What can we learn about the Higgs with 10 fb$^{-1}$ at the LHC?

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BNL
Outline

With 10 fb$^{-1}$:

• Which channels could be visible?
• What kind of deviation from the SM could we expect?
• Which mass and property measurements could we achieve? With which precision?

But I will discuss early physics first …
Twenty-five years...

- 1984: First LHC workshop (Lausanne)
  - Use LEP tunnel for protons
- 1992: First ‘expressions of interest’ for experiments
- 1996: First exp’ts approved
- 1998: First full-size magnet test
- 2003: End of civil engineering
- 2006: Last magnet produced
- 2008: First beam
- 2009: First collisions

Some vital statistics
- Tunnel circumference 27 km
- 1232 main magnets, 8 T field
- Another 7000 smaller magnets
- Operating temperature 1.9K
- Cost: ~4700 MCHF (incl. manpower)
- Experiment cost: ~500 MCHF each for ATLAS & CMS (excl. manpower)
16 June 2008: Last piece of LHC ring being put in place
First Events: Collimators Closed

\(~2.10^9\) protons on collimator \(~150\) m upstream of CMS

ECAL - pink; HB,HE - light blue; HO,HF - dark blue; Muon DT - green; Tracker Off

On 10 September, collimators 140m upstream of each experiment closed, as first beam sent around: “beam splash” events
Timing of all TRT readout channels could be performed with accuracy of \~1\,ns per event! Differences in colour due to cosmic timing:

**Top:** early  \hspace{1cm} **Bottom:** late

2D display in $\eta-\phi$ of energy deposited in LAr EM calorimeter per cell (layer 2):

- structures seen are due to material between collimators and calorimeter (mostly 8-fold structure of end-cap toroid coils)
- energy seen per event is huge!
Commissioning with 2008 Data

Very much use of data that are available:
- Cosmic rays
- Splash events
- Single beam

Many months of cosmic rays
- Detector alignment: especially muon and central tracking systems
- Detector timing & uniformity
- ...

10 milliseconds of cosmics through ATLAS
Example: CMS Electromagnetic Calorimeter

A “Dee” of endcap ECAL

Barrel ECAL clusters matching muon tracks

sometimes:
huge energy deposition from cosmic muon in ECAL

Energy: 250 GeV

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Using Cosmics

>200 million cosmic ray events since Sept

See transition radiation turn-on with $\mu$!

Pixel detector alignment

[Graphs and diagrams showing data and analysis related to cosmic events and detector performance]

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LHC Machine Status

- With circulating beam the LHC worked remarkably well. Unfortunately only for 3 days...

- The incident on Sept. 19th was due to a poor quality bus-bar joint.
  - Quench protection system upgrade under way.
  - New diagnostics for online monitoring and protection of all joints.
  - Improvements of the pressure relief and magnet support (mitigation).

- During repair of S34 a new joint quality issue was discovered.
  - Systematic problem on many joints due to soldering (voids).
  - Limits operating energy to 3.5 TeV for initial operation.

- S34 repair is finished, the sector is at 4 K.
  - Insulation vacuum is stable, cool-down & commissioning continues.
HWC progressing rather well, but commissioning of the new quench protection system is delicate.

May limit energy in 2009 to 1.1 TeV (2 kA).

Beam preparation are advancing well.

Injection tests into 2 sectors (23+78) next week-end.
Startup with beam ~ 20th November.

Beam commissioning aims for collisions before Christmas 2009.

Collisions at 450 GeV well within reach.
Collisions at 1.1 or 3.5 TeV before Christmas are challenging.

Aiming for luminosities of $10^{32}$ cm$^{-2}$ s$^{-1}$ in 2010.

Pushing the energy beyond (to?) 5 TeV will require a long stop to consolidate the joints.

Strategy is not yet defined.
Physics Commissioning

First collisions: work to establish detector and trigger performance, measure Standard Model processes

- Min bias - timing in, tracking & calorimeter uniformity & performance
- Dijets - calorimeter uniformity, jet uniformity and inter-calibration
- \(\gamma\)-jet - photon ID, jet energy scale
- \(J/\psi\) - \(\mu\) ID, tracking performance (e ID)
- \(b\bar{b}\) - lifetime-based b-tagging
- \(W/Z\) - e/\(\mu\) ID, resolutions, efficiencies, \(\tau\) ID (in time), missing \(E_t\)
- \(Z\)+jets - jet energy scale
- Top - many things, once we have statistics...

You will need to be patient - this will take some time...
Calibration and Alignment

Much work to be done before physics, building on:

- test-beam
- calibration and alignment systems
- cosmics being taken now

<table>
<thead>
<tr>
<th></th>
<th>Initial</th>
<th>Ultimate</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>e/\gamma E scale</td>
<td>~2%</td>
<td>0.1%</td>
<td>Z→ee, J/ψ, π⁰</td>
</tr>
<tr>
<td>e/\gamma uniformity</td>
<td>1-4%</td>
<td>0.5%</td>
<td>Z→ee</td>
</tr>
<tr>
<td>jet E scale</td>
<td>5-10%</td>
<td>~1-2%</td>
<td>W→jj in tt, γ/Z+jets</td>
</tr>
<tr>
<td>tracking alignment</td>
<td>10-100μm</td>
<td>&lt;10 μm</td>
<td>tracks, Z→μμ</td>
</tr>
<tr>
<td>muon alignment</td>
<td>?</td>
<td>30 μm</td>
<td>inclusive μ, Z→μμ</td>
</tr>
</tbody>
</table>

Early data very important:

- tracks for alignment
- azimuthal asymmetry for calo. uniformity
- conversions for material assay
- …
Missing-$E_T$

Challenging to commission:
- dependence on all calorimetry, even FCAL
- modelling of crack regions, eg
- machine backgrounds, etc

ATLAS studies shown here

Detailed studies ready for control samples of data…

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Minimum Bias

Early measurements - need tracker alignment, efficiency and material, to be understood

Challenge to extend tracking to low $p_T$ (high B-fields at LHC!)

CMS tracker: dE/dx (digitised readout of Si)
Individual particle yields

ATLAS, $p_T > 150$ MeV

1 minute @ $L=10^{31} \text{cm}^{-2}\text{s}^{-1}$ 14 TeV

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Huge statistics very fast, especially in $\mu\mu$ channel
- important standard candle for commissioning

With 1 pb$^{-1}$ could already measure

$$R = \frac{\sigma(bb\rightarrow J/\psi)}{\sigma(pp\rightarrow J/\psi)}$$

with <5% statistical precision

provided: muon trigger working; tracking understood well enough
Jets

Huge cross-sections

Very rapidly sensitive beyond Tevatron at 10 or 14 TeV

Main experimental challenge:
jet energy scale uncertainty
- $\gamma$-jet, Z-jet events
- $E_T$-balance in dijet and multijet events

LHC

10 events with 100 pb$^{-1}$

Tevatron

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New Physics in Dijets

Other sensitive distributions, such as:
- dijet mass
- dijet ratios, e.g. \( N(|\eta|<0.7)/N(0.7<|\eta|<1.3) \)

100 pb\(^{-1}\) at 14 TeV: sensitive well beyond Tevatron limit at 0.8 TeV

Sensitive to spin of a high-mass resonance observed

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W and Z

Clean selections anticipated: excellent lepton ID

\[ Z \rightarrow e^+e^- \]
\[ 50 \text{ pb}^{-1} \]

25k \( Z \rightarrow e^+e^- \) for 50 pb\(^{-1}\) at 14 TeV
Quickly dominated by systematics

Initial precision of W/Z cross sections 4-5%

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Top Physics

Top ($t\bar{t}$) cross-section at 14 TeV ~ 850 pb
Cf Tevatron ~ 7 pb
NLO + corrections

Invaluable channel for data-driven calibration
- can select without b-tags
- commission b tagging
- general performance
- calibrate the light jet energy scale with $W\rightarrow jj$

Cross-section about half at 10 TeV

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**Simplest New Physics Signature?**

- **Z'** mass peak on top of small Drell-Yan background
- with 100 pb$^{-1}$ large enough signal for discovery up to $m \sim 1.5$ TeV in sequential SM \[ \sigma(10 \text{ TeV}) \sim \frac{1}{2} \sigma(14 \text{ TeV}) \]
- current Tevatron 95% CL limit $\sim 1$ TeV
- ultimate calorimeter performance not needed
- ultimate reach (300 fb$^{-1}$) $\sim 5$ TeV
SUSY - mSUGRA

QCD production of squarks, gluinos - $E_T^{\text{miss}}$ signatures

Need to understand whole detector well to rely on $E_T^{\text{miss}}$

→ problem will be to know if an excess is real, and what it is...
Improvement in Higgs Studies at the LHC

- Many studies have meanwhile been performed using detailed GEANT simulations of the detectors

- New (N)NLO Monte Carlos (also for backgrounds)
  - MC@NLO Monte Carlo, S. Frixione and B. Webber, wwwweb.phy.cam.ac.uk/theory/
  - ….

- New approaches to match parton showers and matrix elements
  - ALPGEN Monte Carlo + MLM matching, M. Mangano et al.
  - SHERPA Monte Carlo, F. Krauss et al.
  - …

  Tevatron data are extremely valuable for validation, work has started

- More detailed, better understood reconstruction methods
  (partially based on test beam results,…)

- Further studies of new Higgs boson scenarios
  (Various MSSM benchmark scenarios, CP-violating scenarios, Invisible Higgs boson decays,…..)
Current limits on $M_H$

- Latest results from Tevatron presented at Lepton-Photon '09 conference (August 2009)

Precision EW fit:

$m_H < 157$ GeV

@95%CL

(<186 GeV with LEPII Limit)

- Updated results available for CDF and D0, but no new combined results yet....
Higgs Production at the LHC

A. Djouadi, Phys. Rept. 457:1-216

\[ \sigma(pp \rightarrow H + X) \text{ [pb]} \]
\[ \sqrt{s} = 14 \text{ TeV} \]
\[ \text{MRST/NLO} \]
\[ m_t = 178 \text{ GeV} \]

**gg fusion process is the more abundant, followed by the Vector Boson Fusion process.**

**Typical uncertainties on cross-section**
- gg: 10% NNNLO
- VBF: 5% NLO
- WH, ZH: 5% NNLO
- ttH: 15% NLO
SM Higgs Decays at the LHC

**GF** $H \rightarrow WW, ZZ, \gamma\gamma$

**VBF** $H \rightarrow WW, \gamma\gamma, \tau\tau$

$H \rightarrow WW, \gamma\gamma$

$H \rightarrow WW, \gamma\gamma, bb$

Many channels explored!
All the mass range is covered!
Light Higgs Boson ...

Tevatron Main Search Channels
- $m_H \sim 115 \text{ GeV}$
  - $WH \rightarrow l\nu bb$
  - $ZH \rightarrow \nu\nu bb$, $llbb$
- $m_H \sim 160 \text{ GeV}$
  - $H \rightarrow WW \rightarrow l\nu l\nu$

LHC Main Search Channels
- $H \rightarrow \gamma\gamma, qqH \rightarrow qq\tau\tau$
- $ttH \rightarrow l\nu bbX$
- $H \rightarrow WW \rightarrow l\nu l\nu, H \rightarrow ZZ^* \rightarrow 4l,$
- $qqH \rightarrow qqWW \rightarrow qql\nu l\nu$

Large backgrounds at the LHC

Cross-sections too small at the Tevatron

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Higgs → γγ

- **Important channel in the low mass region.**
- **It gives the best mass resolution thanks to excellent electromagnetic energy resolution**

### ATLAS SELECTION

- **Trigger:** at least 2 isolated photons, with $p_T > 20 \text{ GeV/c}$ each
  \[ \varepsilon (\text{respect to offline}) = (93.6 \pm 0.4)\% \]
- **Identification cut** exploiting the shower shape.
- **Fiducial cut:** $0 < |\eta| < 1.37$ & $1.52 < |\eta| < 2.37$.
- **Isolation cut:** $\Sigma p_T < 4 \text{ GeV/c}$, considering all tracks with $p_T > 1\text{ GeV/c}$ in a $\Delta R = 0.3$ cone around the electromagnetic cluster.
- **Momentum cut:** $p_T > 25\text{ GeV/c}$ and $p_T > 40\text{ GeV/c}$ for the two most energetic photons.

### Selection efficiency:

\[ \varepsilon = 36.0 \% \text{ (32.2\% with pileup 10^{33} \text{cm}^{-2}\text{s}^{-1})} \]

### Table: In a mass window $M_H +/- 1.4\sigma \text{ GeV}$:

<table>
<thead>
<tr>
<th>Signal Process</th>
<th>Cross-section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H$</td>
<td>21</td>
</tr>
<tr>
<td>VBF $H$</td>
<td>2.7</td>
</tr>
<tr>
<td>$ttH$</td>
<td>0.35</td>
</tr>
<tr>
<td>$VH$</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Higgs → $\gamma \gamma$ backgrounds

ATLAS

Within a mass window $M_H +/− 1.4\sigma GeV$:

<table>
<thead>
<tr>
<th>Background Process</th>
<th>Cross-section (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>562</td>
</tr>
<tr>
<td>Reducible $\gamma j$</td>
<td>318</td>
</tr>
<tr>
<td>Reducible $jj$</td>
<td>49</td>
</tr>
<tr>
<td>Drell Yan</td>
<td>18</td>
</tr>
</tbody>
</table>

- Background is evaluated with NLO simulations.
- It will be measured from data sidebands.

Example: $\gamma$-jet processes

Strategy for jet rejection:
- Longitudinal segmentation of the calorimeter.
- Fine segmentation of the first layer (η-strips) => good $\pi^0$ rejection.
- Isolation of the electromagnetic cluster.
- Isolation based on tracks reconstructed by the inner detector.
Higgs $\rightarrow \gamma\gamma$ reconstruction

**PRIMARY VERTEX**

If the vertex is unknown, add 1.4 GeV to the mass resolution. Combine calorimeter and tracker informations!

- Calorimeter $\rightarrow$ vertex position accuracy of 19 mm
- Combining with the tracker information $\rightarrow$ $\sim$0.1 mm
Calorimeter information is useful in case of pile-up or events with low tracks multiplicity.

**CONVERSIONS**

$\sim$50% of the events with at least one converted $\gamma$!

- conversion vertex used in computation of the direction;
- used for gamma-jet background estimation.

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**CMS:** fraction of converted $\gamma$s
Barrel region: 42.0 %
Endcap region: 59.5 %
Higgs $\rightarrow \gamma\gamma$ significance

New elements of the analyses:

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

- Comparable results for ATLAS and CMS
- Improvements possible by using more exclusive $\gamma\gamma$ + jet topologies
Higgs → ZZ* → 4l

ATLAS

**Selection**

- **Trigger:**
  - single isolated $\mu$ ($e$) with $p_T > 20$ (25) GeV/c;
  - two $\mu$ ($e$) with $p_T > 10$ (15) GeV/c.

- **Kinematic:**
  - 2 pairs of same flavor opposite charge lept.
    - $p_T > 7$ GeV (at least two with $p_T > 20$ GeV)
    - calorimeter identification
    - $|M_{lll} - M_Z| < \Delta M_{12}$ and $M_{\mu\mu} > M_{34}$

- **Fiducial cut:** $|\eta| < 2.5$

- **Isolation cut:** Calorimeter: $\Sigma E_T/p_T < 0.23$
  - tracker: $\Sigma p_T/p_T < 0.15$ ($\Delta R < 0.2$)

- **Vertexing cut** on maximum lepton impact parameter:
  
  \[ d_0/\sigma_{d0} < 3.5 \text{ (6.0 ) for } \mu (e) \]

- Look to the Z with first data to understand lepton reconstruction and detectors response.
  - $Z \rightarrow ee$ mass peak is affected by electron bremsstrahlung.

It is the “golden channel”!

- Observation of a clear peak on top of a smooth background!
- Wide range of masses explored

Background will be estimated in sidebands → low systematic uncertainties
Higgs $\rightarrow$ ZZ$^*$ $\rightarrow$ 4l

ATLAS

L = 10 fb$^{-1}$

CMS

$\int L = 9.2$ fb$^{-1}$

4 lepton invariant mass (GeV)

ee$\mu\mu$

ee$\mu\mu$

5 fb$^{-1}$ to claim discovery $\sim m_H = 150$ GeV or $200 < m_H$(GeV) $< 400$

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Vector Boson Fusion  $qq \, H$

**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 tag jets
- little jet activity in the central region
$\Rightarrow$ central jet Veto

![Diagram of Higgs decay and tagging jets]

Rapidity distribution of jets in $tt$ and Higgs signal events:
Vector Boson Fusion \( qq \rightarrow H(\rightarrow \tau\tau) \)

- **High BR in the low mass region.**
- **3 channels:** \( ll, lh, hh \) (65\% of \( \tau \) gives hadrons)

### SELECTION

- **Trigger:** isolated electrons (\( \mu \)) with \( p_T > 22 \) (20) GeV/c (\( \epsilon \sim 10\% \))
  - \( \tau + E_T^{\text{miss}} (\epsilon \sim 3.7\%) \) for the \( hh \) channel
- **Isolation cut**
- **Likelihood** exploiting the shower shape and the track quality to separate \( \tau \) and jet.
- **b-jet veto** to kill \( tt(+jets) \rightarrow lvb \) (background for the \( ll \) channel)
- select highest \( E_T \) jets in opposite hemispheres
- **Central jet veto**

### BACKGROUNDS

- \( Z \rightarrow \tau\tau + \text{jets} \)
- \( W \rightarrow \tau\nu + \text{jets} \)
- \( tt + \text{jets} \)
- \( QCD \) multi-jets for the \( hh \) channel

### MAIN ISSUES:

- Discrepancies in Monte Carlo generator \( \rightarrow \) impact on veto efficiency
- Pileup \( \rightarrow \) impact on \( E_T^{\text{miss}} \) and jet veto
- Estimation of QCD multi-jet \( \rightarrow \) no sensitivity yet on \( hh \) channel
VBF $qq \, H(\to \tau\tau)$

$qq \, H \rightarrow qq \, \tau \tau$
$qq \, \ell \nu \nu \, \ell \nu \nu$
$qq \, \ell \nu \nu \, h\nu$

Experimental challenges:
- In-time pileup, out-of-time pileup, underlying event.
  - Test simulations & use vertexing for the jet
  - Calorimeter timing
- Early data underlying event measurement
- Identification of hadronic $\tau$
- Good $E_T^{miss}$ resolution (since there are neutrinos...)
- Knowledge of the $Z \rightarrow \tau\tau$ background shape in the high mass region: use data $Z \rightarrow \mu\mu$ to emulate it!

Higgs mass reconstructed using the angle between the two $\tau$ and the collinear approximation:

$m_{\tau\tau} = m_h/sqrt(X_1 X_2)$

with $X_i = P_T(\ell_i)/P_T(\tau_i)$

$\sim 5\sigma$ combining $ll$ and $lh$ channels in the low mass region with 30 fb$^{-1}$
Interesting for \(2M_W < M_H < 2M_Z\) where all other decay modes are suppressed.

Signature is \(e \mu\) (or \(lq\)) + \(E_T^{\text{miss}}\).

Three channels:
- \(H \rightarrow WW \rightarrow e \nu \mu \nu\) (\(H+0\) jet)
- \(H \rightarrow WW \rightarrow e \nu \mu \nu\) \(VBF\) (\(H+2\) jet)
- \(H \rightarrow WW \rightarrow l \nu q q\)
  (only for \(M_H = 300\) GeV)

Measure of spin and CP properties possible for heavy \(H \rightarrow WW \rightarrow lvqq\)

Comments:
- No mass peak \(\Rightarrow\) use transverse mass. \(M_T = \sqrt{(E_T^l + E_T^\nu)^2 - (\slashed{p}_T + \slashed{E}_T^{\text{miss}})^2}\)
- High backgrounds: \(WW, Wt, t\bar{b}, Z \rightarrow 2l, bb, cc, QCD\) multijet

CMS: ee, \(\mu\mu\), \(e\mu\) final states have been analyzed
ATLAS: ee, \(\mu\mu\) analysis in preparation
Large $H \rightarrow \text{WW}$ BR for $m_H \sim 160 \text{ GeV/c}^2$

- Neutrinos $\rightarrow$ no mass peak,
- Large backgrounds: WW, Wt, tt

Two main discriminants:

(i) Lepton angular correlation

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

Selection criteria:

- Lepton $P_T$ cuts and tag jet requirements ($\Delta \eta$, $P_T$)
- Require large mass of tag jet system
- Jet veto (important)
- Lepton angular and mass cuts

\[ M_T = \sqrt{(E_{T}^{l} + E_{T}^{\nu})^2 - (p_T^{\text{miss}})^2} \]

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
   $\rightarrow$ reliable Monte Carlo generators, data driven-background normalizations
$H \rightarrow WW \rightarrow \ell\nu\ell\nu$

**Significance $> 5\sigma$ @ 10 fb$^{-1}$**

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**CMS**

![CMS Graph 1](Image)

**CMS**

![CMS Graph 2](Image)

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**ATLAS**

$\int L \, dt = 10 \text{ fb}^{-1}$

![ATLAS Graph 1](Image)

![ATLAS Graph 2](Image)
\[ \text{ttH} \rightarrow \text{ttbb} \]

Complex final states: \( H \rightarrow bb, \ t \rightarrow b\ell\nu \)
\( t \rightarrow b\ell\nu, \ t \rightarrow b\ell\nu \)
\( t \rightarrow bjj, \ t \rightarrow bjj \)

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

- Updated CMS study (2006): ALPGEN matrix element calculations for backgrounds
  → larger backgrounds (\( ttjj \) dominant), experimental + theoretical uncertainties, e.g. \( \text{ttbb} \),
  exp. norm. difficul. Maybe some hope in the highly boosted regime …

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

Signal events only
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... backgrounds added
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Signal significance as function of background uncertainty
LHC discovery potential

Full mass range can already be covered after a few years at low luminosity
Similar performance in ATLAS
Several channels available over a large range of masses
Vector boson fusion channels play an important role at low mass!

Important changes w.r.t. previous studies:
- $H \rightarrow \gamma \gamma$ sensitivity of ATLAS and CMS comparable
- $ttH \rightarrow tt bb$ disappeared in both ATLAS and CMS studies

With 2 fb$^{-1}$, > 5σ discovery in $143 < m_H$(GeV) < 179
Combined Exclusion Limit

Luminosity required for exclusion as function of $m_H > 115$ GeV at 95% CL with 2 fb$^{-1}$

Luminosity required for exclusion as function of $m_H$
Update

With 1 fb⁻¹, exclude SM-like Higgs with $m_H > 185$ GeV in the 4l channel.

With 1 fb⁻¹, 5σ discovery around $m_H = 160$ GeV in $H \rightarrow WW \rightarrow ll\nu\nu$ channel.

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Higgs mass measurements

- 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 extraction of ratios of couplings
- Higgs boson mass measurement dominated $ZZ \to 4l$ and $\gamma\gamma$ resonances
  - Well identifiable with good resolution

\[ \gamma/\text{lepton energy scale} - \text{assume } 1\% (\text{ultimately } 0.2\%) \]
  - Lepton energy scale from $Z \to ll$ (close the light Higgs)
Higgs mass measurements

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

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)

Requires good understanding of the detector ($\tau$, $E_T^{miss}$), resolution limited

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Total width, $\Gamma_H$, cannot be measured below $\sim 200$ GeV - detector resolution; An upper limit of a few GeV could be set.

Above $\sim 200$ GeV intrinsic width could be measured with a precision of $\sim 35\%$ with 30 fb$^{-1}$ (one experiment)
Spin/CP measurements

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

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

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

\[ \Delta \phi_{jj} \]

References:

T. Plehn, D. Rainwater and D. Zeppenfeld, Phys Rev Lett 88, 051801, 2002
Spin/CP measurements

- 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:

**CPE and CPO anomalous couplings:**
- with $10 \text{ fb}^{-1}$ can be excluded at $5\sigma$ in $H \rightarrow WW \rightarrow llvv$ for $m_H = 160 \text{ GeV}$.
- with $30 \text{ fb}^{-1}$ can be excluded at $2\sigma$ in $H \rightarrow \tau\tau$ for $m_H = 120 \text{ GeV}$. 
Summary

• **Exclusion**
  - With 2 fb\(^{-1}\) (one experiment), exclude SM-like Higgs with \(m_H > 115\) GeV, if it does not exist

• **Higgs Searches**
  - ATLAS and CMS are well-prepared to discover Higgs bosons. The SM mass range and the MSSM parameter space are well covered
  - With 1-2 fb\(^{-1}\), discovery possible in \(H \rightarrow WW \rightarrow ll\nu\nu\) depending on \(m_H\). > 5\(\sigma\) discovery possible in \(143 < m_H(\text{GeV}) < 179\)
  - With 10 fb\(^{-1}\), normally 1 year of low luminosity operation, discovery possible for \(m_H \in [120, 500] \text{ GeV}\)

• **Higgs Mass Measurement - needs more than 10 fb\(^{-1}\)**
  - 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

• **Spin and CP**
  - Angular correlations in \(H \rightarrow ZZ(*) \rightarrow 4\ell\) and \(\Delta\phi_{jj}\) in VBF events are sensitive to spin and CP (achievable precision is statistics limited, requires high luminosity)