Weakly supervised methods for LHC analyses

Based on JHEP08(2022)015 TF, Michael Krämer, Maximilian Lipp and Alexander Mück

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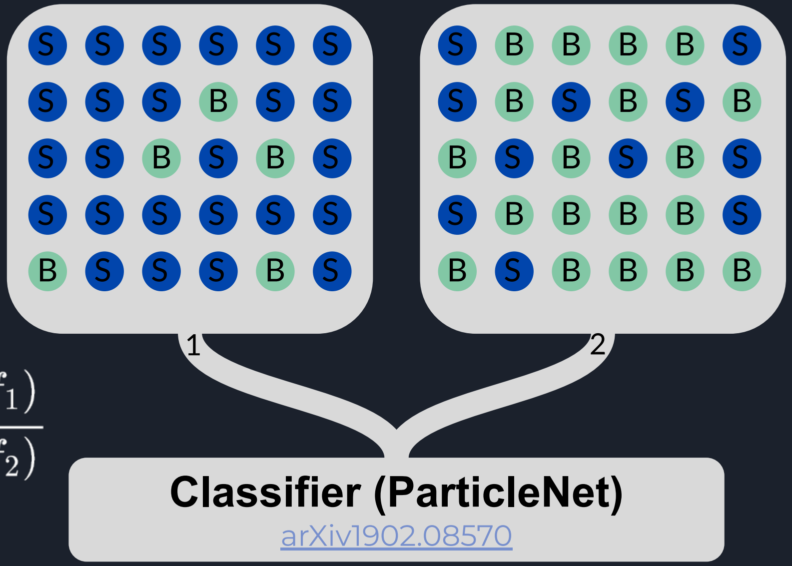
Classification without labels (CWoLa) arXiv1708.02949

- Two samples **M_1 and M_2** with signal fractions f_1 and f_2 **with $f_1 > f_2$**
- Optimal classifier for M_1 and M_2 also optimal for signal (S) and background (B)

$$L_{M_1/M_2} = \frac{p_{M_1}}{p_{M_2}} = \frac{f_1 p_S + (1-f_1)p_B}{f_2 p_S + (1-f_2)p_B} = \frac{f_1 L_{S/B} + (1-f_1)}{f_2 L_{S/B} + (1-f_2)}$$

$$\partial_{L_{S/B}} L_{M_1/M_2} = \frac{(f_1 - f_2)}{\left(f_2 L_{S/B} + 1 - f_2\right)^2} > 0$$



The ATLAS mono-jet search arXiv2102.10874

Selection cuts:

- **E_T^{miss} > 200 GeV**
- leading AK4 jet with p_T > 150 GeV and $|\eta| < 2.4$
- < 4 additional jets with p_T> 30 GeV and $|\eta| < 2.8$
- **$\Delta\phi(p_T^{jet}, E_T^{miss})$ > 0.4**
- lepton veto

SM backgrounds:

- **Z+jet** production with invisibly decaying Z (61 %)
- W+jet production with leptonically decaying W and non-identification of the charged lepton (31 %)
- Top quark production (3.5 %)
- Di-boson production (2 %)

Resulting in **$O(10^6)$ background events** and a model agnostic limit of 40k additional events at 95 % CL

What is our data?

- Simulation using Pythia and Delphes
- Low level inputs
  - 40 leading constituents of leading p_T fat jet (R=0.8)
  - 7 features per constituent
- Jet of Z+j indistinguishable for Z->ll (CR) and Z->$\nu\nu$ (SR) ⇒ same background simulation for *M1* and *M2*

SR

- Background of signal region
- Varying fraction f1 of semi-visible jets

CR

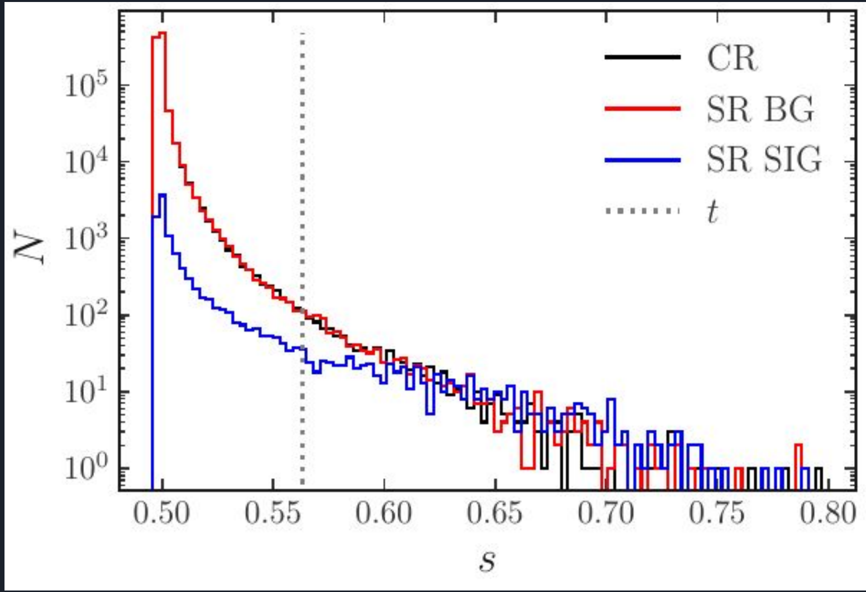
- Background of signal region
- No signal (f2=0)

1 2

Classifier (ParticleNet) arXiv1902.08570

Classifier output
(f_1 = 1 %; only Z+j background)

- Peak at ~0.5
  - Expected from indistinguishable background
- Background in signal and control region follow same distribution
- Choose a threshold based on control region
  - Set to keep 0.1 % (1000 events)
- Beyond threshold significant enhancement of S/B



Results using only main background (Z+jet)

- CWoLa does not introduce fake signal
- High sensitivity beyond current ATLAS limits (<40k events at 95 % CL)

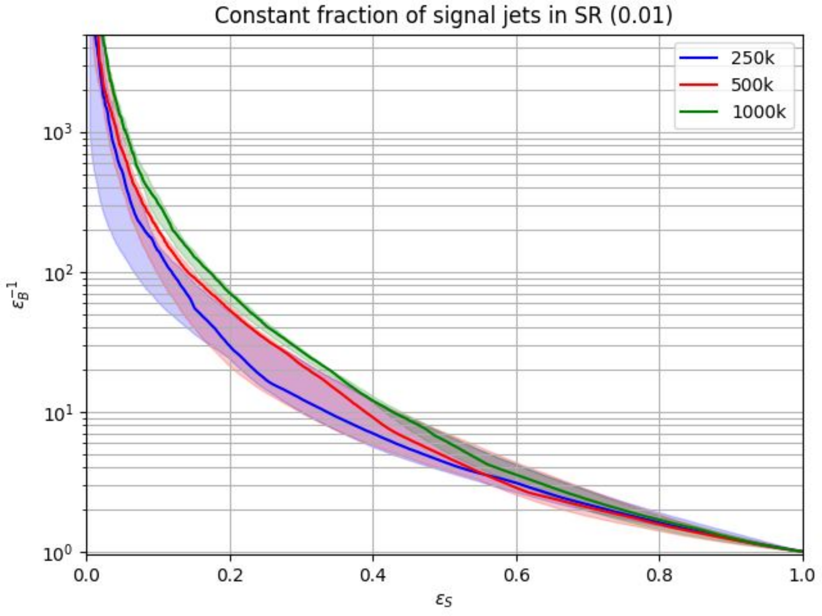
f_1	n^{SR}	n^{SIG}	stat. sign.
0 %	1048	0	1.07
0.6 %	1306	247	6.84
1 %	1666	625	14.89

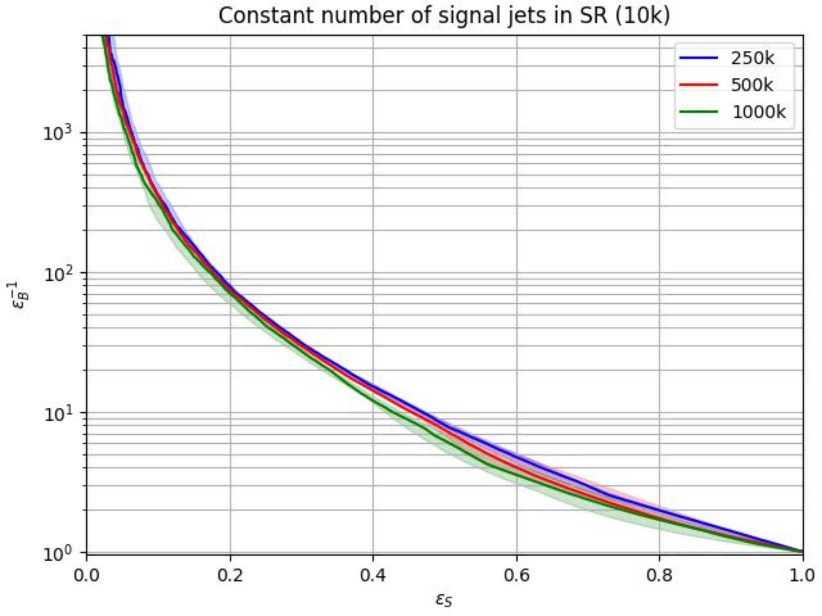
Results using also additional backgrounds

r_{tt}^{CR}	r_{VV}^{CR}	n^{SR}	n^{DM}
0 %	0 %	4383	223
2.8 %	1.6 %	1465	456
3.5 %	2.0 %	1686	633

- Added 3.5 % top and 2 % di-boson background to 1 % signal in signal region
- Ignoring additional backgrounds in control region leads to wrong signal
- Matching the background perfectly recovers the previous performance
- Not matching the background perfectly decreases performance, but does not spoil it completely ⇒ Control region does not need to be perfect

How does the method scale with region size and signal fraction?





- The total number of signal events sets the performance
  - Statistics needed in high dimensions for the signal to stand out of noise

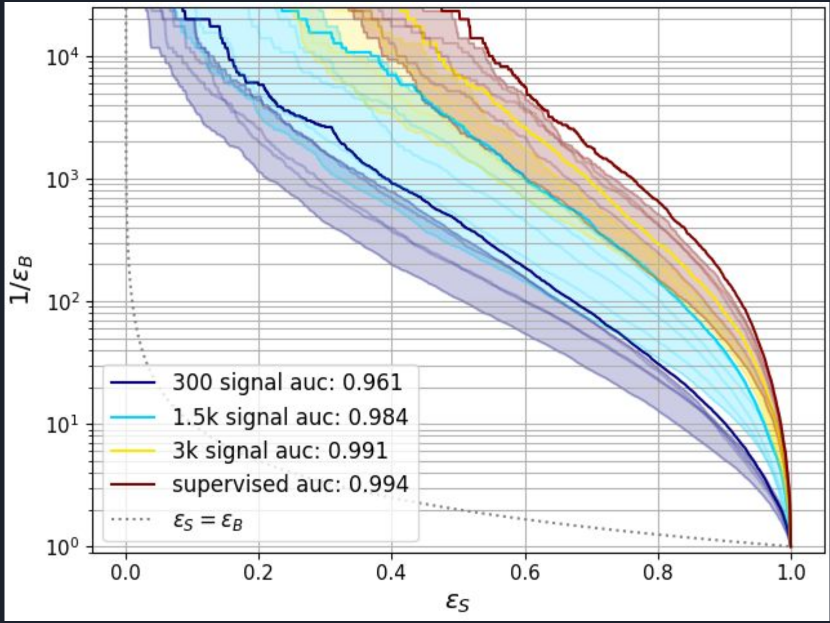
The LHCO R&D dataset[LHCO] and CATHODE[arXiv2109.00546]

- The LHCO dataset consists of high p_T di-jet events with a resonant signal
  - Modified classifier setup with two EdgeConv heads processing the leading two jets
- CATHODE gives an alternative way to define *M1* and *M2*
  - Use resonant feature (m_{jj}) to define SR and CR (SB)
  - Use conditional density estimation and sample background in SR by interpolation
- Idealized setup: perfect background samples in SR ⇔ our setup before

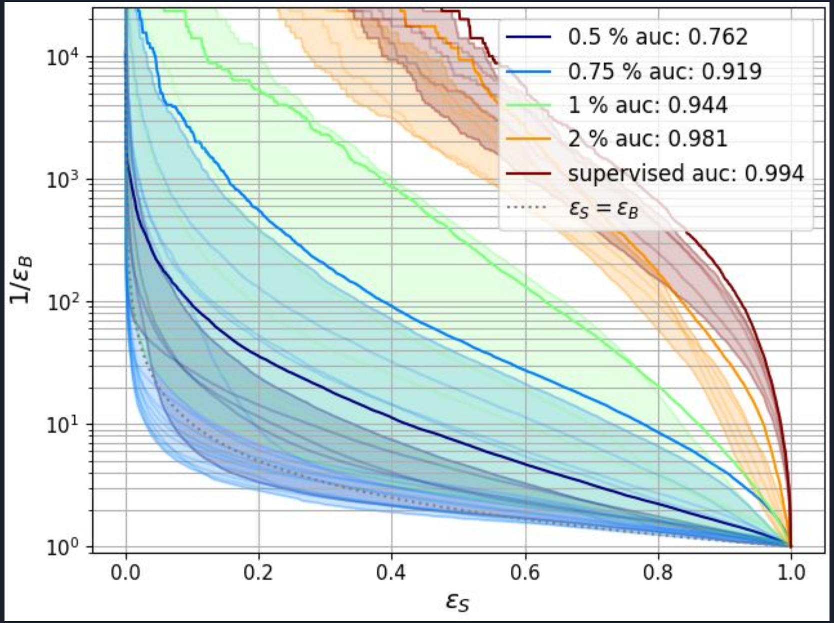
Work in progress

Imbalanced supervised vs. weakly supervised training

Supervised varying #signals

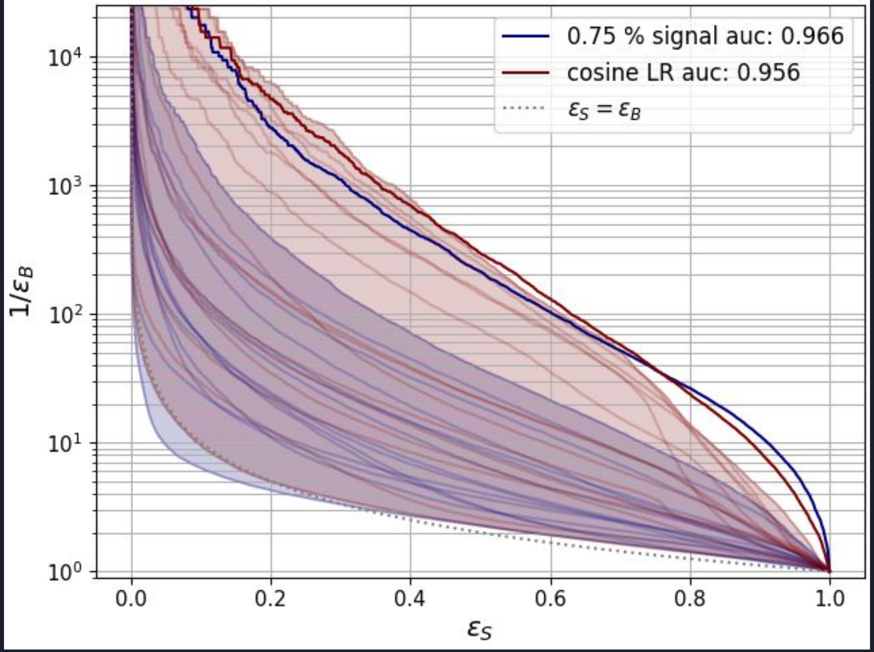


Weakly supervised varying f1



Ensembles for boosting performance

- The mean prediction of 15 classifiers outperforms individual classifiers significantly
- If a strong classifier exists, weak classifiers do not harm performance much
- Training can be optimized to need fewer networks



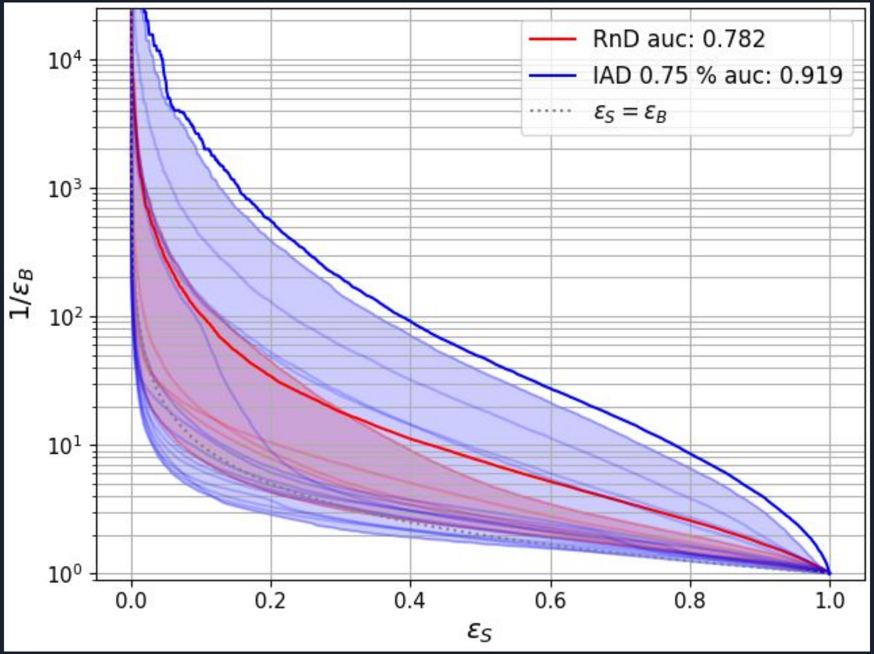
Conclusion

- The CWoLa method allows for enhanced sensitivity without using truth level information
- Sensitive to any difference in control and signal region
  - Can be used to check validity of the control region
- The method will benefit from more statistics as the total number of signal events is more crucial than the fraction
- Presented findings can be transferred to the idealized anomaly detection setup in CATHODE
  - Further studies within that framework are currently ongoing, especially the classifier training and improvements with ensembles
  - Adding symmetries to enhance training: LorentzNet or PELICAN?

Backup

CATHODE R&D setup

- R&D setup:
  - SR: 120k events, f1=0.64% (768 signal events)
  - CR: 300k events
- IAD 0.75:
  - SR: 300k events, f1=0.75 (2250 signal events)
  - CR: 300k events



Modified signal to stand out

- Modify signal such that $\mathbf{p}_7=\mathbf{p}_2+\mathbf{p}_5$
  - Leads to signal being outside of background distribution
- If this correlation is picked up, performance is better than supervised regular signal

⇒ Signal needs to be significantly different from background, either by number or by structure