Weakly supervised methods for LHC analyses

Thorben Finke (finke@physik.rwth-aachen.de)
RWTH Aachen University
Institute for Theoretical Particle Physics and Cosmology

What is the strength of weakly supervised methods?

No need for truth level labels

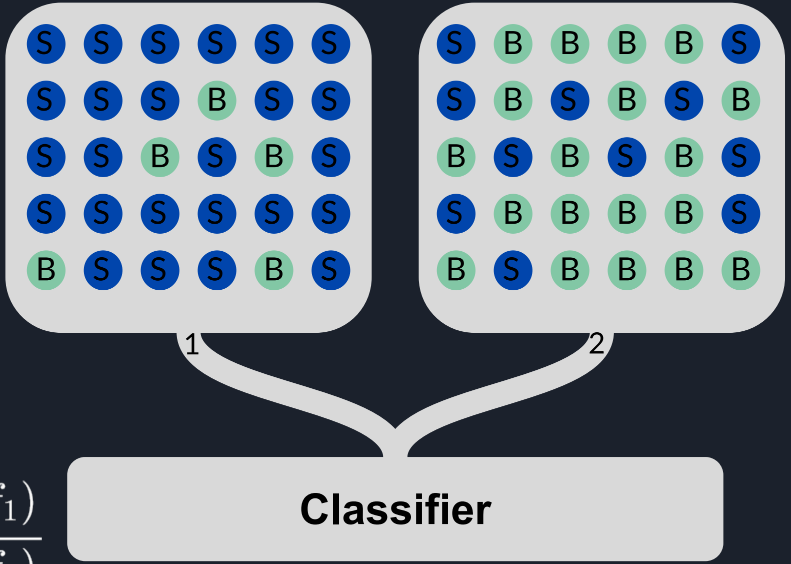
⇒ Can train directly on data
- Avoid systematic uncertainties arising when applying a NN trained on Monte Carlo to experimental data

⇒ Signal (and background) model independence

Classification without labels (CWoLa) arXiv1708.02949

- Two samples **M_1 and M_2** with signal fractions f_1 and f_2 **with $f_1 > f_2$**
- Same background and signal distributions in M_1 and M_2

⇒ Optimal classifier for M_1 and M_2 also optimal for signal (S) and background (B)

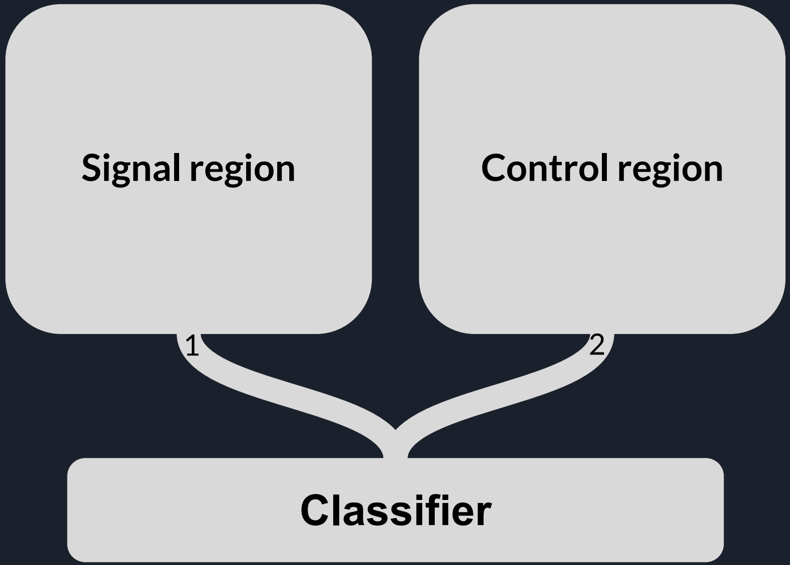


$$L_{M_1/M_2} = \frac{p_{M_1}}{p_{M_2}} = \frac{f_1 p_S + (1-f_1)p_B}{f_2 p_S + (1-f_2)p_B} = \frac{f_1 L_{S/B} + (1-f_1)}{f_2 L_{S/B} + (1-f_2)}$$

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

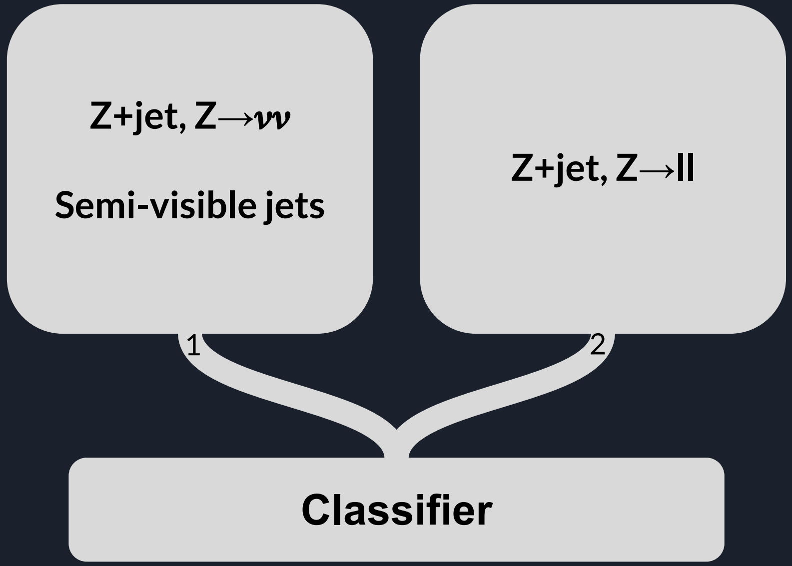
How to use this for a physics analysis?

- Use control and signal regions as M_1 and M_2
- Need to ensure same distribution of features (x) for background and signal in the two regions
- CWoLa gives sensitivity to differences in the two regions
- Use control region as proxy for the classifier behavior on background in the signal region



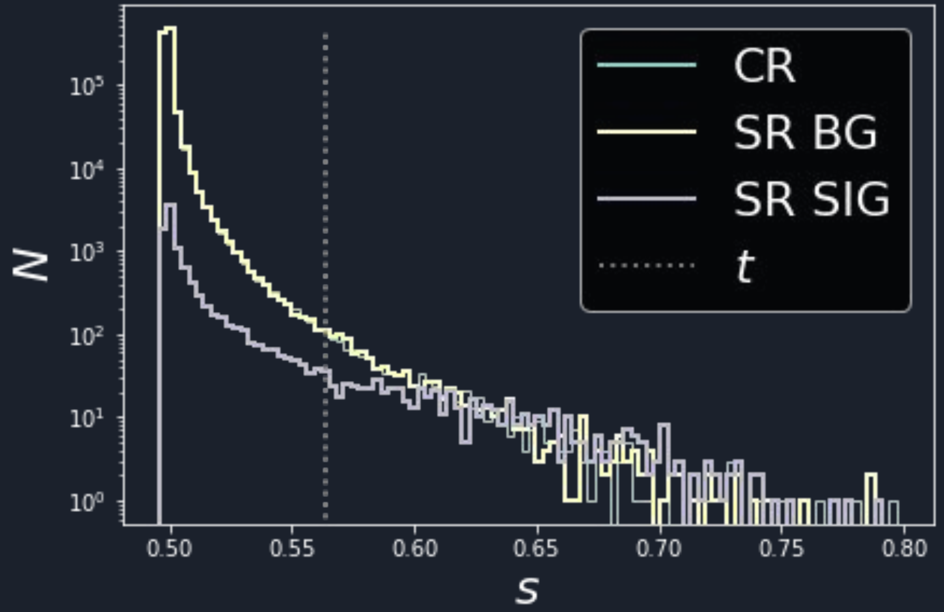
Example: mono-jet search for finding semi-visible jets arXiv2204.11889

- Signal region with energetic jet recoiling against missing energy
- Semi-visible jets from strongly interacting dark sector as example
  - One jet stays invisible
- O(10^6) background events
- Classify according to jet properties



Classifier output

- 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)

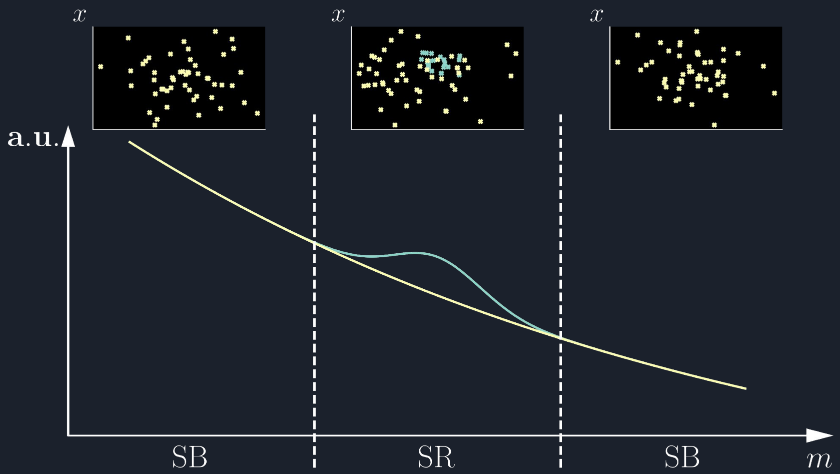
- CWoLa does not introduce fake signal
- High sensitivity beyond current ATLAS limits (<40k events at 95 % CL)

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

CWoLa for bump hunts

Use sidebands (SB) around resonance to estimate background estimation of auxiliar features x

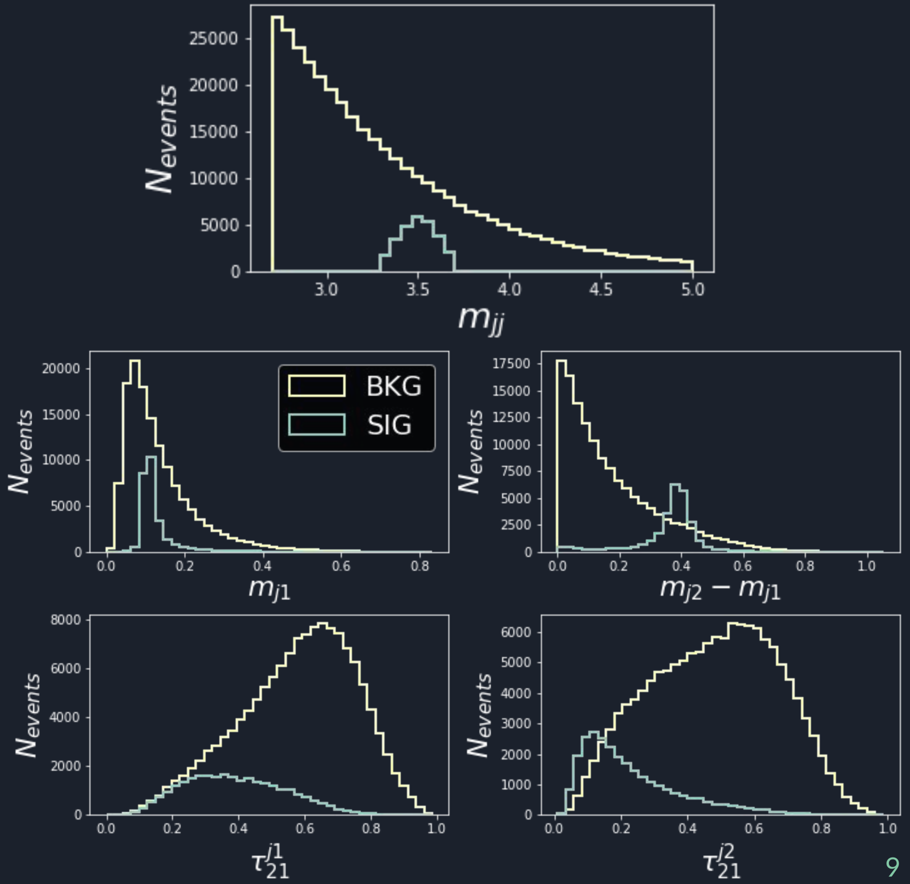
1. Use SB data as CR/M_1
   a. x must be uncorrelated with m
2. Interpolate background features from SB into the SR and use that estimate as CR, e.g. via conditional density estimation -> CATHODE



Recreated from arXiv2109.00546

Example LHCO2020 R&D data set

LHCO2020



Benchmark data set for anomaly detection

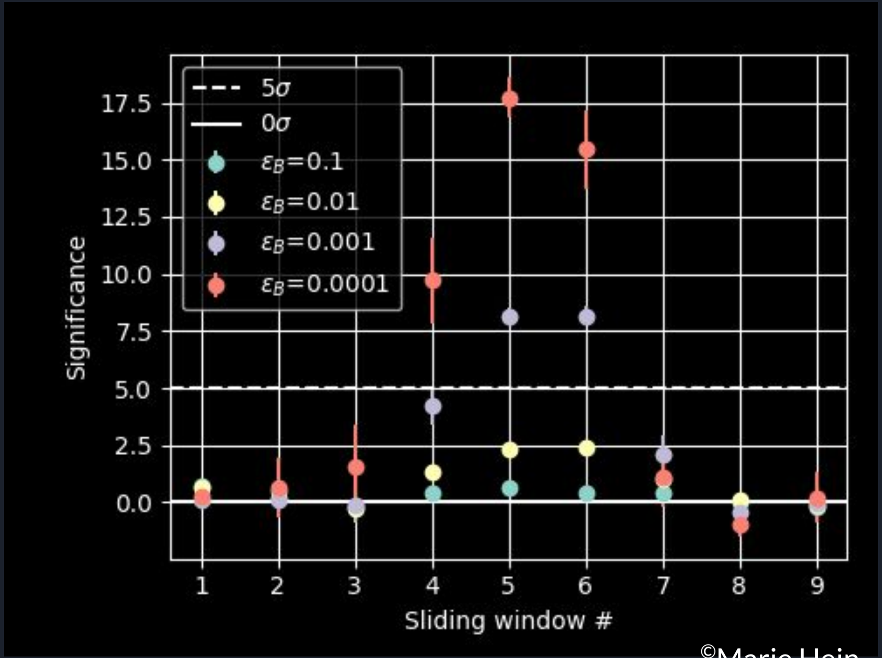
- W -> XY and X/Y -> qq
- m_W=3.5 TeV, m_X=0.5 TeV, m_Y=0.1 TeV
- m_{jj} as resonant feature
- Auxiliary features for the classifier
  m_{j1}, m_{j2} - m_{j1}, τ_{21}^{j1}, τ_{21}^{j2}

For unknown resonant mass:

divide into several regions and repeat

Results of a CATHODE like scan through m_{jj}

- Stronger cuts (smaller ε_B) yield higher significance
- Weaker cuts suffer from systematic uncertainty
- Starting from 2.2 σ, we reach a significance improvement of ~10



Conclusion

- Weakly supervised methods need no truth level labels
  - ⇒ Avoid systematics from differences in Monte Carlo and data
  - ⇒ Can be applied directly on data
  - ⇒ Are model agnostic and sensitive to a variety of signals
- CWoLa is sensitive to any difference in control and signal region
  - ⇒ Can be used to check validity of the control region
- Setting limits only possible for benchmarks, no model independent limits!

Backup

The ATLAS mono-jet search arXiv2102.10874

Selection cuts:

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

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

Results of scan through m_{jj} with SB as CR

- Larger systematic uncertainties reduce the sensitivity compared to CATHODE
- Hardly scratching 5 sigma in wrong window