Beyond the Standard Model Higgs Searches at ATLAS

Anna Kaczmarska
IFJ PAN, Kraków, Poland
On behalf of the ATLAS Collaboration

Higgs Hunting 2019
29 - 31 July 2019
• So far...
• Discovery of a neutral scalar particle of mass \( \sim 125 \text{ GeV} \) confirmed the predicted electroweak symmetry breaking mechanism of the SM
• Experimental results show consistency with the SM Higgs boson
• But the SM is not perfect...
• Hierarchy problem, dark matter, unification of the forces etc.
• Fortunately consistency with SM doesn’t exclude Beyond SM scenarios

• Extended scalar sector appears in many extensions of the SM
• They allow for SM-like Higgs phenomenology with smaller or larger modification of couplings
## Beyond the Standard Model Higgs

**General recipe:** \( \text{SM Higgs Doublet} + \text{Additional Field} = \text{Additional Higgs Bosons} \)

- **SM + another Higgs doublet = Two Higgs Doublet Model, 2HDM**
  - 5 Higgs bosons: \( h, H, A, H^+, H^- \)
  - Free parameters: \( \tan\beta, \alpha \) and \( m_A \)
  - Four variants to couple SM fermions to the 2HDs

<table>
<thead>
<tr>
<th>Coupling scale factor</th>
<th>Type I</th>
<th>Type II</th>
<th>Lepton-specific</th>
<th>Flipped</th>
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</thead>
<tbody>
<tr>
<td>( \kappa_V )</td>
<td>( \sin(\beta - \alpha) )</td>
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<tr>
<td>( \kappa_d )</td>
<td>( \cos(\alpha) / \sin(\beta) )</td>
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<td>( \kappa_d )</td>
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<td>( \kappa_\ell )</td>
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<td>( \cos(\alpha) / \sin(\beta) )</td>
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</table>

Table 5: Couplings of the light Higgs boson \( h \) to weak vector bosons \( (\kappa_V) \), up-type quarks \( (\kappa_u) \), down-type quarks \( (\kappa_d) \), and charged leptons \( (\kappa_\ell) \), expressed as ratios to the corresponding SM predictions in 2HDMs of various types.

- **Minimal Supersymmetric SM (MSSM)**
  - “type II” 2HDM with fixed \( \alpha \)
  - numerous benchmark models: hMSSM, \( m_{h^{mod^+}} \), etc.
  - **SM Higgs Run1 results => strict constraints on 2HDM. Data prefers alignment limit: \( \cos(\beta - \alpha) = 0 \)**
  - \( h \) recovers properties of the SM Higgs

- **SM + triplet = Higgs triplet models**
  - Double charged Higgs boson + 2HDM Higgses

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**ATLAS**

\[ \text{Obs. 95\% CL} \]
\[ f_\beta = 7 \text{ TeV}, 4.5-4.7 \text{ fb}^{-1} \]
\[ f_\beta = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

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Higgs Hunting 2019
Strategies that use Higgs to find new physics:

- Indirectly, by looking for non-standard properties of light Higgs (spin, CP, couplings, LFV decays etc.)

- **Directly, by explicit search for BSM objects**
  - Additional Higgs bosons (neutral and charged, decays to SM particles or to Higgs bosons)
  - Higgs decays to BSM states (light scalar resonances, invisible decays, long lived particles etc.)
    - see talks by L. Truong and Y. Gershtein

Today:

- **Neutral Higgs to fermions**
  - $H \rightarrow \tau \tau$  JHEP 01 (2018) 055
  - $bH \rightarrow bb$  arXiv:1907.02749

- **Charged Higgs**
  - $H^\pm \rightarrow \tau \nu$  JHEP 09 (2018) 139
  - $H^\pm \rightarrow t \bar{b}$  JHEP 11 (2018) 085
  - $H^{\pm\pm} \rightarrow l^\pm l^\pm$  Eur. Phys. J. C78 (2018) 19
  - $H^{\pm\pm} \rightarrow W^\pm W^\pm$  Eur. Phys. J. C (2019) 79

- **Higgs to dihiggs**
  - see talk by S. Shrestha, C. Amendola

- **Neutral Higgs to bosons**
  - $H \rightarrow \gamma \gamma$  ATLAS-CONF-2018-025

Disclaimer:
Incomplete set of analysed Higgs channels. Only most recent results shown. New results with full Run-2 dataset coming!
Heavy neutral Higgs decays to fermions

In the MSSM, the heavy Higgs boson couplings to down-type fermions (τ, b) are strongly enhanced for a large part of the parameter space for large tanβ:

- increased BRs to τ-leptons and b-quarks
- higher cross section for Higgs boson production in association with b-quarks

Searches for both decays to b-quarks and τ-leptons needed to cover all 2HDM Types:

- τ-leptons sensitive to II and Lepton-specific Types
- b-quarks sensitive to II and Flipped Types

Dominant production modes in the MSSM:

- gluon fusion (low tanβ)
- b-associated production (high tanβ)

**References:**

- **H/A → ττ**  JHEP 01 (2018) 055
- **bH/A → bbb**  arXiv:1907.02749
- **H/A → ttbar**  ATLAS-CONF-2016-073, Run1
- **H/A → μμ**  arXiv:1901.08144
Neutral Higgs searches: $H/A \rightarrow \tau\tau$

- Mass range 200 - 2250 GeV
- Final states: $\tau_{\text{lep}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$
- Two categories: $b$-veto (gluon fusion) and $b$-tag (b-associated production)
- Discriminant: total transverse mass

$$m_T^{\text{tot}} \equiv \sqrt{(p_T^{T1} + p_T^{T2} + E_T^{\text{miss}})^2 - (p_T^{T1} + p_T^{T2} + E_T^{\text{miss}})^2}$$

$\sigma \times B(\phi \rightarrow \tau\tau)$

$\sigma \times B(\phi \rightarrow \tau\tau)$

$\tan\beta$

ATLAS $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

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$\phi \rightarrow \tau\tau$ 95% CL limits

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$\phi \rightarrow \tau\tau$ 95% CL limits

$H/A \rightarrow \tau\tau$ 95% CL limits

0.78 - 0.0058 pb

0.70 - 0.0037 pb

$0.70 \pm 0.0037$ pb

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Neutral Higgs searches: $bH/A \rightarrow bb$

- Mass range 450 - 1400 GeV
- Targets Type II and Flipped 2HDM at high $\tan\beta$ (where $H/A$ mainly couple to $b$-quarks)
- Challenging $b$-jet trigger
- Events classified according to the number of jets and $b$-jets
- $m'_bb$ from diagonalized ($m_{bb}, PT_{b1}, PT_{b2}$) improves $S/B$ separation
- Fully data driven background with $bb$(anti-$b$) CR

ATLAS

$\sqrt{s} = 13$ TeV, 27.8 fb$^{-1}$

MSSM scenarios $bb, \phi \rightarrow bb$

$\sigma(pp \rightarrow bb\phi) \times B(\phi \rightarrow b\bar{b})[pb]$
Charged Higgs searches

**H^±** predicted by 2HDM, Higgs triplets...

In Type II 2HDM:
- Main production in association with a top quark
- At high mass \( H^± \to tb \) is the dominant decay mode
- \( BR(H^± \to \tauν) \) significant for a large range of masses for high tan\( β \)

**H^±±** predicted by Left-Right Symmetric Models (LRSM), Higgs Triplet Model (HTM), Zee-Babu and Georgi-Machacek models

In LRSM and HTM:
- Dominant production at the LHC: DY pair production
- Decays: \( H^±± \to ℓ±ℓ± \) or \( H^±± \to W±W± \)
  - \( BR \sim f(m_{H^±±}, \text{vev of Higgs triplet}) \)
  - Low \( m_{H^±±} \) and low vev: \( H^±± \to ℓ±ℓ± \) dominates

\[
(m_{H^+} < m_{\text{top}}) \\
(m_{H^+} > m_{\text{top}})
\]

- \( H^±\to\tauν \) \( JHEP \) 09 (2018) 139
- \( H^±\to \text{tb} \) \( JHEP \) 11 (2018) 085

- \( H^± \to W±Z \) Phys. Lett. B 787 (2019) 68
- \( H^± \to cs \) Eur. Phys. J. C, 73 6 (2013) 2465, Run1
Charged Higgs searches: $H^\pm \rightarrow \tau\nu, \tau b$

- $H^\pm \rightarrow \tau\nu$, mass range 90-2000 GeV
  - Final states $\tau_{had}^{+}\text{jets}, \tau_{had}^{+}\text{lep}$
  - Tau polarisation variable used
  - BDT trained in different mass bins

- $H^\pm \rightarrow \tau b$, mass range 200-2000 GeV
  - Final state single- and di-lepton (opposite-sign)
  - SR and CRs according to the number of jets and b-jets (7 regions)
  - BDT trained in each SR and for each signal mass hypothesis

$H^\pm \rightarrow \tau\nu$

- ATLAS
  - $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
  - $\tau$-jets signal region
  - Data vs. SM
  - BDT score, 160 to 180 GeV

$H^\pm \rightarrow \tau b$

- ATLAS
  - $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
  - $H^\pm$ signal region
  - Data vs. SM
  - BDT output

$H^\pm \rightarrow \tau\nu, \tau b$

- ATLAS
  - 95% CL$_s$ exclusions
  - hMSSM
  - $\sqrt{s} = 13$ TeV
  - 36.1 fb$^{-1}$
  - Observed, $\tau\nu$ vs. $\tau b$
  - Expected, $\tau\nu$ vs. $\tau b$

4.2 pb-2.5 fb

2.9 pb- 0.07 pb
Doubly charged Higgs searches: $H^{\pm\pm}H^{\mp\mp} \rightarrow 4W, 4l$

$H^{\pm\pm}H^{\mp\mp} \rightarrow 4W$ (THM), mass range 200-700 GeV
- Signature: $2l^{SS}, 3l, 4l$ light leptons + missing $E_T$
- Mass- and channel-dependent cuts on discriminating variables
- Final fit based on six bin counting experiment

$H^{\pm\pm}H^{\mp\mp} \rightarrow 4l$ (LRS), mass range 250-1300 GeV
- Signature: isolated $2l^{SS}, 3l$ (1 pair SS), $4l$ (2 pairs SS) light leptons
- Discrimination: dilepton invariant mass, for SR with 4 leptons mean mass of two SS pairs

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Neutral Higgs decays to bosons: $H \rightarrow \gamma \gamma$ (low-mass)

- Generic search for diphoton resonances in mass range 65-110 GeV
- Three categories depending on how 2 $\gamma$’s candidates reconstructed (converted or not)
- Main backgrounds described with analytic functions validated on data
  - Continuum: $\gamma \gamma, \gamma j, jj$ (jets misidentified as $\gamma$’s)
  - $Z/\gamma* \rightarrow e^+e^-$ (Drell-Yan): e’s reconstructed as $\gamma$’s
- The fit is performed to the $m(\gamma \gamma)$ spectra in the three conversion categories
Summary

- There is a plethora of searches for BSM physics in the Higgs sector at the LHC
- Only a small selection of results were presented here
- No evidence for any BSM Higgs Boson... yet
- Dedicated efforts in the combinations help improve sensitivity
- By now only impressive agreement with SM observed, instead of inspiring surprises
- But we have not yet finished! Much more Run2 data (140/fb) to analyse!

- We will turn every stone 😊 - but for now we need to wait a bit to tell an inspiring story to stimulate the HL-LHC and future experiments
Beyond the Standard Slides

Courtesy of J. Keller
Neutral Higgs decays to bosons

- BSM scenarios tested also for decay of neutral Higgs to di-boson final states
  - WW, WZ, ZZ, VH, Zγ and γγ
- Large variety of final states including leptonic and hadronic decays

Neutral Higgs searches: $H/A \rightarrow \tau\tau$

**ATLAS $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$**

- $\tau_{lep}\tau_{had} b$-veto
- $\tau_{had}\tau_{had} b$-tag

- Significance vs $m_{T}\tau$ [GeV]
- Events / GeV

**JHEP 01 (2018) 055**

$\sigma \times B(\phi \rightarrow \tau \tau)$ [pb]

**Observed**

- Expected

- ATLAS 2015

- ± 1σ
- ± 2σ

- $m_{\phi}$ [GeV]

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Higgs Hunting 2019
Neutral Higgs searches: $H/A \to \tau\tau$

The observed and expected 95% CL upper limit on the production cross section times branching fraction for $\phi \to \tau\tau$ as a function of the fractional contribution from $b$-associated production and the scalar boson mass. The solid and dashed lines represent contours of fixed $\sigma \times B$.
Neutral Higgs searches: $bH/A \rightarrow bb$

In order to isolate events with small FSR and good $m_{\phi}$ resolution, a principal component analysis (PCA) is performed on the three dimensional distribution of the variables $m_{bb}$, $p_{T1}$, and $p_{T2}$ using events drawn from the signal MC sample with the $bbb$ classification following pre-selection. Separate PCA's are performed for each of the fifteen simulated values of $m_{\phi}$ and for each of the three $n$-jet regions. Upon diagonalization of the covariance matrix for $m_{bb}$, $p_{T1}$, and $p_{T2}$, the first, second and third principal components define the variables $m'_{bb}$, $p'_{T1}$, and $p'_{T2}$, respectively. The point $(m'_{bb}, p'_{T1}, p'_{T2}) = (0, 0, 0)$ corresponds to the vector of mean values for $m_{bb}$, $p_{T1}$, and $p_{T2}$. Two-dimensional distributions of $p'_{T1}$ versus $m'_{bb}$ and of $p'_{T2}$ versus $m'_{bb}$ are shown in Figure 4.
H$^\pm$ decay modes

- For $m_{H^+} < m_{\text{top}}$, the decay $H^\pm \to \tau \nu$ usually dominates in a type-II 2HDM.
- For $m_{H^+} > m_{\text{top}}$, the dominant decay is $H^\pm \to t\bar{b}$, however the branching fraction of $H^\pm \to \tau \nu$ can reach 10-15% at large values of $\tan \beta$ in a type-II 2HDM.

$tan\beta=10$

$tan\beta=50$
$H^{\pm} \rightarrow \tau \nu$: Selection

$\tau_{\text{had}}+\text{jets: } pp \rightarrow bbWH^{\pm} \rightarrow bb(jj)(\tau_{\text{had}}\nu)$

Sensitive at large $m_{H^{\pm}}$
- $E_T^{\text{miss}}$ trigger
- Select events with a $\tau_{\text{had}}$ and a hadronic top-quark decay:
  - 1 $\tau_{\text{had}}$ object with $p_T > 40$ GeV,
  - 3 jets with $p_T > 25$ GeV, including 1 b-tag
  - Electron and muon veto
  - $E_T^{\text{miss}} > 150$ GeV
  - $m_T > 50$ GeV

$$m_T = \sqrt{2p_T^\tau E_T^{\text{miss}}(1 - \cos \Delta \phi_{T,\text{miss}})}$$

$\tau_{\text{had}}+\text{lepton: } pp \rightarrow bbWH^{\pm} \rightarrow bb(l\nu)(\tau_{\text{had}}\nu)$

Sensitive at low/intermediate $m_{H^{\pm}}$
- Single lepton trigger
- Select events with a $\tau_{\text{had}}$ and a leptonic top-quark decay:
  - 1 $\tau_{\text{had}}$ object with $p_T > 30$ GeV,
  - 1 lepton with $p_T > 30$ GeV
  - Two opposite sign channels: $e^+\tau_{\text{had}}, \mu^+\tau_{\text{had}}$
  - At least 1 b-tagged jet with $p_T > 25$ GeV
  - $E_T^{\text{miss}} > 50$ GeV

Dominant backgrounds: SM ttbar production, misidentified jets as fake $\tau_{\text{had}}$

Backgrounds with a true $\tau_{\text{had}}$:
- MC

Backgrounds with $e, \mu$ faking $\tau_{\text{had}}$:
- MC + data-driven corrections
- data-driven fake-factor method

Backgrounds with jets faking $\tau_{\text{had}}$: 
- MC
H$^\pm \rightarrow \tau \nu$: Analysis Strategy

**Multivariate discriminant:**
- FastBDTs trained in 5 H$^\pm$ mass bins
- Separate training for $\tau_{\text{had}}$+jets and $\tau_{\text{had}}$+lepton final states
- Polarisation variable used for 1-prong $\tau_{\text{had}}$ objects when $m_{H^\pm} < 500$ GeV
  - discrimination between $H^\pm \rightarrow \tau \nu$ (signal) and $W^\pm \rightarrow \tau \nu$ (top background)
  - increase of sensitivity for low H$^\pm$ masses

\[
\tau = \frac{E_T^{\pi^\pm} - E_T^{\pi^0}}{E_T^{\pi^0}} \approx 2 \frac{p_T^{\text{track}}}{p_T} - 1
\]

- No statistically significant deviation from the SM predictions
- Exclusion limits obtained from a fit of the BDT distributions

**Systematic uncertainties:**
- dominant at low $m_{H^\pm}$: fake factors method
- dominant at high $m_{H^\pm}$: signal modelling


\[ H^\pm \rightarrow \tau \nu: \text{Fake Factors method} \]

- Define an anti-tau region, which is similar to the signal region but where a tau candidate fails the ID-tau requirement, instead of fulfilling it.

\[
FF = \frac{N_{\tau-\text{id}}}{N_{\text{anti-}\tau-\text{id}}}
\]

\[
N_{\text{fakes}}^\tau = N_{\text{fakes}}^{\text{anti-}\tau} \times FF
\]

- Two control region with different jet compositions are used in order to determine the rate of the fake tau object
  - Multi-jet CR (dominated by gluon-initiated jets)
  - W+jet CR (dominated by quark-initiated jets)
- In the anti-tau regions, the fractions of quark- and gluon-initiated jets misidentified as tau candidates are measured using a template-fit approach, based on variables that are sensitive to the difference in quark- and gluon-fractions between these two types of jets
H$^\pm \to t\bar{b}$: Selection

- At least one leptonic top-quark decay
  - single-lepton triggers
- Considers $200 \text{ GeV} < m_{H^\pm} < 2000 \text{ GeV}$
- Single- and di-lepton (OS) channels
- Z-veto in $ee$ and $\mu\mu$ channels;
- Event categorisation in Signal and Control Regions according to the number of jets and b-jets

**Single-lepton:** CR 5j2b, SR 5j3b, SR 5j4b, CR 6j2b, SR 6j3b, SR 6j4b

**Di-lepton:** CR 3j2b, CR/SR 3j3b, CR 4j2b, SR 4j3b, SR 4j4b
H\(^{-}\)\(\rightarrow\)tb: Analysis Strategy

- The dominating background: ttbar + jets
  - Model = Powheg+Pythia8
  - Categorised according to the flavour of additional jets (b/c/light)
- Prompt leptons modelled with MC
- Non-prompt leptons in \(\ell\ell\) modelled with MC and normalised with data in CR
- Non-prompt leptons in \(\ell+\)jets modelled with a data-driven matrix method
  - Use sample with enhanced non-prompt leptons (use loose selection)
  - Weight events by efficiencies for prompt and non-prompt leptons to pass default tight selection

- Separate BDT trained in each SR and for each signal mass hypothesis
- Trained against all backgrounds in single lepton channel
- Trained against ttbar in di-lepton channel

- No statistically significant deviation from the SM predictions
- Exclusion limits obtained from a fit of the BDT distributions in SRs and a single bin in CRs

Dominant systematic uncertainties:
- Jet flavour tagging
- Background modelling
The BDT variables include various kinematic quantities with the optimal discrimination against the ttbar + >=1b background.

For H+ masses above 400 GeV the most important variables are the scalar sum of the pT of all jets and the leading jet pT.

For a mass at or below 300 GeV, a kinematic discriminant, D is used as an input variable for the BDT.
Kinematic Discriminant $D$

- $D = P_{H^+}(x)/(P_{H^+}(x) + P_{\bar{t}t}(x))$
- $P_{H^+}(x)$ and $P_{\bar{t}t}(x)$ are probability density functions for $x$ under signal and background hypotheses
- $x$ is $E_T^{miss}$ and four-momentum of $e, \mu$, and jets
- $P_{H^+}(x)$ defined as the product of probability density functions for:
  - the mass of the semileptonically decaying top quark, $m_{b_\ell \ell' \nu}$
  - the mass of the hadronically decaying W boson, $m_{q_1 q_2}$
  - the difference between the masses of the hadronically decaying top quark and the hadronically decaying W boson, $m_{b_h q_1 q_2} - m_{q_1 q_2}$
  - the difference between the mass of the charged Higgs boson and the mass of the leptonically or hadronically decaying top quark, $m_{b_{H^+} b_\ell \ell' \nu} - m_{b_\ell \ell' \nu}$ or $m_{b_{H^+} b_\ell q_1 q_2} - m_{b_\ell q_1 q_2}$, depending on whether or not the top quark from the charged Higgs boson decays leptonically or hadronically

Where:
- $q_1$ and $q_2$ are quarks from the hadronic $W$ decay
- $\ell$ and $\nu$ are from the leptonic $W$ decay
- $b_h$ is the $b$-quark from the hadronic top quark decay
- $b_\ell$ is the $\ell$ quark from the leptonic top quark decay
- $b_{H^+}$ is the $b$-quark from the $H^+$ decay

courtesy of B. Burghgrave
$H^{\pm\pm}$: Production and Decays

$H^{\pm\pm}$ predicted by variety of BSM models:
- Left-Right Symmetric Models (LRSM)
  - addition of two triplets, L and R
- Higgs Triplet Model (HTM)
  - addition of one triplet, L
- Zee-Babu models, Georgi-Machacek models

Motivations
- Restoring parity symmetry in weak interactions at higher energy (LRSM)
- Explain light neutrino masses through Type II See-Saw mechanism

Most unique feature of such models: $H^{\pm\pm}$
- left and right-handed in LRSM or left-handed only in HTM

Decays: $H^{\pm\pm} \rightarrow l^\pm l^\pm$ or $H^{\pm\pm} \rightarrow W^\pm W^\pm$
- $\text{BR} \sim f(m_{H^{\pm\pm}}, \text{vev of Higgs triplet})$
- Low $m_{H^{\pm\pm}}$ and low vev: $H^{\pm\pm} \rightarrow l^\pm l^\pm$ dominates

Production at the LHC: pair-produced $H^{\pm\pm}$ via the Drell-Yan process (dominant in LRSM and HTM)
H^{±±} → l^{±}l^{±}: Selection and Backgrounds

- Considered decays: $H^{±±} \rightarrow e^{±}e^{±}, e^{±}\mu^{±}, \mu^{±}\mu^{±}$
  - no preference for decays into taus - coupling not proportional to $m_{lept}$ like for the SM Higgs
- Masses studied: 250 - 1300 GeV
- Search for isolated, same sign lepton pairs
- Discrimination observable
  - dilepton invariant mass distribution in all CRs and SRs
  - For SR with 4 leptons $M = (m^{++} + m^{--})/2$

Backgrounds:
- real prompt leptons
  - estimated with MC
- oppositely charged leptons with charge mis-ID
  - estimated with MC but with data-driven correction factors
- non-prompt
  - estimated from data
  - real e or $\mu$ from non-prompt decays, e.g. from heavy flavoured mesons
  - jets mis-reconstructed as electrons

![Graph showing dilepton invariant mass distribution and event rates in SR1P2L (e^{±}\mu^{±})](image-url)
$H^{\pm\pm} \rightarrow l^{\pm}l^{\pm}$: Signal and Control Regions

- **SRs with 2-, 3-, and 4-leptons and flavour categories**
- **Control Regions (CRs)** to constrain background parameters in the statistical analysis
- **Validation Regions (VRs)** to check background model against data
- Regions defined by $m(l^{\pm}l^{\pm}) > 200$ GeV in SRs and below 200 GeV in most CRs and VRs

### Table

<table>
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<tr>
<th>Channel</th>
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<td>$\mu^{\pm}\mu^{\mp}$</td>
<td>$\mu^{\pm}\mu^{\mp}$</td>
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</table>
**H^{±±} \rightarrow l^{±}l^{±}: Results**

- No significant excesses observed
- Lower limit evaluated as a function of the branching into electrons and muons
- Separate limits for $H^{±±}_L$ and $H^{±±}_R$
- Limits on $H^{±±}_L$ vary from 770 GeV to 870 GeV, and 660 GeV to 760 GeV for $H^{±±}_R$ (depending on BR composition)

**Systematic uncertainties:** fake factor method, statistical uncertainty, theory description
**H^{±±}\rightarrow W^{±}W^{±}: Selection and Backgrounds**

- **Signature**: 2L^{SS}, 3L, 4L light leptons + missing $E_T$
- **Masses studied**: 200-700 GeV
- **Dominant backgrounds**: dibosons, Z+jets, ttbar
  - Prompt sources estimated from MC
  - Fake estimation: data-driven fake factor method
  - Charge misID: data-driven method

**Mass-dependent and channel-dependent cuts on discriminating variables:**
- $m_{X_l}$ of all leptons in the event;
- $\Delta R(|\pm|)$
- $m_{\text{jets}}$ only in the 2L channel
- $p_T$ leading jet
- $\Delta \phi(|\pm|, E_T^{\text{miss}})$ in the 2L channel
- $\Delta R(l, \text{jet})$ any lepton and its closest jet in the 3L channel
- $S$, used in 2L^{SS} channel, describes the event topology in the transverse plane, defined using the spread of the $\phi$ angles of the leptons, $E_T^{\text{miss}}$ and jets
Higgs Hunting 2019

**$H^\pm \rightarrow W^\pm W^\pm$: Results**

Final fit based on six bin counting experiment

**Dominating uncertainties:** statistics, data-driven fakes and charge mis-ID
Neutral Higgs searches: H/A→ttbar

- ttbar lepton+jets channel (one W to hadrons, one to leptons)
- re-interpretation for the ttbar resonance search (JHEP 08 (2015) 148)

- For a neutral pseudoscalar A (scalar H) with a mass of 500 GeV, the parameter values tanβ < 0.85 (< 0.45) are excluded in the type-II 2HDM at 95% confidence level
- No tanβ values can be excluded for the higher mass point at 750 GeV

• interference between the signal and ttbar background production modes taken into account for the first time
  - the MadGraph code is modified to remove the SM ttbar matrix element to yield the pure signal + interference contribution on an event-by-event basis.
Neutral Higgs searches: $H/A \rightarrow \mu \mu$

**ATLAS**

$\sqrt{s}=13$TeV, 36.1 fb$^{-1}$

- **b-associated production**
  - Observed
  - Expected
  - $\pm 1\sigma$
  - $\pm 2\sigma$

- **gluon-gluon fusion**
  - Observed
  - Expected
  - $\pm 1\sigma$
  - $\pm 2\sigma$