Search for the SM Higgs boson in the 4 leptons channel with the ATLAS detector

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on behalf of the ATLAS Collaboration

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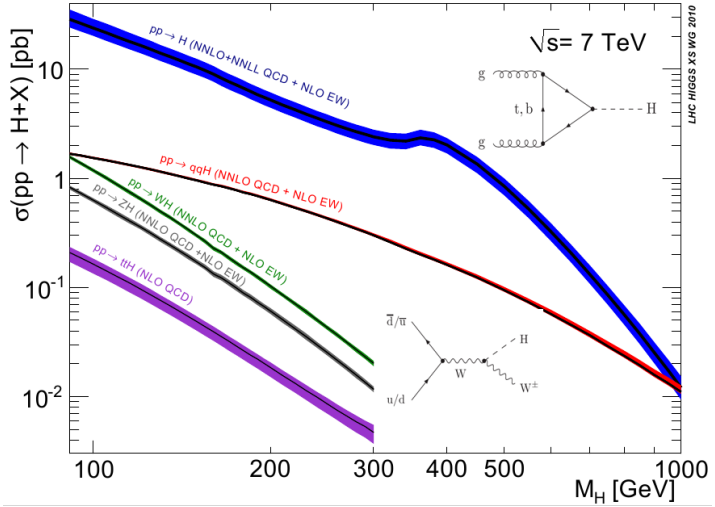
Higgs Boson Production in the 4ℓ channel

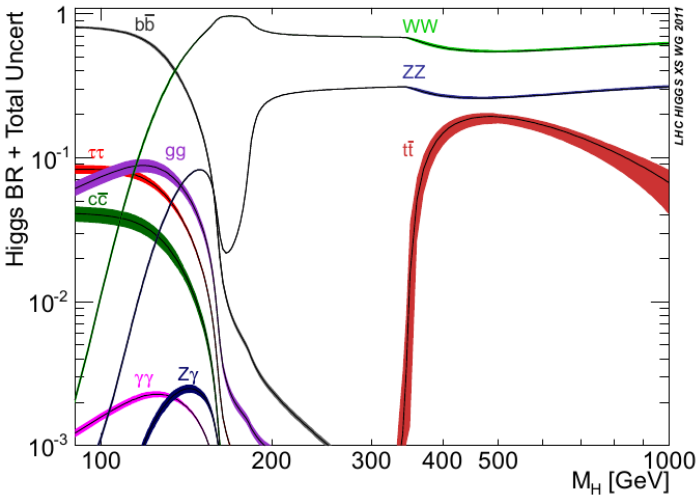
Higgs production :

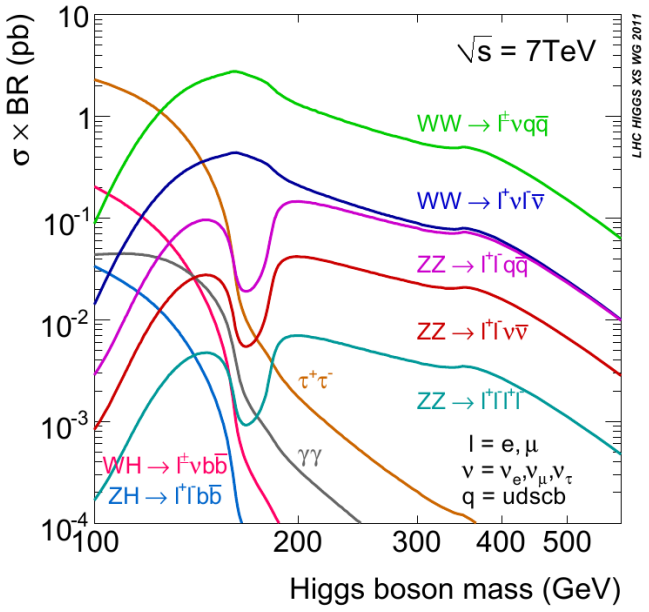
- gg fusion dominant
- VBF comes next ($\sim 10\,\%$), relative contribution increases with m_H.

4 leptons channel :

- Large BR for ZZ above threshold
- Small fraction once BR($ZZ \to 4\ell$), $\ell = e, \mu$ included
- Cross-sections $\sim 1-10$ fb : $\ll \sigma(H \to \gamma\gamma)$ at low mass







$H \to 4\ell$: characteristics

4 leptons (e,μ) in the final state :

- ⇒ Full reconstruction of the Higgs, with excellent experimental resolution ($\sim$ 2 GeV at low mass)
- ⇒ Clean channel, low background rates

Backgrounds :

- Irreducible SM ZZ continuum
- With leptons from Heavy-Flavour decays : $Zb\bar{b}$, $t\bar{t}$
- With fake leptons : Z+light jets, multijets

Cross-section in $1-10$ fb over whole search range :
Important channel from 115 to 600 GeV.

- Low mass : complementary to $\gamma\gamma$
- High mass : Higgs width sizeable, experimental resolution less critical

Experimental challenges

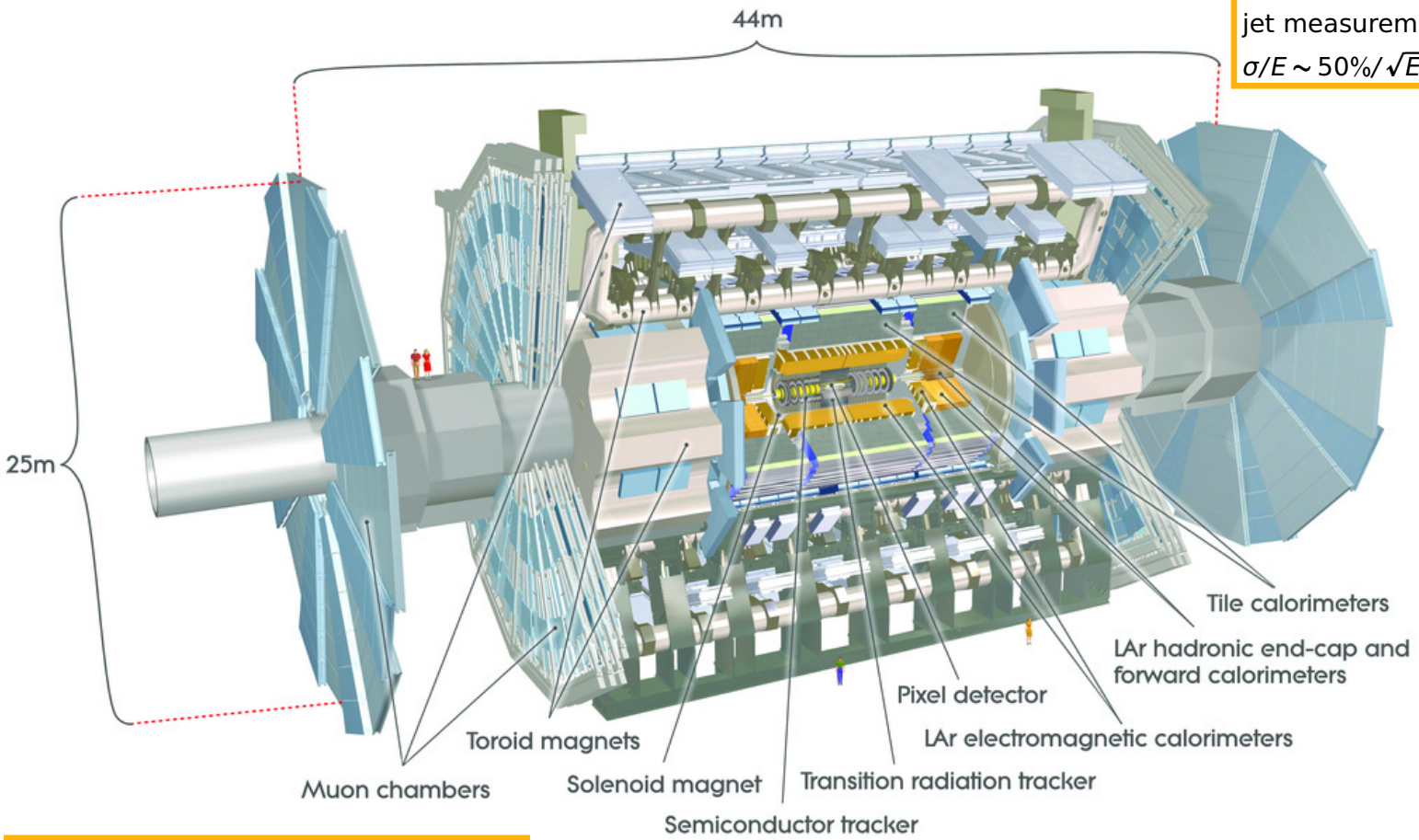
- High lepton reconstruction efficiency and acceptance
- Good resolution on leptons
- Good measurement of lepton properties (cut reducible backgrounds) : isolations, impact parameters, electron shower shapes

Search driven by lepton performance.

The ATLAS detector

Inner Detector : ($|\eta| < 2,5$, B=2T)
Si Pixels, Si Strips, Transition Radiation tracker
provides precise tracking, vertexing, e/π separation
$\sigma/p_T \sim 3,8\,10^{-4}\,(\mathrm{GeV}) \oplus 0,015$

Hadronic Calorimeter :
Scint/Fe tiles in the central ($|\eta| < 3,2$)
W/Cu-LAr in the fwd region ($|\eta| < 4,9$)
provides trigger,
jet measurement and E_T^{miss}
$\sigma/E \sim 50\%/\sqrt{E} \oplus 3\%$



EM Calorimeter : ($|\eta| < 3,2$)
Pb-LAr accordion structure
provides e/γ trigger,
identification and measurement
$\sigma/E \sim 10\%/\sqrt{E} \oplus 0,7\%$

Muon Spectrometer : ($|\eta| < 2,7$)
air core toroids with gas chambers
provides μ trigger and standalone momentum measurement
resolution $< 10\%$ up to $E_T \sim 1$ TeV

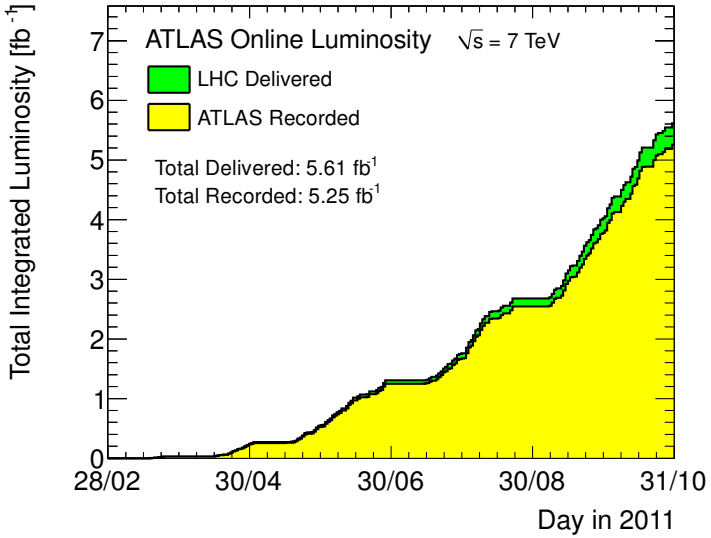
Data-taking in 2011

Very efficient data-taking

- $5.25\,\mathrm{fb}^{-1}$ recorded by ATLAS in 2011, with peak luminosity up to $3.65\,10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Very high efficiency of all subdetectors

⇒ $4.9\,\mathrm{fb}^{-1}$ analysed in the $4e$ channel

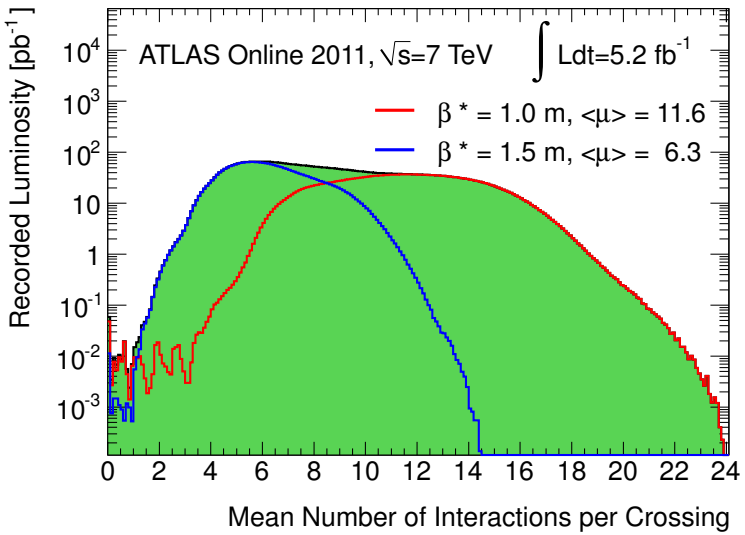
⇒ $4.8\,\mathrm{fb}^{-1}$ analysed in the $2e2\mu$ and 4μ channels



ATLAS 2011 p–p run												
Inner Tracking			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	97.5	99.2	99.5	99.2	99.4	98.8	99.4	99.1	99.8	99.3

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and October 30th (in %), after the summer 2011 reprocessing campaign

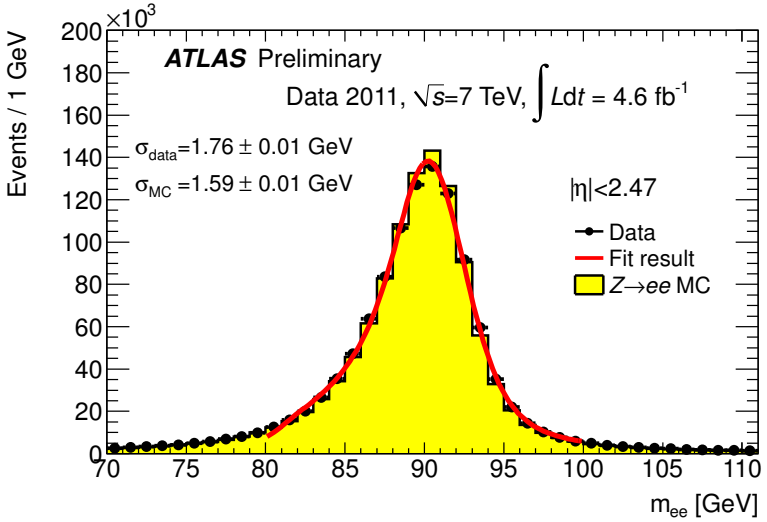
Pile-up conditions increasing with instantaneous luminosity :
$<\mu> \sim 6 \rightarrow <\mu> \sim 12$
⇒ Simulations corrected to match observed distribution



Electron performance

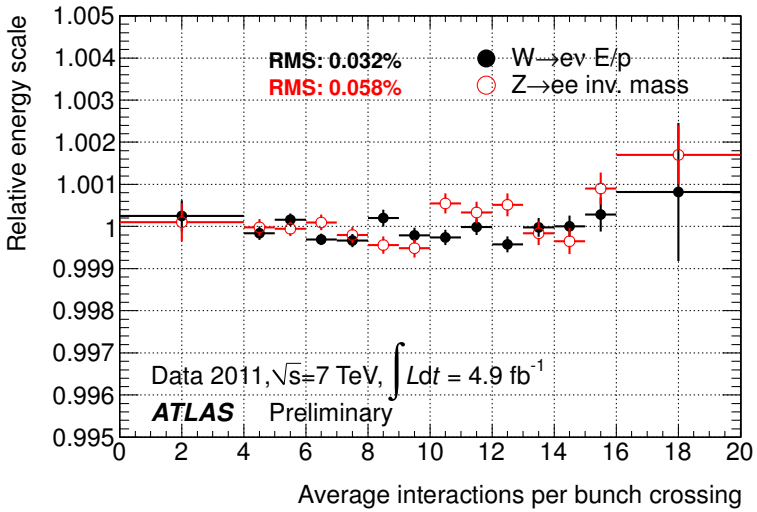
Reconstruction :

- Good quality track matched to an EM cluster
- Track refitted, taking Bremsstrahlung possibility into account : improve track parameters in bending plane



Energy scale and resolution :

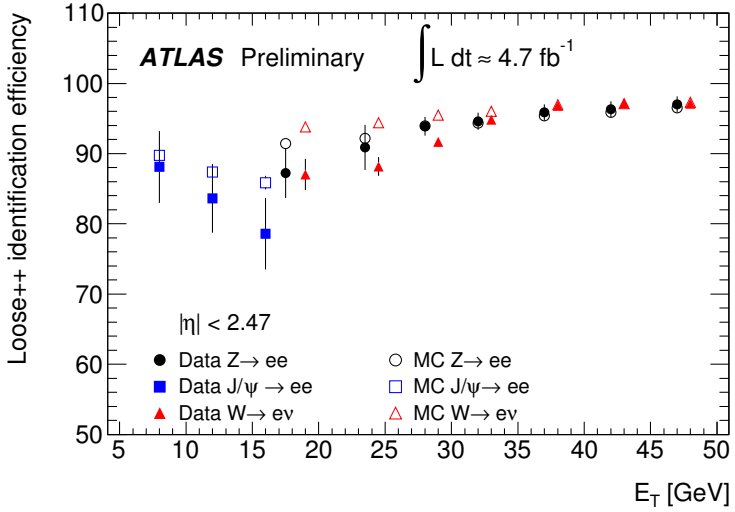
- Measured using Z decays
- Simulations corrected to match resolution in data
- Energy scale flat with pile-up



Electron Identification

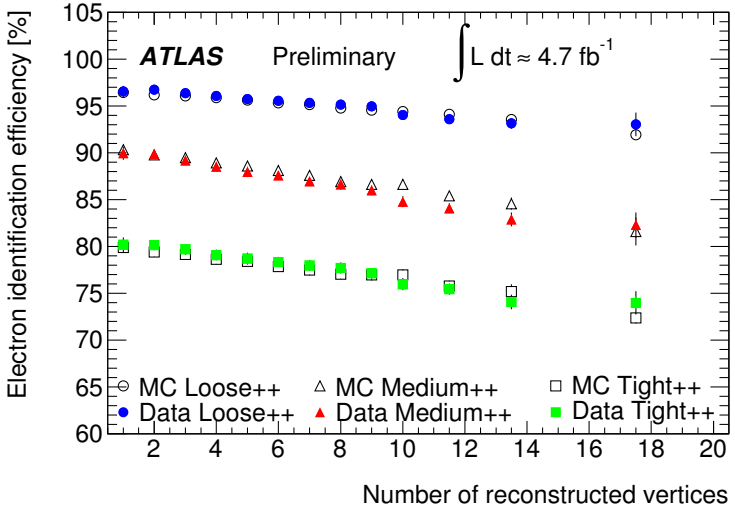
Identification :
Set of cuts to reduce fakes

- track quality
- track-cluster matching
- cluster shower shapes, transverse and longitudinal



Performance :

- Over 90 % efficiency
- Efficiencies measured in data with W, Z and J/ψ
- Simulations corrected to match data
- Small efficiency dependance with pile-up, well reproduced by simulations



Muon performance

Reconstruction :

Two types of muons used

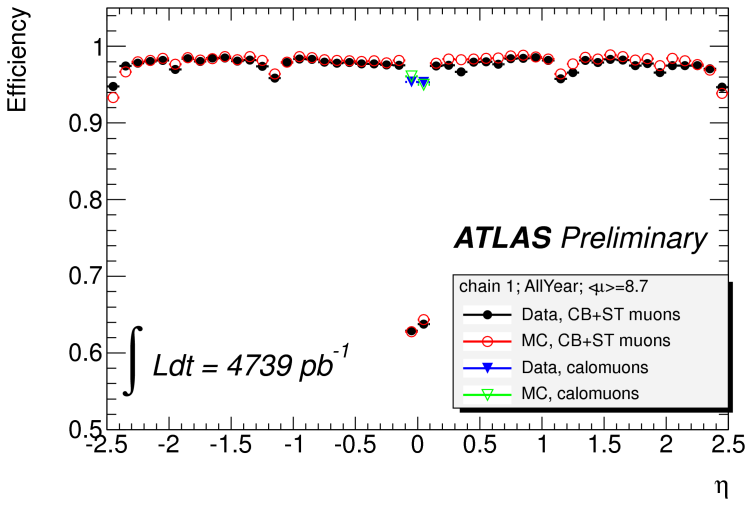
- Good quality track in ID, combined with spectrometer track
- Good quality track in ID, tagged in spectrometer
- Rejection of cosmic rays through impact parameter cuts (1 mm)

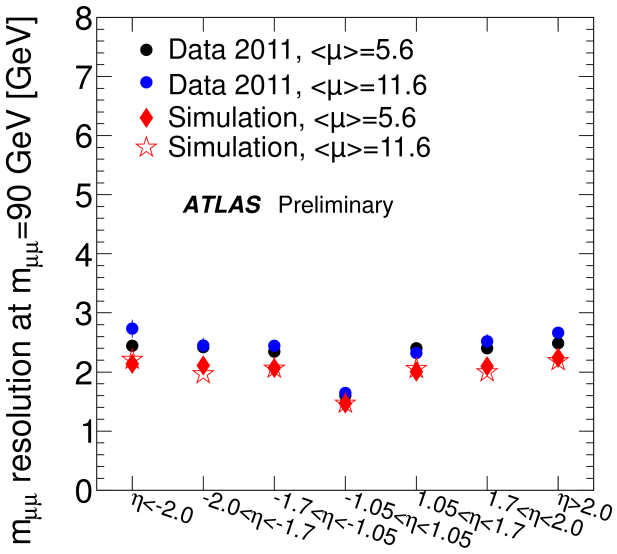
Efficiencies :

- Very high (∼ 98 %, measured with Z decays)
- Well reproduced by simulations
- Simulations corrected to match data

Resolution :

- Measured with Z decays
- Data/MC difference due to non-nominal alignment of MS and ID
  - ⇒ Simulations corrected to match data
- Small degradation with pile-up





Selection of a candidate

Trigger :

- Single-lepton : muon $p_T > 18$ GeV, electron $E_T > 20 - 22$ GeV
- Di-lepton : 2 muons $p_T > 10$ GeV, 2 electrons $E_T > 12$ GeV

Lepton selection :

- $p_T > 7$ GeV
- $|\eta| < 2.47$ (electrons), $|\eta| < 2.7$ (muons)

Reconstruction of a candidate :

- 2 same-flavor, opposite-sign pairs
- $p_T > 20$ GeV for 2 leptons
- Angular separation $\Delta R > 0.1$ between all leptons
- Pair with mass closest to m_Z : $|m_{12} - m_Z| < 15$ GeV
- Second pair : $m_{\min} < m_{34} < 115$ GeV

$m_{4\ell}$ (GeV)	≤ 120	130	140	150	160	165	180	190	≥ 200
m_{34} threshold (GeV)	15	20	25	30	30	35	40	50	60

Additional cuts

Aim : suppress reducible backgrounds

Lepton isolations. Target : Z+jets, multijets

- Relative track and calorimeter isolations in cones of size $\Delta R < 0.2$
- Corrected for pile-up
- Corrected for the other leptons of the candidate
  - track isolation : $(\sum p_T)/p_T^\ell < 0.15$
  - calorimetric isolation : $(\sum E_T)/E_T^\ell < 0.30$

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

- Used when $m_{4\ell} < 190$ GeV
- Applied on 2 lowest p_T leptons
- $|d_0/\sigma(d_0)| < 3.5$ (muons), 6 (electrons)

Efficiencies.

- Checked with $Z \to \ell\ell$ decays (isolated leptons), $Z+\ell$ and heavy-flavor enriched di-jet sample (non-isolated leptons)
- Excellent data/MC agreement : ratio compatible with 1
- Dependence on pile-up also well represented
- Small systematic uncertainties ;
  one exception : isolation of low-p_T electrons. Uncertainty 5 %.

Signal : Simulation

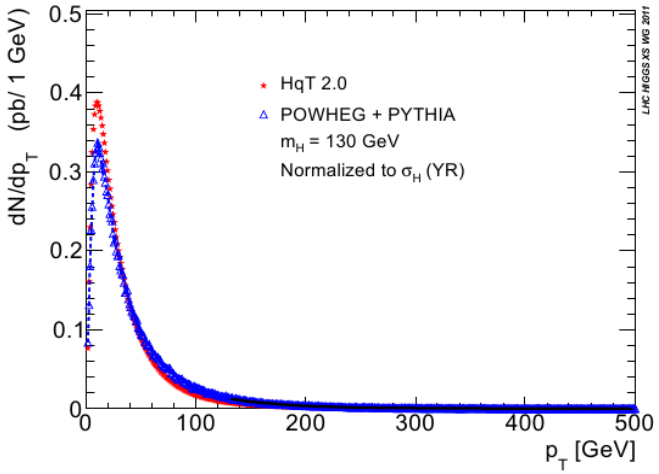
Generators :

- Powheg+Pythia for *gg* and VBF
- Pythia for *WH* and *ZH*

Cross-sections

Follow LHC Higgs σ working group recommendations :

- Use state-of-the-art computations : NNLO+NNLL (QCD) and NLO (EW) for *gg*, NNLO (QCD) and NLO (EW) for VBF
- Decays by Prophecy4f (NLO)
- Reweight p_T spectrum of *gg* production to prediction by HqT
- Theory uncertainty : envelope of PDF and α_s (8 %), QCD scales (10 %)



m_H [GeV]	$\sigma(gg \to H)$ [pb]	$\sigma(qq' \to Hqq')$ [pb]	$\sigma(q\bar{q} \to WH)$ [pb]	$\sigma(q\bar{q} \to ZH)$ [pb]	$\mathrm{BR}\left(H \to ZZ^{(*)} \to 4\ell\right)$ [10^{-3}]
130	$14.1^{+2.7}_{-2.1}$	$1.154^{+0.032}_{-0.027}$	0.501 ± 0.020	0.278 ± 0.014	0.19
150	$10.5^{+2.0}_{-1.6}$	$0.962^{+0.028}_{-0.021}$	0.300 ± 0.012	0.171 ± 0.009	0.38
200	$5.2^{+0.9}_{-0.8}$	$0.637^{+0.022}_{-0.015}$	0.103 ± 0.005	0.061 ± 0.004	1.15
400	2.0 ± 0.3	$0.162^{+0.010}_{-0.005}$	–	–	1.21
600	0.33 ± 0.06	$0.058^{+0.005}_{-0.002}$	–	–	1.23

Signal : Results of event selection

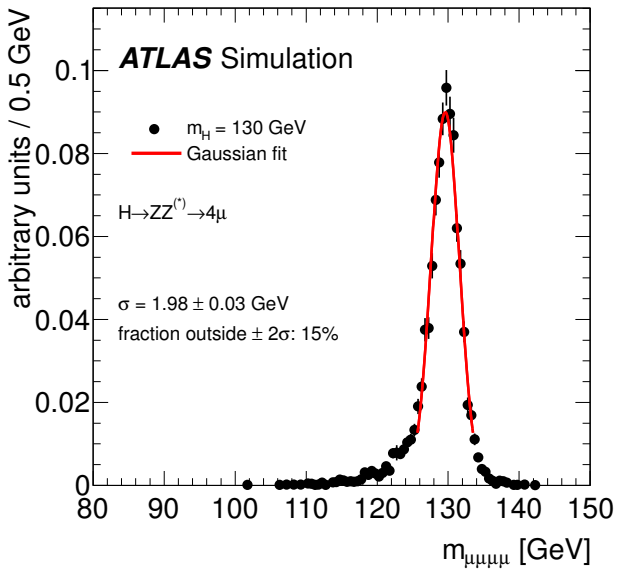
Reconstruction and selection efficiencies :

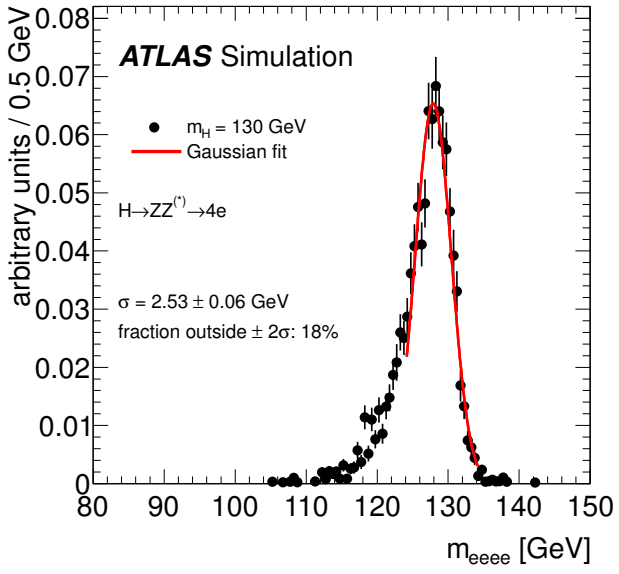
Mass [GeV]	4μ	$2e2\mu$	$4e$
130	27 %	18 %	14 %
360	60 %	52 %	45 %

Resolutions at 130 GeV :
2 GeV (4μ), 2.2 GeV ($2e2\mu$), 2.5 GeV ($4e$)

$4e$: lower mean value and tails, due to energy losses from Bremsstrahlung

Natural width of Higgs dominant from 350 GeV on : FWHM$\sim$ 35 GeV at $m_H = 400$ GeV.

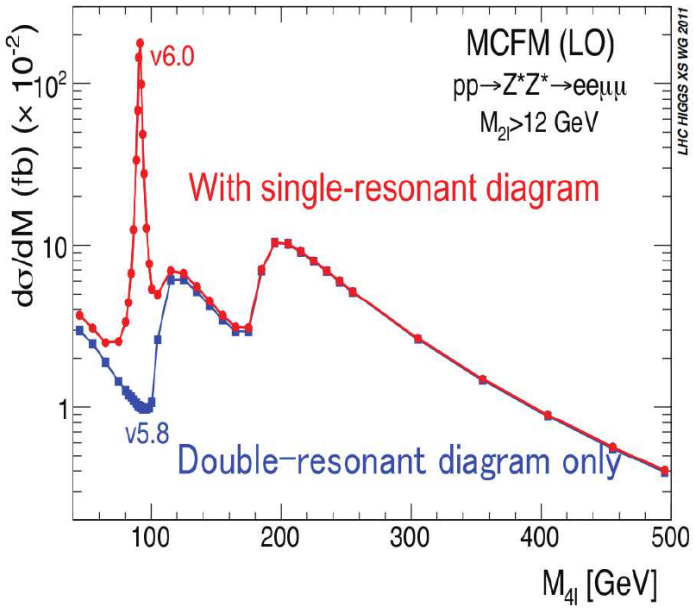


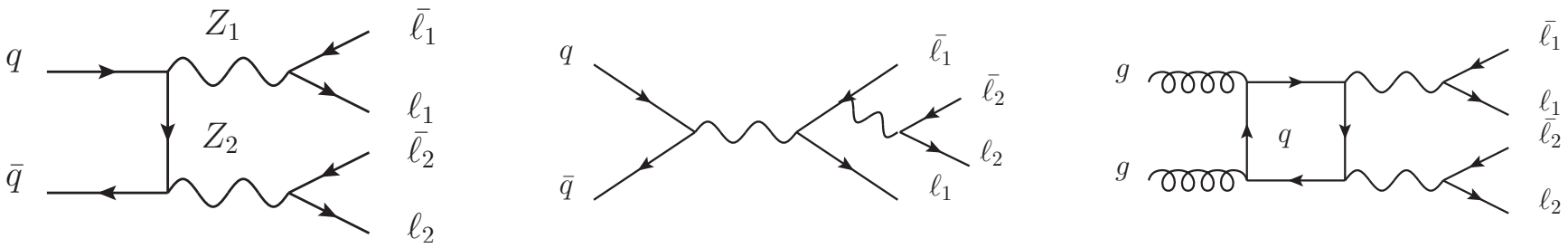


ZZ^* background

SM ZZ^* production : irreducible background.

- Generated with Pythia (only double-resonant diagrams)
- m_{ZZ} spectrum reweighted to MCFM prediction (single-resonant diagrams, leading gg)
- Uncertainties from QCD scales (5 %) and PDF+α_s variations (4 %)
- Additional normalisation (10 %) + shape uncertainty from varying gg contribution





Reducible backgrounds

Reducible backgrounds contributions derived using data-driven techniques.

$t\bar{t}$:

- Generated with MC@NLO
- Cross-section at NNLO (Hathor)
- Checked in control region with $e^{\pm}\mu^{\mp}$ leading pairs
- Good data-MC agreement
- Sizeable contribution in $Z+\mu\mu$ final states

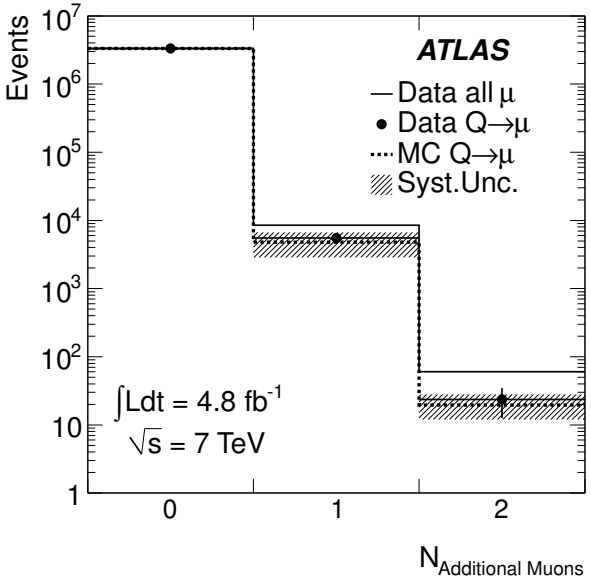
Z+jets :

- Generated with Alpgen+Herwig
- Two types of samples :
  - Z+light jets (incl. c), normalised to inclusive FEWZ NNLO cross-section
  - $Zb\bar{b}$, normalised to MCFM NLO cross-section
  - Overlap removed between samples
- Control regions : $Z+\ell\ell$, no isolation nor impact parameter cuts
- Dominant background depends on flavor of second pair

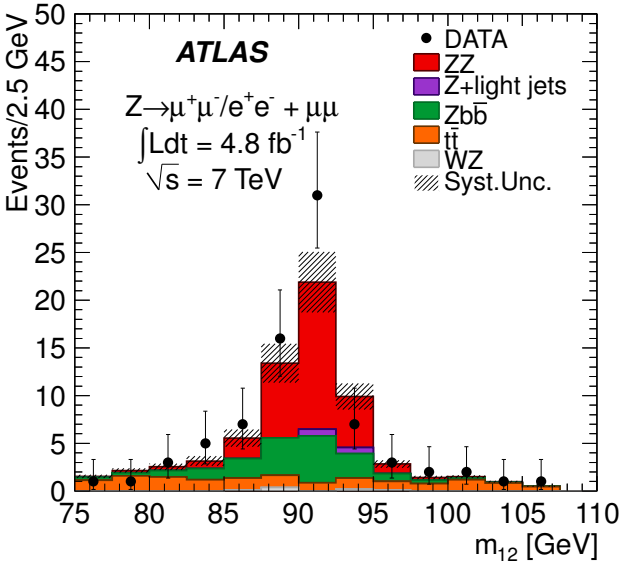
$Z+\mu^+\mu^-$

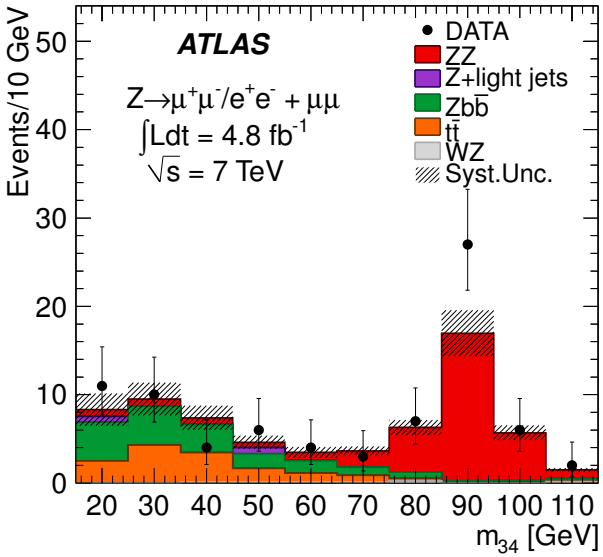
$Z+\mu\mu$ dominated by HF decays

- Z+light jets contribution in control region estimated using probabilities that tracks fake muons, checked on $Z+\mu$
- Then $Z+b\bar{b}(\rightarrow \mu\mu)$ estimated by subtraction : good data/MC agreement
- Finally propagation to signal region



Distributions in control region :

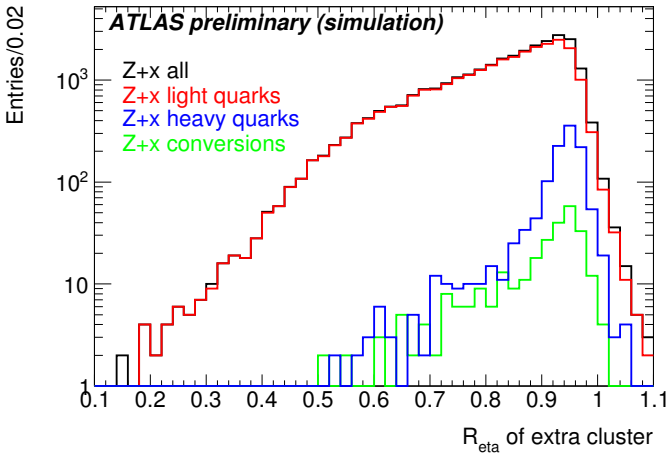




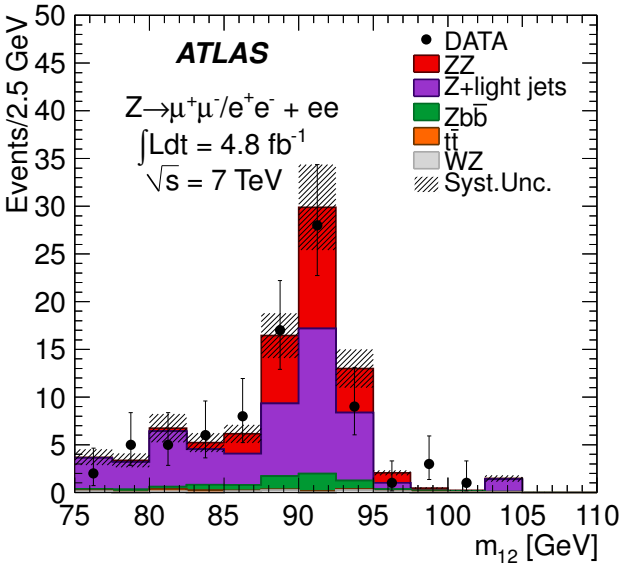
$Z+e^+e^-$

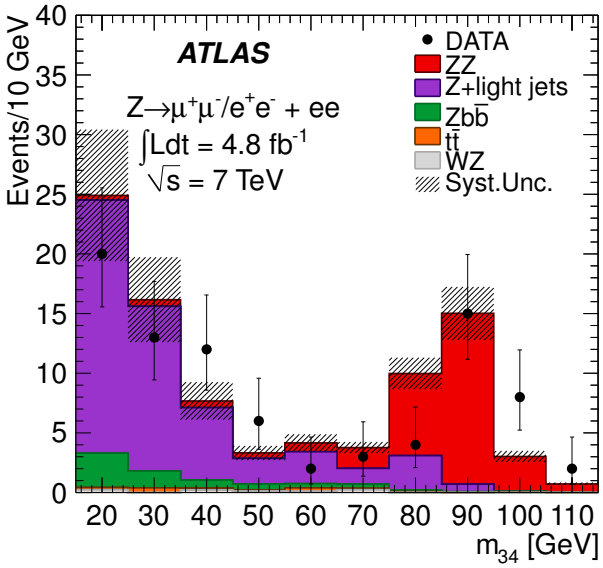
$Z+ee$ dominated by light jets

- Normalize $Z+ee$ events in MC using control region with reversed shower shape cut
- Compute isolation and impact parameter efficiencies in $Z+e$ samples : good data/MC agreement
- Extrapolate to signal region



Distributions in control region :





Systematic Uncertainties

Normalizations :

- Effects of PDF, α_s and QCD scales computed correlated between signal and backgrounds
- Additional systematics for high mass signal (off-shell effects) : $150\% \times m_H^3$[TeV] for $m_H > 300$ GeV
- Luminosity : 3.9 %

Backgrounds :

- $t\bar{t}$: 10 % cross-section, 10 % selection efficiencies
- $Zb\bar{b}$: 40 %
- Z+light jets : 45 %
  - origin : statistics in control region, uncertainty on composition of control region, uncertainty on extrapolation

Reconstruction and selection efficiencies :

- Muon efficiency : 0.22 % (4μ), 0.16 % ($2e2\mu$), uniform with $m_{4\ell}$.
- Electron efficiency : 2.3 % ($4e$), 1.6 % ($2e2\mu$) at 600 GeV. 8.0 % (4.1 %) at 110 GeV
- Lepton resolution : negligible
- Electron energy scale : uncertainty 0.6 % ($4e$) and 0.3 % ($2e2\mu$) on mass scale
- Isolations : negligible, except low-p_T electrons (5 %)
- Impact parameters : negligible
- Modelling of Higgs p_T spectrum : 2 %

Results

71 candidate events observed in data, for 62 ± 9 estimated background events

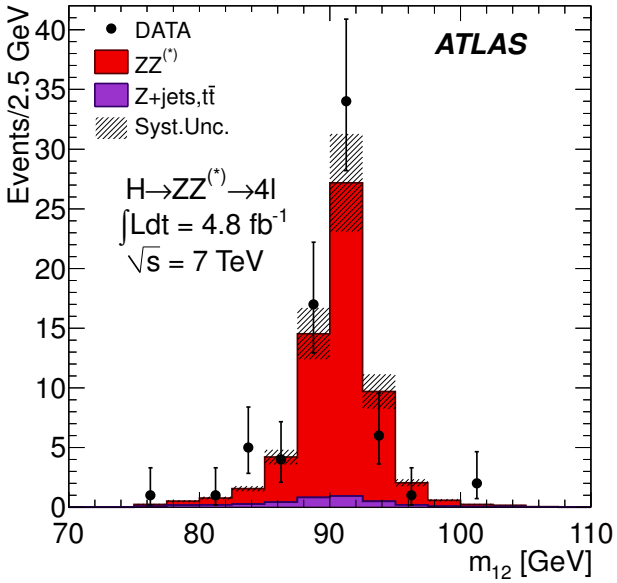
Breakdown per channel, in low-mass ($m_{4\ell} < 180$ GeV) and high-mass ($m_{4\ell} > 180$ GeV) regions :

	$\mu^+\mu^-\mu^+\mu^-$		$e^+e^-\mu^+\mu^-$		$e^+e^-e^+e^-$	
	Low-$m_{4\ell}$	High-$m_{4\ell}$	Low-$m_{4\ell}$	High-$m_{4\ell}$	Low-$m_{4\ell}$	High-$m_{4\ell}$
Int. Luminosity	4.8 fb^{-1}		4.8 fb^{-1}		4.9 fb^{-1}	
$ZZ^{(*)}$	2.1 ± 0.3	16.3 ± 2.4	2.8 ± 0.6	25.2 ± 3.8	1.2 ± 0.3	10.4 ± 1.5
$Z +$ jets and $t\bar{t}$	0.16 ± 0.06	0.02 ± 0.01	1.4 ± 0.5	0.17 ± 0.08	1.6 ± 0.7	0.18 ± 0.08
Total Background	2.2 ± 0.3	16.3 ± 2.4	4.3 ± 0.8	25.4 ± 3.8	2.8 ± 0.8	10.6 ± 1.5
Data	3	21	3	27	2	15
$m_H = 130$ GeV	1.00 ± 0.17		1.22 ± 0.21		0.43 ± 0.08	
$m_H = 150$ GeV	2.1 ± 0.4		2.9 ± 0.4		1.12 ± 0.18	
$m_H = 200$ GeV	4.9 ± 0.7		7.7 ± 1.0		3.1 ± 0.4	
$m_H = 400$ GeV	2.0 ± 0.3		3.3 ± 0.5		1.49 ± 0.21	
$m_H = 600$ GeV	0.34 ± 0.04		0.62 ± 0.10		0.30 ± 0.06	

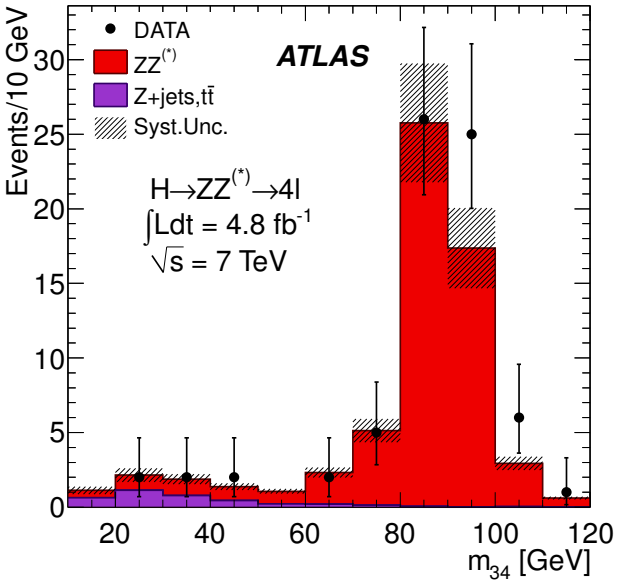
- Good agreement between data and SM background prediction
- Reducible backgrounds negligible in the high mass region
- Significant contribution of reducible backgrounds in the low mass region in $4e$ and $2e2\mu$ channels

Distributions

After the full selection :
Comparisons of data with SM backgrounds, separated into reducible and irreducible contributions.



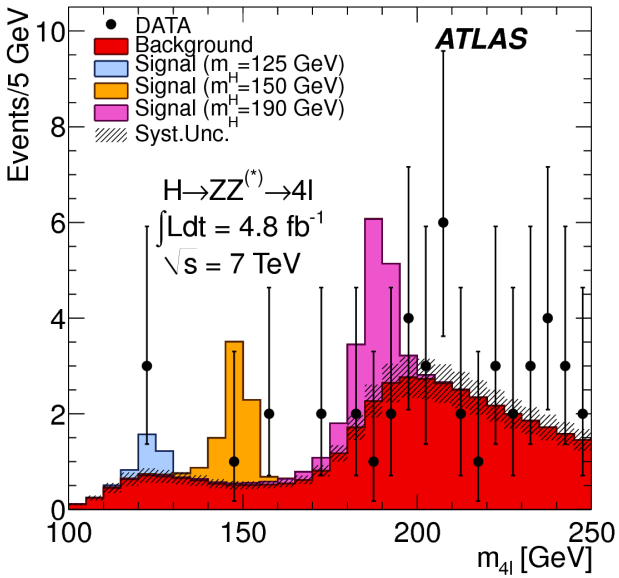
Invariant mass of first pair



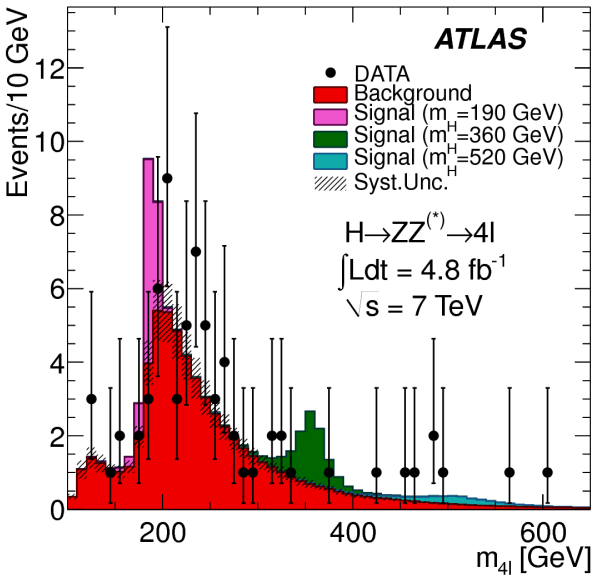
Invariant mass of second pair

Good agreement between data and SM expectations

Invariant mass



Invariant mass of the candidates, low mass



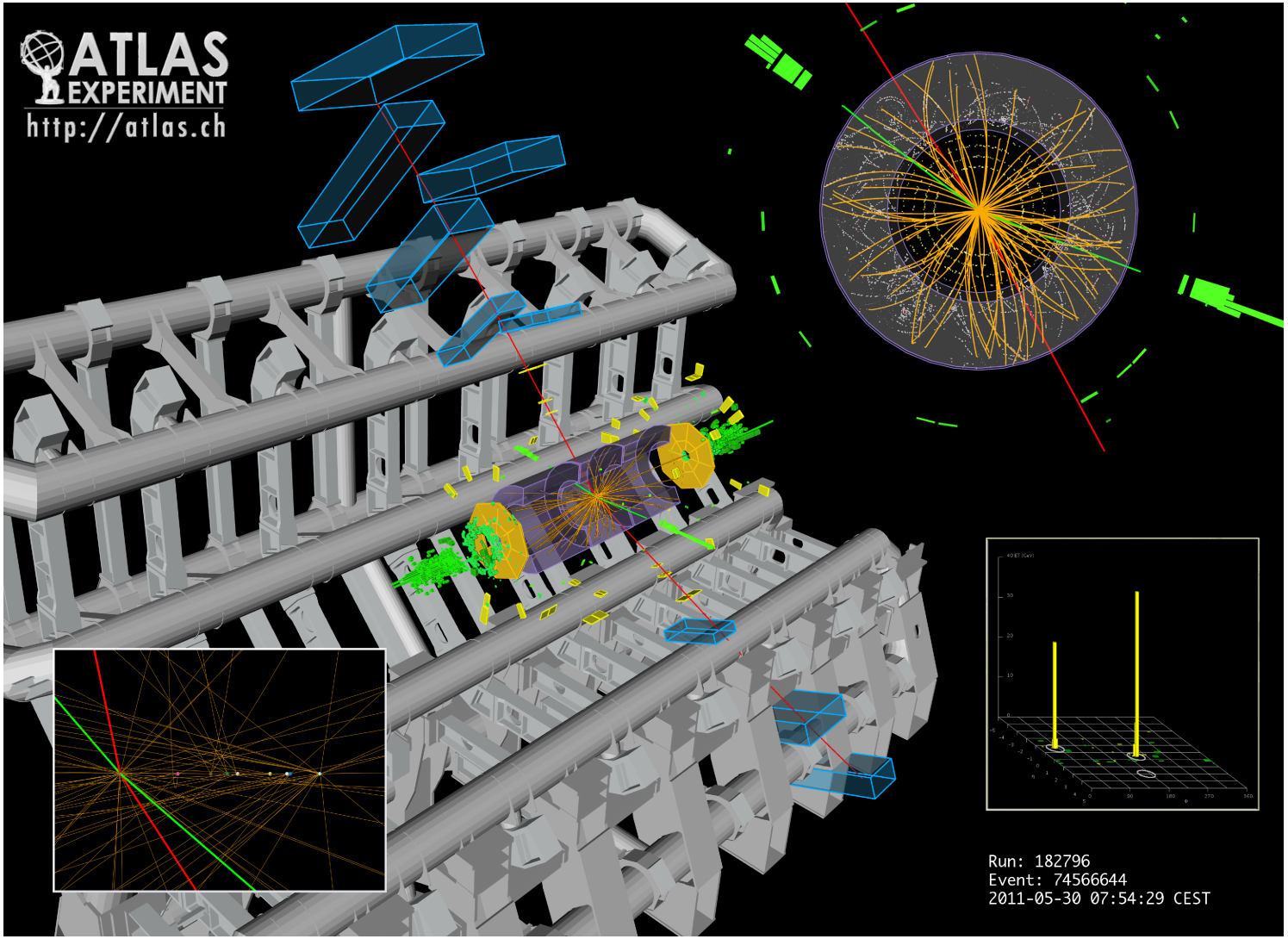
Invariant mass of the candidates, full mass range

Good agreement between data and SM expectations
3 excesses of events in the mass range :

- around 125 GeV, with 3 events
- around 245 GeV
- around 500 GeV, with 3–4 events

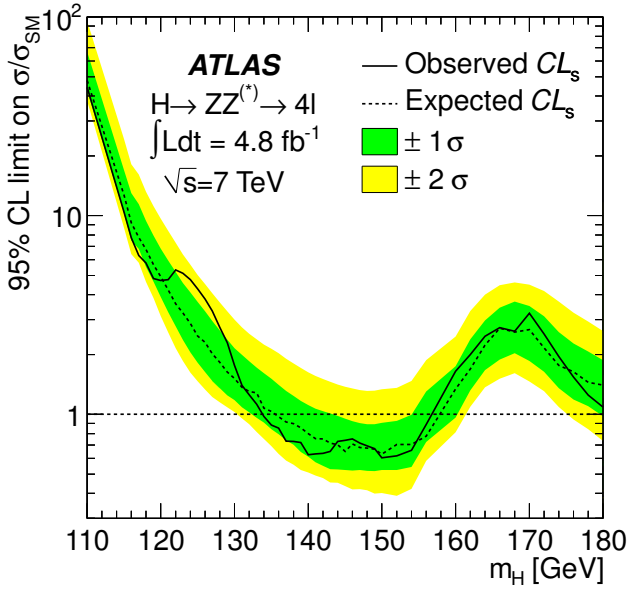
Event display

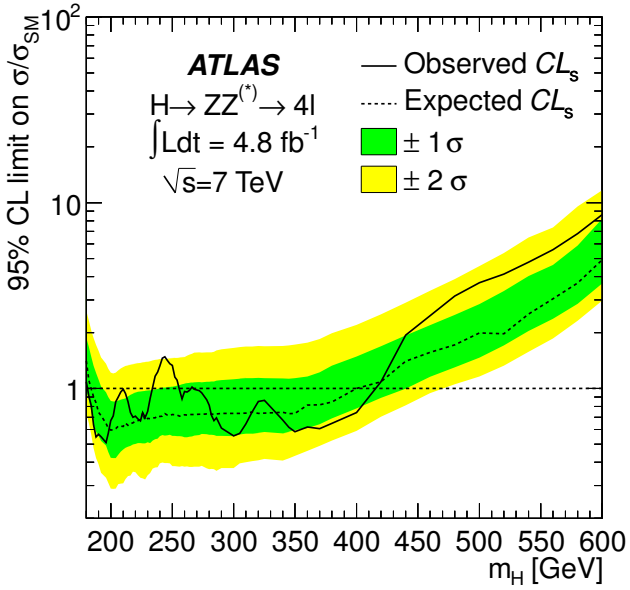
$2e2\mu$ **candidate.** $m_{4\ell} = 124.3$ GeV.
Masses of pairs : 76.8 GeV and 45.7 GeV



Limit-setting

- Limits set with CL_s formalism.
- Test statistic : profile likelihood ratio, evaluated with binned maximum-likelihood fits of the signal and background distributions to the observed data.
- Observed 95 % CL limit curve matches well expected one
- Exclusion of SM Higgs in 134–156 GeV, 182–233 GeV, 256–265 GeV and 268–415 GeV
- Exclusion expected in 136–157 GeV and 184–400 GeV
- Largest deviations from expected limit observed around 125 GeV, 244 GeV and 500 GeV

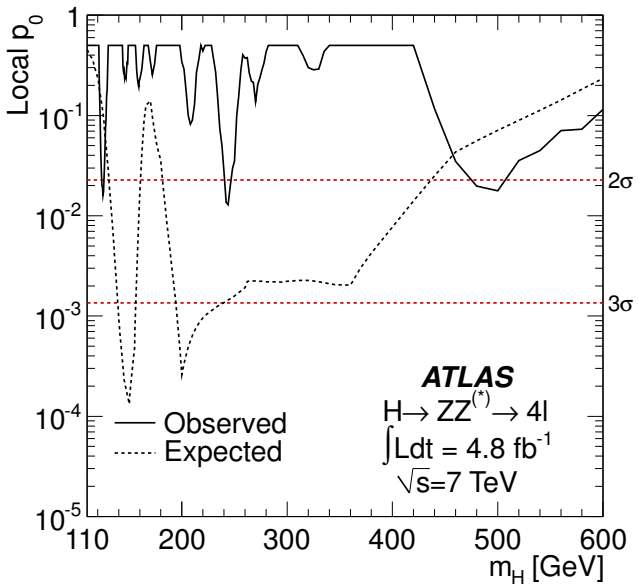




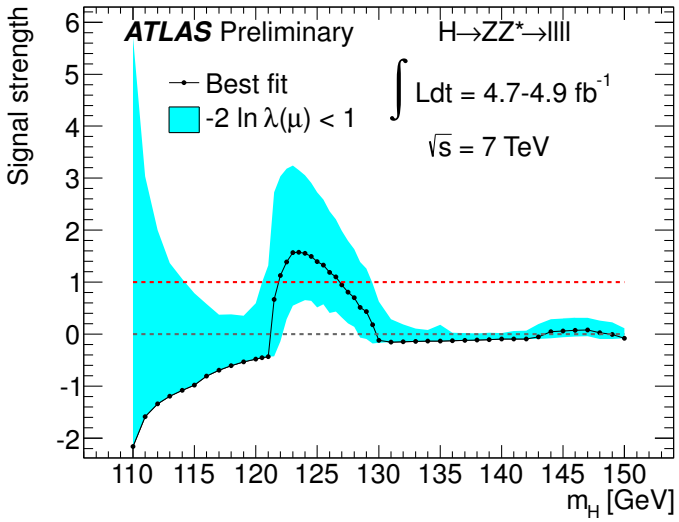
Discussion of results

Quantification of excesses : compute p_0 values

- Use pseudo-experiments, check with asymptotic formulae
- 1.6 % (2.1 σ) at 125 GeV
- 1.3 % (2.2 σ) at 244 GeV
- 1.8 % (2.1 σ) at 500 GeV
- Expected in presence of a SM-like signal : 1.3, 3.0 and 1.5 σ respectively
- Global p_0 around 50 % when look-elsewhere effect included



Observed p_0 value and expected one in presence of a signal

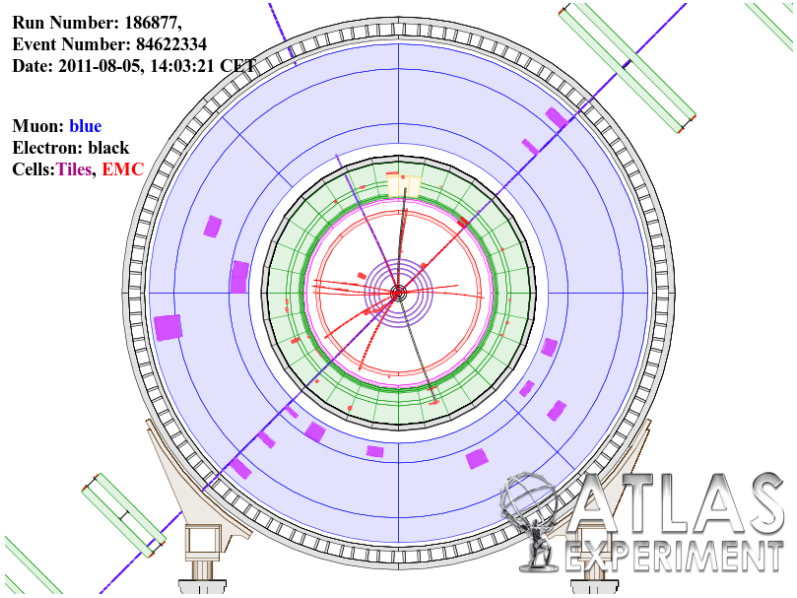


Observed signal strength

Conclusions

Search for the SM Higgs boson in the 4 lepton channel with 4.8 fb^{-1} :

- Thanks to a very successful run of the LHC and efficient data-taking, 4.8 fb^{-1} of data analyzed !
- Study of backgrounds shows good agreement with expectations
- 71 4 leptons candidates in data
- SM Higgs excluded by this channel in 134–156 GeV, 182–233 GeV, and ∼ 256–415 GeV
- Small excesses at 125, 244 and 500 GeV, of probabilities around 2.1 – 2.2 σ
- None of them significant once look-elsewhere effect included
- Nevertheless intriguing when compared to other ATLAS results ($\gamma\gamma$)
- Look forward to 2012 data !

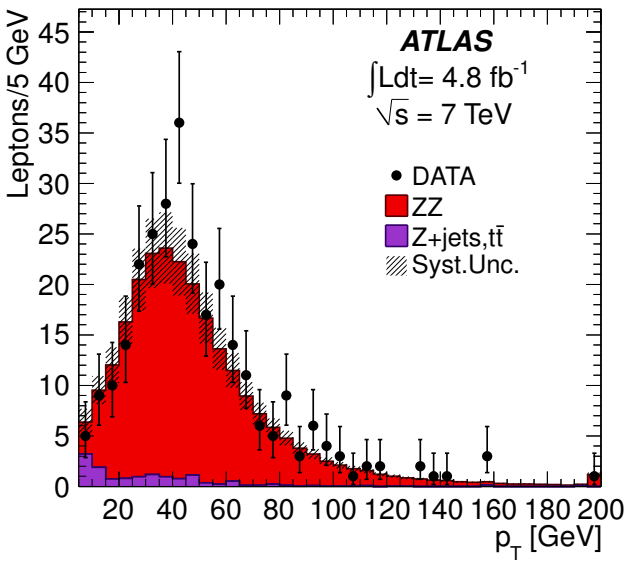


$2e2\mu$ candidate, $m_{4\ell} = 123.6$ GeV

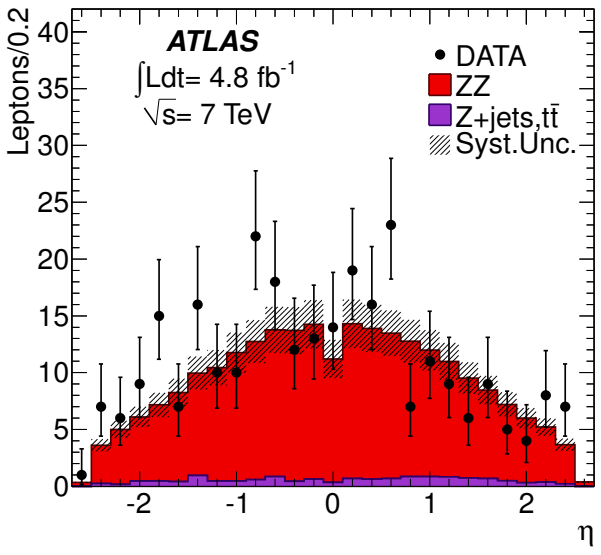
For more details, analysis published in Phys. Lett. B 710 (2012) 3

Backup

Lepton kinematics

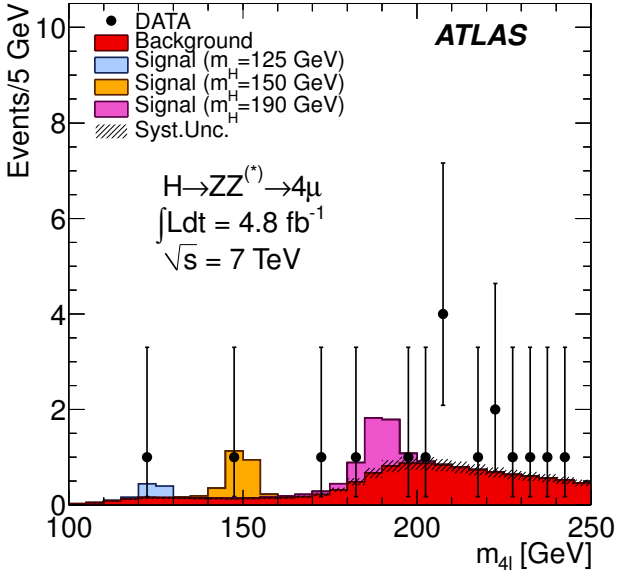


p_T spectrum of leptons of candidates

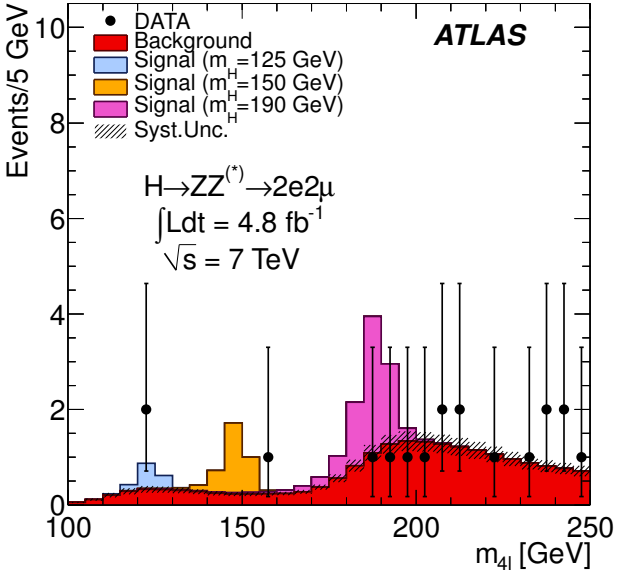


η spectrum of leptons of candidates

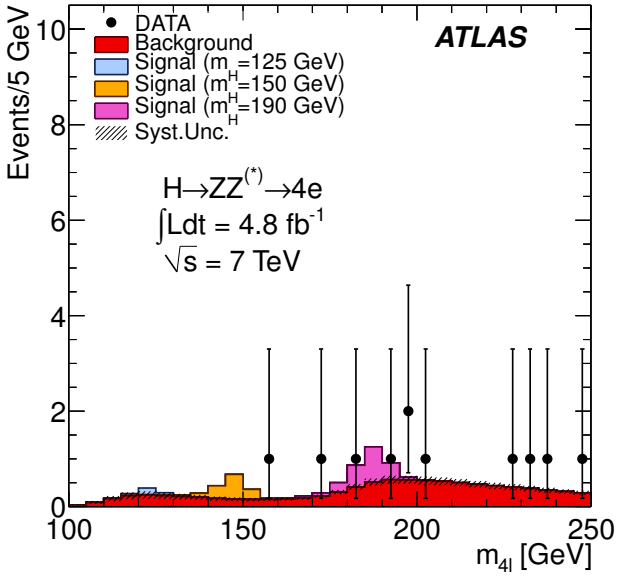
Invariant mass for different channels



Invariant mass of 4μ candidates



Invariant mass of $2e2\mu$ candidates



Invariant mass of $4e$ candidates

Projected sensitivity for 8 TeV