Higgs boson production at the LHC

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Higgs at the LHC

Breathtaking progress in $O(2)$ years

±15% (from dedicated coupling measurements)

±0.2%
ATLAS and CMS experiments

**ATLAS**: emphasis on excellent jet and missing $E_T$ resolution, particle identification, and standalone muon measurement

**CMS**: emphasis on excellent electron/photon and tracking (muon) resolution

Detectors well understood, stable operation and data taking efficiencies above 90%
Challenges with high luminosity

Continuous improvement required for triggering, reconstruction, and identification algorithms.

Main impact on jets, missing $E_T$, and tau reconstruction (as well as on trigger rates and computing).

$Z \rightarrow \mu\mu$ event with 25 reconstructed vertices.
Jets and missing $E_T$

Include tracking information to mitigate effects from pileup interactions

Several algorithms from ATLAS and CMS

Example:
Track based measurement of soft objects, $O(20\%)$ resolution improvement

Reconstructed - True missing $E_T$
Higgs production at the LHC

8 TeV pp collisions

- $pp \rightarrow H$ (NNLO+NNLL QCD + NLO EW)
- $pp \rightarrow q\bar{q}H$ (NNLO QCD + NLO EW)
- $pp \rightarrow WH$ (NNLO QCD + NLO EW)
- $pp \rightarrow ZH$ (NNLO QCD + NLO EW)
- $pp \rightarrow t\bar{t}H$ (NLO QCD)

$\sqrt{s} = 8$ TeV

$M_H$ [GeV] vs. $(pp \rightarrow H+X)$ [pb]

- Gluon fusion: $g \rightarrow t\bar{t}H$, $t \rightarrow qW, Zq$, $H \rightarrow qq$, $q \rightarrow W, Zq$
  - $\sim 19$ pb

- Vector boson fusion (VBF): $q \rightarrow W, Zq$, $W, Z \rightarrow qH$
  - $\sim 1.6$ pb

- Associated production with $W/Z$:
  - $q \rightarrow W, Zq$
  - $W, Z \rightarrow qH$
  - $H \rightarrow qq$, $q \rightarrow W, Zq$

- Associated production with $t\bar{t}$:
  - $g \rightarrow t\bar{t}H$
  - $t \rightarrow qW, Zq$, $H \rightarrow qq, q \rightarrow W, Zq$

$\sim 500k$ Higgs bosons produced at the LHC
Higgs production at the LHC

Only one in \(~10^{10}\) events will be a Higgs boson at the LHC.

*pp cross sections*

- $\sigma_{\text{tot}}$ 
- $\sigma_{b}$ 
- $\sigma_{W}$ 
- $\sigma_{Z}$ 
- $\sigma_{t}$ 
- $\sigma_{ggH}$

LHC at $\sqrt{s} = 8$ TeV

- Gluon fusion: $\sim 19$ pb
- Vector boson fusion (VBF): $\sim 1.6$ pb
- Associated production with $W/Z$: $\sim 1.1$ pb
- Associated production with $tt$: $\sim 0.13$ pb
Higgs decays
Higgs decays
Higgs decays

Best experimental mass resolution
Higgs decays

Coupling to bosons

Best experimental mass resolution
Higgs decays

Coupling to fermions

Coupling to bosons

Best experimental mass resolution
Overall experimental strategy

Investigate a large number of final states, with sub-channels to separate different productions (and to increase overall significance)

Probe Lagrangian structure. Measure mass, spin and CP properties → Next talk from Guillelmo

<table>
<thead>
<tr>
<th>Channel</th>
<th>ggF</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
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</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$ZZ \rightarrow 4\ell$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$WW \rightarrow ll + 2\nu$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$bb$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>✓</td>
<td>✓</td>
<td></td>
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<tr>
<td>$Z\gamma$</td>
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<table>
<thead>
<tr>
<th>Mass</th>
<th>Spin</th>
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<tr>
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<td>✓</td>
</tr>
<tr>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

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Main discovery channels

Simple signatures, with excellent mass resolution

$H \rightarrow \gamma \gamma$

- BR $\sim 0.2\%$
- Exp. signal yield $\sim 450$
- S/B $\sim 3\%$

$H \rightarrow 4\ell$

- BR $\sim 0.013\%$
- Exp. signal yield $\sim 20$
- S/B $\sim 1.6$
Optimise for high lepton selection efficiency and good 4-lepton mass resolution

Main backgrounds: SM $ZZ^*$ production (irreducible), $Z+jj$, top

$H \rightarrow ZZ^* \rightarrow 4\ell$
Di-photon decay mode

Select events with two isolated high pT photons

Quantify excess in steeply falling di-photon mass spectrum

![Graph showing di-photon mass spectrum with data points and signal predictions.]

Critical to reach rejections $O(10^4)$

- **Reducible**
  \[ q \rightarrow \pi^0 \]

- **Irreducible**
  \[ q \rightarrow \gamma \]
Energy scale and resolution

Electron and muon energy scale (and resolution) corrections determined from large Z and J/ψ samples

Photons need accurate material description for $e \rightarrow \gamma$ extrapolation, studied with several *in-situ* measurements
Improving the sensitivity

Separate events into categories with different S/B, resolutions and different relative contributions of signal production modes

CMS Unpublished

<table>
<thead>
<tr>
<th>Category</th>
<th>Signal Fraction (%)</th>
</tr>
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<tbody>
<tr>
<td>Untagged 0</td>
<td>6.0 total expected signal</td>
</tr>
<tr>
<td>Untagged 1</td>
<td>50.6 total expected signal</td>
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<tr>
<td>Untagged 2</td>
<td>117.2 total expected signal</td>
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<tr>
<td>Untagged 3</td>
<td>153.1 total expected signal</td>
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<tr>
<td>Untagged 4</td>
<td>121.4 total expected signal</td>
</tr>
<tr>
<td>VBF Dijet Tag 0</td>
<td>4.5 total expected signal</td>
</tr>
<tr>
<td>VBF Dijet Tag 1</td>
<td>5.6 total expected signal</td>
</tr>
<tr>
<td>VBF Dijet Tag 2</td>
<td>13.7 total expected signal</td>
</tr>
<tr>
<td>VH Lepton Tight</td>
<td>1.4 total expected signal</td>
</tr>
<tr>
<td>VH Lepton Loose</td>
<td>0.9 total expected signal</td>
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<tr>
<td>VH MET Tag</td>
<td>1.8 total expected signal</td>
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<tr>
<td>VH Dijet Tag</td>
<td>1.6 total expected signal</td>
</tr>
<tr>
<td>tth Leptonic Tag</td>
<td>0.5 total expected signal</td>
</tr>
<tr>
<td>tth Multijet Tag</td>
<td>0.6 total expected signal</td>
</tr>
<tr>
<td>Combined</td>
<td>475.0 total expected signal</td>
</tr>
</tbody>
</table>

$H \rightarrow \gamma\gamma$

19.7 fb$^{-1}$ (8 TeV)

$S/\left(S+B\right)$ (8 TeV)
CMS

$H \to \gamma \gamma$

$S/(S+B)$ weighted sum

Data

$S+B$ fits (weighted sum)

B component

$\pm 1\sigma$

$\pm 2\sigma$

$\hat{\mu} = 1.14^{+0.26}_{-0.23}$

$m_H = 124.70 \pm 0.34$ GeV

B component subtracted

$m_{\gamma\gamma}$ (GeV)
H → Zγ and H → μμ

Both analyses exploit similar experimental techniques to H → γγ

No significant excesses observed yet, limits σ/σ_{SM} ~ 7-10 at m_H = 125 GeV
Differential cross sections

Probe underlying kinematic properties of Higgs boson production and decay

Variables specifically sensitive to:
- Spin-parity
- Different production modes
- Higher-order corrections

Number of jets

$H \rightarrow \gamma\gamma$
Differential cross sections

Probe underlying kinematic properties of Higgs boson production and decay

Variables specifically sensitive to:

- Spin-parity
- Different production modes
- Higher-order corrections

Higgs boson transverse momenta

\[ p_T^H \]

\[ H \rightarrow ZZ \]
$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and two jets with VBF topology

**Longitudinal view**

**Projected $\eta$-$\varphi$ view**

<table>
<thead>
<tr>
<th>Exp. signal yield</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim500$</td>
<td>$\sim15%$</td>
</tr>
</tbody>
</table>
Analysis strategy

Various missing $E_T$ related cuts to remove main DY contribution

Split by jet-multiplicity and lepton flavour

Topological cuts for further bkgr. reduction / VBF selection
Analysis strategy

Various missing $E_T$ related cuts to remove main DY contribution

Split by jet-multiplicity and lepton flavour

Topological cuts for further bkgr. reduction / VBF selection

Same flavour

Opposite flavour

Most sensitive channel
Final signal extraction

Most sensitive variable: transverse mass

Need good understanding of all high-energy SM processes
Evidence for VBF production

Crucial for coupling measurements
$H \rightarrow \tau\tau$

Exp. signal yield: \(~300\)

S/B: \(~1\sim30\%\)
Due to overwhelming multi-jet backgrounds, need additional signature from exclusive production modes (VH, ttH, VBF)
Increase signal discrimination by combining several kinematic distributions into a multivariate discriminant.
Evidence for Higgs-Yukawa coupling

A fundamental part of the Standard Model
### Higgs boson rates per decay channel

#### ATLAS Preliminary

**$m_H = 125.36 \text{ GeV}$**

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Total uncertainty</th>
<th>$\sigma_{\text{stat.}}$</th>
<th>$\sigma_{\text{sys inc.}}$</th>
<th>$\sigma_{\text{theory}}$</th>
<th>$\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>$1.17^{+0.28}_{-0.26}$</td>
<td>$0.23$</td>
<td>$0.16$</td>
<td>$0.11$</td>
<td>$1.17^{+0.28}_{-0.26}$</td>
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<tr>
<td>$H \to ZZ^*$</td>
<td>$1.46^{+0.40}_{-0.34}$</td>
<td>$0.35$</td>
<td>$0.31$</td>
<td>$0.29$</td>
<td>$1.46^{+0.40}_{-0.34}$</td>
</tr>
<tr>
<td>$H \to WW^*$</td>
<td>$1.18^{+0.24}_{-0.21}$</td>
<td>$0.16$</td>
<td>$0.17$</td>
<td>$0.14$</td>
<td>$1.18^{+0.24}_{-0.21}$</td>
</tr>
<tr>
<td>$H \to bb$</td>
<td>$0.63^{+0.39}_{-0.37}$</td>
<td>$0.31$</td>
<td>$0.24$</td>
<td>$0.16$</td>
<td>$0.63^{+0.39}_{-0.37}$</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>$1.44^{+0.42}_{-0.37}$</td>
<td>$0.30$</td>
<td>$0.29$</td>
<td>$0.16$</td>
<td>$1.44^{+0.42}_{-0.37}$</td>
</tr>
<tr>
<td>$H \to \mu\mu$</td>
<td>$-0.7^{+3.7}_{-3.7}$</td>
<td>$-3.0$</td>
<td>$-1.7$</td>
<td>$-0.7$</td>
<td>$-0.7^{+3.7}_{-3.7}$</td>
</tr>
<tr>
<td>$H \to Z\gamma$</td>
<td>$2.7^{+4.6}_{-4.5}$</td>
<td>$4.2$</td>
<td>$2.7$</td>
<td>$1.1$</td>
<td>$2.7^{+4.6}_{-4.5}$</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td>$1.18^{+0.15}_{-0.14}$</td>
<td>$0.10$</td>
<td>$0.10$</td>
<td>$0.09$</td>
<td>$1.18^{+0.15}_{-0.14}$</td>
</tr>
</tbody>
</table>

\[ \mu = \frac{\sigma \cdot BR}{(\sigma \cdot BR)_{SM}} \]

**$\overline{s} = 7 \text{ TeV, 4.5-4.7 fb}^{-1}$**

**$\overline{s} = 8 \text{ TeV, 20.3 fb}^{-1}$**
Higgs boson production

Present rates in different production and decay channels in agreement with the SM expectations

The top-Yukawa coupling will be one of the most important measurements of LHC Run 2
Conclusions

The LHC Run 1 was an exciting time and a great success for particle physics

An entire new field emerged with a large number of interesting analyses

Present measurements indicate no deviations from the SM

Looking forward to LHC Run 2 for further exciting discoveries!