BSM Higgs Physics at LHC (CMS)

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Iran, Tehran October 2013
Why BSM ?
• **Problems of the Standard Model**
  
  – “huge fine-tuning is needed to have $m_H \sim 125$ GeV after the radiative corrections”
  
  – “Big hierarchy problem”:
    
    • $\Lambda (M_{GUT} \sim 10^{16}$ GeV or $M_P \sim 10^{18}$GeV) $>> M_Z$
  
  – Does not include Dark Matter particle(s)
The Higgs gives us a hard time!

- Both the EW symmetry breaking and fermion masses are economically achieved by the fundamental scalar, Higgs.

\[ \delta M_H^2 = \frac{|y_f|^2}{16\pi^2} \left[ -2\Lambda_{UV}^2 + 6m_f^2 \ln \frac{\Lambda_{UV}}{m_f} \right] \]

- But the quantum correction is UV sensitive:

\[ (M_H)_{phys} = (M_H)_{bare} + \delta M_H \]

100 GeV \( \sim \) (100 GeV)_{bare} \( - (100 \text{GeV})_{QC} \)

⇒ Gauge Hierarchy Problem
“Hierarchy problem”

Why so big difference?
Searches for BSM Physics with Higgs bosons

- Non SM decays of h(125)

The present accuracy of Higgs boson measurement (in CMS) allows $BR(h\rightarrow\text{BSM decays}) < 0.65$ at 95 % CL

CMS PAS HIG-13-005

- Additional Higgs bosons
- precise coupling measurements for h(125)
Searches for $H \rightarrow \text{invisible decays}$ at LHC

Detection of Dark Matter
Evidence for dark matter

Milky Way:
\[ M_{\text{halo}} \sim 10 \times M_{\text{visible}} \]

Rotation curves
Dark Matter
OR
MODified Newtonian Dynamics
(acceleration \( \neq GM/r \))

Dark Energy
\[ 0.73 \pm 0.03 \]

Stars
0.005
Baryonic DM
0.04 \pm 0.004
Non-baryonic DM
0.23 \pm 0.03

and is flat
\[ \Omega_T = 1.01 \pm 0.01 \]

WMAP launched in 2001 from Florida. 9 years data released in 2012
Two galaxy clusters collide.
Most baryonic matter is in the gas.
The gas is stopped in the collision, the stars continue.
Grav. lensing shows that the potential follows the stars.
Hence most of the matter is hidden around the stars.
No alternative theory of gravitation can explain this.
One of simplest models of DM: Higgs-portal DM

- DM consists of real scalars $S$, or vectors $V$ or Majorana fermions $f$ which interact with the SM fields only through the Higgs boson
  - It is the simplest extension of the SM

DM annihilation
Y.Mambrini arXiv:1108.0671

$Z_2$ symmetry $\rightarrow$ DM is stable
No DM - Higgs mixing
No cosmological domain walls

$$\begin{align*}
\Delta \mathcal{L}_S &= -\frac{1}{2} m_S^2 S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{4} \lambda_{h,SS} H^\dagger H S^2, \\
\Delta \mathcal{L}_V &= \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4} \lambda_V (V_\mu V^\mu)^2 + \frac{1}{4} \lambda_{hVV} H^\dagger HV_\mu V^\mu, \\
\Delta \mathcal{L}_f &= -\frac{1}{2} m_f \bar{\chi}\chi - \frac{1}{4} \frac{\lambda_{h,ff}}{\Lambda} H^\dagger H \bar{\chi}\chi. 
\end{align*}$$
Connection between LHC H-$\rightarrow$inv. and XENON measurements

\[ \sigma_{SI}^{S-N} = \frac{\lambda_{hSS}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2}, \]
\[ \sigma_{SI}^{V-N} = \frac{\lambda_{hVV}^2}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2}, \]
\[ \sigma_{SI}^{f-N} = \frac{\lambda_{hff}^2}{4\pi \Lambda^2 m_h^4} \frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2}, \]

where \( f_N \) – Higgs-nucleon coupling

DM-nucleon scattering (by XENON exp.)

H-$\rightarrow$invisible decay at LHC

\[ \Gamma_{h\rightarrow SS}^{inv} = \frac{\lambda_{hSS}^2 v^2 \beta_S}{64\pi m_h}, \]
\[ \Gamma_{h\rightarrow VV}^{inv} = \frac{\lambda_{hVV}^2 v^2 m_h^3 \beta_V}{256\pi M_V^4} \left( 1 - 4 \frac{M_V^2}{m_h^2} + 12 \frac{M_V^4}{m_h^4} \right), \]
\[ \Gamma_{h\rightarrow \chi\chi}^{inv} = \frac{\lambda_{hff}^2 v^2 m_h \beta_f^3}{32\pi \Lambda^2}, \] where \( \beta_X = \sqrt{1 - 4M_X^2/m_h^2}. \)

A. Djouadi et. al. arXiv:1112.3299
DM (WIMP) detection on Earth with XENON experiment (I)

Start data taking in 2007 at Gran Sasso in Italy. Current XENON100 – 165 L xenon. Plan for 1000 L
DM (WIMP) detection on Earth with XENON experiment (II)

XENON collaboration, arXiv:1207.5988
LHC is currently most sensitive DM detection apparatus, at least in the context of simple Higgs-portal models.
H-\rightarrow\text{invisible BR in (N)MSSM}

- NMSSM $H_2 \rightarrow \chi^0 \chi^0$
  King, arXiv:1211.5074

- pMSSM $h \rightarrow \chi^0 \chi^0$
  Djouadi arXiv:1211.4004

Compatible with LHC Higgs data (green color)
H->invisible: topologies proposed for LHC searches

- **VBF H->invis.**
  - D. Zeppenfeld, O.J. Eboli 2000

- **ZH, H->invis., Z->ee, bb**
  - D.P. Roy, D. Choudhuri 1994
  - Recently R. Godbole et al arXiv:1211.7015

- **gg->H+jet, H->invisible**
VBF H-\rightarrow\text{invisible analysis}

VBF Higgs production features:

- two jets in forward-backward direction with large rapidity separation
- large di-jet invariant mass
- no jets in the central detector region

EWK Z+jj as benchmark process
EWK Z+jj vs VBF H+jj

- **EWK Z+jj production graphs**

![Diagram of EWK Z+jj production graphs]

Figure 1: Representative diagrams for EWK $\ell\ell jj$ production processes. Left - bremsstrahlung, middle - VBF process, right - multiperipheral.

- **DY Z+jets production – dominant background**

+ many more types of processes with $\alpha_{\text{QCD}}^2$
Extracting EWK $Z+jj$ signal

- Signal significance:
  - 2.6 for 7 TeV
  - 4.9 for 8 TeV
- Agreement with SM predictions
What did we learn from EWK Z+jj analysis useful for VBF H?

- Identify and solve problem with Jet Energy Scale in the forward region
  - *important for all VBF Higgs analyses*

- Study central jet veto performance (although did not use it in final selections)

- Found that MadGraph Monte Carlo does not describe well $m_{jj}$ and $y^* = y_Z - 0.5(y_{j1} + y_{j2})$ data distributions for DY Z+jets
  - *use NLO corrections from MCFM program*

- Agreement with SM predictions made us sure that we understand our selections and systematics (tagging jets,...)
VBF H→invisible:
offline signal selections and topology

- two jets $p_T > 50$ GeV, $|\eta| < 4.7$
- $m_{jj} > 1100$ GeV
- $\Delta \eta_{jj} > 4.2$
- $E_T^{\text{miss}} > 130$ GeV
- $\Delta \phi_{jj} < 1.0$
- Central jet veto

Signal: small $\Delta \phi_{jj}$
QCD: large $\Delta \phi_{jj}$

multijets ("QCD")
\[ \Delta \phi_{jj} \text{ and } m_{jj} \]

- \( \Delta \phi_{jj} \) after selections on:
  - \( m_{jj}, E_T^{\text{miss}}, \Delta \eta_{jj}, \text{CJV} \)

- \( m_{jj} \) after selections on
  - \( \Delta \phi_{jj}, E_T^{\text{miss}}, \Delta \eta_{jj}, \text{CJV} \)
Central Jet Veto ("rapidity gap") in VBF (VV->H) production
first discussed in:

From D. Zeppenfeld talk on TeV4LHC, 2004

Gluon emission in WBF events
Color singlet exchange in t-channel
"synchrotron" radiation between initial and final quark direction

⇒ central jets suppressed

Major backgrounds: t-channel color exch

1/σ dσ/dη^3

deflection of color charge by ~180°
⇒ central gluon emission
Veto region in CJV

\[ \eta_{\text{tag.j}}^{\text{min}} < \eta_{j^3} < \eta_{\text{tag.j}}^{\text{max}} \]

- reject event with \( j_3 \) “between” two tagging jets in \( \eta \)
Signal region, with CJV (x,y view)
Signal region, with CJV (Z view)
Cut-and-counting analysis

- All background are obtained from data-driven methods with minimized dependence of MC
- QCD multijet bkg. is reduced to ~ 10 % level
- Number of events after all selections

<table>
<thead>
<tr>
<th>Background</th>
<th>$N_{est}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \nu\nu$</td>
<td>$102 \pm 30 \text{ (stat.)} \pm 26 \text{ (syst.)}$</td>
</tr>
<tr>
<td>$W \rightarrow \mu\nu$</td>
<td>$67.2 \pm 5.0 \text{ (stat.)} \pm 15.1 \text{ (syst.)}$</td>
</tr>
<tr>
<td>$W \rightarrow e\nu$</td>
<td>$68.2 \pm 9.2 \text{ (stat.)} \pm 18.1 \text{ (syst.)}$</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>$54 \pm 16 \text{ (stat.)} \pm 18 \text{ (syst.)}$</td>
</tr>
<tr>
<td>QCD multijet</td>
<td>$36.8 \pm 5.6 \text{ (stat.)} \pm 30.6 \text{ (syst.)}$</td>
</tr>
<tr>
<td>Other SM</td>
<td>$10.4 \pm 3.1 \text{ (syst.)}$</td>
</tr>
<tr>
<td>Total</td>
<td>$339 \pm 36 \text{ (stat.)} \pm 50 \text{ (syst.)}$</td>
</tr>
<tr>
<td>Observed</td>
<td>390</td>
</tr>
</tbody>
</table>
Upper limit on BR(H->invisible) in VBF analysis

- At $m_h=125$ GeV
  - 0.53 expected – the best limit so far among ATLAS and CMS analyses with ZH, H->invisible, Z->ee,bb
  - 0.69 observed; within 1σ of expected
Upper limits from ZH, H->invisible analyses

- **Z->ee**, for $m_h=125$ GeV
  - Expected 0.91
  - Observed 0.75

- **Z->bb**, for $m_h=125$ GeV
  - Expected 2.04
  - Observed

$m_T(Z,H)$ shape analysis

BDT shape analysis
Summary on H-\(\rightarrow\)invisible analyses

- VBF H-\(\rightarrow\)invisible mode has the best sensitivity which can be improved using shape instead of counting analysis

- Combination of all H-\(\rightarrow\)invisible modes provides upper limit on BR – 0.54 (0.46 expected) better than indirect limit from visible SM modes, 0.65.

- Analysis will become really interesting for physics once sensitivity better than ~ 30% will be reached with 14 TeV data
Higgs analysis in the framework of SUSY models (MSSM, NMSSM,...)
• Super Symmetry (SUSY) is one of the possible solutions of “SM problems”

  – SUSY is symmetry relating particles of integer spin (bosons) and particles of spin $\frac{1}{2}$ (fermions). Each particle has a partner (“sparticle”) with the same quantum numbers, but spin.

  – SUSY must be explicitly broken since $m_{\text{spart}} \neq m_{\text{part}}$
One way to solve the gauge hierarchy problem is introducing a new boson in the loop of $\delta M_H^2$. Because fermion and boson have different statistic, such that

$$
\delta M_H^2 \sim \frac{|y_f|^2}{16\pi^2} \left[ -\Lambda_{UV}^2 + m_f^2 \mathcal{O}(1) \right] + \frac{|y_b|^2}{16\pi^2} \left[ +\Lambda_{UV}^2 - m_b^2 \mathcal{O}(1) \right]
$$

### SUSY algebra

$$Q |\text{fermion}\rangle = |\text{boson}\rangle, \quad Q |\text{boson}\rangle = |\text{fermion}\rangle$$

guarantees that $|y_f|^2 = |y_b|^2$. If one can also manages $|m_b^2 - m_f^2| < TeV$, the gauge hierarchy problem is solved.
• RG running of the gauge coupling

\[
\frac{1}{\alpha_i(M_X)} = \frac{1}{\alpha_i(M_Z)} - \frac{\beta_i}{4\pi} \ln \left( \frac{M_X^2}{M_Z^2} \right)
\]

• For SM, the beta function is

\[
\begin{pmatrix}
0 \\
-\frac{22}{3} \\
-11
\end{pmatrix} + \begin{pmatrix}
\frac{4}{3} \\
\frac{4}{3} \\
\frac{4}{3}
\end{pmatrix} F + \begin{pmatrix}
\frac{1}{10} \\
\frac{1}{6} \\
0
\end{pmatrix} N_H
\]

• With SUSY, the running becomes

\[
\begin{pmatrix}
0 \\
-6 \\
-9
\end{pmatrix} + \begin{pmatrix}
2 \\
2 \\
2
\end{pmatrix} F + \begin{pmatrix}
\frac{3}{10} \\
\frac{5}{6} \\
0
\end{pmatrix} N_H
\]

\(N_H\) number of Higgs doublets (SM = 1, MSSM = 2)

\(F\) number of flavors, SM = MSSM = 3
MSSM and
Higgs bosons in MSSM
• **Unconstrained MSSM is the most “economic” version of SUSY**
  
  – Minimal gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$
  
  – Minimal particle content; tree generation of spin $\frac{1}{2}$ quarks and leptons [no right handed neutrino] as in SM; **The Higgs sector consists of two scalar doublet fields $H_u$ and $H_d$ that leads, after EW symmetry breaking to five Higgs particles:** two CP even $h$, $H$ bosons, a pseudoscalar $A$ boson and two charged $H^+/-$ bosons
  
  – R parity conservation: $R_p = (-1)^{2S+3B+L}$
  
  – Minimal set of soft SUSY-breaking terms
  
  – Unconstrained MSSM has 124 free parameters (104 from SUSY breaking terms + 19 parameters of the SM)
  
• **Constrained MSSM (or phenomenological MSSM) reduces number of free parameters to 22**
  
  – all the soft SUSY-breaking parameters are real => no new source of CP-violation in addition to the one from CKM matrix
  
  – no FCNC at tree level
  
  – the soft SUSY-breaking masses and trilinear couplings of the 1$^{st}$ and 2$^{nd}$ sfermion generations are the same at low energy
  
• **So far most of the MSSM Higgs boson searches at LHC were performed within the framework of phenomenological MSSM (pMSSM) without assuming any particular soft SUSY-breaking scenario (mSUGRA, AMSB, GMSB, ..)**
At tree level Higgs sector of MSSM is determined by two parameters:

\[ M_A \text{ and } \tan(\beta) \]

\[ 1 < \tan(\beta) = \frac{v_2}{v_1} = \frac{v \sin(\beta)}{v \cos(\beta)} < 60 \]

where \( v_1 \) and \( v_2 \) are vacuum expectation values (vev) of the neutral components of two Higgs doublets.

\[ v_1^2 + v_2^2 = v^2 = 2M_Z^2 \left/ \left( g_2^2 + g_1^2 \right) \right. = (246 \text{ GeV})^2 \]

Higgs masses at tree level

\[ m_{H,h}^2 = \frac{1}{2} \left[ (m_A^2 + m_Z^2) \pm \left( (m_A^2 + m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta \right) \right]^{1/2} \]

\[ m_{H^+}^2 = m_A^2 + m_W^2 \]

\[ m_h < m_Z \]
The radiative corrections increase the upper bound of $m_h$ significantly

$$
\epsilon = \frac{3 \bar{m}_t^4}{2\pi^2 v^2 \sin^2 \beta} \left[ \log \frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12 M_S^2} \right) \right]
$$

with leading 1 loop corrections

there $X_t = A_t - \mu / \tan(\beta)$, $M_S^2 = \frac{1}{2} (M_{stop1}^2 + M_{stop2}^2)$

$A_t$ is trilinear Higgs-stop coupling, $\mu$ is Higgs-higgsino mass parameter

$m_h$ reaches maximum value at $X_t = 2 M_S$ (FD) and local minimum at $X_t = 0$; these are two scenarios ($m_h^{\text{max}}$ and no-mixing) used in LEP Higgs searches:

Masses of MSSM Higgs bosons

- Five Higgs bosons in 2HD and MSSM model:
  - two CP-odd $h, H$;
  - one CP-even $A$;
  - two charged $H^+/-$
Total width of MSSM Higgs bosons
Neutral Higgs boson couplings to fermions and gauge bosons in the MSSM at tree level normalized to the SM Higgs boson couplings $g_{Hff} = (2^{1/2} G_{f})^{1/2} m_f$, $g_{HVV} = (2^{1/2} G_{V})^{1/2} M_V^2$ and the couplings of two Higgs bosons with one gauge boson, normalized to $g_w = (2^{1/2} G_{\mu})^{1/2}$ for $g_{\Phi H+W-}$ and $g_z = (2^{1/2} G_{\mu})^{1/2} M_Z$ for $g_{\Phi AZ}$

<table>
<thead>
<tr>
<th>$\Phi$</th>
<th>$g_{\Phi uu}$</th>
<th>$g_{\Phi dd}$</th>
<th>$g_{\Phi VV}$</th>
<th>$g_{\Phi AZ}$</th>
<th>$g_{\Phi H^{\pm}W^{\mp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{SM}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$h$</td>
<td>$\cos \alpha$ / $\sin \beta$</td>
<td>$- \sin \alpha$ / $\cos \beta$</td>
<td>$\sin(\beta - \alpha)$</td>
<td>$\cos(\beta - \alpha)$</td>
<td>$\mp \cos(\beta - \alpha)$</td>
</tr>
<tr>
<td>$H$</td>
<td>$\sin \alpha$ / $\sin \beta$</td>
<td>$\cos \alpha$ / $\cos \beta$</td>
<td>$\cos(\beta - \alpha)$</td>
<td>$- \sin(\beta - \alpha)$</td>
<td>$\pm \sin(\beta - \alpha)$</td>
</tr>
<tr>
<td>$A$</td>
<td>$\cot \beta$</td>
<td>$\tan \beta$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

$\alpha$ is a mixing angle between neutral components for two Higgs doublets $H_1^0, H_2^0$ to give the physical CP-even Higgs bosons $h, H$

$$\cos 2\alpha = -\cos 2\beta \left( (M_A^2 - M_Z^2) / (M_H^2 - M_h^2) \right)$$

**Radiative corrections introduce dependence on other parameters:**

- $\mu, M_2, M_{\text{gluino}} + 5$ “physical” parameters: $m_{\text{stop1,2}}, m_{\text{sbottom1,2}}, \theta_{\text{stop}}$
- or
- $\mu, M_2, M_{\text{gluino}} + 5$ “unphysical parameters”: $m_{\text{stopL}}, m_{\text{stopR}}, m_{\text{sbottomR}}, A_t, A_b$
MSSM neutral $\phi \rightarrow \tau \tau$ : the most sensitive channel at high values of $\tan \beta$.

- $g_{\phi bb}^{\text{MSSM}} = g_{\phi bb}^{\text{SM}} \times \tan \beta (\phi=A)$ at tree level.
- $\text{Br}(\phi \rightarrow \tau \tau) \sim 10\%$
τ identification (I)

- Step 1: decay mode finding

Reconstructed using the Hadron plus Strips (HPS) algorithm

- $\tau^\pm \rightarrow \pi^\pm \pi^\mp \pi^\pm \nu_T$
- $\tau^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \nu_T$
- $\tau^\pm \rightarrow \pi^\pm \pi^0 \nu_T$
- $\tau^\pm \rightarrow \pi^\pm \nu_T$

Correct tau energy scale with the tau mass
- Fitting MC to data → a shift in respect to data would indicate a incorrect tau energy scale

$\sim 3\% \tau$ JES uncertainty
• Step 2: isolation of $\tau_h$
B-tagging

Two b-jet candidates
CMS b-tagging algorithms used in 2012 data analyses (PAS BTV-13-001)

- **Track Counting**
  - high purity; use 3rd track 3d ip significance

- **Jet Probability**
  - use 3d ip significance of all tracks to build likelihood that all tracks come from PV

- **Combined Secondary Vertex**
  - uses SVs and track-based life-time information to build likelihood-based discriminator between jets from b, c, or light quarks and g’s

*Signs of Impact parameter and of vertex decay length are defined according to jet direction.*
• CMS b-tagging performance with 8 TeV data

Fake rate:
for $80 < p_T < 120$ GeV
$|\eta| < 2.4$
Preparation for \( pp \rightarrow \phi + X, \phi \rightarrow \tau \tau \) discovery

- CMS "discovery" of \( Z \rightarrow \tau \tau \), 2010, 1.7 pb\(^{-1}\)

\( \tau_h \)

\( \mu \) from \( \tau \rightarrow \mu \nu \nu \) decay

---

Events / 9.0 GeV/c\(^2\)

![Histogram](chart.png)

CMS Preliminary 2010

\( L_{\text{int}} = 1.7 \text{ pb}^{-1}, \sqrt{s} = 7 \text{ TeV} \)
CMS $Z\rightarrow\tau\tau$ measurement, 36 pb$^{-1}$

**Left Diagram:**
- Title: 36 pb$^{-1}$ at $\sqrt{s} = 7$ TeV
- Subtitle: $Z \rightarrow \tau\tau \rightarrow \tau_\mu \tau_\text{had}$
- Y-axis: Events / (10 GeV)
- X-axis: Visible Mass [GeV]
- Legend:
  - Black dots: data
  - Yellow: $Z \rightarrow \tau\tau$
  - Orange: EWK+t$t$
  - Purple: QCD
- Note: Yields from fit

**Right Diagram:**
- Title: 36 pb$^{-1}$ at $\sqrt{s} = 7$ TeV
- Subtitle: $Z \rightarrow \tau\tau$ (combined)
- Graph:
  - $\tau_\mu + \tau_\text{had}$
  - $\tau_\mu + \tau_\mu$
  - $\tau_e + \tau_\mu$
  - $\tau_e + \tau_\text{had}$
- Note: Luminosity uncertainty not shown

**Additional Information:**
- NNLO, FEWZ+MSTW08 [PDF4LHC 68% CL] (60-120 GeV)
Z+b as a benchmark for MSSM H+b

J. Campbell talk on CMS meeting, 2006

- The production of Z+b is very similar to that of H+b, even lying in a similar kinematic region for a low mass Higgs.
- Theoretically, the two processes have the same inputs and uncertainties.
  - same initial state, similar (x, Q^2)
  - the same H and Z decays
- Test the experimental analysis procedure by re-discovering the Z –
  a) Z + one jet which is b-tagged;

Data vs MC comparison
- kinematics => acceptance
- cross-sections 4FS vs 5FS
  - relevant for low mass Higgs boson
b-PDF – to be studied

1st CMS Z+b analysis with 2.2 fb^{-1} at 7 TeV
Triggers

- Distinct triggers for each channel
  - $\mu\tau$: isolated $\mu > 17$ GeV + isolated $\tau > 20$ GeV
  - $e\tau$: $e > 22$ GeV + isolated $\tau > 20$ GeV
  - $e\mu$: $\mu > 17(8)$ GeV + $e > 8(17)$ GeV
  - $\mu\mu$: $\mu > 17$ GeV + $\mu > 8$ GeV
  - $\tau\tau$: 2 isolated $\tau > 35$ GeV
    - Using parked dataset
    - Not need to use ditau+jet trigger

Not changed since HCP 2012

$\tau\tau$ turn-on curve
Event selection overview

- Two well reconstructed, isolated leptons of opposite sign:

| channel | $p_T$       | $|\eta|$     | $p_T$       | $|\eta|$     |
|---------|-------------|--------------|-------------|--------------|
| $e\mu$  | $> 20$ GeV (e/\mu) | $< 2.3$ (e/\mu) | $> 10$ GeV (\mu/e) | $< 2.3$ (\mu/e) |
| $e\tau$ | $> 24$ GeV (e)     | $< 2.1$ (e)    | $> 20$ GeV (\tau)  | $< 2.1$ (\tau)  |
| $\mu\mu$| $> 20$ GeV (\mu)  | $< 2.1$ (\mu)  | $> 10$ GeV (\mu)  | $< 2.1$ (\mu)   |
| $\mu\tau$| $> 20$ GeV (\mu)  | $< 2.1$ (\mu)  | $> 20$ GeV (\tau)  | $< 2.3$ (\tau)  |
| $\tau\tau$| $> 45$ GeV (\tau) | $< 2.1$ (\tau)  | $> 45$ GeV (\tau)  | $< 2.1$ (\tau)  |

- $e\mu$: $D_\zeta = P_\zeta - 1.85 \cdot P_\zeta^{vis} > -20$ GeV
- $e\tau, \mu\tau$: $M_T < 30$ GeV
- $\mu\mu$: Special BDT trained for rejection of $Z/\gamma^* \rightarrow \mu\mu$ events
Categorization

B-Tag:
≥ 1 b-tagged jets with $p_T > 20$ GeV
< 2 jets with $p_T > 30$ GeV
Sensitive to $bb\Phi$

No-B-Tag (inclusive):
no b-tagged jets with $p_T > 20$ GeV
Contains rest of signal events.

The chosen categorization is Higgs-$p_T$ independent in order to stay as model independent as possible
gg->H in SM and MSSM

- At high $\tan\beta$ and in $m_h^{\text{max}}$ scenario b-loop dominates in MSSM gg->h production leading to change of $p_T^H$ in comparison with SM gg->h where top loop dominates:

  2. J. Alwall, Q Li, F. Maltoni arXiv:1110.1728
Acceptance of kinematic selections

- Acceptance selections at generator level (corresponds to current CMS cuts at reconstruction level):
  - electron from $\tau \rightarrow e\nu\nu$ decay: $p_T > 20$ GeV, $|\eta| < 2.1$
  - $\tau_h$ from $\tau \rightarrow$ hadrons($\tau_h$) $\nu$ decay: $p_T > 20$ GeV, $|\eta| < 2.3$
  - $\Delta R_{e\tau} > 0.5$

<table>
<thead>
<tr>
<th>$M_H$ [GeV]</th>
<th>Acceptance, PYTHIA $gg \rightarrow H$</th>
<th>Acceptance, re-weighted for b-loop</th>
<th>Correction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>$0.072 \pm 0.001$</td>
<td>$0.070 \pm 0.001$</td>
<td>$0.97 \pm 0.01$</td>
</tr>
<tr>
<td>400</td>
<td>$0.149 \pm 0.001$</td>
<td>$0.152 \pm 0.001$</td>
<td>$1.02 \pm 0.02$</td>
</tr>
</tbody>
</table>

Table 1: The $e + \tau_h$ acceptances before and after re-weighting to correct for b-loop contribution.
Background estimation in $\Phi \rightarrow \tau\tau$

**$Z/\gamma^* \rightarrow \tau\tau$:**
- Embedding: in $Z \rightarrow \mu\mu$, replace $\mu$ by sim. $\tau$ decay
- Normalized from $Z \rightarrow \mu\mu$ events

**ttbar:**
- From simulation
- Normalization from sideband

**QCD:**
- Normalization & shape taken from SS/OS or fakrate

**Di-boson/W+jets:**
- From simulation or data
- Normalization from sideband

**$Z/\gamma^* \rightarrow ee$ ($\mu\mu$):**
- From simulation or data
- Corrected for jet $\rightarrow \tau$, $e/\mu \rightarrow \tau$ fakrate

---

**CMS Preliminary, $H \rightarrow \tau\tau$, 19.8 $fb^{-1}$ at 8 TeV**

$e_{\tau_h}$

B-Tag

$m_{\tau\tau}$ [GeV]

$N/dm_{\tau\tau}$ ($[1/\text{GeV}]$)

$m_{\tau\tau}^b$ ($m_A=160$ GeV, $\tan\beta=8$)
Example: control region for W+jets bkg

- Normalize W+jets MC on $m_T > 70$ GeV region
- Predict W+jets event yield in signal region $m_T < 30$ GeV using $m_T$ shape from MC
• $\mu\tau_h$

• $\tau_h\tau_h$

$\tau\tau$ mass after all selections
Sensitivity in $M_A$-$\tan\beta$ plane for different event categories

- $\tau$ decay modes
- $b$-tag. vs no-$b$-tagging
Expected exclusion limits

- In $m_A$-tan$\beta$ plane
- Model independent
MSSM benchmark scenarios (I)
(from M. Carena et al arXiv:13027033)

• $m_h^{\text{max}}$ updated scenario:
  – green strip is allowed region of $M_A$-$\tan\beta$

\[ m_t = 173.2 \text{ GeV}, \]
\[ M_{\text{SUSY}} = 1000 \text{ GeV}, \]
\[ \mu = 200 \text{ GeV}, \]
\[ M_2 = 200 \text{ GeV}, \]
\[ X_t^{\text{OS}} = 2 M_{\text{SUSY}} \text{ (FD calculation)}, \]
\[ X_t^{\text{MS}} = \sqrt{6} M_{\text{SUSY}} \text{ (RG calculation)}, \]
\[ A_b = A_\tau = A_t, \]
\[ m_{\tilde{g}} = 1500 \text{ GeV}, \]
\[ M_{\tilde{l}_3} = 1000 \text{ GeV}. \]
MSSM benchmark scenarios (II)
(from M. Carena et al arXiv:13027033)

- $m_h^{\text{mod}}$ scenario:
  - green area is allowed region of $M_A$-$\tan \beta$

\[
\begin{align*}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 1.5 M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\text{MS}} &= 1.6 M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_{\tau} = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{l_3} &= 1000 \text{ GeV}. \\
\end{align*}
\]
How to access allowed region?
(from M. Carena et al arXiv:13027033)

- $m_h^{\text{mod}}$ updated scenario:
  - green area is allowed region of $M_A$-$\tan\beta$
  - $A/H$ decays to charginos/neutralinos are open here

- Latest LHC analysis $H/A\rightarrow cc\rightarrow 4l+\text{MET}$ arXiv:0709.1029
Latest development: “hMSSM”
A. Djouadi et.al. arXiv:1307.5205

• For $m_A \gg M_Z$ and heavy sparticles $\sim > 1$ TeV measured value of $m_h$ defines radiative corrections at any order
  – no need anymore for “benchmark” scenarios

• Only three input parameters in hMSSM
  – $\beta$, $m_h$, $m_A$

\[
\begin{align*}
M_H^2 &= \frac{(M_Z^2 + M_A^2 - M_h^2)(M_Z^2 c_\beta^2 + M_A^2 s_\beta^2) - M_A^2 M_Z^2 c_\beta^2}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2} \\
\alpha &= -\arctan\left(\frac{(M_Z^2 + M_A^2) c_\beta s_\beta}{M_Z^2 c_\beta^2 + M_A^2 s_\beta^2 - M_h^2}\right) \\
M_{H^\pm} &\approx \sqrt{M_A^2 + M_W^2}
\end{align*}
\]
\(m_A - \tan \beta\) in “hMSSM”
from A. Djouadi et.al. arXiv:1307.5205

- From LHC measurement of h and searches for H/A/H^+
Is low $\tan \beta$ region excluded? 
(from A. Djouadi arXiv:1304.1787)

- Low $\tan \beta$ region is not excluded for large $M_S$
- Accessible with a number of channels:

with $m_t$ uncertainty 3 GeV (from $t\bar{t}$ cross-section) $\Delta^th m_h$ is $\sim$ 6 GeV
H→hh mode at low tanβ MSSM

- Scalars: H, h, A, H⁺; h(125) is discovered
- For $m_A=300$ GeV, $\tan\beta=2.5$
  - $\sigma(gg\to H) \sim 1$ pb
  - $\text{Br}(H\to hh) \sim 0.6$
- $\sigma \times \text{Br}$ and $N_S$ for 20 fb⁻¹, 8 TeV:
  - $\gamma\gamma bb \sim 1$ fb => 20 ev
  - $\tau\tau bb \sim 60$ fb => 1200 ev
  - $bbbb \sim 300$ fb => 6000 ev.
H->h(125)h(125)->γγbb (I)

• **Search strategy**
  – select $γγjj$ events with at least 1 b-tag
  – select events within $m_{jj}$ and $m_{γγjj}$ mass windows
  – fit $m_{γγ}$ for selected events
H→h(125)h(125)→γγbb (II)

\( m_H = 300 \text{ GeV} \) with \( \tan\beta = 2.5 \)

- \( \sigma \times B \) for signal \( \sim 1.3 \text{ fb} \) for \( m_H = 300 \text{ GeV} \)
  - Signal efficiency for 2b-tag category \( \sim 0.06 \)
- \( m_{\gamma\gamma} \) after \( m_{jj} \) and \( m_{\gamma\gamma jj} \) mass window selections

Expected \( N_S \sim 1.5 \text{ ev} \)

\[
\begin{align*}
\text{CMS preliminary 19.785/fb} \\
\text{Events / (1 GeV)} \\
\text{2 btag} \\
\end{align*}
\]

Expected \( N_S \sim 2.0 \text{ ev} \)

\[
\begin{align*}
\text{CMS preliminary 19.785/fb} \\
\text{Events / (1 GeV)} \\
\text{1 btag} \\
\end{align*}
\]
Searches for $t \to H^+ b$ ($m_{H^+} < m_t$)

$$g_{H^+ \bar{t} b} \propto m_b \tan \beta (1 + \gamma_5) + m_t \cot \beta (1 - \gamma_5)$$

- Study decay mode $H^+ \to \tau \nu$ assuming $\text{BR}(H^+ \to \tau \nu) = 1$

- $m_{H^+} < m_t$ to $m_{H^+} > m_t$

$pp \to tbH^+$ is in MC@NLO (T. Plehn et al) recipe for $m_{H^+} \sim m_t$: add $tt$ and $tbH^+$ 4FS and 5FS NLO calculations exist
CMS \( H^+ \to \tau \nu \). Topologies considered:

**Fully hadronic**

\[
g/q \quad g/q \quad g/\bar{q} \quad g/\bar{q}
\]

**Leptonic I\(\tau\)**

\[
g/q \quad g/\bar{q} \quad g/q \quad g/\bar{q}
\]

**Leptonic II**

\[
g/q \quad g/\bar{q} \quad g/q \quad g/\bar{q}
\]

\[\mathcal{N}_{tt}^{SUSY} > \mathcal{N}_{tt}^{SM}\]

\[\mathcal{N}_{tt}^{SUSY} < \mathcal{N}_{tt}^{SM}\]
Access or deficit of events in data is related to the difference between MSSM and SM $\tt~$ event yields:

$$\Delta N = N_{\tt}^{\text{MSSM}} - N_{\tt}^{\text{SM}} = 2x(1-x)N_{WW} + x^2N_{HH} + [(1-x)^2 - 1]N_{tt}^{\text{SM}}.$$  

$x = \text{Br}(t \rightarrow H^+b)$

$\tau_h$+jets channel is most sensitive, since most of the $\tt~$->WbWb background is measured from the data and $m_T$ shape is used.
Results of $H^+\rightarrow \tau \nu$ analysis with 2.3 fb$^{-1}$

In the next iteration of analysis with whole 2011/12 dataset it might be possible to exclude $m_{H^+} < \sim 130$ GeV, since for this mass region exp. exclusion limits on $\text{Br}(t\rightarrow H^+b)$ might be smaller than minimal possible values in MSSM $m_h^{\text{max}}$. 

At $\tan\beta \sim 8$ $\text{Br}(t\rightarrow H^+b)$ has a minimum in MSSM at a given $\mu$. 

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Update for light $H^+$ analysis with $2.3 - 4.9$ fb$^{-1}$

- to understand $m_{H^+} \cdot \tan \beta$ plots remember the $H^+tb$ coupling structure:

$$g_{H^+tb} \propto m_b \tan \beta (1 + \gamma_5) + m_t \cot \beta (1 - \gamma_5)$$

$\mu \tau_h$ analysis is updated with $4.9$ fb$^{-1}$ at $7$ TeV and using shape of $\tau$ polarization variable.
Heavy charged Higgs decay modes to be searched for at 14 TeV runs

- $\tau\nu$, $tb$, $Wh$
- Production process: $gb\to tH^+$

NMSSM and Higgs bosons in NMSSM

- **Enlarged (pseudo-)scalar and neutralino sector:** 2 complex doublets $\hat{H}_u, \hat{H}_d$, 1 complex singlet $\hat{S}$

  7 bosons: $H_1, H_2, H_3, A_1, A_2, H^+, H^-$

  5 neutralinos: $\tilde{\chi}^0_i (i = 1, ..., 5)$

- **Significant changes of the phenomenology**

**Recent NMSSM scans of LHC h(125):**

S.F. King, M. Muehlleitner, R. Nevzorov, K. Walz
arXiv:1211.5074, accepted by Nucl. Phys. B,
“Natural NMSSM Higgs Bosons”
S.F. King, M. Muehlleitner, R. Nevzorov
“NMSSM Higgs Benchmarks Near 125 GeV”
Next-to Minimal Supersymmetric Standard Model

Field content:

NMSSM superfields = MSSM superfields + Higgs superfield singlet $\hat{S}$

Superpotential:

$W_{\text{NMSSM}} = W_{\text{MSSM}}|_{\mu=0} - \lambda \hat{S} \hat{H}^1_d \hat{H}^2_u + \lambda \hat{S} \hat{H}^2_d \hat{H}^1_u + \frac{1}{3} \kappa \hat{S}^3$

2 new coupling parameters: $\lambda, \kappa$  \quad (\hat{H}_d, \hat{H}_u: \text{Higgs doublet superfields})

$\mu$ term of the MSSM: $W_{\text{MSSM}} = \ldots \mu \hat{H}^1_d \hat{H}^2_u + \ldots$

$\rightarrow$ dynamically generated in the NMSSM  \quad $\mu=\lambda \langle S \rangle$

(scalar Higgs singlet field has a vacuum expectation value $v_S$)

Soft-breaking part extended: New parameters: $m_S^2, A_\lambda, A_\kappa$

- solve “$\mu$-problem” of MSSM (Kim, Nilles 1984)
  - $\mu$ must be order of SUSY breaking scale $M_{\text{SUSY}}$
    - two scales in the MSSM theory – EWSB and $M_{\text{SUSY}}$
    - one scale in the NMSSM theory – $M_{\text{SUSY}}$
NMSSM Scalar Boson Mass in View of the LHC Results

- Vast literature on NMSSM scalar boson of $\sim 125\text{-}126$ GeV
  Hall eal; Ellwanger; Gunion eal; King,MMM,Nevzorov; Albornoz Vasquez eal; Cao eal; Gabrielli eal; Ellwanger, Hugonie; Kang eal; Cheung eal; Jeong eal; Hardy eal; Kim eal; Arvanitaki eal; ...

- Compatibility of NMSSM scalar boson mass with LHC Searches:
  ★ Upper mass bounds + corrections to the MSSM, NMSSM scalar boson mass:
  MSSM: $\mu_h^2 \approx M_Z^2 \cos^2 2\beta + \Delta m_h^2$
  NMSSM: $\mu_h^2 \approx M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \Delta m_h^2$

  $\Rightarrow M_H \approx 126$ requires:

  MSSM: $\Delta m_h \approx 85$ GeV ($\tan \beta$ large) $\Rightarrow$ large corrections are needed $\sim$ conflict with fine-tuning
  NMSSM: $\Delta m_h \approx 55$ GeV ($\lambda = 0.7, \tan \beta = 2$)

  $\Rightarrow$ NMSSM requires less fine-tuning
  Hall, Pinner, Ruderman; Ellwanger; Arvanitaki, Villadoro; King, MMM, Nevzorov; Kang, Li, Li; Cao, Heng, Yang, Zhang, Zhu
$\text{NMSSM Higgs Mass}$

$\begin{align*}
\lambda &= 0.6, 0.7 \\
m_t &= 1200, 500 \text{ GeV} \\
x_t &= 0
\end{align*}$

$m_h = 124-126 \text{ GeV}$

- $m_h$ maximized for small values of $\tan \beta$
- $m_h \approx 126 \text{ GeV}$ can be achieved also for zero mixing $x_t = 0$ and $m_{\tilde{t}_1} \geq 500 \text{ GeV}$
Landscape for NMSSM

- ** Scalars:**
  - $H_1, H_2, H_3; m_{H_1} < m_{H_2} < m_{H_3}$
  - $A_1, A_2; m_{A_1} < m_{A_2}$

- **LHC discovered $H_2(125)$**

- **How to access $H_1$ and $H_3$**
  - $H_2(125) \rightarrow H_1 H_1, \text{Br} \sim 10\text{-}20\%$
  - $H_3 \rightarrow H_2(125) H_1$

- **Favorable final state decay modes depend on $m_{H_1}$**

2m$_{\mu}$  2m$_{\tau}$  2m$_{b}$  125/2 GeV  125 GeV

$m_{H_1}$ axis
H2(125)→H1H1: 2m_μ < m_H1 < 2m_τ

- H2→H1H1→μμμμ
  - CMS PAS HIG-13-010

Although recent NMSSM scans do not favor very low m_{A1, H1}

![Graph showing CMS Prelim. 2012 results with m_A1, H1 limits and σ(pp → h, B(h → 2μ, 2τ)) predictions.]

- 2m_μ
- 2m_τ
- 2m_b

125/2 GeV

125 GeV

m_{H1} axis
H2(125) -> H1H1: 2m_τ < m_{H1} < 2m_b

- H2 -> H1H1 - > ττττ ~ 3 pb => 60K ev. for 20 fb^{-1} at 8 TeV
  - τ_μ τ_h τ_μ τ_h with SS μ’s looks very promising!

- on going analysis

2m_μ 2m_τ 2m_b 125/2 GeV 125 GeV

m_{H1} axis
H2(125) -> H1H1: $2m_b < m_{H1} < m_{H1}/2$ (I)

- H2 -> H1H1 -> $\tau\tau bb$; $\sim 0.4 \text{ pb} \Rightarrow 8 \text{ K events for 20 fb}^{-1} \text{ at 8 TeV}$
- $\tau_\mu \tau_h bb$ mode looks hopeless with SUSY $H \rightarrow \tau_\mu \tau_h$ selections:
  - $p_T^{\mu} > 20 \text{ GeV}$, $|\eta^{\mu}| < 2.1$
  - $p_T^{\tau_h} > 20 \text{ GeV}$, $|\eta^{\tau_h}| < 2.3$
  - Two jets $p_T > 25 \text{ GeV}$, $|\eta| < 2.4$
  - At least one b-tag jets
    - $N_S \sim 2-6$ for $m_{H1} (20-60) \text{ GeV}$
    - $N_B \sim 3\text{K}$ from data

$2m_\mu$, $2m_\tau$, $2m_b$, $125/2 \text{ GeV}$, $125 \text{ GeV}$
H2(125) -> H1H1: 2m_b < m_{H1} < m_{H1}/2 (II)

- WH2 -> H1H1 -> bbbb, 100 fb => 2000 ev with 20 fb^{-1} => 400 ev. with W->e/\mu \nu
- Particle level estimates with VH->bb analysis selections
  - \textbf{p}_T^\mu > 24 \text{ GeV}, |\eta^\mu| < 2.1
  - \textbf{p}_T^e > 27 \text{ GeV}, |\eta^e| < 2.5
  - \textbf{p}_T^b > 20 \text{ GeV}, |\eta^b| < 2.4

\begin{align*}
2m_\mu & \quad 2m_\tau & \quad 2m_b & \quad 125/2 \text{ GeV} & \quad 125 \text{ GeV} \\
\end{align*}

\begin{itemize}
  \item m_{H1}
\end{itemize}
$\Delta R_{bb}$ and b-jet definition

$\Delta R_{bb} < 0.5 \Rightarrow$ consider as one jet
b-jet topologies in $H_{1_1} \rightarrow bb + H_{1_2} \rightarrow bb$

- 2 jets
- 3 jets
- 4 jets
<table>
<thead>
<tr>
<th>Lepton Selection</th>
<th>N events at 20 fb$^{-1}$ for a given $m_{H1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 GeV</td>
</tr>
<tr>
<td>$\sigma Br^2(H1\rightarrow bb) Br(W\rightarrow e/\mu \nu)$</td>
<td></td>
</tr>
<tr>
<td>cuts on $p_T^\ell$, $\eta^\ell$</td>
<td>284</td>
</tr>
<tr>
<td>$</td>
<td>\eta^b</td>
</tr>
<tr>
<td>$\Delta R(b-l) &gt; 0.5$</td>
<td>186</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Jets selection and b-tagging</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 GeV</td>
</tr>
<tr>
<td>two jets/passed $p_T$ cut</td>
<td>16.9/16.6</td>
</tr>
<tr>
<td>three jets/passed $p_T$ cut</td>
<td>105/14.4</td>
</tr>
<tr>
<td>four jets/passed $p_T$ cut</td>
<td>63/3.7</td>
</tr>
<tr>
<td>sum/passed $p_T$ cut</td>
<td>185/35</td>
</tr>
</tbody>
</table>

Tagging with Inclusive Vertex Finder*: 0.54
Rare not reducible backgrounds for WH2->H1H1->bbbb need to be estimated

- Z+tt
- ttbb
- W+bbbb, W->e\nu
- WZ+bb, W->e\nu, Z->bb
- From DPS
  - W+bb & bb
  - W+bb & Z->bb
  - W & bbbb
H3→H2(125)H1: $m_{H2}/2 < m_{H1} < m_{H2}$

- It is for 14 TeV LHC:
  - H3(300-600 GeV)→H2H1→$W_\ell W_h b\bar{b}$, proposed in arXiv:1301.0453
  - H3(300-500 GeV)→H2H1→$bb\bar{b}\bar{b}$, KIT started analysis. They conclude that:
    - $ggf \rightarrow H_3 \rightarrow H_1 H_2 \rightarrow b\bar{b}b\bar{b}$ is an interesting search channel
    - $xsec$ at 8 TeV is 54 fb $\quad 170$ fb at 14 TeV
    - TMVA Optimization
    - $\frac{s}{\sqrt{b}}$ may reach 8.47 for 14 TeV and high luminosity $500$ fb$^{-1}$
    - Data driven method promising
    - $Todo$
      - understand influence of trigger

2m$_\mu$ 2m$_\tau$ 2m$_b$ 125/2 GeV 125 GeV

$m_{H1}$
conclusion about NMSSM part of talk

• good prospects for H2(125)-\to H1H1-\to \tau\tau\tau\tau at 8 TeV
  – Higgs-Exotics lunched analysis; \(2m_\tau < m_{H1} < 2m_b\)
• difficult region \(2m_b < m_{H1} < m_{H2}/2\)
  – most probably need 14 TeV data
  – WH2-\to H1H1-\to bbbb – need bkg. estimations
  – H2-\to H1H1-\to bbbb – not addressed yet
• good prospects for H3-\to H2(125)H1-\to WWbb, bbbb at 14 TeV
  – Higgs-Exotics lunched analysis; \(m_{H1} > 60\) GeV
• still need to be considered decays H1(\sim 100 GeV)-\to A1A1
2 Higgs Doublet Model

Theoretical structure of the 2HDM

- The scalar fields of the 2HDM are complex SU(2) doublet, hypercharge-one fields, $\Phi_1$ and $\Phi_2$.
  
  - the most general scalar potential:

\[
\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 \\
+ \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
+ \left\{ \frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + [\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\},
\]

- compare to SM with single doublet scalar field $\Phi$:

  scalar potential $V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$

\[
M_H^2 = 2\lambda v^2 = -2\mu^2 \quad m_e = \frac{\lambda_e v}{\sqrt{2}} \quad m_u = \frac{\lambda_u v}{\sqrt{2}} \quad m_d = \frac{\lambda_d v}{\sqrt{2}}
\]
• Yukawa couplings are given by:

\[- \mathcal{L}_Y = \overline{U}_L \Phi^0_a \Phi^*_a \Phi_a^U U_R - \overline{D}_L K^\dagger \Phi_a^D \Phi_a^U U_L + \overline{U}_L K \Phi_a^D \Phi_a^D \dagger D_R + \overline{D}_L \Phi^0_a \Phi_a^D \dagger D_L + \overline{N}_L \Phi_a^L \Phi_a^L \dagger E_R + \overline{E}_L \Phi^0_a \Phi_a^E \dagger E_R + \text{h.c.}, \]

– where $\Phi_a^U$ and $\Phi_a^D$ are Yukawa coupling matrices and $K$ is CKM matrix; $a=1,2$

• It yields however three-level FCNC mediated by neutral Higgs exchange, since only one of $\Phi_a^U$ and $\Phi_a^D$ are diagonal

• The problem is solved by imposing discrete symmetry on the Higgs and fermion fields to set two of four Yukawa coupling matrices to zero
Four possibilities exist in the 2HDM:

1. Type-I Yukawa couplings: $h_1^U = h_1^D = h_1^L = 0$,

2. Type-II Yukawa couplings: $h_1^U = h_2^D = h_2^L = 0$.

3. Type-X Yukawa couplings: $h_1^U = h_1^D = h_2^L = 0$,

4. Type-Y Yukawa couplings: $h_1^U = h_2^D = h_1^L = 0$.

The four types of Yukawa couplings can be implemented by a discrete $\mathbb{Z}_2$ symmetry, with the following charge assignments:

<table>
<thead>
<tr>
<th></th>
<th>$\Phi_1$</th>
<th>$\Phi_2$</th>
<th>$U_R$</th>
<th>$D_R$</th>
<th>$E_R$</th>
<th>$U_L$, $D_L$, $N_L$, $E_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Type II</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>(MSSM like)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type X</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>(lepton specific)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type Y</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>(flipped)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Couplings and free parameters

• Higgs couplings to fermions

<table>
<thead>
<tr>
<th></th>
<th>$hUU$</th>
<th>$hDD$</th>
<th>$hEE$</th>
<th>$HUU$</th>
<th>$HDD$</th>
<th>$HEE$</th>
<th>$iA\bar{U}\gamma_5U$</th>
<th>$iA\bar{D}\gamma_5D$</th>
<th>$iA\bar{E}\gamma_5E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>$\cos \alpha \over \sin \beta$</td>
<td>$\cos \alpha \over \sin \beta$</td>
<td>$\cos \alpha \over \sin \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$- \cot \beta$</td>
<td>$\cot \beta$</td>
<td>$\cot \beta$</td>
</tr>
<tr>
<td>Type II</td>
<td>$\cos \alpha \over \sin \beta$</td>
<td>$- \sin \alpha \over \cos \beta$</td>
<td>$- \sin \alpha \over \cos \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$- \cot \beta$</td>
<td>$- \tan \beta$</td>
<td>$- \tan \beta$</td>
</tr>
<tr>
<td>Type X</td>
<td>$\cos \alpha \over \sin \beta$</td>
<td>$\cos \alpha \over \sin \beta$</td>
<td>$- \sin \alpha \over \cos \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$- \cot \beta$</td>
<td>$\cot \beta$</td>
<td>$- \tan \beta$</td>
</tr>
<tr>
<td>Type Y</td>
<td>$\cos \alpha \over \sin \beta$</td>
<td>$- \sin \alpha \over \cos \beta$</td>
<td>$\cos \alpha \over \sin \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$\sin \alpha \over \sin \beta$</td>
<td>$- \cot \beta$</td>
<td>$- \tan \beta$</td>
<td>$\cot \beta$</td>
</tr>
</tbody>
</table>

• couplings to bosons:

$$\frac{c_\beta - \alpha}{\cos \beta} \quad \frac{s_\beta - \alpha}{\sin \beta}$$

$$hW^+W^- \quad hW^+W^-$$

$$HZ\bar{Z} \quad hZ\bar{Z}$$

$$ZAh \quad ZAH$$

$$W^\pm H^\mp h \quad W^\pm H^\mp H$$

• Free parameters :
  - $m_h$, $m_H$, $m_A$, $m_{H^\pm}$, $\alpha$, $\beta$, $m_{12}$
Recent scans in 2HDM with LHC h(126)

- from arXiv:1305.4587, Ferreira, Santos. Sher, Silva

Figure 3: Points in the $(\sin(\beta - \alpha), \tan \beta)$ plane that passed all the constraints in model type II using the ATLAS data analysis (left) and using the CMS data analysis (right) at 1σ in green (light grey) and 2σ in blue (dark grey). Also shown are the lines for the SM limit $\sin(\beta - \alpha) = 1$ and for the limit $\sin(\beta + \alpha) = 1$. 
Recent scans in 2HDM with LHC $h(126)$ and $H \rightarrow VV$

- from arXiv:1305.1624, Chen, Dawson, Sher
Recent discussion by Howard E. Haber on “Higgs Days in Santander 13”, Sept. 2013:

However, there are various reasons to consider the more general 2HDM without imposing an additional discrete symmetry on the model.

1. It would be useful to consider a formalism that can treat all four Yukawa coupling types simultaneously. (After all, experiment should decide which Yukawa interactions are relevant in nature.)

2. It may be that the suppression of tree-level Higgs-mediated FCNCs is a consequence of some new high scale physics. When this new physics is integrated out, the effective low energy 2HDM takes on its most general form.

Strategy for benchmarks in the general 2HDM with a new set of free parameters will be proposed soon to ATLAS and CMS
Conclusions

• Very reach physics program for BSM Higgs boson searches at LHC
• We expect to have a second discovery in Higgs sector during LHC and HL-LHC operation
• You are very welcome to join our searches