$H \rightarrow ZZ \rightarrow 4\ell$ *for high Higgs masses*

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Event selection

Event Preselection

1. lepton quality and kinematical cuts

Muons
combined or low-pT
$p_T > 5$ GeV and $\|\eta\| < 2.5$

Electrons
at least LooseElectron
$E_T > 5$ GeV and $\|\eta\| < 2.5$

2. creation of lepton pairs

leading (i.e. dilepton candidate closest to Z mass) : p_T (E_T) > 20 GeV/c (GeV/c^2)
following : p_T (E_T) > 7 GeV/c (GeV/c^2)

Event Selection

1. *four leptons (e,μ) in pairs of opposite charge and same flavor*
2. electrons: *additional lepton pair quality*
   - leading: LooseElectron
   - following: LooseElectron
3. *Z mass constraint* (i.e. Breit-Wigner + Gaussian distribution, with σ equal to the experimental resolution) - applied to both Z's if $M_H > 200$ GeV/c^2
4. *Kinematic cuts on Z objects*
5. *Higgs mass window* $M_H \pm 2\sigma_{MH}$

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leading (i.e. [illegible] Z mass) : p_T (E_T) > 20 GeV/c (GeV/c²)

following : p_T (E_T) > 7 GeV/c (GeV/c²)

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Different electrons selection wrt the one used for the low masses analysis: moving from Medium-Medium to Loose-Loose

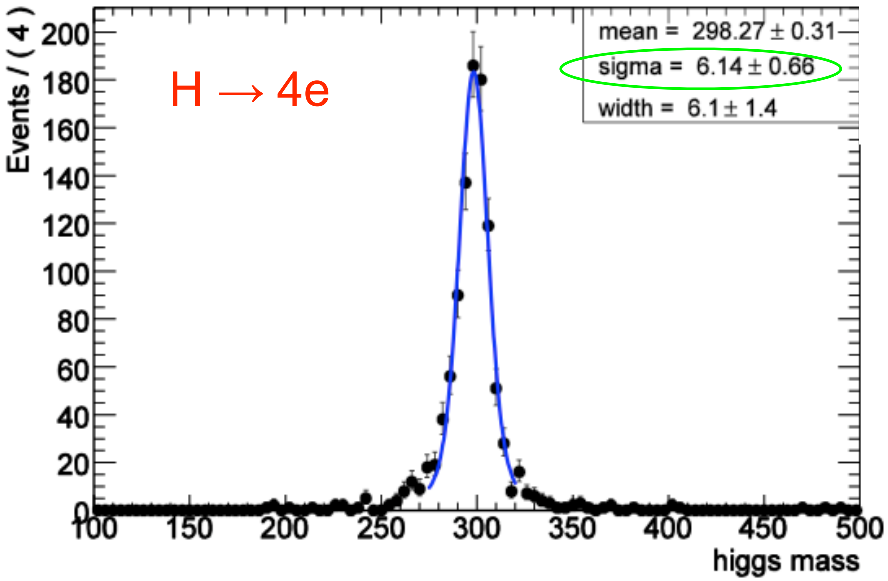
signal efficiencies increase ~40%

over a small ZZ background

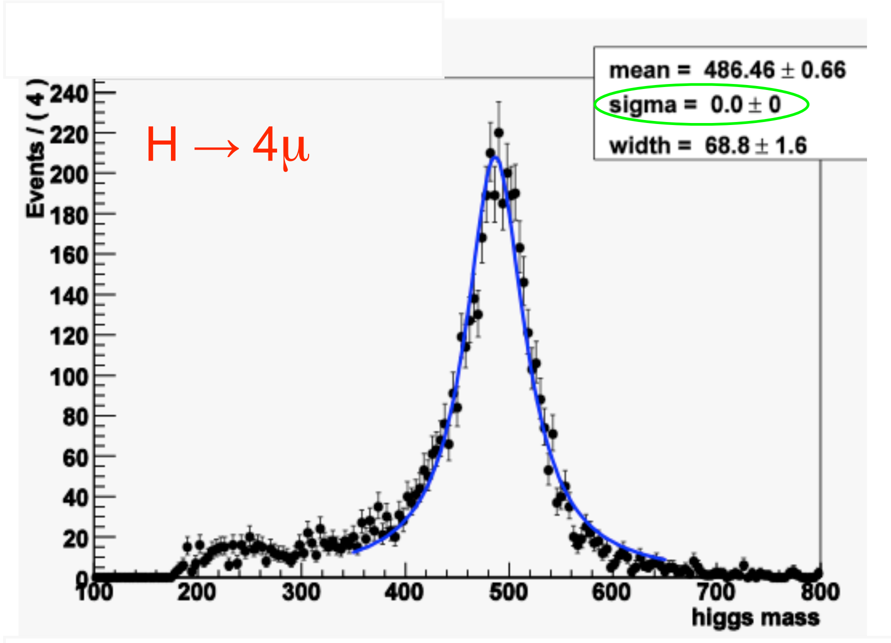
Z(→ee) and Zbb background contribution ~0 in high m_H region

Kinematic cuts

H Mass (GeV)	Z1 mass window (GeV)	Z2 mass cut (GeV)	H mass window (GeV)		
			$4e$	4μ	$2e2\mu$
200	± 12	>60	3.9	3.7	3.8
300	± 12	± 12	8.4	8.4	8.4
400	± 12	± 12	16.5	17.3	17.2
500	± 12	± 12	33.8	34.4	32.8
600	± 12	± 12	52.2	57.2	53.2



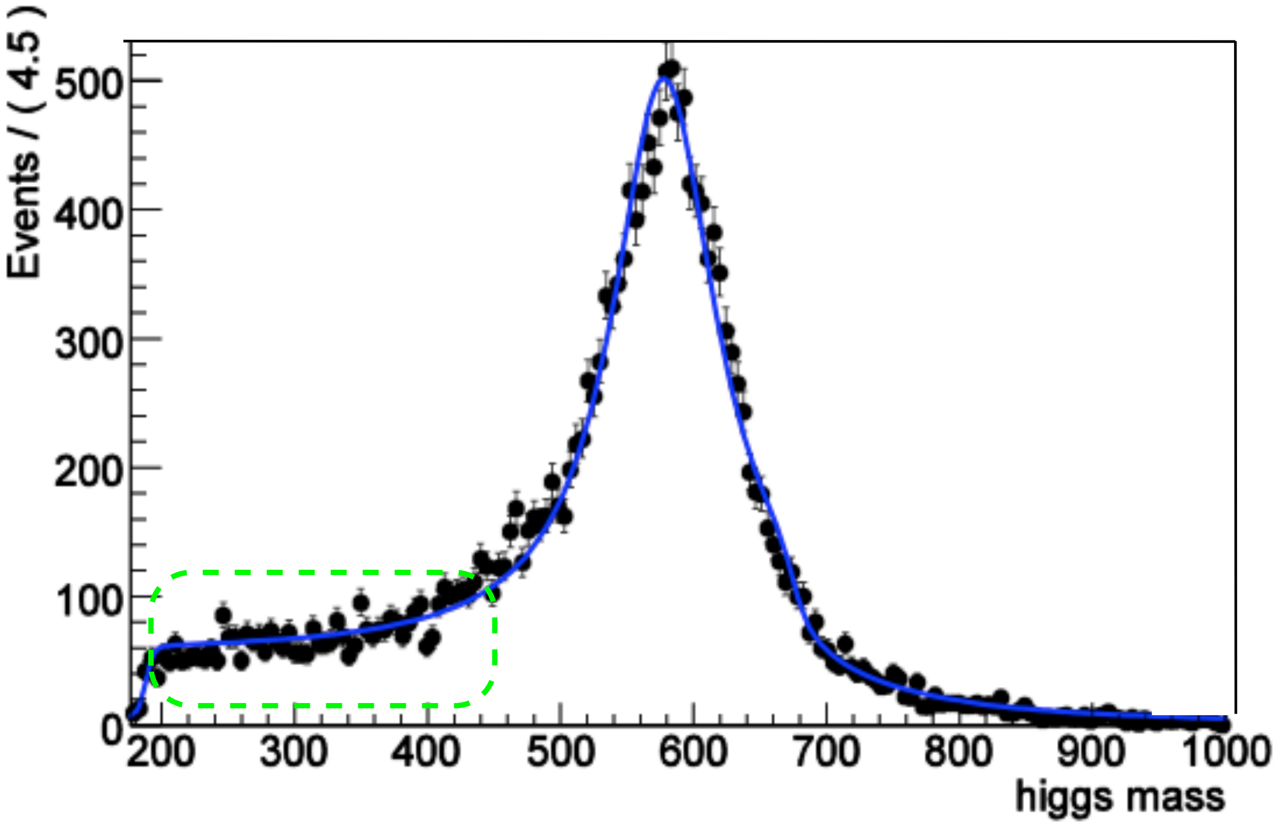
Convolution Rel. Breit Wigner + Gauss



dominated by intrinsic resolution

Signal pdf

signal modeled by a relativistic Breit-Wigner convoluted with a Gaussian + Fermi function to describe the tail



photons coming from final state radiation not considered in the m_H reconstruction: fast check using MC truth ⇒ events with high p_T photon (~100 GeV) from Z

photon recovery to implement to gain a better resolution on the mass

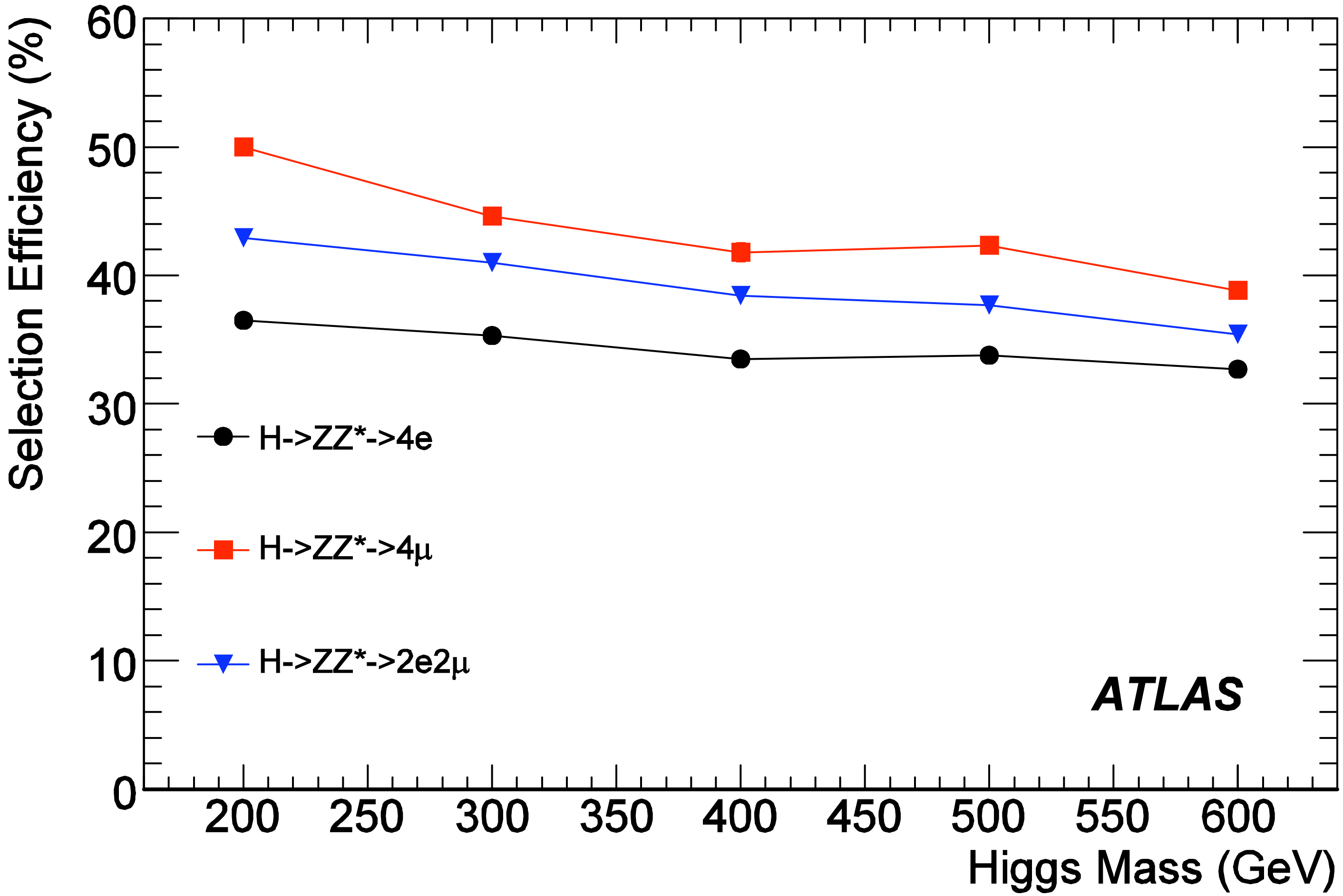
An example: selection cut flow for M_H =400 GeV

Selection cut		Signal 4e	Signal 4μ	Signal $2e2\mu$
Generated events		9776	9631	19443
Trigger selection	1	99.7%	99.3%	99.7%
Lepton preselection	2	68.1%	76.7%	73.6%
Lepton quality and p_T	3	64.1%	76.0%	69.8%
Z's mass cuts	4	51.0%	58.6%	56.2%
Calo Isolation	5	51.0%	56.6%	55.3%
Tracker Isolation	6	49.9%	56.2%	54.5%
IP cut	7	44.1%	54.4%	50.6%
H Mass cut	8	**33.5%**	**41.8%**	**38.4%**

Selection cut		ZZ 4e	ZZ 4μ	ZZ $2e2\mu$	Zbb 4e	Zbb 4μ	Zbb $2e2\mu$
Generated event		95900			429500		
Trigger	1	96.6%	96.6%	96.6%	91.4%	91.4%	91.4%
Preselection	2	13.8%	17.6%	31.4%	2.6%	9.4%	12.0%
Lepton quality and p_T	3	12.0%	16.0%	27.9%	$6.4{\cdot}10^{-1}$%	2.1%	2.7%
Z mass cuts	4	7.6%	9.9%	18.0%	$1.0{\cdot}10^{-2}$%	$7.3{\cdot}10^{-2}$%	$7.7{\cdot}10^{-2}$%
Calo Isolation	5	7.6%	9.6%	17.5%	$1.0{\cdot}10^{-2}$%	$4.4{\cdot}10^{-3}$%	$1.7{\cdot}10^{-2}$%
Track Isolation	6	7.4%	9.5%	17.2%	$1.2{\cdot}10^{-3}$%	$1.6{\cdot}10^{-3}$%	$3.7{\cdot}10^{-3}$%
IP cut	7	6.5%	9.1%	15.8%	$4.7{\cdot}10^{-3}$%	$2.3{\cdot}10^{-4}$%	$1.9{\cdot}10^{-3}$
H Mass window	8	**$3.5{\cdot}10^{-1}$%**	**$6.0{\cdot}10^{-1}$ %**	**$9.6{\cdot}10^{-1}$%**	**0**	**0**	**0**

No Z(→ee) and $t\bar{t}$ bkg contributions at high Higgs masses

Selection efficiency on signal



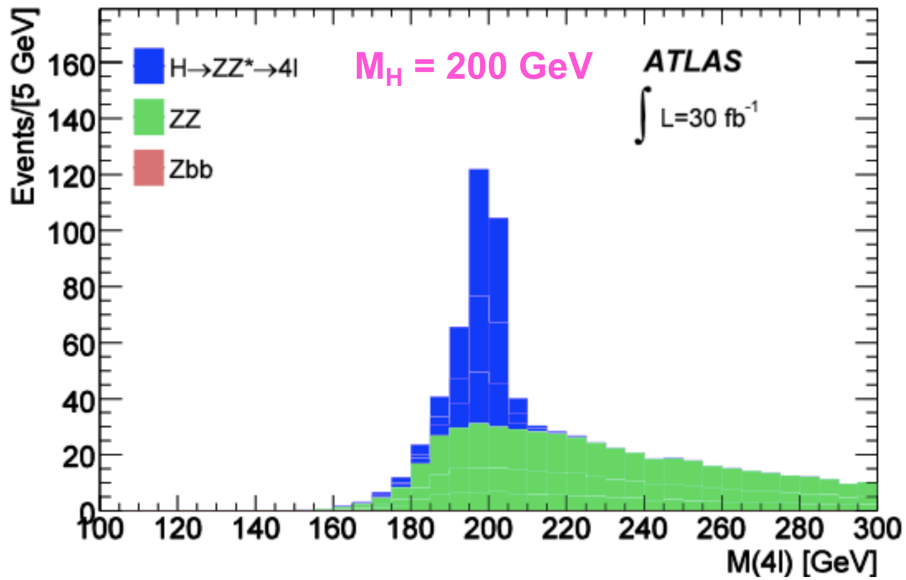
Results : events numbers and significances

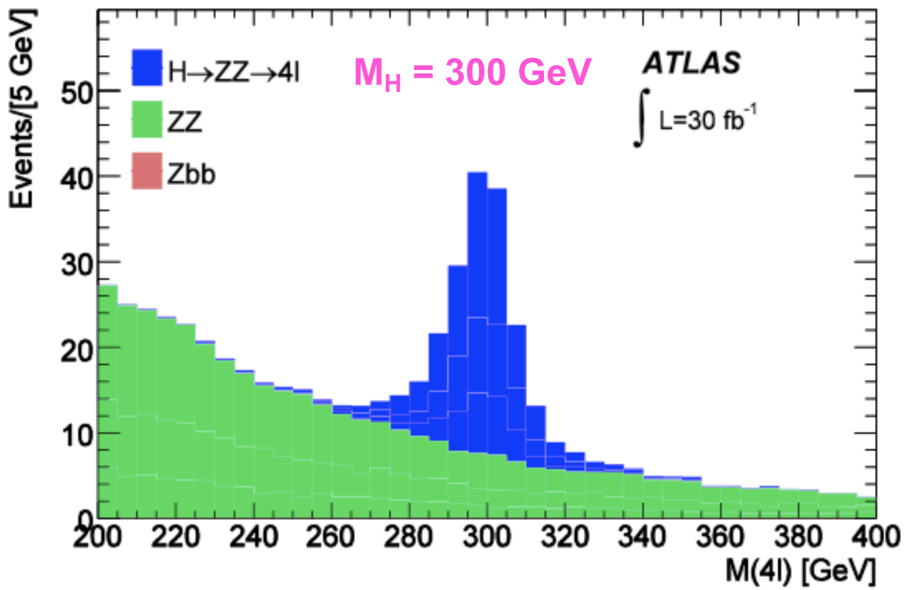
- NLO cross section
- normalized to **30 fb^{-1}**

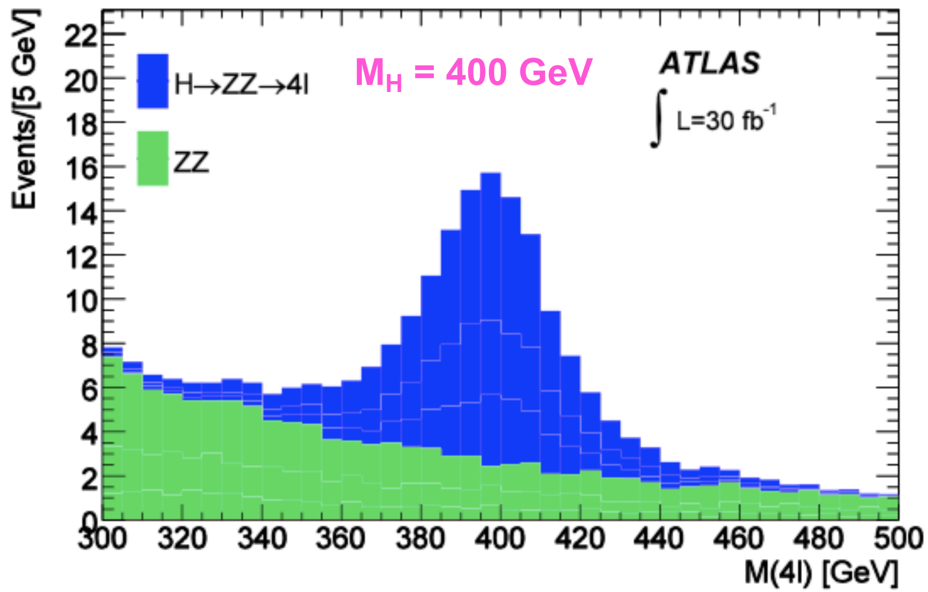
Mass (GeV)		200	300	400	500	600
Selection						
$4e$	Signal	1.41	0.917	0.737	0.370	0.174
	ZZ^*/γ^*	0.689	0.342	0.225	0.228	0.179
	Significance (30 fb^{-1})	7.4	6.6	6.3	3.4	1.9
4μ	Signal	1.94	1.16	0.918	0.463	0.206
	ZZ^*/γ^*	0.867	0.468	0.379	0.346	0.296
	Significance (30 fb^{-1})	9.0	7.2	6.3	3.6	1.8
$2e2\mu$	Signal	3.33	2.13	1.69	0.825	0.377
	ZZ^*/γ^*	1.53	0.836	0.610	0.570	0.438
	Significance (30 fb^{-1})	11.7	9.8	9.0	5.0	2.7
All	Signal	6.68	4.21	3.34	1.66	0.76
	ZZ^*/γ^*	3.09	1.65	1.21	1.14	0.914
	Significance (30 fb^{-1})	16.5	13.8	12.7	7.1	3.8

Mass distributions

- reconstructed 4-lepton mass after full event selection
- all 3 channels included
- no pileup, no systematics
- normalized to **30 fb^{-1}**







Mass distributions

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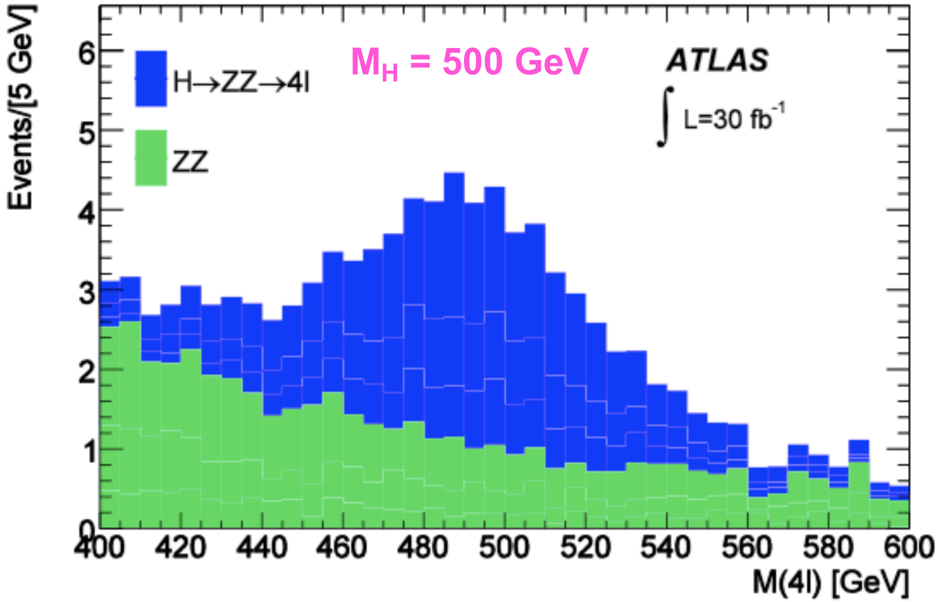
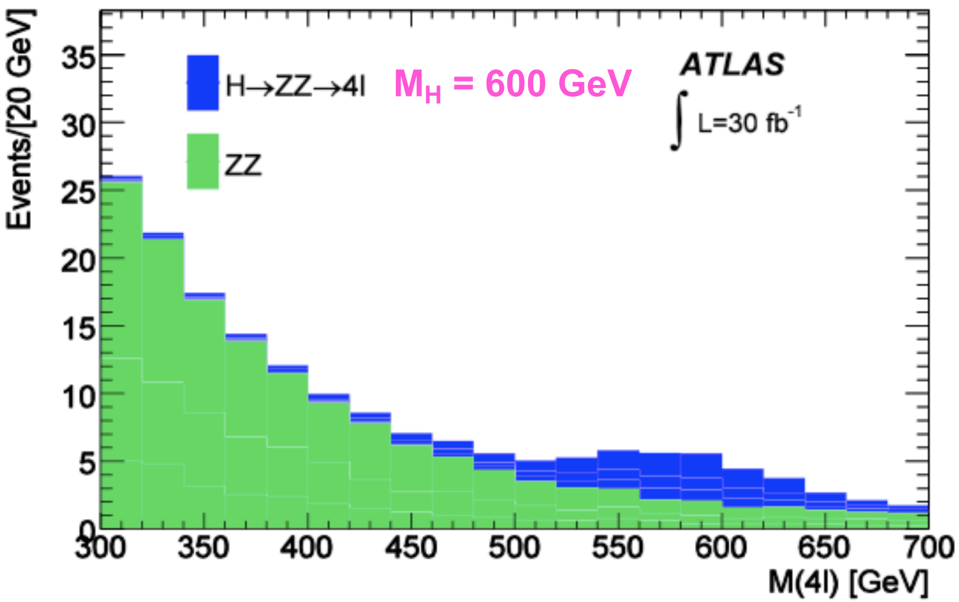
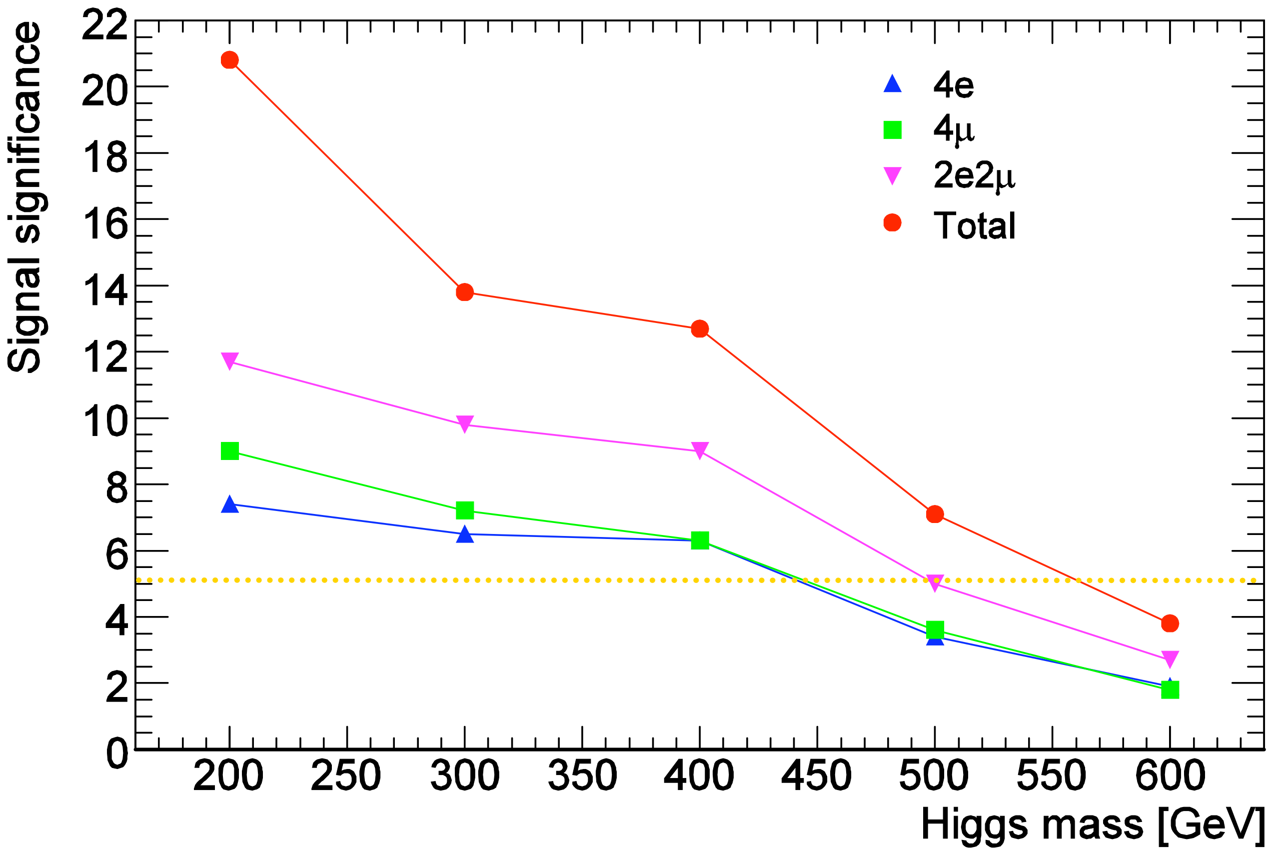




Signal significance

- signal events selected within a $\pm 2\sigma_{MH}$ mass window
- results for integrated luminosity **30 fb^{-1}**
- only statistical fluctuation
- background assumed to be known with a negligible uncertainty



Significance extraction from data

- evaluation of background uncertainties to include in the significance calculation → reduce the confidence level for claiming a discovery
- four fit-based approaches for background and significance extraction
    - ✦ full range fit using signal hypothesis at fixed mass and profile likelihood method to extract the significance
    - ✦background-only sideband fit in a restricted mass range using number counting with frequentist treatment of background uncertainty
    - ✦background-only sideband fit using the full mass range and assuming knowledge of the shape of the M_{ZZ} distribution
    - ✦2D (M4l,MZ*) fitting method with floating Higgs mass and signal hypothesis

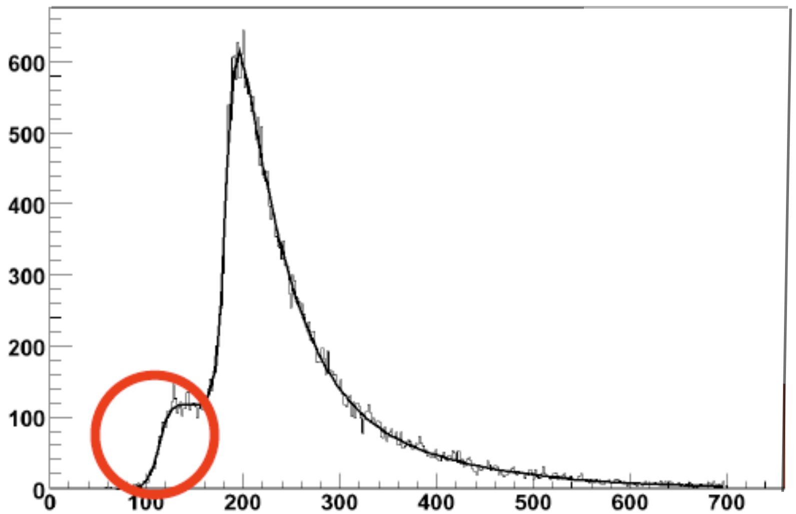
Profile Likelihood Ratio Method

- method used to provide $H \rightarrow 4\ell$ input to the combination of all ATLAS SM Higgs search
- four lepton mass used as discriminant variable to construct the likelihood

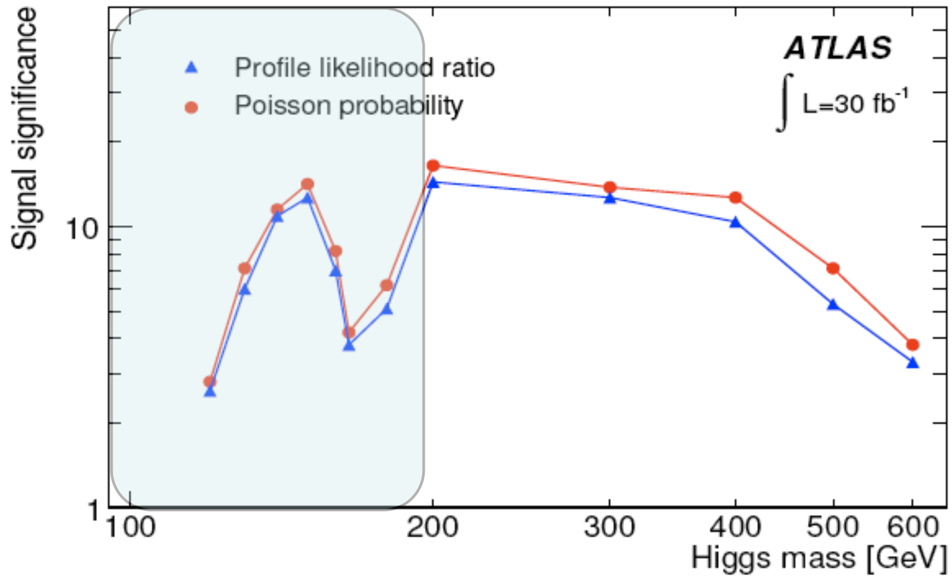
$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\vec{p}}})}{L(\hat{\mu}, \hat{\vec{p}})}$$

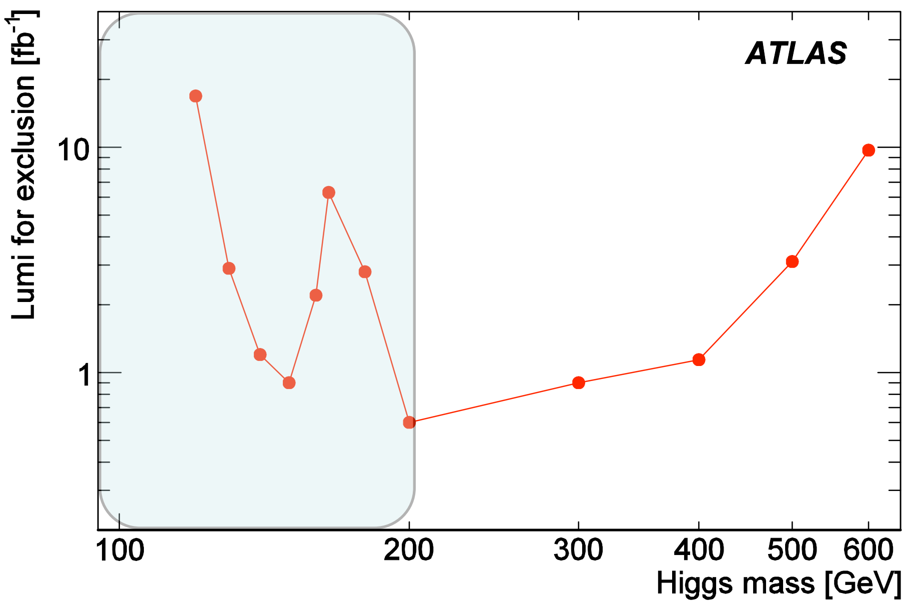
$$\begin{aligned}
\hat{\hat{\vec{p}}} &= \text{pdf parameters which maximize the likelihood } L \text{ for a given } \mu \\
\vec{p} &= \text{pdf parameters} \\
\mu &= \text{ratio of the signal cross section to the SM expectation} \\
(\hat{\mu}, \hat{\vec{p}}) &= \text{values of } \mu \text{ and } \vec{p} \text{ that maximize the } L \text{ function}
\end{aligned}$$

- signal and background probability density functions determined from MC
  - signal modeled by a relativistic Breit-Wigner + Fermi function
  - ZZ background modeled using a combination of Fermi functions

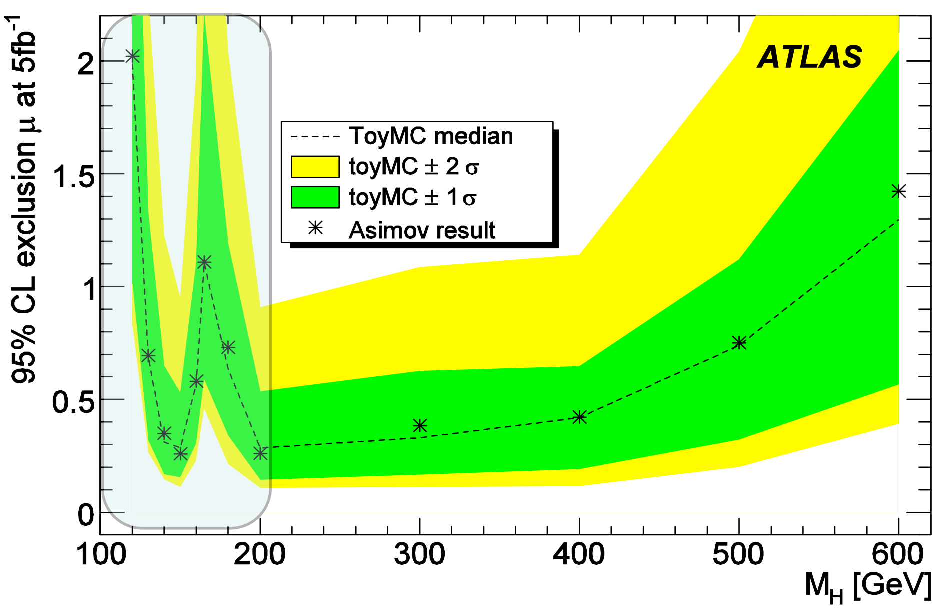


Profile Likelihood Ratio Method : Results





luminosity needed for 95% CL exclusion



Conclusions

- $H \to ZZ \to 4\ \ell$ covers a wide mass range (from 120 GeV/c^2 to 600 GeV/c^2 with a large discovery potential
    - ✓ gold-plated channel when Higgs is heavier then 200 GeV/c^2
- Exclusion for high Higgs masses possible with few fb^{-1}

Back Up Slides

MC samples

Process	Filter acc	$\sigma_{LO}[fb]$	$\sigma_{NLO}[fb]$	Events
$H[200] \rightarrow 4l$	0.753	12.39	20.53	50K
$H[300] \rightarrow 4l$	0.782	7.65	13.32	10K
$H[400] \rightarrow 4l$	0.814	6.07	10.78	40K
$H[500] \rightarrow 4l$	0.842	2.97	5.12	40K
$H[600] \rightarrow 4l$	0.853	1.53	2.53	40K

signal

NLO cross section

Background

Process	Generator	FA	$\sigma[fb]$	Corrections	Events (K)
$q\bar{q} \rightarrow ZZ \rightarrow 4\ell$	Pythia6.3	0.219	158.8	+47.64 (quark box, 30%)	100
$gg \rightarrow Zb\bar{b} \rightarrow 2\ell b\bar{b}$	AcerMC/Pythia6.3	[4ℓ] 0.00942	52000	+8500 ($q\bar{q} \rightarrow Zb\bar{b}$)	430
$gg \rightarrow Zb\bar{b} \rightarrow 2\ell b\bar{b}$	AcerMC/Pythia6.3	[3ℓ] 0.147	52000	+8500 ($q\bar{q} \rightarrow Zb\bar{b}$)	200
$gg, q\bar{q} \rightarrow t\bar{t}$	MC@NLO/Jimmy	[4ℓ] 0.00728	833000		400

qq → ZZ

$\sigma_{eff} = \sigma_{LO} \cdot [BR(Z \rightarrow ll)]^2 \cdot \text{Filter acc} \cdot (K + 0.3) = 34.82 \cdot (K(M_{ZZ}) + 0.3)$ fb

gg → Zb$\bar{b}$

K = 1.42

$\sigma_{eff} = \sigma_{LO} \cdot BR(Z \rightarrow ee, \mu\mu) \cdot \text{Filter acc} \cdot K = 812.1$ fb

M_{ZZ} (GeV)	K-factor
[115,125]	1.15
[125, 135]	1.21
[145, 155]	1.25
[155, 165]	1.34
[175, 185]	1.31
[195, 205]	1.32
[295, 305]	1.40
[395, 405]	1.52
[495, 505]	1.84
[595, 605]	1.81

Systematic uncertainties

1. **theoretical uncertainties**: PDF, QCD scales
   - accounted in the effective NLO cross section evaluation

2. **experimental uncertainties**: related to lepton reconstruction

provided by the ATLAS performance WGs

   - *lepton energy scale*: uncertainty of ±1% on muon p_T and of ±0.5% on electron E_T
   - *lepton energy resolution*: Gaussian smearing with $\sigma_{ET} = 0.0073\ E_T$ (energy) or $\sigma_{1/pT[GeV]} = 0.011\ 1/p_{T[GeV]} \oplus 0.00017$ (momentum)
   - *lepton reconstruction efficiency*: discarded 0.2% of reconstructed electrons and 1% of reconstructed muons
   - *material effects* in electron efficiency: < 2% overall (can be measured using data)

3. **uncertainty on LHC luminosity** of 3%

Overall impact on the selection efficiencies of 2. and 3. : *from 3.2% to 6.0% on the signal* and *from 3.1% to 5.4% on ZZ and Zbb backgrounds* (tt contribution negligible)

Profile Likelihood Ratio Method

- MC distributions after event selection (*Asimov data*) fitted to derive pdf parameters
  - M_H fixed to its true value, σ_H floating in a ±20% range
  - background parameters floating within sensible ranges
- ZZ modeled using a combination of Fermi functions

$$f(M_{ZZ}) = \frac{p0}{(1+e^{\frac{p6-M_{ZZ}}{p7}})(1+e^{\frac{M_{ZZ}-p8}{p9}})} + \frac{p1}{(1+e^{\frac{p2-M_{ZZ}}{p3}})(1+e^{\frac{p4-M_{ZZ}}{p5}})}$$

- Zbb contribution modeled by a Fermi contribution similar to the second term above

significance obtained from the median profile likelihood ratios for discovery $-2\ln\lambda(\mu=0)$

L (fb^{-1})	200	300	400	500	600
1	2.62	2.28	1.88	0.94	0.56
2	3.71	3.23	2.77	1.32	0.79
5	5.86	5.08	4.21	2.08	1.24
10	8.29	7.19	5.96	2.91	1.76
30	14.4	12.7	10.4	5.28	3.31