Have we found the Higgs boson yet?

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RHUL
NExT meeting – Sussex, March 14, 2012
The LHC in 2011

- data taking from mid March to end October
- pp collisions at $\sqrt{s} = 7$ TeV
- bunch spacing: 50 ns
- integrated luminosity for analysis: 4.6-4.9 fb$^{-1}$
- instantaneous luminosity x10 wrt start of year
- “low” pileup (Mar-Aug): $<\mu> \approx 6$
- significant pileup (Sep-Oct): $<\mu> \approx 12$

ATLAS $Z \rightarrow \mu\mu$ event with 20 pp interactions
(error ellipses x20 for visibility)
### SM Higgs production modes (LHC)

<table>
<thead>
<tr>
<th>Mode</th>
<th>GF – gluon fusion</th>
<th>VBF – vector boson fusion</th>
<th>WH/ZH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>- v. low rate at 7 TeV</td>
</tr>
<tr>
<td>Mechanism</td>
<td>dominant</td>
<td>not feasible in purely</td>
<td>lower</td>
<td>- large hadr. bgds.</td>
</tr>
<tr>
<td></td>
<td>mechanism</td>
<td>hadronic final states</td>
<td>prod.</td>
<td>- not targeted at 7 TeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>rate</td>
<td>+ bgd supression with</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>b-tagging, leptons,</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Etmiss, mass</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>constraints</td>
</tr>
</tbody>
</table>

- ~10% rate
- + discriminating feature: 2 “tag-jets”
- + background suppression using W/Z leptons and/or missing energy (Etmiss)
- large hadr. bgds.
- not targeted at 7 TeV
- bgd supression with b-tagging, leptons, Etmiss, mass constraints
SM Higgs production at the LHC and decay

LHC SM Higgs production cross sections, $\sigma$

Prod x Decay: $\sigma \times \text{BR}$

Theoretical uncertainties (QCD scales, PDFs, $\alpha_s$): from < 5% (VBF, VH) to 10-15% (GF, ttH)
A little (recent) history...

• December 2011: CERN Higgs seminars
• ATLAS and CMS publications at the end of January 2012
• ATLAS and CMS results updated for Moriond 2012
• Many (>20!) ATLAS and CMS publications on 2011 data
• TeVatron: full dataset results released for Moriond 2012
### ATLAS and CMS Higgs searches

#### ATLAS

<table>
<thead>
<tr>
<th>Channel</th>
<th>$m_H$ range (GeV)</th>
<th>Backgrounds</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>low-$m_H$, good mass resolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>110-150</td>
<td>$\gamma\gamma, \gamma\gamma, J\ell$</td>
<td>4.9</td>
<td>arXiv:1202.1414</td>
</tr>
<tr>
<td>$H \to ZZ^{(*)} \to 4\ell$</td>
<td>110-600</td>
<td>$ZZ^{(*)}, Z + \text{jets}, t\bar{t}$</td>
<td>4.8</td>
<td>arXiv:1202.1415</td>
</tr>
<tr>
<td>low-$m_H$, limited mass resolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \to WW^{(*)} \to \ell\nu\ell\nu$</td>
<td>110-600</td>
<td>$WW, t\bar{t}, W/Z + \text{jet}$</td>
<td>4.7</td>
<td>CONF-2012-012</td>
</tr>
<tr>
<td>$H \to \tau\tau(ll, lh, hh)$</td>
<td>100-150</td>
<td>$Z \to \tau\tau, t\bar{t}$</td>
<td>4.7</td>
<td>CONF-2012-014</td>
</tr>
<tr>
<td>$VH, H \to bb$</td>
<td>110-130</td>
<td>$W/Z + \text{jets}, t\bar{t}$</td>
<td>4.7</td>
<td>CONF-2012-015</td>
</tr>
<tr>
<td>high-$m_H$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H \to ZZ \to \ell\nu\ell\nu$</td>
<td>200-600</td>
<td>$\text{diboson}, t\bar{t}, Z + \text{jets}$</td>
<td>4.7</td>
<td>CONF-2012-016</td>
</tr>
<tr>
<td>$H \to ZZ \to \ell\ell\ell\ell$</td>
<td>200-600</td>
<td>$Z + \text{jets}, t\bar{t}, \text{diboson}$</td>
<td>4.7</td>
<td>CONF-2012-017</td>
</tr>
<tr>
<td>$H \to WW \to \ell\nu\ell\nu$</td>
<td>300-600</td>
<td>$W + \text{jets}, t\bar{t}, \text{multijets}$</td>
<td>4.7</td>
<td>CONF-2012-018</td>
</tr>
</tbody>
</table>

#### CMS

<table>
<thead>
<tr>
<th>Channel</th>
<th>$m_H$ range (GeV)</th>
<th>Luminosity (fb$^{-1}$)</th>
<th>Sub-channels</th>
<th>$m_H$ resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>new $H \to \gamma\gamma$</td>
<td>110–150</td>
<td>4.8</td>
<td>2</td>
<td>1–2%</td>
</tr>
<tr>
<td>new $H \to \tau\tau \to e\nu_{\tau}/\mu\nu_{\tau}/e\mu + X$</td>
<td>110–145</td>
<td>4.6</td>
<td>9</td>
<td>20%</td>
</tr>
<tr>
<td>new $H \to \tau\tau \to \mu\mu + X$</td>
<td>110–140</td>
<td>4.5</td>
<td>3</td>
<td>20%</td>
</tr>
<tr>
<td>new $WH \to e\nu_{\tau}/\mu\nu_{\tau} + \nu's$</td>
<td>100–140</td>
<td>4.7</td>
<td>2</td>
<td>20%</td>
</tr>
<tr>
<td>(W/Z)H $\to (e\nu/\mu\nu/ee/\mu\mu/\nu\nu)(bb)$</td>
<td>110–135</td>
<td>4.7</td>
<td>5</td>
<td>10%</td>
</tr>
<tr>
<td>$H \to WW^{(*)} \to 2\ell2\nu$</td>
<td>110–600</td>
<td>4.6</td>
<td>5</td>
<td>20%</td>
</tr>
<tr>
<td>new $WH \to W(WW^{(*)}) \to 3\ell3\nu$</td>
<td>110–200</td>
<td>4.6</td>
<td>1</td>
<td>20%</td>
</tr>
<tr>
<td>$H \to ZZ^{(*)} \to 4\ell$</td>
<td>110–600</td>
<td>4.7</td>
<td>3</td>
<td>1–2%</td>
</tr>
<tr>
<td>{ $H \to ZZ^{(*)} \to 2\ell2q$</td>
<td>130–164</td>
<td>4.6</td>
<td>6</td>
<td>3%</td>
</tr>
<tr>
<td>$H \to ZZ \to 2\ell2\tau$</td>
<td>190–600</td>
<td>4.7</td>
<td>8</td>
<td>10–15%</td>
</tr>
<tr>
<td>$H \to ZZ \to 2\ell2\nu$</td>
<td>250–600</td>
<td>4.6</td>
<td>2</td>
<td>7%</td>
</tr>
</tbody>
</table>
Sensitivity of SM Higgs searches

Expected 95% CL exclusion limits on $\sigma/\sigma_{\text{SM}}$

Sensitivity depends on integrated luminosity, production cross-section, decay branching fractions, selection efficiency, and background levels.

Most sensitive channels are:
- Low mass (eg for $m_H=125$ GeV): $H-\gamma\gamma$, $H-ZZ-4\ell$, $H-WW-\ell\nu\ell\nu$
- High mass: single most sensitive channel is $H-ZZ-\ell\ell\nu\nu$

95%CL exclusion sensitivity is not same as discovery sensitivity... but close enough.
H → γγ

- small branching ratio ~ 1 – 2 x 10^{-3}
- 110 ≤ m_H ≤ 150 GeV
- clear signature: two high p_T isolated photons
- excellent m_{γγ} mass resolution: 1-3%
- continuum backgrounds:
  - irreducible γγ QCD
  - reducible γj, jj, ee Drell-Yan
- very good γ–jet separation needed

- both experiments categorise events in many sub-classes, for improved sensitivity

- CMS targets VBF explicitly (γγ + 2 fwd-bwd jets), ATLAS does this less directly
H → γγ candidate events

Two photons (both unconverted)
\( m_{γγ} = 126.6 \text{ GeV} \)

VBF candidate!
\( m_{γγ} = 121.9 \text{ GeV} \)
H$\rightarrow\gamma\gamma$ results: 95%CL exclusion limits

Excess of events in ATLAS and CMS around $m_{\gamma\gamma} \approx 125 - 126.5$ GeV

CMS also sees a smaller excess at $m_{\gamma\gamma} \approx 136$ GeV

Compare event selection:

- Cut-based
- Multi-Variate Analysis (BDT)
Quantifying the significance of an excess

$p_0$ is the probability that a background-only experiment is more signal-like than observed in data (local $p_0$ value: for a given $m_H$ hypothesis)

$\gg p_0$ probabilities can easily be converted into standard deviations (significance)

The global $p_0$ is the probability that a background only-experiment would produce a local significance more signal-like than observed anywhere in the search region

$\gg$ this so-called Look Elsewhere Effect (LEE) reduces the local significance.
$H \rightarrow \gamma\gamma$ results: quantifying excesses

$p_0$ value plots

Maximum significances near 125 GeV:

<table>
<thead>
<tr>
<th></th>
<th>Local signif.</th>
<th>Global signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>2.8σ</td>
<td>1.5σ</td>
</tr>
<tr>
<td>CMS</td>
<td>2.9σ</td>
<td>1.6σ</td>
</tr>
</tbody>
</table>

(LEE effect evaluated in $110 < m_H < 150$ GeV search region)
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ (4e, 2e2\mu, 4\mu)

- small branching ratio: between 1\% and 1%
- $100 < m_H < 600$ GeV
- excellent mass resolution, $m_{4\ell}$: $\approx$ 1-2%
- very clear signature: 2 high mass isolated ee/\mu\mu pairs
- high lepton (e/\mu) id, down to low $p_T = 7$ GeV
- backgrounds: irreducible: ZZ reducible: Z+jets, Zbb, tt, WZ

[Graph showing data and distributions related to Higgs boson decay]

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Excesses seen at $m_H = 125$ GeV (2.1σ), 244 GeV (2.2σ) and 500 GeV (2.1σ) (local significances)

“Once the look-elsewhere effect is considered, none of these excesses are significant.”
Largest excess seen at $m_H = 119.5$ GeV: local significance 2.5 $\sigma$

Look elsewhere effect in 110-160 GeV, reduces this to a global significance of 1.6 $\sigma$
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ candidate events

$2e2\mu$: $m_{4\ell} = 124.3$ GeV  
$m_{12} = 76.8$ GeV; $m_{34} = 30.0$ GeV

$4\mu$: $m_{4\ell} = 119$ GeV  
$m_{Z1} = 90$ GeV; $m_{Z2} = 25$ GeV
$H \rightarrow WW(*) \rightarrow \ell\nu\ell\nu$

- most sensitive channel in $125 < m_H < 200$ GeV
- $110 < m_H < 600$ GeV
- however: limited mass resolution, can’t reconstruct $m_H$ fully (as $2\nu$ emitted)
- signature: 2 high $p_T$ isolated leptons + missing transverse energy
- main backgrounds:
  - irreducible: $WW$
  - reducible: $Z+$jets, $WZ$, $ZZ$, $tt$, $W+$jets
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$

- **No significant excesses** seen by either ATLAS or CMS in latest analyses.

- **ATLAS result in Dec. 2011** (based on 2.1 fb$^{-1}$) was 1.4$\sigma$ broad excess, consistent with 1.4$\sigma$ SM Higgs expectation.

- This result has in the meantime been updated to the full dataset (4.7 fb$^{-1}$), a new H+2-jet (VFB) category has been added, and $m_T$ discriminant is now used (cf sliding window).

  $\Rightarrow$ Sensitivity improved by 15%.

- the data in this channel are now more consistent with the background-only scenario (0.2 $\sigma$)
Additional searches

In low-\(m_H\) region (100 < \(m_H\) < 160 GeV)

- \(H \rightarrow \tau\tau (\ell\ell, \ell\tau_{h}, \tau_h\tau_h)\)
- \(WH (H \rightarrow \tau\tau) \rightarrow e\mu\tau_h/\mu\mu\tau_h + \nu's\) (CMS only)
- \(VH (H \rightarrow bb) \rightarrow bb\ell\nu, bb\ell\ell, bb\nu\nu\)
- \(WH (H \rightarrow WW^{(*)}) \rightarrow 3\ell3\nu\) (CMS only)
Additional searches

In high-mH region

• $H \to ZZ \to \ell\ell\nu\nu$

• $H \to ZZ \to \ell\ell\tau\tau$ (CMS only)

• $H \to ZZ \to \ell\ell jj$

• $H \to WW \to \ell\nu jj$
Combinations: putting it all together...

March 2012: TWO *separate* combinations: ATLAS combination and CMS combination
SM Higgs Exclusion limits

95% CL exclusion:

- **ATLAS**
  - 110.0 – 117.5, 118.5 – 122.5, 129 – 539 GeV
  - (120 – 555 GeV expected)

- **CMS**
  - 127.5 – 600 GeV
  - (114.5 – 543 GeV expected)

99% CL exclusion:

- **ATLAS**
  - 130 – 486 GeV

- **CMS**
  - 129 – 525 GeV
Incompatibility with background-only hypothesis

**ATLAS:**
Maximum observed local significance is 2.5$\sigma$, observed at $m_h=126.5$ GeV

**CMS:**
Maximum observed local significance is 2.8$\sigma$, observed at $m_h=125$ GeV
Compatibility with SM Higgs signal?

• Best-fit Higgs signal strength, $\mu = \sigma/\sigma_{SM}$.
• Scale all channels coherently at every $m_H$.

Data from both ATLAS and CMS are consistent with a SM Higgs boson with $m_H \approx 125$ GeV
LHC Plans for 2012

• Increase $\sqrt{s} = 8$ TeV

• 50 ns bunch spacing

• instantaneous luminosity up to $7 \times 10^{33}$ cm$^{-2}$s$^{-1}$ (double the maximum in 2011 – expect even more pileup)

• Deliver 7 fb$^{-1}$ data to each GPD for summer conferences?... And 15-20 fb$^{-1}$ by the end of the year?

• 18 month shutdown starts November 2012 (preparation for higher lumi and $\sqrt{s}=13-14$ TeV)
Beyond the SM: fermiophobic Higgs

ATLAS: $H \rightarrow \gamma\gamma$

CMS: $H \rightarrow \gamma\gamma$, WW and ZZ
Beyond the SM: MSSM

Large $\tan \beta$: enhanced Higgs couplings to $b/\tau$

+ increased production rates (via $b$-loops in GF, and also $bb$ production)
+ Use $H \to \tau\tau$ searches
Conclusion

• very exciting 2011 – the most exciting it’s been in over a decade
• hints of a possible signal
• we are in a very good position this time (unlike last time...): should be able to settle low mass SM Higgs (either signal at 125, or elsewhere...) this year
• looking forward to an exciting 2012!
• Thanks to Moriond LHC speakers (S Kortner, M Pieri, S Dasu) and colleagues in ATLAS/CMS
Backup slides
TeVatron Run II Preliminary, $L \leq 10$ fb$^{-1}$
TeVatron

Tevatron RunII Preliminary
SM Higgs, $L_{int} \leq 10.0$ fb$^{-1}$

Background p-value

Tevatron RunII Preliminary
$L_{int} \leq 10.0$ fb$^{-1}$

Best Fit

$\pm 1$ s.d.

Feb 24 2012