Beyond Standard Model Higgs at CMS

Evan Friis
on behalf of the CMS Collaboration
Overview

in this talk we present three CMS analyses using 1.1 fb⁻¹ of 2011 data

• Doubly charged Higgs search
• MSSM Higgs analyses
  • $H \rightarrow \tau \tau$ search
  • Charged Higgs BR($t \rightarrow H^+ b$)
• Interpretation of results in the MSSM
Doubly Charged Higgs

- Extend standard model with scalar triplet:
  - $\phi^{++}$, $\phi^{+}$, $\phi^{0}$ (type II seesaw model)
- Triplet responsible for neutrino masses
- Unknown neutrino mass matrix
- We assume decays to leptons only
- Signature: 3 or 4 final state leptons
- Dilepton made by same sign leptons
- Backgrounds: ZZ, WZ, Z/W+jets, top anti-top
- Lepton efficiencies and backgrounds from data
Doubly Charged Higgs results

- Excluded by Tevatron or LEP
- CMS Preliminary

**3 lepton final events**

- BP4, $m(\Phi^{±±}) = 150$ GeV

**4 lepton final events**

- Equal branching ratios: BP4

- CMS Preliminary
  \[ \sqrt{s} = 7 \text{ TeV} \quad L = 0.98 \text{ fb}^{-1} \]

**95% CL upper limit on $\sigma / \sigma_{\text{model}}$**

- Combined observed limit
- Combined expected limit
- Pair production observed limit
- Pair production expected limit
- Associated production observed limit
- Associated production expected limit

- BP1: normal hierarchy
- BP2: inverse hierarchy
- BP3: degenerate masses
- BP4: equal branchings

**New world limits!**

- Combined observed limit
- Combined expected limit
- Pair production observed limit
- Pair production expected limit
- Associated production observed limit
- Associated production expected limit

**Lower limit on mass of $\Phi^{±±}$**
MSSM Higgs and Tau

- Minimal Supersymmetric Standard Model
- Higgs to $\tau/b$ couplings enhanced by $\tan\beta$
- Higgs $\rightarrow \tau$ discovery channel in full mass range
- Two Higgs doublet model:
  - Includes charged Higgs

two MSSM analyses using 1.1 fb$^{-1}$ of CMS data

search for neutral MSSM Higgs bosons in di-tau events

measurement of $BR(t \rightarrow H^+ b)$
MSSM Production at the LHC

neutral MSSM Higgs

charged MSSM Higgs

M. Bachtis
# $H\rightarrow\tau\tau$ Analysis Strategy

## Analysis Channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu + \tau_h$</td>
<td>High statistics, clean</td>
</tr>
<tr>
<td>$e + \tau_h$</td>
<td>High statistics, larger background</td>
</tr>
<tr>
<td>$e + \mu$</td>
<td>Low statistics, very clean</td>
</tr>
<tr>
<td>$\mu + \mu$</td>
<td>Large Drell-Yan background</td>
</tr>
</tbody>
</table>

$\tau_h =$ hadronic tau decay

Selected events are divided into two categories: events with and without b-tagged jets

$M_{vis}$ spectrum is fitted simultaneously in all channels and categories
Tau Reconstruction at CMS

Hadrons + Strips (HPS) Algorithm

Hadron + Strip

3 Hadrons

taus use CMS Particle Flow algorithm objects

selections applied on isolation, mass, collimation

efficiency measured to 6% in data
**H→ττ Event Selection**

**trigger and kinematic selections**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Trigger</th>
<th>Offline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>μ + τh</strong></td>
<td>μ</td>
<td>$p_T &gt; 15$ GeV</td>
</tr>
<tr>
<td></td>
<td>τ</td>
<td>$p_T &gt; 15,20$ GeV</td>
</tr>
<tr>
<td><strong>e + τh</strong></td>
<td>e</td>
<td>$p_T &gt; 18$ GeV</td>
</tr>
<tr>
<td></td>
<td>τ</td>
<td>$p_T &gt; 20$ GeV</td>
</tr>
<tr>
<td><strong>e + μ</strong></td>
<td>e</td>
<td>$p_T &gt; 8/17$ GeV</td>
</tr>
<tr>
<td></td>
<td>μ</td>
<td>$p_T &gt; 17/8$ GeV</td>
</tr>
<tr>
<td><strong>μ + μ</strong></td>
<td>$\mu_1$</td>
<td>$p_T &gt; 17$ GeV</td>
</tr>
<tr>
<td></td>
<td>$\mu_2$</td>
<td>$p_T &gt; 17$ GeV</td>
</tr>
</tbody>
</table>
\( H \rightarrow \tau \tau \) Event Selection

- \( P_\zeta \) selection introduced at CDF
- Effective against \( W+\)jets and top
- Leptons required to have opposite charge
- Less than 2 jets with \( p_T > 30 \) GeV
- \( \mu + \mu \) requires \( M_{E_T} < 65 \) GeV
- \( \mu + \mu \) channel has additional likelihood based selection
$H \rightarrow \tau\tau$ Event Categorization

MSSM enhances associated b-quark production

selected events divided exclusively:
with/without at least one b-tagged jet ($p_T > 20$ GeV)
$H \rightarrow \tau \tau$ Selected Events

$\mu + \tau_h$ final state

<table>
<thead>
<tr>
<th></th>
<th>no b-tag</th>
<th>b-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>background</td>
<td>14514±640</td>
<td>193±13</td>
</tr>
<tr>
<td>data</td>
<td>15057</td>
<td>243</td>
</tr>
</tbody>
</table>

**CMS Preliminary**

$1.1 \text{ fb}^{-1} \sqrt{s}=7 \text{ TeV}$

$\tau_\mu \tau_h$

- $\phi \rightarrow \tau \tau$ ($m_\phi=120$, $\tan\beta=20$)
- Observed
- $Z \rightarrow \tau \tau$
- $t\bar{t}$
- Electroweak
- QCD

Events vs. $m_{\text{vis}}$ (GeV)

- no b-tag
- with b-tag
$H \rightarrow \tau \tau$ Selected Events

e + $\tau_h$ final state

<table>
<thead>
<tr>
<th>no b-tag</th>
<th>b-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>background</td>
<td>9398±320</td>
</tr>
<tr>
<td>data</td>
<td>10283</td>
</tr>
</tbody>
</table>
H→ττ Selected Events

e + μ final state

<table>
<thead>
<tr>
<th>no b-tag</th>
<th>b-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>background</td>
<td>3643±131</td>
</tr>
<tr>
<td>data</td>
<td>3942</td>
</tr>
</tbody>
</table>

**CMS Preliminary**

1.1 fb⁻¹ √s=7 TeV

τₑτₑ and τₑτₑ (mₐ=120, tanβ=20)

- Observed
- Z→ττ
- ττ
- Electroweak
- Fakes

no b-tag

with b-tag
$H \rightarrow \tau \tau$ Selected Events

$\mu + \mu$ final state

<table>
<thead>
<tr>
<th></th>
<th>no b-tag</th>
<th>b-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>background</td>
<td>15645$\pm$105</td>
<td>460$\pm$12</td>
</tr>
<tr>
<td>data</td>
<td>15711</td>
<td>479</td>
</tr>
</tbody>
</table>

CMS Preliminary $1.1 \text{ fb}^{-1} \sqrt{s}=7 \text{ TeV}$

$\tau_\mu \tau_\mu$ channel

- Observed
- $\phi \rightarrow \tau \tau \ (m_\phi=120, \tan\beta=20)$
- $Z \rightarrow \mu \mu$
- $Z \rightarrow \tau \tau$
- $t\bar{t}$

$\mu + \mu$ final state

Selected Events

- no b-tag
- with b-tag
<table>
<thead>
<tr>
<th>background</th>
<th>affects</th>
<th>strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>all</td>
<td>normalized to CMS 2010 $Z\mu\mu$</td>
</tr>
<tr>
<td>QCD</td>
<td>$\mu + \tau_h$, $e + \tau_h$</td>
<td>estimated from OS/SS data</td>
</tr>
<tr>
<td>W+jets</td>
<td>all</td>
<td>shape from MC normalization from $P_{\tau}$ sideband</td>
</tr>
<tr>
<td>fake electrons</td>
<td>$e + \mu$</td>
<td>fake rate method* using data</td>
</tr>
<tr>
<td>top anti-top</td>
<td>all</td>
<td>shape from MC normalization: CMS 2010 $\sigma(tt)$</td>
</tr>
<tr>
<td>di-boson</td>
<td>all</td>
<td>taken from MC (negligible)</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>$\mu + \mu$</td>
<td>taken from likelihood variable sidebands</td>
</tr>
</tbody>
</table>

*described in backup
**H→ττ Systematics**

Uncertainties either effect normalization or shape. Numbers shown here are **input** uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton ID/trigger</td>
<td>1%</td>
</tr>
<tr>
<td>tau ID efficiency</td>
<td>6%</td>
</tr>
<tr>
<td>tau energy scale</td>
<td>3% (shape)</td>
</tr>
<tr>
<td>(\sigma (Z\rightarrow ee/\mu\mu))</td>
<td>3%</td>
</tr>
<tr>
<td>(\sigma (\text{top anti-top}))</td>
<td>12%</td>
</tr>
<tr>
<td>b-tag efficiency</td>
<td>10%</td>
</tr>
<tr>
<td>b-tag mistag rate</td>
<td>14%</td>
</tr>
<tr>
<td>jet energy scale</td>
<td>2-5%</td>
</tr>
<tr>
<td>PDFs</td>
<td>3%</td>
</tr>
<tr>
<td>UE/parton shower</td>
<td>4%</td>
</tr>
<tr>
<td>QCD scale</td>
<td>4-12%</td>
</tr>
<tr>
<td>luminosity</td>
<td>6%</td>
</tr>
</tbody>
</table>
**H→ττ Yield Limit**

limit on 
\[ \sigma_\phi \times BR_{\phi \rightarrow \tau\tau} \]

- Not model independent
- \( gg/bb \) cross section ratio assumes MSSM and \( \tan\beta = 30 \)

Uses \( CL_s \) method

### CMS preliminary

- \( \sqrt{s} = 7 \text{ TeV}, 1.1 \text{ fb}^{-1} \)
- \( \sigma \times BR(\phi \rightarrow \tau \tau)_{95\% \text{ CLs}} \)

![Graph showing CMS preliminary limits on \( \sigma \times BR(\phi \rightarrow \tau \tau) \)]
Charged Higgs Strategy

- Measurement of branching fraction of $H^+ \rightarrow \tau^+ \nu$
- Three final states considered
Charged Higgs Selection

all hadronic

- tau + ME_T trigger
- \( \tau \ p_T > 40 \) GeV, \( \eta < 2.3 \)
- 1 prong taus
- \( \geq 3 \) jets \( p_T > 30 \) GeV
- ME_T > 70 GeV
- 1 b-tag

\( \mu + \tau_h \)

- single muon trigger
- \( \tau \ p_T > 20 \) GeV, \( \eta < 2.3 \)
- \( \mu \ p_T > 20 \) GeV, \( \eta < 2.1 \)
- \( \geq 2 \) jets \( p_T > 30 \) GeV
- ME_T > 40 GeV
- 1 b-tag

\( \mu + e \)

- e (8) + \( \mu \) (17) trigger
- lepton \( p_T > 20 \) GeV, \( \eta < 2.4 \)
- \( \geq 2 \) jets \( p_T > 30 \) GeV
Charged Higgs Backgrounds

fully hadronic

QCD multijet background taken from data
EWK + top anti-top estimated by embedding
simulated taus in muon events
EWK + top anti-top + fake taus from MC

$\mu + \tau$

QCD tau fakes estimated with fake rate method
other backgrounds from simulation

e + $\mu$

top anti-top background estimated from simulation
Charged Higgs Limits

Limit on $\text{BR}(t \rightarrow H^+ b)$

Assumes $B(H^+ \rightarrow \tau^+ \nu) = 1$

$\text{BR} > 5\%$ excluded!
Interpretation in MSSM

Santander matching for mapping $\sigma \rightarrow \tan \beta$

$H \rightarrow \tau\tau$ drives limit
$H^+$ contributes at low mass

Theory uncertainties:
PDF + $\alpha_s$ + $\mu$ scale
Interpretation in MSSM

huge improvement w.r.t. CMS winter result!

more data, b-tagging, and τ-ID systematics
Summary

- Inclusive search for $\phi^{++}$ performed
- No excess observed, new world limits
- Search for neutral MSSM Higgs performed
- No excess observed
- Upper limit of 5% placed on $\text{BR}(t \rightarrow H^+ b)$
- Large new region of MSSM parameter space excluded by these results
Particle Flow Algorithm

- Clusters and links signals from all subdetectors
- Produces a list of particle candidates
  \[ h h^0 e \mu \gamma \]
- To the user looks just like Monte Carlo
Particle Flow Algorithm

Figure 3: Charged (hadron tracks - lines with squares - representing the hits measured in the tracker and the various extrapolation positions to the ECAL and HCAL: each linked to .a: one or two ECAL clusters and .b: an HCAL cluster - dots). Each square represents a calorimeter cell. The grey area is proportional to the logarithm of the energy measured in each cell. The clusters represented by a star are linked to neither of the two tracks and are therefore photon candidates.

Figure 4: Track (cluster link distance in .a: the ECAL and .b: the HCAL - for tracks with $p_T$ larger than 1 GeV/c - in the data - dots with error bars - and in the simulation - histogram). The typical cell size is 0.02 in the ECAL and 0.1 in the HCAL.

see CMS PAS PFT-10-002
Hadrons Plus Strips Algorithm

build signal components combinatorially

cluster gammas into $\pi^0$ candidates using $\eta$-$\phi$ strips

build all possible taus that have a ‘tau-like’ multiplicity from the seed jet

$\pi^+$
$\pi^+ \pi^0$
$\pi^+ \pi^+ \pi$

tau that is ‘most isolated’ with compatible $m_{vis}$ is the final tau candidate associated to the seed jet
Tau ID Efficiency

measured in data by fitting tau-ID passed and failed $M_{\text{vis}}$ spectrum for loosely selected taus

**tau ID failed**

**tau ID passed**
H→ττ Limits per Channel

expected

observed

Upper Limit on σ x BR(Φ → ττ)

m A (GeV/c²)
H$^+$ tan$\beta$ Limit

NB: $(m_{H^+})^2 = (m_A)^2 + (m_W)^2$
CMS Luminosity

Data delivered by LHC: 1.28 fb^{-1}
Data recorded by CMS: 1.18 fb^{-1}

About 93% of the data is high quality with a total of 1.1 fb^{-1}.

Analyzed data: 1.1 fb^{-1}.
Doubly charged Higgs boson ($\Phi^{++}$)

- Standard model extension by a scalar triplet adding three new particles
  - $\Phi^{++}, \Phi^+, \Phi^0$ (e.g. Type-$||$ seesaw model)
- The triplet is responsible for neutrino masses, the couplings being directly linked to the mass matrix
  - $M_{ij} = k Y_{ij}$
- Unknown neutrino mass matrix → unknown branching ratios
- We assume branching ratios to leptons only
  - Six standard searches covered, where $\text{BR}(\Phi^{++} \rightarrow l^+ l^+)=100\%$
  - Four additional model dependent points to describe the neutrino sector

A Nayak, 22/07/2011
Signatures: **3 or 4 leptons** in the final state, dilepton made by same sign lepton

**Backgrounds:**

- **ZZ, WZ, Z+jets, tt+jets, (W+jets, QCD)**

**Selection strategy:**

- dilepton triggers
- lepton id and charge matching
- $\Sigma p_T$ cuts on leptons
- tight isolation of leptons
- $Z$ veto
- cut on $\Delta \phi$ between leptons

**Pre-selection:**

- At least two leptons with $p_T > 35 / 10$ GeV
- Loose isolation requirement
- Veto of low invariant mass resonances ($<12$ GeV)

- Additional topological cuts on leptons depending on final states
  - Three OR four leptons

**Control from real data of**

- the lepton-related efficiencies
- the estimation of background rate

**Inclusive search** in order to cover the whole phase space

**Results provided for** integrated lumi $= 0.98$ fb$^{-1}$
Results

CMS Preliminary
\( \sqrt{s} = 7 \text{ TeV} \) \( \mathcal{L} = 0.98 \text{ fb}^{-1} \)
BP4, \( m(\Phi^{\pm}) = 150 \text{ GeV} \)

3-leptons
- Preselection
- Full selection

Events / 20 GeV

4-leptons
- Preselection
- Full selection
Lower limit on $\Phi^{++}$

95% CL lower Limits obtained using CLs method
In addition to the model independent search, the type II seesaw model is tested in four benchmark points (BP) [8] that characterize different characteristic neutrino mass matrix structures. BP1 describes the neutrino sector with normal mass hierarchy and a massless lightest neutrino, $m_1 = 0$ eV. BP2 describes the same but with the inverse mass hierarchy. BP3 represents a degenerate neutrino mass spectrum with $m_1 = 0.2$ eV. Those three benchmark points are the extremes allowed by varying the neutrino mass and hierarchy in the allowed ranges without consideration for $\theta_{13}$ or CP phases and cover a large region of the parameter space. The fourth benchmark point BP4 represents the case in which all $\Phi^{++}$ branching fractions are equal. This is achieved with the following values of Majorana phases: $\alpha_1 = 0$, $\alpha_2 = 1.7$. In all benchmark points an exact tri-bi-maximal neutrino mixing matrix and vanishing CP-phases is assumed except in BP4, where $\alpha_2$ is nonvanishing. The branching fractions of the benchmark points are summarized in Table 1.

Table 1: Branching fractions of $\Phi^{++}$ to the various final states ($\tau$ means a $\tau$ lepton before decay) in the four benchmark point models.

<table>
<thead>
<tr>
<th>Benchmark point</th>
<th>ee</th>
<th>e(\mu)</th>
<th>e(\tau)</th>
<th>(\mu\mu)</th>
<th>(\mu\tau)</th>
<th>(\tau\tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP1</td>
<td>0</td>
<td>0.01</td>
<td>0.01</td>
<td>0.30</td>
<td>0.38</td>
<td>0.30</td>
</tr>
<tr>
<td>BP2</td>
<td>0.50</td>
<td>0</td>
<td>0</td>
<td>0.125</td>
<td>0.25</td>
<td>0.125</td>
</tr>
<tr>
<td>BP3</td>
<td>1/3</td>
<td>0</td>
<td>0</td>
<td>1/3</td>
<td>0</td>
<td>1/3</td>
</tr>
<tr>
<td>BP4</td>
<td>1/6</td>
<td>1/6</td>
<td>1/6</td>
<td>1/6</td>
<td>1/6</td>
<td>1/6</td>
</tr>
</tbody>
</table>
Fake Rate Method

goal: estimate fake background contribution

- Measure object fake rate in data in background enriched control regions
  - $W+\text{jets}$, QCD $\mu$ enriched, etc
- Disable object-ID in analysis
- Final events now $\sim$pure background
- Weight each event by probability to fake identification