ATLAS Results from Higgs searches

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ATLAS collaboration

UNLP/IFLP/CONICET
Higgs at the LHC: 7 TeV and 8 TeV runs

SM Higgs production cross sections vs Higgs mass at $\sqrt{s} = 8$ TeV

- At LHC, low mass SM Higgs production is dominated by gluon-gluon fusion ($\sim 19.5$ pb at $m_H = 125$ GeV).
- VBF is 10 times smaller ($\sim 1.6$ pb at $m_H=125$), two extra jets: used in several analyses to increase sensitivity and reduce background.
- Z/W/tt associated production: Used in $b\bar{b}$ final state to deal with huge jet backgrounds.
Higgs searches in ATLAS

1. **Higgs searches in ATLAS**
   - $H \rightarrow ZZ^* \rightarrow 4l$
   - $H \rightarrow \gamma\gamma$
   - $H \rightarrow WW(*)$
   - $H \rightarrow \tau\tau$
   - $H \rightarrow b\bar{b}$

2. **Combination**

Please visit [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults) for more information, conference notes, latest public results, plots, etc...
Higgs searches in ATLAS Combination

Higgs BR + Total Uncert

The “golden channel”

- Searches in mass range [110 GeV, 600 GeV]
- Small rates, but high S/B,
- Can be fully reconstructed, mass resolution \( \sim 2\% \) at 130 GeV
- Cross section times branching ratio (at \( m_H=125 \) GeV):
  - \( \sim 2.2 \) fb at \( \sqrt{s}=7 \) TeV
  - \( \sim 2.8 \) fb at \( \sqrt{s}=8 \) TeV

Optimised phase space to enhance low mass sensitivity

- \( p_T^{1,2,3,4} > 20,15, 10, 7 \) GeV (6 GeV for \( \mu \))
- Leading di-lepton mass: \( 50 < m_{1,2} < 106 \) GeV
- Subleading di-lepton mass: \( m_{thr}(m_{4l}) < m_{34} < 115 \) GeV ; \( m_{thr} = 17.5 - 50 \)
- All same-flavour opposite-sign pairs \( m_{ll} > 5 \) GeV
- \( \Delta R(l,l') > 0.10(0.20) \) for all same(different)-flavour
- Track and Calorimeter isolation requirements and impact parameter significance
Leptons identification performance

**Electron identification performance**

- Improved reconstruction and ID in 2012
  - New track finding/fitting
  - Pile-up robust Calorimeter based isolation
  - Higher rejection and efficiency with respect to 2011 data

**Muon identification performance**

- Combining/Matching ID tracks with complete or partial tracks in Muon Spectrometer
  - Extended muon coverage
  - ID-track + energy deposit profile in calorimeter ($|\eta| < 0.1 / p_T >$GeV)
  - MS stand-alone ($2.5 < |\eta| < 2.7$)
Event selection performance

**pp → Z → 4l**

- Relax analysis requirements: $m_{12(34)} > 30(5)$ GeV, lower $p_T$ for muons (4 GeV)
- Cross-check of analysis configuration
- Good behaviour of lepton reconstruction / identification

- Ratio of data-driven efficiency and MC efficiency of the reconstruction of $Z \rightarrow \mu\mu$ candidates vs $p_T$ of the $Z$
- Similar performance found for $Z \rightarrow ee$
- Excellent agreement between Data and MC → Detector and lepton ID performance well understood
The background composition depends on the flavour of the sub-leading di-lepton

Subleading di-muons: $m_{12}$ fit

- Remove isolation, fail IP significance (removes ZZ)
- $t\bar{t}$ and $Z+\text{jet}$ background dominated by $Zb\bar{b}$
- Yields from fitting the two components (shapes obtained from MC)
- Extrapolate to signal region
  - Transfer factors from MC
  - Cross-checked with data on different control regions

Main contribution from $Z+\text{jets}$

- Hadrons mis-identified as electrons ($f$)
- Electrons from photon conversions ($c/\gamma$)
- Electrons from semi-leptonic decays of heavy flavour ($Q$)

Cross checked using Same-Charge sub-leading di-electron as control region

Subleading di-electrons: Baseline method:

- Relax identification in sub-leading di-electron
- Use detector to ascertain the composition
  - Transition Radiation ($f$)
  - Number of B-layer hits ($c/\gamma$)
  - Fraction of energy in first sampling of e/m calorimeter ($f$)
  - Lateral containment of cluster along $\phi$ in 2nd e/m sampling ($f$)
  - Allows for a check of the MC composition
- Extrapolate yields in each category to the signal region using MC
Results: Event Yields

Observed events in the range $80 < m_{4\ell} < 600$ GeV for 7 and 8 TeV

For $m_{4\ell} > 160$ GeV:
- Observe slightly more events than expected: Reflected in the ATLAS measurement of $\sigma_{ZZ}$

Events in a mass window of $125\pm 5$ GeV

<table>
<thead>
<tr>
<th></th>
<th>$ZZ^{(*)}$</th>
<th>$Z +$ jets, $tt$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4\mu$</td>
<td>2.09±0.30</td>
<td>1.12±0.05</td>
<td>0.13±0.04</td>
</tr>
<tr>
<td>2$\mu$2$\mu$2$e$</td>
<td>2.29±0.33</td>
<td>0.80±0.05</td>
<td>1.27±0.19</td>
</tr>
<tr>
<td>$4e$</td>
<td>0.90±0.14</td>
<td>0.44±0.04</td>
<td>1.09±0.20</td>
</tr>
</tbody>
</table>

Expected S/B ($m_H=125$ GeV)
- $4\mu \sim 1.7$
- $2e2\mu2\mu2e \sim 1.1$
- $4e \sim 0.6$
Results: Exclusion limits

Expected and observed 95% CL upper limit on the SM Higgs boson production XS as a function of $m_H$

- Exclusion limits using $CL_S$, profile likelihood ratio
  - Exclusion: Expected: 124-164 and 176-500 [GeV]
  - Observed: 131-162 and 170-460 [GeV]
  - Much weaker than expected at 120-130 GeV

Statistics Treatment:
- profile likelihood ratio
- nuisance parameters for systematic uncertainties
Higgs searches in ATLAS Combination

Result: Significance of the excess

Observed local $p_0$ value for the combination of 2011 and 2012 data vs $m_H$. All mass range and Zoom in 110-180 GeV

At high $m_H$ small fluctuations from background
At low $m_H$ consistent excesses in 2011 and 2012
- Combined: $3.6\sigma$ @ 125 GeV
- Expected significance $2.7\sigma$
Results: Signal Strength

- $\mu = (\text{best fit signal rate at } m_H) / (\text{expected SM rate at } m_H)$
- Best fit value at $m_H = 125$ GeV (lowest $p_0$): $1.4 \pm 0.6$

### Data

![Data Plot]

### Signal Injection

![Signal Injection Plot]

### Best fit

![Best fit Plot]

$\mu = (\text{best fit signal rate at } m_H) / (\text{expected SM rate at } m_H)$
Best fit value at $m_H = 125$ GeV (lowest $p_0$): $1.4 \pm 0.6$
Higgs Searches

**Signature:** two high pt isolated photons

- Low branching ratio and High reducible background
- Expected signal: narrow resonance over smooth background

**Conceptually simple reconstruction**
- Trigger with diphoton trigger (more than 99% efficient)
- Two high pT photons $p_T > 40$ GeV, $p_T > 30$ GeV
- Tight photon Identification and isolation requirement to reject reducible background: Event selection efficiency $\sim 40\%$
- Data is splitted in categories to best exploit detector response and expected S/B.

**Requirements**

**Observable:** diphoton mass: $m_{\gamma\gamma}^2 = 2 \cdot E_1 E_2(1 - \cos(\alpha))$
- Robust photon reconstruction, identification and isolation
- Good energy calibration
- Good primary vertex identification (affects $\alpha$)
- Good background modeling
Performance on photons

- Photon reconstruction from LAr clusters and conversion vertices in the ID \( \rightarrow \) Robust against increased pile-up conditions.
- Isolation from positive energy topological clusters in calorimeters within \( \Delta R < 0.4 \)

Data-driven methods to determine photon identification efficiency, uncertainty estimated from MC

Photon ID uncertainty <5% above 40 GeV. Dominant uncertainty on signal Yield: \( \sim 10\% \)
Events Categorization

- Define categories with different S/B ratios
- Categories based on photon $\eta$, photon conversions and $p_{tT}$ ($p_T$ orthogonal to the thrust).
- Additional 2-Jet category (VBF)

Both Unconverted
- Central
- Rest

At least one converted
- Central
- Transiton
- Rest

Additional 2-Jet category (VBF)
- **Signature**: Two high $p_T$ jets from the PV and $\Delta\phi_{\gamma\gamma} - jj > 2.6$
- **Rapidity separation**: $\Delta\eta_{jj} > 2.8$ and $m_{jj} > 400$ GeV
Background composition

- **Data driven methods** used to estimate background composition
- Technique based on isolation template fits on background enriched sample and extrapolated to the signal region

After full event reconstruction, resulting background composition obtained:
- di-photon $\sim 80\%$
- photon-jet $\sim 20\%$
- jet-jet $\sim 1\text{-}2\%$

Electron contamination estimated to be $<< 1\%$

<table>
<thead>
<tr>
<th>$m_{\gamma\gamma}$ [GeV]</th>
<th>$\gamma\gamma$+DY</th>
<th>$\gamma$-jet</th>
<th>jet-jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV (NN ID)</td>
<td>(80 $\pm$ 4)%</td>
<td>(19 $\pm$ 3)%</td>
<td>(1.8 $\pm$ 0.5)%</td>
</tr>
<tr>
<td>8 TeV (Cut ID)</td>
<td>(75 $\pm$ 3)%</td>
<td>(22 $\pm$ 2)%</td>
<td>(2.6 $\pm$ 0.5)%</td>
</tr>
</tbody>
</table>
Higgs searches in ATLAS Combination

Signal and background modeling

- Signal is modeled with a **Crystall Ball function** (width dominated by detector resolution) + wide Gaussian to account for poorly reconstructed energy
- Functional form of background is determined using MC but normalization and parameters set using fit to data \(m_{\gamma\gamma}\) distribution

Test Bias on background models

- Accept model if the spurious signal is < 10% of expected signal or < 20% of fitted signal uncertainty
- Among the models left, choose the one with the best expected \(p_0\) at 125 GeV

<table>
<thead>
<tr>
<th>Category</th>
<th>Parametrization</th>
<th>Uncertainty [(N_{\text{evt}})]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(\sqrt{s} = 7) TeV</td>
</tr>
<tr>
<td>Inclusive</td>
<td>4th order pol.</td>
<td>7.3</td>
</tr>
<tr>
<td>Unconverted central, low (p_{Tt})</td>
<td>Exp. of 2nd order pol.</td>
<td>2.1</td>
</tr>
<tr>
<td>Unconverted central, high (p_{Tt})</td>
<td>Exponential</td>
<td>0.2</td>
</tr>
<tr>
<td>Unconverted rest, low (p_{Tt})</td>
<td>4th order pol.</td>
<td>2.2</td>
</tr>
<tr>
<td>Unconverted rest, high (p_{Tt})</td>
<td>Exponential</td>
<td>0.5</td>
</tr>
<tr>
<td>Converted central, low (p_{Tt})</td>
<td>Exp. of 2nd order pol.</td>
<td>1.6</td>
</tr>
<tr>
<td>Converted central, high (p_{Tt})</td>
<td>Exponential</td>
<td>0.3</td>
</tr>
<tr>
<td>Converted rest, low (p_{Tt})</td>
<td>4th order pol.</td>
<td>4.6</td>
</tr>
<tr>
<td>Converted rest, high (p_{Tt})</td>
<td>Exponential</td>
<td>0.5</td>
</tr>
<tr>
<td>Converted transition</td>
<td>Exp. of 2nd order pol.</td>
<td>3.2</td>
</tr>
<tr>
<td>2-jets</td>
<td>Exponential</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- Categories with low statistics → exponential
- “Spurious” defined by fitting S+B model to B only MC
Higgs searches in ATLAS Combination

Higgs searches in ATLAS Combination

Invariant mass distribution

Dominant sources of systematic uncertainty on yield

- Photon ID efficiency: \( \sim 10\% \)
- Energy resolution: \( \sim 0.6\% \)
- Isolation: \( \sim 1\% \)
- Pileup: \( \sim 4\% \)
- Lumi: 1 - 3.6 \% (2011-2012)
- Theory cross section:
  - < 25\% (for VBF contributions)
  - < 12\% (in other ggF)
  - Underlying event: < 5\%
  - \( p_T \) distribution: < 5\% (for high \( p_T \))
- Background parameters: 0.2-4.6\% (0.3-6.8\%) for 2011 (2012)

For VBF category

- Jet energy scale: 9-10\%
- Underlying event: 6-30\%
- Higgs \( p_T \): < 12.5\%

23788 events (7 TeV) and 35251 events (8 TeV)

Background+signal fit, signal fixed at 126.5 GeV
Quantifying the excess

- Maximum deviation from SM-only expectation at $m_{\gamma\gamma}=126.5$ GeV
- Local significance $4.5\sigma$ (2.4 $\sigma$ expected from SM)

Effect of combining 2011 and 2012

Results consistent between 2011 and 2012 and improved by VBF category

Results consistent between inclusive analysis (no categories) and with categories
Higgs searches in ATLAS Combination

\[ H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu \]

**Signature:** \( \ell\ell\not{E}_T \)

- **Major backgrounds:** continuum WW, top production, W+jets with a fake lepton, Z/\( \gamma^* \) + fake \( \not{E}_T \), W\( \gamma^*(\ast) \)
- We use only the “different flavor” channel \( e\nu\mu\nu \) to avoid the contamination of Z/\( \gamma^* \rightarrow ee, \mu\mu \)
  - Pileup \( \rightarrow \) bad \( \not{E}_T \) resolution for Z/\( \gamma^* \) rejection
- Higgs decays kinematically different from backgrounds, allows definition of signal-rich and control regions
- **Higgs mass proxy:** transverse mass variable

\[
m_T \equiv \sqrt{\left( \sqrt{p_T^{\ell\ell}^2 + m_{\ell\ell}^2 + \not{E}_T^2} \right)^2 - |p_T^{\ell\ell} + \not{E}_T|^2}
\]

- \( H \rightarrow WW \rightarrow \ell\nu\ell\nu \) is one of the more abundant Higgs final states at 125 GeV
- Provides best current probe of HWW coupling
- Results of \( H \rightarrow WW \) production analysis with 13 fb\(^{-1}\) of 8 TeV data
Higgs event selection

- Opposite sign $e\mu$ candidates, $M(\ell\ell) > 10$ GeV
- $E_T^{\text{rel}} > 25$ GeV to remove $Z \rightarrow \tau\tau$
  \[ E_T^{\text{rel}} = E_T \sin(\min(\Delta\phi_m, \pi/2)) \]
  \[ \phi_m \equiv \min(\Delta\phi(\ell \text{ or } j, E_T)) \]
- $\leq 1$ jet to remove top quark background
- Reduces our sensitivity to vector boson fusion production

**ATLAS Preliminary**

\[ \sqrt{s} = 8 \text{ TeV}, \int L dt = 13.0 \text{ fb}^{-1} \]

$H \rightarrow WW^{(*)} \rightarrow e\nu\mu/\mu\nu e\nu$

\[ \sqrt{s} = 8 \text{ TeV}, \int L dt = 13.0 \text{ fb}^{-1} \]

$H \rightarrow WW^{(*)} \rightarrow e\nu\mu/\mu\nu e\nu$
Composition in Signal region

- $m_T$ distributions, showing data, expected signal at $m_H = 125$ GeV (red) and Background composition from data-driven enriched background control regions (see backup) and MC simulations

- S/B ratio ranging 13% to 16%

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**ATLAS Preliminary**
- **0Jet**

- **ATLAS Preliminary**
- **1Jet**

F. Monticelli - ATLAS
SILAFAE2012, December 11, 2012
Results

- signal significance $2.6\sigma$ (expected $1.9\sigma$)
- signal strength (ratio to SM rate) $\mu = 1.5 \pm 0.6$

$m_H = 125$ GeV

From data
\[ \sigma(pp \to H) \cdot Br(H \to WW) = 7.0^{+1.7}_{-1.6}\,(stat) \pm 1.6\,(theory) \pm 1.3\,(exp) \pm 0.3\,(lumi) \,pb \]

From SM expectations
\[ \sigma(pp \to H) \cdot Br(H \to WW) = 4.77 \pm 0.64\,(x-sec) \pm 0.2\,(BR) \,pb \]
Higgs searches in ATLAS Combination

\[ H \rightarrow \tau\tau \]

- \( H \rightarrow \tau\tau \) provides an unique opportunity to probe the Yukawa coupling, which gives mass to quarks and leptons
- It has one of the largest branching ratios for low mass Higgs

Three production mechanisms considered

Results with 4.6 fb\(^{-1}\) (7TeV) and 13 fb\(^{-1}\) (8TeV) data

Separate analysis dot three different \( \tau\tau \) decay mode:

- lep-lep: \( \ell\ell 4\nu \): (ee) + e\(\mu\) + \(\mu\mu\)
- lep-had: \( \ell\tau_{had} 3\nu \): e\(\tau_{had}\) + \(\mu\tau_{had}\)
- had-had: \( \tau_{had}\tau_{had} \nu\nu \): \(\tau_{had}\tau_{had}\)

Combined all three channels to search for \( H \rightarrow \tau\tau \)
Event categorization

- **Single Lepton + \( \tau_{\text{had}} \)**
  - VBF Selection (high pt 2jets with high \( \Delta\eta_{jj} \) and \( m_{jj} \))
  - Not VBF
  - Boost Selection (high pt jets + high Higgs pT)
  - Not Boost
  - 0-jet
  - \( \geq 1 \)-jet

- **Two Lepton**
  - VBF Selection (high pt 2jets with high \( \Delta\eta_{jj} \) and \( m_{jj} \))
  - Not VBF
  - Boost Selection (high pt jets + high Higgs pT)
  - Not Boost
  - VH selection (\( m_{jj} \sim m_{Z/W} \))
  - \( \geq 1 \)-jet

- **Two \( \tau_{\text{had}} \)**
  - Not VBF
  - Not Boost
  - 2 two \( \tau_{\text{had}} \) Category
  - Not VH

- **6 Single lepton Category**
  - 4 two-lepton Category

Quite similar categorization for 2011. 2011 and 2012 data were treated as separate categories.
Di-tau mass reconstruction

- Di-tau invariant mass should be a important discriminating variable from backgrounds.
- **But:** there are 2 to 4 $\nu$ in each event!

Event by Event estimator of true di-$\tau$ mass likelihood

Full reconstruction of event kinematics.

**Missing Mass Calculator (MMC)**

- Solves $\tau, E_T^\tau$ in $\Delta\phi(\tau_{\text{vis}}, \nu)$ parameter space using $\Delta\phi_{3D}(\tau, \nu)$ template from simulation as PDF.
Background estimation

**Higgs searches in ATLAS Combination**

- $H \rightarrow ZZ^* \rightarrow 4l$  
- $H \rightarrow \gamma\gamma$  
- $H \rightarrow WW^{(*)}$  
- $H \rightarrow \tau\tau$  
- $H \rightarrow b\bar{b}$

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**Background estimation**

$Z \rightarrow \tau\tau$ estimated by **embedding+MC**

- Used $Z \rightarrow \mu\mu$ data and replace $\mu$ by full simulated $\tau$, so that all the objects except tau decay product are obtained by real data.
- Used high statistics MC for VBF channel with correction by data.

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**Background processes considered**

- $Z \rightarrow \tau\tau$ (Dominant and largely irreducible)
- QCD jets
- W/Z+jets
- pairs of top quarks ($t\bar{t}$)
- single tops
- pair of EW gauge bosons (WW, WZ, ZZ)

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$Z \rightarrow ee/\mu\mu$+ Jets, di-boson

- Determined by scaling in MC + correction factors from comparing data to simulation in control regions enriched in these backgrounds

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**QCD and W+Jets**

- **lep-had**: Estimated from Same Sign events
- **lep-lep, had-had**: Template fit by loose selection

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Higgs Signal is on the right hand side tail of $Z$. 

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F. Monticelli - ATLAS

SILAFAE2012, December 11, 2012
Results: combined limit and p0

- Calculated limit and significance using MMC distribution as the discriminant.
- To extract signal, Profile likelihood was used.

<table>
<thead>
<tr>
<th>95% CL limit</th>
<th>local p0</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="" /></td>
<td><img src="image2" alt="" /></td>
</tr>
</tbody>
</table>

Expected: $1.2 \times$ SM, Observed: $1.9 \times$ SM

Expected: $1.7 \sigma$, Observed: $1.1 \sigma$

Best fit value of Signal Strength ($\mu$) is $0.7 \pm 0.7$
The search for $H \rightarrow b\bar{b}$ is important to understand if new particle is SM

- Most prevalent SM Higgs decay
  - At $m_H \sim 125\text{GeV}$: $\text{BR}(H \rightarrow b\bar{b}) \sim 58\%$
  - Direct constraint on coupling to fermions

Input to measuring VH & tH couplings

- Very challenging jet backgrounds
  - 7-8 orders of magnitude greater
- Utilise associated production $V=W,Z$ and $tt$
- Clean leptonic decay signatures for trigger and offline analysis to reject background events
Search strategy

- Search for Higgs decaying to pair of b-quarks
  - Associated production to reduce backgrounds
- The analysis is divided into three channels
  - Two ($\ell\ell bb$), one ($\ell\nu bb$), or zero ($\nu\nu bb$) lepton final state: ($\ell = e, \mu$)
- Cuts common to all channels
  - Two or three jets $p_T^{1\text{st Jet}} > 45\text{GeV}$, $p_T^{\text{others}} > 20\text{GeV}$
  - Two b-tags: 70% efficiency per tag (mis-tag $\sim 1\%$)
- Data used: 4.7$fb^{-1}$ for $\sqrt{s}=7\text{ TeV}$ (2011) & 13$fb^{-1}$ at $\sqrt{s}=8\text{ TeV}$ (2012)
  - S/B is not large, but increases as $p_T^{bb}$ increases

<table>
<thead>
<tr>
<th>Two $\ell$</th>
<th>One $\ell$</th>
<th>Zero $\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ZH \rightarrow \ell\ell bb$</td>
<td>$WH \rightarrow \ell\nu bb$</td>
<td>$ZH \rightarrow \nu\nu bb$</td>
</tr>
<tr>
<td>- No additional leptons</td>
<td>- No additional leptons</td>
<td>- No leptons</td>
</tr>
<tr>
<td>- $E_T &lt; 60\text{ GeV}$</td>
<td>- $E_T &gt; 25\text{ GeV}$</td>
<td>- $E_T &gt; 120\text{ GeV}$</td>
</tr>
<tr>
<td>- $83 &lt; m_Z &lt; 99\text{ GeV}$</td>
<td>- $40 &lt; m_T^W &lt; 120\text{ GeV}$</td>
<td>- met trigger</td>
</tr>
<tr>
<td>- Single &amp; di-lepton trigger</td>
<td>- Single lepton trigger</td>
<td></td>
</tr>
</tbody>
</table>
Analysis

16 signal categories with cuts optimised for each

0-lepton: $E_T^{[120-160]} [160-200] [>200]$ GeV x (2 jets or 3 jets)

1 & 2 leptons: $p_T^{W/Z}$ [0-50], [50,100], [100-150], [150-200], [>200] GeV

Some improvements

- Muon energy ($p_T > 4$ GeV) added for b-jets (increased resolution)
- Apply ttbar based b-tagging calibration (reduces systematic at high pT)

Background

- Background shapes from simulation and normalised using data (flavour & signal fit)
- Multi-jet bkg determined by data-driven techniques
- $WZ(Z \rightarrow b\bar{b})$ & $ZZ(Z \rightarrow b\bar{b})$ resonant bkg normalisation and shape from simulation
Results: Di-boson production

- WZ & ZZ production with $Z \rightarrow b\bar{b}$ similar signature, but 5 times larger cross-section
- Perform a separate fit to search for it and to validate the analysis procedure
  - Profile likelihood fit performed (with full systematics)
  - All backgrounds (except diboson) subtracted
  - Uses full $p_T^{W,Z}$ range, done individually for each channel & year
- Clear excess of $Z \rightarrow b\bar{b}$ is observed in data at expected mass (all lepton channels combined)
- Results: $\sigma/\sigma_{SM} = \mu_D = 1.09 \pm 0.20 \text{ (stat)} \pm 0.22 \text{ (syst)}$. The significance is $4.0\sigma$

![Plot showing data and background for WZ, ZZ, WH, and ZH channels at 125 GeV, with integrated luminosities of 13.0 fb$^{-1}$ at 8 TeV and 4.7 fb$^{-1}$ at 7 TeV for 0, 1, or 2 leptons.](attachment:image.png)
Results: Limits and p0

- **Observed (expected) limit at m_H = 125 GeV**
  - 1.8 (1.9) x SM prediction
  - $\sigma/\sigma_{SM} = \mu = -0.4 \pm 0.7\,(\text{stat.}) \pm 0.8\,(\text{syst.})$
- **Observed (expected) p0 value:** 0.64 (0.15)
- **Exclusion at m_H $\sim$ 110 GeV**

More than doubled the analysis sensitivity w.r.t. 2011!
### Atlas Combined results: Channels and data

<table>
<thead>
<tr>
<th>Higgs Boson Decay</th>
<th>Subsequent Decay</th>
<th>Sub-Channels</th>
<th>∫LdT [fb⁻¹]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \rightarrow ZZ^{(*)} )</td>
<td>4( \ell )</td>
<td>{4e,2e2( \mu ),2( \mu )2e,4( \mu )}</td>
<td>4.8</td>
<td>[1]</td>
</tr>
<tr>
<td>( H \rightarrow \gamma\gamma )</td>
<td>–</td>
<td>10 categories {( p_T )( \otimes )( n_\gamma )( \otimes )conversion} ( \otimes ){2-jet}</td>
<td>4.8</td>
<td>[1]</td>
</tr>
<tr>
<td>( H \rightarrow \tau\tau )</td>
<td>( \tau_{lep} \tau_{lep} )</td>
<td>{e( \mu )( \otimes )0-jet} ( \otimes ){( \ell\ell )( \otimes )1-jet, 2-jet, ( p_{T,\tau\tau} ) &gt; 100 GeV, ( V\bar{H} )}</td>
<td>4.6</td>
<td>[4]</td>
</tr>
<tr>
<td>( H \rightarrow \tau\tau )</td>
<td>( \tau_{lep} \tau_{had} )</td>
<td>{e,( \mu )( \otimes )0-jet, 1-jet, ( p_{T,\tau\tau} ) &gt; 100 GeV, 2-jet}</td>
<td>4.6</td>
<td>[4]</td>
</tr>
<tr>
<td>( H \rightarrow \tau\tau )</td>
<td>( \tau_{had} \tau_{had} )</td>
<td>{1-jet, 2-jet}</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>( VH \rightarrow Vbb )</td>
<td>( Z \rightarrow \nu\nu )</td>
<td>( E_{T,miss}^{miss} \in [120 - 160, 160 - 200, \geq 200 \text{ GeV}] \otimes {2-jet, 3-jet} )</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>( VH \rightarrow Vbb )</td>
<td>( W \rightarrow \ell\nu )</td>
<td>( p_{T,\ell} \in [&lt; 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}] )</td>
<td>4.7</td>
<td>[5]</td>
</tr>
<tr>
<td>( VH \rightarrow Vbb )</td>
<td>( Z \rightarrow \ell\ell )</td>
<td>( p_{T,\ell} \in [&lt; 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}] )</td>
<td>4.7</td>
<td></td>
</tr>
</tbody>
</table>

### Data from 2011 and from 2012

- **Combining results from different channels in several categories**
- **Data from 2011 and from 2012**
- **Strength from channels at m\( H \)=126 \text{ GeV}**
New particle with local significance of 5.9$\sigma$

<table>
<thead>
<tr>
<th>Channel Fitted</th>
<th>$m_H$</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>126.5 GeV</td>
<td>4.5$\sigma$</td>
<td>2.5$\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow ZZ^* \rightarrow 4\ell$</td>
<td>125.0 GeV</td>
<td>3.6$\sigma$</td>
<td>2.7$\sigma$</td>
</tr>
<tr>
<td>$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$</td>
<td>125.0 GeV</td>
<td>2.8$\sigma$</td>
<td>2.3$\sigma$</td>
</tr>
<tr>
<td>Combined</td>
<td>126.0 GeV</td>
<td>5.9$\sigma$</td>
<td>4.9$\sigma$</td>
</tr>
</tbody>
</table>

- local p0 vs Higgs mass
**Atlas Combined results: Signal Strengths**

- $H \rightarrow b\bar{b}$, $\tau\tau$ and $WW^*$ analyses have been updated using $13fb^{-1}$ data collected at 8 TeV in 2012.

- Higgs decays to $\gamma\gamma$, $ZZ^*$ and $WW^*$ are established, but $H \rightarrow b\bar{b}$, $\tau\tau$ still lack of statistics to draw definitive conclusion.

**Best-fit signal strength:**

$$\mu = 1.3 \pm 0.3$$

**Best-fit Higgs mass $m_H$:**

$$126.0 \pm 0.4{\text{(stat)}} \pm 0.4{\text{(syst)}} \text{ GeV}$$
Updated ATLAS results on observation of new particle presented

- Very good understanding of final state particles/jets/$E_T$ identification, performance and uncertainties
  - Using Data-driven methods for efficiency measurements and background composition
- Several Higgs decay channels and several categories: complex analysis, very challenging
- Analysis on each channel improved in 2012 w.r.t. 2011 inspite of higher pile-up.

**Brief summary in numbers**

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\int L dt$ [$fb^{-1}$]</th>
<th>$m_H$ for lowest $p_0$</th>
<th>Significance</th>
<th>$\mu @126$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow ZZ^{(*)}$</td>
<td>4.8 5.8</td>
<td>125 GeV</td>
<td>3.6$\sigma$</td>
<td>1.2 $\pm$ 0.6</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>4.8 5.9</td>
<td>126.5 GeV</td>
<td>4.5$\sigma$</td>
<td>1.8 $\pm$ 0.5</td>
</tr>
<tr>
<td>$H \rightarrow WW^{(*)}$</td>
<td>— 13</td>
<td>111 GeV</td>
<td>2.8$\sigma$</td>
<td>1.4 $\pm$ 0.6</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>4.6 13</td>
<td>—</td>
<td>1.1$\sigma$</td>
<td>0.7 $\pm$ 0.7</td>
</tr>
<tr>
<td>$VH \rightarrow Vbb$</td>
<td>4.6 - 4.7 13</td>
<td>—</td>
<td>—</td>
<td>-0.4 $\pm$ 1.1</td>
</tr>
<tr>
<td>Combined</td>
<td>$\sim 5$ $\sim 6, \sim 13$</td>
<td>126 GeV</td>
<td>5.9 $\sigma$</td>
<td>1.3 $\pm$ 0.3</td>
</tr>
</tbody>
</table>
Select a background-dominated control region

Remove isolation/impact parameter requirements on sub-leading di-lepton

Normalisation taken from data-driven estimates

Normalization/shape of reducible backgrounds well described
Reducible background estimates:

<table>
<thead>
<tr>
<th>Method</th>
<th>Estimated number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8 TeV</strong></td>
<td></td>
</tr>
<tr>
<td>$m_{12}$ fit: $Z + \text{jets}$ contribution</td>
<td>$0.51 \pm 0.13 \pm 0.16$†</td>
</tr>
<tr>
<td>$m_{12}$ fit: $\tilde{t}\tilde{t}$ contribution</td>
<td>$0.044 \pm 0.015 \pm 0.015$†</td>
</tr>
<tr>
<td>$\tilde{t}\tilde{t}$ from $e^+\mu^+ + \mu^+\mu^+$</td>
<td>$0.058 \pm 0.015 \pm 0.019$</td>
</tr>
<tr>
<td><strong>7 TeV</strong></td>
<td></td>
</tr>
<tr>
<td>$m_{12}$ fit: $Z + \text{jets}$ contribution</td>
<td>$0.25 \pm 0.10 \pm 0.08$†</td>
</tr>
<tr>
<td>$m_{12}$ fit: $\tilde{t}\tilde{t}$ contribution</td>
<td>$0.022 \pm 0.010 \pm 0.011$†</td>
</tr>
<tr>
<td>$\tilde{t}\tilde{t}$ from $e^+\mu^+ + \mu^+\mu^+$</td>
<td>$0.025 \pm 0.009 \pm 0.014$</td>
</tr>
</tbody>
</table>

- Multiple methods are used which yield compatible results
\( \mu = 1.48^{+0.35}_{-0.33} \pm 0.05 \) (lumi)

\( \mu = 1.48^{+0.41}_{-0.36} \) (systheory) \( \mu = 0.28 \) (sysexp)
**Higgs searches in ATLAS Combination**

**H → ww* candidate selection: 0J**

- Expect leptons to preferentially have small separation:
  - high total momentum, small azimuthal separation, small invariant mass
  - Require $E_T$ in opposite hemisphere from dilepton system

---

**ATLAS** Preliminary

$\sqrt{s} = 8$ TeV, $\int L dt = 13.0$ fb$^{-1}$

$H \rightarrow WW^{(*)} \rightarrow e\nu\mu/\mu\nu\nu$ (0 jets)

- Data
- $WW$
- $t\bar{t}$
- Single Top
- $Z$+jets
- $W$+jets
- $H$ [125 GeV]

---

**ATLAS** Preliminary

$\sqrt{s} = 8$ TeV, $\int L dt = 13.0$ fb$^{-1}$

$H \rightarrow WW^{(*)} \rightarrow e\nu\mu/\mu\nu\nu$ (0 jets)

- Data
- $WW$
- $t\bar{t}$
- Single Top
- $Z$+jets
- $W$+jets
- $H$ [125 GeV]
Higgs searches in ATLAS Combination

**H → ww* candidate selection: 1J**

- Jet cannot be b-tagged
- Z → ττ veto using collinear approximation
- Require small $m_{\ell\ell}$ and $\Delta\phi_{\ell\ell}$ as in 0 jet bin

After b-veto and Z → ττ veto

Additional $m_{\ell\ell} < 50$ GeV requirement

---

**Graphs:**

- Left graph: Events / 10 GeV vs. $m_{ll}$ (GeV) for $H \rightarrow WW^{(*)} \rightarrow \ell\ell\nu\nu$ (1 jet).
- Right graph: Events / 0.13 rad vs. $\Delta\phi_{ll}$ (rad) for $H \rightarrow WW^{(*)} \rightarrow \ell\ell\nu\nu$ (1 jet).
**Background**

**Top control region**

- **ATLAS Preliminary**
  - $\sqrt{s} = 8$ TeV, $L_{\text{int}} = 13.0$ fb$^{-1}$
  - $H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu e\nu$ (1 jet)

- *Reverse b-jet veto in 1 jet bin.*
- *Good agreement between MC and data*

**WW Continuum control region**

- **Normalization differences to between data and MC. Data/MC ratios:**
  - 0 Jet category: $0.840 \pm 0.078$
  - 1 Jet category: $1.125 \pm 0.040$
- *Taken into account in the signal yield fit*
- *Top contribution normalized via top CR*

F. Monticelli - ATLAS
SILAFAE2012, December 11, 2012
## Uncertainties on expected Yields

<table>
<thead>
<tr>
<th>Source (0-jet)</th>
<th>Signal (%)</th>
<th>Bkg. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive ggF signal ren./fact. scale</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>1-jet incl. ggF signal ren./fact. scale</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>PDF model (signal only)</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>QCD scale (acceptance)</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>W+jets fake factor</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>WW theoretical model</td>
<td>-</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source (1-jet)</th>
<th>Signal (%)</th>
<th>Bkg. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-jet incl. ggF signal ren./fact. scale</td>
<td>26</td>
<td>-</td>
</tr>
<tr>
<td>2-jet incl. ggF signal ren./fact. scale</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>Parton shower/ U.E. model (signal only)</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>$b$-tagging efficiency</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td>PDF model (signal only)</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>QCD scale (acceptance)</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Jet energy scale and resolution</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>W+jets fake factor</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>WW theoretical model</td>
<td>-</td>
<td>3</td>
</tr>
</tbody>
</table>

## Uncertainties on measured signal strength $\mu$

<table>
<thead>
<tr>
<th>Source</th>
<th>Upward uncertainty (%)</th>
<th>Downward uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainty</td>
<td>+23</td>
<td>-22</td>
</tr>
<tr>
<td>Signal yield ($\sigma \cdot Br$)</td>
<td>+14</td>
<td>-9</td>
</tr>
<tr>
<td>Signal acceptance</td>
<td>+9</td>
<td>-6</td>
</tr>
<tr>
<td>WW normalisation, theory</td>
<td>+20</td>
<td>-20</td>
</tr>
<tr>
<td>Other backgrounds, theory</td>
<td>+9</td>
<td>-9</td>
</tr>
<tr>
<td>W+jets fake rate</td>
<td>+11</td>
<td>-12</td>
</tr>
<tr>
<td>Experimental + bkg subtraction</td>
<td>+14</td>
<td>-11</td>
</tr>
<tr>
<td>MC statistics</td>
<td>+8</td>
<td>-8</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>+41</td>
<td>-38</td>
</tr>
</tbody>
</table>
Highest sensitivity channels are VBF category.
Limited statistics but Good S/B ratio.
Dominant systematics are Embedding, Tau Energy Scale and Jet Energy Scale Table in backup.
Boost category is the best sensitivity in non-VBF category.
0/1 jet non-boost events also used for limit calculation.

<table>
<thead>
<tr>
<th>Boost category</th>
</tr>
</thead>
<tbody>
<tr>
<td>lep-lep</td>
</tr>
</tbody>
</table>

![Boost category plots](image-url)
Systematic uncertainties for $Z \rightarrow \tau\tau$ background and Signal.

- Dominant systematics are Embedding, Tau Energy Scale and Jet Energy Scale.
- Both Shape and Normalization variation are taken into account.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$H \rightarrow \tau_{lep}\tau_{lep}$</th>
<th>$H \rightarrow \tau_{lep}\tau_{had}$</th>
<th>$H \rightarrow \tau_{had}\tau_{had}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embedding</td>
<td>1–4% (S)</td>
<td>2–4% (S)</td>
<td>1–4% (S)</td>
</tr>
<tr>
<td>Tau Energy Scale</td>
<td>--</td>
<td>4–15% (S)</td>
<td>3–8% (S)</td>
</tr>
<tr>
<td>Tau Identification</td>
<td>--</td>
<td>4–5%</td>
<td>1–2%</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>2–4%</td>
<td>2–5%</td>
<td>2–4%</td>
</tr>
<tr>
<td>Normalisation</td>
<td>4.7%</td>
<td>4% (non-VBF), 16% (VBF)</td>
<td>9–10%</td>
</tr>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$H \rightarrow \tau_{lep}\tau_{lep}$</th>
<th>$H \rightarrow \tau_{lep}\tau_{had}$</th>
<th>$H \rightarrow \tau_{had}\tau_{had}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>1.0–5.0% (S)</td>
<td>3–9% (S)</td>
<td>2–4% (S)</td>
</tr>
<tr>
<td>Tau Energy Scale</td>
<td>--</td>
<td>2–9% (S)</td>
<td>4–6% (S)</td>
</tr>
<tr>
<td>Tau Identification</td>
<td>--</td>
<td>4–5%</td>
<td>10%</td>
</tr>
<tr>
<td>Theory</td>
<td>7.9–28%</td>
<td>18–23%</td>
<td>3–20%</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>small</td>
<td>small</td>
<td>5%</td>
</tr>
</tbody>
</table>

See backup for ggF plots
Higgs searches in ATLAS Combination

Production dependence

\[ \mu_{ggF} = \frac{\sigma_{ggH}}{\sigma_{SM}} \]

\[ \mu_{VBF+VH} = \frac{\sigma_{VBF}}{\sigma_{SM}} = \frac{\sigma_{WH}}{\sigma_{SM}} = \frac{\sigma_{ZH}}{\sigma_{SM}} \]

Best fit and likelihood contours for the H→ττ channel in the \((\mu_{ggF} \times B/B_{SM}, \mu_{VBF+VH} \times B/B_{SM})\) plane are shown for the 68% and 95% CL.

- Consistent both to SM and bkg only hypothesis with large error.
- It is quite important to see where this best fit converged to!
1. **Flavour fit:** maximum likelihood fit over control (0, 1, 2 b-tagged and top) and signal regions.

- Exploits that the b-tagging efficiency is very different for b, c and light jets.
- Determine V+light and V+c scale factors

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + c$</td>
<td>$1.99 \pm 0.51$</td>
<td>$0.71 \pm 0.23$</td>
</tr>
<tr>
<td>$Z + \text{light}$</td>
<td>$0.91 \pm 0.12$</td>
<td>$0.98 \pm 0.11$</td>
</tr>
<tr>
<td>$W + c$</td>
<td>$1.04 \pm 0.23$</td>
<td>$1.04 \pm 0.24$</td>
</tr>
<tr>
<td>$W + \text{light}$</td>
<td>$1.03 \pm 0.08$</td>
<td>$1.01 \pm 0.14$</td>
</tr>
</tbody>
</table>

2. **Improved understanding of bkg V pT**

- Using the high statistics at 8 TeV it was found that the V pT spectrum falls more rapidly in data than expected from MC.
- $W + \text{jets}$ and $Z + \text{jets}$: 5-10% correction required
- Top background: 15% correction required

Flavour fit produces excellent MC/data agreement in 12 data regions

3. **Binned profile likelihood fit to 16 signal regions & top control regions**

- $W+b$, $Z+b$ and top bkg are floated in fit
- Rescaling factors from the fit

<table>
<thead>
<tr>
<th></th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>$1.10 \pm 0.14$</td>
<td>$1.29 \pm 0.16$</td>
</tr>
<tr>
<td>$Z + b$</td>
<td>$1.22 \pm 0.20$</td>
<td>$1.11 \pm 0.15$</td>
</tr>
<tr>
<td>$W + b$</td>
<td>$1.19 \pm 0.23$</td>
<td>$0.79 \pm 0.20$</td>
</tr>
</tbody>
</table>
Systematic uncertainties

Main experimental uncertainties

- **b-tagging and jet energy dominate**
  - Jets: components (7 JES, 1 pTReco, resol.)
  - ETmiss – scale and resolution
  - bTagging – light, c & 6 pT efficiency bins
  - Top, W, Z background modelling
  - Lepton/ Multijet / diboson / Luminosity
  - MC statistics

Main theoretical uncertainties

- W/Z+jet mbb and V pT
- BR($H \rightarrow b\bar{b}$) @ mH=125 GeV
- Signal cross-sections include pT-dependent electroweak correction factors
- Single top/top normalisation
- W+c, Z+c

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>0 lepton</th>
<th>1 lepton</th>
<th>2 lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$-tagging</td>
<td>8.9</td>
<td>9.0</td>
<td>8.8</td>
</tr>
<tr>
<td>Jet/Pile-up/$E_T^{miss}$</td>
<td>19</td>
<td>25</td>
<td>6.7</td>
</tr>
<tr>
<td>Lepton</td>
<td>0.0</td>
<td>0.0</td>
<td>2.1</td>
</tr>
<tr>
<td>$H \rightarrow bb$ BR</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>VH $p_T$-dependence</td>
<td>5.3</td>
<td>8.1</td>
<td>7.6</td>
</tr>
<tr>
<td>VH theory PDF</td>
<td>3.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>VH theory scale</td>
<td>1.6</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Statistical</td>
<td>4.9</td>
<td>18</td>
<td>4.1</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.6</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>24</td>
<td>34</td>
<td>16</td>
</tr>
</tbody>
</table>
Fits for 2-parameter benchmark models probing coupling strength scale factors for fermions and vector bosons.

**Assumptions**
- Total width is negligible → \( \sigma \times \text{BR}(ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{H}} \)
- No BSM particles contributes to \( gg \rightarrow H\gamma\gamma \) and to total width
- Two coupling scale factors: \( k_f = k_t = k_b = k_\tau \) and \( k_v = k_W = k_Z \)

<table>
<thead>
<tr>
<th>( k_f )</th>
<th>( k_v )</th>
</tr>
</thead>
<tbody>
<tr>
<td>([-1.0, -0.7] \cup [0.7, 1.3])</td>
<td>([0.9, 1.0] \cup [1.1, 1.3])</td>
</tr>
</tbody>
</table>

**Relaxing assumption**
- Same as above, but without the assumption on the total width: \( \lambda_{FV} = k_F/k_V, k_{VV} = K_V \cdot K_V/K_H \)

<table>
<thead>
<tr>
<th>( \lambda_{FV} )</th>
<th>( k_{VV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>([-1.1, -0.7] \cup [0.6, 1.1])</td>
<td>(1.2^{+0.3}_{-0.6})</td>
</tr>
</tbody>
</table>
Statistics: profiled likelihood ratio

\[ \Lambda(\mu) = \frac{L(\mu, \hat{\phi})}{L(\hat{\mu}, \phi)} \]

- Model independent coupling studies which are directly related to experimental observables. 2D contour \( \mu_{VBF+VH} \) vs \( \mu_{ggF+ttH} \)
- The signal strength ratios cancel the branching ratios of different channels so that the results can be compared directly.