Search for the SM Higgs boson at LHC

Patricia Lobelle Pardo
(Universidad de Cantabria)

On behalf of the ATLAS and CMS collaborations

XVII International Conference on Deep-Inelastic Scattering and Related Subjects
DIS09, 26\textsuperscript{th}-30\textsuperscript{th} April 2009, Madrid
Higgs current limits

• **Theoretical limits**
  Finite and positive Higgs couplings

• **Experimental limits**
  - **LEP**: $m_H > 114.4 \text{ GeV/c}^2$ at 95% CL
  - **Tevatron**: Excluded the mass range of \(160 \text{ GeV/c}^2\) to \(170 \text{ GeV/c}^2\) at 95%CL

• **Indirect constraints**
  Derived from precise EWK measurements:
  
  $m_H = 90^{+36}_{-27} \text{ GeV/c}^2$
  
  ($m_H < 163 \text{ GeV/c}^2$)  ($m_H < 191 \text{ GeV/c}^2$ if including LEP2 results)

A light Higgs is favoured by measurements

28/04/09 DIS09 Madrid P.Lobelle (U.Cantabria)
SM Higgs production at LHC

- **Gluon-gluon fusion: dominant mode at LHC**

  ![Gluon-gluon fusion diagram]

- **Vector Boson Fusion**

  ![Vector Boson Fusion diagram]

- **Associated production**

  ![Associated production diagram]

\[\sigma(pp \rightarrow H+X)\]
\[\sqrt{s} = 14 \text{ TeV}\]
\[m_t = 175 \text{ GeV}\]

CTEQ4M

- M. Spira et al.
- NLO QCD

28/04/09 DIS09 Madrid

P. Lobelle (U.Cantabria)
SM Higgs decays

At Low mass \( (m_H<2m_Z) \)

- \( H \rightarrow bb \): BR \( \sim 0.85 \) but huge QCD background
- \( H \rightarrow \tau\tau \): accessible through VBF
- \( H \rightarrow \gamma\gamma \): very important despite the low BR \( \sim 0.002 \) due to the excellent \( \gamma/jet \) separation and \( \gamma \) resolution
- \( H \rightarrow WW^* \rightarrow 2l2\nu \): accessible through gg fusion and VBF, BR \( \sim 1 \) at \( m_H \sim 160 \) GeV/c\(^2\)
- \( H \rightarrow ZZ^* \rightarrow 4l \): also performant

For Higher masses

\( H \rightarrow WW^* \rightarrow 2l2\nu \) and \( H \rightarrow ZZ^* \rightarrow 4l \)

P.Lobelle (U.Cantabria)
# ATLAS and CMS

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>2T solenoid + toroid (0.5T barrel 1T endcap)</td>
<td>4T solenoid + return yoke</td>
</tr>
<tr>
<td>Tracker</td>
<td>Si pixels, strips + TRT</td>
<td>Si pixels, strips</td>
</tr>
<tr>
<td></td>
<td>$\sigma/p_T \approx 5 \times 10^{-4} p_T + 0.01$</td>
<td>$\sigma/p_T \approx 1.5 \times 10^{-4} p_T + 0.005$</td>
</tr>
<tr>
<td>EM calorimeter</td>
<td>Pb+LAr</td>
<td>PbWO4 crystals</td>
</tr>
<tr>
<td></td>
<td>$\sigma/E \approx 10%/\sqrt{E} + 0.007$</td>
<td>$\sigma/E \approx 2%-5%/\sqrt{E} + 0.005$</td>
</tr>
<tr>
<td>Hadronic</td>
<td>Fe+scint. / Cu+LAr (10\lambda)</td>
<td>Cu+scintillator (5.8\lambda + catcher)</td>
</tr>
<tr>
<td>calorimeter</td>
<td>$\sigma/E \approx 50%/\sqrt{E} + 0.03$ GeV</td>
<td>$\sigma/E \approx 100%/\sqrt{E} + 0.05$ GeV</td>
</tr>
<tr>
<td>Muon</td>
<td>$\sigma/p_T \approx 2% @ 50$ GeV to 10% @ 1$\text{TeV}$ (ID+MS)</td>
<td>$\sigma/p_T \approx 1% @ 50$ GeV to 5% @ 1$\text{TeV}$ (ID+MS)</td>
</tr>
<tr>
<td>Trigger</td>
<td>L1 + Rol-based HLT (L2+EF)</td>
<td>L1+HLT (L2 + L3)</td>
</tr>
</tbody>
</table>
State of the art

• Better detector description and simulation: geometry, material budget, Geant4

• New approaches to match parton showers and matrix elements (ALPGEN + MLM matching, SHERPA etc.)

• New (N)NLO Monte Carlos for signals & backgrounds (MCFM, MC@NLO)

Sensitivities at NLO!! (NNLO maybe available before data taking, which will increase x-sections)

• More detailed, better understood reconstruction methods (partially based on test beam results), improved trigger simulation, event reconstruction and analysis tools

• Strategies to estimate backgrounds from data and express AlCa streams

• Improved statistical treatment (also including treatment of systematic uncertainties)

• Tevatron data are extremely valuable for validation, work has started

NEW results with Full Simulation!

P.Lobelle (U.Cantabria)

28/04/09 DIS09 Madrid
Small branching ratio (0.002 at $m_H = 120 \text{ GeV}/c^2$)

Final states produced through W, top and b loops

Important channel for discovery at low mass ($m_H < 130 \text{ GeV}/c^2$)

Very clear signature: 2 high Et isolated photons

**Requirements**

- Good understanding of electromagnetic calorimeter performance and calibration
- Excellent $\gamma$/jet separation
- Good mass resolution
- and Vertex reconstruction

**Backgrounds:**

- Irreducible: $\gamma\gamma$, $\gamma\gamma+$jets
- Reducible: $\gamma+$jets, jets, DY
**ATLAS**

- Vertex determined from extrapolation using calorimeter samplings
- Converted photons used to improve vertex determination: 57% Higgs events have \( \geq 1 \) conversion
- Signal divided into categories according to \( \eta_\gamma \), \#jets, \#converted photons
- Inclusive analysis + search for di-photons with jets
- Unbinned maximum-likelihood fit

**CMS**

- Background reduction using photon isolation and kinematic information
  - \( M_{\gamma\gamma} \) observed as a peak above background
  - **Cut-based analysis**
    - Splitting in categories according to \( \eta_\gamma \) and lateral shower shape variable
  - **Optimized analysis**
    - Loose sorting and additional kinematical variables
    - Event-by-event kinematical Likelihood Ratio with background pdf taken from sidebands, signal pdf from MC

28/04/09 DIS09 Madrid P.Lobelle (U.Cantabria)
Results for $H\rightarrow\gamma\gamma$

**ATLAS**
- For $m_H=120 \text{ GeV}/c^2$ and $10 \text{ fb}^{-1}$:
  - Inclusive analysis, using event counting $\sigma = 2.6$
  - Combining the 0,1,2 jets analysis + using an unbinned maximum-likelihood fit:
    
    Floating (fixed) mass fit: $\sigma=2.8 (3.6)$

**CMS**
- $5\sigma$ discovery between LEP lower limit and 140 GeV/c$^2$ with less than 30 fb$^{-1}$ of integrated luminosity
- $5\sigma$ discovery with event by event estimation of the S/B ratio possible at $m_H=120 \text{ GeV}/c^2$ with 7-8 fb$^{-1}$
\[ H \rightarrow WW^* \rightarrow 2l2\nu \]

- **Main search channel for range** \( 140 < m_H < 2m_Z \)
- Highest branching ratio for \( m_H > 140 \text{ GeV/c}^2 \): 95% at \( m_H = 160 \text{ GeV/c}^2 \)

**Signal**: 2 high \( p_T \) isolated leptons, MET and no central jets

**Backgrounds**:
- WW, tt, W+jets, Z+jets, tW, WZ, ZZ...

No mass peak (undetected neutrinos) \( \Rightarrow \) Needs a good background understanding

**Two main discriminants**:
- Angle between leptons in the transverse plane: main variable to reject WW (small opening angle for the signal due to spin correlations)
- Central Jet Veto for \( t\bar{t} \)bar reduction

\[ \int L \, dt = 1 \text{ fb}^{-1} \]
**Analysis strategy**

**ATLAS (eμ final state, H+ 0j, H+2j analysis)**

- **Preselection**:
  - 2 opposite-sign isolated and identified leptons
  - Cuts on $m_\parallel$, MET, $\Delta\phi_\parallel$, $Z_{\tau\tau}$ removal
  - Central Jet veto & b-tag veto
- **Final selection**:
  - 2D Fit of transverse mass and Higgs candidate $p_T$ in 2 bins of di-lepton azimuthal angle $\Delta\phi_\parallel$ to extract S/B ratio in signal region

**CMS (ee, μμ, eμ final states, H+0j analysis)**

- **Preselection**:
  - 2 opposite-sign isolated and identified leptons
  - Cuts on $m_\parallel$, MET
  - Central Jet Veto
- **Variables used to reduce background**:
  - $p_T$ of the leptons, $m_\parallel$, $\Delta\phi_\parallel$, MET
- **Final selection**:
  - Mass dependent cut based & multivariate analysis (optimization for 1fb$^{-1}$)
  - Control regions: fake leptons, background normalization

\[ \int L \, dt = 1 \, fb^{-1} \]
Results for $H \rightarrow WW^{*} \rightarrow 2l2\nu$

**ATLAS**

- Combined significance above the $5\sigma$ level for $\sim m_H > 140 \text{ GeV}/c^2$

**Updated CMS result:**

Sensitivity to a SM Higgs improved using a mass dependent multivariate analysis

**Improvements on Lepton ID, mass dependent cuts, more data driven approaches (compared to TDR)**

Cuts have been optimized separately for $1\text{fb}^{-1}$ maximizing the expected statistical significance.

28/04/09 DIS09 Madrid P.Lobelle (U.Cantabria)
**Signal:** Very clean signature (2 pairs of isolated leptons $4e, 4\mu, 2e2\mu$) with high branching ratio except at $m_H \approx 2m_W$

- Excellent mass resolution (1.5 – 2 GeV/$c^2$ for $M_H = 130$ GeV/$c^2$)
- Powerful analysis in a wide mass range

**Backgrounds:**
- Irreducible: $ZZ^*$ dominant
- Reducible: $Zbb, tt, ZW, Z + X$

- Selection of isolated (tracker + calorimeter) muon and electron pairs with opposite charge
- Isolation and Impact Parameter Significance main variables to reject $Zbb, tt$
- At least one $Z \rightarrow ll$ on shell (Mass of the leptons pairs some discrimination against the background)
- 4-lepton mass reconstruction
  Peak in the mass spectrum of the signal most discriminating variable against ZZ
Results for $H \rightarrow ZZ^* \rightarrow 4l$

- 3 channel independent +1 combined analysis with several levels of systematic uncertainties treatment

- Comparable significance
- Highly sensitive in the high mass region ($200 \text{ GeV}/c^2 < m_H < 400 \text{ GeV}/c^2$) and in the $150 \text{ GeV}/c^2$ region, where the Higgs boson could be discovered with 5 fb$^{-1}$

**CMS update:**
- Cuts optimised for 1 fb$^{-1}$ and data driven methods for background optimization control
- Significance of about 3σ can be reached for $m_H \sim 200 \text{ GeV}/c^2$ at $\int L dt = 1 \text{ fb}^{-1}$
- SM Higgs boson can be excluded for $m_H > 185 \text{ GeV}/c^2$ with $\int L dt = 1 \text{ fb}^{-1}$
- "look-elsewhere" effect: in real search, significance to be de-rated by ~1 sigma
VBF H→ττ

- Important channel for range 115-145 GeV/c²

**Signal**: 2 leptons or τ-jets in central region, MET and 2 forward jets

**Backgrounds**
- Zjj, tt, Z/γ*→ττ

3 final states:
- Lepton-lepton
- lepton-hadron (CMS only this)
- hadron-hadron

- Invariant mass of the τ pair reconstructed via the collinear approximation (breaks down when the 2 taus are back to back)

**Important items**:
- Tau tagging (Likelihood, NN methods)
- tt rejection (b-jet ID and veto for lepton-lepton)
- Z+jets background, especially at low masses
SM channel combination

- With 10 fb$^{-1}$ (normally considered as one LHC year at low luminosity), 5σ discovery for $m_H$ in $[\sim120, \sim500]$ GeV/$c^2$
- With 5 fb$^{-1}$ 5σ discovery for $m_H$ in $[\sim130, \sim450]$ GeV/$c^2$

*Combining results from both experiments, around half of this luminosity*
LHC will start working with center of mass energy lower than 14 TeV around 10 TeV

► Main Effect: cross section changes

✓ Different energy of LHC has two effects:
  ● Cross section for signals (and background) goes down
  ● Signal (Higgs production) goes down slightly faster: *Higgs is mainly produced from gg and backgrounds from qq*

✓ Efficiency and Acceptance:
  ● Higgs becomes relatively “heavier”, i.e. decay products become relatively more central for smaller LHC energies

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma_{\sqrt{s}=10\text{ TeV}}$</th>
<th>$\sigma_{\sqrt{s}=6\text{ TeV}}$</th>
<th>$\sigma_{\sqrt{s}=14\text{ TeV}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>0.450</td>
<td>0.113</td>
<td></td>
</tr>
<tr>
<td>$Wt$</td>
<td>0.450</td>
<td>0.113</td>
<td></td>
</tr>
<tr>
<td>$WW$</td>
<td>0.650</td>
<td>0.320</td>
<td></td>
</tr>
<tr>
<td>$WZ$</td>
<td>0.650</td>
<td>0.320</td>
<td></td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.650</td>
<td>0.320</td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>0.681</td>
<td>0.371</td>
<td></td>
</tr>
<tr>
<td>$W \rightarrow \ell\nu$</td>
<td>0.681</td>
<td>0.371</td>
<td></td>
</tr>
<tr>
<td>$gg \rightarrow H$</td>
<td>0.540</td>
<td>0.190</td>
<td></td>
</tr>
</tbody>
</table>

**Example:** HWW + HZZ combined

<table>
<thead>
<tr>
<th>$\mathcal{L}$ for 5$\sigma$</th>
<th>14 TeV</th>
<th>10 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H = 200$ GeV</td>
<td>0.6 fb-1</td>
<td>1.3 fb-1</td>
</tr>
</tbody>
</table>

PYTHIA for HZZ (LO) and MCFM for HWWW cross section calculations, standard CMS MC Samples used for estimate
CMS projection for LHC@10TeV

- **LHC 2009 - 2010 luminosity performance – estimate:**
  ~200 pb⁻¹ of “good data”

- **Strategy:**
  - First understand detectors,
  - do SM measurements,
  - then search for the Higgs...

- **Signal and bkgd yields re-scaled 14→10 TeV:** loss of a factor of 1.5 in sensitivity, or a factor of ~2 in luminosity

- **With roughly ~200 pb⁻¹:**
  Reach sensitivity for a SM Higgs with \( m_H \sim 160-170 \text{ GeV/c}^2 \) (comparable to the current Tevatron sensitivity)
  (but region just excluded by Tevatron)
Conclusions

- If the Higgs boson is there, **ATLAS and CMS are ready** to find it...
  ...unless it is discovered or excluded first at the Tevatron!!!

- For a SM Higgs, **with a combination of ATLAS & CMS @14TeV**, between ~ 1 and 5 fb\(^{-1}\) are needed depending on mass value. Benchmark luminosities:
  - ~0.1 fb\(^{-1}\) → *exclusion limits will start carving into SM Higgs cross section*
  - ~0.5 fb\(^{-1}\) - 1 fb\(^{-1}\) → *discoveries start to become possible in the region near the one excluded by Tevatron (M\(_H\)~160-170 GeV/c\(^2\))*
  - ~5 fb\(^{-1}\) - 10 fb\(^{-1}\) → *SM Higgs could be discovered (or excluded) in full mass range (~110-500 GeV/c\(^2\))*

- LHC efforts focused to get **as much luminosity as possible** to get sensitivity to a SM Higgs boson.

- **ATLAS and CMS** are doing their best to commission and understand the detectors to be ready when collisions start
Post-discovery questions that would need to be answered...

- Is it a Standard Model Higgs?
- What are the couplings to the rest of particles?
- Is there only one Higgs? MSSM, other models?
- What is its precise mass, width, quantum numbers?
- Does it generate electroweak symmetry breaking and give mass to fermions?
- Higgs discovery also raises the “hierarchy” problem...

Ready for Higgs discovery, but if it is not found, detectors are able to search for objects with similar signatures...

LHC will answer these fundamental questions in the next years