Higgs Status and combinations
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Acknowledgements: Giovanni Petrucciani for his help and many ATLAS, CDF, CMS and D0 Colleagues
Higgs Search at LEP

- Mass 114.3 GeV/c²;
- Good HZ fit;
- Poor WW and ZZ fits;
- \( P(\text{Background}) : 2\% \)
- \( s/b(115) = 4.7 \)
LEP Limit

2.4 fb^{-1} \sqrt{s} > 189 \text{ GeV}

0.5 fb^{-1} \sqrt{s} > 206 \text{ GeV}

(sum of the 4 experiments)

Limit on \( M_{H} \) at the kinematical limit
\[ \sim \sqrt{s} - M_{Z} \]

Observed exclusion 95% CL
\[ < 114.4 \text{ GeV} \]

Expected exclusion 95% CL
\[ < 115.3 \text{ GeV} \]

± 1σ background only hypothesis

± 2σ background only hypothesis
Higgs production $p\bar{p}@2\text{TeV}$ vs $pp@7\text{TeV}$

(a) $gg \to H$
(b) VBF
(c) $VH$
(d) $t\bar{t}H$

$x\ 15\ gg \to H$

**SM Higgs production**

$\sigma$ [fb]

- $gg \to H$
- $qq \to Wh$
- $qq \to q\bar{q}b$
- $bb \to h$
- $qq \to Zh$
- $gg, qq \to t\bar{b}$

$m_H$ [GeV]

- $100$
- $120$
- $140$
- $160$
- $180$
- $200$

$M_H$ [GeV]

- $100$
- $200$
- $300$
- $400$
- $500$
- $600$
- $700$
- $800$
- $900$
- $1000$

**Branching ratios**

- $bb$
- $WW$
- $ZZ$
- $t\bar{t}$
- $\tau\tau$
- $gg$
- $cc$
- $YY$
- $ZZ$

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

- $pp \to H (\text{NLO QCD} + \text{NLO EW})$
- $pp \to WH (\text{NLO QCD} + \text{NLO EW})$
- $pp \to Zh (\text{NLO QCD} + \text{NLO EW})$
Key SM Background processes

AT LHC

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

- **W + jets**
  - \( W \to \ell^+\ell^- \)
  - 28,000 pb NLO

- **Z + jets**
  - \( Z \to \ell^+\ell^- \)
  - 28,000 pb NLO
  - \( t\bar{t} \)

- **ttbar**
  - 165 pb
  - approx. NLO

- **t + X**
  - (t-chan)
  - 63 pb NLO

- **tW**
  - 10.6 pb

- **W^+W^-**
  - 43 pb

- **WZ**
  - 18 pb

- **ZZ**
  - 5.9 pb

V. Sharma
Data sets for Higgs Searches

**Tevatron Luminosity**

HCP2011 analyses <8.6 fb⁻¹

**LHC Luminosity**

HCP2011 analyses <2.3 fb⁻¹
Higgs Search at the Tevatron

Run, Event: 229879, 3787664
Dijet Mass: 113.06 GeV/c²
Z Mass: 86.22 GeV/c²
N Jets: 2
MET: 8.52 GeV
ZH NN: 0.95, tt NN: 8.6x10⁻⁴
S/B @ 115 GeV/c²: 0.42

Jet 1
Pt 87.5 GeV/c

Jet 2
Pt 88.0 GeV/c

Lepton 1
Pt 151.0 GeV/c

Lepton 2
Pt 54.8 GeV/c
Tevatron results

Best sensitivity obtained by combining many channels. 

VH→Vbb is the most sensitive channel for $M_H \sim 115$ GeV

$\mu_{up}$ expected/observed upper limit on the signal strength modifier, $\mu = \sigma / \sigma_{SM}$.

LHC expected limit $H \rightarrow bb@1$ fb$^{-1} \sim 5 \times$ SM
Dibosons searches as proxy for VH→Vbb

For MH=115 GeV, VH→Vbb is 46 fb, while VZ→Vbb is 202 fb. The cross section for diboson production is 4.5 times larger than for VH. But the background situation at lower mass is more difficult.

WW+WZ in lν+HF

WW/WZ ratio fixed as in the SM
Large contribution from WW→lνcs
3.0 σ from the B-only hypothesis (3.0 expected)
Good agreement with S+B:
σ(WW+WZ) = (1.1 +0.3 -0.4) σ_SM

WZ/ZZ in MET + HF

The combination of these searches has been done using the same technique as for the Higgs.

2.8 σ from the B-only
(1.9 expected)
σ(WZ+ZZ) = (1.5 ± 0.5) σ_SM
Sensitivity shared by ZZ and WZ

3.3 σ evidence for WZ+ZZ combined (2.9 expected)

Good agreement with S+B:
σ(WZ+ZZ) = (1.13 ± 0.36) σ_SM
Tevatron Limits

Observed exclusion 95% CL
100-109   156-177 GeV

Expected exclusion 95% CL
100-108   148-181 GeV
Higgs Search at LHC
**LHC Combination SM Higgs searches**

Performed by LHC Higgs Combination Group

- Combining the results presented at Summer Conferences
- All ATLAS and CMS analyses entering in the combination are documented
- Consistent treatment of the systematic errors in the two Collaborations
- Careful (conservative) attention to correlations

ATLAS-CONF-2011-157 - CMS-PAS-HIG-11-023
Channels entering in the combination

<table>
<thead>
<tr>
<th>Channel</th>
<th>Collab.</th>
<th>$m_H$ range</th>
<th>Lumi.</th>
<th>Type of analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow bb$</td>
<td>CMS</td>
<td>110-135</td>
<td>1.1</td>
<td>MVA cut &amp; count mass shape</td>
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<tr>
<td></td>
<td>ATLAS</td>
<td>110-130</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>CMS</td>
<td>110-140</td>
<td>1.6</td>
<td>mass shape (binned)</td>
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<tr>
<td></td>
<td>ATLAS</td>
<td>110-150</td>
<td>1.1</td>
<td>mass shape (binned)</td>
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<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>CMS</td>
<td>110-150</td>
<td>1.7</td>
<td>mass shape (unbin.)</td>
</tr>
<tr>
<td></td>
<td>ATLAS</td>
<td>110-150</td>
<td>1.1</td>
<td>mass shape (unbin.)</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow 2l2\nu$</td>
<td>CMS</td>
<td>110-600</td>
<td>1.5</td>
<td>cut &amp; count</td>
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<tr>
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<td>ATLAS</td>
<td>110-300</td>
<td>1.7</td>
<td>cut &amp; count</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
<td>CMS</td>
<td>110-600</td>
<td>1.7</td>
<td>mass shape (unbin.)</td>
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<td>ATLAS</td>
<td>110-600</td>
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<td>mass shape (binned)</td>
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<tr>
<td>$H \rightarrow ZZ \rightarrow 2l2\tau$</td>
<td>CMS</td>
<td>180-600</td>
<td>1.1</td>
<td>mass shape (binned)</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 2l2q$</td>
<td>CMS</td>
<td>225-600</td>
<td>1.6</td>
<td>mass shape (unbin.)</td>
</tr>
<tr>
<td></td>
<td>ATLAS</td>
<td>200-600</td>
<td>1.0</td>
<td>mass shape (binned)</td>
</tr>
<tr>
<td>$H \rightarrow ZZ \rightarrow 2l2\nu$</td>
<td>CMS</td>
<td>250-600</td>
<td>1.6</td>
<td>cut &amp; count m_T shape (binned)</td>
</tr>
<tr>
<td></td>
<td>ATLAS</td>
<td>200-600</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

Search in the range 110 to 600 GeV
Weight of the individual channels

In the combination presented today

$w_i = \frac{1}{\sum_j \frac{1}{\mu_{up,j}^2}} \frac{1}{\mu_{up,i}^2}$

$\mu_{up}$ expected upper limit on the signal strength modifier, $\mu = \sigma / \sigma_{SM}$.

The $w_i$ depend on the amount of integrated luminosity of each channel. They are computed in the asymptotic approximation.

Cowan, Cranmer, Gross, Vittels EPJC 71:1554
High Mass Region

H→ZZ→llνν: Signature two isolated high pt leptons of opposite charge and missing transverse energy

Candidate Event with a Z→μμ and missing $E_T$

$p_T\mu = 50.126$ GeV
$m_{\mu\mu} = 94$ GeV
$E_T^{\text{miss}} = 161$ GeV
High Mass region

$H \to ZZ \to ll \, vv$

$H \to ZZ \to ll \, qq$
H→ZZ→4 leptons (golden channel)

Very clean, full reconstruction of the event
H→ZZ→4 leptons (golden channel)

Very clean with full reconstruction of the event

Resolution: FWHM 3.5 ÷ 6.5 GeV

Small excess for m<180 GeV
CMS 6 events ~3 expected*
ATLAS 3 events ~ 3 expected*

CMS $M_H=140$ ~ 3 expected*
ATLAS $M_H=150$ ~ 2.3 expected*

* at ~ 10% level
H → ZZ combined

ZZ channels alone exclude 180<MH<480 GeV

High mass search has little background

For m<180 GeV the number of expected events in 4 leptons per bin of mass resolution is less than 0.5. This reflects the good mass resolution, however the observation of a candidate in a given bin appears (statistically) unusual.
H → WW → 2l2ν

The shape is different because of the cut flow (invariant mass applied in ATLAS)
H→WW→2l2ν

CMS, $M_H$ 140 GeV
141 events, expected 120±11
(expected signal 46)

ATLAS, $M_H$ 150 GeV
93 events, expected 76±10
(expected signal 46)

The shape is different because of the cut flow (invariant mass applied in ATLAS)
ATLAS and CMS see both a less than 2σ positive fluctuation (mainly 0 jet in ATLAS, mainly 1 jet in CMS) that appear then in the combination. Since this channel has very limited mass resolution, the excess spans in a correlated way over a large mass range.
Low mass: $H \rightarrow \gamma \gamma$
Low mass: $H \rightarrow \gamma\gamma$

- $\gamma_1 = 86$ GeV
- $\gamma_2 = 56$ GeV

FWHM $\sim 4$ GeV
LHC Combination SM Higgs Boson

All Channels combined

Observed exclusion 95% CL
141-476 GeV

Expected exclusion 95% CL
124-520 GeV
Theoretical systematic uncertainties

Expected exclusion changes by 1 GeV at low mass and 20 GeV at High mass

Thanks to the advances in theory and to LHC Higgs cross section group!
Zoom on low mass

Excess largely due to the WW channel with modulations induced by ZZ and γγ
Zoom on low mass

Excess largely due to the WW channel with modulations induced by ZZ and γγ
Combination: p-values and $\sigma/\sigma_{SM}$

LEE CORRECTED MAX SIGNIFICANCE $1.6\sigma$
The full 2011 LHC dataset

1 fb⁻¹ projected 95 % exclusion winter 2011

Statistical sensitivity will improve by 1.5÷2 depending on the channel, WW may be the exception because one starts seeing the systematics.

Sensitivity will also improve, especially at low mass: basic physics object identification, reconstruction and calibration (e.g. γγ), use of MVA, more analyses (VBF and boosted bb in ATLAS). Higher pileup will somewhat degrade.
In the non excluded region both colliders show an excess compared to the expectation. Tevatron observed 95% limit is in the 1σ band. LHC excess has a max significance of 1.6σ.
Comparison LHC/Tevatron

In the non excluded region both colliders show an excess compared to the expectation. Tevatron observed 95% limit is in the $1\sigma$ band. LHC excess has a max significance of $1.6\sigma$.

Every discovery starts with the inability to exclude, it is good to see that we have excess compared to expectation!
In the non excluded region both colliders show an excess compared to the expectation. Tevatron observed 95% limit is in the 1σ band. LHC excess has a max significance of 1.6σ.

Every discovery starts with the inability to exclude, it is good to see that we have excess compared to expectation!

However here we do not have the clear picture of why do we have this excess. More data (that we have already) will tell us more about the WW excess. And the other channels will become more and more sensitive. **Stay tuned!**
The good news....... Only a small stable region left at 95% CL


Excluded at 95% CL

Shown are 1σ error bands, including theoretical errors

LEP exclusion at >95% CL

$M_H$ [GeV]

$\log_{10}(\Lambda/\text{GeV})$
The good news....... Only a small stable region left at 95% CL

And furthermore the region between \( \sim 132 \) and 141 GeV is also excluded at 90% CL by the LHC combination.
Impact of the new limits on the green band

Before LHC 2011 Run
Impact of the new limits on the green band

With < 2.3 fb\(^{-1}\) from LHC
Conclusions

Little room left for the SM Higgs! $114 < m_H < 141$ GeV @ 95% CL

LHC experiments will analyze the x3 data already collected before 2012 Winter Conferences

Tevatron will provide the final results on 10 fb$^{-1}$ by the 2012 Summer Conferences

On the same time scale there will be a combination LHC + Tevatron
Backup
## Correlated uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Affected Processes</th>
<th>Typical uncertainty</th>
</tr>
</thead>
</table>
| PDFs+\(\alpha_s\) (cross sections) | \(gg \to H, \, \ttbar H, \, gg \to VV\)  
VBF \(H, \, VH, \, VV@NLO\) | \(\pm 8\%\)  
\(\pm 4\%\) |
| Higher-order uncertainties on cross sections | total inclusive \(gg \to H\)  
inclusive “\(gg\)” \(\to H + \geq 1\) jets  
inclusive “\(gg\)” \(\to H + \geq 2\) jets  
VBF \(H\)  
associated \(VH\)  
\(\ttbar H\)  
uncertainties specific to high mass Higgs boson, see Section 2.1  
\(V\)  
\(VV\) up to NLO  
\(gg \to VV\)  
\(\ttbar, \text{ incl. single top productions for simplicity}\) | \(+12\%\)  
\(-7\%\)  
\(+20\%\)  
\(\pm 20\%\) (NLO), \(\pm 70\%\) (LO)  
\(\pm 1\%\)  
\(\pm 1\%\)  
\(+4\%\)  
\(-10\%\)  
\(\pm 30\%\)  
\(\pm 1\%\)  
\(\pm 5\%\)  
\(\pm 30\%\)  
\(\pm 6\%\) |
| acceptance | acceptance for \(H \to WW \to \ell\nu\ell\nu\) events | \(\pm 2\%\) |
| phenomenology | modelling of underlying event and parton showering  
fake lepton probability \((W + jets \to \ell\ell^{\text{fake}})\) | \(\pm 10\%\)  
\(\pm 40\%\) |
| luminosities | ATLAS and CMS uncertainties on their luminosity measurements | \(\pm 3.7\%\), \(\pm 4.5\%\) |
Individual Channels $H \rightarrow bb$

- CMS Preliminary, $\sqrt{s} = 7$ TeV
  - Observed
  - Expected ± 1σ
  - Expected ± 2σ
  $H \rightarrow bb$, $L_{\text{int}} = 1.1$ fb$^{-1}$

- ATLAS Preliminary
  - Observed
  - Expected ± 1σ
  - Expected ± 2σ
  ATLAS + CMS Private, $\sqrt{s} = 7$ TeV
  - $H \rightarrow bb$, $L_{\text{int}} = 1.0-2.3$ fb$^{-1}$/exp.

- Integral $L dt = 1.04$ fb$^{-1}$, $\sqrt{s} = 7$ TeV
  - Expected CLs
  - Observed (CLs)

- VH, $H \rightarrow bb$
  - ATLAS Preliminary

Paris
18/11/11

HCP2011

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HCP2011
Individual Channels $H \rightarrow \tau \tau$

ATLAS

ATLAS Preliminary

$\sqrt{s} = 7$ TeV, $L_{\text{int}} = 1.06$ fb$^{-1}$

$H \rightarrow \tau \tau$

Observed CLs
Expected CLs

$\pm 2s$
$\pm 1s$

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

$H \rightarrow \tau \tau$, $L_{\text{int}} = 1.0-2.3$ fb$^{-1}$/exp.

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

ATLAS only

CMS Preliminary, $\sqrt{s} = 7$ TeV
$H \rightarrow \tau \tau$, $L_{\text{int}} = 1.1$ fb$^{-1}$

Observed
Expected $\pm 1\sigma$
Expected $\pm 2\sigma$
Individual channels $H \rightarrow 2l2\tau$
Comparison of different combination methods

ATLAS + CMS Preliminary, \( \sqrt{s} = 7 \text{ TeV} \)

\( \text{L}_{\text{int}} = 1.0-2.3 \text{ fb}^{-1}/\text{experiment} \)

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

Higgs boson mass (GeV/c^2)

- CL\(_S\) Observed
- CL\(_S\) Expected ± 1σ
- CL\(_S\) Expected ± 2σ
- Bayesian Observed
- Asymptotic CL\(_S\) Obs.
Exclusion Regions SM Higgs

Union
LHC
Tevatron
LEP

100 200 300 400 500 600
Higgs boson mass (GeV/c²)
Tevatron $H \rightarrow \gamma \gamma$
Expected limit - low mass zoom

ATLAS + CMS Preliminary, √s = 7 TeV

\[ L_{\text{int}} = 1.0-2.3 \text{ fb}^{-1}/\text{experiment} \]

Expected limits
- Combined
- \( H \rightarrow bb \)
- \( H \rightarrow \tau\tau \)
- \( H \rightarrow \gamma\gamma \)
- \( H \rightarrow WW \)
- \( H \rightarrow ZZ \)

Expected limit - low mass zoom

1.0+1.1

1.1+1.6

1.1+1.7

2.3+1.7

1.7+1.5
Excluded region at 90% CL
Statistical analysis: modelling

• For each measurement directly entering the combination, expected outcome depends on:
  – The lack or presence of a higgs boson signal. represented by the signal strength \( \mu = \sigma/\sigma_{SM} \)
  – Quantities affected by systematical uncertainties: represented by nuisance parameters \( \theta \)
    These parameters usually have an associated measurement that provides a preferred value \( \theta_0 \) (e.g. from control sample, theory calculation, ...), and a probability distribution around that value.
Statistical analysis: modelling

The likelihood function is built as a product

\[ L(\text{data} | \mu, \theta) = L_{\text{obs}}(\text{data} | \mu, \theta) \cdot L(\theta_0 | \theta) \]

- Prob. of observing the data given \( \mu, \theta \).
- In the case of counting experiment with \( b(\theta) \) background and \( s(\theta) \) signal
  it’s just a Poisson( \( N | \mu \cdot s(\theta) + b(\theta) \) )

Likelihood of \( \theta_0 \) given \( \theta \) (Frequentist).
Posterior prob. of \( \theta \) after measuring \( \theta_0 \) and assuming flat prior on \( \theta \) (Bayesian)
Statistical analysis: modelling

P.d.fs for nuisance parameters:
- For yields measured from a control sample with stat. uncertainties: Gamma
- Other uncertainties on yields: log-normal distribution (remains “regular” for large uncertainties)
- Parameters with no prior knowledge, e.g. the $\gamma\gamma$ background: uniform distrib.
- Other parameters, usually affecting shapes: Gaussians
Two paradigms for limits:

- Frequentist: test values of $\mu = \sigma / \sigma_{SM}$ by tossing pseudo-experiments and evaluating how often they are more signal-like than the real data observation.
- Use “CLs” construction to be conservative in the presence of background fluctuations

Small differences w.r.t. LEP and Tevatron (see backup)
Statistical analysis: limits (2)

- Bayesian: interpret the likelihood function as a p.d.f. for $\mu = \sigma/\sigma_{SM}$ assuming a flat prior, compute the interval $[0, \mu]$ that contains 95% of prob. Exactly as PDG & Tevatron

- CLs and Bayesian are different definitions, results are within 10%