Higgs coupling measurements with ATLAS

Richard Mudd

University of Birmingham

HEP Seminar, Birmingham
12th November 2014
Higgs Mechanism

- $SU(2)_L \otimes U(1)_Y$ describes electroweak sector in terms of massless gauge bosons
- In the SM a complex scalar doublet is introduced

\[ \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \]

- For Higgs mechanism potential chosen such that electroweak symmetry is hidden
  - Higgs field gets non-zero vacuum expectation value
  - Three degrees of freedom give $W^+, W^-, Z$ mass, one gives new scalar boson - the Higgs boson

*Image credit: Philip Tanedo*
Higgs Mechanism: Scalar Couplings Structure

Bosonic sector:
- **EWSB** gives mass to $W^+, W^-, Z$ bosons
- Higgs couplings proportional to $m_{W/Z}^2$

\[ g_{HVV} = \frac{2m_V^2}{v} \]

Fermionic sector:
- After introducing Higgs field, can add **Yukawa terms** to Lagrangian
- Higgs couplings proportional to fermion mass

\[ g_{Hf\bar{f}} = Y_f = \frac{m_f}{v} \]

- $v$ is Higgs field vacuum expectation value
- Loops (e.g. $\gamma$, gluon) sensitive to BSM physics
Higgs Production at the LHC

- Gluon fusion mode dominates
- Subleading modes essential to tag more difficult decay modes and measure couplings
Higgs Decays at the LHC

- $H \rightarrow b\bar{b}$ has highest rate but challenging due to very large background.

- $H \rightarrow WW(*) \rightarrow l\nu l\nu$, $H \rightarrow \tau\tau$ also have relatively high rates but complex final states.

- $H \rightarrow ZZ(*) \rightarrow 4\ell$, $H \rightarrow \gamma\gamma$ challenging because of low rates but clean final states.
Possible Extensions to SM Higgs Sector

• In the SM EWSB is achieved through a single complex scalar doublet but many extensions possible

Additional EW singlet

• Mixing between singlet original Higgs doublet → two CP-even bosons

• Couple to SM particles in a similar way to SM Higgs

Two Higgs Doublet

• Predict 5 Higgs Bosons: 2 neutral CP-even, one neutral CP odd, 2 charged

• e.g. MSSM

• Typically require that models satisfy Glashow-Weinberg condition, e.g:
  ○ Type I: one doublet couples to vector bosons, one to fermions
  ○ Type II: one doublet couples to up-type quarks, the other to down-type and leptons
How does new physics modify Higgs couplings?

- New physics (e.g. extended Higgs sectors) can modify the Higgs couplings
- Modifications depend on mass scale of new physics
- For new physics at 1 TeV scale modifications are typically $\sim 1 - 10\%$

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_V$</th>
<th>$\kappa_b$</th>
<th>$\kappa_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet mixing</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
</tr>
<tr>
<td>2HDM</td>
<td>$\sim 1%$</td>
<td>$\sim 10%$</td>
<td>$\sim 1%$</td>
</tr>
<tr>
<td>Decoupling MSSM</td>
<td>$\sim -0.001%$</td>
<td>$\sim 1.6%$</td>
<td>$\sim -0.4%$</td>
</tr>
<tr>
<td>Composite</td>
<td>$\sim -3%$</td>
<td>$\sim -(3-9)%$</td>
<td>$\sim -9%$</td>
</tr>
<tr>
<td>Top Partner</td>
<td>$\sim -2%$</td>
<td>$\sim -2%$</td>
<td>$\sim +1%$</td>
</tr>
</tbody>
</table>

From Snowmass Higgs Working Group Report
ATLAS detector

- Successful operation of ATLAS detector in run I
  - $4.6 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$,
  - $20.3 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$
  - $\approx 95\%$ of recorded luminosity good for physics

- Strong detector performance achieved in challenging environment
  - Average 21 interactions per bunch crossing
  - Higher than design pileup

---

Graphs showing:
- **ATLAS Online Luminosity**
  - 2010 pp $\sqrt{s} = 7 \text{ TeV}$
  - 2011 pp $\sqrt{s} = 7 \text{ TeV}$
  - 2012 pp $\sqrt{s} = 8 \text{ TeV}$

- **Recorded Luminosity**
  - $\sqrt{s} = 7 \text{ TeV}$, $L_{int} = 5.2 \text{ fb}^{-1}$, $\langle q \rangle = 9.1$
  - $\sqrt{s} = 8 \text{ TeV}$, $L_{int} = 21.7 \text{ fb}^{-1}$, $\langle q \rangle = 20.7$
Atlas Higgs physics programme

- ATLAS has published a broad selection of results in the Higgs sector in run I
  - Mass
  - Couplings
  - Spin/CP
  - Differential distributions
  - Rare decays
  - and more ...

- Focus on measurement of **coupling properties** today

- Don’t have time to discuss individual analyses in detail
  - Instead a selection of highlights from main inputs to ATLAS combined coupling measurements
  - For $bb$ see Paul Thompson’s recent seminar
ATLAS Higgs couplings measurements

ATLAS has recently released updated results for the five most sensitive SM channels using full run I data:

- $H \rightarrow 4\ell$
- $H \rightarrow \gamma\gamma$
- $VH, H \rightarrow b\bar{b}$
- $H \rightarrow WW$
- $H \rightarrow \tau\tau$

ATLAS Preliminary

$\sigma / \sigma_{SM}$

95% C.L. limit on

$m_{H}$ (GeV)

Log$_{10}$ (S/B)

Local $p_{0}$

Events / bin

- $\mu_{ggF, VBF, WH, ZH}$
- $\mu_{Ht}$
- $\mu_{H}$

Total

Stat.

Syst.

Observed (CLs)

Expected (no Higgs)

Expected ($m_{H} = 125$ GeV)
‘Signal Strength’ $\mu$

- Measured rates reported relative to SM prediction
- **Signal strength** defined as:

$$\mu = \frac{\sigma \cdot BR}{\sigma_{SM} \cdot BR_{SM}}$$

- Measured in decay modes and also for their combination
- Also able to measure rates for **specific production modes**
  - Typically denoted with a subscript
    $$\mu_{ggF} = \frac{\sigma(ggF) \cdot BR}{\sigma_{SM}(ggF) \cdot BR_{SM}}$$
  - Often combine bosonic/fermionic production modes
    - $\mu_{ggF+ttH}$, $\mu_{VBF+VH}$
Statistical techniques

- Confidence intervals based on **profile likelihood ratio**

\[
\Lambda(\alpha) = \frac{L(\alpha, \hat{\theta}(\alpha))}{L(\hat{\alpha}, \hat{\theta})} = \frac{\text{Maximum likelihood for given } \alpha}{\text{Global maximum likelihood}}
\]

- Depends on one of more **parameters of interest**, \(\alpha\)
  - e.g. \((\mu, m_H), (\mu_{ggF}, \mu_{VBF})\)

- **Systematic uncertainties** modelled using **nuisance parameters**, \(\theta\)
  - Typically constrained by gaussians
  - Model uncertainties and their correlations

- Likelihood functions built using sums of signal and background pdfs in discriminating variables
**$H \rightarrow ZZ(\ast) \rightarrow 4\ell$ analysis**

- **Low rates** but final state with **good mass resolution** (1.6 - 2.2 GeV) and **high S/B** (0.7 - 1.8)
  - $\sigma \times BR \simeq 2.9$ fb for $m_H = 125.5$ GeV

- Two same-flavour, opposite sign lepton pairs

- Low $p_T$ electron/muon performance critical
  - $p_T > 7$ (6) GeV for electrons (muons)
  - Isolation and impact parameter requirements to reduce background

- $m_Z$ constrained kinematic fit for $m_{12}$

- FSR photon recovery for $m_{12}$ candidates

- E-p combination for $p_T^e < 30$ GeV
**$H \rightarrow ZZ^*(\rightarrow 4\ell$) categorisation and fit model**

- **Multi-observable fit in production-tagged categories**
  - Exploit use of BDTs

### ATLAS

**4\ell selection**

- **High mass two jets**
  - VBF enriched
  - $W(\rightarrow jj)H$, $Z(\rightarrow jj)H$

- **Low mass two jets**
  - VH enriched
  - $W(\rightarrow ll)H$, $Z(\rightarrow ll)H$

- **Additional lepton**
  - ggF enriched
  - $W(\rightarrow ll\nu)H$, $Z(\rightarrow ll\nu)H$

#### ggF categories:
- Fit $m_{4\ell}$ and BDT with LO matrix element kinematic discriminant, $p_T^{4\ell}$, $\eta^{4\ell}$

#### VBF category:
- Fit $m_{4\ell}$ and BDT with jet kinematic variables

#### VH categories:
- 1D fit to $m_{4\ell}$
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ categorisation and fit model

- 5 events in VBF-enriched category, 1 with $BDT_{VBF} \approx 0.7$

\[
\mu_{ggF+bbH+ttH} \times B/B_{SM} = 1.7^{+0.5}_{-0.4}
\]

\[
\mu_{VBF+VH} \times B/B_{SM} = 0.3^{+1.6}_{-0.9}
\]

- Uncertainties dominated by statistical component
- Expected uncertainty on $\mu_{VBF+VH}$ reduced by $\approx 40\%$ compared to preliminary result
**$H \rightarrow \gamma\gamma$ analysis**

- $H \rightarrow \gamma\gamma$ decays through t and W loops in SM
  - Negative interference between t and W contributions
- Two isolated, high $p_T$ photons
- Search for narrow peak (mass resolution 1.3 - 1.8 GeV) on top of background ($S/B \sim 3\%$)

- **Diphoton invariant mass:**
  \[ m_{\gamma\gamma}^2 = 2E_1E_2(1 - \cos \alpha) \]
  - Neural network based identification of primary interaction vertex
- **Backgrounds** $\gamma\gamma(75\%), \gamma j, jj$
  - Estimated from sideband fit
$H \rightarrow \gamma \gamma$ categories

Comprehensive categorisation scheme targeting 5 main production mechanisms

![Signal strength vs. $p_{TT}$](image)

**Untagged:**
- Split based on $p_{TT}$ and position in detector

**VBF:**
- Cut on output of BDT
- Loose and tight categories

**VH:**
- Sensitivity to separate WH and ZH
- Hadronic, leptonic and $E_T^{miss}$ signatures

**ttH:**
- Hadronic and leptonic top decays

Signal strength for each production mode consistent with SM
\[ H \rightarrow WW(*) \rightarrow \ell\nu\ell\nu \] analysis

- **High rate, relatively clean final state** (ee, e\(\mu\), \(\mu\mu\) with \(E_T^{\text{miss}}/p_T^{\text{miss}}\))
  - Mass resolution \(\simeq 15\) GeV
    \(\Rightarrow\) background control crucial

- **Several background sources**
  - \(WW, W+\text{jets}, tt, \text{single top}, Z\gamma^*, Z \rightarrow \ell\ell\) estimated in data using control regions
  - Other diboson process estimate using MC
  - Background composition depends on lepton flavour, \(N_{jets}\)

- **Improvements with respect to preliminary analysis**
  - Track-based missing \(E_T\)
  - Electron Likelihood ID
    - Reduce lepton \(E_T\) threshold \(15 \rightarrow 10\) GeV
  - Optimised event categorisation

- **Overall 30\% reduction of uncertainties** on \(\mu\)
  w.r.t preliminary results
The decay $H \rightarrow WW^{(*)}\rightarrow \ell\nu\ell\nu$ categories and fit model

- Transverse mass $m_T$ used as discriminant in fit
  - In VBF categories use $BDT$ instead
  - Fit in several signal and control regions

- Rates for ggF and VBF processes consistent with SM

- Observe VBF production with $3.2\sigma$ significance

\[ \mu_{ggF} \quad -2 \ln \Lambda \]

\[ \mu_{VBF} \quad -2 \ln \Lambda \]
$H \rightarrow \tau\tau$ analysis

- Three final states used in analysis depending on $\tau$ decays:
  - $\tau_{lep}\tau_{lep}$
  - $\tau_{lep}\tau_{had}$
  - $\tau_{had}\tau_{had}$

- $Z \rightarrow \tau\tau$ and fake $\tau$ backgrounds dominate

- Use missing mass calculator
  - Use visible $\tau$ decay products and $E_T^{miss}$ to find most-likely $m_{\tau\tau}$

- $Z \rightarrow \tau\tau$ background from $Z \rightarrow \mu\mu$ embedding method

- BDT used as a discriminating variable in a 6 category (VBF and boosted for each final state) fit
  - Cut-based analysis as cross check
$H \rightarrow \tau\tau$: evidence for Higgs decays to fermions

- **Direct evidence for coupling to fermions at 4.5\sigma level (3.5\sigma exp)**
- $\mu = 1.42^{+0.44}_{-0.38}$ consistent with SM Yukawa coupling prediction

- ATLAS also searches for $H \rightarrow \mu\mu$
- No observed excess of events
- In SM $BR(\tau\tau)/BR(\mu\mu) \simeq 300$
  \[ \Rightarrow \text{The Higgs does not couple universally to different flavour leptons} \]
Higgs mass measurement

- Precise measurement of $m_H$ important for determining couplings
  - For a shift in mass $\Delta m_H = 400$ MeV, $\sigma \times BR(ZZ)$ changes by $\approx 3\%$

- **ATLAS** $m_H$ measurement uses high resolution modes $H \to \gamma\gamma \ H \to ZZ(*) \to 4\ell$

- Improvements with respect to preliminary results
  - Significantly improved $e/\gamma$ calibration
    - Systematic on $m_H$ in $\gamma\gamma$ due to photon energy scale reduced by factor 2.5
  - Improved lepton performance
    - Likelihood-based electron ID
    - E-p combination for electrons
    - $S/B$ for $2\mu 2e$ final state improved from 1.2 $\rightarrow$ 1.8
  - Multivariate techniques in $H \to ZZ(*) \to 4\ell$
    - BDT as additional observable in fit $\rightarrow 8\%$ improvement compared to 1D
Higgs mass measurement

\( H \to \gamma\gamma : m_H = 125.98 \pm 0.42\text{(stat)} \pm 0.28\text{(sys)} \)

\( H \to 4\ell : m_H = 124.51 \pm 0.52\text{(stat)} \pm 0.06\text{(sys)} \)

Combined: \( m_H = 125.36 \pm 0.37\text{(stat)} \pm 0.18\text{(sys)} \)

- Combined mass from a simultaneous max. likelihood fit, where \( \mu_{\gamma\gamma} \) and \( \mu_{4\ell} \) treated as independent free parameters

- Individual measurements compatibility \( \sim 2.0\sigma \)
  - Compatibility in preliminary result was \( 2.5\sigma \)
Measuring coupling properties

• Most recent ATLAS couplings combination released March 2014
  ○ $\gamma\gamma$, $ZZ(\ast) \rightarrow 4\ell$, $WW(\ast) - \rightarrow l\nu l\nu, \tau^+\tau^-$, $b\bar{b}$
  ○ Also use combination to put constraints on new phenomena
  ○ Many of the results shown so far today **not yet included** in combination

• Note measuring absolute couplings **depends on total width**:

\[
\sigma \times BR(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}
\]

• In SM $\Gamma_H \simeq 4$ MeV!
  ○ Not possible to measure directly at the LHC

• Alternatively, measure **ratios of couplings**
  ○ Dependence on $\Gamma_H$ cancels

• **Updated couplings combination** with final results planned
  ○ Possibility to include searches for **rare decays** and $t\bar{t}H$ production in future combinations
**Production mode rates**

<table>
<thead>
<tr>
<th>Production mode</th>
<th>ATLAS Prelim.</th>
<th>( m_H = 125.5 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>H ( \rightarrow \gamma\gamma )</td>
<td></td>
<td>( \frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+ttH}}} = 1.2^{+0.8}_{-0.6} )</td>
</tr>
<tr>
<td>H ( \rightarrow \text{ZZ}^* \rightarrow 4l )</td>
<td></td>
<td>( \frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+ttH}}} = 0.6^{+2.4}_{-0.9} )</td>
</tr>
<tr>
<td>H ( \rightarrow \text{WW}^* \rightarrow \ell\ell \nu \nu )</td>
<td></td>
<td>( \frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+ttH}}} = 1.8^{+1.9}_{-1.0} )</td>
</tr>
<tr>
<td>H ( \rightarrow \tau\tau )</td>
<td></td>
<td>( \frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+ttH}}} = 1.7^{+\infty}_{-1.2} )</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td>( \frac{\mu_{\text{VBF+VH}}}{\mu_{\text{ggF+ttH}}} = 1.4^{+0.7}_{-0.5} )</td>
</tr>
</tbody>
</table>

- No combination of \( \mu_{\text{ggF}}, \mu_{\text{VBF}} \) possible between decay modes
  - Can’t distinguish between production and decay for deviations
- Combine ratio instead
  \( \mu_{\text{VBF}}/\mu_{\text{ggF+ttH}} = 1.4^{+0.5}_{-0.4} (\text{stat})^{+0.4}_{-0.3} (\text{sys}) \)
- 4.1\( \sigma \) evidence for VBF Higgs production
κ-framework

- Framework for couplings based on LHC Higgs Cross Section Working Group recommendations

- **Leading order framework** for a single, SM-like Higgs boson under specific assumptions:
  - Single resonance with a mass near 125 GeV
  - Zero width approximation holds
  - Tensor structure of couplings assumed to be the same as SM
    - $J^P = 0^+$

- Define couplings scale factors $\kappa$:

  $$
  \sigma \cdot BR(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}
  $$

- $\kappa_i = 1$ corresponds to the SM

  ⇒ Idea is to Look for deviations from SM rates
- Framework makes no specific assumptions on additional states of new physics which could interact with the state at $\simeq 125$ GeV, in particular on:
  - Additional Higgs bosons
  - Additional fermions, vector bosons or others scalars (which don’t acquire a VEV)
  - Invisible decay modes

- Test benchmark scenarios based on this framework

- Fermion vs vector couplings:
  - Tests EWSB, Yukawa coupling model
  - One scale factor for vector bosons and one for fermions

- Fermion structure:
  - Many SM extensions (e.g. 2HDMs) predict deviations in fermion sector
  - One scale factor for up-type fermions and one for down-type
  - One scale factor for quarks and one for leptons

- Several other benchmarks also tested
**Vector boson vs fermion couplings: \( H \rightarrow ZZ^\ast \) example**

- Benchmark model with one scale factor for all vector bosons (\( \kappa_V \)), one for all fermions (\( \kappa_F \))

\[
\mu_{ggF;H\rightarrow ZZ} = \frac{\sigma(ggF) \cdot BR(H \rightarrow ZZ)}{\sigma_{SM}(ggF) \cdot BR_{SM}(H \rightarrow ZZ)} \rightarrow \frac{\kappa_F^2 \cdot \kappa_V^2}{\kappa_H(\kappa_F^2, \kappa_V^2)}
\]

\[
\mu_{VBF;H\rightarrow ZZ} = \frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H(\kappa_F^2, \kappa_V^2)}
\]

- \( \kappa_H(\kappa_F, \kappa_V) \) is a scale factor for \( \Gamma_H^{total} \)

\[
\kappa_H^2(\kappa_F^2, \kappa_V^2) = \alpha \cdot \kappa_F^2 + \beta \cdot \kappa_V^2
\]
Vector boson vs fermion couplings

- Total width is sum of known SM Higgs decay modes
  - Modified appropriately with $\kappa_V$ and $\kappa_F$

$$\kappa_V = 1.15 \pm 0.08$$

$$\kappa_F = 0.99^{+0.17}_{-0.15}$$

- Only relative sign physical $\rightarrow$ set $\kappa_V > 0$

- Sensitivity to relative sign from interference in $H \rightarrow \gamma\gamma$ decays

- 2D compatibility of SM with best fit 10%

Free parameters:

$\kappa_V, \kappa_F$
Vector boson vs fermion couplings

- Assumption on total width gives **strong constraint on** $\kappa_F$
  - Total width in SM dominated by $b, \tau$ and gluon decay widths
- Relax assumption by measuring **ratios of scale factors**

- Take ratio of fermion and vector scale factors $\lambda_{FV}$
- Then $\kappa_{VV}$ is an overall scale factor which applies to all rates

$$\lambda_{FV} = 0.86^{+0.14}_{-0.12}$$
$$\kappa_{VV} = 1.28^{+0.16}_{-0.15}$$

**Free parameters:**

$$\lambda_{FV} = \kappa_F / \kappa_V, \kappa_{VV} = \kappa_V \cdot \kappa_V / \kappa_H$$
Up-type vs down-type fermions

- One scale factor for up-type fermions and one for down-type
- Some SM extensions (e.g. some 2HDMs) predict different couplings for up- and down-type fermions
  - e.g. MSSM
- Take ratio of down and up scale factors $\lambda_{du}$

$$\lambda_{du} = 0.95^{+0.20}_{-0.18} \times$$

$$\lambda_{Vu} = 1.21^{+0.24}_{-0.26} \times$$

$$\kappa_{uu} = 0.86^{+0.41}_{-0.21} \times$$

For positive minima

- Little sensitivity to relative sign
- 3D compatibility with SM 20%
- $3.6\sigma$ evidence for coupling to down-type fermions

**Free parameters:**

$$\lambda_{du} = \frac{\kappa_d}{\kappa_u}, \quad \lambda_{Vu} = \frac{\kappa_V}{\kappa_u}, \quad \kappa_{uu} = \frac{\kappa_u \cdot \kappa_u}{\kappa_H}$$
Off shell Higgs couplings

- $H \rightarrow VV$ high mass region has sensitivity to off-shell Higgs production

$$\frac{d\sigma_{pp\rightarrow H\rightarrow ZZ}}{dM_{4\ell}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4\ell}^2 - m_H^2) + m_H^2 \Gamma_H^2}$$

- Using $\kappa$ language

$$\mu_{on-shell} = \frac{\kappa_H^2 \kappa_Z^2}{\kappa_g^2} \quad \mu_{off-shell} = \frac{\kappa_g \kappa_Z^2}{\kappa_H^2}$$

- Combining on- and off-shell results, can interpret as measurement of $\Gamma_H$

- Measurement performed by ATLAS using $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ and $H \rightarrow ZZ^{(*)} \rightarrow 2\ell 2\nu$

$$\frac{\Gamma_H}{\Gamma_{H,SM}} < 5.7 \text{ at } 95\% \text{ CL}$$
Constraints on new phenomena I: Additional Electroweak singlet

- Two Higgs bosons, one light ($h$), one heavy ($H$)
- Couple to vector bosons and fermions similar to SM but modified by scale factors
  - $\kappa + \kappa' = 1$
- $h$ couplings same as SM, modified by $\kappa$
- $H$ couplings modified to take into account new decay modes (e.g. $H \rightarrow hh$)

\[
\mu_H = \kappa'^2 (1 - BR_{H,new})
\]
\[
\kappa'^2 = 1 - \mu_h
\]

- Best fit at $\kappa'^2 = -0.30^{+0.17}_{-0.18}$
  - $1.5\sigma$ from physical boundary $\kappa'^2 \geq 0$
- Set limits in $\mu_H, BR_{H,new}$ plane

**ATLAS** Preliminary

- $\sqrt{s} = 7$ TeV: $\int L dt = 4.6$-4.8 fb$^{-1}$
- $\sqrt{s} = 8$ TeV: $\int L dt = 20.3$ fb$^{-1}$
- Combined $h \rightarrow \gamma\gamma, ZZ^*, WW^*, \tau\tau, b\bar{b}$

<table>
<thead>
<tr>
<th>$\mu_H$</th>
<th>$BR_{H,new}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Obs. 95% CL
Exp. 95% CL
SM
Constraints on new phenomena II: Invisible branching ratio and dark matter portals

- Derive upper limits on Higgs BR to invisible final states
- Uses couplings combination combined with upper limits on $ZH \rightarrow \ell\ell + E_T^{miss}$ process
- $BR_i < 0.37$ at 95% CL

- Higgs portal models introduce weakly-interacting massive particles as dark matter candidates
  - Assumed to interact weakly with SM particles except Higgs boson
- Can compare limits with direct dark matter searches
  - Assuming $m_{WIMP} < 0.5 \cdot m_H$ and $H \rightarrow 2WIMPs$ accounts for all of $BR_i$
LHC upgrade timescale

- HL-LHC upgrade proposed
  - Goal to collect $3000 \text{ fb}^{-1}$ by 2035

LHC / HL-LHC Plan

- Corresponding proposals for upgrades of the LHC experiments
  - Central feature of ATLAS upgrade programme a new, all silicon tracking system
Prospects for Higgs coupling measurements at a HL-LHC

**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 14 \text{ TeV}; \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \]

- **ATLAS** has studied the prospects for Higgs coupling studies with 3000 fb\(^{-1}\).

- **Generator-level MC** with parameterised model for detector efficiency and resolution:
  - Parameterisations from Geant4 simulation
    - 140 interactions per bunch crossing
  - Systematic uncertainties same as run I
    - Data-driven uncertainties scaled with int lumi

- **Hashed bands:** theoretical uncertainties at their current level

- **Projections** typically based on older versions of analyses - do not include recent improvements

- **Possible to measure** decay rates to sub 10% level
Prospects for Higgs coupling measurements at a HL-LHC

**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 14 \text{ TeV}; \int \text{Ldt} = 300 \text{ fb}^{-1}; \int \text{Ldt} = 3000 \text{ fb}^{-1} \]

- Potential to measure coupling ratios down to few % level with 3000 fb\(^{-1}\)
- Projections in terms of scaling of couplings as for run I, but likely to move to a more general framework, e.g. effective field theory
### Conclusion

- **ATLAS used LHC run I dataset to probe the coupling properties of the Higgs**
  - Results suggest that a non-zero VEV of a scalar doublet is indeed responsible for EWSB
  - Evidence for Higgs decays to fermions also seen in $\tau\tau$ final state
    - Observed rates agree with SM Yukawa coupling prediction

- So far no significant deviation from SM
- Increased precision anticipated during next LHC runs and beyond