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

Marco Vanadia on behalf of the ATLAS Collaboration

Sapienza University of Rome & INFN

28 April 2015, DIS2015
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?

**SM $h$ constraints**
- BSM interpretation of $h$ couplings

**Model-independent**
- SM-like searches
  - $H \rightarrow \gamma\gamma$, $H \rightarrow VV$, ...

**Specific models**
- Search for new particles $A$, $H^\pm$, ...

**Exotic signatures**
- $H \rightarrow INV, LFV$, long-lived particles...
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 $t\bar{t}$ 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
- \( VBF \ h \text{ with } h \rightarrow \text{invisible} \): 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 \( \gamma \), \( E_{\text{miss}}^{\gamma} \) and 2 forward jets ATLAS-CONF-2015-001
- \( H(\text{narrow scalar}) \rightarrow t\bar{t} \): 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 \( H^\pm \): 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
- Constraints from \( h \) couplings: ATLAS-CONF-2014-010, ATLAS-CONF-2015-007
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
  - $\tan \beta = \nu_2 / \nu_1$, 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>$u_R^l$</th>
<th>$d_R^l$</th>
<th>$e_R^l$</th>
</tr>
</thead>
<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>
</tr>
<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>
</tbody>
</table>

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:
- $\tau\tau \rightarrow \ell\ell (+\text{neutrinos})$, low mass
- $\tau\tau \rightarrow \ell + \text{hadrons} (+\text{neutrinos})$, low/high mass
- $\tau\tau \rightarrow \text{hadrons} (+\text{neutrinos})$, 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):
- $E_T^{\text{miss}}$ and 4-momenta of all visible objects are used
- $m_{\tau\tau}$ most probable value is calculated with a likelihood

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

 MMC mass in the $\ell\ell$ channel, $b$ — tagged category
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

$\rightarrow$ focus of the following slides
**A → Zh**: PLB 744 (2015) 163-183

**A → Zh → (ℓℓ/νν)b¯b**

- **ℓℓ**: 2 b–jets selected, >2 vetoed, 105 < m_{bb} < 145 GeV. \( \sigma(m_A)/m_A \approx 2-3\% \)
- **νν**: discriminant variable \( m_A^{\text{rec}} = \sqrt{E_{bb}^T + E_{\text{miss}}^T} + (\vec{p}_{bb}^T + \vec{E}_{\text{miss}}^T)^2 \)

**A → Zh → ℓℓττ**

- **ττ** decay reconstructed with MMC
- Constraints to \( m_{ℓℓ} \) and \( m_{ττ} \):
  \[ m_A^{\text{rec}} = m_{ℓℓττ} - m_{ℓℓ} - m_{ττ} + m_Z + m_h \]
- \( \sigma(m_A)/m_A \approx 3-5\% \)
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 \( m_A = 300 \text{ GeV} \), and the one obtained by indirect constraints produced measuring \( h \) couplings, for 2HDM Type II models.

2HDMs with \( m_A \approx 300 \text{ GeV} \) are significantly constrained.
$H^\pm$ ATLAS searches

- $tb$ decays dominating BR for high mass, but $\tau\nu$ decays have cleaner signature

Recently published search for VBF
$H^\pm \to W^\pm Z$ [ATLAS-HIGG-2014-13]

- $H^\pm \to W^\pm Z$ 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 $H^+ \to \tau\nu +$ jets [JHEP03 (2015) 088]: most of the $m_{H^\pm} \lesssim m_{top}$ region excluded
**hh searches in Run-1**

$H \to hh$ 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**

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

**BR $hh$ decay**

- $bb$: 0.32
- $WW$: 0.25, 0.05
- $\tau\tau$: 0.071, 0.028, 0.0039
- $ZZ$: 0.031, 0.012, 0.0034, 0.00076
- $\gamma\gamma$: 0.0026, 0.001, 0.00029, 0.00013, 5.3e-06

**$hh \to bb\gamma\gamma$ PRL 114, 081802**

- 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 pb ($1.0^{+0.5}_{-0.2}$ pb)

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

*H → 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, 4th generation, ...

**ATLAS publications**

*hh → bbγγ, hh → 4b*

![Image](image_url)

- *hh → 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
Many BSM models predict invisible $h$ decays
- SUSY
- extra-dimensions
- 4th generation $\nu$
- ...

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

ATLAS-CONF-2015-007

Direct measurements by ATLAS
- $Vh$ with $V \to hadrons$, $h \to invisible$ (arXiv:1504.04324)
- $VBF \ h$ with $h \to invisible$ ATLAS-CONF-2015-004
- $Zh$ with $Z \to \ell\ell$, $h \to invisible$ PRL 112, 201802 (2014)
- Mono-jet general search, with $h \to invisible$ results arXiv:1502.01518
VBF $h$ with $h \rightarrow$ invisible ATLAS-CONF-2015-004

- 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 $V \rightarrow$ hadrons: 78% (86%) [arXiv:1504.04324]
- Result from $Zh$ with $Z \rightarrow \ell\ell$, $h \rightarrow$ invisible: 75% (63%) [PRL 112, 201802 (2014)]
Many BSM models introduce new scalar or pseudoscalar particles, e.g. NMSSM

- \( m_h = 125 \text{ GeV} \) 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, \( m_H > 107 \text{ GeV} \) 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

$h \rightarrow ZZ_d \rightarrow 4\ell$ and $h \rightarrow Z_d Z_d \rightarrow 4\ell$ 

ATLAS-CONF-2015-003

- Models with dark gauge symmetry mediated by vector boson $Z_d$
- $ZZ_d$: same selection as $h \rightarrow 4\ell$, search excess in $m_{\ell\ell}$
- $Z_d Z_d$: search in $m_{Zd}$ for both pairs, 2 candidates found (both have local sign. $< 2\sigma$)

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

- Gauge mediated symmetry breaking (GMSB) models predict $h$ decays to $\tilde{G}$ and $\tilde{\chi}_0$, with $\tilde{\chi}_0 \rightarrow \gamma + \tilde{G}$
- VBF production used to enhance sensitivity
- More stringent limits obtained for di-$\gamma$ final states
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 → 13 TeV: high priority to ≈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$^{-1}$

- $H/A \rightarrow \tau\tau$
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ \rightarrow 4\ell$
- $H^+ \rightarrow \tau\nu + jets$
- ...

...