Higgs and BSM searches at LHC: results and perspective

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TeV Scale Physics workshop (7th)
Tsinghua University, Beijing
Nov. 12-15, 2012
The Large Hadron Collider (LHC)

- **27 km** circumference, **100 m** underground
- Two proton beam in parallel pipes, rotating in opposite directions
- Dipole field increases from **0.54 T** to **8.3 T** in about 20 minitues. Protons are stored for 10 – 24 hours
- **25 ns** bunch separation, **23 pp collisions per bunch crossing @ 10^{34} cm^{-2}s^{-1}**

**ATLAS and CMS**: general purpose detectors

**ALICE**: heavy ions

**LHC-B**: b-physics
To claim a discovery, it is important to have 2 independent experiments giving consistent results!
Tracking and calorimetry

Missing transverse energy (MET), a 2D vector of:
sign-inversed vectorial sum of all visible objects on the transverse plane
Higgs mechanism in a nutshell

The local gauge invariant Higgs ($\phi$) Lagrangian is

$$L_\phi=\left(i\partial_\mu-\frac{g}{2}\vec{W}_\mu-g^{}'\frac{Y}{2}B_\mu\right)\phi^2-V(\phi),$$

with the Higgs potential defined as

$$V(\phi)=-\mu^2\phi^\dagger\phi+\lambda(\phi^\dagger\phi)^2,$$

which has a minimum at $\phi=\mu/\sqrt{2}=\sqrt{\mu^2/2\lambda}$. Make the substitution:

$$\phi=\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}=\frac{1}{\sqrt{2}}\begin{pmatrix} \phi_1+i\phi_2 \\ \phi_3+i\phi_4 \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \mu+h(x) \end{pmatrix},$$

$\phi_1, \phi_2$ and $\phi_4$ become the Goldstone bosons in the Lorentz gauge – absorbed into the longitudinal polarizations of the three weak bosons in the Unitarity gauge. Electroweak gauge symmetry is broken, and Higgs field aquires a mass:

$$m_H=\sqrt{2\lambda}\mu, \quad \mu=(\sqrt{2}G_F)^{-1/2}=246 \text{ GeV}$$

Thus, Higgs mass is not predicted in the Standard Model.
Higgs production modes

Higgs couplings to fermions and bosons:

\[ g_{Hf} = \frac{g m_f}{2 m_W}, \quad g_{HWW} = g m_W, \quad g_{HZZ} = \frac{g m_Z}{\cos \theta_W} \]

Yukawa  Gauge  Gauge

Higgs production channels at LHC:

1. Gluon-gluon fusion
2. Vector-boson fusion
3. VH Associated
4. ttH
Bounds on the Higgs mass as of June 2012

Electroweak precision measurements

\[ m_H = 94^{+29}_{-24} \text{ GeV} \]

\[ m_H < 152 \text{ GeV}, \text{ at } 95\% \text{ CL} \]

Tevatron direct search limit as of June 2012
Higgs decay channels

Braching ratios for a Higgs mass of 125 GeV:

<table>
<thead>
<tr>
<th>channel</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbar</td>
<td>57.7%</td>
</tr>
<tr>
<td>WW</td>
<td>21.5%</td>
</tr>
<tr>
<td>ττ</td>
<td>6.3%</td>
</tr>
<tr>
<td>ZZ</td>
<td>2.6%</td>
</tr>
<tr>
<td>γγ</td>
<td>0.23%</td>
</tr>
</tbody>
</table>

- **bbar**: highest BR, but suffers from bad mass resolution and large QCD background
- **WW**: only the dilepton decay modes are useful at low mass, and cannot reconstruct the mass
- **ττ**: bad mass resolution (MET used), high signal efficiency (all final states are used: ll, lh, hh)
- **ZZ** and **γγ**: low BR, but good mass resolution. Very low background for ZZ and powerful S/B shape separation for γγ
$H \rightarrow \gamma\gamma$

**ATLAS**

Selected diphoton sample
- Data 2011 and 2012
- Sig + Bkg inclusive fit ($m_H = 126.5$ GeV)
- 4th order polynomial

\[ \sqrt{s} = 7 \text{ TeV}, \quad \int L = 4.8 \text{ fb}^{-1} \]
\[ \sqrt{s} = 8 \text{ TeV}, \quad \int L = 5.9 \text{ fb}^{-1} \]

**CMS**

CMS Preliminary
- $\sqrt{s} = 7 \text{ TeV}, \quad \int L = 5.1 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}, \quad \int L = 5.3 \text{ fb}^{-1}$

**ATLAS**

Local $p_0$ vs $m_H$ (GeV)
- Data 2011, $\sqrt{s} = 7 \text{ TeV}, \quad \int L = 4.8 \text{ fb}^{-1}$
- Data 2012, $\sqrt{s} = 8 \text{ TeV}, \quad \int L = 5.9 \text{ fb}^{-1}$

**CMS**

Local $p$-value vs $m_{h_1}$ (GeV)
- Interpretation Requires LEE

CMS Preliminary
- $\sqrt{s} = 7 \text{ TeV}, \quad \int L = 5.1 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}, \quad \int L = 5.3 \text{ fb}^{-1}$
H → γγ candidate event (ATLAS)
Both ATLAS and CMS have found a 4-lepton excess, and the mass is consistent with the one found in $\gamma\gamma$ channel!

Maximum local significance: $3.6\sigma$ ($3.2\sigma$) for ATLAS (CMS)
H → ZZ → 2e2μ candidate event
The first proposal on WW at Tevatron by T. Han and R. Zhang in PRL 82, 1999

Due to spin correlation between the 2 Ws, the signal has the following properties:
- Large $p_T(\ell\ell)$
- Small $m_{\ell\ell}$
- Small $\Delta\Phi(\ell\ell)$

Results for ICHEP: 0/1/2-jet
Results for HCP: 0-jet and 1-jet
Main background: WW

Due to 2 neutrinos, it is difficult to reconstruct the Higgs mass - ATLAS (CMS) uses $m_T(m_{\ell\ell})$
H → WW → 2l2ν

Fitted signal strength:
ICHEP(4.7 fb⁻¹ + 5.8 fb⁻¹) : \( \mu = 1.3 \pm 0.5 \)
2012 13 fb⁻¹: \( \mu = 1.5 \pm 0.6 \)
Combination of 3 channels at ATLAS

The combination at ATLAS alone yields $>6\sigma$ discovery

And the signal excess stays with time!
Combination of 5 channels at CMS

With a 5-channel combination, CMS reaches a local Significance of 4.9σ

The discovery is reflected by the inability to exclude a Higgs at ~125 GeV in the mass landscape.
The July 4th Higgs discovery
Higgs coupling strengths

The overall fitted signal strength \( \mu \), in unit if SM, is 1.4 ± 0.3 (0.80 ± 0.22) for ATLAS (CMS).

H → γγ rate is a bit higher than SM – new charged particle in the loop?
H → ττ result from CMS
Central jet veto is initially suggested by V. Barger, K. Cheung and T. Han in PRD 42 3052 (1990)

Wisconsin Pheno (D. Zeppenfeld, D. Rainwater, et al.) proposed searching for a low mass Higgs in association with 2 jets plus central jet veto

Very powerful to suppress the color-exchanging QCD backgrounds. Best suited for $H \rightarrow \tau \tau$ and $H \rightarrow \gamma \gamma$
The S/B ratio is much improved w.r.t. inclusive search (see slide 10)
\( H \rightarrow \tau\tau \) channels and objects

### Pre-selection

| \( ll+4\nu \) | Exactly 2 leptons with opposite signs \( 30 < m_{ll} < 75 \) (100) GeV for ee/\( \mu\mu \) (e\( \mu \)) |
| \( lh+3\nu \) | Exactly 1 lepton and 1 hadronic \( \tau \) \( p_T > 25 \) (20) GeV for e (\( \mu \))  
**Di-lepton veto**  
\( m_T < 30 \) GeV |
| hh+2\nu | Exactly 2 hadronic taus \( p_T > 35 \) (25) GeV for the leading (subleading) tau  
**Single lepton veto** |

### Common object selection

#### Electron

- \( p_T > 15 \) GeV, \( |\eta| < 2.47 \) with crack excluded  
- Calo and track isolation

#### Muon

- \( p_T > 10 \) GeV, \( |\eta| < 2.5 \)  
- Calo and track isolation

#### Hadronic tau

- \( p_T > 20 \) GeV, \( |\eta| < 2.5 \)  
- 1 or 3 tracks (prongs) in \( \Delta R < 0.2 \)  
- Multivariate BDT for ID

#### Jet

- \( p_T > 25 \) GeV, \( |\eta| < 4.5 \)  
- AntiKt4 jets, \( |JVF| > 0.75 \) if \( |\eta| < 2.4 \)
## Categories, MET cut and mass

<table>
<thead>
<tr>
<th>II</th>
<th>lh</th>
<th>hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-jet VBF (p_T &gt;40,25)</td>
<td>2-jet VBF (p_T &gt;40,30)</td>
<td>2-jet VBF (p_T &gt;50,30)</td>
</tr>
<tr>
<td>2-jet VH (p_T &gt;40,25)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boosted: p_{T,H} &gt;100</td>
<td>Boosted: p_{T,H} &gt;100</td>
<td>1-jet inclusive (p_T &gt;70)</td>
</tr>
<tr>
<td>1-jet inclusive (p_T &gt;40)</td>
<td>1-jet inclusive (p_T &gt;30)</td>
<td></td>
</tr>
<tr>
<td>0-jet inclusive in eμ channel</td>
<td>0-jet exclusive (p_T &lt;30)</td>
<td></td>
</tr>
<tr>
<td>MET&gt;40 for SF MET&gt;20 for DF</td>
<td>MET&gt;20</td>
<td>MET&gt;20</td>
</tr>
<tr>
<td>MMC</td>
<td>MMC</td>
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</tr>
</tbody>
</table>

**All categories are mutually exclusive**

All 3 channels: use Z→μμ data to simulate Z→ττ background
Control plots

![Control plots](image)

**Legend:**
- Data
- $20 \times H(125) \rightarrow \tau \tau$
- $Z \rightarrow \tau \tau$
- $Z \rightarrow e e \mu \mu$
- $t \bar{t}$+single-top
- $WW$/$WZ$/$ZZ$
- Fake leptons
- Bkg. uncert.

**ATLAS Preliminary**

**Integrals:**
- $\int L dt = 13.0 \text{ fb}^{-1}$
- $\sqrt{s} = 8 \text{ TeV}$
Final mass distributions (VBF and boosted)

VBF and boosted categories are most sensitive
The largest deviation of observed from expected limit is in the 2leptons channel.

The best fitted signal strength @ 125 GeV: $\mu = 0.7 \pm 0.7$

The lower combined $H \to \tau\tau$ rate is consistent with CMS.
$H \rightarrow \tau\tau \rightarrow e\mu+4\nu$ candidate event

NEW!
The channels we are adding: 2l+h and 3l+h

Adding the 2l+h and 3l+h channels for the VH production of Higgs:

These channels can be even more interesting in the context of MSSM or 2HDM, with possible double Higgs production modes and sensitivity to new physics:

An exclusion limit of ~10xSM has been reported by CMS with the 2l+h channel
### $H \rightarrow b\bar{b}$

<table>
<thead>
<tr>
<th>$ZH \rightarrow \nu \bar{\nu} b\bar{b}$</th>
<th>$WH \rightarrow \ell \nu b\bar{b}$</th>
<th>$ZH \rightarrow \ell^+ \ell^- b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 lepton</td>
<td>1 lepton</td>
<td>2 leptons</td>
</tr>
<tr>
<td>2 b-jets</td>
<td>2 b-jets</td>
<td>2 b-jets</td>
</tr>
<tr>
<td>2 or 3 jets</td>
<td>2 jets</td>
<td>no $N_{\text{jet}}$ requirement</td>
</tr>
<tr>
<td>MET &gt; 120</td>
<td>MET &gt; 25-50</td>
<td>MET &lt; 60</td>
</tr>
<tr>
<td>40 &lt; $m_T &lt; 120$</td>
<td>83 &lt; $m_{\ell\ell}$ &lt; 99</td>
<td></td>
</tr>
</tbody>
</table>

3 bins in $p_T(Z)$ | 5 bins in $p_T(W)$ | 5 bins in $p_T(Z)$

$Z^0 \rightarrow \nu \bar{\nu}$ | $W^+ \rightarrow \ell \nu$ | $Z^0 \rightarrow \ell\ell$

$H^0 \rightarrow b\bar{b}$ | $H^0 \rightarrow b\bar{b}$ | $H^0 \rightarrow b\bar{b}$
Signal regions $b\bar{b}$ mass spectra

0-lep, 2-tag, 2 jets

0-lep, 2-tag, 3 jets

1-lep, 2-tag

2-lep, 2-tag
Statistical results

To validate the bbar decays of diboson background, subtract all other background from data except diboson – we have confidence in signal modeling.

A SM Higgs in bbar decay is excluded for 1-2xSM rate.

The fitted signal strength \( \mu = -0.4 \pm 1.1 \)

Does Higgs couple less to down-type fermions?
### Updated ATLAS Higgs signal strengths (1)

<table>
<thead>
<tr>
<th>Higgs Boson Decay</th>
<th>Subsequent Decay</th>
<th>Sub-Channels</th>
<th>∫L dt [fb⁻¹]</th>
<th>Ref.</th>
</tr>
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<tbody>
<tr>
<td>H → ZZ(*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4ℓ</td>
<td>{4e, 2e2µ, 2µ2e, 4µ}</td>
<td>4.8</td>
<td>[1]</td>
</tr>
<tr>
<td>H → γγ</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>10 categories {p_TT ⊗ ηγ ⊗ conversion} ⊕ {2-jet}</td>
<td>4.8</td>
<td>[1]</td>
</tr>
<tr>
<td>H → ττ</td>
<td>τlepτlep</td>
<td>{eµ} ⊕ {0-jet} ⊕ {ℓℓ} ⊕ {1-jet, 2-jet, p_{T,ττ} &gt; 100 GeV, VH}</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>τlepτhad</td>
<td>{e, µ} ⊕ {0-jet, 1-jet, p_{T,ττ} &gt; 100 GeV, 2-jet}</td>
<td>4.6</td>
<td>[4]</td>
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<tr>
<td></td>
<td>τhadτhad</td>
<td>{1-jet, 2-jet}</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>VH → Vbb</td>
<td>Z → νν</td>
<td>E_{miss}^Z ∈ {120 − 160, 160 − 200, ≥ 200 GeV} ⊕ {2-jet, 3-jet}</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W → ℓν</td>
<td>p_{T,W} ∈ {&lt; 50, 50 − 100, 100 − 150, 150 − 200, ≥ 200 GeV}</td>
<td>4.7</td>
<td>[5]</td>
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<td></td>
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<td>5.9</td>
<td>[1]</td>
</tr>
<tr>
<td>H → WW(*)</td>
<td>eµµν</td>
<td>{eµ, µe} ⊗ {0-jet, 1-jet}</td>
<td>13</td>
<td>[6]</td>
</tr>
<tr>
<td>H → ττ</td>
<td>τlepτlep</td>
<td>{ℓℓ} ⊕ {1-jet, 2-jet, p_{T,ττ} &gt; 100 GeV, VH}</td>
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<td></td>
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<td>13</td>
<td></td>
</tr>
</tbody>
</table>

*Updates since ICHEP 2012 for HCP*
Updated ATLAS Higgs signal strengths (2)

The signal strengths are not commensurate among different channels

Combined fitted strength is $\mu = 1.3 \pm 0.3$
Implication of a light Higgs

The running of Higgs quartic coupling $\lambda$

Higgs potential positive – vacuum stability

Expect new physics at high energy scales – is it SUSY?

arXiv:1205.6497

$M_h = 125 \text{ GeV}$

$M_t = 173.1 \pm 0.7 \text{ GeV}$

$\alpha_s(M_Z) = 0.1184 \pm 0.0007$

$M_t = 171.0 \text{ GeV}$

$\alpha_s(M_Z) = 0.1205$

$M_t = 175.3 \text{ GeV}$

$\alpha_s(M_Z) = 0.1163$
The top channels

Direct stop pair production. Assuming 100% BR of stop → top+LSP for heavy stop (>200 GeV), and 100% BR of stop → bχ₁⁻ → b+W+LSP for light stop (<200 GeV)

Gluino pair production with gluino → ttbar+LSP:
4 tops + 2 LSPs in the final state
The generic modes

0-lepton

1-lepton

Same-Sign 2-lepton
The electroweak modes becomes important if the gluino and squark masses are very high.

Final state is 3 leptons + large MET with very few jets.

Dominant background is WZ. The top is the sub-dominant background – require b-jet veto or on-shell Z → ll to suppress top.
The neutral MSSM Higgs is carried out in 4 search channels:

- $\mu\mu$
- $e\mu$
- $lh$
- $hh$

Explored 2 important regions

- $b$-tag vetoed region → $gg$ fusion
- $b$-tagged region → $b\bar{b}$ associated
Charged Higgs

ATLAS Preliminary

Data 2011

ATLAS Preliminary

$B(t \to bH^+) = 5\%$

$\int Ldt = 4.6 \text{ fb}^{-1}$

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

$3 \sigma$ confidence level

Combined limit on BR

$\tan\beta$

$\sigma_{\text{Higgs}}^{\text{MSSM}}$

$\sigma_{\text{Higgs}}^{\text{SM}}$

$\sigma_{\text{Higgs}}^{\text{data}}$

$\sigma_{\text{Higgs}}^{\text{theory}}$

$\sigma_{\text{Higgs}}^{\text{obs}}$

$\sigma_{\text{Higgs}}^{\text{expected}}$

$\sigma_{\text{Higgs}}^{\text{MSSM}}$

$\sigma_{\text{Higgs}}^{\text{SM}}$

$\sigma_{\text{Higgs}}^{\text{data}}$

$\sigma_{\text{Higgs}}^{\text{theory}}$

$\sigma_{\text{Higgs}}^{\text{obs}}$
## Summary for SUSY

### ATLAS SUSY Searches - 95% CL Lower Limits (Status: HCP 2012)

### Inclusive searches

<table>
<thead>
<tr>
<th>Process</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g} \rightarrow b\tilde{b}$ (virtual $b$)</td>
<td>$0 \text{ lep} + 3 \text{ b-jets} + E_T$</td>
<td>$3 \text{ lep} + 0 \text{ b-jets} + E_T$</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow t\bar{t}$ (virtual $t$)</td>
<td>$2 \text{ lep} + E_T$</td>
<td>$2 \text{ lep} + E_T$</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow t\bar{t}$ (virtual $b$)</td>
<td>$1 \text{ lep} + 0 \text{ b-jets} + E_T$</td>
<td>$1 \text{ lep} + 0 \text{ b-jets} + E_T$</td>
</tr>
<tr>
<td>$\tilde{t}$ (virtual $t$)</td>
<td>$1 \text{ lep} + 0 \text{ b-jets} + E_T$</td>
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</tr>
<tr>
<td>$\tilde{t}$ (virtual $b$)</td>
<td>$0 \text{ lep} + 2 \text{ b-jets} + E_T$</td>
<td>$0 \text{ lep} + 2 \text{ b-jets} + E_T$</td>
</tr>
</tbody>
</table>

### 3rd gen. squarks direct production

<table>
<thead>
<tr>
<th>Process</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{q} \rightarrow b\tilde{b}$ (virtual $b$)</td>
<td>$0 \text{ lep} + 3 \text{ b-jets} + E_T$</td>
<td>$0 \text{ lep} + 3 \text{ b-jets} + E_T$</td>
</tr>
<tr>
<td>$\tilde{q} \rightarrow t\bar{t}$ (virtual $t$)</td>
<td>$2 \text{ lep} + E_T$</td>
<td>$2 \text{ lep} + E_T$</td>
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<td>$\tilde{q} \rightarrow t\bar{b}$ (virtual $b$)</td>
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<td>$\tilde{q}$ (virtual $b$)</td>
<td>$0 \text{ lep} + 2 \text{ b-jets} + E_T$</td>
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</tr>
</tbody>
</table>

### EW direct

<table>
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<th>Process</th>
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<tbody>
<tr>
<td>$\tilde{Z} \rightarrow W\nu\ell$</td>
<td>$2 \text{ lep} + E_T$</td>
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</tr>
<tr>
<td>$\tilde{Z} \rightarrow W\tilde{Z}^\pm$</td>
<td>$2 \text{ lep} + E_T$</td>
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<td>$\tilde{Z} \rightarrow Z\tilde{Z}^\pm$</td>
<td>$3 \text{ lep} + E_T$</td>
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</tbody>
</table>

### Long-lived particles

<table>
<thead>
<tr>
<th>Process</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable $\tilde{g}$-R-hadrons</td>
<td>low $\beta$, $\gamma$ (full detector)</td>
<td></td>
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<tr>
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<td></td>
</tr>
</tbody>
</table>

### GMSB

<table>
<thead>
<tr>
<th>Process</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable $\tilde{g}$</td>
<td>$2 \text{ lep} + E_T$</td>
<td>$2 \text{ lep} + E_T$</td>
</tr>
</tbody>
</table>

### R-parity violation

<table>
<thead>
<tr>
<th>Process</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g} \rightarrow q\nu$ (RPV)</td>
<td>$\mu + \text{heavy displaced vertex}$</td>
<td>$\mu + \text{heavy displaced vertex}$</td>
</tr>
<tr>
<td>Bilinear RPV CMSMM</td>
<td>$1 \text{ lep} + 2 \text{ jets} + E_T$</td>
<td>$1 \text{ lep} + 2 \text{ jets} + E_T$</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow q\nu$</td>
<td>$3 \text{ jet resonance pair}$</td>
<td>$3 \text{ jet resonance pair}$</td>
</tr>
</tbody>
</table>

### WIMP interaction (DS, Dirac $\chi$)

<table>
<thead>
<tr>
<th>Process</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi \rightarrow q\nu$</td>
<td>$2 \text{ jet resonance pair}$</td>
<td>$2 \text{ jet resonance pair}$</td>
</tr>
</tbody>
</table>

### Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena shown.

All limits quoted are observed minus 1 for theoretical signal cross section uncertainty.
The “prospect” for SUSY

★ So far, no evidence from direct SUSY search channels. Gluino/squark mass of ~1 TeV, stop mass of ~400 GeV, and chargino mass of ~250 GeV are excluded.

★ The non-standard SUSY scenarios (“hidden modes”) are also possible:
  - R-parity violating SUSY → lead to low MET
  - GMSB scenarios → long-lived charged sleptons or R-hadrons
  - Compressed scenario → sparticle masses are highly degenerate. Use ISR jet to trigger the event. For example, soft leptons + mono-jet
  - Lower cross section → Dirac gluino
  - Sparticle mass > 10 TeV ?

★ However, care should be taken as many of the results have assumptions (e.g., branching ratios, particular mass hierarchy). Search should continue in all aspects, including the “hidden modes”
Exotics: fun in the wild

Black Holes

Extra Dimensions

LQ
Q*, W', Z' ...

ATLAS Preliminary

q* → jj

NEW!

ATLAS Preliminary

Z' → μμ Search

Z' → μμ

ATLAS

W' → ev

W' → ev

WZ resonance
$W_R$, leptoquark, extra dimension, H$^{++}$...
# Summary for Exotics

## ATLAS Exotics Searches - 95% CL Lower Limits (Status: HCP 2012)

<table>
<thead>
<tr>
<th>Process</th>
<th>Lower Limit</th>
<th>95% CL Lower Limit</th>
<th>95% CL Lower Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}^\pm \to \gamma \gamma$</td>
<td>$M_{\text{H}}$</td>
<td>$M_{\text{H}}$</td>
<td>$M_{\text{H}}$</td>
</tr>
<tr>
<td>$\text{H}^0 \to \gamma \gamma$</td>
<td>$M_{\text{H}}$</td>
<td>$M_{\text{H}}$</td>
<td>$M_{\text{H}}$</td>
</tr>
<tr>
<td>$\text{H}^0 \to \text{W}^+ \text{W}^-$</td>
<td>$M_{\text{H}}$</td>
<td>$M_{\text{H}}$</td>
<td>$M_{\text{H}}$</td>
</tr>
</tbody>
</table>

### Extra dimensions

- Large ED (ADD): monojet + $E_T^{miss}$
- Large ED (ADD): monophoton + $E_T^{miss}$

### RS
- RS $g_0 \to tt$ (BR=0.925)
- ADD BH ($M_{\text{R}^1}/M_{\text{R}^2}=3$): SS dimuon, $N_{\text{rec}}=2$
- ADD BH ($M_{\text{R}^1}/M_{\text{R}^2}=3$): leptons + jets, $N_{\text{jet}}=2$

### Quantum black hole: dijet, $F(m_T)$

### ATLAS Preliminary

- $L = (1.0 - 1.30) \text{ fb}^{-1}$
- $\sqrt{s} = 7.8 \text{ TeV}$

*Only a selection of the available mass limits on new states or phenomena shown.
Summary and outlook

★ We have found a new Higgs-like particle with mass around 125 GeV

★ The properties if the particle are not fully known

  • All Higgs decay channels seems to agree with SM so far
  • There is a tendency that γγ is a bit high, and ττ and bbbar are a bit low. We need to analyze more data to shrink the error bars
  • The decay width, spin and CP are not determined yet

★ Searches for SUSY, including MSSM Higgs, are null

★ Searches for Exotics (q*, Z'/W', leptoquark, W_R, extra dimensions, ...) are null

For experimentalists: more data and higher energy (14 TeV 2014)

For theorists: constraints and new models based on the current results

stay tuned for more exciting news from LHC!
LHC timeline

- 2012 End of December: \textbf{Reach 20-25 \textit{fb}^{-1}/experiment}
- 2013-2014: \textbf{LS1}

Consolidation of the interconnections

Run at 6.5 to 7 TeV
To \textasciitilde 100 \textit{fb}^{-1}

Injection and collimation upgrade

Ultimate LHC
To \textasciitilde 300\textit{fb}^{-1}

HL-LHC
3 \textit{ab}^{-1}
Backup Slides
The Higgs decay width increases dramatically when above 200 GeV, and its interference with SM processes becomes sizable – tough for heavy SM-like Higgs search.
**H → γγ**

- **H → γγ** proceeds via W and top loops (σxBR≈50 fb @125 GeV)

- New charged particle in the loop: enhanced H → γγ rate

- Irreducible γγ background (σ≈40 pb, theoretical error ~20%)

- Reducible background: γ+jet (σ≈μb), and jet+jet (σ≈mb)

  One or more photons are fake photon from jets (mainly π⁰ → γ). The fake rate to hard to model with simulation.

  Have to rely on data to normalize the diphoton backgrounds
Categorization of events

<table>
<thead>
<tr>
<th>Category</th>
<th>$\sigma_{CB}$ [GeV]</th>
<th>FWHM [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>1.63</td>
<td>3.87</td>
</tr>
<tr>
<td>Unconverted central, low $p_Tt$</td>
<td>1.45</td>
<td>3.42</td>
</tr>
<tr>
<td>Unconverted central, high $p_Tt$</td>
<td>1.37</td>
<td>3.23</td>
</tr>
<tr>
<td>Unconverted rest, low $p_Tt$</td>
<td>1.57</td>
<td>3.72</td>
</tr>
<tr>
<td>Unconverted rest, high $p_Tt$</td>
<td>1.51</td>
<td>3.55</td>
</tr>
<tr>
<td>Converted central, low $p_Tt$</td>
<td>1.67</td>
<td>3.94</td>
</tr>
<tr>
<td>Converted central, high $p_Tt$</td>
<td>1.50</td>
<td>3.54</td>
</tr>
<tr>
<td>Converted rest, low $p_Tt$</td>
<td>1.93</td>
<td>4.54</td>
</tr>
<tr>
<td>Converted rest, high $p_Tt$</td>
<td>1.68</td>
<td>3.96</td>
</tr>
<tr>
<td>Converted transition</td>
<td>2.65</td>
<td>6.24</td>
</tr>
<tr>
<td>2-jets</td>
<td>1.57</td>
<td>3.70</td>
</tr>
</tbody>
</table>

Classify events with different mass resolution:

- High $p_Tt$ is better than low $p_Tt$
- Unconverted is better than converted
- Central is better than rest, and rest better than transition

There is a special 2-jet category for VBF. There are 10 categories in total.
Mass and signal strength

Left: likelihood of the fit floating both the mass and signal strength parameter $\mu$

Right: Fitted signal strength for 126.5 GeV: $\mu = 1.9 \pm 0.5$
For a fermiophobic Higgs, since only VBF and VH diagrams contribute, the Higgs $p_T$ is expected – better S/B separation

Higher (lower) $\sigma \times \text{BR}$ in low (high) mass region compared to SM.
Expect to exclude $m_H < 123.5$ GeV (2011)
H → ZZ → 4l

☆ H → ZZ → 4l is the gold-plated channel – good mass resolution, powerful rejection of SM background due to 4-lepton requirement

☆ Suffers from low rate and total lepton acceptance loss

\[ \text{BR}(ZZ \rightarrow 4l) = 0.45\% \quad \Rightarrow \quad \sigma \times \text{BR}(H \rightarrow ZZ \rightarrow 4l) = 2.6 \text{ fb} \]

Single lepton acceptance (tracking volume, trigger and reconstruction) is high (∼80%), but the total acceptance is low (0.8^4 = 0.4)

☆ Higgs mass resolutions – 1.8 to 2.5 GeV:
Selection cuts and mass spectrum

 Require 2 pairs of same-flavor opposite-sign leptons

- 4 leptons with $p_T > 20, 15, 10, 7$ (6 for muon) GeV (lep1, 2, 3, 4)
- $50 \text{ GeV} < m_{12} < 106 \text{ GeV}$, and $m_{\text{min}} < m_{34} < 115 \text{ GeV}$. $m_{\text{min}}$ depends on the 4l mass
- $m_{LL} > 5 \text{ GeV}$ for all same-flavor opposite-sign pair – J/ψ rejection

Lepton isolation (calo-energy and tracks around real leptons should be small) and track d0 cut (should come from hard IP)
Mass and signal strength

Left: likelihood of the fit floating both the mass and signal strength parameter $\mu$. Fitted signal strength: $\mu = 1.4 \pm 0.6$

Right: scan of discovery p-value and significance: $3.6\sigma$
H → WW → lνlν

Can not reconstruct the Higgs mass – background rates estimation is crucial in this channel

Devide analysis into 6 categories: (eμ, μe) x (0-jet, 1-jet, ≥2-jet)

Preselection

- Lepton $p_T > 25, 15$ GeV, $m_{ll} > 10$ GeV
- $E_{T,\text{rel}}^{\text{miss}} > 25$ GeV. $E_{T,\text{rel}}^{\text{miss}}$ is the MET component perpendicular to the closest object (lepton or jets). $E_{T,\text{rel}}^{\text{miss}} = E_T^{\text{miss}}$ if $\Delta \Phi > \pi/2$
- anti-kt jet $p_T > 25$ GeV (>30 GeV if $|\eta| > 2.5$)
Final yields and distribution

Yields for 2012 5.8 fb\(^{-1}\) (94 GeV < m\(_T\) < 125 GeV):

<table>
<thead>
<tr>
<th></th>
<th>Signal</th>
<th>WW</th>
<th>WZ/ZZ/W\gamma</th>
<th>t\bar{t}</th>
<th>tW/tb/tqb</th>
<th>Z/\gamma^* + jets</th>
<th>W + jets</th>
<th>Total Bkg.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>H + 0-jet</td>
<td>20 ± 4</td>
<td>101 ± 13</td>
<td>12 ± 3</td>
<td>8 ± 2</td>
<td>3.4 ± 1.5</td>
<td>1.9 ± 1.3</td>
<td>15 ± 7</td>
<td>142 ± 16</td>
<td>185</td>
</tr>
<tr>
<td>H + 1-jet</td>
<td>5 ± 2</td>
<td>12 ± 5</td>
<td>1.9 ± 1.1</td>
<td>6 ± 2</td>
<td>3.7 ± 1.6</td>
<td>0.1 ± 0.1</td>
<td>2 ± 1</td>
<td>26 ± 6</td>
<td>38</td>
</tr>
<tr>
<td>H + 2-jet</td>
<td>0.34 ± 0.07</td>
<td>0.10 ± 0.14</td>
<td>0.10 ± 0.10</td>
<td>0.15 ± 0.10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.35 ± 0.18</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ m_T = \sqrt{\left(E_T^{\ell\ell} + E_{T\text{miss}}^\ell\ell\right)^2 - \left|\mathbf{p}_T^{\ell\ell} + \mathbf{E}_{T\text{miss}}^\ell\ell\right|^2} \]
Higgs mass reconstruction

- Effective mass: invariant mass of the visible tau decay products and MET

- Collinear mass:
  
  - Assume neutrinos and visible decay products from the tau are collinear, then ditau mass can be calculated as
  
  \[ m_{\tau\tau} = \frac{m_{\ell\ell}}{x_1 \cdot x_2} \]

  - \( x_{1,2} \) are the fractions of momenta carried away by the visible decay products from the tau

- Missing Mass Calculator (MMC):
  
  - Mass estimation by requiring the mutual orientations between neutrinos and other tau decay products are consistent with the mass and decay kinematics of a tau
  
  - Scan in the allowed phase space region (including MET variables) for the most likely solutions
**Embedding sample for $Z \rightarrow \tau\tau$ background**

- $Z \rightarrow \tau\tau$ is the dominant background for all 3 sub-channels. To estimate this background from data, an embedding method is used:
  - Select $Z \rightarrow \mu\mu$ events from data, replace the two muons by taus, and remove muons and calorimeter cells passed in the original event
  - Pass the taus through Tauola decay, and fully simulate the tau decay products
  - Embed the simulated tau decay products into the original event

- The embedding procedure is validated by replacing the muons in data by muons from full simulation (mu-embedding)

- Only shapes and relative efficiencies are provided by the embedding sample. The absolute normalization comes from MC predictions after lepton/tau selections or from control regions
**ll-channel**: Drell-Yan and top background

* Z → ee, μμ Drell-Yan is controlled by the MET distribution in events under the Z peak:

\[
A_{\text{corrected}} = A_{\text{MC}} \times \frac{B_{\text{data}}}{B_{\text{data}} + D_{\text{data}}} \frac{B_{\text{MC}} + D_{\text{MC}}}{B_{\text{MC}}}
\]

* Top background: estimated from MC, and validated in top control regions:

- Require b-tag to obtain the top control sample
- Correct the top normalization in the control sample:

\[
\frac{N_{\text{CR,Data}}^{\text{top}}}{N_{\text{CR,MC}}^{\text{top}}} = \frac{N_{\text{CR,Data}} - N_{\text{other bkgd}}^{\text{CR,MC}}}{N_{\text{CR,MC}}^{\text{top}}}
\]
lh-channel: background estimation – Same Sign sample

Basic idea is that the background in OS signal region is equal to the background in SS signal region, plus any excess expected from OS than SS:

\[ n_{\text{OS} } = n_{\text{SS}} + n_{QCD}^{\text{OS-SS}} + n_{W+\text{jets}}^{\text{OS-SS}} + n_{Z\rightarrow\tau\tau}^{\text{OS-SS}} + n_{\text{other}}^{\text{OS-SS}} \]

- ”other” contains Z\rightarrow ee, \mu\mu, top (ttbar and single top) and diboson
- QCD excess (OS than SS) is expected to be zero – checked in a control region with MET<15 GeV:
  
  \[ r_{QCD}^{\text{OS/SS}} = 1.10 \pm 0.01(\text{stat.}) \pm 0.09(\text{syst.}) \rightarrow n_{QCD}^{\text{OS-SS}} = 0 \]
  
  - W+jet excess is estimated from a control region with \( m_{\tau} > 50 \text{ GeV} \)
  - Z\rightarrow\tau\tau excess is estimated from the embedding sample
  - ”other” excess is estimated from MC simulation

![Graph showing data and control regions](image)
**hh-channel**: background estimation – track fitting

- Anti-$K_T$ style track counting in a cone of $\Delta R<0.6$ around the tau
- 2-D fit to the track multiplicity distributions of the 2 taus
- Signal tau ($Z \rightarrow \tau\tau$) template is taken from MC, fake tau (QCD) template is from SS taus in data
- Fractions of QCD background can be obtained from the fits in both control sample and signal region

![Graphs showing track multiplicity distributions for Z→ττ and QCD](image-url)
Pinning down the Higgs couplings

**Global signal strength:**
\[ \mu = 1.4 \pm 0.3 \]

Equivalent to a global coupling ratio
\[ k = \frac{g}{g_{SM}} = \sqrt{\mu} = 1.19 \pm 0.13 \]

Double minima because of the $H \rightarrow \gamma\gamma$ loop:
\[ \sim k_Y^2 = |1.28 k_W - 0.28 k_t|^2 \]
Pinning down the Higgs couplings

- W and Z couplings are consistent
- Not enough data from $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$ to determine the up/down coupling ratios
- Not enough data from $H \rightarrow \tau\tau$ to determine the lepton/quark coupling ratios
Higgs decay width, spin and CP

\[ -2 \ln \Lambda(BR_{\text{inv., undet.}}) \]

\[ \Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{\text{inv., undet.}})} \Gamma_{H}^{\text{SM}} \]

\[ \text{BR}(H \to \text{invisible/undetected}) < 0.65 \text{ @ 68\% CL} \]