BSM Higgs searches

Yu. Naryshkin
Petersburg Nuclear Physics Institute
On behalf of the ATLAS and CMS Collaborations

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**BSM Models**

- **2HDM** (Two Higgs Doublet Model) is an extension of Standard Model: second Higgs doublet is added to SM leads to 5 physical states, 3 neutral, 2 charged: CP-even $h$ and $H$, CP-odd pseudoscalar ($A$), charged $H^+$, $H^-$. The minimal model has 6 free parameters: Higgs masses $m_h$, $m_H$, $m_A$, $m_{H^\pm}$ and the ratio of doublet vacuum expectation values $\tan\beta = v_1/v_2$ and a mixing angle $\alpha$ between the CP-even Higgs bosons.

- **MSSM** (Minimal Supersymmetric Standard Model): extension of SM (each SM particle has a supersymmetric partner). MSSM higgs sector is a particular case of 2HDM type II.

- **NMSSM**: Higgs singlet is added to MSSM→7 physics states, 5 neutral, 2 charged: CP-even $H_1$, $H_2$, $H_3$, CP-odd $A_1$, $A_2$, charged $H^+$, $H^-$.

- **HTM**: (Higgs Triplet Model): Higgs triplet is added, lead to 7 physical states: $H^{\pm\pm}$, $H^\pm$, $A$, $H$ and $h$.

- **LRSM**: (Left Right Symmetric model) several variations: e.g. addition of triplet + two doublets (bi-doublet) ....

- ... and more ...
• **Neutral Heavy Higgs:** $h/H/A \rightarrow \tau\tau$, $H \rightarrow WW \rightarrow \ell\nu\ell\nu,$
  
  $A \rightarrow Zh(Z \rightarrow ll,h \rightarrow b\bar{b}(\tau\tau))$, $h/H/A \rightarrow t\bar{t}$ ...

• **Neutral Higgs decaying to di-Higgs:** $H \rightarrow hh \rightarrow b\bar{b}\tau\tau$, $hh \rightarrow b\bar{b}b\bar{b}$,
  
  $hh \rightarrow bb\gamma\gamma$, $hh \rightarrow WW\gamma\gamma$, $hh \rightarrow WWbb$, $hh \rightarrow WWWW$

• **Charged Higgs:** $H^\pm \rightarrow \tau\nu$, $H^+ \rightarrow tb$, $H^+ \rightarrow WZ \rightarrow 3\ell + \nu_\ell$,
  
  $H^+ \rightarrow \mu\nu$, $H^+ \rightarrow Wh/WA/W\gamma$, light $H^+ \rightarrow cs, cb$

• **Double charged Higgs boson:** $H^{\pm\pm} \rightarrow \ell^+\ell^-$, $H^{++} \rightarrow WW$

• … and more …
Neutral Heavy Higgs
MSSM $h/H/A \rightarrow \tau\tau$: ATLAS@13TeV

- **gg-fusion**
- **$b$-associated production**

- **2 channels:** $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$
- **Discriminating variable:**

$$m_T^{\text{tot}} = \sqrt{m_T^{\text{miss}}(\tau_1) + m_T^{\text{miss}}(\tau_2) + m_T^{\text{miss}}(\tau_1, \tau_2)}.$$  

**Events category:**
- **$b$-veto:** no $b$-jets in the event
- **$b$-tag:** at least one $b$-jet
**MSSM h/H/A→ττ: ATLAS@13TeV**

**Limits on cross-section × BR**

- **gg-fusion**
- **b-associated production**

**Limits on tanβ**

**hMSSM**

**m_h^{mod+} MSSM**

In the context of the MSSM $m_h^{mod+}$

The limits on β:
- $\beta<9$, $m_A=200$
- $\beta<50$, $m_A=1200$
The are two production mechanism: VBF and ggF.

- only different-flavor lepton pairs in the final state are considered
- two oppositely-charged leptons and no additional lepton with $p_T > 15$ GeV in order to suppress diboson backgrounds

Discriminating variable:

$$m_T = \sqrt{(E_{T\ell}\ell + E_{T\text{miss}})^2 - |p_{T\ell\ell} + E_{T\text{miss}}|^2},$$

$$E_{T\ell\ell} = \sqrt{|p_{T\ell\ell}|^2 + m_{\ell\ell}^2}. $$

ATLAS-CONF-2016-074
Two different hypotheses are tested:

- a narrow width approximation (NWA), where the width of the heavy Higgs boson is smaller than the experimental resolution
- large width assumption (LWA), where widths of 5%, 10%, and 15% of the heavy Higgs boson mass are considered.

**gg-fusion, LWA**

<table>
<thead>
<tr>
<th>Process</th>
<th>NWA</th>
<th>LWA (5%)</th>
<th>LWA (10%)</th>
<th>LWA (15%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>4.3 pb (m_H = 300 GeV)</td>
<td>0.051 pb (m_H = 3 TeV)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>1.1 pb (m_H = 300 GeV)</td>
<td>0.03 pb (m_H = 3 TeV)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**VBF, NWA**

**gg-fusion, NWA**

**upper exclusion limits (95% CL):**

- ggF NWA
  - 4.3 pb (m_H = 300 GeV)
  - 0.051 pb (m_H = 3 TeV)
- VBF NWA
  - 1.1 pb (m_H = 300 GeV)
  - 0.03 pb (m_H = 3 TeV)
Event selection:
• only different-flavour lepton pairs in the final state are considered
• The event is required to have two oppositely-charged isolated leptons
• Events categories: 0, 1 jets and VBF events
• Discriminating variable:

\[ m_{T,i} = \sqrt{(p_{T1} + E_{T\text{miss}}^1)^2 - (\vec{p}_{T1} + \vec{p}_{T\text{miss}}^1)^2} \]
limits on the sum of ggH and VBF cross sections times branching fraction were set (ATLAS presented results for two channels separately)

• The limits are interpreted in the electroweak singlet model

• 4 different signal width have been used

CMS-PAS-HIG-16-023
Search for a CP-odd (pseudoscalar) Higgs boson
• Leptonic decay of Z-boson
• Analysis was done separately for the events categories:
  0 or 2 – leptons and 1 or 2 of b-tagged jets
• Resolved or merged jets are considered
• The discriminant variable:
  in the case of “2” reconstructed leptons is invariant mass,
  in the case of “0” reconstructed leptons is transverse mass:

\[ m_{Zh}^T = \sqrt{(E_T^h + E_{miss}^T)^2 - (p_T^h + E_{miss}^T)^2} \]

**ggF**  
**b-quark associative production**

Upper limits were set on the production cross sections × BR
in the range:
[4.0 - 0.017] pb ggF  
[6.9 - 0.026] pb b-quark-ass.
Results are interpreted in the context of 2HDM (type I and II) as a function of the model parameters $\tan\beta$ and $\cos(\beta-\alpha)$

- $A \rightarrow W^+ H^-$, $A \rightarrow ZH$ are assumed to be forbidden
- The width of the $A$ boson is corrected to the width ($\Gamma_A$) predicted by the 2HDM.
- Only points in parameter space where $\Gamma_A/m_A < 5\%$ are considered.
Di-Higgs
\( H \rightarrow hh \rightarrow bb \tau \tau : \text{CMS@13TeV} \)

- \( H \rightarrow hh \rightarrow bb \tau \tau \)
  - \( bb \rightarrow 2\text{jet}(1 \text{~b-tag, 2 ~b-tag}) \)
  - \( \tau \tau \rightarrow (\mu \tau_h \epsilon \tau_h \tau_h) \) OS final states
  - \( \tau_h \) visible products of a hadronically decaying \( \tau \)

- discriminant variable – inv mass

Result interpreted in the context of the \( h\text{MSSM} \)

The gray dotted lines plotted for different \( m_H \) values.

CMS PAS HIG-17-002
**H → hh: ATLAS@13 TeV**

![Graph showing the 95% CL limit on σ_x → BR(H → hh) for varying m_H, with observed and experimental limits and their uncertainties.]

- **H → hh(→b\bar{b}γγ)** ATLAS-CONF-2016-004
  - Advantages: H → b\bar{b} decay (BR 58%), clean diphoton signal
  - Events are selected if there are at least two isolated photons and exactly two b-jets.
  - Discriminating variable: invariant mass
  - The observed limits are in the range 7.0 - 4.0 pb

![Graph showing the cross-section limits for H → hh → b\bar{b}b\bar{b} for varying m_H, with resolved and boosted analysis.]

- **H → hh → b\bar{b}b\bar{b}** Phys. Rev. D 94 (2016) 052002
  - “resolved” for low mass and “boosted” for high mass analysis
  - Discriminating variable: invariant mass
  - The cross-section upper limits with ranging from 30 -300 fb

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SM@LHC 2017 Amsterdam May 2 - 5 Yu. Naryshkin, PNPI
Charged Higgs
$H^\pm \rightarrow \tau^\pm \nu_\tau$: CMS@13TeV

$pp \rightarrow tbH^\pm$, $pp \rightarrow H^\pm W^\pm b\bar{b}$

- top-quark decay (low mass) or direct prod (high mass)
- Fully hadronic final state is considered.
- Event selection: $\tau_h$, large missing $E_T$ ($N_{\text{jets}} \geq 3$), and one $b$-tagged jet.
- Discriminating variable – transverse mass ($m_T$):

$$m_T^2 = 2 \cdot p_T^h |\vec{E}_T| \left(1 - \cos \Delta \phi(\vec{E}_T, \tau^h)\right)$$

CMS-PAS-HIG-16-031

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$H^\pm \rightarrow \tau^\pm \nu_\tau$: CMS@13TeV

**Low mass:** $m_{H^\pm} < m_t - m_b$

**High mass:** $m_{H^\pm} > m_t - m_b$

- Model independent limits on charged Higgs bosons BR and cross section $\times$ BR

- Exclusion limits in the $m_H$ vs $\tan\beta$ plane is interpreted in the context of the $m_h^{\text{mod}+}$ MSSM model
• The production of a charged Higgs boson in association with a single top quark and its decay via $H \rightarrow \tau \nu$ based on fully hadronic final states
• Event selection: one $\tau$ and $\geq 3$ jets with $\geq 1$ b-tagged jets
• Discriminating variable is the transverse mass
• Only high mass case is considered

Interpretation in the hMSSM benchmark scenario.

Excluded regions:
$42 < \tan \beta < 60$
for $m_{H^\pm} = 200$ GeV.
$200 < m_{H^\pm} < 540$ GeV at $\tan \beta = 60$. 
• \((pp \rightarrow btH^\pm) \times BR(H^\pm \rightarrow tb)\)
• events must have exactly one lepton (electron or muon) and \(\geq 4\) jets, \(\geq 2\) b-tagged jets
• Discriminating variables:
  scalar sum \(p_T(HT_{had})\) of the selected jets in CR
  Multivariate techniques (BDT) used in SR

The observed (expected) 95% CL upper limits range \(\sigma \times BR:\)
1.09 (1.45) pb - 0.18 (0.17) pb
H^+ → WZ → 3ℓ+ν_ℓ : CMS@13TeV

- VBF production mechanism is assumed
- Lepontic decay (e,µ) W,Z bosons
- Events selection: 3 leptons, 2 jets with large rapidity separation and high dijet mass, and moderate MET
- b-jet veto to suppress top background
- Discriminating variable:

  \[ m_{T}(WZ) = \sqrt{(E_{T}(W) + E_{T}(Z))^{2} - (p_{T}(W) + p_{T}(Z))^{2}} \]

- Higgs Triplet Model used for interpretation
- Limits on the charged Higgs \( \sigma \times BR \) are given for \( 200 < m_{H^+} < 1000 \) GeV.

CMS PAS HIG-16-027
Yu. Naryshkin, PNPI
Double Charged Higgs
Double charged Higgs: ATLAS@13TeV

- Interpretation: LRSM
- Decay mode: $H^{\pm\pm} \rightarrow e^\pm e^\pm$
- Events selected: same-charge, isolated, high-$p_T$ electrons inv mass > 300 GeV
- Discriminating variable inv mass of SS electron pairs

The observed(expected) lower mass limits at 95% C.L.:
(100% BR) lower mass limit
420 (460) GeV for: $H_R^{\pm\pm}$
570 (580) GeV for: $H_L^{\pm\pm}$
(50% BR) lower mass limit
380 (400) GeV for: $H_R^{\pm\pm}$
530 (530) GeV for: $H_L^{\pm\pm}$
Double charged Higgs: CMS@13TeV

- 100% decay to $ee$, $\mu\mu$, $e\mu$, $e\tau$, $\mu\tau$, and $\tau\tau$
- 3(4) lepton candidates with charge configuration: $(++-), (---)$ and $(+++)$
- Discriminating variable is inv mass of SS lepton pairs
- $m(\Phi^+) = m(\Phi^{++})$

Lower bounds on the $\Phi^{\pm\pm}$ mass are set to:
- 800 - 820 GeV ($ee$, $e\mu$, and $\mu\mu$)
- 714 GeV ($e\tau$)
- 643 GeV ($\mu\tau$)
- 535 GeV ($\tau\tau$)
- 100% BR is assumed
The recent results on BSM Higgs searches on LHC with the different final states and in large mass ranges (up to 3000 GeV) were presented.

No excess of the data over SM prediction were observed and the upper limits on the cross section production and BR were obtained as a function of BSM Higgs boson mass for neutral heavy Higgs $H, A$, charged Higgs $H^\pm$ and double charged Higgs bosons $H^{\pm\pm}$.

The results were interpreted considering different BSM models: $2HDM, MSSM, HTM, LRSM$ and the limits on the model’s parameters were set for: $\tan\beta, \cos(\beta-\alpha)$ and $m_A$. 
• A lot of searches done for the last years for a lot of final states and in wide mass ranges, but result is still negative 😞
• We will increase our statistics next years, hopefully it helps.
• If the signal is too weak, is it possible to improve signal to background separation (better background modeling, new optimization criteria etc ...)?
• most promising final states are covered but should we study more decay channels?
Back Up
A→Zh→llττ: CMS@8TeV

- 2HDM used for interpretation
- A → Zh → llττ: 
  \[ ll \rightarrow (\mu\mu \text{ or } ee) \]
  \[ h \rightarrow (\mu_{\text{had}} \epsilon \tau_{\text{had}} \tau_{\text{had}} e\mu) \]
- 8 final states were analyzed
- Discriminant variable – inv mass (Zh)

H^+ → W^± Z → 2ℓ+jj : ATLAS@8TeV

- Higgs Triplet Model used for interpretation
- VBF production mechanism is assumed
- The VBF process reconstructed with two jets, with high |η| moving in opposite directions.
  - Z → e^+e^− / μ^+μ^- two OS leptons
  - W^± → q̅q' reconstructed from two high p_T central jets
- Discriminating variable: invariant mass m_{ℓjj}

PRL 114, 231801 (2015)
The limit falls off rapidly as $m_A$ approaches 350 GeV because decays of the $A$ to two top quarks are becoming kinematically allowed.

The areas highlighted in blue bounded by the black curves mark the observed exclusion.
H → hh: ATLAS

\[ \sqrt{s} = 8\text{TeV} \]

\[ \sqrt{s} = 8\text{TeV} \]

\[ s = 8\text{TeV}, 20.3\text{ fb}^{-1} \]

\[ s = 13\text{TeV} \]

\[ \text{Observed exclusion} \]

\[ \text{Expected exclusion} \]

\[ \pm 1\sigma \text{ expected} \]

\[ \pm 2\sigma \text{ expected} \]

\[ \text{bb\tau\tau} \]

\[ \text{bb\gamma\gamma} \]

\[ \text{bbbb} \]

\[ \text{ATLAS} \]

\[ \text{Phys. Rev. D 92, 092004} \]

\[ \text{Phys. Rev. D 94 (2016) 052002} \]
### 2HDM

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>up-type quarks couple to</th>
<th>down-type quarks couple to</th>
<th>charged leptons couple to</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>Fermiophobic</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
<td>charged fermions only couple to second doublet</td>
</tr>
<tr>
<td>Type II</td>
<td>MSSM-like</td>
<td>$\Phi_2$</td>
<td>$\Phi_1$</td>
<td>$\Phi_1$</td>
<td>up- and down-type quarks couple to separate doublets</td>
</tr>
<tr>
<td>X</td>
<td>Lepton-specific</td>
<td>$\Phi_2$</td>
<td>$\Phi_2$</td>
<td>$\Phi_1$</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>Flipped</td>
<td>$\Phi_2$</td>
<td>$\Phi_1$</td>
<td>$\Phi_2$</td>
<td></td>
</tr>
<tr>
<td>Type III</td>
<td></td>
<td>$\Phi_1, \Phi_2$</td>
<td>$\Phi_1, \Phi_2$</td>
<td>$\Phi_1, \Phi_2$</td>
<td>Flavor-changing neutral currents at tree level</td>
</tr>
</tbody>
</table>

By convention, $\Phi_2$ is the doublet to which up-type quarks couple.

**Fermiophobic Higgs** - whose couplings to fermions are suppressed. In the fermiophobic scenario the Higgs boson production is restricted to vector boson fusion and associated production with vector bosons.