Search for the Higgs boson in the 4 leptons channel at ATLAS.

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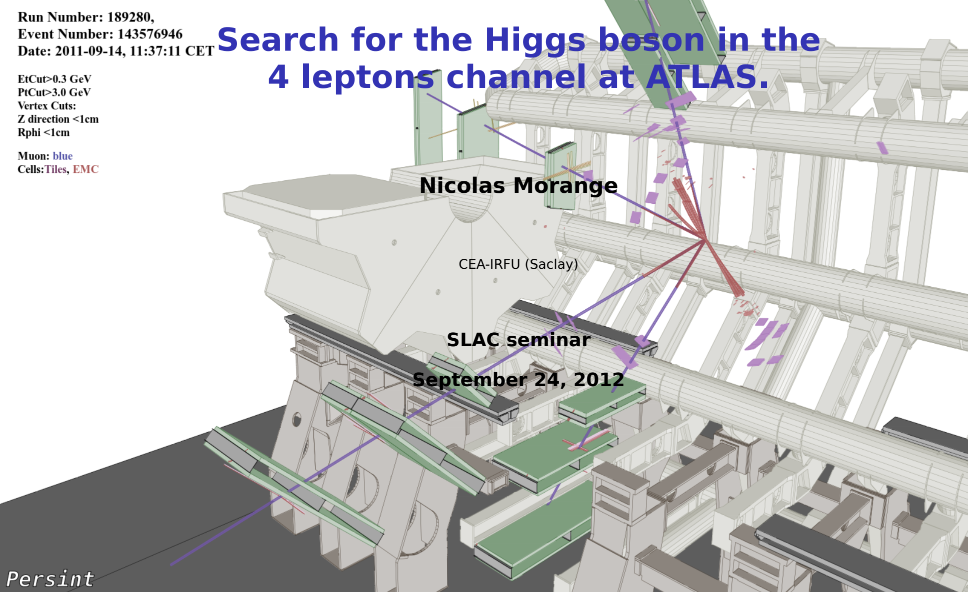
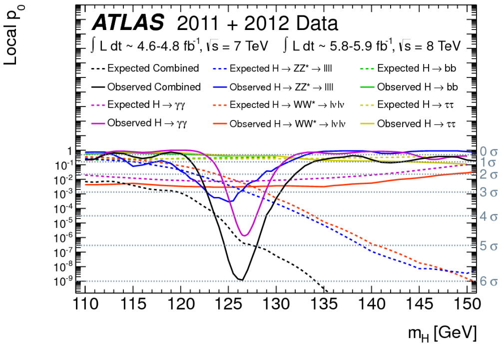
SLAC seminar

September 24, 2012



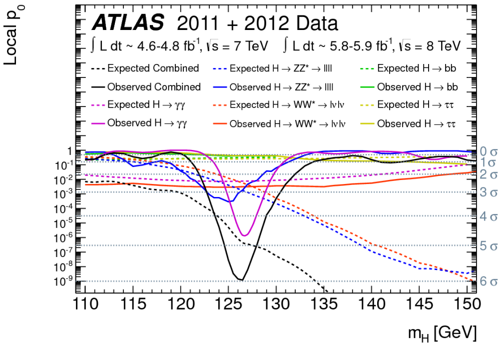
You all know the conclusion...



- Discovery of a new particle in the search for the SM Higgs boson
- 4 leptons channel one of the major players in game
- Published Phys.Lett., B716 (2012) 1-29

Starting with the conclusion

You all know the conclusion...

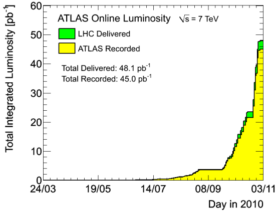


... which has been achieved after (only) 2.5 years of data-taking !

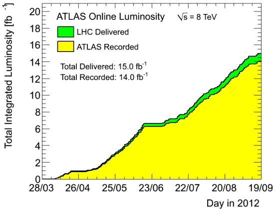
Thanks to... the LHC

- E_{cm}:
  - 900 GeV (2009),
  - 7 TeV (2010,2011),
  - 8 TeV (2012),
  - 13–14 TeV (2015-)
- Instantaneous luminosity:
  - $\sim 10^{32}\,cm^{-2}s^{-1}$ (2010),
  - $\sim 10^{33}\,cm^{-2}s^{-1}$ (2011, 2012),
  - $10^{34}\,cm^{-2}s^{-1}$ (nominal)
- Spacing between proton bunches:
  - 50 ns (2010-2012)
  - 25 ns (nominal)

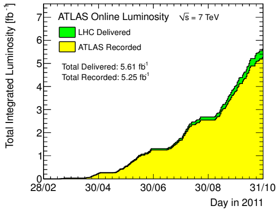
Integrated luminosities:



2010: 45 pb^{-1}



2012: 15 fb^{-1} and ongoing

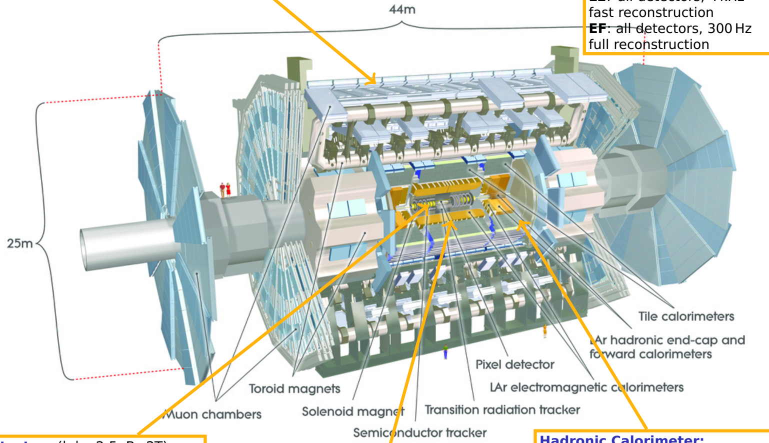


2011: 5.25 fb^{-1}

Thanks to... the ATLAS detector

Muon Spectrometer: ($|\eta| < 2.7$)
Air toroid with drift chambers,
Provides μ trigger and momentum measurement,
Resolution $< 10\%$ up to $p \sim 1$ TeV.

Trigger System:
3 levels
L1: calo and muons, 75 kHz
dedicated electronics
L2: all detectors, 4 kHz
fast reconstruction
EF: all detectors, 300 Hz
full reconstruction



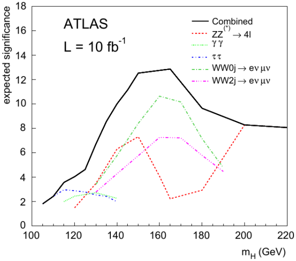
Inner Detector: ($|\eta| < 2.5$, B=2T)
Si Pixels, SCT, TRT
Precision tracking,
Vertex reconstruction,
e/π separation
$\sigma/p_T \sim 3.8 10^{-4} p_T \oplus 0.015$

EM Calorimeter: ($|\eta| < 3.2$)
Pb-LAr, accordion structure
Provides trigger on e/γ,
Identification and measurement
$\sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

Hadronic Calorimeter:
Scint/Fe tiles in barrel ($|\eta| < 1.7$)
W/Cu-LAr in endcaps ($|\eta| < 4.9$)
Provides jet trigger and energy measurement,
$\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$
Hermetic coverage for MET

2.5 years of data-taking to:

- Commission and understand finely the detector
- Understand and improve reconstruction performance
- Measure basic SM processes ("re-discover" the SM)
- Improve and perform the search for the Higgs



ATLAS simulation 14 TeV, 2008
$< 5\sigma$ at 125 GeV with 10 fb^{-1}.

All of these steps absolutely crucial to obtain the current results !

Going through the steps

1. **Commissionning the ATLAS detector: the L1Calo trigger system at high energies**

2. **The Higgs boson at the LHC**

3. **Measuring basic processes: b-jets associated with Z bosons**

4. **Improving and performing searches: the $H \to 4\ell$ channel**

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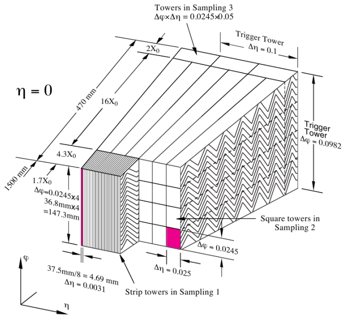
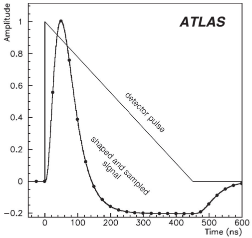
The electromagnetic calorimeter



Geometry

- sampling Pb/LAr calorimeter, accordion structure
- contains EM showers
- Barrel $|\eta| < 1.47$, endcaps $1.37 < |\eta| < 3.2$
- 3 layers in depth, plus a presampler
- fine transverse segmentation

⇒ ∼170 000 cells



Calorimeter Readout

- Drift time 400 ns
  - ⇒ bipolar shaping, rise time 45 ns
- Optimal filtering
  - ⇒ energy, timing, signal quality

The L1 calorimeter trigger system

Search for deposits compatible with physics objects

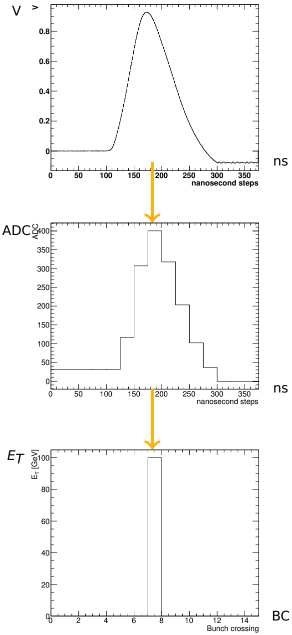
- Computation of transverse energies,
- Bunch-crossing identification (BCID).

Trigger towers

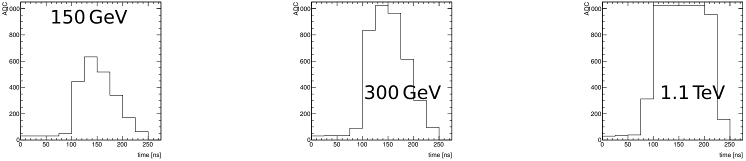
- Lowered granularity: mostly $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$,
- Obtained by analog sums (dedicated electronics, Saclay involvement),
- Signals digitized at 40 MHz on 10 bits, with steps of 250 MeV,
- Energy computation: Finite Input Response filter (FIR ∼ optimal filtering) with 5 samples,
- BCID: look for maximum of FIR output.

Trigger logic

- Find Regions of Interest (local maxima),
- If event accepted, transmit to L2.



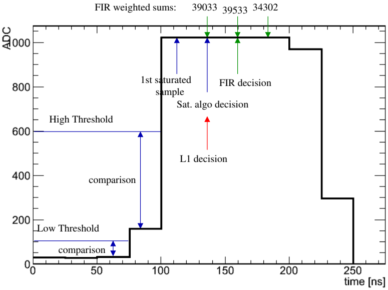
The trigger system at high energies



At very high energies:

- Saturation: digital range 256 GeV. Large pulses may also be distorted
- Digital saturation ⇒ L1 trigger fired. But on which bunch-crossing ?

BCID for saturated pulses:
Use a threshold algorithm



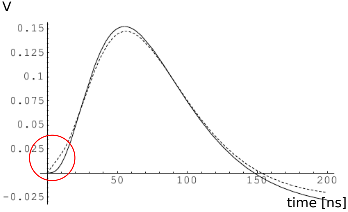
Commissioning the Trigger for large pulses

Problem: initial calibration of threshold algorithm valid only for very large pulses (eg 500 GeV), leaving "hole" in trigger range in 250–500 GeV

Solution: changing the trigger logic

- Leave FIR algorithm on beyond 250 GeV: actually works at least up to 700 GeV
- Trigger BCID: the earlier of the two outcomes

⇒ Then must prove the whole range is covered with high efficiency



Difficulties with thresholds algorithm calibration

- Sensitivity to electronics noise,
- Sensitivity to digitization timings,
- Shape differences between calibration and physics signals.

Results and consequences

Validation

- Uses both calibration and physics data
- Makes use of the linearity of the system
- Must be done for each Trigger Tower and each data-taking period

Results

- BCID validated up to 3.5 TeV for most trigger towers,
- Computation of uncertainties per period, for barrel and endcaps,

⇒ Application: uncertainty on W' (1 %) and Z' (1.8 %) searches

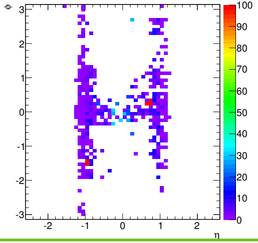
- Changes in trigger configuration (thresholds) for 2011 data-taking:
  - Better behaviour at the highest energies,

  ⇒ Uncertainties become almost negligible.

Uncertainty on trigger efficiency for a deposit of $E = 3.5$ TeV (%):

- 5 problematic towers,
- some with uncertainties $\sim 5\%$
- η and ϕ structures due to detector effects.

ATL-DAQ-INT-2011-001 (ATLAS members) or CERN-THESIS-2012-087



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2 The Higgs boson at the LHC

3 Measuring basic processes: b-jets associated with Z bosons

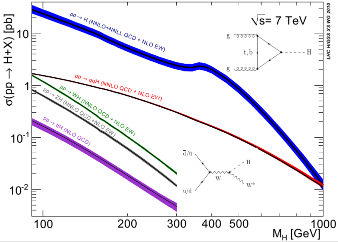
4 Improving and performing searches: the $H \to 4\ell$ channel

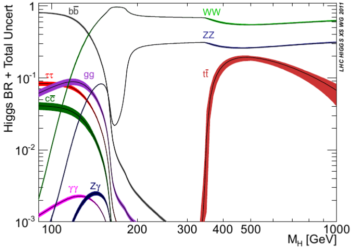
The Higgs boson at the LHC

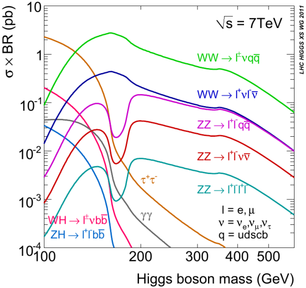
Production and decay

- 3 main production modes, cross-sections known to NLO or NNLO,
- Many decay modes, branching ratios known to NLO,
- Importance of different channels depends on hypothesised mass: ZZ, WW, $\gamma\gamma$, $V+H(b\bar{b})$, $\tau\tau$,...

$H \to ZZ$: different final states, including $ZZ \to 4\ell$







The Higgs to 4 leptons channel

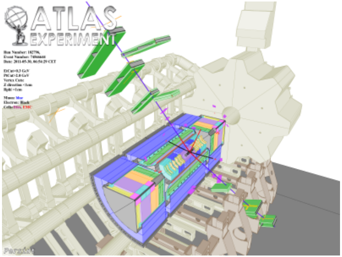
$H \to ZZ \to 4\ell$

- Decays $Z \to ee$ and $\mu\mu$: 3 channels, $4e$, $2e2\mu$, 4μ

⇒ low branching ratio: $\sigma \times BR \sim 1 - 10\,\mathrm{fb}$

- Excellent resolution on M_H: ~ 2 GeV
- Very clean signature, low backgrounds

⇒ Important channel on 120–600 GeV



Backgrounds

- Irreducible background: ZZ
- Backgrounds with leptons from heavy-flavor decays: $t\bar{t}$, $Zb\bar{b}$
- Backgrounds with fake leptons: Z+light jets

$Zb\bar{b}$ background

Uncertainties on QCD computations of its production (see $W+b$ at Tevatron):

- Multi-scales process: Q^2, M_Z, M_b
- b-quarks mass effects
- Uncertainties on processes with b-quarks in the initial state

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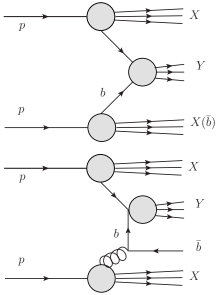
$Zb\bar{b}$: b-quarks in the initial state

Origin of the issue: incompatibility between quark masses and PDF

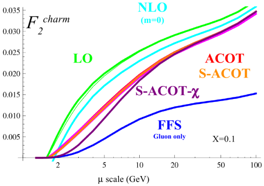
2 different schemes

- *Variable* number of flavors (SHERPA): use a b PDF above threshold
  - Good behaviour at large Q^2
  - Difficulties around threshold
- *Fixed* number of flavors (ALPGEN): b created by gluon-splitting only
  - Needs special 4 flavors PDF.
  - Kinematics correct around threhsold
  - Lacks logarithmic resummations at large Q^2



Merging the schemes

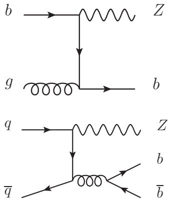
- At NLO, possibility to interpolate between the schemes
  - Good behaviour in both limits
  - Smooth transition
  - Several possible prescriptions: S-ACOT (MCFM)



The $Z + b$ analysis

Preparing the $H \to 4\ell$ analysis: control $Zb\bar{b}$

- Early data (2010) : $36\,\text{pb}^{-1}$ ⇒ allows measurement of $Z + b$−jet
- Test QCD prediction for this type of events
  - Background to other Higgs and SUSY searches
  - On longer term, measurement of b-jets energy scale, and of b PDF.

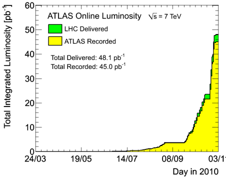


In a nutshell:

- Inclusive measurement on b jets
- Cross-section of b-jets in Z events:

$$\sigma_b = \frac{N(b\text{-jets})}{\mathcal{L}\mathcal{A}}$$

  $N(b$-jets) measured after b-tagging and statistical fit.
- Ratio σ_b/σ_Z (number of b jets per Z event) also measured



Selection of events

Standard Z selection:

- Single lepton triggers (e, μ)
- Good quality leptons, $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$
- Pair of leptons, $76 < m_{\ell\ell} < 106$ GeV

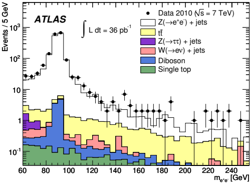
Adding (b-)jets:

- Anti-k_T, parameter 0.4, $p_{\mathrm{T}} > 25 GeV$, $|y| < 2.1$
- Separated from leptons by $\Delta R > 0.5$
- b-tagging: reconstruct a secondary vertex
  - Cut on the significance of the distance to primary vertex
  - Calibrated for 50 % efficiency

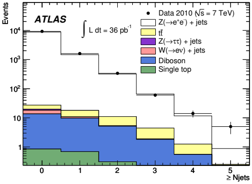
Simulations

Z+**jets**	(signal and backgrounds) SHERPA and ALPGEN
$t\bar{t}$	MCNLO
Dibosons	ALPGEN
Single top	MCNLO

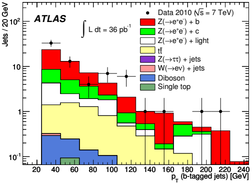
Simulations corrected to match data as best as possible



Invariant mass $Z \to ee$



Number of jets ($Z \to ee$)



b-tagged jets spectrum ($Z \to ee$)

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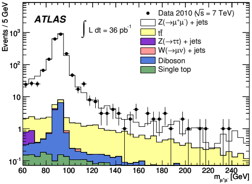
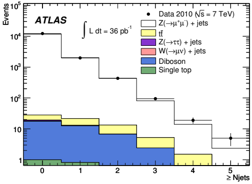
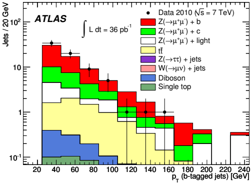


Invariant mass $Z \to \mu\mu$



Number of jets ($Z \to \mu\mu$)



b-tagged jets spectrum ($Z \to \mu\mu$)

Results of the event selection

In data:

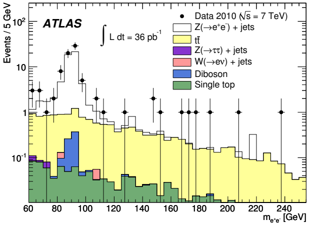
Selection	Electron	Muon
≥ 1 *b*-tag	64	67
$= 1$ *b*-tag	62	63
$= 2$ *b*-tag	1	4
$= 3$ *b*-tag	1	0

Data-MC agreement:

- Reasonable
- For both generators used
- In electron and muon channels
- For both yields and spectra.

Backgrounds:

- Selection purity: $\sim 50\%$
- $Z+c$ and $Z+l$ dominant (tagging efficiency)
- Important contribution $t\bar{t}$
- Dibosons, single top sub-leading
- Contribution of multijets (1 event): data-driven



Invariant mass $Z \to ee$, *b*-tagged jet

Extraction of the number of *b*-jets

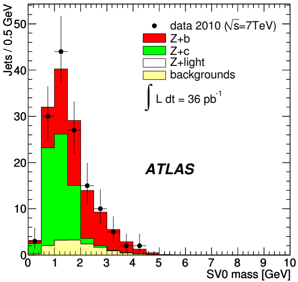
Issue:

- Purity not sufficient to measure cross-section directly
  - ⇒ Need of a statistical extraction
- Main backgrounds made of *Z*+non-*b*-jets
  - ⇒ Chose invariant mass of tracks associated to the secondary vertex as discriminant variable

Method

- Muon and electron channels added,
- Templates for signal and backgrounds taken from MC,
- Sub-leading backgrounds (mainly real *b*-jets) normalized to their estimated contributions,
- Normalizations of signal and dominant backgrounds are the result of the fit.

Method validated with pseudo-experiments.



Fit results

$N_b = 63.6^{+14.7}_{-13.2}$ $N_c = 59.9^{+13.4}_{-14.0}$

$N_l = 0.0^{+5.1}_{-0.0}$ $N(\text{other}) = 14.5$ (fixed)

Systematic uncertainties

Uncertainties affect result in several ways

- Distorsion of templates
- Normalization of sub-leading backgrounds
- Change in acceptance (efficiencies)

The final result takes correlation and asymmetric uncertainties into account.

Main sources:

Tagging efficiency and modeling
$\Rightarrow$ will significantly decrease.

Source	Fit (%)	Acceptance (%)
Electron and Muon		
Tagging efficiency	1.7	9.1
Template modeling	3.5	-
Model dependence	2.7	10.0
Jet energy scale	0.7	4.0
$\sigma_{t\bar{t}}$	2.0	-
MPI	negl.	1.0
Electron only		
MC statistics	negl.	1.3
Multijets background	1.6	-
Electron efficiency	negl.	5.0
Total Electron	5.6	15.0
Muon only		
MC statistics	negl.	1.3
Multijets background	0.7	-
Muon efficiency	negl.	2.0
Total Muon	5.4	14.3
Total uncertainty	**+21% -16%**	

Results

Measurement of the fiducial cross-section σ_b

- Theory (MCFM): partonic NLO + hadronization corrections
- Theory uncertainties: PDF, renormalization scale, α_s

Experiment	$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})$ pb
MCFM	3.88 ± 0.58pb

Published in Physics Letters B706:295-313, 2012.

Measurement of the ratio σ_b/σ_Z:

- Mean number of b jets per Z event
- Interest: Direct comparison with LO generators

Experiment	$(7.6^{+1.8}_{-1.6}(\text{stat})^{+1.5}_{-1.2}(\text{syst})) \times 10^{-3}$
MCFM	$(8.8 \pm 1.1) \times 10^{-3}$
ALPGEN	$(6.20 \pm 0.2(\text{stat only})) \times 10^{-3}$
SHERPA	$(9.5 \pm 0.1(\text{stat only})) \times 10^{-3}$

- MCFM: good agreement with measurement
- LO generators: both at 1 sigma, large Alpgen/Sherpa difference

⇒ Advocates the use of k-factors specific to $Z+b$.

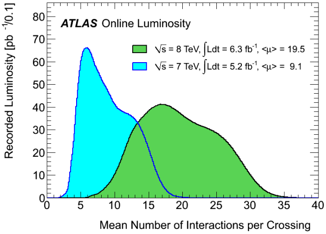
⇒ Actually used for background evaluation in $H \to 4\ell$ december 2011 search

Search for $H \to 4\ell$ with $11\,\text{fb}^{-1}$ of data

Data used:
Good quality data recorded by ATLAS in 2011 and 2012

- $4.9\,\text{fb}^{-1}$ for $4e$ in 2011,
- $4.8\,\text{fb}^{-1}$ for 4μ and $2e2\mu$ in 2011,
- $5.8\,\text{fb}^{-1}$ in 2012.

High pile-up environment: up to $<\mu>= 30$.



Principle of the search:

- Select events with 2 pairs of leptons
- Reconstruct a candidate by applying cuts on invariant masses
- Further reduce backgrounds with cuts on isolations and impact parameters
- Look for a peak in the 4 leptons invariant mass distribution, over a countinuous background made of *ZZ* and reducible backgrounds.

Sensitivity depends on:

- Signal reconstruction efficiency
  - ⇒ Lepton reconstruciton efficiency
- Peak width
  - ⇒ Lepton resolution
- Backgrounds rejection and control

Analysis dominated by lepton performance

Improving the electron reconstruction

Low cross-sections involved in H4l ⇒ every increase of efficiency counts.

An improved electron reconstruction (ATLAS-CONF-2012-047)

- Until 2011, track reconstruction does not take Bremsstrahlung into account
  ⇒ loss of tracking efficiency at low p_T
  ⇒ poor estimation of track parameters.
- Improved reconstruction for ATLAS, effort led by $H \to 4\ell$ analysis:
  ⇒ Refit of existing electron tracks (2011-)
  ⇒ Plus account for Bremsstrahlung possibility in track finding (2012)
- Improvements of track parameters in transverse plane (d_0, ϕ, q/p)
- Does not change the energy measurement (calorimeter only)

Consequence on the analysis

- +10 % efficiency on the signal in $4e$ and $2\mu 2e$ after impact parameter cuts
- further gains from new tracking

What about $Zb\bar{b}$ and $t\bar{t}$ backgrounds ?

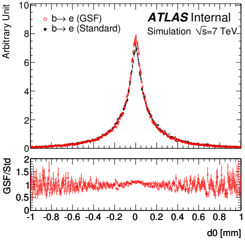
- Non-0 impact parameters ⇒ possible bias ?
- Efficiency of impact parameter cuts ?

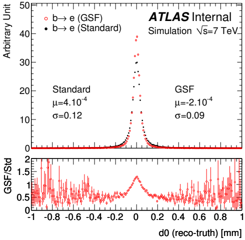
Validation for leptons from heavy-flavor decays

Validation on simulations

Study electrons from decays of b hadrons using $Z+b$ (ALPGEN)
Electrons with $p_T > 7$ GeV, $|\eta| < 2.5$.

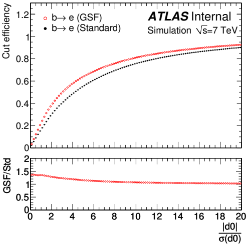
- Unchanged d_0 distribution
- Significantly improved d_0 resolution

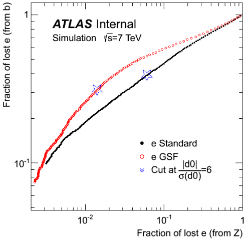




For an unchanged cut

- Slightly worse rejection of electron from b quarks,
- Far better efficiency for Z electrons.

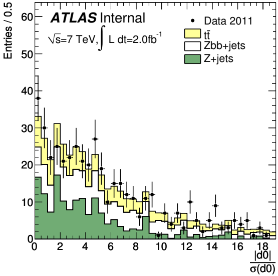




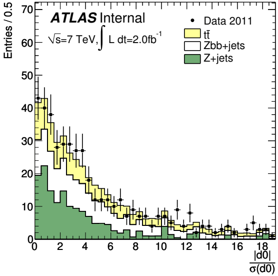
Validation for leptons from heavy-flavor decays

Validation with data

- Select a sample enriched with electrons from HF decays
  - $Z+b$ and $t\bar{t}$ (dilepton) selections
  - Select electrons near ($\Delta R < 0.5$) tagged jets
  - 490 electrons selected ; purity: $\sim 60\%$.
- Study electron properties



Standard reconstruction



Improved reconstruction

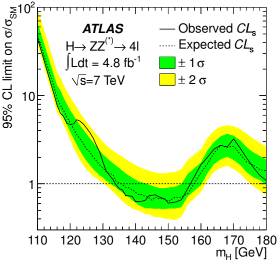
Results

- data-MC agreement as good as with the standard reconstruction.
- Improvement of the observed resolution.

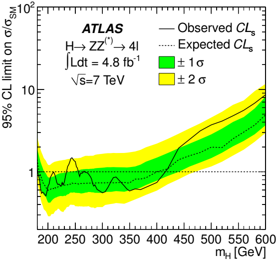
December 2011 results in a nutshell

Phys.Lett. B710 (2012) 383-402:

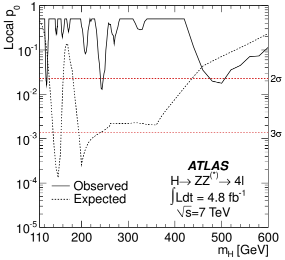
- $H \rightarrow 4\ell$: Observed 95 % CL_s exclusion curve close to the expected one: analysis well understood
  - Exclusion of SM Higgs: 134–156 GeV, 182–233 GeV, 256–265 GeV and 268–415 GeV
  - Exclusion expected: 136–157 GeV and 184–400 GeV
- $H \rightarrow 4\ell$: Deviations observed around 125 GeV, 244 GeV and 500 GeV ($\sim 2.1\sigma$)



Exclusion limits, low mass



Exclusion limits, high mass



p_0 values

December 2011 results in a nutshell

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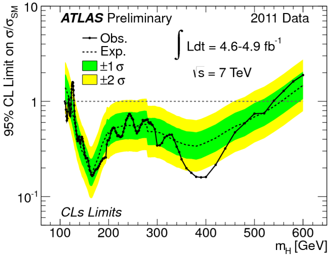
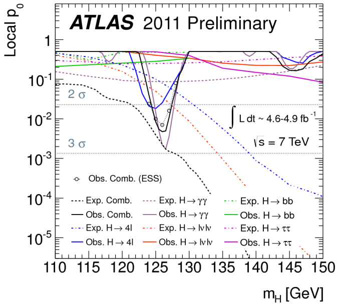
  - Exclusion expected: 136–157 GeV and 184–400 GeV
- $H \to 4\ell$: Deviations observed around 125 GeV, 244 GeV and 500 GeV ($\sim 2.1\sigma$)
- ATLAS combination: non excluded 122.5 – 129 GeV and > 539 GeV
- ATLAS combination: excess of 2.6σ at 126 GeV

⇒ If the SM Higgs exists, it is there !



Combined exclusion limits



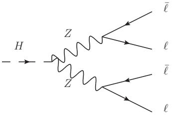
Combined p_0 values

Improving the $H \to 4\ell$ analysis

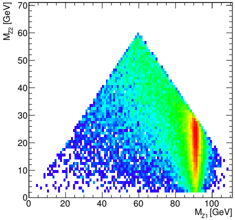
December 2011 analysis:

- Very good results
- Still not fully optimized for very low mass searches

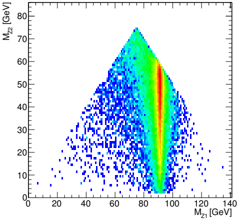
$\Rightarrow$ Optimizations performed with simulations and 2011 data in control regions



$M_H < 2M_Z$
$\Rightarrow Z$ off-shell
At very low masses ($\lesssim 130$ GeV), higher probability for both Z off-shell



(M_{Z1}, M_{Z2}), $M_H = 120$ GeV



(M_{Z1}, M_{Z2}), $M_H = 150$ GeV

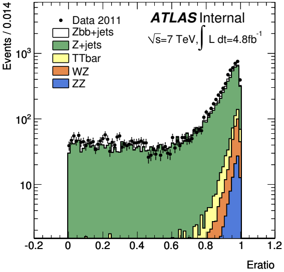
Adapting to the kinematics of low-mass Higgs

- Some cuts need relaxing to gain acceptance
- Needs good control of backgrounds
  - Reasonable for $Zb\bar{b}$,
  - Z+jets less well controlled, and significant in $4e$ and $2\mu 2e$.

Optimizing light jets rejection

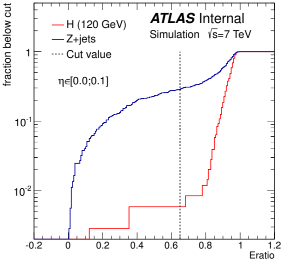
Light jets rejection

- Quite low at low p_T
- Study one additional shower shape cut at $p_T < 10$ GeV
- Check simulations with a study of $Z + e$ events



Adding the cut

- Optimization in η bins
- Simulations (4e and 2μ2e channels):
  - Signal: -2 %
  - Backgrounds: Z+jets -50 %, $Zb\bar{b}$ -40 %
  - Significance: +15 %



Optimizing analysis cuts

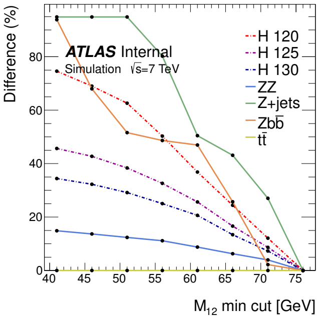
Re-analyzing 2011 data

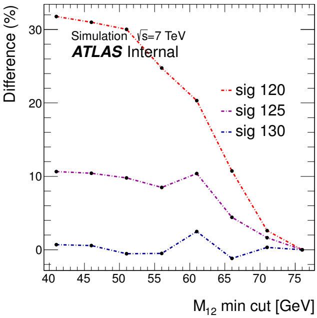
- Optimization efforts carried separately for channels with subleading electrons or muons (different backgrounds)
- Here channels with subleading electrons shown
- Optimizations done on simulations and control regions of 2011 data

Optimizations studied

Issue: low MC statistics for Z+jets
⇒ Use control region to measure its variations

- Invariant mass 1st pair of leptons: $M_Z - 15$ GeV → $M_Z - 40$ GeV





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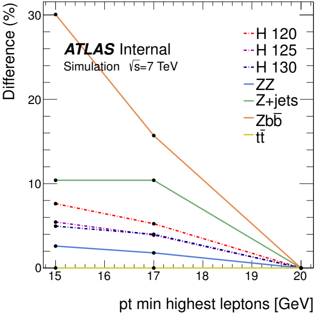
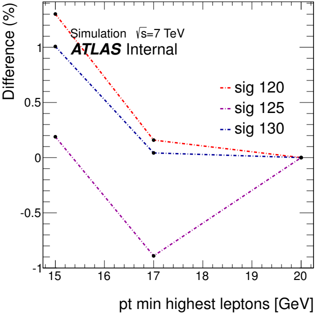
Optimizations studied

Issue: low MC statistics for Z+jets
⇒ Use control region to measure its variations

- Momentum 2 highest p_T leptons: 20 GeV → 15 GeV





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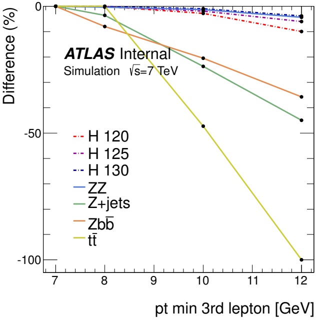
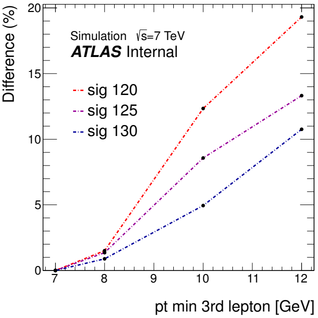
- Here channels with subleading electrons shown
- Optimizations done on simulations and control regions of 2011 data

Optimizations studied

Issue: low MC statistics for Z+jets
⇒ Use control region to measure its variations

- Momentum 3rd lepton: 7 GeV → 10 GeV





July 2012 analysis: Event selection

Numerous improvements wrt December 2011 analysis

Trigger:

- Single or di-lepton triggers, thresholds evolving with luminosity

Lepton selection:

Electrons: $p_T > 7$ GeV, $|\eta| < 2.5$, quality optimized for high efficiency

Muons: $p_T > 6$ GeV, $|\eta| < 2.7$, maximizing the acceptance:

- include spectrometer-only muons at $|\eta| > 2.5$
- include calorimeter-tagged muons at $|\eta| < 0.1$

Reconstruction of a candidate:

- 2 pairs of leptons, same flavor, opposite signs,
- p_T cuts at 20, 15 and 10 GeV for the 3 highest-p_T leptons,
- Angular separation $\Delta R > 0.1$ for e-e and μ-μ, 0.2 for e-μ
- Pair closer to the Z pole: $50 < m_{12} < 106$ GeV,
- Second pair: $m_{min} < m_{34} < 115$ GeV.

$m_{4\ell}$ [GeV]	≤120	130	150	160	165	180	≥190
m_{min} threshold [GeV]	17.5	22.5	30	30	35	40	50

Additional cuts

Goal: suppress reducible backgrounds.

Lepton isolation Target: Z+jets, multijets

- Relative isolations of tracks and clusters in cones of size $\Delta R < 0.2$
- Take pileup into account
- Take other leptons of the candidate into account

Track isolation: $(\sum p_{\mathrm{T}})/p_{\mathrm{T}}^{\ell} < 0.15$

Calo isolation: $(\sum E_{\mathrm{T}})/E_{\mathrm{T}}^{\ell} < 0.30$ for muons, 0.15 for standalone muons, 0.2 (2012) or 0.3 (2011) for electrons

Transverse impact parameters Target: $Zb\bar{b}$, $t\bar{t}$

- $|d_0/\sigma(d_0)| < 3.5$ (muons), 6.5 (electrons)

Efficiencies

- Checked with $Z \to \ell\ell$ decays (isolated leptons), $Z+\ell$ and heavy flavor dijet events (non isolated leptons)
- Good data/MC agreement : ratios compatibles with 1
- Good simulation of pileup dependence
- Small systematic uncertainties

Final discriminant

- Z mass constraint applied to leading lepton pair ($m_{4\ell} < 190$ GeV) or both ($m_{4\ell} > 190$ GeV): improvement of ~10 % on resolution.

Signal: Simulations

Generators:

- Powheg+Pythia for *gg* and VBF.
- Pythia for *WH* and *ZH*
- Normalized to best NNLO/NLO computations available
- Uncertainties: PDF and α_s envelope (8 %), QCD scales (8 %)

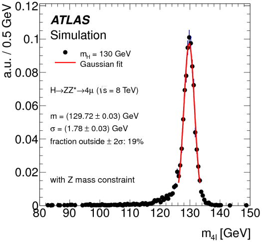
Reconstruction and selection efficiencies at 130 GeV:

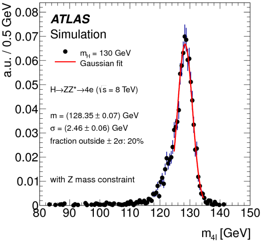
	4μ	$2e2\mu$	$4e$
8 TeV data	41 %	27 %	23 %
7 TeV data	43 %	23 %	17 %
december 2011	27 %	18 %	14 %

Resolutions at 130 GeV:

1.8 GeV (4μ), 2.0 GeV ($2e2\mu$), 2.4 GeV ($4e$)

- $4e$: tails and lower mean value (Bremsstrahlung),
- Higgs natural width dominates from 350 GeV : width∼ 29 GeV à $m_H = 400$ GeV.

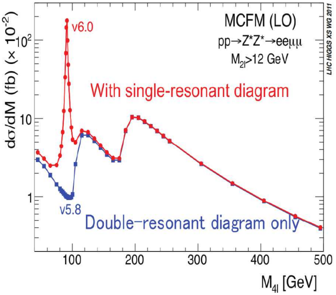


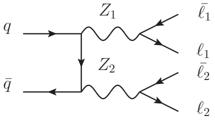


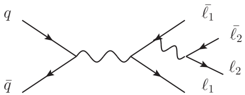
Controlling backgrounds: ZZ^*

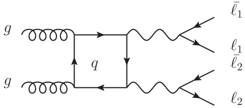
Production of SM ZZ^*:
Irreducible background

- Generated with Powheg ($q\bar{q}$ diagrams) and gg2ZZ (gg diagrams)
- Cross-section normalized to MCFM prediction
- Uncertainties from QCD scales (5 %) and PDF+α_s (4 % for $q\bar{q}$, 8 % for gg)
- Shape uncertainty from varying the gg contribution





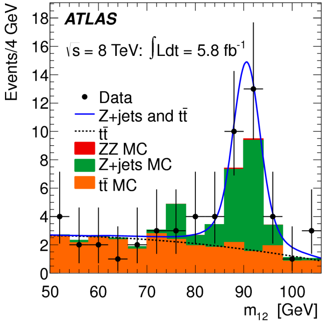




Controlling backgrounds: $\ell\ell + \mu\mu$ channels

Reducible bkg dominated by $t\bar{t}$ and $Zb\bar{b}$

- Control region pure in those backgrounds: no isolation cuts, revert impact parameter cuts
- Fit m_{12} distribution using analytic functions (shapes taken from MC, normalizations free)
- Extrapolate to signal region using MC ; cross-check transfer factors in data
- Cross-check for $t\bar{t}$: $e\mu + \mu\mu$ control region

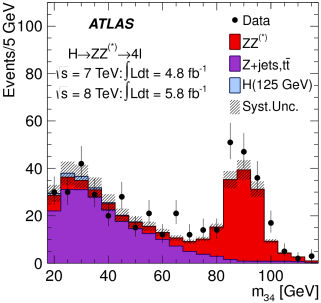


Data	4μ	$2e2\mu$
Z+jets 8 TeV	$0.51 \pm 0.13 \pm 0.16$	$0.41 \pm 0.10 \pm 0.13$
Z+jets 7 TeV	$0.25 \pm 0.10 \pm 0.08$	$0.20 \pm 0.08 \pm 0.06$
$t\bar{t}$ 8 TeV	$0.044 \pm 0.015 \pm 0.015$	$0.040 \pm 0.013 \pm 0.013$
$t\bar{t}$ 7 TeV	$0.022 \pm 0.010 \pm 0.011$	$0.020 \pm 0.009 \pm 0.011$

Controlling backgrounds: $\ell\ell + ee$ channels

Reducible bkg dominated by Z+jets

- Control region: relax identification of subleading electrons. ∼100 events per year and per channel
- Categorize electrons in electron-like, conversion-like and fake-like using info from tracker and calorimeter (9 categories)
- Extrapolate contamination in signal region from these categories using MC
- Two other methods used for cross-checks



Data	$4e$	$2\mu 2e$
Background 8 TeV	3.9±0.7±0.8	4.9±0.8±0.7
Background 7 TeV	3.1±0.6±0.5	2.6±0.4±0.4

Systematic uncertainties

Normalizations:

- Effects of PDF, α_s and QCD scales,
- Additional uncertainty for high mass searches: $150\% \times m_H^3$[TeV] for $m_H > 300$ GeV,
- Luminosity: 3.6 % (2012), 1.8 % (2011).

Reducible backgrounds:

- $\ell\ell + \mu\mu$ channels: 50 %,
- $\ell\ell + ee$ channels: 25 %,
  Origin: Statistical uncertainties in control regions, uncertainties on the methods themselves and on the extrapolations

Reconstruction and selection efficiencies:

- Muon efficiency: 0.16 % (4μ), 0.12 % ($2e2\mu$),
- Electron efficiency: 3.0 % ($4e$), 1.7 % ($2e2\mu$) at 600 GeV. 8.0 % and 4.6 % at 110 GeV,
- Lepton resolution: negligible,
- Electron energy scale: uncertainty 0.7 % ($4e$) and 0.4 % ($2e2\mu$) on mass scale.
- Isolations and impact parameters: negligible

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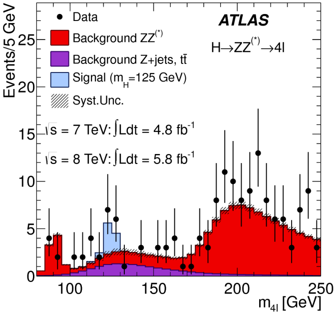
Results: Phys. Lett. B 716 (2012) 1-29

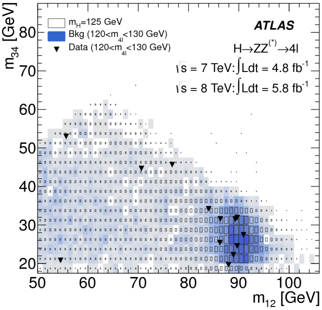
Events in window 120–130 GeV

	Signal	$ZZ^{(*)}$	$Z+$jets, $t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

- Reducible backgrounds still large in $4e/2\mu2e$ channels
- Data exceed background expectations around 125 GeV



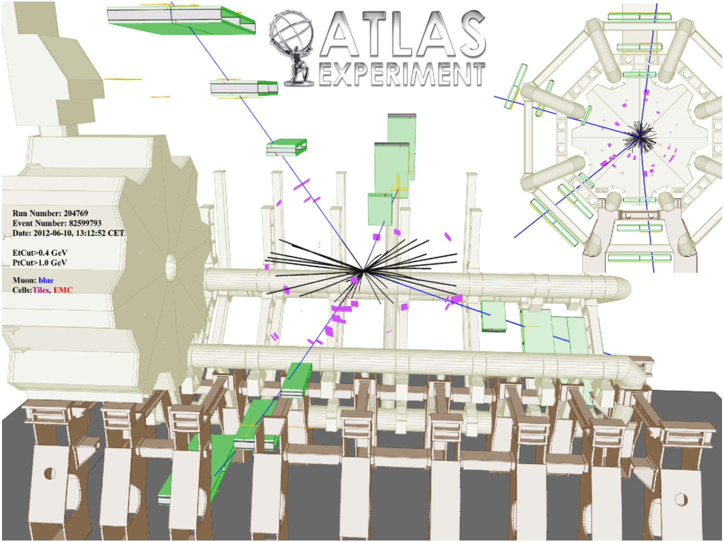
Invariant mass distribution



Masses of the reconstructed Z pairs

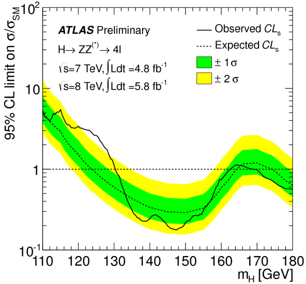
Event display

4μ candidate. $m_{4\ell} = 123.5$ GeV.
Masses of the lepton pairs: 84 GeV and 45.7 GeV.

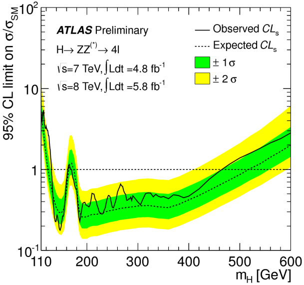


Investigation of the excess

- Test statistic: maximum likelihood fit to data using signal and background histograms.
- $H \rightarrow 4\ell$ Exclusion limits set with CL_s formalism:
  - Expected 124–164 GeV and 176–500 GeV
  - Observed 131–162 GeV and 170–460 GeV
- One significant excess in mass range: p_0 of 3.6σ at 125 GeV (2.7 expected)
  - ⇒ Evidence for new particle
  - With look-elsewhere effect in 110–150: global p_0 of 2.5σ
- ATLAS combination: observation at 6.0σ of a new particle of mass 126.0 ± 0.6 GeV
  - signal strength parameters compatible with 1
  - 4ℓ and $\gamma\gamma$ masses compatible



$H \rightarrow 4\ell$ low-mass exclusion limits



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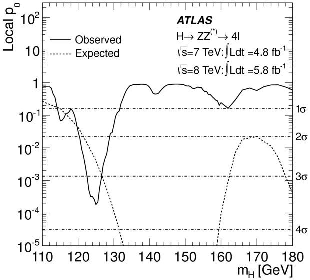
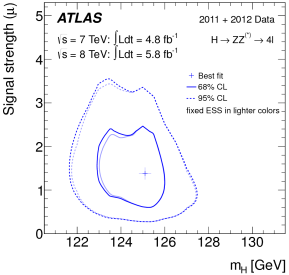


$H \to 4\ell$ p_0 values



$H \to 4\ell$ (μ, m_H) contour

Investigation of the excess

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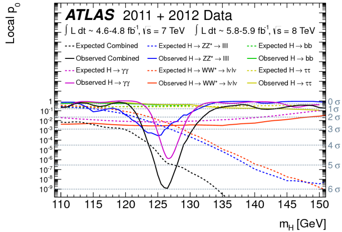
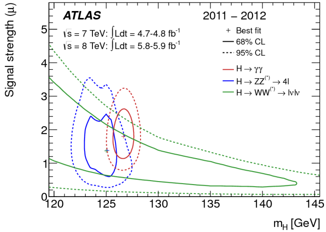
  - signal strength parameters compatible with 1
  - 4ℓ and $\gamma\gamma$ masses compatible



Combined p_0 values



Superposition of (μ, m_H) contours

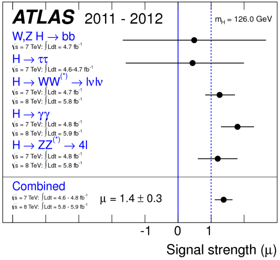
What next ?

Have we discovered the SM Higgs ?

Goal: Test compatibility of SM or alternative theories to the measurements

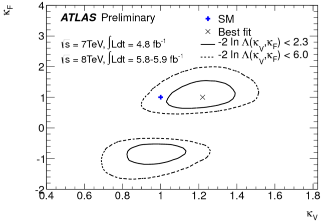
What can we achieve ?

- Measurement of mass
- Determination of spin
- Determination of parity
- Measurement of the couplings



How ?

- Go for precision measurements in the "discovery" channels
- Look for a signal in other modes: $H \to b\bar{b}$, $H \to \tau\tau$, $t\bar{t}H$ of prime importance
- Look for exclusive signatures: VBF, associated production



Lot of work ahead !

Conclusions

Discovery of a new Higgs-like particle : a major result

- It took 20 years of preparation, and 2.5 years of data-taking to achieve it

Commissioning ATLAS: high energy pulses at L1

- An important part of the detector to get ready at the start of data-taking
- Difficult validation, which led to changes in trigger logic
- Direct consequences for some exotic searches

Prepare for the $H \to 4\ell$ search: $Z + b$ measurement with 2010 data

- Measurement with 30 % uncertainty, in agreement with NLO
- Gives confidence in evaluation of $Zb\bar{b}$ background in the $H \to 4\ell$ channel: computation of k-factor applied on ALPGEN samples

Searching for the Higgs: the 4 leptons channel

- Lepton performance of prime importance
  - Developement of a new electron reconstruction
- After december 2011 results, series of optimizations for low-mass searches
  - Improvements on background rejection and optimized kinematical cuts
- Search with 2011 and 2012 data: 3.6σ excess at 125.0 GeV
- Compatible with SM Higgs and the excesses in other channels
- A new field now opens: precision tests of SM and alternative theories
  - All decay channels should be studied to obtain the best possible precision
  - Soon $20\,\text{fb}^{-1}$ available and improved analyses in the high resolution channels

Backup slides

Basics of validation of the settings

Goal

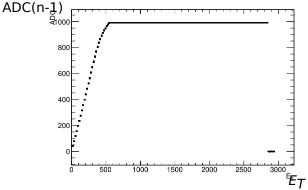
- Determine energy ranges where BCID algorithms are valid,
- Compute lower bounds on trigger efficiency at high energy.

Constraints

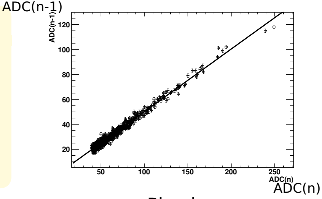
- Should be done for each trigger tower,
- Should be done for each data-taking period,
- Cannot rely on calibration data only,
- Very small statistics of high energy deposits in physics data.

Solution

- Use calibration data to detect hardware issues,
- Use calibration data to understand behaviour of signals at high energies,
- Make use of signal linearities to extrapolate low energy physics data up to high energies.



Calibration

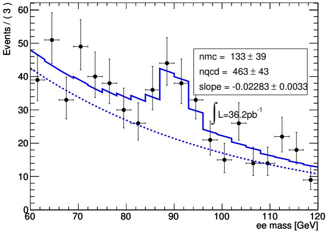


Physics

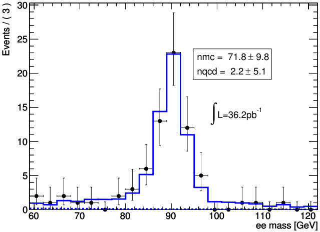
Estimation of multijets background

Data-driven estimate
Assume an exponential invariant mass spectrum for this background.

- Relax electron identification: 1 *medium* 1 *candidate*, or 2 *loose* no *medium* (cross-check)
- Fit $m(Z)$: function for multijets, MC distributions for signal and other backgrounds
- Fit standard selection, with expo. slope from previous fit.
- Extract number of events under Z peak: $\mathbf{1.0 \pm 2.2}$



Extraction of slope, *cand+medium*



Fit *medium+medium*

Muons channel: Use non isolated muon pairs. Result: $\mathbf{N = 0.0 \pm 0.9}$.

Cross-section computation

Measurement: mean cross-section per lepton flavor

$$\sigma_b = \frac{N_b}{\mathcal{A}^e \mathcal{L}^e + \mathcal{A}^\mu \mathcal{L}^\mu}$$

- N_b: fit result
- $\mathcal{A}$: from simulation. Take into account:
  - Tagging efficiency,
  - Jets reconstruction,
  - Lepton reconstruction
  - Small extrapolation of leptons acceptance.

  ALPGEN and SHERPA numbers compatible.
  $\mathcal{A}^\mu = 0.286$, $\mathcal{A}^e = 0.214$
- $\mathcal{L}$: luminosity: $36\,\mathrm{pb}^{-1}$.

Fiducial volume

Truth-level selections

***Z* boson:**

- Two leptons $p_\mathrm{T} > 20$ GeV, $|\eta| < 2.5$
- Invariant mass in $M_Z \pm 15$ GeV

Jets:

- Reconstrcuted from all final state particles, Z leptons excepted.
- $p_\mathrm{T} > 25$ GeV, $|y| < 2.1$
- Separated from Z leptons
- Presence of a B hadron with $p_\mathrm{T} > 5$ GeV within $\Delta R < 0.3$