Standard Model Higgs
Search at CMS

Aaron Dominguez
Wichita State, September 7, 2011
# Known Force Particles

**BOSONS**

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W^-$</td>
<td>80.39</td>
<td>-1</td>
</tr>
<tr>
<td>$W^+$</td>
<td>80.39</td>
<td>+1</td>
</tr>
<tr>
<td>Z boson</td>
<td>91.188</td>
<td>0</td>
</tr>
</tbody>
</table>

**Strong (color)** spin = 1

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Graviton?
## Known Matter Particles

**FERMIIONS**  

**Leptons**  

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_L$ (lightest neutrino*)</td>
<td>$(0-0.13) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_e$ (electron)</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_M$ (middle neutrino*)</td>
<td>$(0.009-0.13) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$ (muon)</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_H$ (heaviest neutrino*)</td>
<td>$(0.04-0.14) \times 10^{-9}$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$ (tau)</td>
<td>1.777</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Quarks**  

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$ (up)</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$ (down)</td>
<td>0.005</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$ (charm)</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$ (strange)</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$ (top)</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$ (bottom)</td>
<td>4.2</td>
<td>-1/3</td>
</tr>
</tbody>
</table>
Something’s Missing...

- Generations of matter different only in mass of the particles, otherwise basically duplicates
- Why do they have different masses?
- Why is the weak force “weak?” Because $m_W, m_Z > 0$.
- OK, so why are $m_W, m_Z > 0$?
- One “solution” is a new particle: Higgs boson
Higgs Field

- According to this model, the Higgs field fills the universe
- It doesn’t disturb gravity, strong or the EM force
- It does disturb the weak force and makes it short ranged
- In simplest model, same particle could also be giving mass to all other particles
Accelerators: currently our best tools
Accelerators: currently our best tools
Interesting physics hard to find

- **Proton-Proton** 1418 bunches/beam
- **Protons/bunch** \( \sim 10^{11} \)
- **Beam energy** 3.5 TeV
- **Inst. Luminosity** \( 2.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \)
- **Crossing rate** 20 MHz
- **Collision rate** \( \sim 10^9 \) Hz
- **New physics rate** \( \sim 0.00001 \) Hz
- **Event selection** 1 in \( \sim 10 \text{ trillion} \)!
Reconstructing High energy collisions

Beam particles collide

- hard interaction, $\sim 10^{-16}$ cm
- quarks, leptons, new particles decay

- hadronization $\sim 10^{-12}$ cm
- resonances decay

- weak decays of b,c quarks $\sim 10^{-2}$ cm .. cm

- detection of what's left 4 cm .. 10 m

$p, n, \pi, K, e, \mu, \gamma$

(Wolfram Erdmann)
Have to be able to “see” the collisions
How Do We “See?”

(Open in FlashPlayer)
Higgs Production in 7 TeV pp Collisions

- gg → H is dominant production mechanism

Irreducible backgrounds in H → WW, ZZ, γγ are from q̅q̅ annihilation; S/B better than at Tevatron except in VH

(V. Sharma)
Search Strategy

- SM Higgs mass is unknown parameter
- It would be produced in a few ways at the LHC, and in association with certain particles
- It would couple to particles in proportion to their mass
- It’s neutral, and interaction would conserve energy and other QM quantities
- So, the decay signature would look different depending on $m_H$
- Do a series of searches, in different mass ranges, for most important, kinematically allowed, decay modes and combine them all together in one big search!
### SM Higgs Decay Modes Vs Mass

<table>
<thead>
<tr>
<th>Mode</th>
<th>Mass Range</th>
<th>Data Used (fb⁻¹)</th>
<th>CMS Document</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>110-150</td>
<td>1.7</td>
<td>HIG-11-021</td>
</tr>
<tr>
<td>$H \rightarrow bb$</td>
<td>110-135</td>
<td>1.1</td>
<td>HIG-11-012 (NEW)</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>110-140</td>
<td>1.1</td>
<td>HIG-11-009</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow 2l 2\nu$</td>
<td>110-600</td>
<td>1.5</td>
<td>HIG-11-014</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>110-600</td>
<td>1.7</td>
<td>HIG-11-015</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 2l 2\tau$</td>
<td>180-600</td>
<td>1.1</td>
<td>HIG-11-013 (NEW)</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 2l 2j$</td>
<td>226-600</td>
<td>1.6</td>
<td>HIG-11-017</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 2l 2\nu$</td>
<td>250-600</td>
<td>1.5</td>
<td>HIG-11-016</td>
</tr>
</tbody>
</table>

(V. Sharma)
Cross Sections for Key SM Background Processes

$\sqrt{s} = 7$ TeV

- **$t\bar{t}$**
  - 165 pb NNLO

- **$t + X$**
  - (t-channel)
  - 63 pb NLO

- **$tW$**
  - 10.6 pb
  - (s-channel)
  - 4.6 pb

- **$W^+W^-$**
  - 43 pb

- **$W + \text{jets}$**
  - $W \rightarrow \ell\nu$
  - 28000 pb NLO

- **$Z + \text{jets}$**
  - $Z \rightarrow \ell^+\ell^-$
  - 2800 pb NLO

(V. Sharma)
CMS Total Integrated Luminosity 2011 (Mar 14 09:00 - Aug 22 16:10 UTC)

- Delivered 2.63 fb$^{-1}$
- Recorded 2.38 fb$^{-1}$
Data set used for latest Higgs search 1.1 to 1.7 fb⁻¹
Data set used for latest Higgs search 1.1 to 1.7 fb$^{-1}$

Since April, the inst. lumi has increased by x10!!!
Data set used for latest Higgs search 1.1 to 1.7 fb$^{-1}$
Data set used for latest Higgs search 1.1 to 1.7 fb$^{-1}$

In dataset used have $\sim$6 simultaneous interactions ("pileup")
Data set used for latest Higgs search 1.1 to 1.7 fb⁻¹
• Would be a narrow peak in a falling diphoton mass spectrum

• Experimental resolutions important

• Trigger on diphotons. Photons required to be isolated and energetic (>40 GeV and >30 GeV)

• Background is mainly from large, irreducible QCD (measured from sidebands in data)

• Split selected events into different 8 categories based on the purity of the sample: both in barrel, both pass conversion veto, \( p_T^{\gamma\gamma} > 40 \text{ GeV} \)
Low Mass Higgs Search: $H \rightarrow \gamma\gamma$

Unconverted $\gamma\gamma$, both in ECAL barrel

1 converted $\gamma$, both in ECAL barrel

Unconverted $\gamma\gamma$, one in ECAL endcap

1 converted $\gamma$, one in ECAL endcap

LEE $\Rightarrow$ Prob. to observe max. excess as large as seen in data = 0.05 (1.7$\sigma$)

CMS Prelim

$95\%$ CL limit on $\sigma/c_{SM}$

$\approx 2 - 4 \times SM$
Look for three final states of tau pair decay (leptonic, hadronic): $e + \tau_{\text{had}}, \mu + \tau_{\text{had}}, e + \mu$

Build visible mass of event from electrons, muons, hadronic taus (doesn’t try to account for neutrinos)

Look for excess of events in visible mass spectrum

Divide into two sets of categories based on VBF-likeness of jets: $p_T > 30 \text{ GeV}, m_{jj} > 350 \text{ GeV}, \Delta\eta_{jj} > 3.5, \eta_1 \cdot \eta_2 < 0$

Dominant background from $Z \rightarrow \tau^+ \tau^-$
VBF

CMS Preliminary
1.1 fb⁻¹ √s=7 TeV
τeτh
(10x) H→ττ m_h=120
- Observed
- Z→ττ
- t̄f
- Electroweak
- QCD

Events

m_{vis} [GeV]

0 100 200 300 400 500

VBF

CMS Preliminary
1.1 fb⁻¹ √s=7 TeV
τμτh
(10x) H→ττ m_h=120
- Observed
- Z→ττ
- t̄f
- Electroweak
- QCD

Events

m_{vis} [GeV]

0 100 200 300 400 500

VBF

CMS Preliminary
1.1 fb⁻¹ √s=7 TeV
τeτμ
(10x) H→ττ m_h=120
- Observed
- Z→ττ
- t̄f
- Electroweak
- Fakes

Events

m_{vis} [GeV]

0 100 200 300 400 500

Low Mass Higgs Search: H→ττ

1.1 fb⁻¹ √s=7 TeV

Jet 2 ET = 46 GeV
Visible Mass (μν) = 75 GeV
Mass (jj) = 580 GeV
(Mjj) = 3.5
Missing ET = 97 GeV
Jet 1 ET = 177 GeV

# + # = 0
# - 1 # < 0

Search H→ττ in two categories:
- VBF: 2 jets (P_T >30 GeV),
  #jj >3.5
- Non-VBF: #1 jet, or #2 jet failing VBF

In μ+μ+, μ+τ, τ+τ final states

Background: top, EWK, Z

VBF modes are cleanest, most sensitive

Important mode, sensitivity improves ~ linearly with data and sophisticated methods

95% CL limit on σ/σ_SM

CMS Preliminary

Observed
- Expected ± 1σ
- Expected ± 2σ

Higgs boson mass (GeV/c²)

110 120 130 135 140

10 100
Low Mass Higgs Search: $H \rightarrow b \bar{b}$

- $gg \rightarrow H \rightarrow bb$ and VBF are dominant production modes but overwhelmed by enormous QCD di-jet background.
- Best option: $qq \rightarrow VH; H \rightarrow bb$
  - Major backgrounds are V+jets, VV, ttbar.
- Use
  - VH topology: $\Delta \Phi(V,H) > 3$
  - $P_T(V) > 100-160$ GeV (boosted W/Z)
  - Tight b-tagging & MET quality
  - Backgrounds estimated from control data.
Signal characteristics:

- Only 2 opposite sign, isolated leptons
- Significant ME_T → No mass peak
- No b-jets, no additional low P_T µ
- With additional 0, 1 or 2 jets (VBF)
- Small ΔΦ (l^+l^-) ← Higgs scalarity

No signal mass peak (missing vv) → Counting expt.

Challenge is to remove & control large backgrounds

Major requirements:

- Lepton P_T > 10 GeV, tight ID & Isolation
  - Removes QCD & W+jets contamination
- Large ME_T & Z → µµ, ee veto
  - Removes Drell-Yan contamination
- Classification by # of jets (P_T > 30 GeV) & b-jet veto
  - Removes Top contamination
- Kinematic discriminants: M_∥ & ΔΦ (l^+l^-)
  - Mitigates pp → ww background
- M_H-dependent cut optimization
CMS Prelim

$\sqrt{s} = 7$ TeV

$H \rightarrow WW$, $L_{\text{int}} = 1.5$ fb$^{-1}$

95% CL limit on $\sigma/\sigma_{\text{SM}}$

- Observed
- Expected ± 1σ
- Expected ± 2σ

Sensitivities

- SM Higgs boson expected sensitivity
  $136 < M_H < 200$ GeV

- SM Higgs boson ruled out at 95% CL
  $147 < M_H < 194$ GeV

PS: This update featured only Cut-based analysis. MV A based result coming soon!
Signal: 4 isolated lepton from common vertex

Fully reconstructed, Mass resolution~ 2-4 GeV

Reducible Backgrounds:
- $t\bar{t}b \rightarrow 2l2\nu2b$ ; $Z+bb$
- Removed by Isolation & Impact parameter requirements

Irreducible background: $pp \rightarrow ZZ$ Continuum

Event Selection: Same Flavor, opposite charge
- $Z_1$: $P_T^{(min)} > 10$, $P_T^{(max)}>20$ GeV, $60 < M_{ll} < 120$
- $Z_2$: $20 < M_{ll} < 120$ GeV
- $M_{4l} > 120$ GeV
- Impact parameter significance > 4

Reducible background contribution from data

$ZZ$ Continuum:
- Shape known at NLO, corrected for $gg \rightarrow ZZ \rightarrow 4l$ evaluated with MCFM
- Rate obtained from Z yield in data & theoretical prediction for ratio of ZZ to Z cross sections
Three pairs of events at $M_{4l} = 122, 142 \text{ & } 165 \text{ GeV}$
Only $M_{4l} = 142 \text{ GeV}$ consistent with SM Higgs expectation (V. Sharma)
More High Mass Channels

• Also have looked in ZZ channels with: 2 leptons + 2 taus; 2 leptons + 2 neutrinos; 2 leptons + 2 quarks (with/without b-tag)

• Neutrino channel most sensitive because of large missing energy and higher branching fraction for Z

• Also have no evidence of Higgs like other channels
The combination presented in this note is based on eight major channels classified by the final Higgs decay chain signature as shown in Table 9. The mass search regions are specific to each analysis. The analyzed integrated luminosity varies from channel to channel in the range from $9.959.6^{-0.9} fb$. From Table 94 one can also see that different analysis strategies are employed in different searches. They include three basic types: cut-and-count analyses, analyses of binned distributions, and unbinned analyses tracking individual events and using parametric models of signal and background shapes. Each of the major analyses is a combination in itself with 0 to $(independent$ sub-channels. In the overall combination there are $(independent$ sub-channels at low mass Higgs boson searches $m_H < 9.8 GeV$ and 0: sub-channels in the high mass region $m_H > 9.8 GeV$. The last column in Table 9 shows the number of nuisance parameters for systematic uncertainties in each analysis. The total number of independent nuisance parameters in the current combination is 0/-4 of which 0:9 are used in the combination in the low mass range and 9:/ in the high mass range. There are 0, correlated sources of uncertainties appearing in more than one major search. The remaining ones are specific to individual analyses. Table 0 shows the full list of uncertainties correlated across more than one major analysis. The top block in the table is a subset of the list prepared by the LHC Higgs Combination Group [08]. The bottom block are correlated errors that are correlated within CMS only. Quantities affected by the uncertainties listed in Table 0 are all positive definite and hence modeled as log-normals. In the following subsections, we give a brief description of search strategies for the eight channels used in this combination. Detailed information can be found in references provided within each sub-section.

Table 1: Summary information on the analyses included in the combination. The first number in the last column gives the number of nuisance parameters correlated across two or more analyses. The second number refers to the number of nuisance parameters specific to one analysis only.

<table>
<thead>
<tr>
<th>channel</th>
<th>mass range (GeV/$c^2$)</th>
<th>luminosity (fb$^{-1}$)</th>
<th>number of sub-channels</th>
<th>type of analysis</th>
<th>number of nuisances</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>110-150</td>
<td>1.7</td>
<td>8</td>
<td>mass shape (unbinned)</td>
<td>3+40=43</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>110-140</td>
<td>1.1</td>
<td>6</td>
<td>mass shape (binned)</td>
<td>10+25=35</td>
</tr>
<tr>
<td>$H \to bb$</td>
<td>110-135</td>
<td>1.1</td>
<td>5</td>
<td>cut&amp;count</td>
<td>10+59 = 69</td>
</tr>
<tr>
<td>$H \to WW \to 2\ell 2\nu$</td>
<td>110-600</td>
<td>1.5</td>
<td>5</td>
<td>cut&amp;count</td>
<td>15 +79 =94</td>
</tr>
<tr>
<td>$H \to ZZ \to 4\ell$</td>
<td>110-600</td>
<td>1.7</td>
<td>3</td>
<td>mass shape (unbinned)</td>
<td>14+20=34</td>
</tr>
<tr>
<td>$H \to ZZ \to 2\ell 2\tau$</td>
<td>180-600</td>
<td>1.1</td>
<td>8</td>
<td>mass shape (unbinned)</td>
<td>13+10=23</td>
</tr>
<tr>
<td>$H \to ZZ \to 2\ell 2\nu$</td>
<td>250-600</td>
<td>1.6</td>
<td>2</td>
<td>cut&amp;count</td>
<td>14+4=18</td>
</tr>
<tr>
<td>$H \to ZZ \to 2\ell 2q$</td>
<td>226-600</td>
<td>1.6</td>
<td>6</td>
<td>mass shape (unbinned)</td>
<td>12+15=27</td>
</tr>
<tr>
<td>TOTAL (8)</td>
<td>110-600</td>
<td>1.1-1.7</td>
<td>27 for low $m_H$</td>
<td>241 for low $m_H$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24 for high $m_H$</td>
<td>146 for high $m_H$</td>
<td></td>
</tr>
</tbody>
</table>
At 95% CL exclude 145-216, 226-228, 310-400 GeV

CMS Preliminary, $\sqrt{s} = 7$ TeV
Combined, $L_{\text{int}} = 1.1-1.7$ fb$^{-1}$
In Near Future

CMS Preliminary: Oct 2010

Significance of Observation ($\sigma$)

Projected Significance of Observation

Higgs mass, $m_H$ [GeV/c$^2$]

(NB: study a little dated)
Conclusions

- LHC and CMS (ATLAS too ;) performing very well
- We are really now, finally!, closing in on the SM Higgs
- If we get something like \( >5 \text{ fb}^{-1} \) at 7 TeV, it looks like we should either be able to make an observation of the SM Higgs, or exclude it
- Either case would be a major result
- Thanks for having me down to Wichita!