Higgs Searches beyond SM and MSSM at the LHC

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on behalf of the ATLAS and CMS Collaborations

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Not all the petals are discussed in this talk.

- No Higgless models, R-parity violation models, Compositeness, Technicolor, Strong Dynamic models are presented

- The exploration of the TeV energy scale at LHC is expected to complete the success of the Standard Model

- The discovery (or the absence) of one or more Higgs bosons will lead to a *flowering of new physics*.

- Revealing the full details of the underlying mechanism of EWSB may be considerably more complex than what is foreseen by SM or MSSM

- There may be interplay between Higgs sectors and the not probed parts of the SM
As in the SM case, the tree-level MSSM Higgs sector is also CP-conserving.

But loop effects (involving CP-violating interactions to top and bottom squarks) may lead to a most general CP-violating two-Higgs doublet model (2HDM).

CP-violation (either explicit or spontaneous) in the Higgs sector → mixing of neutral Higgs states of opposite CP and/or (direct) CP-violating Higgs interactions.

Mass eigenstates:

<table>
<thead>
<tr>
<th>CP-violating 2DHM</th>
<th>CP-conserving MSSM</th>
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</thead>
<tbody>
<tr>
<td>$H_1, H_2$ and $H_3$</td>
<td>$h, H$ and $A$</td>
</tr>
<tr>
<td>$H^\pm$</td>
<td>$H^\pm$</td>
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*Experimental limits*: no absolute lower bounds on Higgs boson masses and couplings exist, but:

- In *decoupling limit* (lightest neutral $H_{2\text{HDM}} \to H_{\text{SM}}$) $M_H > 114.4$ GeV at 95% CL, but $H_1$ may have mass *smaller* than 70 GeV, escaping detection at LEP2.

- Charged Higgs: $M_{H^\pm} > 78.6$ (76.7) GeV at 95% CL for 2HDM Type-I (2HDM Type-II) from LEP2 measurements - $b \to s\gamma$ decay implies $M_{H^\pm} \geq 320$ GeV (2HDM Type-II).
In MSSM with large loop-induced CP-violating Higgs Yukawa interactions → **CPX benchmark scenario** chosen for phenomenological studies

<table>
<thead>
<tr>
<th>CPX Scenario</th>
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<tbody>
<tr>
<td>$\tilde{M}_Q = \tilde{M}<em>t = \tilde{M}<em>b = M</em>{SUSY}$, $\mu = 4M</em>{SUSY}$, $\arg(A_t) = 90^\circ$</td>
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- $M_{H\pm}$ and $\tan\beta$ are the only free parameters (at Born level) - here $M_{SUSY} = 500 \text{ GeV}$

**Lightest neutral Higgs** (left):

All Higgs production process and the most relevant decays → angular distributions of final state Higgs decay products studied

**Overall Discovery Potential** (right):

No updated study
Only LO cross sections
No systematic uncertainties
More investigation needed in the uncovered regions
Lepton Flavor Violating (LFV) Scenarios

- In MSSM tree-level LF is protected by the soft supersymmetry breaking terms
- In models with several Higgs doublets, FCNC and LFV exist at tree level → ad hoc discrete symmetries (in 2HDM Type-I and 2HDM Type-II) are invoked to cope with the known experimental limits
  - LFV effects can arise in SUSY models with RH Majorana Neutrinos or with R-parity violation
- In 2HDM Type-III, no discrete symmetries are present and FCNC and LFV exist → flavor changing couplings parameterized to agree with experimental constraints on FCNC and LFV couplings
- Experimentally:
  - $(g-2)_\mu$ deviation from SM prediction constraints the LFV $\lambda_{\tau\mu}$ coupling
  - At LHC bounds on LFV couplings can be obtained from $B(s)$ decays, $\tau^{\pm}\rightarrow\mu^{\pm}\gamma$, $\tau\rightarrow cV$ ($V = h, A, H$), $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tau \mu$ and $A/H \rightarrow \tau^\pm \mu^\mp$ (allowed in 2HDM Type-III)
Sensitivity in terms of the lepton flavor violating parameter $\kappa_{\tau \mu}$ defined by:

$$BR(A/H \rightarrow \tau \mu) = \kappa_{\tau \mu}^2 \left( \frac{2m_\mu}{m_\tau} \right) BR_{SM}(H \rightarrow \tau \tau)$$

**Analysis Details:**

- **Low mass region**
- **Final states with** $\tau \rightarrow \text{had} \nu_\tau$ (BR $\sim$65%) or $\tau \rightarrow e \nu_e \nu_\tau$ (BR $\sim$18%)
- **Backgrounds:** MSSM $A/H \rightarrow \tau \tau$, $Z(\gamma^*) \rightarrow \tau \tau$, $W(\rightarrow \mu \nu_\mu) + \text{jets}$ and $WZ, WW, tt$

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With 100 fb$^{-1}$ LHC can improve sensitivity on $\lambda_{\mu \tau}$ by up to a factor 100 w.r.t (g-2) data
Higgs in Next-to-MSSM (NMSSM)

\(\text{NMSSM solves MSSM } \mu\text{-problem by adding one singlet } S, \text{ at the cost of adding 3 more particles}\)

- MSSM suffers from \textit{\(\mu\)-problem}: \(\mu\), the Higgs/higgsino mixing parameter, has a priori no knowledge about EWSB, but phenomenologically constrained around EW scale (\(\mu \sim 100\text{-}1000 \text{ GeV}\)) or large cancellations needed

- Problem solved in NMSSM by adding a neutral singlet Higgs chiral super-field \(S\)

\[-L_{\text{soft}} \supset m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + (\lambda A_\lambda S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.})\]

\(\lambda, \kappa = \text{dimensionless couplings and } \mu = \mu_{\text{eff}} = \lambda < S >\)

\(<S>\) constrained by the Higgs potential minimization (100-1000 GeV)

\(\rightarrow \mu\) is \textit{naturally} constrained to the EWSB scale

- Particle content (if CP is conserved):

<table>
<thead>
<tr>
<th>NMSSM Higgs Sector</th>
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<tbody>
<tr>
<td>3 neutral scalars: (H_1, H_2,) and (H_3)</td>
</tr>
<tr>
<td>2 neutral pseudoscalars: (A_1) and (A_2)</td>
</tr>
<tr>
<td>2 charged: (H^\pm)</td>
</tr>
</tbody>
</table>

- \textit{Five neutralinos}, from neutral fermion mixing with neutralinos
- Charged Higgs and charginos remain practically unchanged w.r.t. MSSM
Six free parameters for Higgs sector: $\mu_{\text{eff}} = \lambda < S >$ - couplings $\lambda$, $\kappa$, $A_\lambda$, $A_\kappa$ - $\tan \beta$

→ According to parameter choices, different scenarios possible

Studies done in two benchmark scenarios:

**Reduced coupling scenario**: $H_1$ very light, $H_2$ SM-like with mass 120 GeV - $H_2 \rightarrow H_1 H_1$ allowed (BR $\sim 6\% \rightarrow$ negligible)

**Light $A_1$ scenario**: $A_1$ light, $H_1$ SM-like with mass 120 GeV - $H_1 \rightarrow A_1 A_1$ allowed and dominant (BR up to $\sim 90\%$)

All other Higgs bosons: either highly reduced couplings or contribution in LEP-excluded region

**NMSSM hard to probe at LHC due to reduced couplings and smaller production rates**
1. In NMSSM, the lower limit on $M_{H^\pm}$ (from LEP and $M_{H^\pm}^2 = M_W^2 + M_A^2$) no longer valid and parameter space is less constrained

$\rightarrow H^\pm \rightarrow W^\pm h$ dominant decay mode for low $\tan\beta$ and $M_{H^\pm} \sim 160$ GeV

2. In large Extra Dimension (ED) models, right-handed neutrinos can freely propagate into the ED (bulk $\nu$)

$\rightarrow$ When interacting with SM fields on the brane they produce Dirac neutrino masses consistent with atmospheric oscillation observation

$\rightarrow$ No additional Higgs bosons required by the model $\rightarrow$ 2HDM Type-II

$\rightarrow$ Allowed and studied decays like

$H^- \rightarrow \tau_R^- \bar{\nu} + \tau_L^- \psi$, $\psi =$ bulk neutrino

H$^\pm$ in NMSSM and Large Extra Dimensions

LHC discovery of $H^\pm$ possible through channels not relevant or not allowed in MSSM
Doubly Charged Higgs at LHC

Doubly charged Higgs bosons predicted in several models

- **Left-Right Symmetric Model**: SU\(_L\)(2) \(\otimes\) SU\(_R\)(2) \(\otimes\) U\(_{B-L}\)(1), broken to SU\(_L\)(2) \(\otimes\) U\(_Y\)(1) by a triplet of complex Higgs fields - physical states: \(\Delta_{R0}^+, \Delta_{R+}^+\) and \(\Delta_{R++}^+\) (and corresponding Left triplet) and a didoublet \(\varphi\)

- **Little Higgs Models**: SM Higgs boson is a pseudo-Goldstone boson of higher EW gauge symmetry after its breakdown into SU(2) \(\times\) U(1) and remains light - physical states \(\Delta\) triplet with masses \(\mathcal{O}(1\text{TeV})\)

- 3-3-1 Models, Supersymmetric LR Models, etc.

- **Clear signature at LHC** → charge conservation prevents doubly charged Higgs to decay into a quark pair

Main production processes:

- Singly (\(WW/\varphi\varphi\) fusion) → cross section \(O(\text{fb})\) for \(|\eta| < 3\) and \(p_T > 200\) GeV

- In pairs (s-channel, \(Z/\gamma^*\) or \(Z'\) exchange) → smaller cross section

Decays: mostly to leptons or \(W^+W^+\) final states (2 same-sign leptons and \(E_T^{\text{miss}}\))

- **Experimental limits** (TeVatron): \(M(\Delta^{\pm\pm}) > 150(127)\) GeV at 95% CL, for \(I_3 = \pm 1\) (0)
**Doubly Charged Higgs LHC Sensitivity**

LHC will be able to probe a large region of unexplored parameter space in the triplet Higgs sector.

**Left-Right Symmetric Models**: $\Delta^{++} \Delta^{-} \rightarrow 4l$

**Analysis details**:
- $\Delta^{++}$ coupling to fermions not known
- Analysis performed assuming 100% BR to leptons
- Background negligible → golden channel
- Discovery = observation of 10 events with 4 (dashed contour) or 3 (full contour) final state leptons

**Little Higgs Models**: $\Delta^{++} \Delta^{-} \rightarrow 4l$

**Analysis details**:
- Analysis performed assuming 100% BR into muons
- Background free channel → golden channel
- Log-likelihood method to estimate exclusion/discovery
- Uncertainties included
Randall-Sundrum models of localized gravity → all SM fields (including the Higgs, originally) confined to one or two TeV branes - gravity is a bulk field in 5D

Two massless excitations described by the 5D metric tensor: the graviton and the radion $\phi_0$, a real scalar field with

- Mass in $[-10 \text{ GeV}, \Lambda_{\pi}]$, $\Lambda_{\pi}$ = cutoff of the effective theory
- Couplings to SM fields similar to the Higgs, large effective coupling to gluons

→ Higgs/radion mixing with $\xi$ mixing parameter: physical mass-eigenstates $h$ and $\phi$

Trilinear terms in Higgs/radion sector →

$\phi \rightarrow hh$ and $h \rightarrow \phi \phi$ decays allowed

Light Higgs discovery at LHC different from SM or MSSM and depending on $|\xi|$ and $M_{\phi}/M_h$

Regions with both $h$ and $\phi$ detectable

$h$ and $gg \rightarrow \phi \rightarrow ZZ^* \rightarrow 4l$ $5\sigma$ detectability

$M_h = 120 \text{ GeV}$, $\Lambda = 5 \text{ TeV}$

Theory $\phi$ $5\sigma$ discovery

Higgs $5\sigma$ discovery

Light Higgs discovery at LHC different from SM or MSSM and depending on $|\xi|$ and $M_{\phi}/M_h$
Higgs/radion sector free parameters: $M_\phi$, $M_h$, $\xi$ and $\Lambda_\phi = \sqrt{6} \Lambda_\pi$

Several radion decays at LHC investigated:

- $\phi \rightarrow \gamma\gamma$, $\phi \rightarrow ZZ^{(*)} \rightarrow 4l$, $\phi \rightarrow hh \rightarrow b\bar{b}\tau\tau$,
- $\phi \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$, $\phi \rightarrow hh \rightarrow b\bar{b}b\bar{b}$

evaluated from:

$$\frac{S/\sqrt{B}(\phi; ZZ)}{S/\sqrt{B}(h; ZZ)} = \frac{\Gamma_{\phi \rightarrow gg}BR(\phi \rightarrow ZZ)}{\Gamma_{h \rightarrow gg}BR(h \rightarrow ZZ)} \sqrt{\frac{\sigma_{ZZ}^{\phi}}{\sigma_{ZZ}^{h}}}$$

Analysis Details:

Single and dilepton w/ and w/o jets triggers
Two jets with $E_T > 30$ GeV and $|\eta| < 2.4$, at least one tagged as b-jet
Cut-based analysis
$tt\bar{t}$ and $W+jets$ backgrounds
Higgs boson(s) invisible decay width foreseen in SUSY and in beyond MSSM models like large Extra Dimensions, R-parity violation models, Majoron models, dark matter models containing a stable singlet scalar, etc.

What is invisible depends on the model: graviscalars, Kaluza-Klein neutrinos, neutralinos etc. will all escape detection

- Modification of SM production modes and decays expected

**Trigger:** need a visible signature → vector boson fusion (VBF) and ttH, ZH Higgs productions (WH impossible due to high background)

No mass reconstruction → discovery = excess of events w.r.t. predicted SM background, therefore stringent experimental requirements:

- Good signal-to-background ratio, optimal background knowledge (from data, soon)
- Optimal jet detection and missing $E_T$ reconstruction

SM Higgs production rates and couplings assumed
Invisible Higgs LHC Sensitivity

LHC can reach sensitivities as low as 50% of SM cross section for 100% decay to invisible - Model independent

- LHC sensitivity expressed in terms of the parameter $\xi^2 = BR(H \to \text{invisible}) \cdot \frac{\sigma_{BSM}}{\sigma_{SM}}$
- Topological search, completely model-independent
- Caveat: pile-up (not included here) may reduce sensitivity

Analysis details
SM Higgs cross sections and 100% invisible BR
VBF and ZH production process - SM backgrounds only
$E_T^{\text{miss}}$ + forward jet trigger (VBF) - lepton triggers (ZH)
Cut-based and Boosted Decision Tree analyses
95% CL, including systematic uncertainties

VBF channel w/ and w/o Systematics
Systematic uncertainties deteriorate dramatically the sensitivity
Summary

- We should not limit our attention to the singly weakly interacting Higgs of the SM
- There may be a close link between the Higgs sector and CP or lepton-flavor violation, and one should consider the possibility of non-standard Higgs representations such as singlets or triplets, or novel decay patterns, including invisible modes
- A light Higgs scalar (arising in NMSSM or in CP-violating models) can still be allowed by LEP constraints
- All searches for non-SM and non-MSSM Higgs particles are very demanding in integrated luminosity → no possibility for early discoveries
- All the searches on the Higgs sector complemented by searches for other evidence of New Physics
- And ... from the theoretical point of view, the absence of Higgs boson(s) at the TeV scale would be, in any case, an interesting outcome from LHC (but experimentalists might be disappointed!)

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References


CP-violation and LFV


**NMSSM**


**Doubly Charged Higgs**


**Radion Searches**

Differentiated by the possible Higgs-fermion Yukawa couplings

<table>
<thead>
<tr>
<th>Two-Higgs Doublet Models (2HDM)</th>
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<tbody>
<tr>
<td><strong>General 2HDM</strong></td>
</tr>
<tr>
<td>two identical (hypercharge-one) scalar doublets $\Phi_1$ and $\Phi_2$</td>
</tr>
<tr>
<td><strong>2HDM Type-I</strong></td>
</tr>
<tr>
<td>one Higgs doublet couples to both up-type and down-type fermions,</td>
</tr>
<tr>
<td>and the other Higgs doublet does not couple at all to the fermions</td>
</tr>
<tr>
<td><strong>2HDM Type-II</strong></td>
</tr>
<tr>
<td>one Higgs doublet couples to up-type fermions and the other Higgs</td>
</tr>
<tr>
<td>doublet couples to down-type fermions.</td>
</tr>
<tr>
<td><strong>2HDM Type-III</strong></td>
</tr>
<tr>
<td>a 2HDM with all possible Higgs-fermion couplings allowed</td>
</tr>
</tbody>
</table>

MSSM is a 2HDM Type-II
discovery potential in the CP-conserving **MAX** (large value of the Higgs mass) scenario

**CPC MAX Scenario**

\[ \tilde{M}_Q = \tilde{M}_t = \tilde{M}_b = M_{SUSY}, \quad A_t = A_b = \sqrt{6} M_{SUSY}, \]

\[ m_{\tilde{g}} = 1 \text{ TeV}, \quad \mu = m_{\tilde{B}} = m_{\tilde{W}} = 200 \text{ GeV} \]
Lepton Flavor Violating $A^0/H^0 \rightarrow \tau\mu$ at TeVatron

$gg \rightarrow A^0/H^0 \rightarrow \tau\mu$

CDF+D0
20 fb$^{-1}$ / Exp.

$\kappa_{\tau\mu}$

$\lambda_{\tau\mu}$

Lower Bounds on $\lambda\tau\mu$ at the TeVatron

$A^0 \rightarrow \tau\mu$

$\mu g-2$

$\tan \beta = 45$

$\alpha = -0.58 \text{ rad}$

$H^0 \rightarrow \tau\mu$

$\kappa_{\tau\mu} = 1$

$\tan \beta = 45$

$\lambda_{\tau\mu}$

© Reference [9]

Daniela Rebuzzi, Higgs searches beyond SM and MSSM at the LHC - Ann Arbor, 14.05.2010
Higgs/Radion in Randall-Sundrum Models

\[ M_h = 120 \text{ GeV}, \Lambda = 2.5 \text{ TeV} \]

h and \( gg \to \phi \to ZZ^* \to 4l \) 5\( \sigma \) detectability

\[ \text{ATLAS} \ 100 \text{ fb}^{-1} \]
LHC sensitivity expressed in term of the $\xi$ parameter $\xi = BR(H \rightarrow \text{invisible}) \cdot \frac{\sigma_{BSM}}{\sigma_{SM}}$

Missing ET plus forward jet trigger for qqH - lepton triggers for ZH

Caveat: pile-up (not included here) may reduce sensitivity

Analysis details
SM Higgs cross sections and 100% invisible BR
qqH production process - SM backgrounds
Cut-based analysis
Systematic uncertainties NOT included