Gravitational-wave detection using multivariate analysis

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What is MVA?

Multivariate analysis methods

What is MVA?

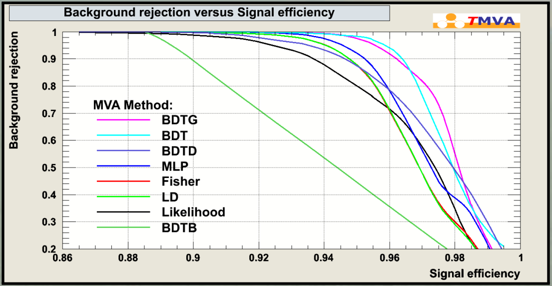
- Multivariate analysis is supervised machine learning.
- Used to separate weak signals from background events.
- Suppresses information from large N dimensional event space to a 1 dimensional real number.
- This “significance” is a measure of the likelihood of an event being a signal.

- Integrated into the analysis framework ROOT.
- Developed at CERN for high-energy physics.
- "*In high-energy physics, with the search for ever smaller signals in ever larger data sets, it has become essential to extract a maximum of the available information from the data.*"
- Large variety of multivariate classification algorithms.
- TMVA - Users Guide

Multivariate analysis methods

Available classifiers in TMVA

- Boosted decision trees (BDTs),
- Neural networks (NNs),
- Projective likelihood estimator,
- and many more.
- Initial tests showed BDTs exhibited the best performance in the shortest processing time.

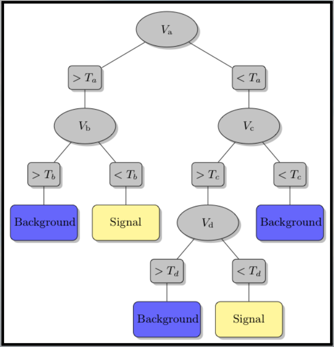


What is a BDT?

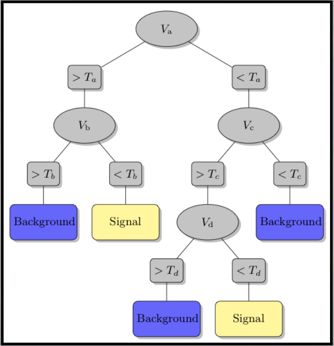
Event classifier

What is a BDT?

- Decision trees consist of a series of binary decision nodes.
- Each node applies a threshold to a single variable, selected to best discriminate signal from background.
- This split results in two branches, each containing a subset of the events.



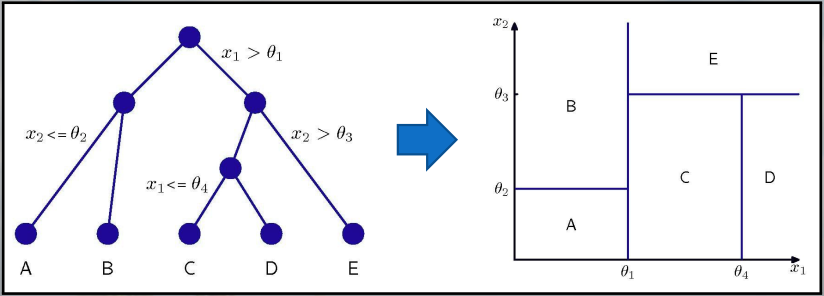
- The process then repeats, with a new split criterion being determined at each node to further separate signal from background.
- The splitting process ends once a minimum number of events has been reached within a node, which then becomes a leaf node.
- Leaf nodes are labelled as either signal or background depending on the class of the majority of events that fall within it.



Event classifier

Toy model

- Decision trees partition event space into rectangles ("leaves").



Event classifier

How we use BDTs

- We have known signal (injection) and background events.
- These events are split randomly into two sets, one for training the classifier and the other for testing its performance.
- This split ensures that the testing produces an unbiased estimate of the classifier performance.
- The training events are passed through the BDT to set up the tree structure.

Event classifier

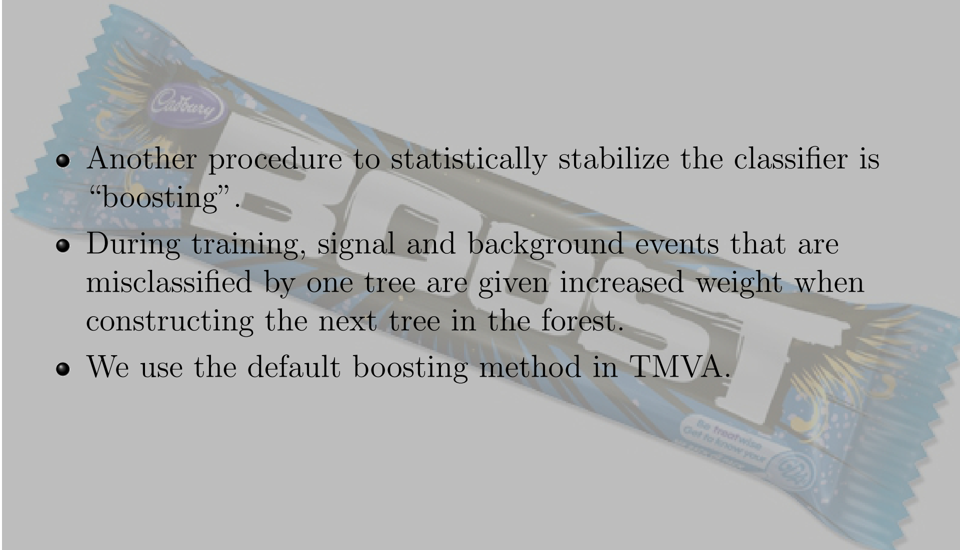
How we use BDTs

- The testing events are then passed through the trained BDT and each testing event is assigned a MVA significance value.
- Events with high values of significance are more likely to be signals.
- Events with small values of significance are more likely to be background.

Event classifier

We need more wood

- Individual decision trees are susceptible to statistical fluctuations within the set of training events used to derive the tree structure.
- To avoid over training, a “forest” of decision trees are used, each generated using a random subset of the training events.
- The final classification of events is determined by a majority vote from the classifications of each individual tree within the forest.



- Another procedure to statistically stabilize the classifier is "boosting".
- During training, signal and background events that are misclassified by one tree are given increased weight when constructing the next tree in the forest.
- We use the default boosting method in TMVA.

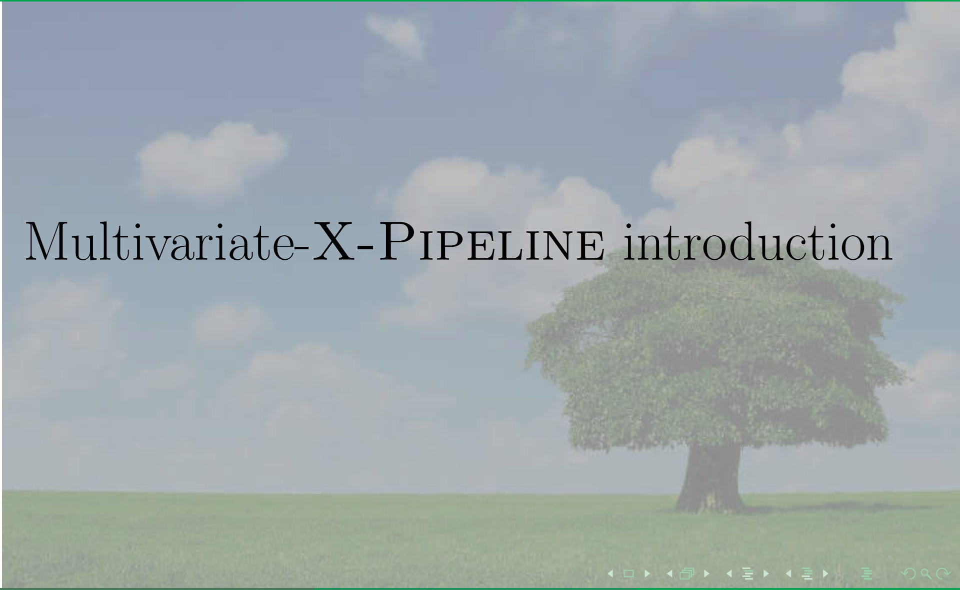
Externally triggered burst searches

- Externally triggered coherent analysis for gravitational wave bursts.
- Identification of weak signals in background detector noise.
- Current noise rejection tests are based on the analysis of a relatively small number of measured properties of the candidate signal, typically correlations between detectors.

Tests

Status of current analyses

- The sensitivity of such searches is often critically limited by non-Gaussian noise fluctuations that are difficult to distinguish from real signals.
- Posing a key problem for transient gravitational-wave astronomy.
- We have integrated MVA classifiers into X-Pipeline to address this problem.



Multivariate-X-Pipeline introduction

- MVA techniques probe the full space of measured properties of events in an attempt to maximize the power to accurately classify events as signal or background.
- The benefit of using MVA techniques to obtain better discrimination between signal and background events has been shown in high-energy physics.
- Here we apply this to the similar problem we have for a gravitational wave burst search.

Tests

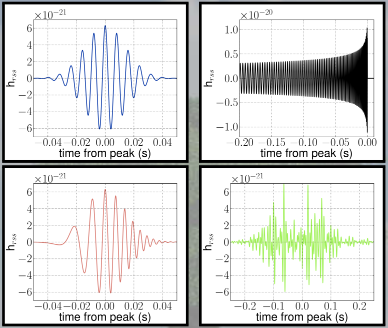
BDT details

- From tuning the classifier parameters an improvement of $\approx 10\%$ was possible.
- For simplicity we use the default BDT parameters.
- Signal events are software injections.
- Background events are off source noise events.

Tests

Signal waveforms

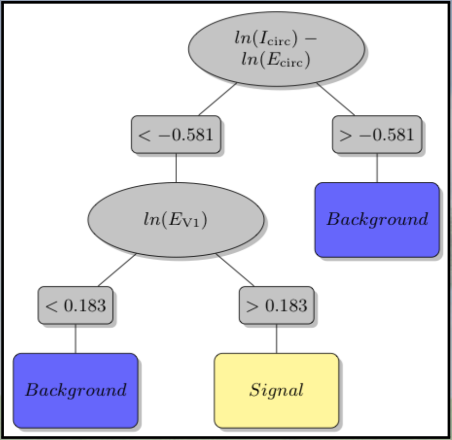
- Circular sine-Gaussian.
- BNS inspiral.
- Chirplet.
- White noise burst.
- Waveform parameters are "jittered" to stop over training.



- 15 event properties.
- Variety of energy measures.
- Combinations of these which are equivalent to X-Pipeline cuts.
- Time-frequency information (duration, bandwidth, and pixel number).

Tests

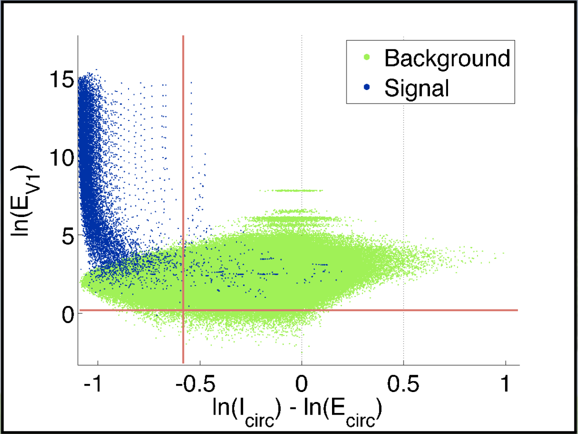
Real decision tree



- First cut on coherent/ incoherent combination (X-Pipeline like).
- Second cut on single detector energy.

Tests

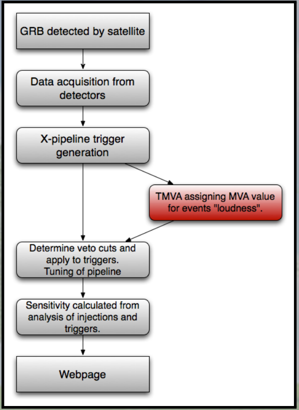
Oooh, look at that



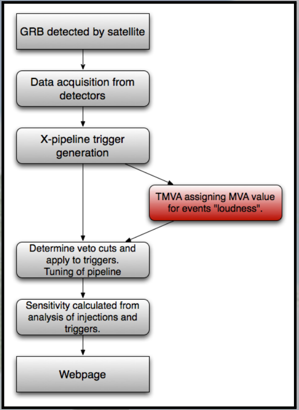
Tests

Analysis flow diagram

- Standard X-PIPELINE analysis is performed on data for a (simulated) GRB trigger (grey only).
- The BDT classifier is then applied to the events recorded by X-PIPELINE to re-evaluate the significance of each event (include red).

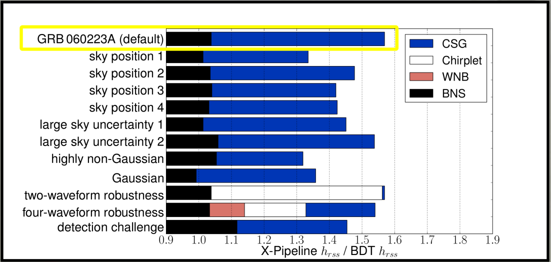


- Analysis sensitivity is characterized by the minimum injection amplitude at which $\geq 50\%$ of simulated signals survive analysis cuts and have significance greater $N\%$ of the background.
- Default is greater than 99% of background, giving a FAP $p \leq 0.01$.
- The relative performance is measured as the ratio of the standard X-Pipeline and BDT results.



Multivariate-X-Pipeline results

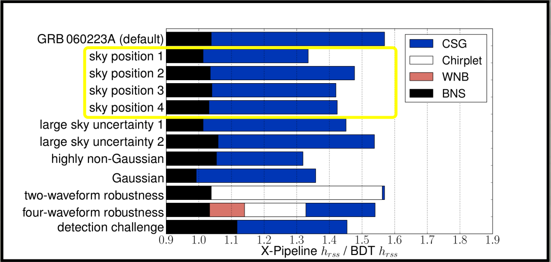
- Baseline analysis using parameters of GRB 060223 (time, sky position).
- Using the same parameters and process as S6 VSR2-3 GRB analysis.
- Training and testing using CSG and BNS waveforms.



Results

Sky position tests

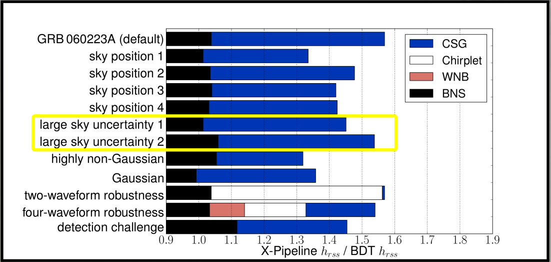
- To verify that the results of the MVA–X-Pipeline comparison are robust, we repeat analysis for a range of difference sky positions.
- Sky positions were chosen to cover a range of different relative detector network sensitivities.



Results

Large position uncertainty

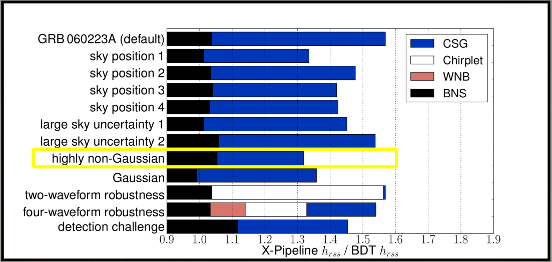
- GRBs detected by the GBM instrument on the Fermi satellite have relatively large sky location uncertainty, $\sim 10^\circ$.
- We test the performance of the MVA analysis in this scenario using two different sky positions with sky position uncertainties of $\approx 9^\circ$.



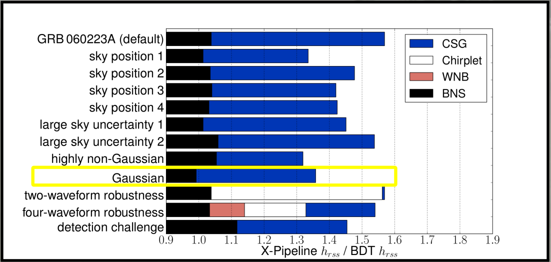
Results

Highly non-Gaussian background

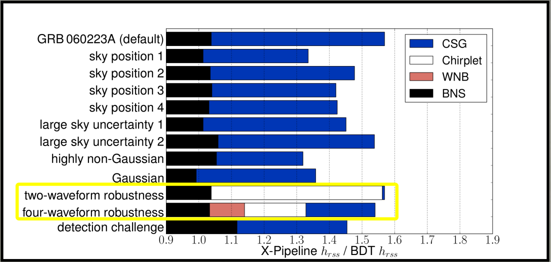
- Noise events can be introduced to the detector by a wide range on known and unknown sources.
- These "glitches" are artefacts of the detectors and can be difficult to distinguish from real weak signals.
- To test the performance of the MVA analysis, we analyse a trigger that is at a time of unusually poor data quality.



- Best-case scenario test.
- Performance of the MVA analysis was tested using simulated Gaussian noise with a spectral density coloured to match that of the real detector noise at the time of GRB 060223A.



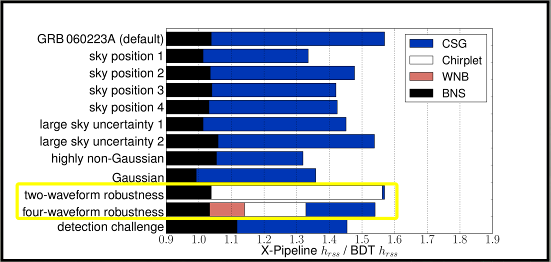
- Important to verify that MVA is able to detect waveforms with morphologies that differ from those used for training.
- two waveform test - Training with CSG and BNS waveforms, testing with CSG, BNS, chirplet, and WNB waveforms.
- four waveform test - Training and testing with CSG, BNS, chirplet, and WNB waveforms.



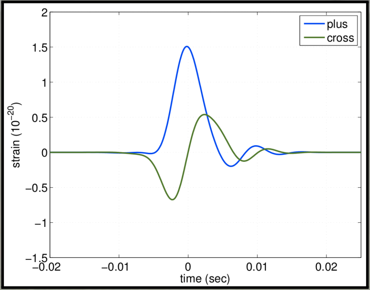
Results

Waveform robustness

- two waveform test - WNB not detectable by X-Pipeline due to uncorrelated polarzations for WNB.
- MVA can detect these signals, albeit with sensitivity half of in four waveform test.
- four waveform test - Reduction in CSG/ chriplet performance due to inclusion of WNB in training, classifier must find compromise.



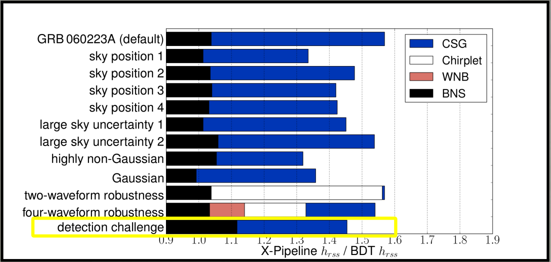
- Demonstrate that the improvement in sensitivity extends to false-alarm rates low enough to permit a detection claim at the 3σ level.
- "Equinox event" hardware injection (22 September 2007).
- 3σ significance requires a false-alarm probability of $p \lesssim 0.0027$.



Results

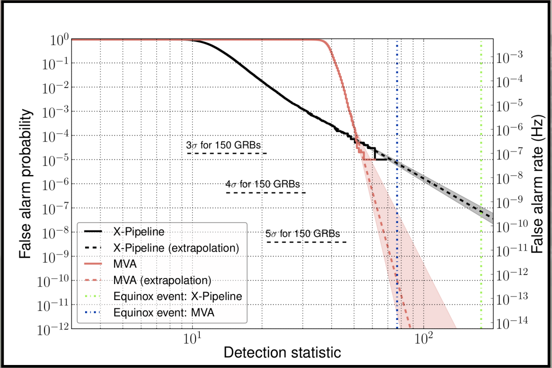
Detection challenge

- Typically analyse 100-150 GRB triggers.
- A 3σ significance with 150 trials requires $p \lesssim 2 \times 10^{-5}$ for an individual event.
- We generate extra background samples and tune the background rejection tests to yield the lowest minimum injection amplitude at a FAP of $p = 10^{-5}$.



Results

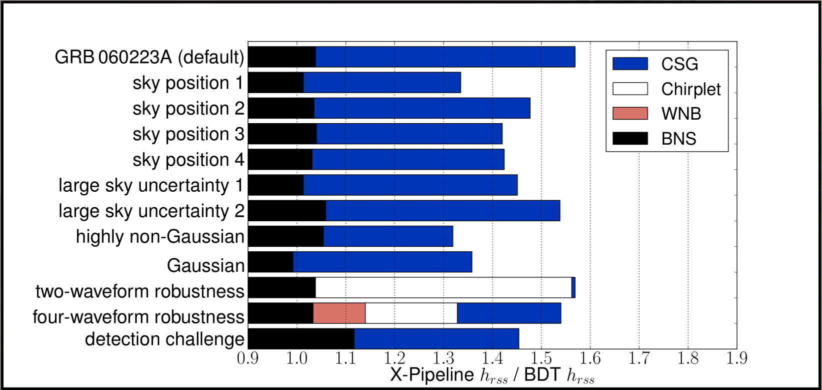
Cumulative background distribution



- Approximate FAP for equinox event, $p = 7 \times 10^{-8} (5.4\sigma)$ for standard X-PIPELINE and $p = 1 \times 10^{-10} (6.5\sigma)$ MVA.
- MVA results consistent with X-PIPELINE results, and could be much better.

Results

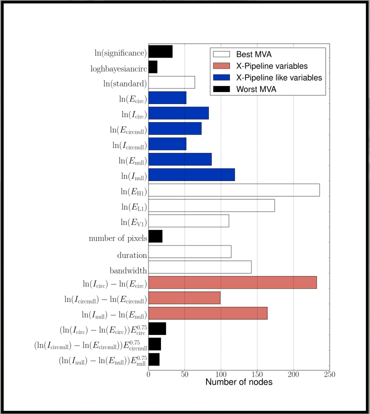
Results summary



Results

Variable node usage

- All nodes in default analysis forest.
- This gives a measure of how useful a variable is for descriminating between signal and background events.



Summary
and I'm done

- Shown that MVA offers consistent improvement in sensitivity to some signal types.
- Improvement holds regardless of sky position, sky location uncertainty, data quality, and network of detectors.
- Importantly, MVA is always at least as sensitive as the standard X-Pipeline analysis.
- Benefits of the MVA analysis extend down to false alarm rates sufficient for 3σ detections in GRB triggered searches.
- The results presented here indicate that MVA techniques may be valuable for improving the sensitivity of searches for unmodelled gravitational-wave bursts.