Discovery potential for the SM Higgs boson in exclusive final states
Outline

- Higgs boson production and decays at the LHC.
- Searches in exclusive channels (related to Higgs production mode).
- Discovery potential for low luminosity running ($\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$).

ATLAS

Detector design optimized for the Higgs search in a wide mass range:

- Good, hermetic calorimetry $\rightarrow$ missing $E_T$ measurement, jet reconstruction up to $|\eta| = 4.9$

- Powerful particle identification:
  - $\sim 90\%$ muon efficiency, cleanest identification (combining tracker and muon spectrometer).
  - $\sim 80\%$ electron efficiency for jet rejection of $\sim 10^5$.
  - $\sim 80\%$ photon efficiency for jet rejection of $\sim 10^3$.
  - $\sim 60\%$ b-tagging efficiency for light-flavour jet rejection of $\sim 10^2$ (good vertexing).
  - $\sim 50\%$ $\tau$-hadron efficiency for jet rejection of $\sim 10^2$.

- Electron, photon and muon energy- and $p_T$-resolution: 2-3%.
Higgs production at the LHC

K–factor (N)NLO/LO:  ~2
Scale uncertainty:  ~15%

PDF uncertainties: 5-15% for all production modes.

σ(Backgrounds) [pb]:
- $t\bar{t}$: $\sim 0.8 \cdot 10^3$
- $Z \rightarrow \ell^+ \ell^-$: $\sim 1.6 \cdot 10^3$
- $W^\pm \rightarrow \ell^\pm \nu$: $\sim 1.2 \cdot 10^4$
- $b\bar{b}$: $\sim 0.6 \cdot 10^9$
- inelastic: $\sim 0.7 \cdot 10^{11}$
Higgs decay modes

\[ m_H < 130 \text{ GeV} \]

- \( H \to b\bar{b} \): Dominant decay; large QCD-background suppressed only in \( t\bar{t}H \) mode.
- \( H \to \tau\tau \): Accessible only via vector boson fusion mode.
- \( H \to \gamma\gamma \): Very low BR (decay via top- and \( W \)-loops), but still significant due to an excellent \( \gamma \)-resolution and \( \gamma/jet \)-separation.

\[ m_H > 130 \text{ GeV} \]

- \( H \to WW^{(*)} \)
- \( H \to ZZ^{(*)} \); Gold-plated channel above \( m_H = 2M_Z \): \( H \to ZZ \to 4\ell \).
Searches in exclusive final states

(i.e. given production and decay products - and nothing else - in the final state.)

Complementary to inclusive searches.
Essential for the measurement of the Higgs boson properties.

**Vector Boson Fusion** \((qq \rightarrow V^*V^* \rightarrow qqH)\):

- \(H \rightarrow \tau^+\tau^-\) (110 - 150 GeV)
- \(H \rightarrow W^+W^-\) (120 - 300 GeV)
- \(H \rightarrow \gamma\gamma\) (110 - 150 GeV)

Associated production with \(t\bar{t}\) \((gg, q\bar{q} \rightarrow t\bar{t}H)\):

- \(H \rightarrow b\bar{b}\) (110 - 130 GeV)
- \(H \rightarrow \gamma\gamma\) (110 - 130 GeV)

Associated production with \(W/Z\) \((q\bar{q} \rightarrow VH)\):

- \(H \rightarrow \gamma\gamma\) (110 - 140 GeV)
- \(H \rightarrow W^+W^-\) (150 - 190 GeV)

Gluon fusion \((gg \rightarrow H)\) is usually considered for inclusive searches.

- Exclusive search needed for measurement of the Higgs couplings ⇒ veto on additional jets to suppress the VBF-contribution.
  \((H \rightarrow \gamma\gamma, H \rightarrow WW, H \rightarrow ZZ \rightarrow 4\ell)\).
**Strategy of ATLAS and CMS analyses**

**ATLAS:**
- Using LO cross-sections for signal and background for consistency, since not all background processes are known to NLO.
- All shown results were taken from the most recent publications; mostly based on parametrized, fast detector simulation. (Parametrization obtained from the detailed detector simulation - realistic performance for the key objects: $\mu$, e, jets, b-tag, $\tau$-jet, $E_T^{\text{miss}}$, jet veto...)
- Ongoing **Computing System Commissioning (CSC) effort:**
  - Detailed G4 detector simulation with an up-to-date detector layout, including trigger simulation and pile-up effects.
  - New preliminary results do not show big discrepancies w.r.t. the present ones.
  - $\Rightarrow$ Final, updated results expected in December 2007.

**CMS:**
- NLO cross-sections used for the Higgs boson production and for the backgrounds when available.
  - HIGLU, HDECAY, HQQ, VV2H, V2HV, MCFM
- Generators at LO, advanced generators for multi-jet events:
  - Alpgen, MADGRAPH, CompHEP, TopRex
- Almost all analyses done using detailed G4 detector simulation.
Vector Boson Fusion (VBF) Channels

First particle-level analyses at LHC by D.Zeppenfeld, D.Rainwater et al. (1997).

Production rates are large enough (10-50% w.r.t gluon fusion).

Very characteristic topology:

- Two forward jets.
- Large rapidity gap (no additional jets in central region).
- Higgs decay products are central, can be used for triggering.

Decay modes:

\[ H \rightarrow \tau^+\tau^- \rightarrow (\ell^+\nu\nu)(\ell^-\nu\nu) \]
\[ H \rightarrow \tau^+\tau^- \rightarrow (\ell\nu\nu)(\tau_{\text{jet}}\nu) \]
\[ H \rightarrow W^+W^- \rightarrow (\ell^+\nu)(\ell^-\nu) \]
\[ H \rightarrow W^+W^- \rightarrow (\ell^\pm\nu)(jj) \]
\[ H \rightarrow \gamma\gamma \]
VBF channels: Forward jets

Forward jet separation: discrimination from QCD-backgrounds.

- $\eta_{j1} \cdot \eta_{j2} < 0$
- $|\Delta \eta_{jj}| > 3.5 - 4$
- $m_{jj} > 500 - 700$ GeV

Jet reconstruction performance:

- Evaluated with full G4 simulation, including pile-up.
- Reliable forward-jet tagging.
VBF channels: Central jet veto

Rapidity gap between the tagging jets (no colour exchange b. quarks).


- Veto on additional jets in the central region:

\[
\alpha_{j3} = \frac{\sum p_{T,trk}}{E_{Tj3}}
\]

Experimental challenge: Fake central jets from the pile-up.
→ matching central jets to the signal vertex (by means of tracks).

Theoretical questions: Jet distributions at NLO. Underlying event.
VBF $H \rightarrow \tau\tau \rightarrow (\ell\nu\nu, \ell\nu\nu\tau_{jet}\nu)$

Hadron-hadron mode difficult to trigger, under investigation.

Backgrounds:

- $Z + jets$, $W + jets$, $WW + jets$, $t\bar{t}$

Higgs mass reconstruction possible despite of neutrinos.

Collinearity approximation:
Decay products of highly boosted $\tau$-s all fly in the $\tau$-direction. Neutrino momenta can be extracted.

(Method is not valid when $\tau$-s are back-to-back, since the missing $E_T$ vanishes in that case.)

- Mass resolution $\sim 10\%$, mostly limited by the measurement of the missing $E_T$. 

Outline
- Higgs Production and Decays
  - Exclusive searches via: VBF, $ttH$, $(W/Z)H$
**VBF $H \rightarrow \tau\tau$: Analysis results**

$H \rightarrow \tau\tau \rightarrow l\nu\nu \tau_{jet}\nu$

**EW/QCD $Z \rightarrow \tau\tau + jets$: dominant contribution after all cuts.**

Expected uncertainty on the background rate: 5-10%.

- Above $m_H > 125$ GeV: Determination from the flat sidebands.
- For $m_H < 125$ GeV: Normalize to the $Z$-peak, but understand shape?
  - Relaxing particular cuts (central jet veto).
  - Estimating $Z \rightarrow \tau\tau$ contribution from the $Z \rightarrow \mu\mu\mu$ data.

Already established as a discovery channel for the high Higgs mass region.

Extending to low masses: complementary to \( H \rightarrow ZZ^* \rightarrow 4\ell \)
when \( 160 < m_H < 180 \) GeV.

- Similar backgrounds as for \( H \rightarrow \tau\tau \).
- Event selection:
  - forward jet tagging, isolated lepton, 4 jets, \( E_T^{\text{miss}} > 30 \).
  - Dominant contribution after cuts: \( t\bar{t} + \text{jets}, W + \text{jets} \).

- Mass reconstruction possible:

Detector systematic uncertainties - impact on signal and background rates:

- Jet energy scale: \( \sim 12\% \).
- Jet energy resolution: \( \sim 1\% \).
- \( E_T^{\text{miss}} \): \( \sim 2\% \).
- Lepton isolation: \( \sim 1\% \).

Largest uncertainty comes from the selection efficiency w.r.t. jet-\( p_T \) cut.
\( \Rightarrow \) reduced by data-driven estimates.
Lower rate than in the semi-leptonic case, but $W + jet$ suppressed.

Backgrounds: Drell-Yan, $EW/QCD \ Z + jets$, $t\bar{t}$, $EW/QCD \ WW + jets$

Event selection:

- high $E_T^{miss}$, $Z \rightarrow \tau\tau$ veto, $\tau$-jet veto
- forward jet tagging, central jet veto ($b$-jet veto for $|\eta| < 2.5$)
- spin corelations

(lepions tend to be emitted in the same direction, $\Delta \Phi_{\ell\ell} < 1.5$):

Dominant background after cuts: $t\bar{t}$, $EW \ WW + jets$. 
No Higgs mass reconstruction possible:

Counting excess of signal events over the background in a given region of transverse mass $m_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{\text{miss}} (1 - \cos \Theta)}$.

$\Rightarrow$ need good knowledge of background distributions ($\pm 10\%$ uncert.):
- $t\bar{t}$ from the semi-leptonic decay mode (after forward jet tagging)
- relaxing selection cuts (on lepton pairs) and then using $m_T$ side bands (if the shape is taken from Monte Carlo) + $\Delta \Phi_{\ell\ell}$-region $>1.5$ for events from the signal region (i.e. $m_T < m_H$).
VBF $H \rightarrow \gamma\gamma$

**Event selection:**

- Photon isolation.  
  (Track- and calorimeter-based).
- Higgs vertex reconstruction.
- Forward jet tagging efficiently reduces the background.
  \[\Rightarrow\text{Remaining bckg. comparable to the expected Higgs signal.}\]

<table>
<thead>
<tr>
<th>Background process</th>
<th>Cross section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD hadronic jets</td>
<td>$2.8 \times 10^7$</td>
</tr>
<tr>
<td>Gluon fusion</td>
<td>83</td>
</tr>
<tr>
<td>Drell Yan</td>
<td>$4.1 \times 10^3$</td>
</tr>
<tr>
<td>$\gamma\gamma + 2$-jets, QCD</td>
<td>47.24</td>
</tr>
<tr>
<td>$\gamma\gamma + 2$-jets, EW</td>
<td>0.33</td>
</tr>
<tr>
<td>$\gamma + 3$-jets, QCD</td>
<td>5970</td>
</tr>
<tr>
<td>$\gamma + 3$-jets, EW</td>
<td>5.15</td>
</tr>
</tbody>
</table>

**Signal significance:**

<table>
<thead>
<tr>
<th>Higgs mass (GeV)</th>
<th>$60\text{fb}^{-1}$</th>
<th>$m_H = 115\text{ GeV/c}^2$</th>
<th>$m_H = 120\text{ GeV/c}^2$</th>
<th>$m_H = 130\text{ GeV/c}^2$</th>
<th>$m_H = 140\text{ GeV/c}^2$</th>
<th>$m_H = 150\text{ GeV/c}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_s$</td>
<td>20.2</td>
<td>21.1</td>
<td>19.1</td>
<td>15.7</td>
<td>11.2</td>
</tr>
<tr>
<td>$\gamma+3$-jets (QCD)</td>
<td>2.7</td>
<td>4.7</td>
<td>3.5</td>
<td>2.0</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>$\gamma+3$-jets (EW)</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma + 2$-jets (QCD)</td>
<td>11.2</td>
<td>13.2</td>
<td>9.85</td>
<td>8.9</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>$\gamma\gamma + 2$-jets (EW)</td>
<td>10</td>
<td>7.0</td>
<td>7.0</td>
<td>11.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Drell Yan</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$N_b$</td>
<td>26.0</td>
<td>26.2</td>
<td>21.4</td>
<td>28.2</td>
<td>14.9</td>
</tr>
<tr>
<td>$\Delta N_b$</td>
<td>2.8</td>
<td>3.2</td>
<td>2.4</td>
<td>3.0</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>$S$</td>
<td>3.07</td>
<td>3.15</td>
<td>3.21</td>
<td>2.32</td>
<td>2.30</td>
<td></td>
</tr>
</tbody>
</table>

$\Delta N_b$ - bck. uncertainty estimated from the side bands.
$t\bar{t}H$ Channels

$t\bar{t}H$ production rate is $\sim 50$ times lower compared to gluon fusion. However, this signature can provide:

- Additional handle for the suppression of a large QCD-background. (In particular for $H \rightarrow b\bar{b}$.)
- In the (semi-)leptonic mode: high-$p_T$ lepton for triggering.

Decay modes:

- $t\bar{t}H \rightarrow (\ell\nu b)(\ell\nu b)b\bar{b}$
- $t\bar{t}H \rightarrow (\ell\nu b)(jjb)b\bar{b}$
- $t\bar{t}H \rightarrow (jjb)(jjb)b\bar{b}$
- $t\bar{t}H \rightarrow (\ell\nu b)(jjb)\gamma\gamma$

$H \rightarrow WW$:
Ongoing studies in ATLAS.
$t\bar{t}H \rightarrow (l\nu b)(jjb)b\bar{b}$

**t\bar{t}H, H → b\bar{b}**

**Complex final state:**
- 6 jets: 4 b-jets and 2 light jets,
- 1 high-$p_T$ lepton,
- missing energy from neutrino,
- additional jets from ISR/FSR.

**Large backgrounds:**
- combinatorial from mis-pairing of jets,
- irreducible from $t\bar{t}b\bar{b}$ events,
- reducible from $t\bar{t} + jets$ events.

Full event reconstruction is required, good jet reconstruction and good b-tagging are essential.
**t\bar{t}H \rightarrow (\ell \nu b)(jjb)b\bar{b}: Results**

Using likelihood methods to improve the selection of jet-pairings.

- Only \(~30\%\) of b-pairings are correct.
- Signal and background mass distributions have a similar shape.
  \(\Rightarrow\) strong sensitivity to the background uncertainties.

<table>
<thead>
<tr>
<th>Channel ((m_H=120\text{ GeV}))</th>
<th>Luminosity ([\text{fb}^{-1}])</th>
<th>S</th>
<th>B</th>
<th>(S/\sqrt{B})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS (t\bar{t}H \rightarrow (\ell \nu b)(jjb)(bb))</td>
<td>60</td>
<td>40</td>
<td>427</td>
<td>1.9</td>
</tr>
<tr>
<td>CMS (t\bar{t}H \rightarrow (\ell \nu b)(\ell \nu b)(bb))</td>
<td>60</td>
<td>132</td>
<td>9090</td>
<td>1.4</td>
</tr>
<tr>
<td>CMS (t\bar{t}H \rightarrow (jjb)(jjb)(bb))</td>
<td>60</td>
<td>45</td>
<td>505</td>
<td>2.0</td>
</tr>
<tr>
<td>ATLAS (t\bar{t}H \rightarrow (\ell \nu b)(jjb)(bb))</td>
<td>30</td>
<td>41</td>
<td>218</td>
<td>2.8</td>
</tr>
</tbody>
</table>

**Outline/ Higgs Production and Decays/ Exclusive searches via:** 

- VBF
- \(ttH\)
- \((W/Z)H\)
- Discovery Potential
Systematic uncertainties from the detector performance (CMS):

- Jet energy scale: 3-10%.
- Jet resolution: 10%.
- b,c-tagging: 4%.
- u,d,s-tagging: 10%.
- Luminosity: 3%.
Lepton from the top-decay allows for
- discrimination of the QCD bckg.,
- and for the primary vertex reconstruction
  \[ \Rightarrow \text{lower sensitivity to the photon resolution}. \]

Analysis results for 100 fb\(^{-1}\) at \(L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}\):

- Systematic uncertainties taken into account.

<table>
<thead>
<tr>
<th>Higgs Boson Mass (GeV)</th>
<th>115</th>
<th>120</th>
<th>130</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sig. Selection Eff. (%)</td>
<td>10.7</td>
<td>11.2</td>
<td>11.3</td>
<td>11.3</td>
</tr>
<tr>
<td>Number Signal</td>
<td>7.42 ± 0.33</td>
<td>7.33 ± 0.33</td>
<td>5.96 ± 0.27</td>
<td>4.21 ± 0.19</td>
</tr>
<tr>
<td>Total Number Bkgd</td>
<td>1.61 ± 0.53</td>
<td>2.79 ± 0.62</td>
<td>1.98 ± 0.66</td>
<td>1.10 ± 0.51</td>
</tr>
<tr>
<td>Total Number Bkgd from fit w. syst.</td>
<td>2.23 ± 0.34</td>
<td>1.94 ± 0.32</td>
<td>1.60 ± 0.22</td>
<td>1.39 ± 0.22</td>
</tr>
<tr>
<td>Signal Significance (ScP)</td>
<td>3.541</td>
<td>3.662</td>
<td>3.257</td>
<td>2.510</td>
</tr>
<tr>
<td>Signal Significance (ScP) w. syst.</td>
<td>3.414</td>
<td>3.523</td>
<td>3.184</td>
<td>2.453</td>
</tr>
</tbody>
</table>
Similarly as for the $t\bar{t}H$ production, additional lepton(s) from $W(Z)$-decay allow for a stronger background discrimination.

- Due to the low production rate, these signatures become significant only at integrated luminosities above 100 fb$^{-1}$.

\[ W H \rightarrow W(WW) \rightarrow (l\nu)(l\nu\ell\nu) \]

\[ W, H \rightarrow \gamma\gamma \]

\[ L = 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]
Discovery potential at 30 fb$^{-1}$

**ATLAS**
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^{(*)} \rightarrow 4l$
- $H \rightarrow WW^{(*)} \rightarrow lvlv$
- $qqH \rightarrow qq WW^{(*)} \rightarrow lvlv, lvjj$
- $qqH \rightarrow qq \tau\tau \rightarrow ll, lh$
- $ttH (H \rightarrow bb)$
- Total significance

**CMS**
- $H \rightarrow \gamma\gamma$ cuts
- $H \rightarrow \gamma\gamma$ opt
- $H \rightarrow ZZ \rightarrow 4l$
- $H \rightarrow WW \rightarrow 2l2\nu$
- $qqH, H \rightarrow WW \rightarrow lvjj$
- $qqH, H \rightarrow \tau\tau \rightarrow l+jet$
- $qqH, H \rightarrow \gamma\gamma$

**Significance**
- $m_H$ (GeV)
- Signal significance
- Total significance

**Outline**
- Higgs Production and Decays
  - Exclusive searches via: VBF, $ttH$, $(W/Z)H$
  - Discovery Potential