-} \approx 1 - b(E_+) b(E_-) \frac{\pi^2}{16} \cos(\varphi^*_\text{CP} - 2\phi_\tau)
\]
Conclusions

- Incredibly rich Higgs phenomenology made possible by $m_H = 125$ GeV
- Huge combination of measurements consistent with SM Higgs
  - LHC beginning to constrain:
    - Self-coupling
    - Width
    - BR($H\rightarrow\text{Inv.}$)
    - Yukawa CP violation
- My money is on SM Higgs
  - If you have to retire and do something else, now is the time