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Study of the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ channel with the full ATLAS detector simulation

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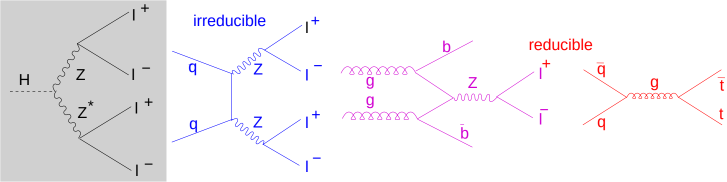
Outline

$H \to ZZ^{(*)} \to 4\ell$ decay provides for one of the clearest Higgs signatures.

Evaluation of the discovery potential with ATLAS detector, using a detailed detector simulation (low luminosity runs up to 30 fb^{-1}):

- Data samples.
- Lepton reconstruction efficiency and resolution.
- Description of the analysis.
- Discriminating variables and cut optimizations.
- Results.

Signal and background processes

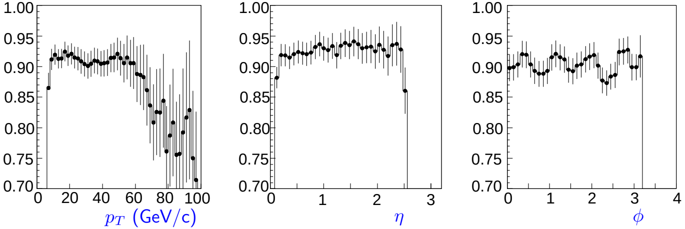


Process	σ x BR (fb) (after 4ℓ-filter)	$N_{30fb^{-1}}$	$N_{reconstructed}$
$H \to 4\ell$, 130 GeV	1.624	48.72	60 000
$H \to 4\ell$, 180 GeV	1.656	49.68	15 000
$H \to 4\ell$, 280 GeV	4.397	131.9	32 000
reducible: $t\bar{t} \to \ell\nu b\ell\nu\bar{b}$	1311	39330	442 000
reducible: $Zb\bar{b} \to \ell\ell b\bar{b}$	519.9	15597	53 000
irreducible: $(ZZ^{(*)}, Z\gamma^*) \to 4\ell$	33.36	1000.8	109 000

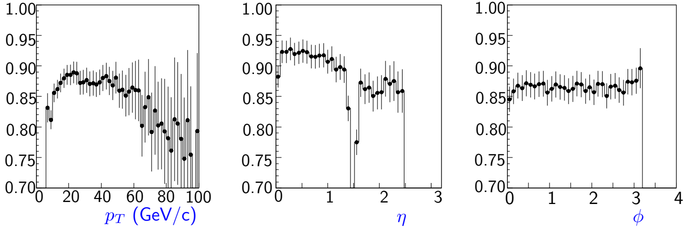
- Pythia(+AcerMC) generator (4ℓ-filter with $p_T > 5$ GeV/c, $|\eta| < 2.5$)
- Detailed simulation of processes in the detector (Athena 10.0.4).
- Largest data sizes produced so far, allow for the cut optimizations.

Lepton reconstruction efficiency

muon reconstruction efficiency



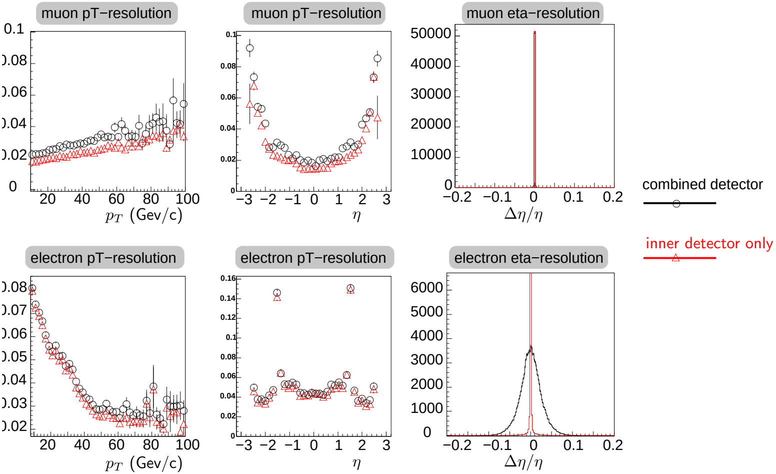
electron reconstruction efficiency



- 92% for muons: in agreement with previous (TDR) studies
- 86% for electrons: degradation w.r.t previous (TDR) studies

Lepton momentum- and angular resolution

- Default track parameters given by the combined information from the inner detector, calorimeter, muon spectrometer.
- Non-intuitive improvement: use the inner detector alone for (p_T, η, ϕ) of muons and (η, ϕ) of electrons.
  - due to the software bugs in the combining procedures



Analysis flow

isolated leptons
impact significance cut

$\geq 4e$	$\geq 4\mu$	$\geq 2e, 2\mu$
4e-combinations	4μ-combinations	2e2μ-combinations

Charge cut: total charge = 0

Kinematic cut: 2 leptons with $p_T > 20$ GeV, other two with $p_T > 7$ GeV ($|\eta| < 2.5$)

Select the best combination:

1. LEADING LEPTONS: (l^+,l^-)-pair with mass m_{12} closest to the Z-resonance
2. FOLLOWING LEPTONS: second (l^+,l^-)-pair with largest mass m_{34}

selected 4-lepton combination

Z-mass cut: $(m_Z - m_{12,low}) < \delta m_{12} < (m_Z + \delta m_{12,upp})$

$Z^{(*)}$-mass cut: $m_{34,low} < m_{34} < m_{34,upp}$

p_T^{4l} cut: $p_T^{4l} > p_T^{4l,cut}$

kinematic fit of the Z-mass (convolution of Breit-Wigner distribution and momentum resolution)

selected Higgs candidate

Mass-window cut: select events within a mass window ($m_H \pm 3\sigma$)

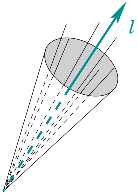
i) + E_T^{miss} cut: $E_T^{miss} < E_T^{miss,cut}$

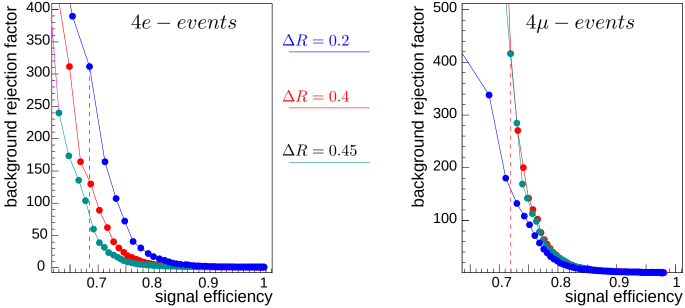
ii) + n_{bjet} cut: $n_{bjet}=0$

Lepton isolation

Provides the strongest rejection against the $t\bar{t}$ and $Zb\bar{b}$ background (2 of 4 leptons surrounded by the jet particles coming from b-decays).

- $\Rightarrow$ maximum energy $E_T^{max}(\Delta R)$ deposited in a cone of size ΔR around the lepton candidate, separately for electrons and muons:



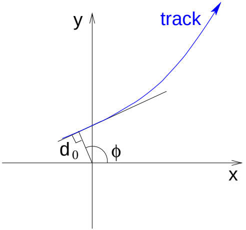


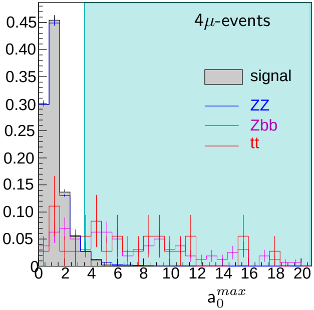
	signal efficiency	rejection factor
electrons: $E_T(\Delta R = 0.2) < 6$ GeV	0.68	320
muons: $E_T(\Delta R = 0.4) < 9$ GeV	0.72	420

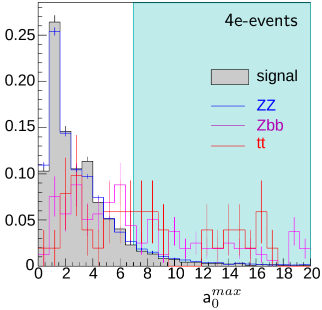
Impact significance

Leptons from b-quarks are displaced from the primary vertex.

- $d0$ - reconstructed distance from the primary vertex
- impact significance $a_0^{max} = \frac{d_0}{\sqrt{Var(d_0)}}$:



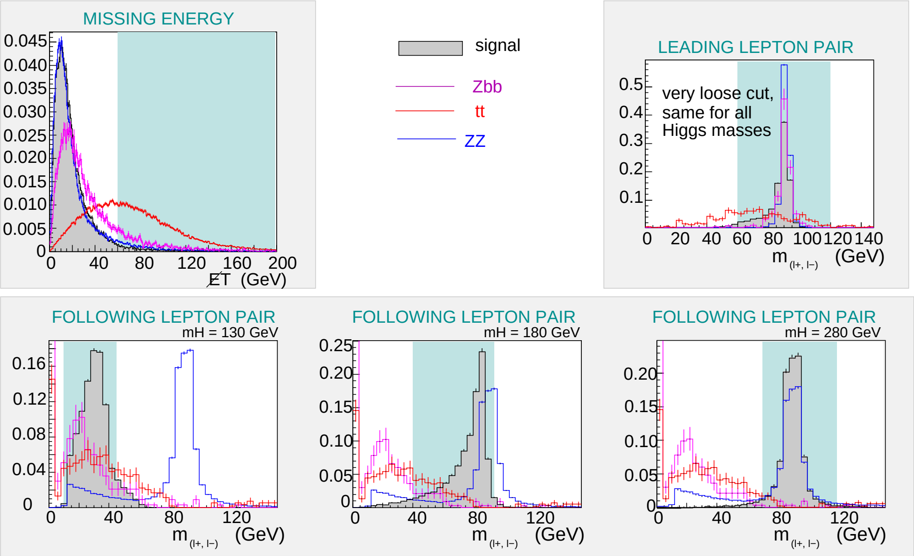




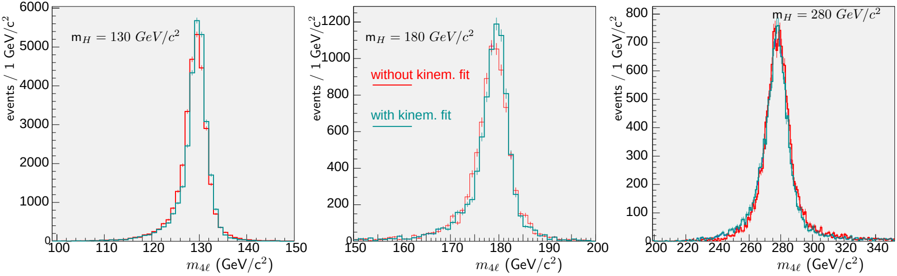
	signal efficiency	rejection factor
electrons: $a_0^{max} < 7$	0.90	2.0
muons: $a_0^{max} < 3.4$	0.95	4.5

Additional discriminating variables

- missing energy, number of b-jets,
  invariant mass of leading- and following lepton pairs



Higgs mass resolution



Channel	σ for m_H=130 (GeV/c²)	σ for m_H=180 (GeV/c²)	σ for m_H=280 (GeV/c²)
$H \to 4\mu$	1.94 (1.74)	2.82 (2.36)	7.79 (7.29)
$H \to 4e$	2.29 (2.26)	2.81 (2.53)	6.90 (6.68)
$H \to 2e2\mu$	2.18 (2.00)	2.79 (2.52)	7.11 (6.81)
$H \to 4\ell$	2.07 (1.85)	2.81 (2.45)	7.30 (6.81)
Δm (GeV/c²)	5.6	7.3	20.4

- In brackets: numbers after the kinematic fit of the Z-mass.
- Mass window for the signal significance: $\Delta m = \pm 3\sigma$

Signal significance at 30 fb^{-1}

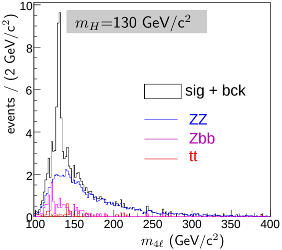
	m_H =130 GeV/c^2	m_H =180 GeV/c^2	m_H =280 GeV/c^2
N_{signal}	19.7±0.1	23.4±0.3	53.0±0.1
N_{ZZ}	12.0±0.3	31.8±0.5	35.2±0.6
$N_{Zb\bar{b}}$	4±2	1±1	0±2
$N_{t\bar{t}}$	0.7±0.4	0.5±0.4	0.4±0.4
Significance	4.0±0.3	3.5±0.2	7.3±0.4
TDR study	4.8	11.2	14.5

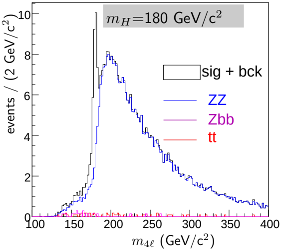
- after all cuts the irreducible ZZ background dominates
- big discrepancy with previous (TDR) studies for $m_H \geq$180 GeV/c^2: only ZZ^* background was taken into account, no ZZ contribution
- degradation of the electron reconstruction efficiency and resolution reflects itself on the signal significance:

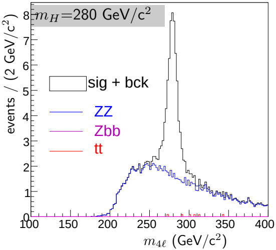
	$H \to 4e$	$H \to 4\mu$	$H \to 2e2\mu$	total
Significance m_H =130 GeV/c^2	1.5	1.9	2.6	4.0
Space left for the improvements of the reconstruction.				

Invariant mass distributions

- Distributions scaled down to the number of events at 30 fb^{-1}:

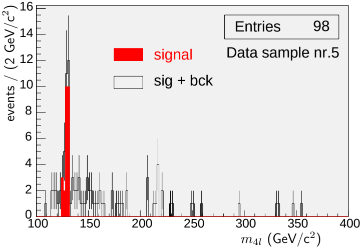






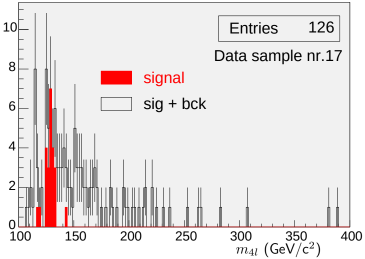
- actual data at 30 fb^{-1} will look more like this (for 130 GeV/c^2):

if we're lucky



(2 independent data subsets)

if we're not so lucky



Ensemble test with data subsets of 30 fb^{-1}

Extracting the signal from the fit to the invariant mass distribution:

- Testing the two hypotheses,

1.) "Background only" fit function:

$$f_b\,(x_b[3], m_k) = N_b \cdot \alpha^2 (m_k - \epsilon) e^{-\alpha(m_k - \epsilon)}$$

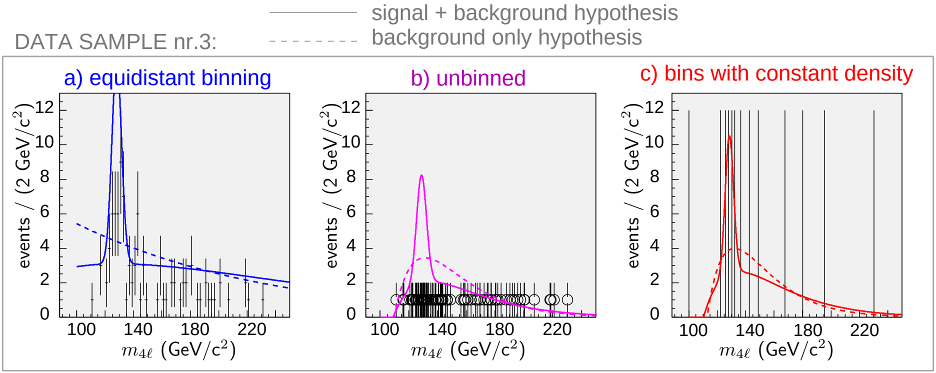
2.) "Signal+Background" fit function:

$$f_{sb}\,(x_{sb}[6], m_k) = \frac{N_s}{\sqrt{2\pi}\sigma} \cdot e^{-\frac{(m_k-\mu)^2}{2\sigma^2}} + N_b \cdot \alpha^2 (m_k - \epsilon) e^{-\alpha(m_k - \epsilon)}$$

- The goodness-of-the-fit determines the most probable hypothesis.
- Signal significance $= \frac{N_s}{Error(N_s)}$.

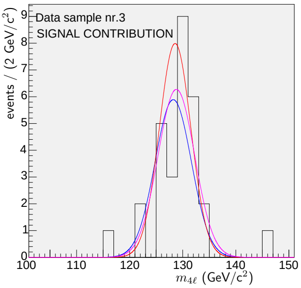
The stability of the fit has been tested on 60 independent data subsets, each with the statistics corresponding to 30 fb^{-1} (m_H=130 GeV/c^2).

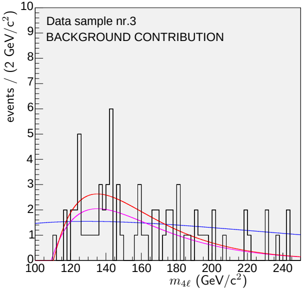
Ensemble test: minimization procedures



- a) k equidistant bins, $\chi^2 = \sum \frac{\left[N_k^{obs} - f(\mathbf{x}, m_k)\right]^2}{N_k^{obs}}$
  Unstable, not reliable for low statistics.
- b) unbinned maximum likelihood : $-\ln \mathcal{L} = -\sum \ln f(\mathbf{x}, m_k)$
  Stable, but difficult to extract the goodnes-of-the-fit.
- c) k bins of constant density, $\chi^2 = \sum \frac{\left[N_k^{obs} - f(\mathbf{x}, m_k)\right]^2}{N_k^{obs}}$
  Very stable, reliable goodnes-of-the-fit for the hypothesis test.

Ensemble test : fit results





Fit result	equidistant	unbinned	const. dens.	remark
$N_{good\ fits}$ (of 60)	45	54	54	
$\langle N_s - N_s^{true} \rangle$ (RMS)	-1 (6)	-3 (6)	2 (6)	N_s^{true}=23 (3)
$\langle N_b - N_b^{true} \rangle$ (RMS)	56 (33)	-6 (6)	3 (12)	N_b^{true}=86 (10)
$\langle \frac{\chi_b^2 - \chi_{sb}^2}{\chi^2_{sb}} \rangle$ (RMS)	0.7 (0.4)	0.2 (0.3)	1.6 (1.0)	hypotheses test
<Signf.> (RMS)	3.1 (1.1)	2.3 (0.6)	2.9 (0.6)	

- best results provided by the χ^2-minimization using the bins of constant density

Summary

We evaluate the ATLAS potential for an early Higgs discovery
in the $H \to ZZ^{(*)} \to 4\ell$ decay channel
by means of a detailed, up-to-date simulation of detector properties.

Large size of data samples allows for the cut optimizations
and for a precise evaluation of the signal significance:

- Degradation of the significance w.r.t the initial ATLAS studies, due to the changes in the detector layout and still-to-be-done improvements of the reconstruction algorithms.
- Signal significance obtained with full Monte-Carlo statistics confirmed by an ensemble test with data subsets corresponding to an integrated luminosity of 30 fb^{-1} (for m_H=130 GeV/c^2).