Beyond-the-Standard Model Higgs Physics using the ATLAS Experiment

Marco Vanadia on behalf of the ATLAS Collaboration

Sapienza University of Rome & INFN

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Introduction

The story so far

- 2012 discovery by ATLAS & CMS of a new resonance, with properties compatible with that of SM Higgs
- No surprises so far for CP properties and couplings; uncertainties on $\sigma \times BR \approx 20-30\%$

Run-2

- $\sqrt{s} : 8 \text{ TeV} \rightarrow 13 \text{ TeV} !!!$
- $O(10) \text{ fb}^{-1}$ in 2015

$\text{BR}(h \rightarrow \text{non-SM})_{LHC} \lesssim 30\% :$ lots of space for BSM physics in the Higgs sector!
What are we looking for?

- **2 Higgs Doublets Models (2HDMs):** 7 parameters, 4 types depending on structure of the couplings
  - Prediction: 5 particles, CP-even $h$ and $H$, CP-odd $A$, $H^\pm$
- **SUSY:** possible solution for hierarchy problem and Dark Matter
  - Prediction of the minimal model (MSSM): Type-2 2HDM-like Higgs sector, 2 free parameters (e.g. $M_A$, $\tan\beta$) for a given benchmark
- **Single additional EW singlet:** mixing between Higgs doublet and EW singlet, possible solution for Dark Matter
  - Prediction: 2 CP-even particles $h$, $H$
- **Higgs portal towards Dark Matter/hidden sectors:** Higgs interacting with WIMPs or non-SM sectors
  - Prediction: invisible decays for Higgs, long lived particles...
- **Composite Higgs:** e.g. MCHMs, naturalness restored by a compositeness scale $f$
  - Prediction: Higgs couplings $\neq$ SM
- **Higgs triplets, next-to-minimal extensions, ...**

And how?

<table>
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<th>SM $h$ constraints</th>
<th>Model-independent</th>
<th>Specific models</th>
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<td>BSM interpretation of $h$ couplings</td>
<td>SM-like searches $H \rightarrow \gamma\gamma, H \rightarrow VV$, ...</td>
<td>Search for new particles $A, H^\pm$, ...</td>
<td>$H \rightarrow INV, LFV$, long-lived particles...</td>
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</table>
### Charged Higgs

- $H^\pm \rightarrow W^\pm Z$: arXiv:1503.04233
- $H^\pm \rightarrow \tau^\pm \nu$: JHEP03 (2015) 088, JHEP06(2012)039
- $H^\pm \rightarrow \tau^\pm \nu$ in $tt$ through lepton universality violation: JHEP03(2013)076
- $H^\pm \rightarrow c\bar{s}$: EPJC, 73 (2013) 2465

### Neutral Higgs

- $A \rightarrow Zh$: PLB 744 (2015) 163-183
- $h/A/H \rightarrow \tau\tau$: JHEP11(2014)056
- $H \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$: PRL 114, 081802
- $H \rightarrow hh \rightarrow b\bar{b}b\bar{b}$: ATLAS-CONF-2014-005, superseeded by ATLAS-EXOT-2014-11
- $H \rightarrow ZZ$: PLB 707 (2012)
- $X \rightarrow \gamma\gamma$: PRL 113, 171801 (2014)

### 2HDM cascade

- $H^0 \rightarrow W^\mp H^\pm \rightarrow W^\mp W^\pm h^0 \rightarrow W^\mp W^\pm b\bar{b}$: PRD 89, 032002 (2014)
ATLAS Run-1: other BSM Higgs searches

**NMSSM**
- $aa \rightarrow \mu\mu\tau\tau$: ATLAS-HIGG-2014-02

**Higgs → invisible**
- $VH \rightarrow \text{hadronic} + \text{INV}$: arXiv:1504.04324
- $VBF \ h \ with \ h \rightarrow \text{invisible}$ ATLAS-CONF-2015-004
- Mono-jet arXiv:1502.01518
- $ZH \rightarrow \ell\ell + \text{INV}$: PRL 112, 201802 (2014)

**Exotic Higgs**
- Exotic $h$ decays with at least 1 $\gamma$, $E_\text{miss}^T$ and 2 forward jets ATLAS-CONF-2015-001
- $H(narrow \ scalar) \rightarrow t\bar{t}$: ATLAS-CONF-2015-009
- $H \rightarrow ZZ_{\text{dark}}, \ H \rightarrow Z_{\text{dark}}Z_{\text{dark}}$: ATLAS-CONF-2015-003
- Pair produced double-charged $H^{\pm\pm}$: CERN-PH-EP-2014-158
- $h \rightarrow \text{long lived particles}$: ATLAS-CONF-2014-041, JHEP11(2014)088
- $Wh \ with \ h \rightarrow \text{hidden sector}$: New J. Phys. 15 (2013) 043009
- Search for $W\gamma$ and $Z\gamma$ resonances: PLB 738, 428 (2014)
- ...

**Indirect measurements**
- $H \rightarrow J/\Psi \gamma$ and $H \rightarrow \Upsilon \gamma$: arXiv:1501.03276
2 Higgs Doublets Models (2HDMs)

- 2 Higgs doublets, 5 particles: \( h \) and \( H \) CP-even, \( A \) CP-odd, \( H^\pm \)
- 7 free parameters (with minimum assumptions: no CP-violation in Higgs sector, no FCNC)
  - 4 masses
  - 1 soft symmetry breaking parameter
  - \( \tan \beta = \frac{\nu_2}{\nu_1} \), fraction of the vacuum expectation values of the doublets
  - \( \alpha \), mixing angle between \( h \) and \( H \). Often \( \cos(\beta - \alpha) \) is used as parameter, which controls couplings (in particular of \( H \) to \( VV \), if \( \rightarrow 0 \) then 2HDM\( \rightarrow \)SM)

- Classified depending on the structure of the couplings in 4 types
  - Type-I (Fermiophobic in the zero mixing limit)
  - Type-II (MSSM-like)
  - Lepton-specific
  - Flipped

- Only one among the possible models, but an important benchmark for interpreting experimental results
- Type-II is an approximation for SUSY with a high mass scale

<table>
<thead>
<tr>
<th>Model</th>
<th>( u_R )</th>
<th>( d_R )</th>
<th>( e_R )</th>
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<tbody>
<tr>
<td>Type I</td>
<td>( \Phi_2 )</td>
<td>( \Phi_2 )</td>
<td>( \Phi_2 )</td>
</tr>
<tr>
<td>Type II</td>
<td>( \Phi_2 )</td>
<td>( \Phi_1 )</td>
<td>( \Phi_1 )</td>
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<tr>
<td>Lepton-specific</td>
<td>( \Phi_2 )</td>
<td>( \Phi_2 )</td>
<td>( \Phi_1 )</td>
</tr>
<tr>
<td>Flipped</td>
<td>( \Phi_2 )</td>
<td>( \Phi_1 )</td>
<td>( \Phi_2 )</td>
</tr>
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Branco et al, arXiv:1106.0034
Indirect constraints on 2HDMs

Plots from ATLAS-CONF-2014-010

2HDM parameter space is significantly constrained by $h_{SM}^*$ couplings measurements
Model-independent search for scalar resonances

Key search for high-tan $\beta$ MSSM

Search channels:
- $ττ → ℓℓ(+neutrinos)$, low mass
- $ττ → ℓ + hadrons(+neutrinos)$, low/high mass
- $ττ → hadrons(+neutrinos)$, high mass

Neutrinos in the final state, thus complete kinematics reconstruction is not possible

**Missing Mass Calculator**

Missing Mass Calculator used for the reconstruction (MMC, NIM A 654 (2011) 481–489):
- $E_T^{miss}$ and 4-momenta of all visible objects are used
- $m_{ττ}$ most probable value is calculated with a likelihood

![ATLAS plot](image)
High tan $\beta$ 2HDMs significantly constrained for $m_A \ll 1$ TeV

High tan $\beta$, $m_A \approx 1$ TeV region is a target for very early Run-2 measurements

Low tan $\beta$, $m_A \approx 300$ GeV region explored by other Run-1 searches

→ focus of the following slides
$A \rightarrow Zh \rightarrow (\ell\ell/\nu\nu)b\bar{b}$

- $\ell\ell$: 2 $b$-jets selected, $>2$ vetoed, $105 < m_{bb} < 145$ GeV. $\sigma(m_A)/m_A \approx 2-3\%$

- $\nu\nu$: discriminant variable $m_{A}^{\text{rec}} = \sqrt{E_{bb}^{T} + E_{miss}^{T}} + (\vec{p}_{bb}^{T} + \vec{E}_{miss}^{T})^2$

$A \rightarrow Zh \rightarrow \ell\ell\tau\tau$

- $\tau\tau$ decay reconstructed with MMC

- Constraints to $m_{\ell\ell}$ and $m_{\tau\tau}$:
  $m_{A}^{\text{rec}} = m_{\ell\ell\tau\tau} - m_{\ell\ell} - m_{\tau\tau} + m_{Z} + m_{h}$

- $\sigma(m_A)/m_A \approx 3-5\%$
Sensitive up to $\tan \beta \approx 5-7$, complementary to $A \rightarrow \tau \tau$
Comparison with indirect constraints

Here shown a “quick-and-dirty” overlay of the exclusion plot in the $\tan \beta$ vs $\cos(\beta - \alpha)$ space of $A \to Zh$ and $A \to \tau\tau$ searches, assuming $m_A = 300$ GeV, and the one obtained by indirect constraints produced measuring $h$ couplings, for 2HDM Type II models.

2HDMs with $m_A \approx 300$ GeV are significantly constrained.
**H± ATLAS searches**

- **tb** decays dominating BR for high mass, but **τν** decays have cleaner signature

- Recently published search for VBF
  
  \[ H^± → W^± Z \] [ATLAS-HIGG-2014-13]

- **H^± → W^± Z** appears at loop level in 2HDMs, but at tree level in Higgs Triplet Model

- Limits are set for 2HDM and for the Georgi-Machacek HTM

- Plot on the right is the limit for \( s_H \), fraction of \( m_W^2 \) and \( m_Z^2 \) due to the triplet, in GMHTM

ATLAS **\( H^± → τν + jets \)** [JHEP03 (2015) 088]: most of the **\( m_{H±} \lesssim m_{top} \)** region excluded
**hh searches in Run-1**

$H \rightarrow hh$ searches already sensitive to BSM models in Run-1, and important for preparation to long-term non-resonant $hh$ measurements

- resonant: 2HDMs, hidden sectors, exotic models (e.g. gravitons), ...
- non-resonant enhancement: compositeness, colored scalars, $4^{th}$ generation, ...

**ATLAS publications**

$hH \rightarrow bb\gamma\gamma$, $hh \rightarrow 4b$

Non-resonant: fit of continuum + SM $h + BSM$ to $m_{\gamma\gamma}$

Resonant: counting analysis cutting on $m_{\gamma\gamma}$ and $m_{bb\gamma\gamma}$

Sensitive for $\tan\beta \approx 1$

Observed (expected) for non-resonant production: $2.2 \text{ pb (1.0}^{+0.5}_{-0.2} \text{ pb}$

plot from PRL 114, 081802
**hh searches in Run-1**

$H \rightarrow hh$ searches already sensitive to BSM models in Run-1, and important for preparation to long-term non-resonant $hh$ measurements

- **resonant:** 2HDMs, hidden sectors, exotic models (e.g. gravitons), ...
- **non-resonant enhancement:** compositeness, colored scalars, 4\textsuperscript{th} generation, ...

**ATLAS publications**

$hh \rightarrow bb\gamma\gamma$, $hh \rightarrow 4b$

$hh \rightarrow 4b$ new paper soon in arXiv (preliminary results were in ATLAS-CONF-2014-005)

- Analysis performed both with resolved jets and for “fat”-jets, for boosted topologies (i.e. high mass)
- Limits set for resonances, e.g. KK graviton or additional Higgs in 2HDM, non-resonant limits set too

plot from ATLAS-EXOT-2014-11

**BR $hh$ decay**

<table>
<thead>
<tr>
<th></th>
<th>$bb$</th>
<th>$WW$</th>
<th>$\tau\tau$</th>
<th>$ZZ$</th>
<th>$\gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb$</td>
<td>0.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$WW$</td>
<td></td>
<td>0.25</td>
<td>0.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td></td>
<td></td>
<td>0.071</td>
<td>0.028</td>
<td>0.0039</td>
</tr>
<tr>
<td>$ZZ$</td>
<td></td>
<td></td>
<td></td>
<td>0.031</td>
<td>0.012</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0026</td>
</tr>
</tbody>
</table>

**ATLAS** Preliminary

$\sqrt{s}=8$ TeV / $\mathbf{L}=19.5$ fb\textsuperscript{-1}

Type-II, $m_h=500$ GeV

Obs. 95\% C.L. Limit -- Exp. 95\% C.L. Limit

$\beta > 0.15$

Exp. Limit $\pm\sigma$
Many BSM models predict invisible $h$ decays

- SUSY
- extra-dimensions
- 4th generation $\nu$
- ...

Indirect measurement constraint $BR(h \rightarrow invisible)$ to less than 30% (but with assumptions on other $h$ couplings...)

Direct measurements by ATLAS

- $Vh$ with $V \rightarrow hadrons$, $h \rightarrow invisible$ (arXiv:1504.04324)
- $VBF \ h$ with $h \rightarrow invisible$ ATLAS-CONF-2015-004
- $Zh$ with $Z \rightarrow \ell\ell$, $h \rightarrow invisible$ PRL 112, 201802 (2014)
- Mono-jet general search, with $h \rightarrow invisible$ results arXiv:1502.01518
2 jets with $p_T^1 > 75$ GeV, $p_T^2 > 50$ GeV
Veto for $b/\tau$-tagging, veto for $e/\mu$ inside jets, veto for third jet
$E_T^{\text{miss}} > 150$ GeV, $\Delta\eta_{jj} < 2.5$, $\Delta\eta_{jE_T^{\text{miss}}} > 1$ to suppress QCD multi-jet
Jets with big rapidity gap $\Delta\eta_{jj} > 4.8$, and $m_{jj} > 1$ TeV

- $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ measured in data control samples
- Extrapolated to signal sample with correction factors evaluated with simulations
- Combined fit to event yields in signal and control samples

- Observed (expected) BR limit 29% (35%) $\rightarrow$ comparable with indirect limit
- New result for VH with $V \rightarrow \text{hadrons}$: 78% (86%) \cite{arXiv:1504.04324}
- Result from Zh with $Z \rightarrow \ell\ell$, $h \rightarrow \text{invisible}$: 75% (63%) \cite{PRL 112, 201802 (2014)}
Many BSM models introduce new scalar or pseudoscalar particles, e.g. NMSSM

- $m_h = 125$ GeV creates a small hierarchy problem for MSSM
- This is solved in NMSSM with the introduction of light pseudoscalar Higgs particles $a$ ($m_a < m_h$)

Scenarios for searches: either SM $h \rightarrow aa$ or additional $H$ decaying in $aa$

Signatures strongly depending on $m_a$: decay channels are $ee/\mu\mu, \tau\tau$ if $m_a > 2m_\tau$, $bb$ if $m_b > 2m_b$

New ATLAS results for $aa \rightarrow \mu\mu\tau\tau$ shown @ Moriond: Limit for $h_{SM}$ decay to $aa$ vs $m_a$

- Request of $a \rightarrow \mu\mu$ decay costs factor 100 due to BR (wrt $a \rightarrow \tau\tau$) but still beneficial due to cleanness and trigger
- Current lower limit by ALEPH, $m_H > 107$ GeV with $a \rightarrow 4\tau$ for $\text{BR}(H \rightarrow aa)=1$
- @LEP: $ZH$ production, coupling could be small in NMSSM, important to exploit $gg$ fusion @ LHC
- Mass region explored complementary to CMS measurements $a \rightarrow \mu\mu$, $h \rightarrow 4\mu$, $a \rightarrow bb$
New results for “exotic” Higgs decays searches

$\begin{align*}
& h \rightarrow ZZ_d \rightarrow 4\ell \text{ and } h \rightarrow Z_d Z_d \rightarrow 4\ell \\
& \text{ATLAS-CONF-2015-003} \\
& \bullet \text{Models with dark gauge symmetry mediated by vector boson } Z_d \\
& \bullet ZZ_d : \text{same selection as } h \rightarrow 4\ell, \text{ search excess in } m_{\ell\ell} \\
& \bullet Z_d Z_d: \text{search in } m_{Zd} \text{ for both pairs, 2 candidates found (both have local sign. } < 2\sigma) \\
\end{align*}$

**SUSY:** $h$ decays with $\geq 1$ $\gamma$, $E_{T}^{miss}$ and 2 forward jets ATLAS-CONF-2015-001

$\begin{align*}
& \bullet \text{Gauge mediated symmetry breaking (GMSB) models predict } h \text{ decays to } \tilde{G} \\
& \text{and } \tilde{\chi}_0, \text{ with } \tilde{\chi}_0 \rightarrow \gamma + \tilde{G} \\
& \bullet \text{VBF production used to enhance sensitivity} \\
& \bullet \text{More stringent limits obtained for di-$\gamma$ final states} \\
\end{align*}$
Conclusion and outlook

- New ATLAS results for Higgs BSM searches have been presented
  - Searches of resonances compatible with 2HDMs
  - Search for di-Higgs production resonant and non-resonant enhancement (2HDMs, KK graviton, ...)
  - Search for invisible decays of the SM Higgs
  - Search for additional light Higgs particles (NMSSM, ...)
  - Search for “exotic” Higgs decays (dark sector, SUSY...)

- No BSM physics discovery, but we have Run-2 for this!

- 8 TeV $\rightarrow$ 13 TeV: high priority to $\approx$ model independent resonance searches for early Run-2

- Early searches will be analogous to Run-1 $h_{SM}$ ones, and will be interesting already with very few fb$^{-1}$
  - $H/A \rightarrow \tau\tau$
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ \rightarrow 4\ell$
  - $H^+ \rightarrow \tau\nu + jets$
  - ...

...
For low tan $\beta$ and $m_\chi < 2m_{top}$ most sensitive channels:

- $H \rightarrow hh$, $H \rightarrow ZZ$, $H \rightarrow WW$, $H \rightarrow \tau\tau$
- $A \rightarrow \tau\tau$, $A \rightarrow Zh$

For high tan $\beta$ both are completely dominated by $b\bar{b}$ (search with associated production) and $\tau\tau$

- $H^+$ most relevant search channels are $tb$ (dominant BR) and $\tau\nu$ (cleaner)
$h/H/A \rightarrow \tau\tau$: single-channel contributions

**ATLAS** $\sqrt{s}=8$ TeV, $\int L \, dt = 19.5 - 20.3$ fb$^{-1}$

MSSM $m_h^{\text{max}}$ scenario, $M_{\text{SUSY}} = 1$ TeV, $h/H/A \rightarrow \tau\tau$

95% CL limit

- $\tau_{\text{lep}}\tau_{\text{had}}$
- $\tau_{\text{had}}\tau_{\text{had}}$
- $\tau_{\text{lep}}\tau_{\text{lep}}$
Dominant channel is $h \rightarrow bb$

$\tau\tau$ channel ensures sensitivity to lepton-specific models, and improves the measured limit @ 300 GeV by 18%
Sensitivity to 2HDM lepton-specific and flipped models thanks to $h \rightarrow \tau\tau$
Hidden or dark sectors included in many BSM models, they provide for example a candidate for DM

- This analysis takes into account models with dark gauge symmetry mediated by a vector boson \( Z_d \)
- \( ZZ_d \): same selection as \( h \to 4\ell \), search for excesses in dilepton mass \( m_{34} \) (pair farthest from \( m_Z \))
  \[ \to \text{per BR}(h \to ZZ_d \, 4\ell)/\text{BR}(h \, 4\ell) > 0.4 \]  
  excluded range 15 < \( m_{Zd} < 55 \) GeV
- \( Z_dZ_d \): dilepton pairs chosen to minimize \( |m_{12} - m_{34}| \), \( Z \) and \( J/\Psi \) veto, search in \( m_{Zd} \) with \( |m_{Zd} - m_{12}| \) and \( |m_{Zd} - m_{34}| < 3-5 \) GeV (depending on channel)
  - 1 event 4\( e \) (\( m_{12} = 28 \) and \( m_{34} = 22 \) GeV, loc. sig. 1.7\( \sigma \)) and 1 event 4\( \mu \) (\( m_{12} = 23 \) e \( m_{34} = 18 \) GeV, loc. sig. 1.7\( \sigma \)), limits calculated in 15 < \( m_{Zd} < 60 \) GeV range