An improved selection optimization method used for the measurement of ZZ production under conditions of ATLAS experiment during LHC Run II.

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Introduction

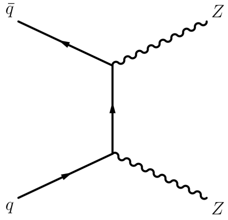
- At the LHC, a large number of particles are produced in p-p collisions.
- Precision measurements and rare process studies require a strict selection of events with intense background suppression.
- The selection of events in the LHC experiments, and in particular in the ATLAS experiment, can be divided into online and offline ones.
- There are various methods for optimizing event selection offline, and one of the simplest and most well-interpreted methods is an optimization using a rectangular cut.
- The work presents consistent and improved multivariate optimization methods and their comparison.

The signal and background

The final state of the $pp \to ZZ \to ll\nu\nu$ process consists of a pair of high-pT isolated leptons and significant missing transverse momentum (E_T^{miss}).

Initial selection:

- Two same flavour opposite-sign leptons (e+e- OR mu+mu-), leading lepton p_T>30 GeV, subleading lepton p_T>20 GeV
- Veto on any additional lepton
- $76 < M_{ll} < 106$ GeV



Main background sources:

- Z+jet
- WZ
- $t\bar{t}$

Monte Carlo event generator:

- MadGraph5_aMC@NLO

Showering and hadronization:

- Pythia8

Detector response simulation:

- Delphes3

Consistent optimization

The goals of optimization:

- search for variables sensitive to background suppression;
- calculation of the optimal threshold of the selected variables to suppress the background with the maximum possible signal retention.

Signal significance Z is a criterion for calculating the best signal-to-background ratio:

$$Z = \sqrt{2 \times [(S + B) \times \ln(1 + (S/B)) - S]}$$

The simplest optimization can be done by finding the threshold of the variable at which the maximum value of Z is reached.
Optimal values for each variable are searched one by one.

Variables for optimization

The variables are optimized in the following order:

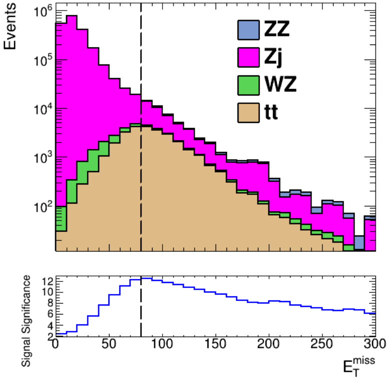
- E_T^{miss} — missing transverse momentum
- $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$ — the azimuthal angle difference between the E_T^{miss} and dilepton system
- ΔR_{ll} — the angular distance between the two leptons
- $E_T^{miss}/\sqrt{H_T}$
- E_T^{miss}/H_T
- N_{b-jets} — number of jets containing b-hadrons.

H_T is the scalar sum of transverse momenta of selected leptons and jets.

Consistent optimization. E_T^{miss} & $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$

Preselection:

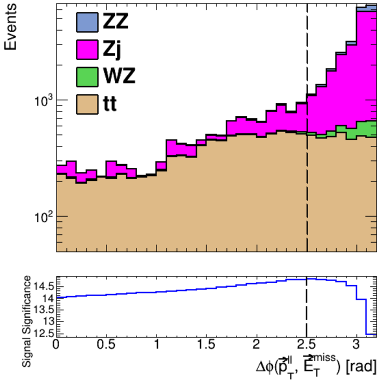
- Initial selection



Cut	E_T^{miss}>80 GeV
Signal signif.	2.45→12.5
Signal	3550→2790
Background	$2.09\cdot10^6$ →49126

Preselection:

- Initial selection + E_T^{miss}>80 GeV

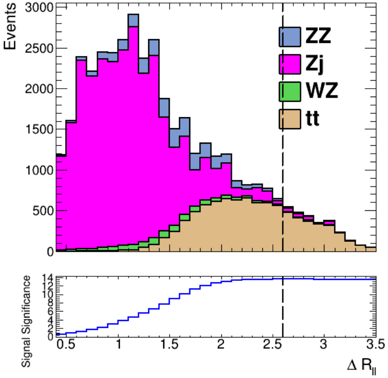


Cut	$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$>2.5
Signal signif.	12.5→13.5
Signal	2790→2636
Background	49136→37483

Consistent optimization. ΔR_{ll} & $E_T^{miss}/\sqrt{H_T}$

Preselection:

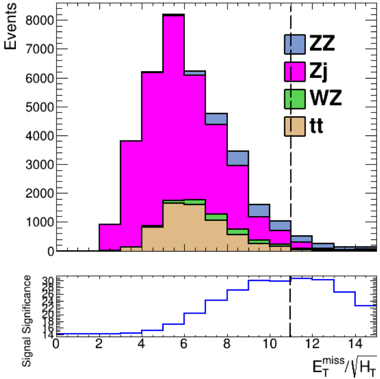
- Initial selection + E_T^{miss}>80 GeV + $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$>2.5



Cut	ΔR_{ll}<2.6
Signal signif.	13.5→13.6
Signal	2636→2560
Background	37483→34854

Preselection:

- Initial selection + E_T^{miss}>80 GeV + $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$>2.5 + ΔR_{ll}<2.6

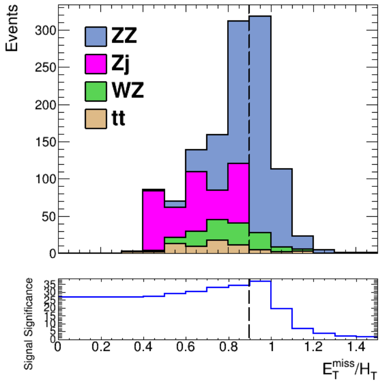


Cut	$E_T^{miss}/\sqrt{H_T}$>11
Signal signif.	13.6→27.1
Signal	2560→723
Background	34854→506

Consistent optimization. E_T^{miss}/H_T & N_{b-jets}

Preselection:

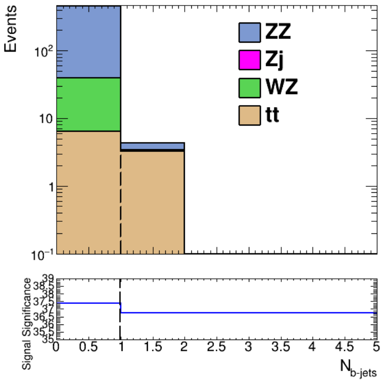
- Initial selection + E_T^{miss}>80 GeV + $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$>2.5 + ΔR_{ll}<2.6 + $E_T^{miss}/\sqrt{H_T}$>11



Cut	E_T^{miss}/H_T>0.9
Signal signif.	27.1→36.8
Signal	723→418
Background	506→43

Preselection:

- Initial selection + E_T^{miss}>80 GeV + $\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$>2.5 + ΔR_{ll}<2.6 + $E_T^{miss}/\sqrt{H_T}$>11 + E_T^{miss}/H_T>0.9



Cut	N_{b-jets}<1
Signal signif.	36.8→37.4
Signal	418→417
Background	43→40

Consistent optimization. Results.

During the optimization process, a significant suppression of the background was achieved, the signal significance increased by an order of magnitude.

Disadvantages of the consistent method:

- The result depends on the sequence in which the variables are optimized
- Result depends on correlations between variables
- Method doesn't cover the full range of possible solutions

Variable	Before	After
$E_T^{miss}/\sqrt{H_T}$, $\sqrt{\text{GeV}}$	—	>11
E_T^{miss}, GeV	—	>80
ΔR_{ll}	—	<2.6
$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$	—	>2.5
N_{b-jets}	—	<1
E_T^{miss}/H_T	—	>0.9

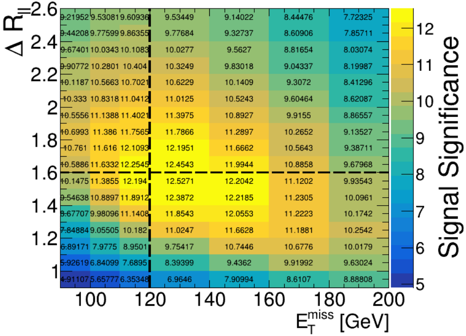
Signal signif.	2.45 ±0.12	37 ±2
S/B	$(1.697 \pm 0.011)\cdot 10^{-3}$	11 ±2
Signal		
ZZ	3550 ±16	417±5
Total signal	3550±16	417±5
Background		
Zj	$(2057\pm9)\cdot 10^3$	0±8
WZ	5859±35	33±2
tt	2880 ±215	6±3
Total bkg.	$(2092\pm9)\cdot 10^3$	40±9

An improved selection optimization method

- All described disadvantages can be avoided in a multivariate method (MV), considering the signal significance Z as a function of the thresholds on the variables.
- The MV optimization method finds the vector of thresholds on variables at which maximum Z is reached.
- MV method is implemented on the basis of the root package using the class of multidimensional histograms ThnSparse.
- This implementation makes it possible to check all possible combinations of selections, which guarantees a solution with the maximum Z.
- The MV method allows the application of additional conditions that satisfy the found solution.

An improved selection optimization method

- The signal significance is calculated for each bin of a multidimensional histogram containing signal and background events.
- Bining determines the accuracy and the phase space area in which the solution will be sought.
- The number of bins determines the time and memory consumption.



- MV method is difficult to visualize when the number of variables is greater than two. The figure illustrates the method in a two-dimensional case.

An improved selection optimization method. Results.

Initial selection:

- Two same flavour opposite-sign leptons (e+e- OR mu+mu-), leading lepton p_T>30 GeV, subleading lepton p_T>20 GeV
- Veto on any additional lepton
- $76 < M_{ll} < 106$ GeV

The method went through all the variations of the cuts for the ZZ process and found the best threshold vector.

Variable	Before	After
$E_T^{miss}/\sqrt{H_T}$, $\sqrt{\text{GeV}}$	—	>6
E_T^{miss}, GeV	—	—
ΔR_{ll}	—	<2.2
$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$	—	>2.4
N_{b-jets}	—	<1
E_T^{miss}/H_T	—	>0.7

Signal signif.	2.45 ±0.12	45 ±3
S/B	$(1.697 \pm 0.011)\cdot 10^{-3}$	1.7 ±0.3
Signal		
ZZ	3550 ±16	1732±11
Total signal	3550±16	1732±11
Background		
Zj	$(2057\pm9)\cdot10^3$	640±160
WZ	5859±35	326±8
tt	2880 ±215	48±9
Total bkg.	$(2092\pm9)\cdot10^3$	1014±160

Consistent and multivariate methods. Comparison.

Variable	Before	Consistent	Multivariate
$E_T^{miss}/\sqrt{H_T}, \sqrt{\text{GeV}}$	—	>11	>6
E_T^{miss}, GeV	—	>80	—
ΔR_{ll}	—	<2.6	<2.2
$\Delta\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$	—	>2.5	>2.4
N_{b-jets}	—	<1	<1
E_T^{miss}/H_T	—	>0.9	>0.7
Signal signif.	2.45 ±0.12	37 ±2	45 ±3
S/B	$(1.697 \pm 0.011)\cdot 10^{-3}$	11 ±2	1.7 ±0.3
Total signal	3550±16	417±5	1732±11
Total bkg.	$(2092\pm 9)\cdot 10^3$	40±9	1014±160

- The consistent optimization method leads to larger background suppression and a higher S/B ratio.
- The MV method results in more relaxed selections to be found with a higher signal significance value and a larger number of signal events.
- Taking into account all the factors, the MV method can be considered the best, since the main goal of the study is to find the maximum signal significance.

Conclusion

- The improved multivariate optimization method compared to the consistent method results in a higher signal significance and a larger number of signal events.
- The MV method has been described by optimizing the $ZZ \to ll\nu\nu$ process, but it can be used to optimize event selection for many other high energy physics processes.
- The MV optimization method can also be used for pre-optimization before using machine learning algorithms.

Backup

The ATLAS detector and coordinate system

Main components of the detector:

- Inner-detector
  - Pixel
  - SCT
  - TRT
- Calorimeter system
  - ECal
  - HCal
- Muon spectrometer

Cylindrical coordinates:

- ϕ — the azimuthal angle around the beam pipe
- θ — the polar angle
- $\eta = -\ln\tan\frac{\theta}{2}$ — the pseudorapidity
- $p_T = |\vec{p}|\sin\theta$ — the transverse momentum
- $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ — the angular distance