Anomaly detection with CATHODE

Matthias Schlaffer, based on arXiv:2109.00546

in colllaboration with Anna Hallin, Joshua Isaacson,
Gregor Kasieczka, Claudius Krause, Benjamin Nachman,
Tobias Quadfasel, David Shih, and Manuel Sommerhalder

DESY Theory Workshop 2021

UNIVERSITÉ
DE GENÈVE

Need for (weakly supervised) anomaly detection

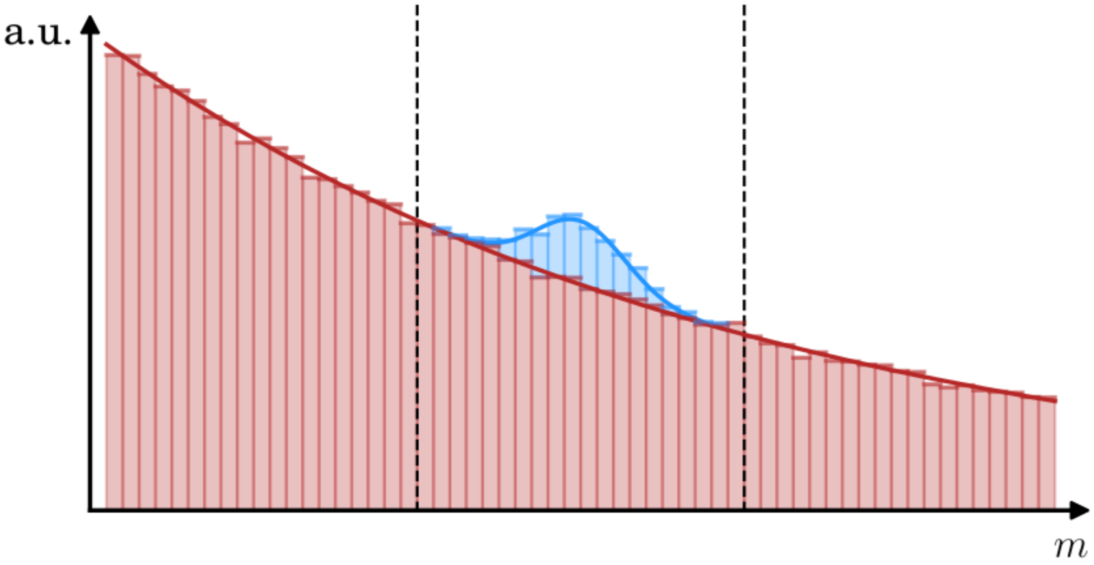
- No clear BSM signal at the LHC
- Is SUSY still “just around the corner” or rather something else?
- Most searches are not universal
- More models than searches

We need searches that are
✓ Sensitive
✓ Model agnostic

Disclaimer: here bump hunt strategies, for Autoencoders see next talk by Alessandro Morandini

Classic bump hunt

- Fit a bump over a smooth background
- Only few assumptions needed
  - Signal localized in one observable
  - (Almost) No Monte Carlo needed
- Sensitive to many models
- Higgs discovery
- Limited sensitivity



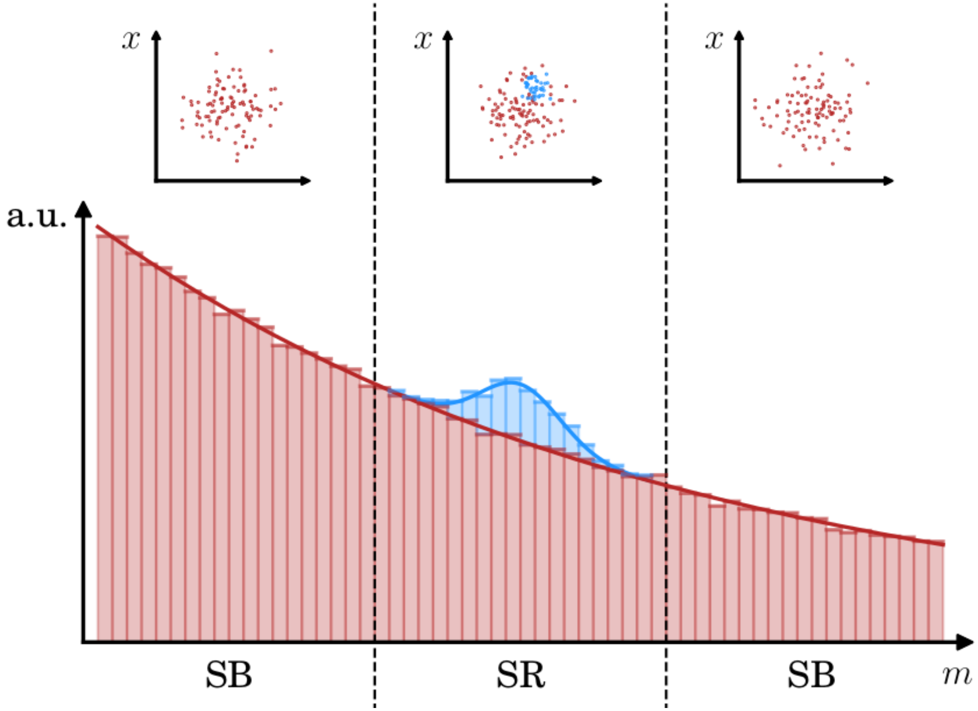
Improve by taking additional observables x into account

Classification Without Labels (CwoLa)

Collins, Howe, Nachman [1805.02664, 1902.02634]
Metodiev, Nachman, Thaler [1708.02949]

- Assume x and m are uncorrelated
- Sideband: $p(x|\mathrm{SB}) = p(x|\mathrm{bkg})$
- Signal region: $p(x|\mathrm{SR}) = f_{\mathrm{sig}}\, p(x|\mathrm{sig}) + f_{\mathrm{bkg}}\, p(x|\mathrm{bkg})$
- Train classifier on SR vs SB and learn

$$R(x) = \frac{p(x|\mathrm{SR})}{p(x|\mathrm{SB})}$$

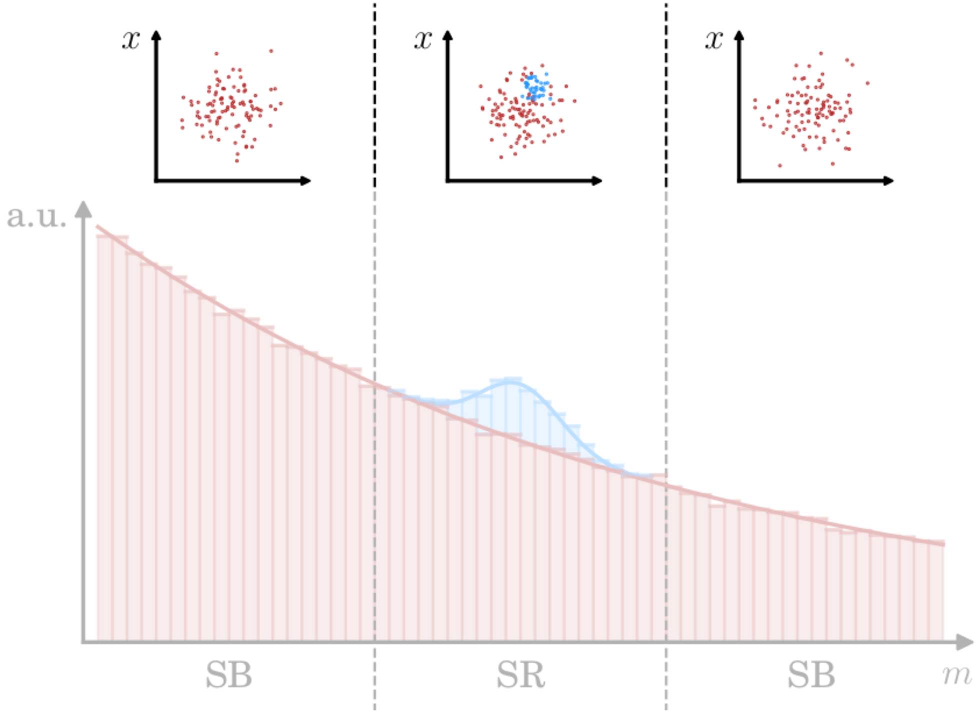


Classification Without Labels (CwoLa)

Collins, Howe, Nachman [1805.02664, 1902.02634]
Metodiev, Nachman, Thaler [1708.02949]

- Assume x and m are uncorrelated
- Sideband: $p(x|\mathrm{SB}) = p(x|\mathrm{bkg})$
- Signal region: $p(x|\mathrm{SR}) = f_{\mathrm{sig}}\, p(x|\mathrm{sig}) + f_{\mathrm{bkg}}\, p(x|\mathrm{bkg})$
- Train classifier on SR vs SB and learn

$$R(x) = \frac{p(x|\mathrm{SR})}{p(x|\mathrm{SB})}$$

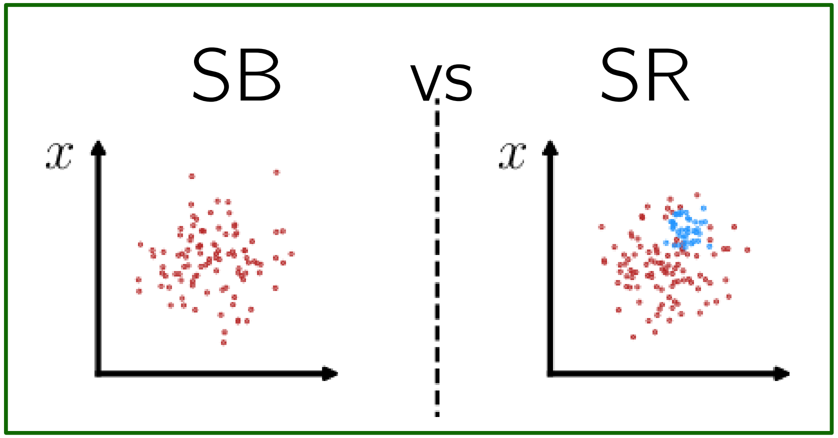


Classification Without Labels (CwoLa)

Collins, Howe, Nachman [1805.02664, 1902.02634]
Metodiev, Nachman, Thaler [1708.02949]

- Assume x and m are uncorrelated
- Sideband: $p(x|\mathrm{SB}) = p(x|\mathrm{bkg})$
- Signal region: $p(x|\mathrm{SR}) = f_{\mathrm{sig}}\, p(x|\mathrm{sig}) \quad + f_{\mathrm{bkg}}\, p(x|\mathrm{bkg})$
- Train classifier on SR vs SB and learn

$$R(x) = \frac{p(x|\mathrm{SR})}{p(x|\mathrm{SB})}$$



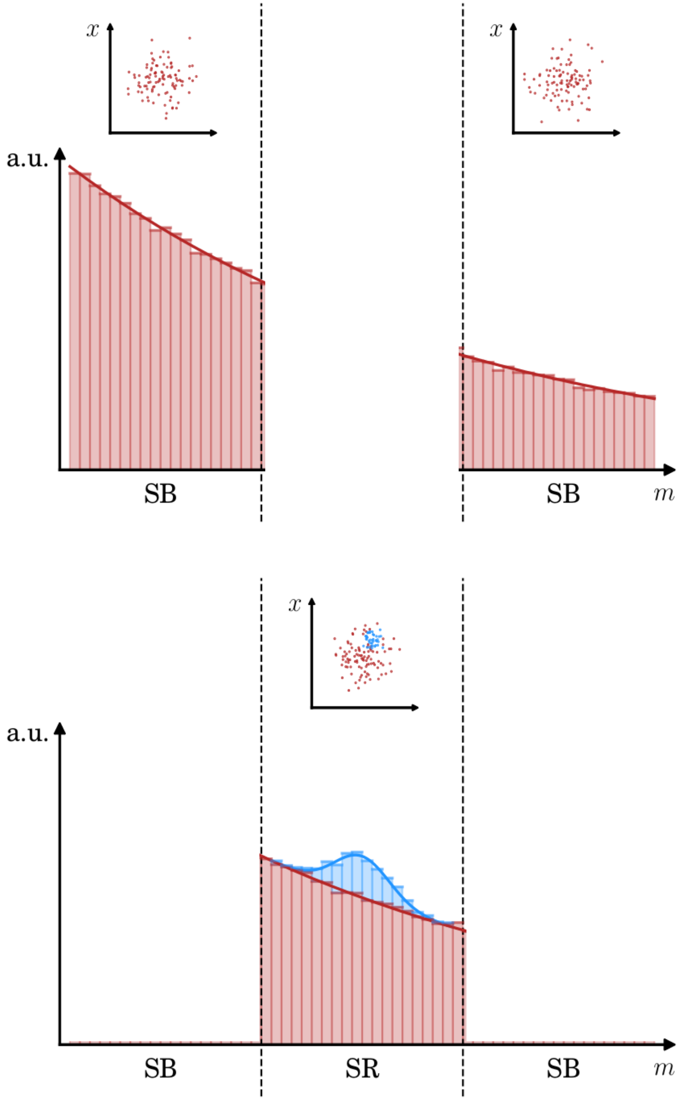
Breaks down with correlation

Anomaly Detection with Density Estimation (ANODE)

Nachman, Shih [2001.04990]

- Learn conditional probability distributions directly

$p_{\text{in}}(x|m \in \text{SR})$ and $p_{\text{out}}(x|m \in \text{SB})$

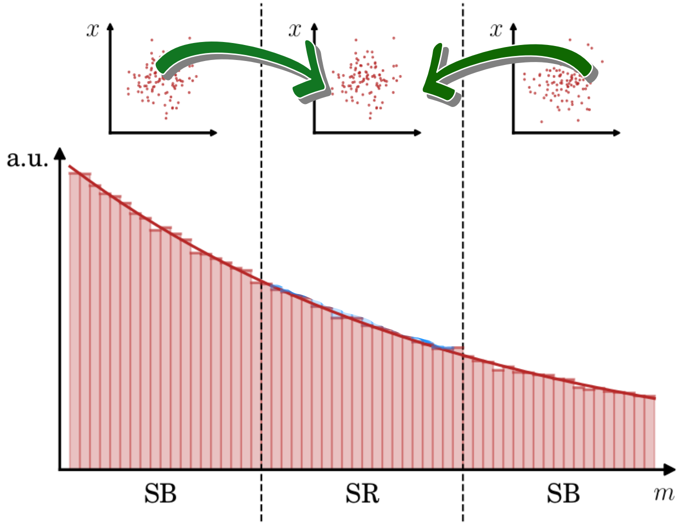


Anomaly Detection with Density Estimation (ANODE)

Nachman, Shih [2001.04990]

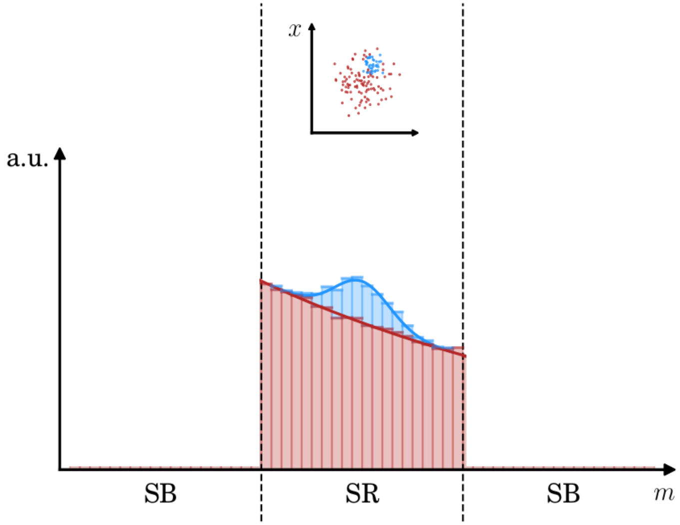
- Learn conditional probability distributions directly

  $p_{\text{in}}(x|m \in \text{SR})$ and $p_{\text{out}}(x|m \in \text{SB})$



- Interpolate p_{out} into SR and calculate

$$R(x|m \in \text{SR}) = \frac{p_{\text{in}}(x|m \in \text{SR})}{p_{\text{out}}(x|m \in \text{SR})}$$



Anomaly Detection with Density Estimation (ANODE)

Nachman, Shih [2001.04990]

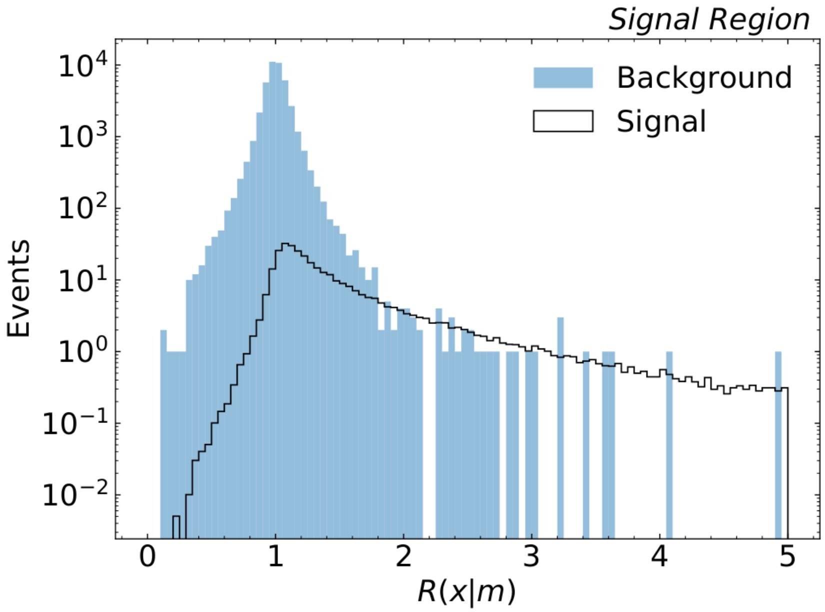
- Learn conditional probability distributions directly $p_{\mathrm{in}}(x|m \in \mathrm{SR})$ and $p_{\mathrm{out}}(x|m \in \mathrm{SB})$

- Interpolate p_{out} into SR and calculate

$$R(x|m \in \mathrm{SR}) = \frac{p_{\mathrm{in}}(x|m \in \mathrm{SR})}{p_{\mathrm{out}}(x|m \in \mathrm{SR})}$$

- Not much affected by mass-correlation

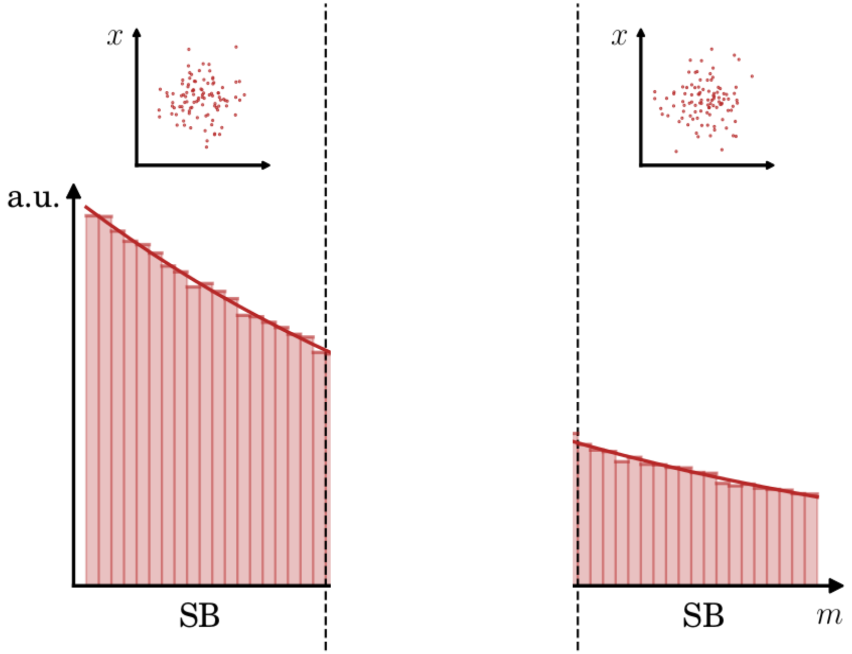
Densities are difficult to learn



CATHODE (Classifying Anomalies Through Outer Density Estimation)

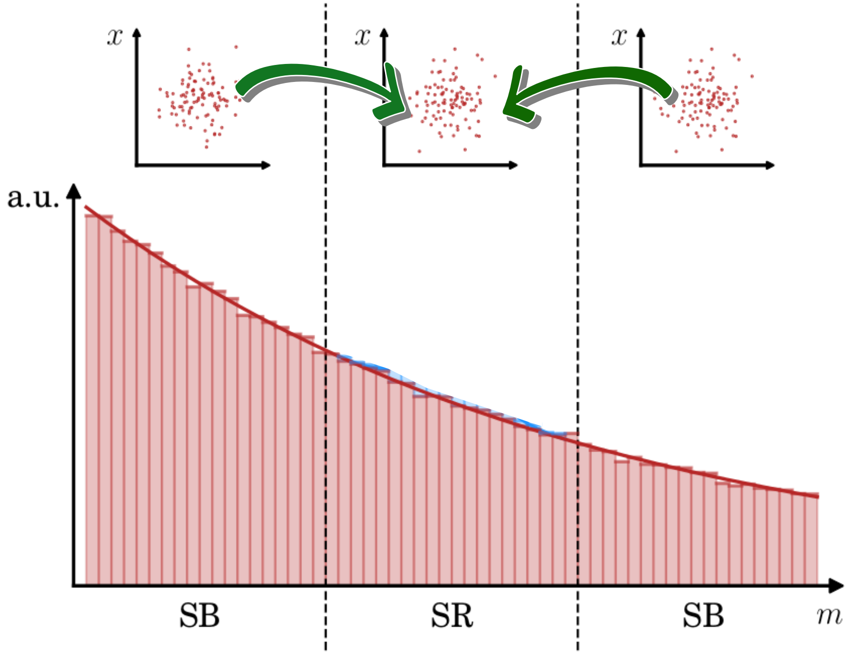
- Combine the best of CwoLa and ANODE

1) Learn $p_{\mathrm{out}}(x|m \in \mathrm{SB})$
2)
3)
4)



CATHODE (Classifying Anomalies Through Outer Density Estimation)

- Combine the best of CwoLa and ANODE
  1) Learn $p_{\text{out}}(x|m \in \text{SB})$
  2) Interpolate to $p_{\text{out}}(x|m \in \text{SR})$
  3) *Sample* from $p_{\text{out}}(x|m \in \text{SR})$
  4)

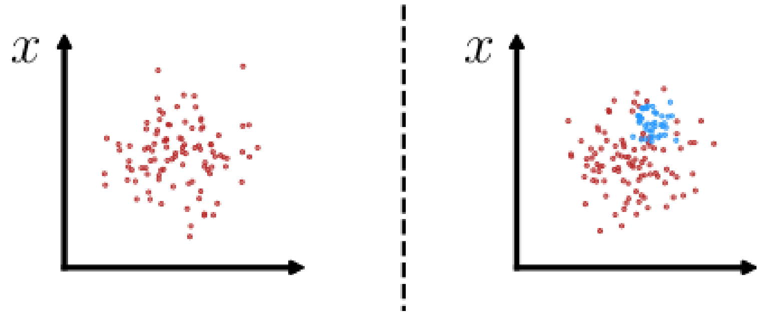


CATHODE (Classifying Anomalies Through Outer Density Estimation)

- Combine the best of CwoLa and ANODE

1) Learn $p_{\mathrm{out}}(x|m \in \mathrm{SB})$
2) Interpolate to $p_{\mathrm{out}}(x|m \in \mathrm{SR})$
3) *Sample* from $p_{\mathrm{out}}(x|m \in \mathrm{SR})$
4) Train classifier on samples vs data in SR

SR sampled vs SR data



✓ Robust against mass correlation
✓ Need to learn only one density

Dataset

- LHC Olympics R&D dataset
- Signal: $W' \to X(\to qq)Y(\to qq)$

  $$m_{W'} = 3.5\,\mathrm{TeV},\ m_X = 500\,\mathrm{GeV},\ m_Y = 100\,\mathrm{GeV}$$

- Background: QCD dijet
- Observables
  - Dijet mass: m_{JJ}
  - Masses and subjettiness ratios of the two jets:

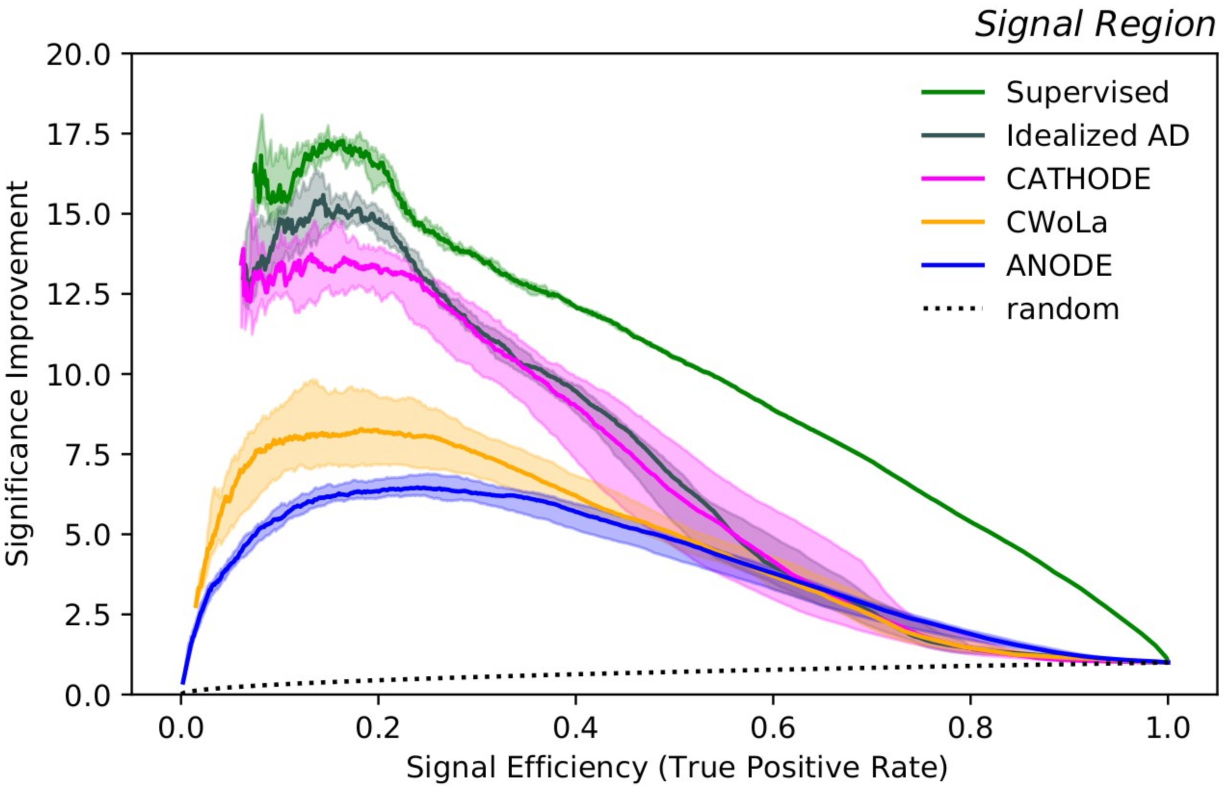
    $$m_{J_1},\ \Delta m_J = m_{J_2} - m_{J_1},\ \tau_{21}^{J_1},\ \tau_{21}^{J_2}$$

CATHODE Results

- Significance Improvement Characteristic: $\epsilon_s / \sqrt{\epsilon_b}$

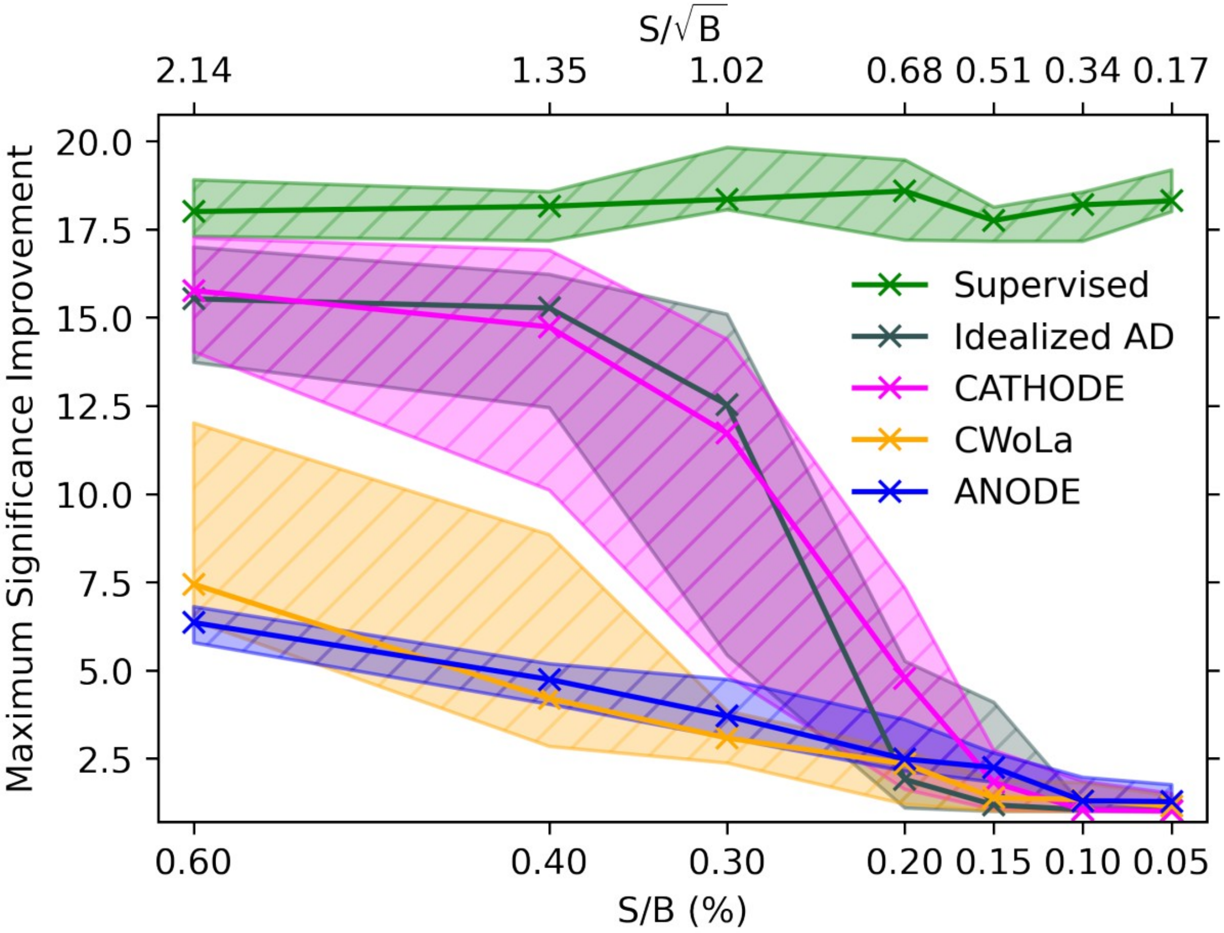
Main results

1) Max SIC of 14
2) Close to Idealized Anomaly Detector (assumes perfect background model)
3) Better than CwoLa and ANODE



CATHODE Results: low S/B

- Still good performance for low S/B
- Breakdown at S/B ≈ 0.2% for all methods



Conclusion

- CATHODE is a new bump hunt method
- Combines the best of CwoLa and ANODE
  - Robust against correlations
  - No need to learn density in SR
- Achieves maximal significance enhancement $\epsilon_s/\sqrt{\epsilon_b}$ of 14 on LHC Olympics R&D dataset
- Performance closely matches idealized Anomaly detector

Conclusion

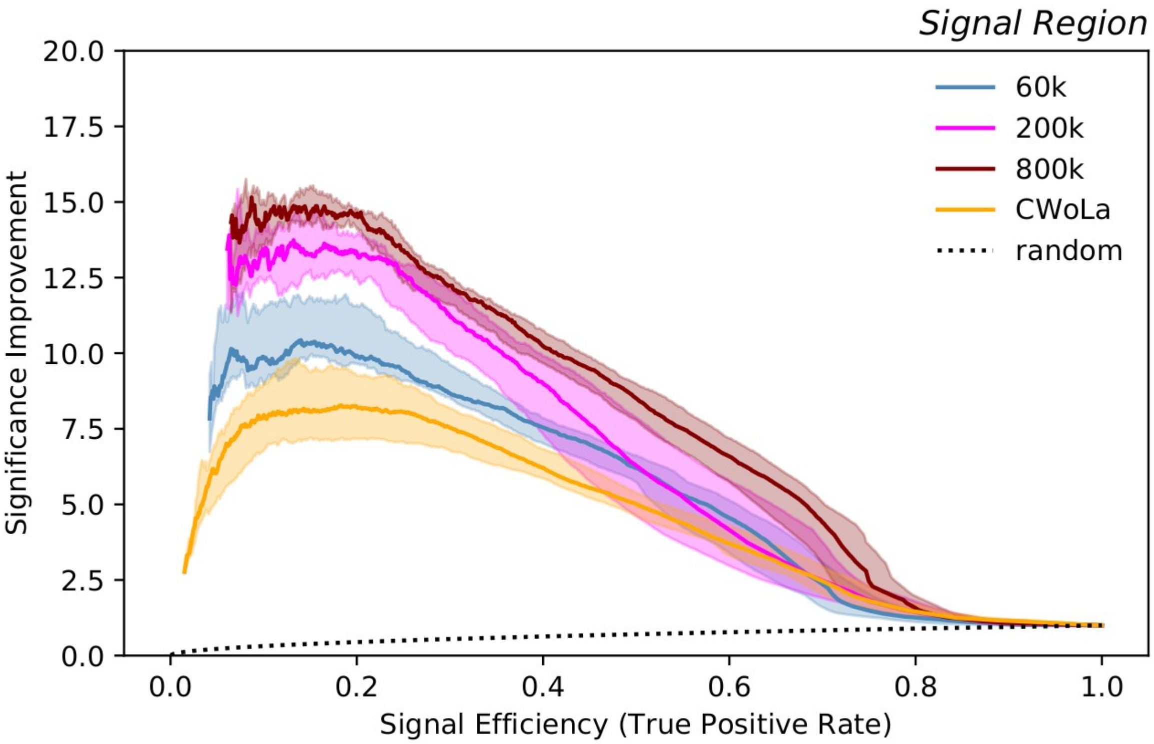
- CATHODE is a new bump hunt method
- Combines the best of CwoLa and ANODE
  - Robust against correlations
  - No need to learn density in SR
- Achieves maximal significance enhancement $\epsilon_s/\sqrt{\epsilon_b}$ of 14 on LHC Olympics R&D dataset
- Performance closely matches idealized Anomaly detector

Thank you!

BACKUP

Oversampling

- More data is better!
- CwoLa has about 60k bkg events for training
- CATHODE can oversample bkg events



Mass correlation

- Introduce artificial shift:
  $m_{J_1} \to m_{J_1} + 0.1\, m_{JJ}$
  $\Delta m \to \Delta m + 0.1\, m_{JJ}$
- As expected CwoLa breaks down
- CATHODE still performs very well