Recent Higgs Search Results
with the CMS Detector

Christoph Paus, MIT

The Zurich Phenomenology Workshop (Zürich)

January 09, 2012
The Standard Model of Particle Physics

Building blocks: matter (fermions), forces (bosons)

Simple Lagrangian formalism describes this very well but only for massless particles....
The Standard Model of Particle Physics

How do particles acquire their masses?

- hand inserted mass terms destroy gauge invariance (local)
- need gauge invariant mechanism to generate mass terms
- Higgs mechanism is the simplest way to do it

The Higgs mechanism

- introduce additional scalar field (a new scalar particle)
- modifies derivatives
- additional terms with mass appear
- vacuum expectation value $\neq 0$
- particles move through field which gives them mass
- no experimental evidence, yet
Higgs Particle: Pros and Cons

The mystery of mass

• can be resolved with one scalar Higgs boson

What is good about it?

• resolves fundamental problem of mass
• nature tends to be economic: few particles
• model makes very precise predictions: decay kinematics (scalar), couplings, cross section, cross section ratios ....

• only one parameter to vary: $m_H$

• search can be very well targeted
• similar mechanisms for example SUSY, partially covered

What is not good about it?

• no physics beyond Standard Model, we like new things
• fundamental problems of Standard Model remain
The Standard Model: Measurements

Experimental data
- LEP, SLC
- Tevatron
- Neutrino experiments
- ....

Measurements
- over a thousand individual measurements combined
- very different accelerator and detector setups
- decent agreement with SM
The Standard Model: Higgs Constraints

Direct searches
- nothing found
- Higgs boson too heavy

What precision data tell us
- radiative corrections modify lowest order processes
- Higgs present in virtual loops
- modifies observables

![Diagram](image-url)
**Higgs Landscape Before LHC**

Fundamental limitations
- center of mass energy (Tevatron 2 TeV, LEP 210 GeV)
- searches limited to low mass region (plots stop at 200 GeV)

Search for the Higgs Particle

Excluded by LEP Experiments
- 114

Excluded by Tevatron Experiments
- 158
- 173

Excluded by Indirect Measurements
- 185

Higgs mass values

C.Paus, MIT: Recent CMS Higgs Results
The CMS Conclusion

Quantum leap in Higgs search in 2011: ~5/fb data
- excluded region: $127 \text{ GeV} < m_H < 600 \text{ GeV}$
- expected: $117 \text{ GeV} < m_H < 543 \text{ GeV}$
- small window left: $114.4 \text{ GeV} < m_H < 127 \text{ GeV}$

Looking beyond 95% CL → 99% CL
- 99% CL exclusion: $128 \text{ GeV} < m_H < 525 \text{ GeV}$
- search will not stop at 95% CL exclusion

Comments on low mass region
- excluded less than expected
- small excess, but inconclusive at this point
- need more data to come to a conclusion (this year, 2012)
Needle in the hay stack problem

- need high energy
- need lots of data
**Higgs Hunting Basics**

**Physics processes**
- production relative to $\sigma_{\text{tot}}$:
  - $bb$ at $10^{-3}$,
  - $W\rightarrow \ell \nu$ at $10^{-6}$ and
  - $Higgs$ ($m=110$ GeV) at $\sim 10^{-11}$
- 32 MHz beam crossing, only about 300 Hz tape writing: $1/10^5$
- fast and sophisticated selection process essential: trigger

**Trigger**
- trigger has to work: otherwise no useful data registered
- already in first data taking: rate enormous and trigger important
- core trigger organization: use electron, muon, jet and energy signatures

![Diagram of proton - (anti)proton cross sections](image)
Higgs Production at the LHC

Higgs production in proton-proton collisions

![Diagram showing Higgs production processes](image-url)

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ \sigma(pp \rightarrow H+X) \text{ [pb]} \]

Area of largest interest

C.Paus, MIT: Recent CMS Higgs Results
Higgs Decays (Tevatron/LHC)

Higgs couples to mass

\[ \Gamma_{Hff} \sim m_f^2 \]
\[ \Gamma_{HVV} \sim m_V^4 \]

area of largest interest

C.Paus, MIT: Recent CMS Higgs Results
Higgs boson couples to mass
\[ \Gamma_{Hff} \sim m_f^2 \]
\[ \Gamma_{HVV} \sim m_V^4 \]

Messy: many channels, many subsequent decays etc. etc.
- common: leptons/photons essential for any search
LHC Location

Proton-proton collisions at 7 TeV (up to 14 TeV)
LHC Status

Super short summary

- proceeding with caution
- no show stoppers so far
- nom. bunch intensity reached
- bunch trains commissioned easily
- no beam related quenches
- very clean beams
- machine parameters better than expected
- all goals reached
- 2011 smooth running
- 2012: 8 TeV? 25 ns or 50 ns?
Delivered and Recorded Collisions

LHC performs better than expected
- summer conference based on 1.66/fb (for Lepton-Photon)
- 2011: 5.73/fb delivered of 5.22/fb recorded (91%)
CMS Overview

Inner Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Installation

Magnet

The tracking volume is given by a cylinder of a length of 6 m and a diameter of 2.6 m. Fine pitch Si detectors provide precise information on the transverse position of the interaction, improving measurement of the azimuthal angle and reconstruction of secondary vertices. In the central rapidity region ($|y|<1.5$), the momentum resolution is given by $\sigma/p = 0.005 \times 0.15 \mu$ ($p$ in TeV).

A Si module in its assembly jig. Strips from pairs of 660 cm Si detector are bonded together.

Layout of a radiation hard front-end detector chip (Hamamatsu) with preamplifier, shaper, pipeline, analog pulse shaping processor and multiplexer unit. 168 channels.

A full size (3m long) lead tungstate crystal with a mounted APD.

Lead tungstate crystals have a short response time (5 ns) and moderate radiation hardness (6x6 cm). This yields a high-performance compact calorimeter with fine segmentation. The signal is detected by specially developed Silicon Avalanche Photodiodes (APD) which allow an amplification of up to 100.

Energy resolution measured with 100 GeV electrons in test beam. The distribution shown is for a sum of 333 crystals with lateral size of (23x2.5) cm$^2$.

A section through one sector of the barrel module. The copper absorber plates are bolted together and held by encircling rings. The gaps between the rings will be filled in the gaps.

CMS is built around a long superconducting solenoid (r = 13 m) with a free inner diameter of 5.9 m and a uniform magnetic field of 4 T. The magnetic flux is provided by a 1.5 m thick iron yoke instrumented with muon chambers.

12500 T, 15m x 15m x 21m

C.Paus, MIT: Recent CMS Higgs Results
CMS Detector in the Cavern
So far CMS does not see the Higgs but ....
.... we could have seen it in some mass interval and thus we exclude those regions.

Let’s see what we have so far.
The approximate main regions

- **low mass region** 110 GeV – 140 GeV
- **intermediate mass region** 140 GeV – 200 GeV
- **high mass region** 200 GeV – 600 GeV
The Main Channel: $H \rightarrow WW \rightarrow 2l\ 2\nu$

**Signature**
- 2 opposite charged leptons (leptons only $e, \mu$)
- 2 neutrinos == missing transverse energy (MET)
- no Higgs mass peak
- basically a counting analysis
- enhance sensitivity by subdividing into + (0,1,2) jets

**Analysis challenges**
- understand backgrounds
- normalize to control regions
- backgrounds: WW, W+jets, top, DY

Higgs is scalar
leptons are close
Top Background to $H \rightarrow WW \rightarrow 2l \ 2nu$

Signature and rejection strategy

- jets and jets from $b$-quarks: remove events with jets and veto $b$-jets
**Drell-Yan Background to $H \rightarrow WW \rightarrow 2l \ 2\nu$**

**Signature and rejection strategy**

- small MET: remove events with small MET

C.Paus, MIT:  Recent CMS Higgs Results
Non Resonant WW Background to $H \rightarrow WW \rightarrow 2l \, 2\nu$

**Signature**
- irreducible
- slightly different kinematics than Higgs decay

**Strategy**
- use kinematics depending on the Higgs mass value
- variables of interest: $\Delta\Phi_\parallel$ and $m_\parallel$
## Counting Analysis .... Numbers

<table>
<thead>
<tr>
<th>$m_H$</th>
<th>DY→$ll$</th>
<th>ttbar+tW</th>
<th>W+jets</th>
<th>WZ+ZZ+Wγ</th>
<th>WW</th>
<th>all BG</th>
<th>H→WW</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>8.8±9.2</td>
<td>6.7±1.0</td>
<td>14.7±4.7</td>
<td>6.1±1.5</td>
<td>100.3±7.2</td>
<td>136.7±12.7</td>
<td>15.7±0.8</td>
<td>136</td>
</tr>
<tr>
<td>130</td>
<td>13.7±7.8</td>
<td>10.6±1.6</td>
<td>17.6±5.5</td>
<td>7.4±1.6</td>
<td>142.2±10.0</td>
<td>191.5±14.0</td>
<td>45.2±2.1</td>
<td>193</td>
</tr>
<tr>
<td>160</td>
<td>3.4±3.4</td>
<td>10.5±1.4</td>
<td>3.0±1.5</td>
<td>2.2±0.4</td>
<td>82.6±5.4</td>
<td>101.7±6.8</td>
<td>122.9±5.6</td>
<td>111</td>
</tr>
<tr>
<td>200</td>
<td>2.7±3.7</td>
<td>23.3±3.1</td>
<td>3.4±1.5</td>
<td>3.2±0.3</td>
<td>108.2±4.5</td>
<td>140.8±6.8</td>
<td>48.8±2.2</td>
<td>159</td>
</tr>
<tr>
<td>250</td>
<td>0.3±0.6</td>
<td>36.2±4.8</td>
<td>6.7±2.1</td>
<td>5.7±0.7</td>
<td>101.8±4.5</td>
<td>150.8±6.9</td>
<td>23.5±1.1</td>
<td>152</td>
</tr>
<tr>
<td>300</td>
<td>0.7±1.9</td>
<td>41.6±5.4</td>
<td>6.5±2.1</td>
<td>7.0±0.7</td>
<td>87.5±3.9</td>
<td>143.3±7.2</td>
<td>20.2±0.9</td>
<td>147</td>
</tr>
<tr>
<td>400</td>
<td>0.2±0.2</td>
<td>35.9±4.7</td>
<td>5.5±1.8</td>
<td>9.3±1.1</td>
<td>59.8±2.7</td>
<td>110.8±5.8</td>
<td>17.5±0.8</td>
<td>109</td>
</tr>
</tbody>
</table>

### Considerations
- key columns here
- large systematic uncertainties on various backgrounds require ‘re-tuning’ of analysis for optimal result: DY background, W+jets ....
- need to be careful in the process to avoid biases
**Conservative Cut and Count Analysis**

Observations

exclude Higgs masses from $132 \text{ GeV} < m_H < 238 \text{ GeV}$

expected exclusion $129 \text{ GeV} < m_H < 236 \text{ GeV}$

C.Paus, MIT: Recent CMS Higgs Results
**Kinematic Variables: $\Delta \Phi_{ll}$**

Higgs at 130 GeV: signature

- small opening angle between leptons in 0 and 1 jet selection
**Kinematic Variables: $m_{ll}$**

Higgs at 130 GeV: signature
- small dilepton mass in 0 and 1 jet selection
Multi Variate Analysis Output (BDT)

Monte Carlo prediction agrees with data
**Full MVA Shape Analysis**

**Observations**

- exclude Higgs masses from $129 \text{ GeV} < m_H < 270 \text{ GeV}$
- expected exclusion $127 \text{ GeV} < m_H < 270 \text{ GeV}$
Low Mass Specialist: $H \rightarrow \gamma\gamma$

Signature and background
- two high momentum photons
- low mass Higgs narrow
- two photon resolution excellent
- looking for narrow peak
- large irreducible background from direct two photons
- smaller fake photon background

Key analysis features
- energy resolution is almost everything: calibrate and optimize
- rejection of fake photons and optimized use of kinematics
Low Mass Specialist: \( H \rightarrow \gamma\gamma \)

Data MC comparison
- only used for illustration
- general agreement
- fake/real photons about: 30%/70%
- perform analysis in optimized 4 categories
- idea: separate well measured from less well measured photons
- assume smooth background shape: no MC needed for mass fit
**Low Mass Specialist: \( H \rightarrow \gamma\gamma \)**

- **Barrel, Unconverted**
  - CMS preliminary: \( \sqrt{s} = 7 \text{ TeV} \ L = 4.76 \text{ fb}^{-1} \)
  - Data
  - Bkg Model
  - \( \pm 1 \sigma \)
  - \( \pm 2 \sigma \)

- **Endcap, Unconverted**
  - CMS preliminary: \( \sqrt{s} = 7 \text{ TeV} \ L = 4.76 \text{ fb}^{-1} \)
  - Data
  - Bkg Model
  - \( \pm 1 \sigma \)
  - \( \pm 2 \sigma \)

- **Barrel, Converted**
  - CMS preliminary: \( \sqrt{s} = 7 \text{ TeV} \ L = 4.76 \text{ fb}^{-1} \)
  - Data
  - Bkg Model
  - \( \pm 1 \sigma \)
  - \( \pm 2 \sigma \)

- **Endcap, Converted**
  - CMS preliminary: \( \sqrt{s} = 7 \text{ TeV} \ L = 4.76 \text{ fb}^{-1} \)
  - Data
  - Bkg Model
  - \( \pm 1 \sigma \)
  - \( \pm 2 \sigma \)
Low Mass Specialist: $H \rightarrow \gamma \gamma$

- most sensitive channel below 120 GeV, exclusion below 2
- no significant excess: structure at 125 GeV ~ 2.3 std (local)
- including LEE over full mass range $p$-value ~ 0.8 std
Low Mass Specialist: $H \rightarrow \gamma\gamma$

- signal strength is about consistent with the SM – a little large – as we are starting to become sensitive to it
CMS History: $H \rightarrow \gamma \gamma$

- **EPS (1.09/fb)**  
- **LP (1.66/fb)**  
- **Dec 19 (4.76/fb)**

- ‘peaks’ come and go
- of course now we are getting into interesting territory
Low Mass Special: \( H \rightarrow \tau\tau \)

Analysis telegram

- 3 categories: incl. / VBF / boosted
- VBF style most sensitive
- require 2 taus (at least one decaying leptonically)
  - \( e-\mu, \mu-\tau_h \) and \( e-\tau_h \)

Backgrounds

- top, EWK, DY (irreducible)
Search Modes in Pictures: $H \rightarrow \tau\tau$

Standard Model

Inclusive

VBF

Boosted

Minimal SuperSymmetric Model

without b-tag

with b-tag
Low Mass Special: $H \rightarrow \tau\tau$

**Full mass spectra**

- inclusive not shown (no sensitivity)
- VBF / boosted substantially reduce the background
- harder $p_T$ also improves resolution
**Low Mass Special: \(H \rightarrow \tau\tau\)**

**Observations**

- observed tracks expected sensitivity
- limit around 3 at low mass, further improvements possible
MSSM: $\Phi \rightarrow \tau\tau$

Observations

- b-tags removes main DY
- impressive improvements in exclusion plane

C.Paus, MIT: Recent CMS Higgs Results
Low Mass Special: VH → Vbb

Analysis telegram
- enormous background in $H \rightarrow bb$
- use VH with leptonic $V$ decays
- also require high momentum: ‘boosted’ analysis

Backgrounds
- $V+$jets ($Wbb$, $Wcc$), $VV$, top

Result
- limit is around 3 at low mass
- further improvements possible
The **Golden Mode**: \( H \rightarrow ZZ \rightarrow 4l \)

**Analysis telegram**
- 4 isolated high \( p_T \) leptons
- consistent with \( Z \) decays
- from same vertex
- fit mass peak with resolution: 2-4 GeV
- little background, main comes from non-resonant ZZ production, irreducible
- also \( Zbb \) and top (2l2nu2b)

**Background removal**
- leptons from \( b \)-decays are non-isolated and displaced
- require isolation and small impact parameter
**The Golden Mode: \( H \rightarrow ZZ \rightarrow 4l \)**

- **Observed events overall consistent with expectations**
  - **72 observed, expected 67.1 \( \pm 6 \)**, mild excess

C.Paus, MIT: Recent CMS Higgs Results
Low Mass: $H \rightarrow ZZ \rightarrow 4l$

Observed events overall consistent with expectations

- 13 observed, expected $9.5 \pm 1.3$, excess
- some clustering around $\sim 119$ GeV and $\sim 125$ GeV
**Low Mass: \( H \rightarrow ZZ \rightarrow 4l \)**

\[ CMS \text{ Preliminary 2011} \]
\[ \sqrt{s} = 7 \text{ TeV} \ L = 4.71 \text{ fb}^{-1} \]

\[ \rho \text{-values (at 119 GeV)} \]

- local significance is 2.5 (2.9) reduced to 1.1 (1.3) after LEE
- signal strength is about 2 ± 1 times the SM
**High Mass Special: $H \rightarrow ZZ \rightarrow 2l2\tau$**

Improved $2l\ 2\tau$ analysis

- replace $ee$ or $\mu\mu$, with $\tau\tau$, analysis sensitivity at 200 GeV at $\sim 4$
High Mass Special: $H \rightarrow ZZ \rightarrow 2l2\nu$

Analysis telegram

- same final state as our $H \rightarrow WW$, smaller production fraction
- similar issues: starts to have sensitivity at about $m_H = 350$ GeV
**High Mass: \( H \rightarrow ZZ \rightarrow 2l\ 2\text{jets (or 2b-jets)} \)**

**Analysis telegram**

- highest rate of \( H \rightarrow ZZ \) analyses
- search peak: detector ~ 10 GeV
- full scale angular analysis
- not yet excluding but getting there
CMS Higgs Result Combination

\[ H \rightarrow WW \rightarrow 2l2nu \]
\[ H \rightarrow \gamma\gamma \]
\[ H \rightarrow t\bar{t} \]
\[ H \rightarrow bb \]
\[ H \rightarrow ZZ \rightarrow 4l \]
\[ H \rightarrow ZZ \rightarrow 2l2\tau \]
\[ H \rightarrow ZZ \rightarrow 2l \, 2\text{nu} \]
\[ H \rightarrow ZZ \rightarrow 2l \, 2\text{jets} \]

ATLAS and CMS use consistent, solid, statistical methods: CLs
CMS SM Higgs Combination

Dominant channels

- 110-120 GeV $H \rightarrow \gamma\gamma$
- 120-200 GeV $H \rightarrow WW \rightarrow 2l\ 2\nu$
- 200-330 GeV $H \rightarrow ZZ \rightarrow 4l$
- 330-600 GeV $H \rightarrow ZZ \rightarrow 2l\ 2\nu$

C.Paus, MIT: Recent CMS Higgs Results
Observations

- exclude (95%): 127-600 GeV (exp. 117-583 GeV)
- exclude (99%): 129-525 GeV (exp. 128-500 GeV)
Comment

- some excess around ~124 GeV
Combined p-Value

Comments
- smallest p-value at 119 GeV: local significance 2.6 std
- global: 0.6 std in 110-600 GeV or 1.9 in 110 -145 GeV
Compare Channel by Channel

Comments
- consistent values for the cross section
- excess drivers: 119.5 GeV by 4l, 124 GeV by $\gamma\gamma$
Conclusion

Quantum leap in Higgs search in 2011: ~5/fb data
- excluded region: $127 \text{ GeV} < m_H < 600 \text{ GeV}$
- expected: $117 \text{ GeV} < m_H < 543 \text{ GeV}$
- small window left: $114.4 \text{ GeV} < m_H < 127 \text{ GeV}$

Looking beyond 95% CL $\rightarrow$ 99% CL
- 99% CL exclusion: $129 \text{ GeV} < m_H < 525 \text{ GeV}$
- search will not stop at 95% CL exclusion

Comments on low mass region
- excluded less than expected
- small excess, but inconclusive at this point
- need more data to come to a conclusion
- this year, 2012 will be the decisive one!
proton-antiproton collisions at 2 TeV
Recent update from Tevatron (Jul 17)

- new limit at 95% CL: 156 GeV – 177 GeV excluded
- mildly worse than last summer but expected limits now much more consistent with observed limit
- ‘no channel left’ behind policy implemented
More Details
Prospects Discovery – Example CMS

Indeed: the Higgs is in reach!
### Sensitivity Prospects – Summary

<table>
<thead>
<tr>
<th>ATLAS + CMS</th>
<th>95% CL exclusion</th>
<th>3σ sensitivity</th>
<th>5σ sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>≈ 2 x CMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 fb(^{-1})</td>
<td>120 - 530</td>
<td>135 - 475</td>
<td>152 - 175</td>
</tr>
<tr>
<td>2 fb(^{-1})</td>
<td>114 - 585</td>
<td>120 - 545</td>
<td>140 - 200</td>
</tr>
<tr>
<td>5 fb(^{-1})</td>
<td>114 - 600</td>
<td>114 - 600</td>
<td>128 - 482</td>
</tr>
<tr>
<td>10 fb(^{-1})</td>
<td>114 - 600</td>
<td>114 - 600</td>
<td>117 - 535</td>
</tr>
</tbody>
</table>

**Think about this**

– how likely is it that we will see a 3 standard deviation evidence by the summer?
Higgs Production at the Tevatron

Higgs production in proton-antiproton collisions

Higgs Production at the Tevatron

gg → H

qq → WH

associated production relatively big

qq → qqH

bb → H

qq → ZH

gg,qq → ttH

W, Z bremsstrahlung

C.Paus, MIT: Recent CMS Higgs Results
Final State: $WW \rightarrow 2l2\nu$

Observe 13 candidate $pp \rightarrow WW$ events

- measure cross section

- $\sigma(pp \rightarrow WW) = (41.1 \pm 15.3 \pm 5.8 \pm 4.5(L))$ pb

- main background for Higgs to $WW$

http://arxiv.org/abs/1102.5429
Experiment Status

Detectors work very well

- no show stoppers
- excellent understanding
- first measurements out
- $W, Z$ as example
- $W\gamma, Z\gamma, WW$ also out
- ways to go, but lumi is rolling in
- others dibosons will follow very soon
- should be ready to do Higgs searches
- all di-bosons by summer
A Dimuon Event, CMS

CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST

Muon $p_T = 67.3, 50.6$ GeV/c
Inv. mass $= 93.2$ GeV/c$^2$
Muons, CMS

Muons in CMS
– W/Z cross section in 36 pb$^{-1}$, extremely clean dimuons
Electrons, CMS

Electrons in CMS
- W/Z cross section in 36 pb$^{-1}$, extremely clean dielectrons