Simulation-assisted decorrelation for resonant anomaly detection

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Anomaly detection basics

- The Standard Model (SM) is known to be incomplete
  - No particles Beyond the Standard Model (BSM) have yet been found
  - **There remains a vast space of models with no dedicated search**
- Machine learning opens doors for model-independent anomaly detection
- Many techniques have recently been developed, e.g.
  - CWoLa [1, 2], SALAD [3], ANODE [4]

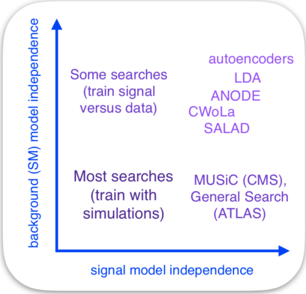


Figure: Snapshot of the current landscape of anomaly detection methods. From [4]

The problem

- Sensitivity of new ML methods rivals or exceeds traditional anomaly searches
- Beginning to see application in data
  - ATLAS analysis using CWoLa was first ML-based anomaly hunt [5]
- Prototypical use case: searches for resonant new physics

Problem (for resonant anomaly detection)

Correlations between training and resonant features are challenging for certain ML anomaly detection methods

- More false positives
- Decreased sensitivity

We need new techniques to mitigate this behavior

Example: CWoLa

- Train supervised classifier to distinguish between two groups of mixed (unlabeled) background/signal
- **Classifier effectively learns to distinguish between signal and background**
- For bump hunt, groups determined by course binning in invariant dijet mass
- Use ‘signal’-tagging to emphasize significance of signal

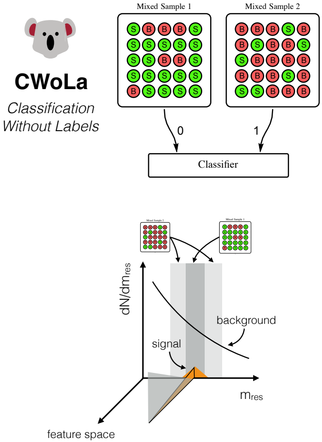


Figure: CWoLa schematic: see e.g. [6]

Example: CWoLa

- Using the 2020 LHC Olympics dataset for prototyping
- Simulation of an LHC-like detector
  - Delphes 3.4.1, CMS detector card
- Signal is $W' \to XY$ with $m_{W'} = 3.5\,\text{TeV}$, $m_X = 500\,\text{GeV}$, and $m_Y = 100\,\text{GeV}$
  - Dijet event
- **Jet masses artificially correlated to M_{JJ} by taking** $m_j \mapsto m_j + 0.1 M_{JJ}$
- Classifier trained between 'signal region' (SR) and 'sideband' (SB)

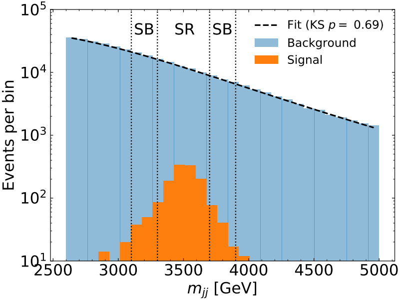


Figure: Background (blue) and signal (orange) of our dataset

Example: CWoLa

- CWoLa classifier trained on several jet features
  - Jet mass, N-subjettiness ratio τ_{21}
- **Classifier able to infer M_{JJ} from correlations**
- SR and SB come from different regions in M_{JJ} $\Longrightarrow$ classifier tags full SR as 'signal'-like
  - Note: ATLAS result in [5] trained only on jet masses and performed explicit decorrelation to avoid this problem
- Result: severe distribution sculpting

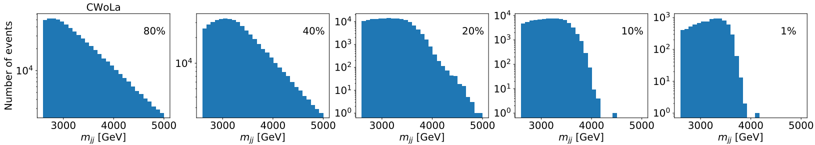


Figure: Sculpting of the M_{JJ} distribution by a CWoLa classifier

Strategy

- Techniques exist to modify data (e.g. forced distribution rescaling) to mitigate the problem
  - Can be finicky in practice
  - Might cause sensitivity reduction by removing information

Goal

It would be nice to have false positive mitigation built into the anomaly detection method itself

Two potential solutions:

1. Eliminate M_{JJ} differences by comparing SR to itself
   - SALAD
2. Penalize the classifier for learning M_{JJ}
   - SA-CWoLa

SALAD

- **Idea**: eliminate SR/SB differences by only looking at SR [3]
- Introduce a simulated dataset (Herwig++)
- Reweight simulation to look like data in sidebands using NN
- Extend reweighting to signal region in simulation
- Train classifier to distinguish simulation signal region and data signal region

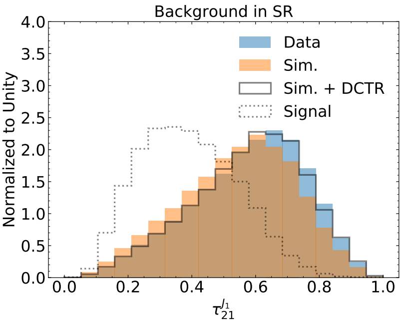


Figure: τ_{21} of the leading jet in data, simulation, signal, and reweighted simulation ('Sim. + DCTR')

SA-CWoLa

- Modification to CWoLa
- **Idea**: penalize classifier for distinguishing SR and SB in a simulated dataset
  - Use normal 'binary cross-entropy' loss function in data and negative binary cross-entropy in simulation
- Loss function minimized by picking out signal, and only signal

$$\mathcal{L}_{\text{SA-CWola}}[f] = \overbrace{-\sum_{i\in\text{SR,data}} \log(f(x_i)) - \sum_{i\in\text{SB,data}} \log(1-f(x_i))}^{\text{normal CWoLa}} \\ \underbrace{+\lambda\left(\sum_{i\in\text{SR,sim.}} \log(f(x_i)) + \sum_{i\in\text{SB,sim.}} \log(1-f(x_i))\right)}_{\text{penalty term}}$$

SA-CWoLa limits M_{JJ} sculpting

- Classifier trained on jet masses and N-subjettiness ratio τ_{21} of leading two jets
- SA-CWola exhibits much less bump sculpting than CWoLa

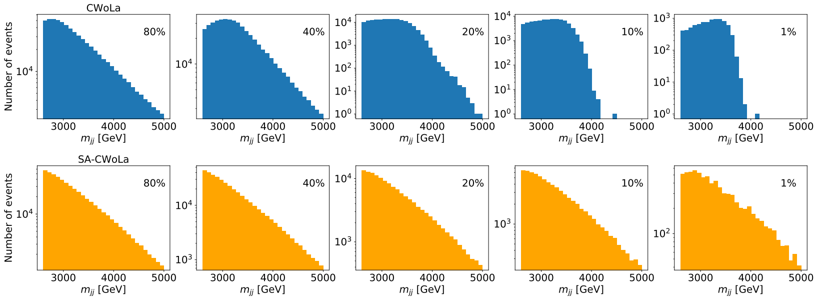
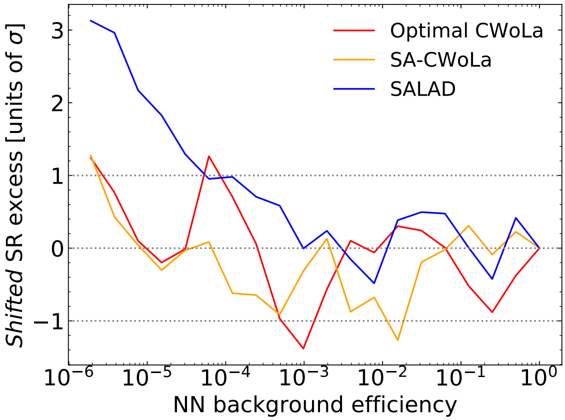


Figure: Sculpting of the M_{JJ} distribution by CWoLa classifier (top) and SA-CWoLa (bottom)

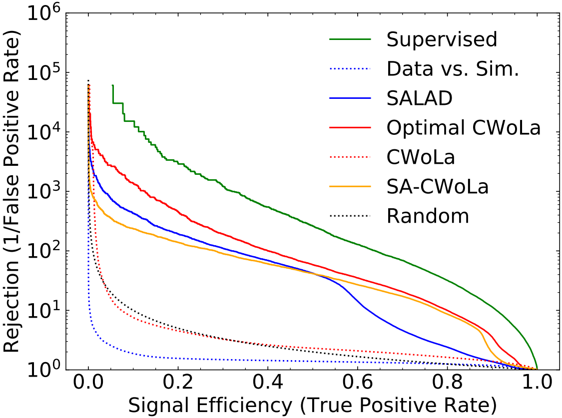
False positive results

- No signal injected, shifted to correct for natural SR deficit
- 'Optimal CWoLa' is CWoLa trained on SR vs SR + signal (instead of SB vs SR + signal)



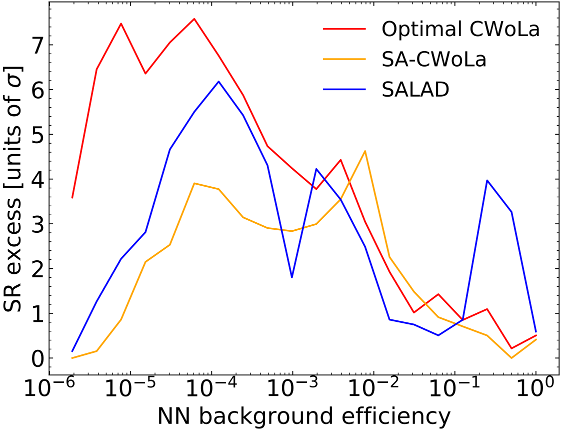
Signal sensitivity results: pure performance

- 2σ signal injected



Signal sensitivity results: with background estimation

- 2σ signal injected



Conclusion

- ML techniques for anomaly detection need to play nice with correlations in data
- Incorporating decorrelation into a ML algorithm itself is desirable
  - More natural, less unwieldy
  - Might be better for signal sensitivity
- SALAD and SA-CWoLa are promising techniques
  - Intrinsically robust to correlations

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References

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