Higgs Boson Searches
With The Early LHC Data

Vivek Sharma
University of California, San Diego
(On behalf of ATLAS & CMS Experiments)
Story So Far: Direct Searches For Higgs

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Higgs Production in 7 Tev pp Collisions

 Dominant production: $gg \to H$

 Dominant decay mode
 At high $H$ mass

 $H \to WW, ZZ$
For $M_X > 140$:

- gg $\sigma$ at 7 TeV > 15x that at Tevatron
- Higher rate for Higgs production
- Irreducible backgrounds (WW, ZZ)

Irreducible backgrounds originate from qqbar which rises relatively slowly

$\Rightarrow$ S/N rises, $\Rightarrow$ LHC competitive with 1fb$^{-1}$

For $M_X < 140$: slow rise in qqbar $\sigma$

- Compared to at Tevatron, Higg-sstrahlung (pp $\rightarrow$ VH) rate @ 7 TeV not much larger
- Major backgrounds are W/Z+bbbar & ttbar which rise sharply due to rapid rise in gg $\sigma$
- $\Rightarrow$ small signal rate & poor S/N
- gg $\rightarrow$ H $\rightarrow$ $\gamma\gamma$ favored in production and even with $\text{Br}(H \rightarrow \gamma\gamma) \approx 0.2\%$
- $\Rightarrow$ Poor S/N
Higgs Sensitivity @ 7 TeV with 1 fb⁻¹

• Predicting future is dodgy business!
  – but one tries nevertheless

• Projections based on published 14 TeV studies (2008 and earlier)
  – Based on analyses constructed to **discover** Higgs, not set **best limits**
  – 7 TeV simulation studies ongoing but not completed

• Projections not rigorous: **Indicative not predictive**! ….& designed to be conservative

• Will mostly show today projections from CMS
  – ATLAS projections in public domain “soon”, expected to be similar to CMS
  – CMS Event reconstruction and analysis methodology as of 2008, not the current (improved) state-of-the-art
  – Projection method verified, in CMS, on complete analyses of 10 TeV pp simulations (but without pileup; which is important)
CMS 7 TeV Projections Workflow

- Start with results at 14 TeV (int. luminosity used varies: 1-30 fb\(^{-1}\))
- Re-scale signal and bkgd event counts by the ratio of 7 to 14 TeV cross sections and project for an integrated luminosity of 1 fb\(^{-1}\)
- Use NNLO \(\sigma\) for gg\(\rightarrow\)H (30% gain), NLO for VBF & VH
- Apply no correction for higher acceptance at smaller \(\sqrt{s}\), which can be up to 20%
- Scaled systematic errors:
  - for backgrounds derived from control samples \(\Rightarrow\) scale as \(1/\text{sqrt}(N)\)
  - other errors: assess whether to keep as is (e.g. theoretical errors) or inflate to correspond to the smaller data set
  - take into account correlations in systematic uncertainties
- Statistical analyses of Sensitivities:
  - Use re-scaled event counts and re-evaluated systematic errors
  - Exclusions: Modified Frequentist (CL\(_s\)), Significance: Profile Likelihood
Background Cross Sections used

General background sources

<table>
<thead>
<tr>
<th>process</th>
<th>(\sqrt{s} = 14) TeV</th>
<th>(\sqrt{s} = 10) TeV</th>
<th>(\sqrt{s} = 7) TeV</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(W \rightarrow \ell\nu)</td>
<td>3*20283.7</td>
<td>3*14253.7</td>
<td>3*9679.9</td>
<td>MCFM NLO</td>
</tr>
<tr>
<td>(DY(20-\infty) \rightarrow \ell\ell)</td>
<td>3*3259.7</td>
<td>3*2323.6</td>
<td>3*1606.6</td>
<td>MCFM NLO</td>
</tr>
<tr>
<td>(WW)</td>
<td>112.5</td>
<td>71.4</td>
<td>42.9</td>
<td>MCFM NLO</td>
</tr>
<tr>
<td>(WZ)</td>
<td>51.0</td>
<td>31.4</td>
<td>18.3</td>
<td>MCFM NLO</td>
</tr>
<tr>
<td>(ZZ)</td>
<td>15.6</td>
<td>9.9</td>
<td>5.9</td>
<td>MCFM NLO</td>
</tr>
<tr>
<td>(tt)</td>
<td>918</td>
<td>415</td>
<td>165</td>
<td>MCFM NLO</td>
</tr>
<tr>
<td>(Wt)</td>
<td>56.1</td>
<td>26.0</td>
<td>10.5</td>
<td>MCFM NLO</td>
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<tr>
<td>(tq-t) channel</td>
<td>244.6</td>
<td>130.5</td>
<td>62.8</td>
<td>MSTW 2008 NNLO</td>
</tr>
<tr>
<td>(tq-s) channel</td>
<td>11.9</td>
<td>7.6</td>
<td>4.6</td>
<td>NLO k-Factor from Bauer</td>
</tr>
<tr>
<td>(W(\rightarrow \ell\nu) + \gamma)</td>
<td>54.7*1.8</td>
<td>35.4*1.8</td>
<td>23.2*1.8</td>
<td>NLO k-Factor from Bauer</td>
</tr>
<tr>
<td>(Z(\rightarrow \ell\ell) + \gamma)</td>
<td>17.5*1.8</td>
<td>11.3*1.8</td>
<td>7.3*1.8</td>
<td></td>
</tr>
</tbody>
</table>

Background Estimate for \(H\rightarrow\gamma\gamma\) mode

Calculated with the \(H\rightarrow\gamma\gamma\) photon cuts

average 0.446
H → WW : Most Prolific Decay mode

• Signal: two isolated leptons with small $\Delta\phi$
  + MET + no central jets (jet veto)

• Backgrounds reduction:
  – WW: $\Delta\phi$ & $m_{ll}$
  – ttbar: central jet veto, $\Delta\phi$ & $m_{ll}$
  – W+jets: lepton id
  – DY alleviated by MET requirement
  – WZ/ZZ: 2 leptons in final state, MET

• Look for excess above a cut on NN output

• Main backgrounds are assessed using data-driven techniques: WW, ttbar, W+jets, Drell-Yan
CMS expected exclusion range: [150-185]
ATLAS expected exclusion range: [140-185]
CMS discovery 3-5σ sensitivity: near 160 GeV
\( H \rightarrow ZZ^(*) \rightarrow 4 \text{ leptons} \)

- Signal: four isolated leptons, look for 4l-mass peak [count in sliding mass window]
- Backgrounds:
  - \( ZZ \) : irreducible background, [rate assessed from data—\( Z \) events]
  - \( tt\bar{t} \) & \( Z\bar{b}b\bar{b} \) removed by lepton isolation & impact parameter veto
- Narrow mass peak, low background
- But low yield \( \Rightarrow \) need to push lepton id

Graph:
- Events counted in mass window at 7 TeV, 1 fb\(^{-1}\)
For SM Higgs with 4 fermion generations
- $gg \rightarrow H$ cross section increases naively by a factor $\sim 3^2 = 9$
- Less naive exclusion limit (based on Kribs et al) $\rightarrow \sim 420$ GeV
- two isolated photons, search for mass peak
- QCD bkgd is large and partly irreducible,
  - measured from sidebands
- Not a viable mode of low mass SM Higgs in 7 TeV/1 fb⁻¹ run
Fermiophobic Higgs: Back-of-Envelope

**CMS SM H→γγ exclusion r~4**

![Graph showing CMS SM H→γγ exclusion]

**Fermiophobic/SM ratios**

![Graph showing Fermiophobic/SM ratios]

**Fermiophobic/SM (see plot on the right)**
- gg→H disappears \(⇒\) loss of a factor of 10 in H cross section [blue line]
- Gain a large factor in BR(H→γγ) [black line]
- CS x BR larger than that of SM up to 130 GeV

**If do nothing special (charateristic kinematics) for fermiophobic Higgs,**
- r~4 for SM Higgs (see left plot) implies that
- Possibly exclude fermiophobic Higgs with m~110 GeV (see right plot), which is better than Tevatron, comparable to LEP limit
CMS: All Modes Combined

SM Higgs expected excluded range: **145-190 GeV**
SM Higgs with 4 fermion generations: $< \approx 420 \text{ GeV}$
SM Higgs expected excluded range approx: **140-200 GeV**

discovery range approx: **160-170 GeV**

SM Higgs with 4 generations can be ruled out to $M_H \approx 530$ GeV
MSSM Higgs In $pp \rightarrow bb\Phi$; $\Phi \rightarrow \tau^+ \tau^-$

- Isolated pairs of $(\tau_{had}\tau_\mu), (\tau_{had}\tau_e), (\tau_\mu\tau_e)$
- With MET, 1 tagged bjet, veto extra jets
- Build $\tau\tau$-mass using collinear approx
- Count events in sliding $\tau\tau$-mass window
- Dominant backgrounds: $t\bar{t}$, $Z+b\bar{b}$ & $Z+c\bar{c}$
  -- assessed from data
From Projections to Reality

Early ATLAS & CMS Performance in LHC Collision data
Key Preparation Before LHC Collisions

- Several Cosmic ray data campaigns prior to LHC collisions
  - ~ 1 Billion cosmics analyzed
  - Has led to well understood detector **in advance** of pp collisions in 2009
- Timing, alignment, resolution, coherent running, trigger, DAQ etc

![Momentum Pull distribution](image)

$$\sigma = 0.99$$

![Impact par resolution](image)
7 TeV Run So Far

More than 4.5 nb\(^{-1}\) accumulated so far

ATLAS & CMS data taking efficiency \(\approx 96\%\) under stable 7 TeV beam conditions
Excellent Hardware Performance

### ATLAS

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Number of Channels</th>
<th>Approximate Operational Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>60 M</td>
<td>97.5%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>3.3 M</td>
<td>99.3%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>350 k</td>
<td>98.0%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>170 k</td>
<td>98.5%</td>
</tr>
<tr>
<td>Tile calorimeter</td>
<td>9800</td>
<td>97.3%</td>
</tr>
<tr>
<td>Hadronic endcap LAr calorimeter</td>
<td>5600</td>
<td>99.9%</td>
</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>99.8%</td>
</tr>
<tr>
<td>LVL1 Muon RPC trigger</td>
<td>370 k</td>
<td>99.7%</td>
</tr>
<tr>
<td>LVL1 Muon TGC trigger</td>
<td>320 k</td>
<td>100%</td>
</tr>
<tr>
<td>MDT Muon Drift Tubes</td>
<td>350 k</td>
<td>99.7%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
<td>31 k</td>
<td>98.5%</td>
</tr>
<tr>
<td>RPC Barrel Muon Chambers</td>
<td>370 k</td>
<td>97.3%</td>
</tr>
<tr>
<td>TGC Endcap Muon Chambers</td>
<td>320 k</td>
<td>98.8%</td>
</tr>
</tbody>
</table>

### CMS

- ~100M channels
- ~98% channels operational

98%
Performance With Collision Data

Collision Event at 7 TeV with Muon Candidate

2010-03-30, 12:59 CEST
Run 152166, Event 322215

Pixel & Silicon Strip Tracker Performance

Pixel Det.

SCT Det.

CMS Pixel cluster charge

CMS SST Signal/Noise
Similar Pileup events also reconstructed in CMS
B-tagging: Works straight out of the box

Basic variables relevant for B-tagging compare well in data Vs MC

Signed 3D impact parameter for all tracks selected for b-tagging in jets with pT > 40 GeV and |η| < 1.5

Track multiplicity in reconstructed secondary vertices
Performance of EM Calorimeters

Crystal Energy

inter-crystal calibration in full swing
Next Step:
Rediscovering the Standard Model

Precondition to searches for new particles and BSM phenomena
Strange, Charm and all that

ATLAS Preliminary
$K_S^0$ Invariant Mass

$\Phi$

ATLAS Preliminary
Data 2009 $\sqrt{s}=900$GeV

$J/\psi$

CMS Preliminary $\sqrt{s}=7$ TeV

$D^*$
Jets are 310 GeV and 350 GeV at EM scale – highest PT di-jet event so far!

 Detector is quiet
Jets & Dijets @ 7 TeV

CMS: Dijet studies using several Jet reconstruction techniques
Excellent agreement between Data and simulations over more than 5 orders of magnitude

For Higgs searches, MET requirement is modest $\sim [40-100]$ GeV
1\textsuperscript{st} event on April 1\textsuperscript{st}!, so far a dozen W candidates seen in 1 nb\(^{-1}\), as expected

\( p_T(\mu^+) = 29 \text{ GeV} \)
\( \eta(\mu^+) = 0.66 \)
\( E_T^{\text{miss}} = 24 \text{ GeV} \)
\( M_T = 53 \text{ GeV} \)
$Z \rightarrow e^+e^-$

CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

Electrons $p_T = 34.0, 31.9$ GeV/c
Inv. mass = 91.2 GeV/c$^2$
The Road Ahead at LHC

<table>
<thead>
<tr>
<th>Summer 2010</th>
<th>End of 2010</th>
<th>Fall 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sim 1 \text{ pb}^{-1} )</td>
<td>( \sim 100 \text{ pb}^{-1} )</td>
<td>( \sim 1000 \text{ pb}^{-1} = 1 \text{ fb}^{-1} )</td>
</tr>
</tbody>
</table>

- QCD, b measurements
- W, Z cross sections
- Electroweak program + Higgs program
- Early \( t \bar{t} \) observation
- Early searches, mainly Exotica

- + top physics program
- + broad search program: Mainly Exotica, SUSY

Higgs program starts With 250 pb\(^{-1} \) →
LHC Plans For Next Weeks

• Increase single bunch intensity to $\sim 1 \times 10^{11}$ p/bunch
• To avoid risking safety of tertiary collimators, beams squeezed only to $\beta^*=5$ m (a factor 2.5 lost)
• To compensate for this increase number of bunches up to 16 (total power of about 1 MJ in the machine)
  • Started with $2 \rightarrow 4 \rightarrow 6$ bunches already
• Priority for LHC will be to give a sizeable amount of data to the experiments in time for the ICHEP
  • More than 300 nb$^{-1}$
Summary

• ATLAS & CMS well calibrated and have demonstrated agility in LHC data analyses: first results after few hour of data taking
  – First papers published

• Currently well on path of re-discovery of SM particles; hard work starts NOW!

• At 7 TeV & with 1 fb\(^{-1}\) data, ATLAS & CMS will begin to explore a sizable range of Higgs mass
  – SM Higgs discovery sensitivity: [160-170] GeV
  – SM Higgs exclusion range: [140-200] GeV
  – Low mass SM Higgs searches require 14 TeV & high lumi running
  – MSSM Neutral Higgs discovery range: down to tan \(\beta\)~20 for small \(m_A\)
  – MSSM Neutral Higgs exclusion range: down to tan \(\beta\)~15 for small \(m_A\)
  – With large tt\(\bar{b}\) cross-sections, will be probing \textit{terra incognita} in searches for \(H^+\) (tt\(\bar{b}\) cross-section is 20x Tevatron)

• Now awaiting luminosity promised, \textbf{stay tuned}!