Higgs boson searches at hadron colliders

Part 3

- Higgs Bosons at the LHC
- Higgs boson parameters
The first Higgs has already been seen

.. jointly by ATLAS

....and CMS

....and even confirmed by ALICE
.... also the prospects for the discovery of the Higgs particle are good
- Luminosity required for a $5\sigma$ discovery or for a 95% CL limit –
  ($< 2006$ estimates)

$\sqrt{s} = 14$ TeV

~ $< 1$ fb$^{-1}$ needed to set a 95% CL limit in most of the mass range
(low mass $\sim 115$ GeV/c$^2$ more difficult)

comments:
- these curves are optimistic on the ttH, H→bb performance
- systematic uncertainties assumed to be luminosity dependent
  (no simple scaling, $\sigma \sim \sqrt{L}$, possible)

J.J. Blaising, A. De Roeck, J. Ellis, F. Gianotti, P. Janot,
G. Rolandi and D. Schlatter,
What is new on LHC Higgs studies?

• Many studies have been performed using detailed GEANT simulations of the detectors
  - Physics Performance Technical Design Report from the CMS collaboration
  - ATLAS CSC book (Computing System Commissioning)

• New (N)NLO Monte Carlos (also for backgrounds)
  - as already discussed (see 1st lecture)

• More detailed, better understood reconstruction methods
  (partially based on test beam results, and first LHC data)

• and: we have first LHC DATA at $\sqrt{s} = 7$ TeV

Important note: most LHC studies are based on $\sqrt{s} = 14$ TeV;
Results presented here are from these studies, however, preliminary sensitivities for $\sqrt{s} = 7$ TeV will be presented, if available
Impact of reduced LHC beam energy

• Ratio of parton luminosities for 7/14 and 10/14 TeV ...

![Graphs showing ratios of parton luminosities at 7 TeV, 10 TeV and 14 TeV LHC](http://projects.hepforge.org/mstwpdf/plots/plots.html)

J. Stirling

http://projects.hepforge.org/mstwpdf/plots/plots.html

<table>
<thead>
<tr>
<th>Process</th>
<th>LHC 7 TeV</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt</td>
<td>7/14 = 0.2</td>
<td></td>
</tr>
<tr>
<td>W' (1.5 TeV)</td>
<td>7/14 = 0.1</td>
<td></td>
</tr>
<tr>
<td>W' (1 TeV)</td>
<td>7(pp) / 2(ppbar) ~ 60</td>
<td></td>
</tr>
</tbody>
</table>

...but still large factor compared to the Tevatron (√s =1.96 TeV)
For a Higgs boson of 160 GeV: reduction by a factor of ~3.6 for \(gg \rightarrow H\) and ~3.7 for \(qq \rightarrow qqH\)
LHC re-start as seen from the experiments

Praying for beam
First beam splash events in ATLAS, 20th Nov 2009
Scientists at Cern in Geneva have restarted the Large Hadron Collider (LHC) experiment, which hopes to shed light on the origins of the universe.
Since 30. March 2010: collisions at $\sqrt{s} = 7$ TeV
(.... first interesting events)

$P_T(j_1) \sim 455$ GeV
$P_T(j_2) \sim 390$ GeV
$m(jj) \sim 800$ GeV
First results on Detector performance
(already published)
Inner Detector performance: hits, tracks, resonances,…

- Very good agreement for the average number of hits on tracks in the silicon pixel and strip detectors

- Material distribution in the inner detector is well described in Monte Carlo (nice cross-check with $K^0$-mass dependence on radius in the Monte Carlo)
Resonances: CMS tracking detector

\[ \Omega^- \rightarrow \Lambda K^- \]

\[ \Xi^- \rightarrow \Lambda \pi^- \]

\[ dE/dx (\text{MeV/cm}) \]

\[ P(\text{GeV/c}) \]

K± band

\[ \phi \rightarrow K^+K^- \]

CMS Preliminary

Yield: 1318 ± 95 \( \phi \) candidates

\( M = (1.01937 \pm 0.00030) \text{ GeV} \)

\( \sigma = (1.69 \pm 0.50) \text{ MeV} \)

Width fixed to PDG value
...towards b-tagging

Two b-jets candidate
The intensity of the transition radiation in the TRT is proportional to the Lorentz Factor $\gamma = E/mc^2$ of the traversing particle. Number of high threshold hits is used to separate electrons and pions.

"Tail" towards high-threshold hits is due to electrons from conversion candidates.
Calorimeters: resonances in the el.magn. calorimeters

First muon signals: 
$J/\psi \rightarrow \mu^+ \mu^-$

$\pi^0, \eta \rightarrow \gamma \gamma$

K. Jakobs, Universität Freiburg

CERN Academic Training Lectures, June 2010
Jets and missing transverse energy

Particle-Flow algorithm:
- Identify all type of particles:
  - Photons (ECAL only)
  - Charged Hadrons (Tracker only)
  - Electrons (ECAL+Tracker)
  - Neutral Hadrons (CALO only)
  - Muons (muon chambers + Tracker)
- And then $\tau$, $\pi^0$, …
- Obtain the best energy estimate for each type of particle
Missing transverse energy, $E_T^{\text{miss}}$

Sensitive to calorimeter performance (noise, coherent noise, dead cells, mis-calibrations, cracks, etc.) and backgrounds from cosmics, beams, ...

Even at this early stage, the missing $E_T$ is well described in simulation!

Particle-flow based $E_T^{\text{miss}}$ relative resolution is significantly better than calorimeter based $E_T^{\text{miss}}$.
The first W signals

ATLAS Preliminary

\[ \int L = 6.4 \text{ nb}^{-1} \]

- Data 2010 (√s = 7 TeV)
- W → µν
- QCD
- W → τν
- Z → µµ

CMS Preliminary 2010

\[ √s = 7 \text{ TeV } \int l_{\text{int}} = 0.012 \text{ pb}^{-1} \]

- Data
- W → eν
- QCD + j
- Others

K. Jakobs, Universität Freiburg
CERN Academic Training Lectures, June 2010
…..however, still lacking luminosity
Signal: \[ \sigma \text{BR} = 5.7 \text{ fb} \] \( (m_H = 100 \text{ GeV}) \)

Background: Top production
\[ tt \rightarrow W_bW_b \rightarrow l\nu c\bar{\nu} l\nu c\bar{\nu} \]
\[ \sigma \text{BR} \approx 1300 \text{ fb} \]

Associated production Z bb
\[ Z b\bar{b} \rightarrow l\bar{l} c\bar{l} c\nu \]

Background rejection: Leptons from b-quark decays
→ non isolated
→ do not originate from primary vertex
(B-meson lifetime: \( \sim 1.5 \text{ ps} \))

Dominant background after isolation cuts: ZZ continuum

\[ P_T^{(1,2)} > 20 \text{ GeV} \]
\[ P_T^{(3,4)} > 7 \text{ GeV} \]
\[ |\eta| < 2.5 \]

Isolated leptons
\[ M(ll) \sim M_Z \]
\[ M(l\bar{l}) \sim < M_Z \]
Main backgrounds: ZZ (irreducible), tt, Zbb (reducible)

Updated ATLAS and CMS studies:
- ZZ background: NLO K factor used
- background from side bands (gg->ZZ is added as 20% of the LO qq->ZZ)
What can be done with 1 fb\(^{-1}\)?

95% C.L. excluded cross sections normalized to Standard Model cross section

\[ \sqrt{s} = 14 \text{ TeV} \]
Main backgrounds:
\( \gamma\gamma \) irreducible background
- photon identification
- jet separation (calorimeter + tracker)

\( \gamma \)-jet and jet-jet (reducible)
- note: also converted photons need to be reconstructed (large material in LHC silicon trackers)

\( \sigma_{\gamma j+jj} \sim 10^6 \sigma_{\gamma\gamma} \) with large uncertainties
\( \rightarrow \) need \( R_j > 10^8 \) for \( \varepsilon_{\gamma} \approx 80\% \) to get
\( \sigma_{\gamma j+jj} \ll \sigma_{\gamma\gamma} \)

- Main exp. tools for background suppression:
  - photon identification
  - \( \gamma \) / jet separation (calorimeter + tracker)

CMS: fraction of converted \( \gamma \)s
Barrel region: 42.0 %
Endcap region: 59.5 %
New elements of the analyses:

- NLO calculations available (Binoth et al., DIPHOX, RESBOS)
- Realistic detector material
- More realistic K factors (for signal and background)
- Split signal sample acc. to resolution functions

- Comparable results for ATLAS and CMS
- Improvements possible by using more exclusive $\gamma\gamma +$ jet topologies
What can be done with 1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV?

95% C.L. excluded cross sections normalized to the Standard Model cross section
**H → WW → ℓν ℓν**

- Large H → WW BR for $m_H \sim 160$ GeV/$c^2$
- Neutrinos → no mass peak, → use transverse mass
- Large backgrounds: WW, Wt, tt

- Two main discriminants:
  
  (i) Lepton angular correlation

  ![Lepton Angular Correlation Diagram]

  (ii) Jet veto: no jet activity in central detector region

**Difficulties:**

(i) need precise knowledge of the backgrounds
   Strategy: use control region(s) in data, extrapolation in signal region

(ii) jet veto efficiencies need to be understood for signal and background events
Expected ATLAS discovery reach at $\sqrt{s} = 14$ TeV for 10 fb$^{-1}$

Separated in:
- H + 0 jet (gluon fusion)
- H + 2 jets (vector boson fusion)
Discovery reach in $H \rightarrow WW \rightarrow \ell \nu \ell \nu$ at $\sqrt{s} = 7$ TeV

- Looks promising, provided backgrounds (systematic uncertainties) can be controlled
- Exclusion reach is comparable to Tevatron reach (nominal performance) (note that a single experiment is quoted above)
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters (couplings to bosons, fermions)

Established (low mass region) by D. Zeppenfeld et al. (1997/98)

Distinctive Signature of:
- two high $p_T$ forward jets (tag jets)
- little jet activity in the central region (no colour flow)
  $\Rightarrow$ central jet Veto
Forward jet tagging

ATLAS full simulation

K. Jakobs, Universität Freiburg  CERN Academic Training Lectures, June 2010
Transverse mass distributions: clear excess of events above the background from tt-production

\[ M_T = \sqrt{(E_T^{\text{H}} + E_T^{\nu})^2 - (p_T^{\ell} + p_T^{\text{miss}})^2} \]
H → ττ  

decay modes visible for a SM Higgs boson in vector boson fusion

qq H → qq ττ  
→ qq ℓνν ℓνν  
→ qq ℓνν ℏν

Experimental challenge:

• Identification of hadronic taus

• Good $E_T^{\text{miss}}$ resolution  
  ($ττ$ mass reconstruction in collinear approximation,  
  i.e. assume that the neutrinos go in the direction of the visible decay products,  
  good approximation for highly boosted taus)

→ Higgs mass can be reconstructed

• Dominant background:  $Z → ττ$

the shape of this background must be controlled in the high mass region
→ use data ($Z → ℓℓ$) to constrain it
LHC Higgs boson discovery potential for $\sqrt{s} = 14$ TeV

- Comparable performance in the two experiments
  [at high mass: more channels (in WW and ZZ decay modes) available than shown here]

- Several channels and production processes available over most of the mass range
  → calls for a separation of the information + global fit (see below)
What can be achieved with 1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV?

- Combination of the WW, $\gamma\gamma$ and ZZ decay channels
  (CMS study, preliminary, numbers from 14 TeV scaled down)

- Mass range in the region between 145 and 190 GeV can be excluded within one experiment
Can the situation at low mass be improved by detecting the $bb$ decay mode?

(needs higher luminosity and energy)
Complex final states: $H \rightarrow bb, t \rightarrow bjj, t \rightarrow b\ell\nu$
$t \rightarrow b\ell\nu, t \rightarrow b\ell\nu$
$t \rightarrow bjj, t \rightarrow bjj$

Main backgrounds:
- combinatorial background from signal (4b in final state)
- $ttjj, ttbb, ttZ, \ldots$
- $Wjjjjjj, WWbbjj, \text{etc. (excellent b-tag performance required)}$

• Updated CMS study (2006): ALPGEN matrix element calculations for backgrounds
→ larger backgrounds ($ttjj$ dominant), experimental + theoretical uncertainties, e.g. $ttbb$, exp. norm. difficult.….

$M (bb)$ after final cuts, $60 \text{ fb}^{-1}$

Signal events only  .... backgrounds added  Signal significance as function of background uncertainty
…..comparable situation in ATLAS      (ttH cont.)

<table>
<thead>
<tr>
<th>Preselection cut</th>
<th>$t\bar{t}H$ (fb)</th>
<th>$t\bar{t}b\bar{b}$ (EW) (fb)</th>
<th>$t\bar{t}b\bar{b}$ (QCD) (fb)</th>
<th>$t\bar{t}X$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton cuts (ID + $p_T$)</td>
<td>57. ± 0.2</td>
<td>141 ± 1.0</td>
<td>1356 ± 6</td>
<td>63710 ± 99</td>
</tr>
<tr>
<td>+ ≥ 6 jets</td>
<td>36 ± 0.2</td>
<td>77 ± 0.9</td>
<td>665 ± 4</td>
<td>26214 ± 64</td>
</tr>
<tr>
<td>+ ≥ 4 loose $b$-tags</td>
<td>16.2 ± 0.2</td>
<td>23 ± 0.7</td>
<td>198 ± 3</td>
<td>2589 ± 25</td>
</tr>
<tr>
<td>+ ≥ 4 tight $b$-tags</td>
<td>3.8 ± 0.06</td>
<td>4.2 ± 0.2</td>
<td>30 ± 0.8</td>
<td>51 ± 2</td>
</tr>
</tbody>
</table>

Normalization from data needed to reduce this (non trivial,…)

estimated uncertainty on the background: ± 25% (theory, + exp (b-tagging))
⇒ Normalization from data needed to reduce this (non trivial,…)
New hope for $H \rightarrow bb$ decays at the LHC: $W/Z H, H \rightarrow bb$

The most important channels at the TEVATRON at low mass!

But: signal-to-background ratio less favourable at the LHC

Follow idea of J. Butterworth, et al. [PRL 100 (2008) 242001]

Select events (≈5% of cross section), in which $H$ and $W$ bosons have large transverse momenta: $p_T > 200$ GeV

$\rightarrow$ b-quarks in one “fat” jet

+ Acceptance (more central in detector)
+ Lepton identification, b-tagging
High $p_T$ W/Z H, H $\rightarrow$ bb

Analyze jet structure:

Combined: $\frac{S}{\sqrt{B}} = 3.7$

- S/B much better than for ttH
- Different backgrounds for different channels
- Still good sensitivity including systematics (e.g. $S/\sqrt{B} = 3.0$ for 15% uncertainty on all backgrounds)

$L^{int.} = 30 \text{ fb}^{-1}$ : $\frac{S}{\sqrt{B}} = 3.0$

$M_H = 120 \text{ GeV}$

$\frac{S}{\sqrt{B}} = 1.5$

$\frac{S}{\sqrt{B}} = 1.6$

(Pileup not yet included)
Is it a Higgs Boson?
-can the LHC measure its parameters?

- Mass
- Couplings to bosons and fermions
- Spin and CP
- Higgs self coupling

Motivation:

- After a discovery of a “Higgs-like” resonance at the LHC one has to measure its parameters and consolidate the evidence for a Higgs boson
- As many parameters as possible have to be measured in as many different production and decay channels as possible! (global fit, see later)
- Discriminate between: SM Higgs boson, MSSM like Higgs boson, Composite Higgs boson, ....
**Measurement of the Higgs boson mass**

- The mass value itself is **important for precision tests of the Standard Model**, but moderate precision seems to be adequate; (as compared to the anticipated $m_t$ and $m_W$ uncertainties)

- In addition: the Higgs mass value is important for the parameter measurements (in particular for the extraction of ratios of couplings) …..

… as many experimental observables / input values need to be compared to the theoretical predictions, which in turn depend -sometimes rather strongly- on $m_H$.
Precision on mass is achieved in el.magn. final states

Dominant systematic uncertainty: \( \gamma / \ell \) energy scale.
assumed: \( 1\% \) (goal \( 0.2\% \))
Scale from \( Z \rightarrow \ell \ell \) (close to light Higgs)

Precision below 1% can be achieved over a large mass range for 30 fb\(^{-1}\);
syst. limit can be reached for higher integrated luminosities \( \rightarrow \) 100 fb\(^{-1}\)
Note: no theoretical errors, e.g. mass shift for large \( \Gamma_H \) (interference resonant / non-resonant production) taken into account
**Higgs boson mass (cont.)**

In case of exotic Higgs boson couplings (e.g. suppressed \( H \rightarrow WW / ZZ \) couplings) the situation is more difficult (even the \( \gamma \gamma \) decay mode would be affected, since the WW loop contribution is dominant)

Remaining channels at low mass:  
- \( H \rightarrow \tau \tau \)  
- \( H \rightarrow bb \)

(difficult S:B situation, difficult as a discovery channel; mass value is most likely needed to extract a signal, if background and mass known, it might be useful and add to coupling measurements)

\[
qq H \rightarrow qq \tau \tau \rightarrow qq \, \ell \nu \nu \, \text{had} \nu
\]

\[
tt \, H, \ H \rightarrow bb
\]

Requires good understanding of the detector (\( \tau, E_T^{miss} \)), resolution limited
Direct extraction of the Higgs boson width:

\[ L = 30 \text{ fb}^{-1} \]

![Graph showing measured Higgs width versus mass](image)
(ii) Higgs boson couplings to fermions and bosons

The Higgs boson couplings can in principle be extracted from rate measurements,

\[ \sigma_{yy \to H} \cdot \text{BR}(H \to xx) \sim \frac{\Gamma_y \cdot \Gamma_x}{\Gamma_H} \]

however, \( \Gamma_H \) is needed, which cannot be directly measured at the LHC for \( m_H < 200 \) GeV.

Two options:

(i) Measure ratios of couplings
Systematic uncertainties taken into account;

(ii) Include more theoretical assumptions and measure absolute couplings
M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein, D. Zeppenfeld,

For both options, the information from all visible Higgs boson production and decay modes can be combined into one global maximum likelihood fit.
Experimental input:

<table>
<thead>
<tr>
<th>Production</th>
<th>Decay</th>
<th>mass range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g g \to H$ (Gluon-Fusion)</td>
<td>$H \to ZZ \to 4l$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td>$q q \to H$ (WBF)</td>
<td>$H \to ZZ \to 4l$</td>
<td>110 GeV - 200 GeV</td>
</tr>
<tr>
<td>$t t H$</td>
<td>$H \to WW \to l\nu l\nu$</td>
<td>110 GeV - 190 GeV</td>
</tr>
<tr>
<td>$W H$</td>
<td>$H \to WW \to l\nu l\nu$</td>
<td>150 GeV - 190 GeV</td>
</tr>
</tbody>
</table>

Mass range is restricted to $m_H < 200$ GeV

Based on „old ATLAS studies“

Most significant differences: ttH channels with $H \to bb$ and $H \to WW$

Updates in preparation, T. Plehn, M. Dürhssen et al.
Higgs-Boson Couplings (cont.)

Global fit
(all channels at a given mass point)
Analysis is done with increasing level of theoretical assumptions

Production cross-sections

\[
\sigma_{ggH} = \alpha_{ggH} \cdot g_t^2 \\
\sigma_{VBF} = \alpha_{WF} \cdot g_w^2 + \alpha_{ZF} \cdot g_Z^2 \\
\sigma_{ttH} = \alpha_{tth} \cdot g_t^2 \\
\sigma_{WH} = \alpha_{WH} \cdot g_w^2 \\
\sigma_{ZH} = \alpha_{ZH} \cdot g_Z^2
\]
(b loop neglected so far in ggH)

Branching ratios

\[
\begin{align*}
BR(H \rightarrow WW) &= \beta_w \frac{g_w^2}{\Gamma_H} \\
BR(H \rightarrow ZZ) &= \beta_z \frac{g_z^2}{\Gamma_H} \\
BR(H \rightarrow \gamma\gamma) &= \frac{(\beta_{\gamma(W)} g_w - \beta_{\gamma(t)} g_t)}{\Gamma_H} \\
BR(H \rightarrow \tau\tau) &= \beta_\tau \frac{g_\tau^2}{\Gamma_H} \\
BR(H \rightarrow bb) &= \beta_b \frac{g_b^2}{\Gamma_H}
\end{align*}
\]

Fit parameters:

\[
\begin{align*}
g_Z^2 & \quad g_\tau^2 & \quad g_b^2 & \quad g_t^2 & \quad g_w^2 & \quad \sqrt{\Gamma_H}
\end{align*}
\]

\[\alpha, \beta \text{ from theory with assumed}
\]

Uncertainties:

\[\Delta \alpha_{ggH} = 20\% \quad \Delta \alpha_{WF} = \alpha_{ZF} = 4\% \quad \Delta \alpha_{tth} = 15\% \quad \Delta \alpha_{WH} = \Delta \alpha_{ZH} = 7\% \]

\[\Delta \beta = 1\%\]
**Step 1: measurement of ratios of partial decay width:**

Assumption: only one light Higgs boson

To cancel $\Gamma_H$, normalization to $\Gamma_W$ is made
(suitable channel, measurable over a large mass range ~120–200 GeV)

Note: optimistic assumptions for $H \rightarrow bb$ (based on old studies)
Step 2: measurement of ratios of couplings:

Additional assumption: particle content in the $gg$- and $\gamma\gamma$-loops are known;

Information from Higgs production is now used as well; Important for the determination of the top-Yukawa coupling
Step 3: measurement of couplings (absolute values):

Needs additional ("mild") theoretical assumptions:
- use lower limit on $\Gamma_H$ from visible decay modes
- assume that $g(H,W)$ are bound from above by the Standard Model value:
  $g^2(H,W) \leq g^2(H,W,\text{SM})$; (valid for any model that contains only Higgs doublets and singlets)
  (upper value is motivated from WW scattering unitarity arguments)

Total width is “measured” as well
(iii) Spin and CP quantum numbers

**Spin:**

- Spin 0: angular correlations in $H \rightarrow WW \rightarrow \ell\nu \ell\nu$ decays
- More general: Angular distributions in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4 \ell$ are sensitive to spin and CP eigenvalues

- Azimuthal angle $\phi$
- Polar angle $\theta$

CMS TDR - M.Bluj CMS NOTE 2006/094

**CP information:**

- Angular distributions in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4 \ell$
- Angular correlation of tagging jets in vector boson fusion production
- Angular correlations in ttH decays

Exploiting angular correlations in $H \rightarrow ZZ(*) \rightarrow 4\ell$ decays:

Fit to

$$F(\phi) = \alpha \cos(\phi) + \beta \cos(2\phi)$$

$$F(\theta) = T \left(1+\cos^2\theta\right) + L \sin^2\theta$$

$$R = \frac{(L-T)}{(L+T)}$$

Exploiting angular correlations in $H \rightarrow ZZ(*) \rightarrow 4\ell$ decays:

Expected results:

Evidence for spin-0 in $H \rightarrow WW \rightarrow \ell\nu\ell\nu$

- Cuts can be relaxed, to get background shape from the data + Monte Carlo:

No kinematical cuts on leptons applied: (ATLAS study)

Evidence for spin-0 of the Higgs boson, $\Delta\phi$ distribution

Spin-0 $\rightarrow$ WW $\rightarrow$ $\ell\nu\ell\nu$ expect leptons to be close by in space

Tensor structure of Higgs couplings in VBF events

• General parametrization of the coupling of a scalar to vector bosons:

\[ T^{\mu\nu}(q_1, q_2) = a_1(q_1, q_2) g^{\mu\nu} + a_2(q_1, q_2) \left[ q_1 \cdot q_2 g^{\mu\nu} - q_2^{\mu} q_1^{\nu} \right] + a_3(q_1, q_2) \varepsilon^{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma. \]

CP even Standard Model term
anomalous CPE term
anomalous CPO term

• Contributions and admixtures can be determined in VBF using the \( \Delta\phi \) distribution between the two tag jets

Shapes of \( \Delta\phi \) distributions
(no backgrounds, large statistics)

Tensor structure of Higgs couplings in VBF events (cont.)

• ATLAS study using the $qqH \rightarrow qqWW$ and $qqH \rightarrow qq\tau\tau$ channels:

• Apply typical VBF selection cuts: central leptons
  two tag jets: $M_{jj}$, $P_T$

After (fast) detector simulation

ATLAS, $qqH \rightarrow qqWW$, $L = 10 \text{ fb}^{-1}$

Expectations:

$WW$ decay mode: $m_H = 160 \text{ GeV}$
Anomalous CP-even and CP-odd couplings can be excluded with $5\sigma$, for $10 \text{ fb}^{-1}$

$\tau\tau$ decay mode: $m_H = 120 \text{ GeV}$
Exclusion with a $2\sigma$ significance requires $30 \text{ fb}^{-1}$
CMS analysis: search for a pseudoscalar admixture

- Use again the angular correlations in $H \rightarrow ZZ \rightarrow 4\ell$ decays
- Assume Spin-0 Higgs boson and allow for a pseudoscalar admixture $\phi = H + \xi A$
  
  (Standard Model (scalar) case: $\xi = 0$)
Results from Monte Carlo experiments for a maximum likelihood fit to the angular distributions and the 4-lepton invariant mass (including signal and background) allows precise measurement of pseudoscalar admixture for 60 fb⁻¹.

(iv) Higgs boson self-coupling?

To finally establish the Higgs mechanism the Higgs boson self-coupling has to be measured:

\[
\lambda_{HHH}^\text{SM} = 3 \frac{m_H^2}{v}, \quad \lambda_{HHHH}^\text{SM} = 3 \frac{m_H^2}{v^2}
\]

Cross sections for HH production:

small signal cross-sections, large backgrounds from \( t\bar{t}, WW, WZ, WWW, ttt, Wtt, \ldots \)

\[ \Rightarrow \text{no significant measurement possible at the LHC} \]

need Super LHC \( L = 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}, 6000 \text{ fb}^{-1} \)
even there: a measurement is very difficult, needs more studies.
Summary: Is it a Higgs Boson?

1. Mass
   Higgs boson mass can be measured with high precision < 1% over a large mass range (130 - ~450 GeV) using $\gamma\gamma$ and $ZZ \rightarrow 4\ell$ resonances

2. Couplings to bosons and fermions
   - Ratios of major couplings can be measured with reasonable precision;
   - Absolute coupling measurements need further theory assumptions
     (Methods established, exp. Updates are needed, in particular for VBF channels at high luminosity)

3. Spin and CP
   Angular correlations in $H \rightarrow ZZ(\ast) \rightarrow 4\ell$ and $\Delta\phi_{ij}$ in VBF events are sensitive to spin and CP (achievable precision is statistics limited, requires high luminosity)

4. Higgs self coupling
   No measurement possible at the LHC;
   Very difficult at the sLHC, there might be sensitivity in $HH \rightarrow WW WW$ for $m_H \sim 160$ GeV
   Situation needs to be re-assessed with more realistic simulations, timescale unknown