Observation and measurement of Higgs boson decays to ZZ* with the ATLAS detector

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LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

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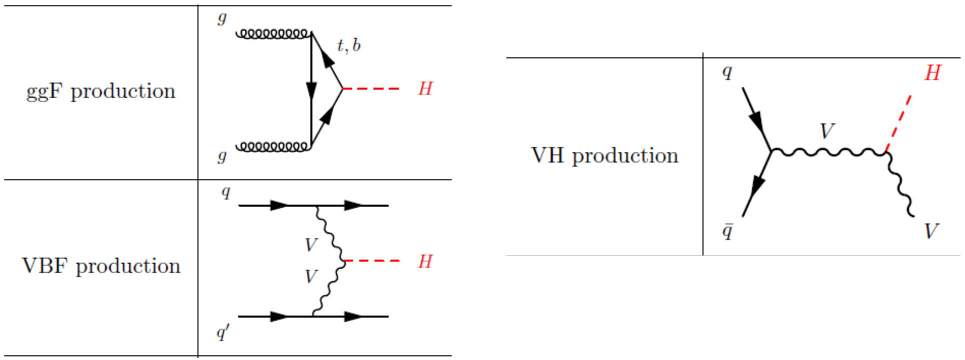
Summary

1.
Higgs boson decay to ZZ*

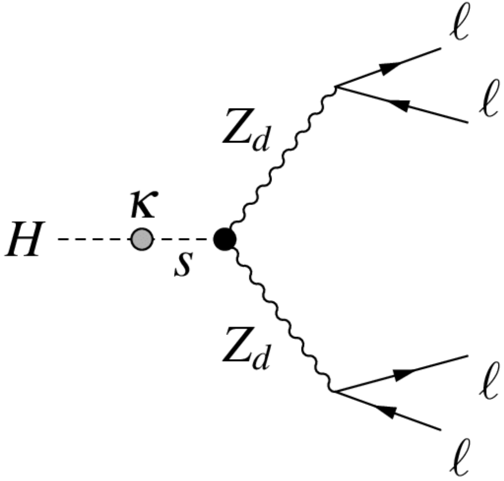
Theoretical introduction

Higgs boson production modes and decay to ZZ*

- Production modes considered: ggF, VBF and WH/ZH;
- Decay to ZZ* which decays to four leptons.



Higgs Production Diagrams.



Higgs decay to ZZ* to 4 leptons.

1

Data, MC samples and SM predictions @ Atlas Open Data

- At 13 TeV, the expected cross-section is 2.9 fb and the integrated luminosity is 10 fb^{-1} (ATLAS Open Data);
- Expected events: 29;
- MC samples generated for a Higgs with mass 125 GeV.

1

Data, MC samples and SM predictions @ Atlas Open Data: Event Selection

Trigger Requirements: trigE || trigM

Lepton Selection: **Electron/Muon Selection**:

- PT cut (> 5000 for loose isolation)
- Pseudo rapidity (< 2.5)
- Impact parameter cuts: (< 5 and < 3)

Exactly Four Leptons: goodlep_n == 4

- PT: first lepton (> 25 GeV), second lepton (> 15 GeV) and third (> 10 GeV)

Lepton Pairing:

- Opposite ;
- Same flavour pairings;
- Invariant mass constraints around the Z boson mass.

Jet Selection:

- Basic jet selection (jet_pt > 30000 and jet_eta < 4.4).

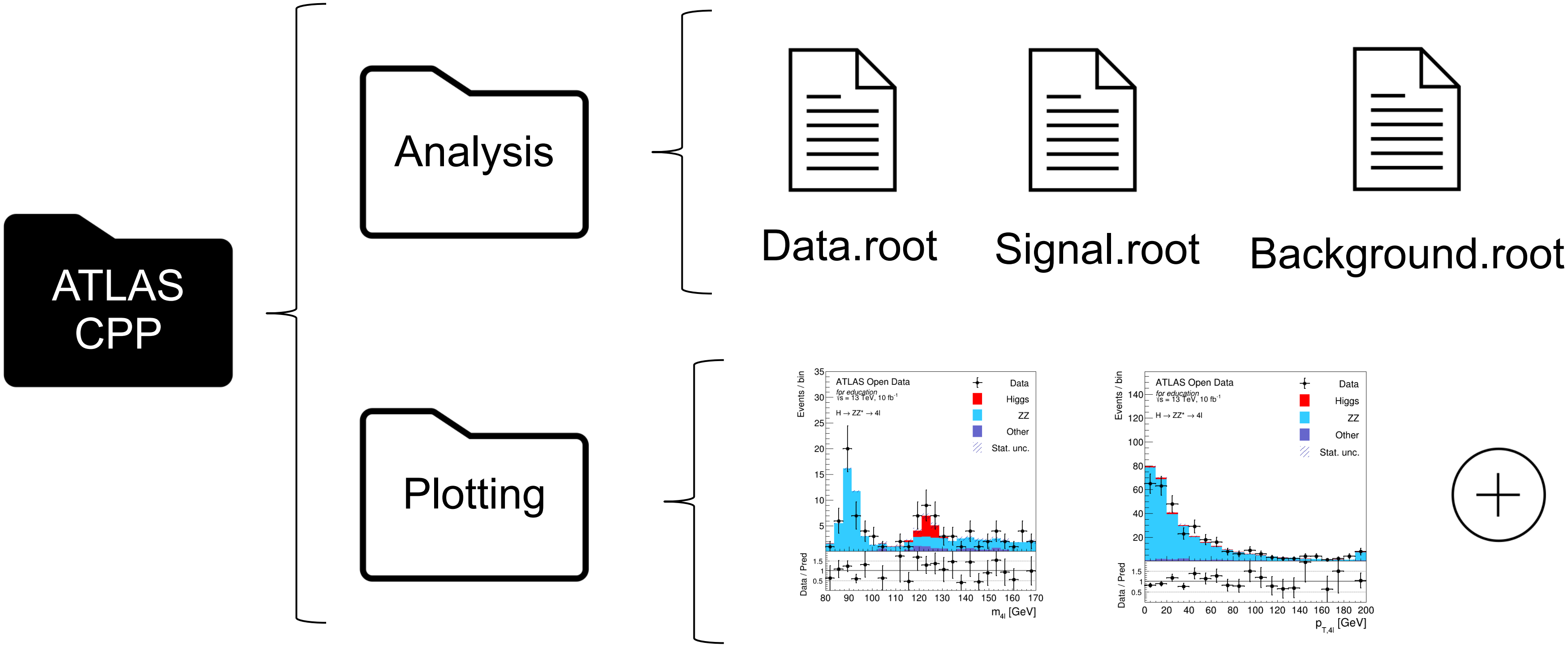
2.
Methods

Computational Procedure

2

Methods:

Plotting: recreating the ‘Plotting’ of ATLAS Open Data



2

Methods:
Analysis - the Significance, Signal Strength, and Cuts

- **Significance Calculation**
  - Utilized both left-to-right and right-to-left (to then improve cuts);
  - Formulas (Z-Value):

$$Z = \frac{S}{\sqrt{S+B}}$$

$$Z = \sqrt{2(S+B)\ln(1+S/B) - 2S}$$

- **Signal Strength Analysis:**
  - Log-likelihood function maximization;
  - Formula: $\mathrm{N} = \mu \mathrm{S} + \mathrm{B}$
- **Efficiency of Cuts:**
  - Evaluation of the effectiveness of our 'cuts’.

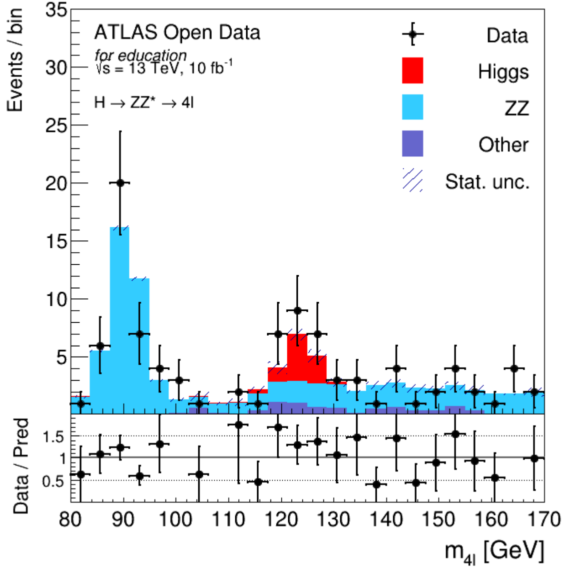
Methods:
Machine Learning

- **Developed a DNN as a classifier:**
  - 2 Layers with 80 and 60 nodes, respectively;
  - Learning rate of 8e-4, 100 training epochs and Early Stopping with patience 4;
  - Train, validation and test samples with 259158 events;
  - Trained with global variables (took into consideration correlations).
- **pyhf library used for fitting the data:**
  - Two models: signal normalisation factor and signal + background normalisation factors.

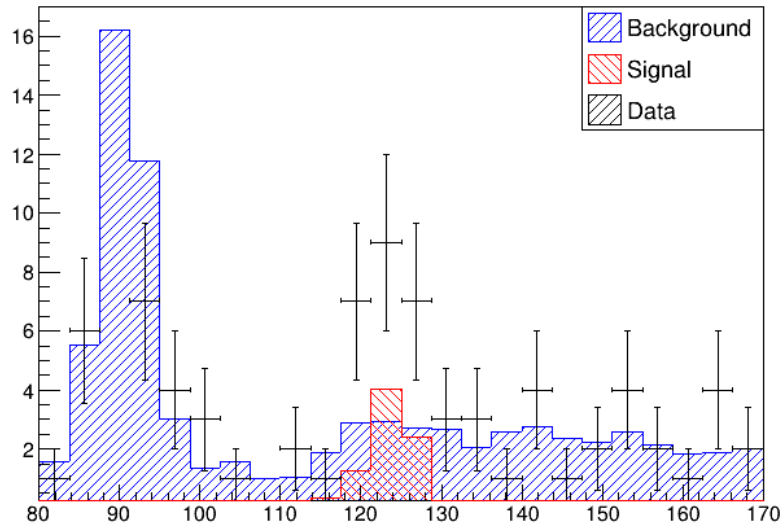
3.
Results

3

Results:



ATLAS Open Data Plot



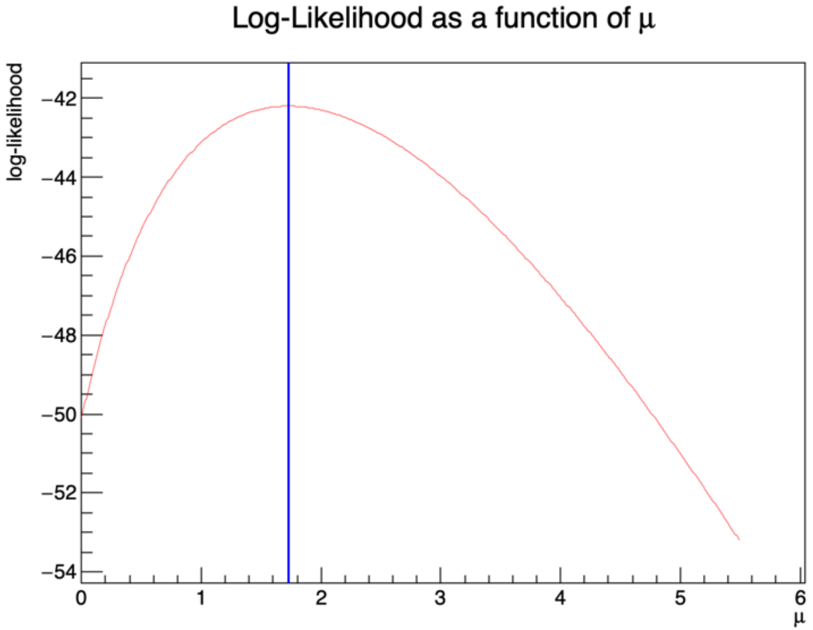
Bruna and Gonçalo’s Plot

3

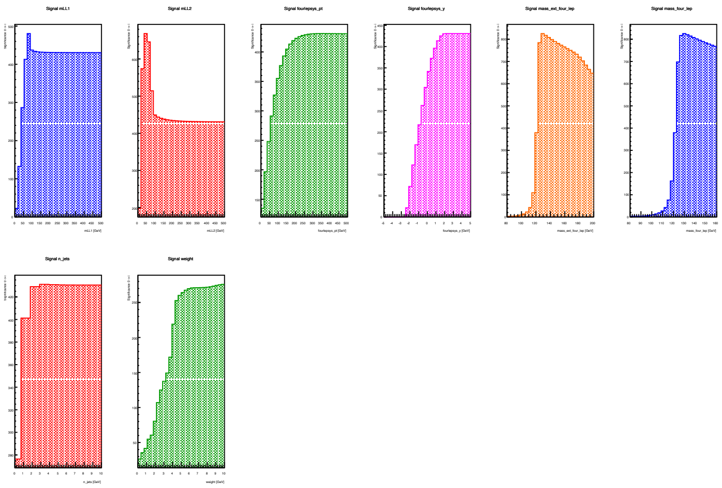
Results:

Analysis - the Signal Strength

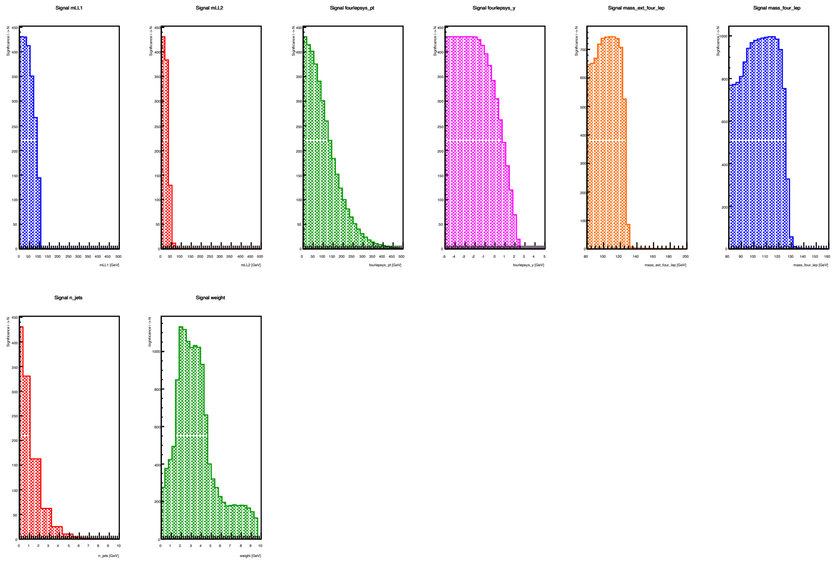
Mass Four Leptons Results	
1 σ	1.73 ± 0.63
2 σ	1.73 ± 1.36
3 σ	1.73 ± 2.17



Results:
Analysis - the Signal Significance and Efficiency



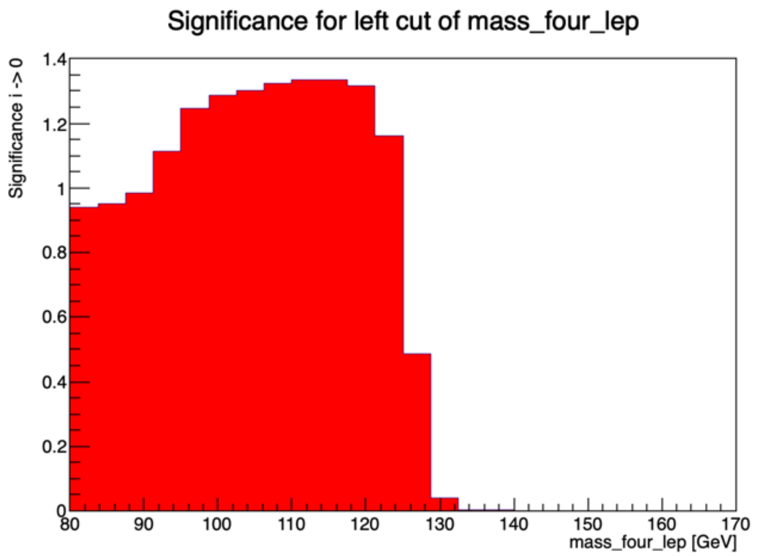
Left Significance Calculation (Cut)



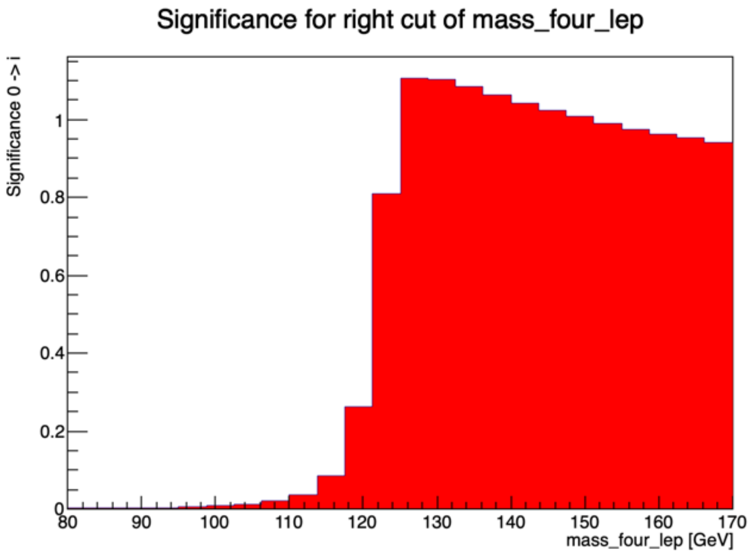
Right Significance Calculation (Cut)

3

Results:
Analysis: the Signal Significance and Efficiency



Left Significance Calculation (Cut)

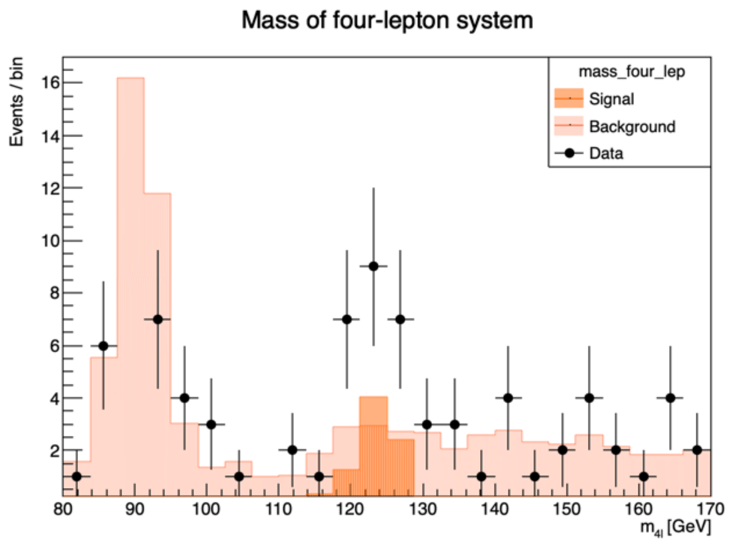


Right Significance Calculation (Cut)

3

Results:

Analysis: the Signal Significance, Efficiency and 'Cuts'



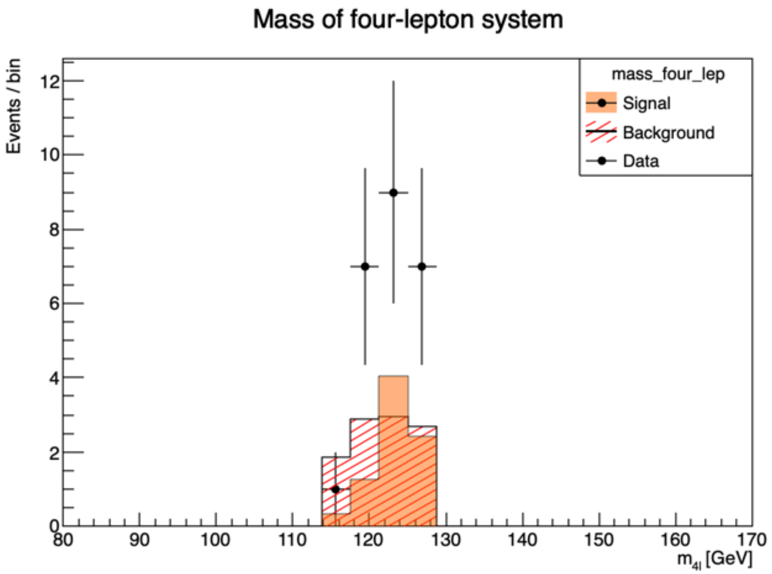
Histogram	Lower Cut	Upper Cut
Mass Dilepton 1	50.933	86.400
Mass Dilepton 2	14.133	52.533
Four Lepton System Momentum	15.000	195.000
Four Lepton System Y	-2.250	2.250
Mass Four Leptons	115.625	126.875
Mass Ext Four Lepton	111.167	128.167
Number Jets	0.000	3.000
Four Lepton Pt	20.000	60.000
Four Lepton Eta	-2.700	2.700
Four Lepton Energy	15.000	75.000
Four Lepton Phi	-2.800	2..800
Four Lepton ID	6.000	13.000

3

Results:

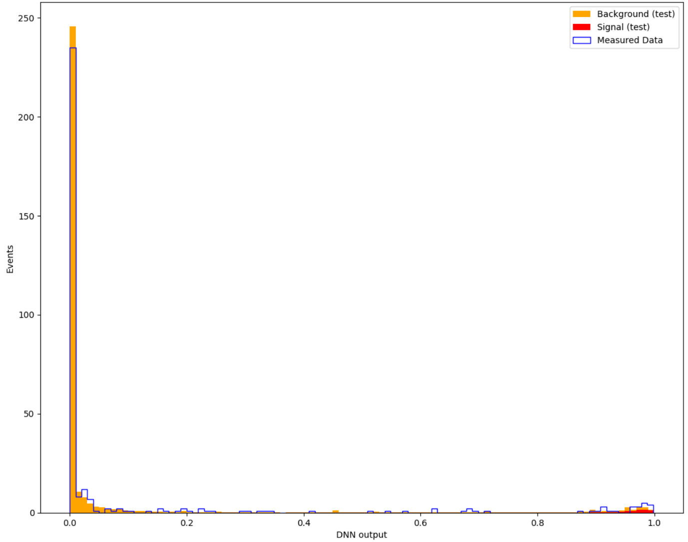
Analysis: the Signal Significance, Efficiency and ‘Cuts’

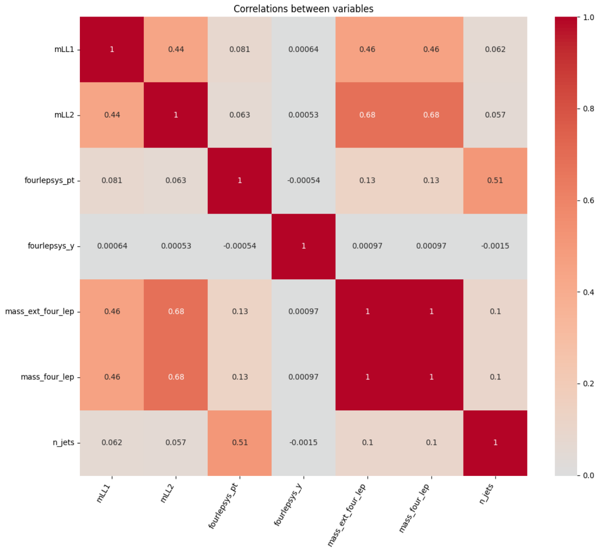
Histogram	Lower Cut
Signal Strength (μ) for 1.0 σ	1.71 ± 0.64
Expected Significance (counting Experiment)	1.87
Expected Significance	2.25
Observed Significance (counting Experiment)	2.81
Observed Significance	3.61
Signal Efficiency	0.97



Results:
Machine Learning

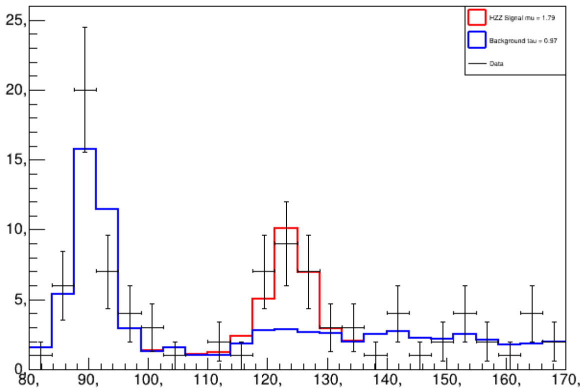
- **Assessed correlation between variables:** reduce the number of train features.
- **Test sample used to compare with data**.





Results:
Machine Learning

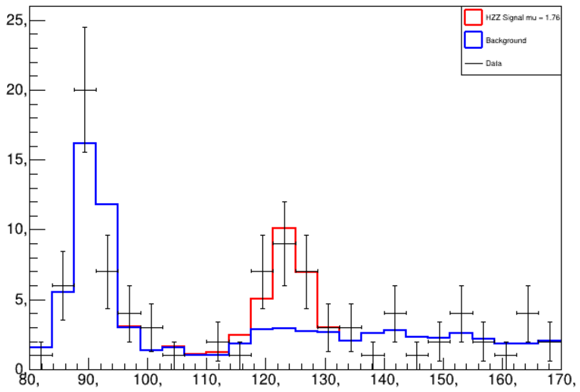
mass_four_lep with mu = 1.79



$$N = \mu \times S + \tau \times B$$

Results	
μ	1.79 ± 1.03
Z_{exp}	3.02σ
Z_{Obs}	5.384σ

mass_four_lep with mu = 1.76



$$N = \mu \times S + B$$

Results	
μ	1.76 ± 1.03
Z_{exp}	3.04σ
Z_{Obs}	5.378σ

4.
Analysis

Comparison of methods and their results

4

Analysis:
Comparison of different methods

	μ	Z_{Exp}	Z_{Obs}
Cuts	1.71 ± 0.64	2.25σ	3.61σ
ML (S+B)	1.79 ± 1.03	3.02σ	5.384σ
ML (S)	1.76 ± 1.03	3.04σ	5.378σ

4

Analysis: Conclusions

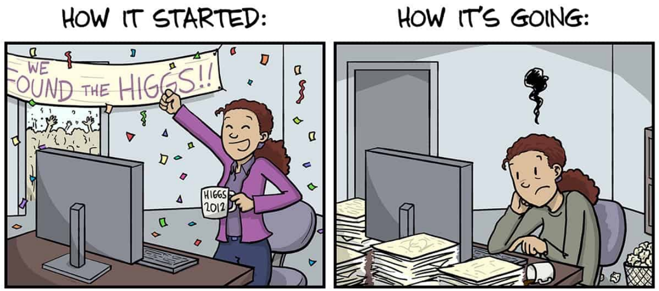
- **Recall: discovery when Z = 5σ!**
    - DNN obtains an expected significance > 5σ, whereas cuts on variables only 3.61σ;
    - Signal Strength values obtained for the three methods are compatible;
    - Machine Learning Methods are extremely powerful: we can argue that we have made a discovery!

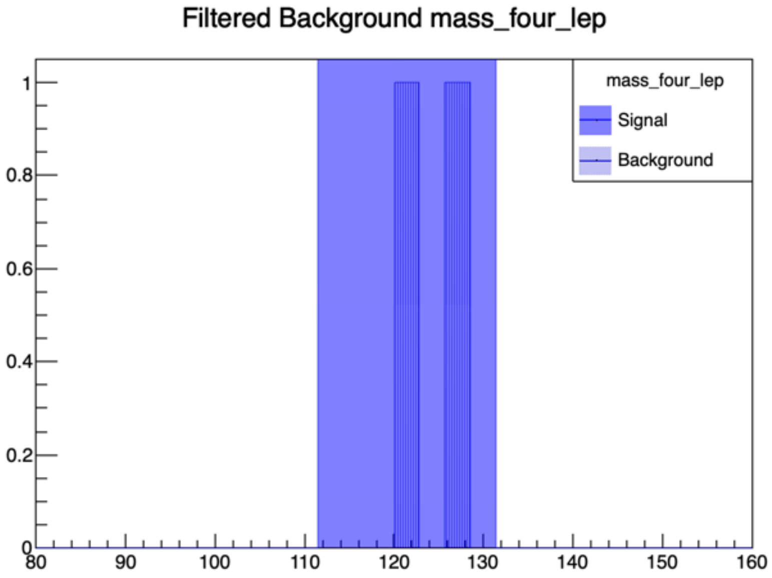
5.
Conclusions and Final Remarks

5

Conclusion:
Over Treating Problems

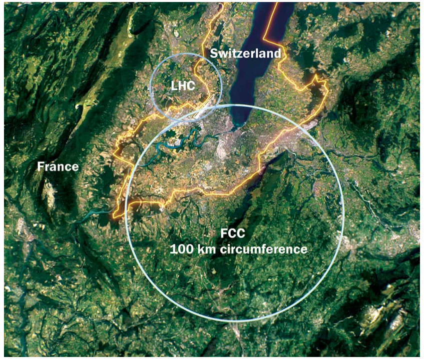
We can see first-hand what happens when we get too deep in the analysis: **2 events in the MC simulation.**





Conclusion:
How can ML improve our analysis?

- With ML algorithms, we achieved a significance > 5σ, whereas 'cuts' only achieved > 3σ;
- The biggest achievement of LHC was the Higg's discovery;
- ML can contribute to solve the current SM limitations: dark matter, neutrino oscillations, ...
- There are still so many questions to be answered...! FCC?



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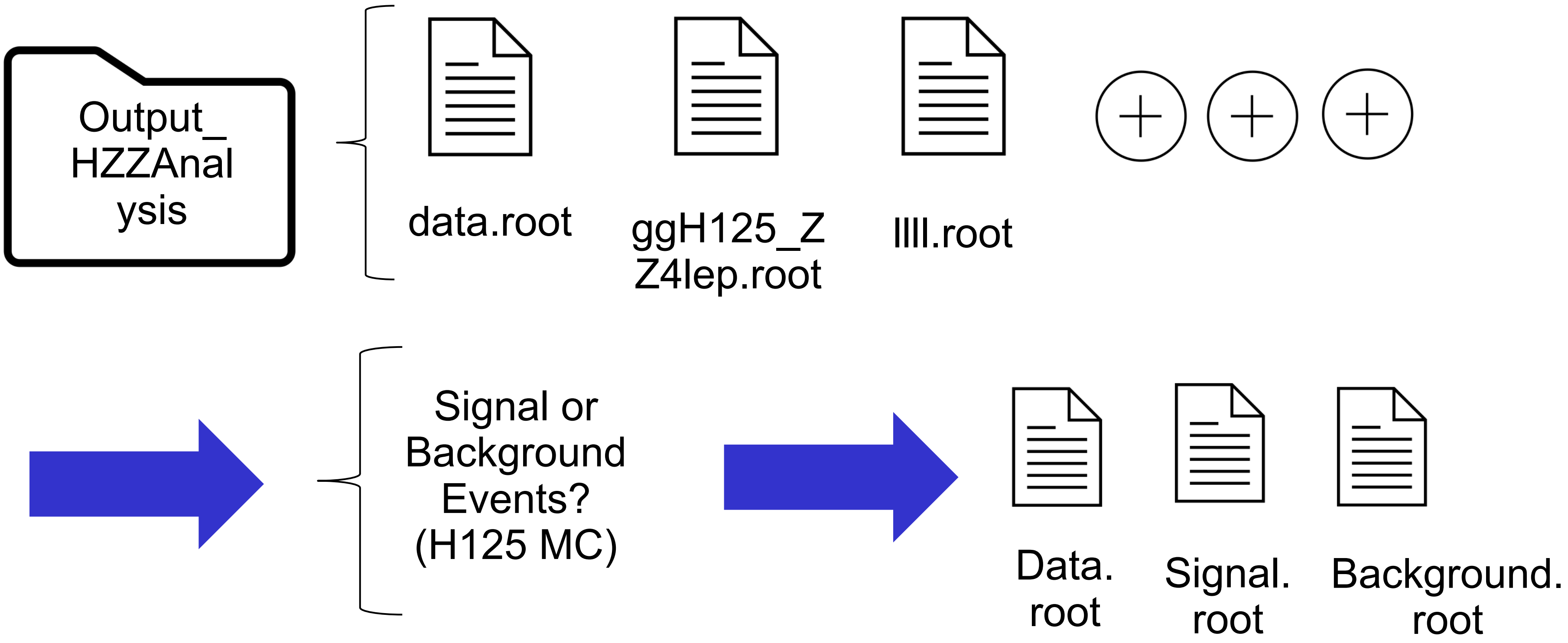
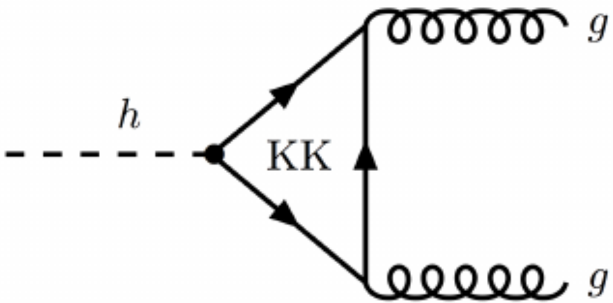
Backup Slides

How we turn things into CSV Files

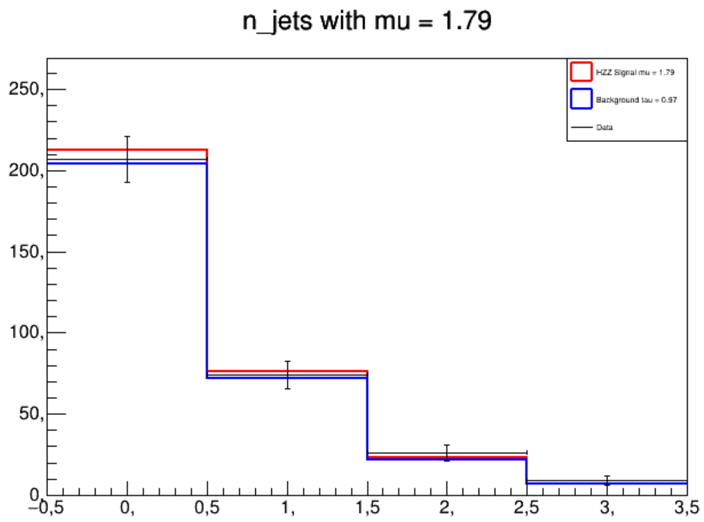


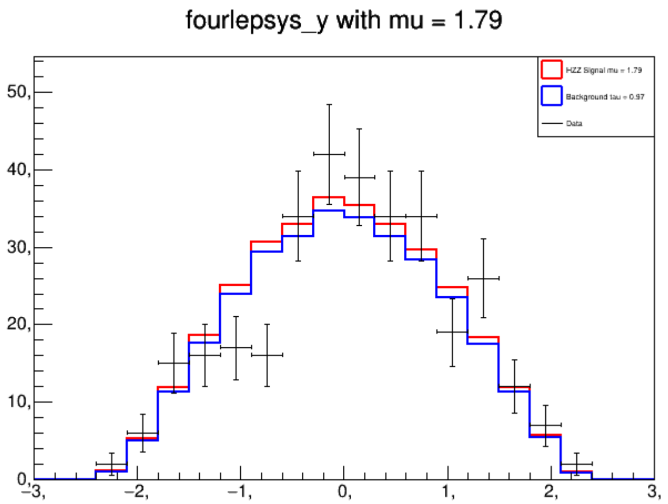
Surprise Scaling Factor

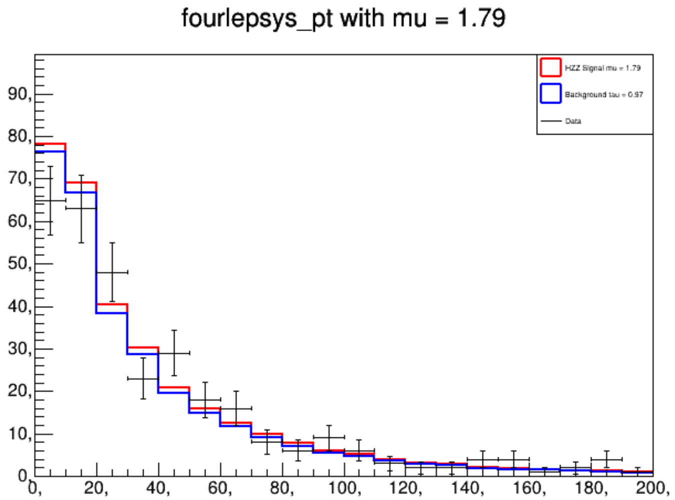
```
Z_Z = (TH1F*)llll[fIter->first]->Clone(); // Z->ll Z->ll
Z_Z->Add(ZqqZll[fIter->first]); // Z->qq Z->ll
Z_Z->Add(llvv[fIter->first]); // Z->ll Z->vv
Z_Z->SetFillColor(kAzure+8);
Z_Z->SetLineWidth(0);
Z_Z->Scale(1.3); // loop-induced gluon-gluon gg->ZZ is not included in the
    current MCs
```



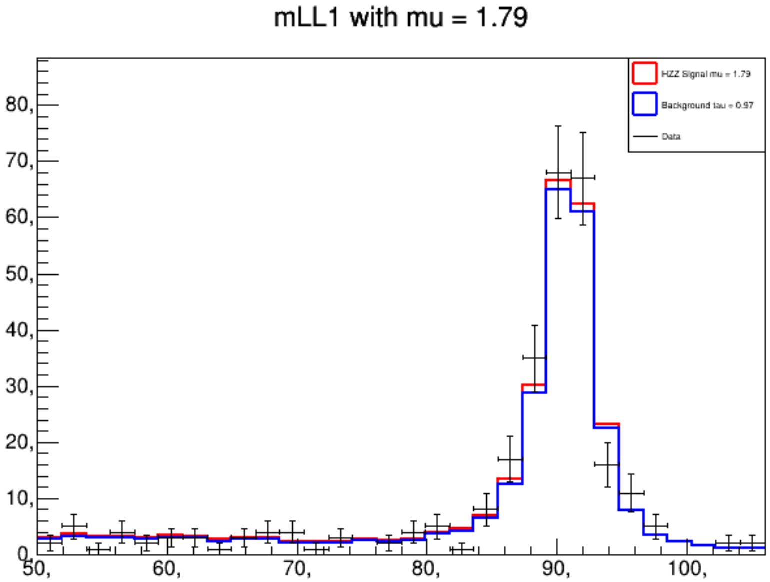
Useful Plots: ML

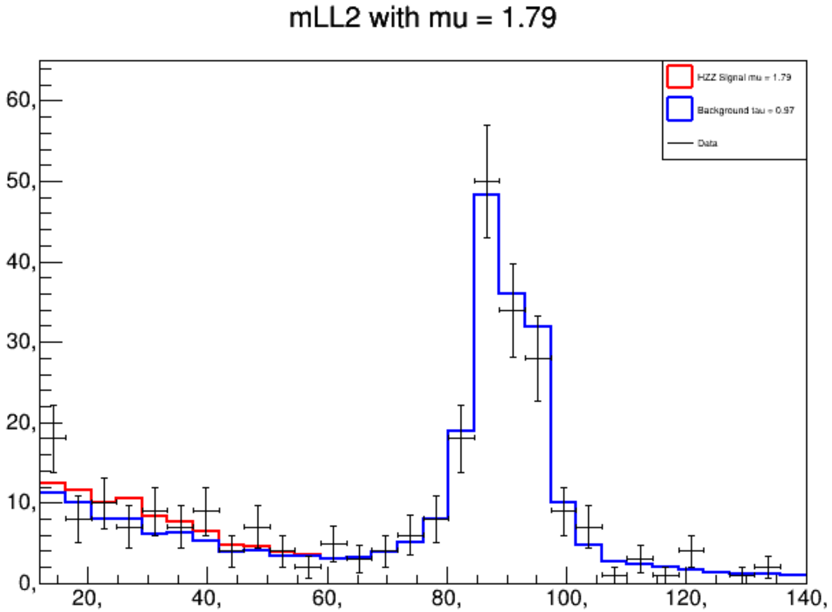




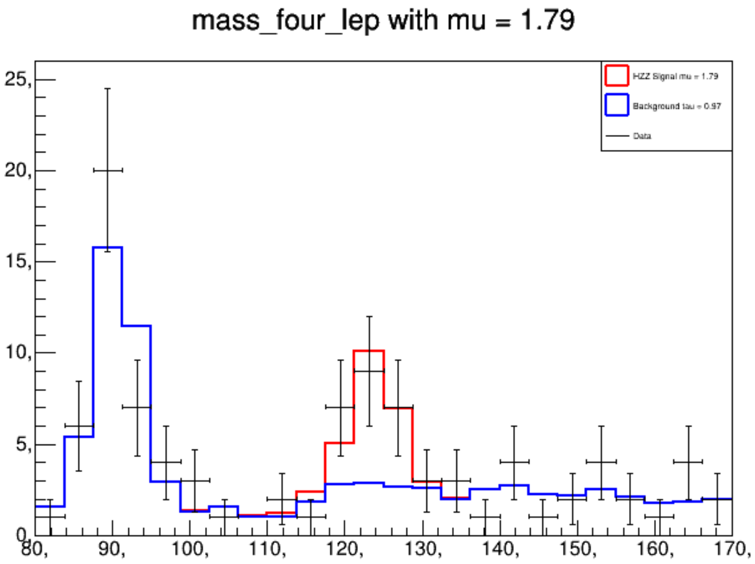


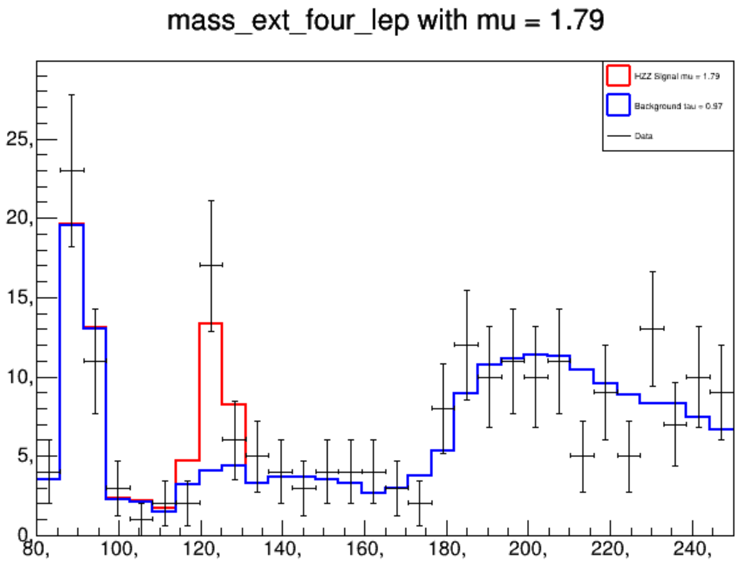
Useful Plots: ML



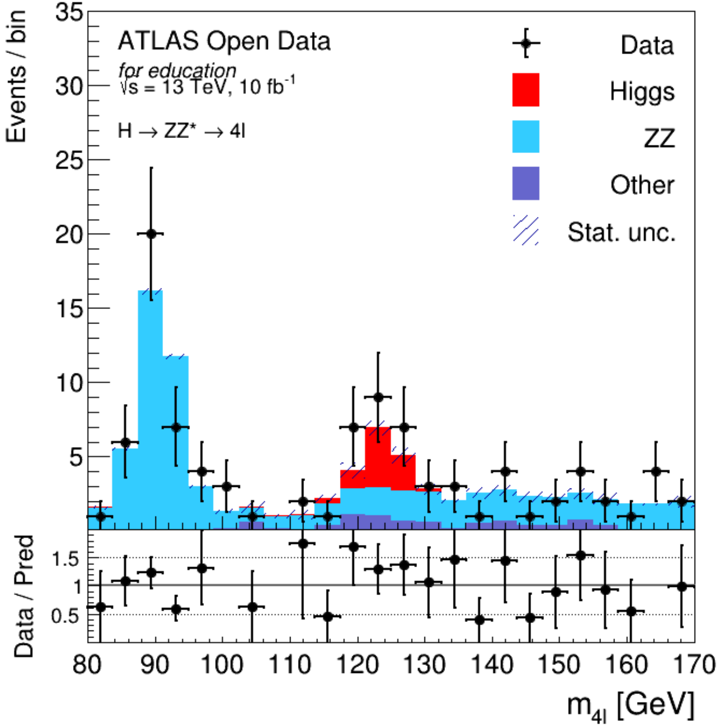


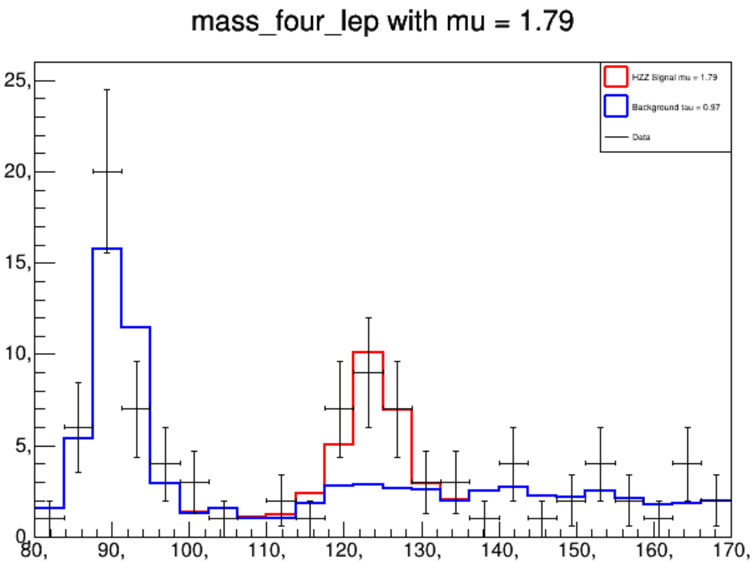
Useful Plots: ML



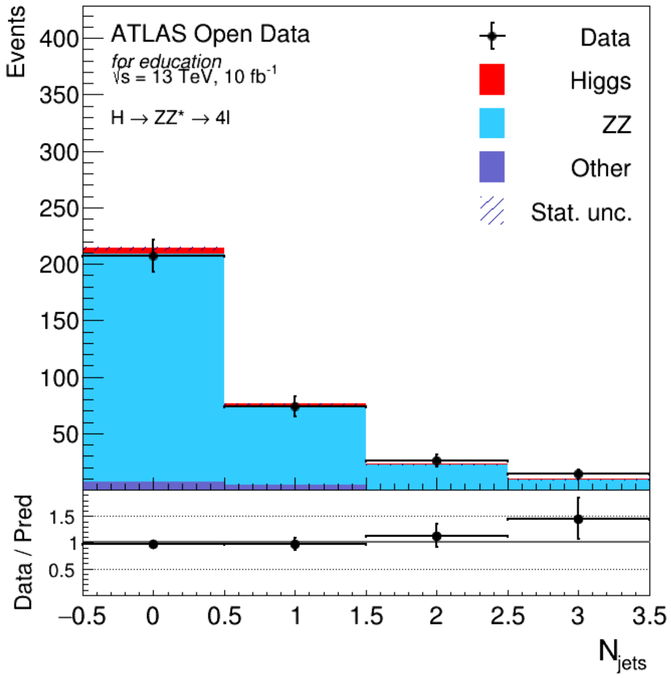


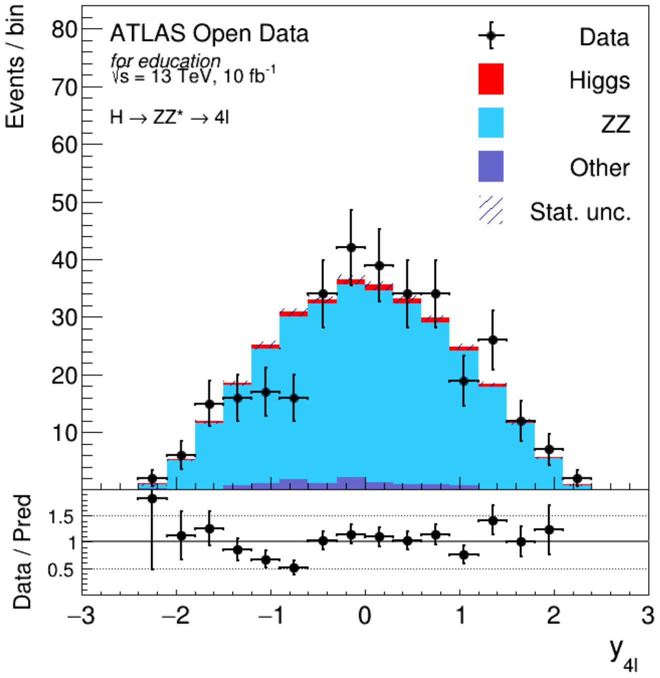
Useful Plots: ATLAS Open Data vs ML – Mass Four Leptons





Useful Plots: Open Data





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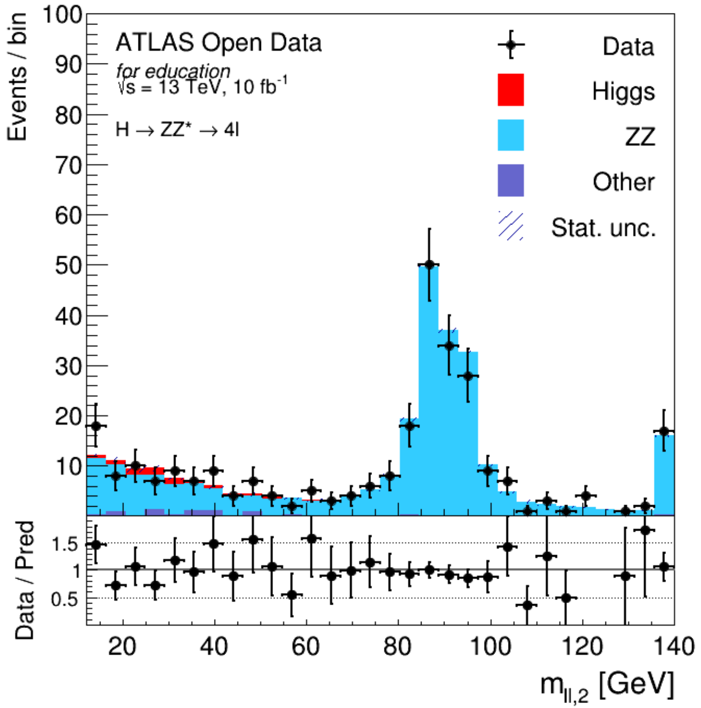

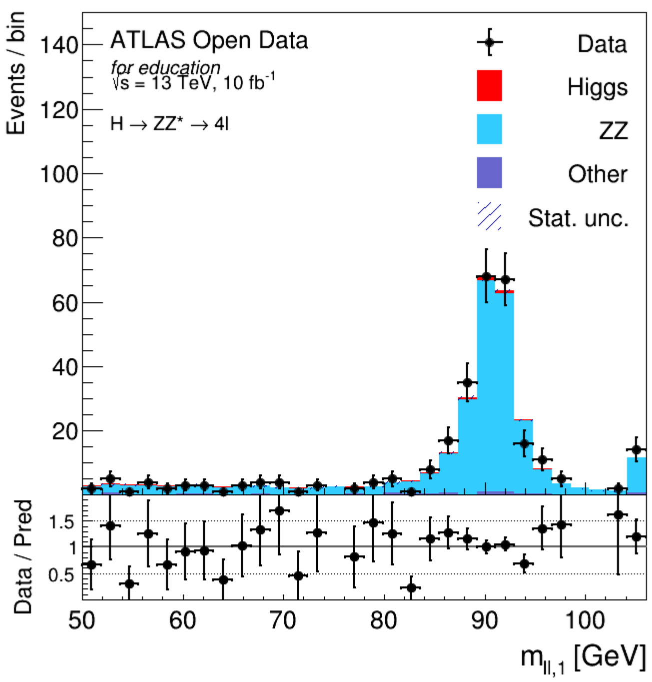

Significance Results Comparison

	Our Results	Paper
Expected	3.043 σ	1.6 σ (7 TeV) and 2.1 σ (8 TeV)
Observed	5.378 σ	5.9 σ