LHC Higgs

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On behalf of the
ATLAS and CMS collaborations

Grenoble
27th July 2011

- What is LHC sensitive to?
- Are there any hints?
First: thanks to LHC people!

- ATLAS and CMS asked for $1\text{fb}^{-1}$ for this meeting

- Steve and all his friends delivered – and more
- Most of it in June
- We have only started digesting this rich meal
Outline

• SUSY Higgs searches
  • 5 Higgs bosons to look for...
  • $H^+ \rightarrow \tau\nu$
  • $H^+ \rightarrow cs$
  • $A/H \rightarrow \tau\tau$

• Standard Model searches
  • Low mass (110-130 GeV)
  • Moderate mass (130-200 GeV)
  • High mass (200 GeV+)
  • Combination
MSSM: Multiple Higgses

Peter visiting LHC, CMS and ATLAS
Charged Higgs to $\tau\nu$

- CMS search for top to $H^+b$, $H^+ \to \tau\nu$ for $1\text{fb}^{-1}$
- Background is mostly $t \to W+b$

No evidence so far
- Limits $\text{BR}(t-H+b) \sim 4\%$
- Far surpassing previous results
**Charged Higgs to cs**

- ATLAS searched for top to $H^+b$, $H^+$ to quarks
- Background is mostly $t \rightarrow W+b$

**No sign was seen in 2010**

- Limits ~20% level; similar to Tevatron results
H/A → ττ

- $\Phi \rightarrow \tau\tau$ 2011 CMS
- $e\mu$, $\mu\tau_h$, $e\tau_h$
- Inclusive, b-tag, VBF
- Very nice results

**Exclusion of very large area**
- Note $H^+$ limit added
The guaranteed discovery?
Electroweak data compatible with the Standard Model
- $m_W$ is a triumph!
- Prefers $m_H < \text{Tevatron range}$

But...it assumes SM is whole story
- This is not well justified
- We know SM is incomplete
  - Gravity? Dark matter? ...
- Take this with a pinch of salt

ATLAS & CMS search over a wide range...
Tevatron results

Tevatron Run II Preliminary, $L \leq 8.6 \text{ fb}^{-1}$

95% CL Limit/SM

LEP Exclusion

- Expected
- Observed
- $\pm 1\sigma$ Expected
- $\pm 2\sigma$ Expected

Tevatron Exclusion

$m_H (\text{GeV}/c^2)$

July 17, 2011
LHC Higgs production

- Higgs cross-sections for gluon fusion
  - LHC
  - TeVatron

- Gluon fusion at least 10x higher cross-section

- Backgrounds to WW, ZZ, γγ are qq annihilation
  - s/b better in these channels than Tevatron
  - But it is worse in associated modes

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections
Higgs cross-sections

- $H \rightarrow ZZ$
  - $ZZ \rightarrow llll$: Golden mode
  - $ZZ \rightarrow llvv$: Good High mass
  - $ZZ \rightarrow llbb$: Also high-mass
- $H \rightarrow WW$
  - $WW \rightarrow lvlv$: Most sensitive
  - $WW \rightarrow lvqq$: highest rate
- $H \rightarrow yy$
  - Rare, best for low mass
- $H \rightarrow \tau\tau$
  - Good s/b, low mass, rare
- $H \rightarrow bb$
  - $ttH$, $WH$, $ZH$ useful but hard

$\sqrt{s} = 7$ TeV

$\sigma \times BR$ [pb]
## Channels used

<table>
<thead>
<tr>
<th>H decay mode</th>
<th>ATLAS</th>
<th>CMS</th>
<th>Tevatron</th>
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<td>$l\nu H, l\bar{H}, u\bar{u} H$</td>
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<td>0jet, 1 jet, VBF</td>
<td>0j / 1j / 2j / 1l</td>
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<td>--</td>
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</table>
Channels reviewed (ATLAS)

ATLAS Preliminary $\int L\,dt \sim 1.0\text{ to } 1.2\,fb^{-1}, \sqrt{s}=7\,\text{TeV}$ CLs limits
Channels reviewed
Low mass searches

ATLAS Preliminary \( \int L \, dt \sim 1.0-1.2 \, fb^{-1}, \sqrt{s}=7 \, TeV \) CLs limits

yy region, (plus \( \tau \tau \), bb)
VH, \( H \rightarrow bb \)

- \( H \rightarrow bb \) is dominant decay mode for light Higgs
  - But very hard to do due to huge \( bb \) backgrounds
  - ATLAS tried WH and ZH modes inclusively:

**Note signal increased by factor 20**

VH, $H \rightarrow bb$

- Top and $Wjj/Wbb$ backgrounds fitted to data
  - Shapes from simulation
  - Sensitivity is $\sim 15\times$SM

**Subset analysis should help**
- $W+$'fatjet' studies suggest $W$ to $qq$ from $tt \rightarrow WbWb$ seen
- Ready to search for $H$ to $bb$
CMS showed 2011 SM results
Including VBF search
  - With a beautiful picture
    - μ-τ candidate
    - Two forward jets
      - Mass 580 GeV
    - Little central activity
  - Looks just as advertised
  - e-μ, μ-μ, μ-τ, e-τ channels studied
Details are here:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig11009TWiki
H → ττ results

- e-μ VBF channel (left) is cleanest
  - Mass calculation can improve

- Limits around 9xSM
  - At 115-125 (where we need this most)
Rare decay
110 < m_H < 150
Tough ECAL requirements
- Mass resolution tested in Z → ee
- Need vertex position too
- Pileup!

Good jet rejection also essential
Photon resolution verified using the Z peak
Different e/γ response in MC largest systematic uncertainty
Higgs mass resolution

- No good calibration in data
  - Until we find Higgs!
  - Has to be simulated

- ATLAS (black) and CMS (blue) compared

![Graphs showing Higgs mass resolution comparison between ATLAS and CMS, with parameters and fit values.](image-url)
**H → γ γ**

- Invariant mass spectra similar
  - Real $γγ$ events dominant for both experiments
  - Fit to this spectrum, looking for sharp peak
  - Both divide events into quality categories
H → yy limits

ATLAS (left) and CMS (right) results similar

Expected limits 3-4 x SM strength
- Observed fluctuates down to 2..
- Closing in even here, the hardest place for LHC
Intermediate searches

ATLAS Preliminary

$\int L \, dt \sim 1.0-1.2 \, fb^{-1}, \sqrt{s}=7 \, TeV$ CLs limits

$WW \rightarrow lluu$ region (Plus $ZZ \rightarrow llll$)

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

$H \rightarrow \gamma\gamma$

$H \rightarrow WW \rightarrow llvv$

$W/Z, H, H \rightarrow bb$

$H \rightarrow ZZ \rightarrow llqq$

$H \rightarrow ZZ \rightarrow llvv$

$H \rightarrow WW \rightarrow llqq$
WW → ℓνℓν

The most sensitive channel for 130<m_H<200
  - Here is where the excess comes
  - But poor mass information due to neutrinos

Good trigger, reasonable rate
  - Largest background is non-resonant WW
    - Also top when looking at WW+1 jet
  - Backgrounds measured from control regions

Request two leptons

Require missing E_T (E_T^{rel}) and p_T(II) for WW

Select signal area with Δφ and m_∥ selections
  - CMS using cut-based and multivariate
  - ATLAS prefers cut-based at this stage.
**WW → ℓνℓν**

- **Missing $E_T$**
  - Vital tool against Z+jets events
  - Costs in signal rate
  - Rate of backgrounds here measured in data
$m_{ll}$ in $WW \rightarrow lvlv$

- Top: CMS
  - $p_T$, $m_{ll}$, $\Delta \Phi_{ll}$, $m_T$
  - Uncut

- Bottom: ATLAS
  - $m_{ll}$, $\Delta \Phi_{ll}$, $m_T$
  - Uncut

- Excess?
  - ATLAS and CMS
  - 1-jet

- Largest?
ATLAS WW → ℓνℓν

Final $m_T$ for ATLAS events
- A window here 25% $m_H$ wide selects final events
- Some tendency for events to be same flavour
CMS WW → ℓνℓν

- Final analysis plots:
  - Boosted decision trees
  - Top 0jet, bottom 1-jet
  - Left: ℓµ
  - Right: ee/µµ
  - Windows here select candidates

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**ATLAS** Preliminary

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

- Observed
- Expected

\[ \int L dt = 1.04 \text{ fb}^{-1} \]

$\sqrt{s} = 7 \text{ TeV}$

**CMS** Preliminary, $\sqrt{s} = 7 \text{ TeV}$

$H \rightarrow WW$ combined, $L_{\text{int}} = 1.09 \text{ fb}^{-1}$

- CL$_S$ limit $\sigma_{95\%}/\sigma_{\text{SM}}$

**ATLAS** (left) exclude $m_H = 158-186$ (exp: 142-186)

**CMS** (right) exclude: $m_H = 150-193$ (exp: 130-200)
**WW → ℓνℓν**

**ATLAS Preliminary**

- Observed
- Expected

\[ \int L dt = 1.04 \text{ fb}^{-1} \]

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

95% CL Limit on \( \sigma / \sigma_{\text{SM}} \)

- ± 1σ
- ± 2σ

**Focus on same region:**

- ATLAS (left) exclude \( m_H \) 158-186 (exp: 142-186)
- CMS (right) exclude: \( m_H \) 150-193 (exp: 130-200)
CMS and ATLAS have excess 110-160 GeV
- Compatible with signal $120 < m_H < 150$
- Best match at about 140
High mass searches

\[ \int L \, dt \sim 1.0 - 1.2 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \]

**ATLAS** Preliminary

**ZZ → llll, ZZ → lluu** (plus ZZ → llqq, WW → llqq)

**m_H [GeV]**
WW → lνqq

- Largest Higgs BR for high mass
- Presence of charged lepton gives good QCD rejection
- But, like in tt, semileptonic mode allows mass reconstruction
- Suffers from LARGE background from W+jets
  - But smooth background
  - Signal is a bump
  - Analysis is relatively straightforward
$WW \to lvqq$

- $M_{lvqq}$ raw (left) and background-subtracted (right)
- Sum over the 0 and 1 extra jet searches
WW → lνqq

- Sensitive to five to ten times SM cross-section
- Limits 'lucky' around 400GeV
- Exclude 2xSM
- No excess anywhere

ATLAS Preliminary

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

\[ \int L \, dt = 1.04 \text{ fb}^{-1} \]

Expected
\[ \pm 1\sigma \]
\[ \pm 2\sigma \]

Observed
Clean decay,
- All leptonic
Higher rate than $\text{llll}$
- $Z \to \nu\nu$ seen through missing energy
  - Only if $Z$ moves
- $m_H > 200\text{GeV}$
Needs good MET
- CMS excellent description of $Z$s

$ZZ \to ll\nu\nu$
**ATLAS** (left) and CMS (right)

- Harder $E_T^{\text{miss}}$ and $\delta \phi$ cuts at high mass
- 380 GeV is excluded by left figure alone!
**ZZ → llvv**

- ATLAS (left) and CMS (right)
- ATLAS excludes 360 to 440 GeV – just!
- Both searches best sensitivity 1-2xSM
  - Both got lucky
**ZZ → llqq**

- Highest rate for a ZZ process
  - Good for Higgs boson mass over 200GeV
- Use 2/3 subchannels:
  - Z to light quarks (inclusively)
  - CMS use quark/gluon tagging to enhance signal
  - Z to b quarks
- CMS use decay angles explicitly

![Graphs showing ZZ mass distributions](image)
CMS sensitivity 2xSM, ATLAS 3xSM at 350-400
Fluctuations never up to 2σ
Require 4 identified leptons
- Backgrounds already rather low
At least one pair compatible with Z peak
- For $m_H < 180\text{GeV}$ one will be off-shell
- At higher masses require both compatible.

Background from:
- $Z\bar{b}b$ can produce two leptons from the $b$ decay
- $t\bar{t}\rightarrow l\nu b l\nu b$ can give the same issue

So suppress:
- $b$ quarks with impact parameters cuts
- Fakes with isolation

Background largely genuine $ZZ(*)$
Both experiments collect a few too many events
ATLAS near 245, CMS below 180
$Z Z^* \rightarrow \mu \mu \mu \mu \mu \mu \mu$ candidate

$M_{12} = 90.6 \text{GeV}$
$M_{34} = 47.4 \text{GeV}$
$M_{zz} = 143 \text{GeV}$
$ZZ^{(*)} \rightarrow \ell\ell\ell\ell$

**CMS (just) excludes SM at 195; ATLAS not there**

Small excess visible near 140
The SM Higgs is a very well-defined thing
- Tell us the mass and we know the rest
- So we know what to expect in all these channels
  - We put them together for optimal sensitivity.

Needs precise understanding of the theory
- LHC cross-section working group did a great job
- We have an agreed set of rates to work with

So what do the combinations look like?
ATLAS & CMS limits

Sensitivities differ in detail
But on average similar

**ATLAS Preliminary**
- Observed CLs
- Expected

\[ \int Ldt = 1.0-1.2 \text{ fb}^{-1} \]

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

Exclude
- 155-190 GeV
- 295-450 GeV

\[ \pm 1\sigma \]
\[ \pm 2\sigma \]

**CMS Preliminary, \( \sqrt{s} = 7 \text{ TeV} \)**
- Combined, \( L_{\text{int}} = 1.1 \text{ fb}^{-1} \)

Exclude
- 149-206 GeV
- 270-290 GeV
- 300-440 GeV

Limit on \( \sigma_{95\%}/\sigma_{\text{SM}} \)

**Higgs boson mass (GeV/c^2)**

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W.Murray
I personally conclude
155-206 & 270-450 GeV
- Nearly half the plot excluded already!
- Hints of excesses in all 3 free regions
- Interesting times!
Tevatron Run II Preliminary, $L \leq 8.6$ fb$^{-1}$

LEP Exclusion

Tevatron Exclusion

95% CL Limit/SM

$10^0$

$11$

$m_H (GeV/c^2)$

$m_H [GeV]$
Tevatron Run II Preliminary, $L \leq 8.6 \text{ fb}^{-1}$

LEP Exclusion

- Expected
- Observed
- $\pm 1\sigma$ Expected
- $\pm 2\sigma$ Expected

Tevatron Exclusion

$95\%$ CL Limit/SM

$m_H (\text{GeV/c}^2)$ vs. $m_H [\text{GeV}]$

July 17, 2011
Combined p-value

- Fraction of time background fluctuates so far
- Beware: there is a look 'elsewhere effect'
- Both experiments have excess at low mass
P-values compared

Some correlated uncertainties

Look-elsewhere effect important

High-mass excesses not corroborated
P-values at low mass

Some correlated uncertainties

Look-elsewhere effect important
The combination of results is complex
- Fits with over 100 parameters are running
  - But are not ready for this meeting
  - Beware. There is **NONSENSE** even on CERN WWW pages
- The limits have large common systematic errors
  - Especially on signal cross-section
- The WW analyses driving excess have similar modeling in both groups
- LHC-HCG will provide update as soon as possible

**Stay Tuned**
Where do we go from here?

- More data!
  - The universal cry
    - It is coming fast
  - A month might double dataset?
- Better analysis
  - Many possible improvements
  - Unlikely to be conclusive

- LHC combination
  - Will allow to test compatibility of datasets
  - Many possibilities will be excluded soon
Summary

With 1fb$^{-1}$ the LHC dominates the SM Higgs

We exclude
- 155-190GeV and 295-450GeV (ATLAS)
- 149-206GeV and 300-440GeV (CMS)
- 155-206GeV and 295-450 GeV (Very Safe)

LHC combination will exclude much more

Interesting hints emerge
- e.g. 144GeV $\sim 2.9\sigma$ in both experiments
- Minutes of LEPC 56$^{th}$ meeting (3$^{rd}$ Nov. 2000):
  `The committee noted that there is unfortunately no single channel that is background-free.'
Celebration

ATLAS and CMS Higgs toasting getting to EPS
Backup
H → yy: Any excess?

ATLAS (left) and CMS (right) results similar
Small excess at 119, 128 and 138.
  - But they contradict each other
  - Entirely normal background fluctuations
Z plus jets shows well-controlled $E_T$ miss
**WW → lvlv**

- Event rates numerically

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>Lepton Flavors</th>
<th>Nominal</th>
<th>$\mu = 0$</th>
<th>$\mu = 1$</th>
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<tbody>
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<td>Total Bkg.</td>
<td>Signal</td>
<td>Total Bkg.</td>
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</table>

**Event Rates**
Higgs sensitivity vs $E_{CMS}$

8TeV: Need only 80% as much data
  Less for a high mass Higgs boson
9TeV 60% of data suffices
Sensitivity of Higgs search

ATLAS Preliminary (Simulation)

- $5 \sigma \sqrt{s}=8$ TeV
- $3 \sigma \sqrt{s}=8$ TeV
- $95\%$ CL $\sqrt{s}=8$ TeV

5 fb$^{-1}$ at 8 TeV gives 3$\sigma$ for 114 to >500 GeV

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Effect of raising $E_{CMS}$

ratios of gluon-gluon luminosities: 8 TeV / 7 TeV and 9 TeV / 7 TeV
(i.e. increase in production rate)

8 TeV: 10% to factor 4 increases
  - Doubled for 9 TeV
  - Higgs increased by 30% 😞

Thanks to James Stirling
E-W symmetry breaking

\[ SU(3) \times SU(2) \times U(1) \]

- This gauge symmetry predicts \( \gamma, W, Z, \) gluons
  - Requires them to be massless
- Symmetry breaking is needed for masses
Why do we need the Higgs?

Fermions

- families, with leptons
  \[ \nu_L, \nu_R, e_R \]
- and quarks
  \[ u_L, u_R, d_R \]

Gauge Symmetries

\[
\begin{align*}
\text{U}(1)_Y: & \quad \psi(x) &\rightarrow& \exp \left[ i \frac{g'}{2} Y_\psi \omega(x) \right] \psi(x) \\
\text{SU}(2)_L: & \quad \psi_L(x) &\rightarrow& \exp \left[ i \frac{g}{2} \vec{\sigma} \cdot \vec{\theta}(x) \right] \psi_L(x) \\
\text{SU}(3)_C: & \quad \psi_q(x) &\rightarrow& \exp \left[ i \frac{g_s}{2} \lambda_a \theta^a(x) \right] \psi_q(x)
\end{align*}
\]

Bosons, Interactions

- \( \gamma: \) QED
- \( \mathcal{Z}, W^\pm: \) Weak
- \( \tan \theta_W = \frac{g'}{g} \) gluons: QCD

A mass term couples L & R and would violate SU(2)_L

Solution: The Higgs mechanism

Thanks: P. Janot

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What is Higgs' mechanism?

- Doublet of $SU(2)_L$, $\Phi=(\Phi_1,\Phi_2)$
- Potential respects $SU(2)_L$
  But Vacuum does not!

**Fermions:**
Interact with Higgs field
slows them down $\rightarrow$
genерates mass

**Bosons:**
$SU(2)_L$ interact, gain mass
$U(1)_Y$ and $SU(3)_c$ do not, massless

$$V(\Phi) = \frac{\lambda}{3!} \left( \overline{\Phi} \Phi - v^2 / 2 \right)^2$$

3 degrees of freedom in Boson masses
$4^{th}$ becomes fundamental scalar