The Higgs Boson and Beyond at the LHC

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Experimental milestones:

- $u,d,s$-quark model in the 1960's
- Electroweak neutral current observed 1973 (CERN)
- $c$ quark in 1974 (SLAC, BNL)
- $b$ quark in 1977 (Fermilab)
- $W$ and $Z$ discovery 1983 (CERN)
- $g$ seen via 3-jet events in early 1980's (DESY ...)
- 3 light neutrino species established by LEP in 1989 (CERN)
- $t$ quark in 1995 (Fermilab)
- $v$ oscillations and mixing (exp'ts in Asia and worldwide)
- $H$ discovery in 2012 (CERN/LHC)

Particle Physics was, and remains, fundamentally global in scope
The basic principle is very familiar now
- Gauge symmetry forbids simple mass terms in the SM Lagrangian
- BEH mechanism → complex scalar doublet of fields gives masses to the W & Z, and leaves one physical massive scalar boson H
- Later developments → same scalar fields give masses to the fermions in SM

“for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”
Large Hadron Collider
Proton-proton & heavy-ion collisions

LHC ring:
- 27 km circumference
- ~100 m underground

Lake Geneva

CERN main site
Large Hadron Collider
Proton-proton & heavy-ion collisions

LHC ring:
27 km circumference
-100 m underground

CERN main site
Lake Geneva
Large Hadron Collider

- 1232 14m-long superconducting main dipoles
- Two-in-one coil design
- Maximum field 8.4 T
- Cooled to 1.9K with 90 tonnes of LHe
CMS Detector

14000t, 29m long x 15m diameter
13m long 6m-bore solenoid, B = 3.8T
All-silicon tracker
PbWO\textsubscript{4} crystal EM calorimeter
Complexity of both experiments: ~100 M channels, with timing capable of separating particles from adjacent bunch-crossings (25ns)

Huge physical size allows precise measurements of momentum as particles bend in B field (~10 µm precision), and depth to absorb high energy jets of hadrons
Each year, ATLAS and CMS write 10's PB of data. Around 250,000 CPU cores on the computing Grid are used, spread over ~200 sites, to analyse them.
Physics landscape at the LHC

Peak luminosity so far:
$$L = 0.77 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$
(77% of design, at 60% of design energy & with half the number of bunches)

Before selections, huge backgrounds from strong interaction processes to the rare/electroweak processes

→ powerful trigger systems to reduce rates online (few μs to few s) by a factor $O(10^5)$

→ exceptional detector performance needed (granularity, resolution, particle ID ...)

→ needs serious computing power via the Grid
Data collected

Key parameters:
Centre-of-mass energy $\sqrt{s}$ and integrated luminosity

$$N_{\text{obs}} = \sigma \varepsilon_{\text{exp}} \int L \, dt$$

Want to be large for interesting processes!

Given by nature, calculated by theorists, measured by experiment!

Experimental efficiency for a process: optimised by experiment

Integrated luminosity: comes from the LHC performance

$$L = \frac{f_{\text{rev}} n_{\text{bunch}} N_p^2}{4\pi\sigma_x\sigma_y}$$
Data collected

Key parameters:
Centre-of-mass energy \( \sqrt{s} \) and integrated luminosity

\[ N_{\text{obs}} = \sigma \varepsilon_{\text{exp}} \int L \, dt \]

The price of high luminosity: pile-up
Data collected

Key parameters:
Centre-of-mass energy $\sqrt{s}$ and integrated luminosity

$$N_{\text{obs}} = \sigma \varepsilon_{\text{exp}} \int L \, dt$$

The price of high luminosity: pile-up
Vast number of measurements and searches (around 800 papers by now from ATLAS and CMS together)

cern.ch/atlasresults
twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Many topics will be discussed in later plenary and parallel talks

In this talk, I focus on our new scalar boson H
The Higgs Boson... (Discovery and since)
July 4th, 2012 (CERN and Melbourne)
H→γγ & H→ZZ(*)→4ℓ

4 July 2012

Discovery relied on the two golden channels

- Full reconstruction of decay products
- Excellent mass resolution

Combining the channels, on 4 July 2012 both ATLAS and CMS had 5σ signals
Candidate H decay into four electrons

Candidate event for $H \rightarrow ZZ^{(*)} \rightarrow eeee$
Since the discovery, with the H

Full Run-1 data sample for analysis, approx:
20 fb\(^{-1}\) at 8 TeV + 5 fb\(^{-1}\) at 7 TeV

\[ N(H, \text{full Run1}) \approx 2.5 \times N(H, \text{July 2012}) \]

Exploring the production, decays and properties of the H
- Measuring more precisely and extensively the decays to bosons
- Investigating the production kinematics & production processes
- Looking for the fermionic decay modes
- Measuring the properties of the H: mass, \(J^P\)
- Searching for unexpected/rare decays

Using the H as a tool for potential further discoveries
- Via unexpected decays (e.g. to invisibles)
- Searching for massive particles decaying to H
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I can only flash a small selection, even of the H results, in this talk
H production processes

$ggF$

$VBF$

$VH$

$ttH$

$\sqrt{s} = 8$ TeV

$\sigma(pp \rightarrow H)$

$M_H$ [GeV]

$H^0$

$qqH$ (NNLO QCD + NLO EW)

$WH$ (NNLO QCD + NLO EW)

$ZH$ (NNLO QCD + NLO EW)

$ttH$ (NLO QCD)
Usefulness of each channel depends on branching ratio, ability to reconstruct fully the H decay products, and backgrounds. “Golden” discovery channels are $H \rightarrow ZZ(\ast) \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$. 
Key ingredients

The Higgs results demonstrate the fantastic performance of the LHC and of the ATLAS and CMS hardware, software and collaborators!

Sophisticated technologies for extracting small signals from large backgrounds (building on a lot of groundwork at the Tevatron etc)

- **Data-driven background techniques** - control directly background levels and shapes from nearby regions in phase-space
  - Different applications & details in different channels, but essential for confidence in understanding of backgrounds
- **Multivariate analysis (MVA) techniques**, e.g. “Boosted Decision Trees” (BDTs)
- **High quality theory predictions**, e.g. NLO+PS Monte Carlos - strong support from theory community, including via LHC HXSWG
- **Excellent detector simulations** with Geant4 - enabled by very large-scale computing resources (CPU and storage)
- **The Grid**: we could not analyse LHC data without it

Also physics helps us: huge statistics of control samples (Z, W, t\bar{t}, J/\psi ... ...)

D Charlton / Birmingham - 30 March 2015, IoP NP/AP/PP Manchester
Performance

Huge samples of $Z\rightarrow\ell\ell$, $W\rightarrow\ell\nu$, $J/\psi$, $t\bar{t}$ events provide clean samples to understand detector and object performance - very few examples.

$\pm0.2\% - 0.6\%$ on $\gamma E_T$-scale at $\sim 60$ GeV

$\pm0.04\% - 0.2\%$ on $\mu p_T$-scale at $\sim 40$ GeV

$b$-tag efficiency to $\sim 2\%$ at 100 GeV
\[ \text{H} \rightarrow \gamma\gamma \quad \text{BR} \sim 0.2\% \]

Best mass resolution needs right primary vertex (PV) - challenge with high pileup! *(Specific to this channel!)*

- Mass res'n: \( m^2(\gamma\gamma) = 2E_1 E_2 (1-\cos \alpha) \), \( \alpha \): \( \gamma\gamma \) opening angle
- Choosing right PV also important for selection and categorisation
- Multivariate approaches in ATLAS/CMS, aided by photon pointing in ATLAS

\[ \sigma_z \sim 1.5 \text{cm} \]

\[ \theta \rightarrow \text{z direction with calo} \rightarrow \text{z of primary vertex} \]

Measure \( \theta \) direction with calo \( \rightarrow \text{z of primary vertex} \)

PV effy vs pileup for \( \text{H} \rightarrow \gamma\gamma \) and \( Z \rightarrow \text{ee control} \)
With full statistics, signal above $5\sigma$ in ATLAS & CMS
Events subdivided into categories according to the
event properties and (optionally) $\gamma\gamma$ mass resolution
- gives information about production mechanisms
- improves mass sensitivity → later slide

ATLAS uses different event categories for different measurements
H→ZZ(*)->4ℓ  \[ \text{BR} \sim 0.013\% \]

With full statistics, signal 6-8σ
Event categories employed again

CMS

\( \sqrt{s} = 7 \text{ TeV}, L = 5.1 \text{ fb}^{-1} \); \( \sqrt{s} = 8 \text{ TeV}, L = 19.7 \text{ fb}^{-1} \)

**ATLAS**

\[ H \rightarrow ZZ^* \rightarrow 4\ell \]

\( \sqrt{s} = 7 \text{ TeV} \int L dt = 4.5 \text{ fb}^{-1} \)

\( \sqrt{s} = 8 \text{ TeV} \int L dt = 20.3 \text{ fb}^{-1} \)

**Data**
- Signal \( m_{H} = 125 \text{ GeV} \mu = 1.51 \)
- Background ZZ*
- Background Z+jets, t\bar{t}
- Systematic uncertainty

**ATLAS Simulation**

\[ H \rightarrow ZZ^* \rightarrow 4\ell \]

\( m_{h} = 125 \text{ GeV} \) 110 < \( m_{4\ell} \) [GeV] < 140

**Signal Composition (%)**
- Inclusive
- VBF enriched
- VH-hadronic enriched
- VH-leptonic enriched
- ggF enriched
$H \rightarrow WW^{(*)} \rightarrow \ell \nu \ell \nu$  BR $\sim$ 1%

Acoplanar dilepton pair with substantial missing-$E_T$

- $b$-veto against $t\bar{t}$ background
- Category-based analyses, crucially for $n$(jet)
- SM WW background separated using angular separation of leptons – exploits spin-0 of the H

CMS 4.3σ significance (expect 5.8σ)

$ATLAS 6.1\sigma$ significance (expect 5.8σ)

Now also at the $>5\sigma$ level → $5\sigma$ observations of all 3 bosonic decays WW, ZZ, $\gamma\gamma$
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and two jets with VBF topology

Longitudinal view

Projected $\eta$-$\varphi$ view

Run 214680, Ev. no. 271333760
Nov. 17, 2012, 07:42:05 CET

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Hadronic & leptonic $\tau$ decays considered

$m(\tau\tau)$ reconstructed using also missing-$E_T$ (e.g. MMC)

Large $Z\rightarrow\tau\tau$ background modelled using data $Z\rightarrow\mu\mu$
with $\mu$ replaced by simulated $\tau$ (“embedding”)

Event categories employed

**Observed 4.5$\sigma$ (expect 3.4$\sigma$)**

**BR ~ 6.3%**

**Observed 3.2$\sigma$ (expect 3.7$\sigma$)**

**ATLAS+CMS combination: reach 5$\sigma$?**

**Strong evidence for $H \rightarrow \tau\tau$ decays**
(W/Z)H, H → b¯b

BR ~ 58%

ggF H production and H→b¯b decay: overwhelming background from strong production of b¯b pairs

- Use associated production WH, ZH with leptonic W, Z decays (ℓℓ, ℓν, νν)
- Challenging backgrounds from V+heavy flavours
- (W/Z) leptonic Z with Z→bb - cross-check

m(b¯b) resolution ~11-15 GeV

Both experiments expect 2.6σ for SM case, ATLAS see 1.4σ, CMS 2.0σ
No evidence yet for H→b¯b decays at 125 GeV
**Associated production \( \bar{t}tH \)**

Signal very difficult to isolate - special analyses

Final states with \( \bar{t}t \) signature and \( H \) decay products

- Searches in the \( b\bar{b}, \gamma\gamma, \tau\tau \) channels, and “multilepton” channels (sensitive to \( WW, ZZ, \tau\tau \) \( H \) decays)

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**ATLAS**

![Graph showing data and fits for \( \bar{t}tH \) search](image)

- \( \bar{t}tH (\mu_{\text{fit}}=1.5) \)
- \( \bar{t}tH (\mu_{\text{95\% excl.}}=3.4) \)
- Background

**arXiv:1593.05066**

\( \bar{t}tH (H \rightarrow b\bar{b}) \)

\( \sqrt{s}=8 \text{ TeV, 20.3 fb}^{-1} \)

Combined

Single lepton and Dilepton

\( \bar{t}tH, H \rightarrow b\bar{b} \) search

Alone: \( \mu<3.4 @ 95\% \text{CL} \)

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**CMS**

![Graph showing CMS results for \( H \) search](image)

- CMS: \( \mu=2.8^{+1.0}_{-0.9} (3.2\sigma, 1.2\sigma \text{ exp.}) \)

Combining channels, modest excess
Signal strength summary

Putting it all together, grouping by decay
Assumes SM-like ratios of production process cross-sections

<table>
<thead>
<tr>
<th>ATLAS Preliminary</th>
<th>m_H = 125.36 GeV</th>
<th>Total uncertainty ± 1σ on μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → γγ</td>
<td>μ = 1.17±0.28</td>
<td>σ(stat.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>σ(sys inc.)</td>
</tr>
<tr>
<td></td>
<td>μ = 1.46±0.40</td>
<td>σ(theory)</td>
</tr>
<tr>
<td></td>
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<td>-0.34</td>
</tr>
<tr>
<td>H → ZZ*</td>
<td>μ = 1.18±0.24</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>-0.21</td>
</tr>
<tr>
<td>H → WW*</td>
<td>μ = 0.63±0.39</td>
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<tr>
<td></td>
<td></td>
<td>-0.37</td>
</tr>
<tr>
<td>H → bb</td>
<td>μ = 1.44±0.42</td>
<td></td>
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<tr>
<td></td>
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<td>-0.37</td>
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<tr>
<td>H → ττ</td>
<td>μ = 0.63±0.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.37</td>
</tr>
<tr>
<td>H → μμ</td>
<td>μ = 2.7±4.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-4.5</td>
</tr>
<tr>
<td>Combined</td>
<td>μ = 1.18±0.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.14</td>
</tr>
</tbody>
</table>

Combined
μ = 1.00 ± 0.14

19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)

CMS
m_H = 125 GeV

Consistent with SM expectation and between experiments
Precision >~20%
Disentangling production processes

Putting it all together, grouping by production process
Assumes SM-like decay branching fraction ratios

This view also consistent with SM

Interesting to watch $t\bar{t}H$ with new data?
Disentangling production processes

Putting it all together, grouping by production process
Remove need to assume SM BRs by comparing VBF and ggF within each decay mode

ATLAS Preliminary
\( \sqrt{s} = 7 \text{ TeV}, 4.5-4.7 \text{ fb}^{-1} \)
\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

- Standard Model
- Best fit
- 68% CL
- 95% CL

HVV production vertex strength

Hff production vertex strength

\( m_{H} = 125.36 \text{ GeV} \)
Production kinematics, including jet(s)

Combined measurements of production properties of H using the $\gamma\gamma$ and 4$\ell$ final states, fully-corrected to particle level (ATLAS speciality)

- $p_T(H)$
- $y(H)$
- $N(\text{jets})$
- $p_T(\text{jet1})$

Mainly sensitive to ggF

Useful, especially with more statistics, for testing models of H production

So far, consistent with SM
Couplings

Put it all together in global combinations, to derive coupling strengths

Many possibilities, too many to describe here - e.g. with “κ parameters” (coupling strength modifiers) and many more

Bottom line: the H is still consistent with being a SM Higgs - so far

κ’s indicate coupling relative to SM (κ=1)
κ_F - all Hff couplings vary together
κ_V - all HVV couplings vary together
High-mass couplings

Probe effects of H propagator at high mass in diboson (ZZ, WW) final-states
- Sensitive to high-mass HVV couplings
- Not sensitive to $\Gamma_H$, unlike on-shell measurements
- With assumptions, can constrain $\Gamma_H$
  - Assumptions poor if new physics enters at a higher mass scale

With SM couplings, small negative interference at high mass
High-mass couplings

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High-mass couplings

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"$\Gamma_H < 22 \text{ MeV @ 95}\% \text{CL}""

With SM couplings, small negative interference at high mass - constraints come mainly because no excess seen at high-mass
Invisible Decays?

Probe for invisible H decays in VH and VBF production

- Large missing-$E_T$ from H decay
- W/Z decay products, or f’wd/b’kwd jets in VBF

Absence of signals $\rightarrow$ limits on dark matter in “Higgs portal” models, where DM interacts with normal matter via H exchange

$\text{BR}(H\rightarrow\text{inv})<0.29@95\%\text{CL}$
Limits on DM in H-portal models

Absence of signals → limits on dark matter in “Higgs portal” models, where DM interacts with normal matter via H exchange
The absence of $H\rightarrow\mu\mu$ (or $H\rightarrow ee$) signals, together with the strong evidence for substantial $H\rightarrow\tau\tau$ decays, gives clear evidence that not only does the $H(125)$ couple to leptons, it does so in a way which depends strongly on the fermion mass.


### Rare decays (II)

**H → Zγ search**

Channel can probe Hcc coupling - but far from SM sensitivity: BR(H → J/ψγ) ~ 3x10⁻⁶ in SM

Limit BR(H → J/ψγ) < 1.5x10⁻³

**Upper limit ~ 10xSM @95% CL**
Mass combination

Only fully reconstructible channels without jets contribute significantly to the mass measurement.

ATLAS and CMS have comparable precisions, and although there is a modest tension within experiments, agreement between experiments is excellent.
Mass combination

\[ m_H = 125.09 \pm 0.24 \text{ GeV} = 125.09 \pm 0.21 \text{(stat)} \pm 0.11 \text{ (syst)} \text{ GeV} \]

Overall precision of 2‰, statistical error dominates

Systematic error can be improved with more statistics, if the excellent understanding of detector performance is maintained as the pileup increases and the detectors age
Spin-parity

Use angular distributions of H decay products to test if decaying object is consistent with $J^P=0^+$

All tests favour $0^+$, alternative models excluded at least 97% CL

It looks just like a $0^+$ state!
SUSY searches in Run-1

Plethora of searches for SUSY “leave no stone unturned”

Example: electroweak production of charginos/neutralinos
Caution: different decay modes overlaid, curves not directly comparable to each other

Amongst these, searches for neutralinos decaying via the H, charginos via W’s as preferred in “natural” SUSY models - challenging analyses!

H as a tool for discovery
<table>
<thead>
<tr>
<th>Model</th>
<th>$e, \mu, \tau, \gamma$</th>
<th>Jets</th>
<th>$E_{T}^{miss}$</th>
<th>$\sqrt{s}$</th>
<th>Mass limit</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.7 TeV</td>
<td>m(\tilde{\ell})-m(\tilde{\nu})</td>
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<tr>
<td>$q_{\tilde{q}}, \tilde{q}_{\tilde{q}}$</td>
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<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>850 GeV</td>
<td>m(\tilde{q})_0-0 GeV, m(1^{st} gen. q)=m(2^{nd} gen. q)</td>
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<td>$m_{\tilde{q}_{\tilde{q}}}$</td>
<td>1</td>
<td>0-1 jet</td>
<td>Yes</td>
<td>20.3</td>
<td>250 GeV</td>
<td>m(\tilde{q})_1 = m(c)</td>
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<td>$g_{\tilde{q}_{\tilde{q}}}$</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.33 TeV</td>
<td>m(\tilde{q})_0-0 GeV</td>
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<tr>
<td>$g_{\tilde{q}_{\tilde{q}}}=m(\tilde{W}^{+}W^{-})$</td>
<td>1</td>
<td>0-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.2 TeV</td>
<td>m(\tilde{q})_0-0 GeV</td>
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<tr>
<td>GMSB (NLSP)</td>
<td>0</td>
<td>0-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.32 TeV</td>
<td>t\bar{t} &gt; 20</td>
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<tr>
<td>GGM (bino NLSP)</td>
<td>1-2 $\tau + 0.1 \gamma$</td>
<td>0-2 jets</td>
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<td>20.3</td>
<td>1.6 TeV</td>
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<td>2 $\gamma$</td>
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<td>20.3</td>
<td>1.28 TeV</td>
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<td>GGM (higgsino-bino NLSP)</td>
<td>1 $\tau + \gamma$</td>
<td>-</td>
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<td>4.8</td>
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<tr>
<td>GGM (higgsino NLSP)</td>
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<td>GGM (higgsino NLSP)</td>
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<td>m(NLSP)=200 GeV</td>
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<td>Gravitino LSP</td>
<td>3 $\gamma$</td>
<td>-</td>
<td>Yes</td>
<td>20.3</td>
<td>865 GeV</td>
<td>(m(\tilde{\chi})<em>S\times 10^{4} eV, m(z(\tilde{\chi})</em>{0/1}+m(\tilde{\nu}))=1.5 TeV</td>
</tr>
</tbody>
</table>

- **Inclusive Searches**

- **3rd gen. quark direct production**

- **EW direct**

- **Direct $t\bar{t}$ production, long-lived $t\bar{t}$**

- **Stable, stopped R-hadron**

- **GMSB, stable $\tilde{\ell}_{3}$, $\tilde{\ell}_{3}$→$t\bar{t}(\ell, \ell')$**

- **GMSB, stable $\tilde{\ell}_{3}$, long-lived $\tilde{\ell}_{3}$**

- **$q\tilde{q}\rightarrow q\tilde{q}_{\tilde{q}}$ (RPV)**

- **Scalar charm, $\tilde{c}_{1}^{0}$**

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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1$\sigma$ theoretical signal cross section uncertainty.*
“Exotic” searches

Beyond SUSY, a host of other model possibilities for Beyond the Standard Model physics, with various levels of motivation

- Open perspective - we do not know what we may find
- There are many many possible models - and event signatures
- Models act as benchmarks and guides - but we are open to as much as we can

H Bachacou
Exotica Limits (II)

CMS Searches for New Physics Beyond Two Generations (B2G)
95% CL Exclusions (TeV)

Excluded Mass (TeV)

Vector-like Q'
Vector-like T'
Vector-like B'

Dark matter

tf Resonances
tb Resonances
Excited tops
Displaced tops
Run-1 searches have not shown any sustained hints of new physics

All the same problems with the SM are still there - and now we ramp the collision energy up from 8 to 13 TeV, and the luminosity above design

The LHC is coming of age
Looking Forward...
“Run-2”

LHC consolidated in last two years (Long Shutdown 1, LS-1)

- Energy increasing to 13 TeV
- Luminosity increasing above $10^{34}$ design
- Pile-up reduced by going to 25ns bunch spacing (from 50ns) - but increases again due to energy and luminosity

<table>
<thead>
<tr>
<th>Year</th>
<th>Nc</th>
<th>Beta</th>
<th>ppb</th>
<th>EmitN</th>
<th>Lumi [cm$^{-2}$s$^{-1}$]</th>
<th>Days (approx)</th>
<th>Int lumi</th>
<th>Pileup</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>50 ns</td>
<td>1300</td>
<td>80</td>
<td>1.2e11</td>
<td>2.5</td>
<td>4.8e33</td>
<td>21</td>
<td>~1 fb$^{-1}$</td>
</tr>
<tr>
<td>2015.1</td>
<td>2592</td>
<td>80</td>
<td>1.1e11</td>
<td>2.5</td>
<td>7.6e33</td>
<td>30</td>
<td>3 fb$^{-1}$</td>
<td>21</td>
</tr>
<tr>
<td>2015.2</td>
<td>2592</td>
<td>40</td>
<td>1.1e11</td>
<td>2.5</td>
<td>1.2e34</td>
<td>48</td>
<td>8 fb$^{-1}$</td>
<td>34</td>
</tr>
</tbody>
</table>

2015 alone

Run-2: aiming for 100-150 fb$^{-1}$

M Lamont
LHC status today

Repairing & requalifying all LHC magnet interconnects is done

Whole LHC is cold, all sectors are “trained” for \( \sqrt{s} = 13 \) TeV

One sector (S34) has a short in the (cold) connection to the protection diodes → actions in progress to fix - more news later today?

This is now causing delays
Cross-section ratio: 13 TeV / 8 TeV

- Substantial discovery potential for high-mass objects already with 1 fb$^{-1}$ $m$(system) > ~2 TeV
- Major increase in reach across ~all searches with 10 fb$^{-1}$
H studies and 2015 data

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (ggF)</td>
<td>2.3</td>
</tr>
<tr>
<td>H (VBF)</td>
<td>2.4</td>
</tr>
<tr>
<td>WH</td>
<td>2.9</td>
</tr>
<tr>
<td>ttH</td>
<td>3.9</td>
</tr>
</tbody>
</table>

With 10 fb⁻¹: similar statistics in the main channels to Run-1 sample (caution: backgrounds increase too!)

Increase in sensitivity for ttH production

Searches for new scalars at higher masses will benefit even more quickly, as for other massive new particles!
Longer-term LHC roadmap

Run 1: energy 7-8 TeV, 25 fb⁻¹ of data

Shutdown 1: phase 0 upgrade

Run 2: energy 13+ TeV, ~120 fb⁻¹ of data

Shutdown 2: phase 1 upgrade

Run 3: energy 14 TeV, ~350 fb⁻¹ of data

Shutdown 3: phase 2 upgrade

HL-LHC: energy 14 TeV, ~3000 fb⁻¹ of data
Long-term prospects for H measurements

Higgs couplings may indicate new physics: a few percent precision is a good target

Higgs Snowmass report (arXiv:1310.8361)

Deviation from SM due to particles with M=1 TeV

<table>
<thead>
<tr>
<th>Model</th>
<th>$\kappa_V$</th>
<th>$\kappa_b$</th>
<th>$\kappa_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet Mixing</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
</tr>
<tr>
<td>2HDM</td>
<td>$\sim 1%$</td>
<td>$\sim 10%$</td>
<td>$\sim 1%$</td>
</tr>
<tr>
<td>Decoupling MSSM</td>
<td>$\sim -0.0013%$</td>
<td>$\sim 1.6%$</td>
<td>$\sim -4%$</td>
</tr>
<tr>
<td>Composite</td>
<td>$\sim -3%$</td>
<td>$\sim -(3-9)%$</td>
<td>$\sim -9%$</td>
</tr>
<tr>
<td>Top Partner</td>
<td>$\sim -2%$</td>
<td>$\sim -2%$</td>
<td>$\sim +1%$</td>
</tr>
</tbody>
</table>

Future LHC data will allow to measure H couplings at 2-10% level (cf 20-50% today), and to access rare decays such as H→μμ
Conclusions

Run-1 of the LHC, at $\sqrt{s} = 7$ and 8 TeV, was a great success. A wealth of measurements have established the continuing validity of the SM at the first LHC energies, and laid the foundation for future searches.

A huge set of measurements of the new H boson have been made, including a 2% measurement of its mass:

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$

So far it looks like the SM Higgs boson in all respects.

The discovery has energised, and helped re-focus, searches beyond the Standard Model - but no sustained hints of BSM physics seen in Run-1.

The increase of centre-of-mass energy to 13 TeV in the coming months will extend the mass reach much further, well into the TeV region → what will we find?

Once more into the unknown…
Spin model investigations

Very extensive studies by CMS on a multitude of possible non-$0^+$ models, also probing a possible anomalous coupling structure in the $0^+$ case

Fraction of pseudo-scalar state $< 0.43$ at 95%CL
Many other results (published and preliminary) on H, also searches for other Higgs bosons, released since April

Search for extra scalars decaying to $\gamma\gamma$

Search for MSSM neutral Higgs bosons
Phase-2 Upgrades

For the HL-LHC era, LHC plans to run with “levelled” luminosity five times the original design, until ~2035 → Requires significant upgrades to the detectors to cope with rate, aging, and radiation damage

CMS
- New inner tracking detector
- Entirely new endcap calorimetry
- Substantial electronics, trigger & DAQ upgrades

ATLAS
- New inner tracking detector
- Substantial electronics, trigger and DAQ upgrades
- Possible new small calorimeter in forward region

Cost < ½ original detectors

Construction should start around 2018
Major R&D is needed, and underway for some time