Higgs Boson discovery at the LHC

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Physics of the Higgs Boson at LHC
Overview of the main inclusive discovery channels

- $H \rightarrow \gamma \gamma$
- $H \rightarrow ZZ \rightarrow 4l$
- $H \rightarrow WW \rightarrow 2l2\nu$

2 brief examples of exclusive channels

- $t\bar{t} \ H; \ H \rightarrow bb$
- $q\bar{q} \ H; \ H \rightarrow WW \rightarrow \mu \nu q\bar{q}$

Higgs properties measurement (Mass, Width, quantum numbers)

Disclaimer: results for CMS only (Physics TDR to appear soon)
LHC status

- No more so far to come
- Installation progressing well on schedule. Pilot run end 2007
- Integrated luminosity in 2008 (4 months) \( \sim < 1 \text{ fb}^{-1} \)
Higgs at LHC

Production

- Gluon-gluon fusion main production mechanism in the whole mass range
- \( 0(10) \text{ pb for } M_H < 200 \text{ GeV} \Rightarrow 1 \text{ Higgs every } \sim 30 \text{ sec at } 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \)
- Vector Boson Fusion has sizable x-section. Important for Higgs coupling and for W-W scattering (unitary-violating \( \sim 800 \text{ GeV} \))
- \( t\bar{t} \) associated production relevant at low \( M_H \)
**Higgs at LHC**

**Decay**

- *b-b̅* dominates for low $M_H$ (till $M_H \sim 130$ GeV)
- *WW* dominant decay mode in the rest of the mass range
- *ZZ* opens up for $M_H \gtrsim 2M_Z$
- $\Gamma_H < 1$ GeV for $M_H < 200$ GeV, afterwards grows $\sim$linearly with the mass (still a resonance?)
**Higgs discovery channels**

At $\sqrt{s} \approx 100$ GeV, QCD but also Electroweak processes have huge $x$-sections. Signal events are overwhelmed by the background.

To isolate a phase-space region with mainly signal events (if possible), background rejection of $O(10^5)$ needed.

**Main channels**

- Mass range $[115, 130]$ GeV
  - $H \to \gamma \gamma$

- Mass range $[130, 150]$ and $[180, \Lambda]$
  - $H \to ZZ \to 4l$ ($l=\mu, e$) golden channel

- Mass range $[150, 170]$ GeV
  - $H \to WW \to 2l2\nu$ ($l=\mu, e$) silver channel

Exclusive (initial) final states can help in reducing the possible SM backgrounds:

- $t\bar{t}$ $H$; $H \to bb$ or $H \to \gamma \gamma$
- $q\bar{q}$ $H$; $H \to WW \to \mu \nu qq\_bar$; $H \to tt$; . . .

usually disfavored by the small $x$-section, by the difficult to predict contribution form SM background and detector performances
In the low mass range no hope for $H \rightarrow b\bar{b}$ inclusive search

Decay occurs via $W$, top and bottom loop. \( BR \sim 2 \times 10^{-3} \) till \( M_H < 140 \) GeV

\( \sigma \cdot BR \) ranging between 100 and 70 fb between LEP limit (115) and 140 GeV

**Backgrounds**

- 2 real prompt photons (irreducible):
  - production via $q\bar{q}$ and $gg$ with a box diagram
  - processes simulated at LO and renormalized with global K factor to NLO

- $\gamma + \text{jet}$ (reducible)
  - the 2nd candidate from photon emitted during jet fragmentation or mis-identified jet or isolated $\pi^0$

- $>2$ jets (reducible)
  - both photon candidates from mis-measured jets
  - huge x-section. Difficult to simulate the needed statistics \( \Rightarrow \) cuts at generator level
**Calorimetry**

- $H\rightarrow\gamma\gamma$ sets the most stringent requirements for electromagnetic calorimeter performances. Optimal energy resolution for $M_H$ determination and granularity for $\pi^0$ suppression

**Primary Vertex**

- At LHC the longitudinal spread of the interaction vertices is of 53 mm resulting in almost 2 GeV smearing in $M_H$ resolution
- The hard scattering produces charged tracks with harder momentum than minimum bias interactions
- Tracking back those tracks allows to define the primary vertex with a 5mm precision in 83% of the signal events at low luminosity (warning for high lumi)
**H-$\gamma \gamma$ Detector Issues**

**Photon Conversion**

- Big amount of material before the Electromagnetic calorimeter
- High probability of the photon to convert into $e^+e^-$ pairs before reaching the E-cal $\Rightarrow M$ resolution spoiled!

- Tracker itself used to reconstruct the $e^+e^-$ pairs and to recover the photon energy resolution
**H → γγ Analysis and Results**

- **Two approaches:**
  - Standard cut-based analysis (photons’ Et and isolation) applied to different |η| regions
  - Neural Network optimized analysis profiting of the different signal-background kinematics and photon candidate isolation

- Background estimation from sidebands. Systematic error from the predicted shape, statistics uncertainty from the mass range to perform the fit on

- At low luminosity 25 fb\(^{-1}\) are needed for discovery in the range 115-140 GeV. Less than 15 fb could be sufficient for the optimized analysis
  
  - ~5 fb sufficient to exclude at 95% CL
muons (cleanest), electrons and combinations (double x-sec) considered as possible final states. Signal produced at LO and reweighted at NLO with $K(P_t^H)$. Further enhancement due to interference of permutation of identical fermions from different $Z$'s (15% at low $M_H$).

Backgrounds:

- $Z\gamma - Z\gamma$ (irreducible). Generated with CompHEP ($t$ and $s$ channels) and reweighted with $K(M_H)$ to NLO (MCFM). $gg\rightarrow ZZ$ also included.
- $Z\gamma - b\bar{b}$. Generated with CompHEP ($gg$ and $qqbar$ initial state) and reweighted with constant $K$ to NLO (MCFM).
- $t\bar{t}$. NLO x-sec (840 pb) used.

Other processes as $bbbb$, $bbcc$, $cccc$, single-top $Z$-$cc$, $Wbb$, $Wcc$ demonstrated to be negligible.

### Table: $2e$ $2\mu$ final state

<table>
<thead>
<tr>
<th></th>
<th>$tt$</th>
<th>$Zbb$</th>
<th>$ZZ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ (fb)</td>
<td>$840\times10^3$</td>
<td>$555\times10^3$</td>
<td>$28.9\times10^3$</td>
</tr>
<tr>
<td>$\sigma$.BR.\varepsilon$ (fb)</td>
<td>744</td>
<td>390</td>
<td>37.0</td>
</tr>
</tbody>
</table>
Cleanest signal possible: 4 isolated, high $\not{p}_T$ leptons pointing to the same primary vertex with at least two lepton with $M_{ll} \sim M_Z$

Two selections strategies:
- $M_H$ independent cuts (all analysis): to reduce systematic uncertainties and MC dependence
- $M_H$ dependent cuts (4$\mu$ final state): $M_{4l}$ is the most discriminating variable
  $\Rightarrow$ Optimization only on isolation, $\not{p}_T$ of the 3$^{rd}$ $\mu$ and window $M_{4l}$

In both cases only $ZZ \rightarrow 4l$ remains as important background the others being negligible

All analysis use to discriminate the presence of the signal the significance estimator(s) based on log-likelihood ratio

\[ S_L = \sqrt{-2 \ln Q} \text{ where } Q = \left(1 + \frac{N_s}{N_b}\right)^{N_s + N_b} e^{-N_s} \]
Sources:
- PDF and QCD scale
- NLO vs LO dynamics
- Isolation efficiency
- Reconstruction efficiency (only for electrons)
- Energy/Momentum Scale
- Identification (charge)

Normalization from data compulsory. Two control samples:
- Drell Yan (no statistical limitation)
- \( M_H \) sidebands (reduces NLO-LO uncertainties, pays low statistics)
H → ZZ → 4\(\mu\)

Systematics for 4\(\mu\) final state

**Drell Yan**

Uncertainty in background, \(\delta b/b\) (%)

- Combined
- dK/K: NLO + (gg → ZZ)
- PDF at NLO
- QCD at NLO
- Muon Reconstruction Efficiency
- Muon Isolation Cut Efficiency
- Muon pT resolution: negligible
- Muon pT-scale: negligible
- Muon Trigger: negligible
- Luminosity: negligible

**ZZ → 4\(\mu\)**

Uncertainty in background, \(\delta b/b\) (%)

- Combined
- dK/K: NLO + (gg → ZZ)
- PDF at NLO
- QCD at NLO
- Muon Reconstruction Efficiency: negligible
- Muon Isolation Cut Efficiency: negligible
- Muon pT resolution: negligible
- Muon pT-scale: negligible
- Muon Trigger: negligible
- Luminosity: negligible
Results

- combining the final states:
  - exclusion in almost the full mass range with \(~1\) fb\(^{-1}\)
  - discovery for \(M_H > ~ 2M_Z\) with \(~5\) fb\(^{-1}\). For \(M_H\) in [140-150] \(\text{GeV}/c^2\), could be sufficient.
Extremely clean signal: 2 isolated high Pt leptons pointing to the same primary vertex, "high" Missing Et and NOTHING else in the detector
High x-sec*BR but NO Invariant mass peak!
Main backgrounds:
- WW. irreducible. Reweighted by NLO Pt_{WW}. gg->WW also simulated
- t-t_bar. reduced by jet veto. NLO x-sec (840 pb) used
- Single top (Wt final state). Non trivial to separate from t-t_bar
- Drell Yan. in the case of same flavor final state, reduced by M_{ll} and MEt
- WZ, ZZ->2l. b-b_bar negligible
Discriminating variable is the opening angle between the 2 leptons (scalar nature of the Higgs + V-A structure of weak interactions). Spin correlation in the simulation matters!
The viability of the channel depends on the possibility to evaluate each background contribution from the data
At the LHC the MEt is never 0. Long tail even in clean events like DY+0 jets. Need to normalize MEt measurement directly on data, best candidate Z boson

Vetoing the jets is an extremely delicate task: difficult to define a jet at low $E_T$ and high rapidity. Tracker information used to reduce fake rate:

$$\alpha = \frac{\sum_{\text{sel. tracks}} p_T}{E_T(\text{jet})}$$
Selections

- Squeezing to the signal phase space:
  - lepton id (#, charge, isolation)
  - Vertex constrain
  - lepton Pt
  - $M_\ell$ cut
  - MET
  - Jet Veto
  - $\phi_\ell$

<table>
<thead>
<tr>
<th>Reaction pp → X</th>
<th>$\sigma_{NLO} \times BR$ (pb)</th>
<th>L1+HLT</th>
<th>2 leptons</th>
<th>All cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow WW \rightarrow \ell\ell$, $m_H = 160$ GeV</td>
<td>2.34</td>
<td>1353 (58%)</td>
<td>359 (27%)</td>
<td>42 (12%)</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow \ell\ell$, $m_H = 165$ GeV</td>
<td>2.36</td>
<td>1390 (59%)</td>
<td>393 (28%)</td>
<td>46 (12%)</td>
</tr>
<tr>
<td>$H \rightarrow WW \rightarrow \ell\ell$, $m_H = 170$ GeV</td>
<td>2.26</td>
<td>1350 (60%)</td>
<td>376 (28%)</td>
<td>33 (8.8%)</td>
</tr>
<tr>
<td>$qq \rightarrow WW \rightarrow \ell\ell$</td>
<td>11.7</td>
<td>6040 (52%)</td>
<td>1400 (23%)</td>
<td>12 (0.9%)</td>
</tr>
<tr>
<td>$gg \rightarrow WW \rightarrow \ell\ell$</td>
<td>0.48</td>
<td>286 (60%)</td>
<td>73 (26%)</td>
<td>3.7 (5.1%)</td>
</tr>
<tr>
<td>$tt \rightarrow WWbb \rightarrow \ell\ell$</td>
<td>86.2</td>
<td>57400 (67%)</td>
<td>15700 (27%)</td>
<td>9.8 (0.06%)</td>
</tr>
<tr>
<td>$tWb \rightarrow WWb(b) \rightarrow \ell\ell$</td>
<td>3.4</td>
<td>2320 (68%)</td>
<td>676 (29%)</td>
<td>1.4 (0.2%)</td>
</tr>
<tr>
<td>$ZW \rightarrow \ell\ell$</td>
<td>1.6</td>
<td>1062 (66%)</td>
<td>247 (23%)</td>
<td>0.50 (0.2%)</td>
</tr>
<tr>
<td>$ZZ \rightarrow \ell\ell, \nu\nu$</td>
<td>1.5</td>
<td>485 (32%)</td>
<td>163 (34%)</td>
<td>0.35 (0.2%)</td>
</tr>
<tr>
<td>Sum backgrounds</td>
<td>105</td>
<td>67600 (64%)</td>
<td>18300 (27%)</td>
<td>28 (0.2%)</td>
</tr>
</tbody>
</table>
Backgrounds normalization

- Compulsory to rely on data to get background contribution in the signal region. A control phase space region for each background eventually with sub-control regions (e.g. for WW)
- The uncertainties on the extrapolated number of background events set the amount of integrated luminosity needed

Normalization schema for 2µ2ν final state
**H→WW→2l2ν**

**t-t_bar background normalization (example)**

- Control region defined by the same selections as for the signal region but the jet veto. 2 b-tagged jets are required in addition
- The procedure relies on the relation:

\[
N_{signal\_reg} = \frac{N_{signal\_reg}^{MC}}{N_{control\_reg}^{MC}} N_{control\_reg} = \frac{\sigma_{signal\_reg}^{MC}}{\sigma_{control\_reg}^{MC}} \varepsilon_{signal\_reg}^{MC} N_{control\_reg}^{MC}
\]

<table>
<thead>
<tr>
<th>Theor. Error</th>
<th>Detector systematics</th>
<th>Stat. Error</th>
<th>Total Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JES</td>
<td>α crit.</td>
<td>b-tagging</td>
</tr>
<tr>
<td>(L = 1 fb⁻¹)</td>
<td>10 %</td>
<td>10 %</td>
<td>4 %</td>
</tr>
<tr>
<td>(L = 5 fb⁻¹)</td>
<td>10 %</td>
<td>6 %</td>
<td>4 %</td>
</tr>
</tbody>
</table>

(L = 1 fb⁻¹)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal region</th>
<th>t\bar{t} region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>14.3</td>
<td>0.0</td>
</tr>
<tr>
<td>t\bar{t}</td>
<td>2.6</td>
<td>17.0</td>
</tr>
<tr>
<td>WW</td>
<td>5.1</td>
<td>0.0</td>
</tr>
<tr>
<td>DY</td>
<td>0.3</td>
<td>0.0</td>
</tr>
<tr>
<td>Wt,ZZ,WZ</td>
<td>0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>all</td>
<td>23.1</td>
<td>17.1</td>
</tr>
</tbody>
</table>

Jet Energy Scale (λ)
High(est) discovery potential: If $M_H = 165 \text{ GeV}$, only $\sim 1 \text{ fb}^{-1}$ may be needed.
Pay attention to the high number of experimental and theoretical systematics in the game.
No mass measurement method yet available.
ttH; $H \rightarrow b \bar{b}$

Extremely exclusive signature suitable for low $M_H$, disfavored by the low $x$-sec.

3 final states taken in consideration:
- $H \rightarrow bb\bar{b}, t_{\bar{t}} \rightarrow \mu/e \nu b, t \rightarrow \mu/e \nu b$ (fully leptonic)
- $H \rightarrow bb\bar{b}, t \rightarrow bqq\bar{b}, t_{\bar{t}} \rightarrow \mu/e \nu b_{\bar{b}}$ (semileptonic)
- $H \rightarrow bb\bar{b}, t \rightarrow bqq\bar{b}, t_{\bar{t}} \rightarrow b_{\bar{b}} qq$ (fully leptonic)

In all cases many jets in the event. Background coming also from the wrong jets combinatorial.

Major backgrounds from $ttbb$, $Ztt$, $tt+Njets$ and multijets QCD events.

Major problem is the normalization of the background from data: Anti b-tag methods used to select $ttNjets$ background w/o signal contribution.

Many sources of uncertainty: manly MC predictions, Jet Energy Scale and b-tagging efficiency. These systematics (too pessimistic?) kill the signal.

$S/sqrt(B)$ for 60 fb$^{-1}$
Exclusive signature suitable for \( M_H \), ranging between 120 and high masses, characterized by two forward tagging jets

Like inclusive \( H \rightarrow WW \) but with hadronic \( W \rightarrow Higgs \) mass

Backgrounds from \( tt+Njets, W(W)+jets \) and QCD

To extrapolate the selection efficiency for QCD events, the selections are factorized into 3 groups and each group’s efficiency measured directly from data

Main systematics from Jet energy scale and resolution, MEt resolution and lepton isolation (~15%)

\[ L = 60 \text{ fb}^{-1} \]
Higgs properties

from $H \rightarrow ZZ \rightarrow 2e2\mu$

**MASS**

![MASS graph](chart)

**WIDTH**

![WIDTH graph](chart)
Higgs properties

CP Properties

\[ C_{\phi VV} = \kappa \cdot \delta^\mu_\nu + \frac{\tan(\xi)}{m^2} \cdot \epsilon^{\mu \nu \rho \sigma} k_1 \rho k_2 \sigma \]

\[ d\sigma (\tan(\xi)) \sim H + \tan(\xi) I + \tan(\xi)^2 A \]

Scalar  CP violating  PseudoScalar
Conclusions

Most up-to-date full simulation studies show that the Higgs boson can be discovered with $\sim$10 fb$^{-1}$ whatever $M_H$. For specific mass ranges ($\sim$160) even $\sim$1 fb$^{-1}$ could be enough.

Exclusion at 95% can be obtained with 5 fb$^{-1}$ for very low masses and $\sim$1fb$^{-1}$ in the rest of the mass range.

However, pay attention to the systematic estimation!

Exclusive channels not suitable for a fast discovery but useful as confirmation and for exploring Higgs properties.

Mass resolution $\sim$0.1% for $M_H$. Width resolution below natural width only above 200 GeV. CP properties for higher luminosity.
BAK UPs
Enhancement of $H \rightarrow ZZ \rightarrow 4\mu$ due to permutations of muons between $Z_1$ and $Z_2$

\[ R = \frac{2 \times \sigma(\mu)}{\sigma(2\mu_\mu e)} \]

\[ M_{H_{i}}, \text{GeV} \]

\[ R \]

\[ M(4\mu) \text{ (GeV)} \]

- Normalisation to single $Z$
  - Theoretical: PDF and QCD scale
  - Theoretical: $g \rightarrow ZZ$
  - Experimental: $E$ scale, trigger and reco.
  - Total

- Normalisation to sidebands
  - Theoretical: PDF and QCD scale
  - Experimental: $E$ scale, trigger and reco.
  - Statistical errors (all cuts)
  - Statistical errors (no $M_{Z}$ cuts)
  - Total (all cuts)
• $m_{4\mu}$ distributions for randomly selected pseudo-experiments (‘data’) with the expected statistics for $L = 5\, \text{fb}^{-1}$ and $L = 15\, \text{fb}^{-1}$, assuming $m_H = 150\, \text{GeV}$

• 1-CL$_b$ distributions show how incompatible with the $B$-only hypothesis are data:
  • Low significance over the background expectation for $L = 5\, \text{fb}^{-1}$
  • Higher significance (above $3\, \sigma$) after accumulating 10 fb$^{-1}$ more
Likelihood Ratio: \[ Q = \frac{\text{Probability}(s+b)}{\text{Probability}(b)} \]

Significance Estimator: \[ S = \sqrt{2 \ln Q} \]

One-bin LLR (counting experiment, \( S_{cL} \))
\[ 2 \ln Q = 2 \ln \frac{(s+b)^n}{n!} e^{-(s+b)} \frac{b^n}{n!} e^{-b} = 2n \ln \left( 1 + \frac{s}{b} \right) - 2s \]

Binned LLR (\( S_L \))
\[ 2 \ln Q = 2 \sum_{\text{bins}} \left( n_i \ln \left( 1 + \frac{s_i}{b_i} \right) - 2s_i \right) \]

Unbinned LLR (\( S_{UL} \))
\[ 2 \ln Q = 2 \sum_{\text{events}} \ln \left( \frac{\text{pdf}_{S+B}(m_i)}{\text{pdf}_B(m_i)} \right) \]
**$W^W$ control region**

- $\Delta \phi$ between muons > 0.8
- 50 GeV < Muon Invariant Mass < 80 GeV

**Number of events** (L = 1 fb$^{-1}$)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Signal region</th>
<th>WW region</th>
<th>$t\bar{t}$(WW) region</th>
<th>DY (WW) region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>14.3</td>
<td>6.0</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>2.6</td>
<td>6.2</td>
<td>24.7</td>
<td>3.2</td>
</tr>
<tr>
<td>WW</td>
<td>5.1</td>
<td>11.5</td>
<td>0.0</td>
<td>4.4</td>
</tr>
<tr>
<td>DY</td>
<td>0.3</td>
<td>15.0</td>
<td>0.0</td>
<td>267</td>
</tr>
<tr>
<td>Wt,ZZ,WZ</td>
<td>0.8</td>
<td>1.9</td>
<td>0.1</td>
<td>7.3</td>
</tr>
<tr>
<td>all</td>
<td>23.1</td>
<td>40.6</td>
<td>24.8</td>
<td>282</td>
</tr>
</tbody>
</table>

\[
\frac{N_{control_{reg}}^{MC}}{N_{control_{reg}}^{MC}} = \frac{11.5}{5.1} \quad \Rightarrow \quad N_{control_{reg}} = \begin{array}{c} N_{tot} - N_{tt} - N_{DY} - N_{Wt, ZZ, WZ} - N_{h165} \\ \end{array} \\
\Rightarrow \quad N_{signal_{reg}} = 5.1 \quad (*)
\]

\[
\frac{N_{signal_{reg}}^{MC}}{N_{control_{reg}}^{MC}} = \frac{5.1}{7.3} \quad \Rightarrow \quad N_{signal_{reg}} = 7.3 \\
\]

(*)& removing the signal contamination

**$tt(WW)$ control region**

- JET veto removed
- 2 b-tagged jets

**$DY(WW)$ control region**

- 80 GeV < $m_{\mu_1\mu_2}$ < 100 GeV
### Systematic error

<table>
<thead>
<tr>
<th></th>
<th>Syst. Error</th>
<th>Stat. Error</th>
<th>Total Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L = 1 fb⁻¹)</td>
<td>20 %</td>
<td>20 %</td>
<td>28 %</td>
</tr>
<tr>
<td>(L = 5 fb⁻¹)</td>
<td>15 %</td>
<td>9 %</td>
<td>17 %</td>
</tr>
</tbody>
</table>

#### WW control region: dominant error from statistics

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>(L = 1 fb⁻¹)</td>
<td>28 %</td>
<td>8 %</td>
<td>9 %</td>
<td>40 %</td>
<td>20 %</td>
<td>7.3±3.0 (41%)</td>
<td>5.1±3.0 (60%)</td>
</tr>
<tr>
<td>(L = 5 fb⁻¹)</td>
<td>17 %</td>
<td>6 %</td>
<td>9 %</td>
<td>40 %</td>
<td>20 %</td>
<td>36.8±7.8 (21%)</td>
<td>25.5±7.8 (21%)</td>
</tr>
</tbody>
</table>


*Ref. WW:* V. Drollinger, CMS NOTE 2005/024

(∗) removing the signal contamination