

Search for the tWZ process using proton-proton collision data at $\sqrt{s} = 13.6$ TeV with the ATLAS Experiment

Carolina dos Santos Costa
Supervisor: Carmen Diez Pardos

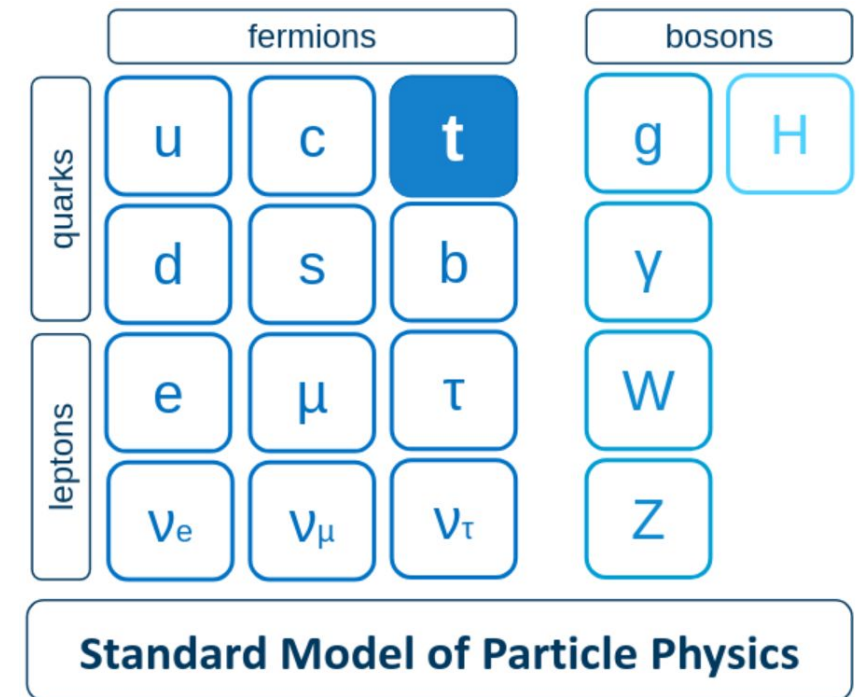
September 2026



57. Herbstschule HEP

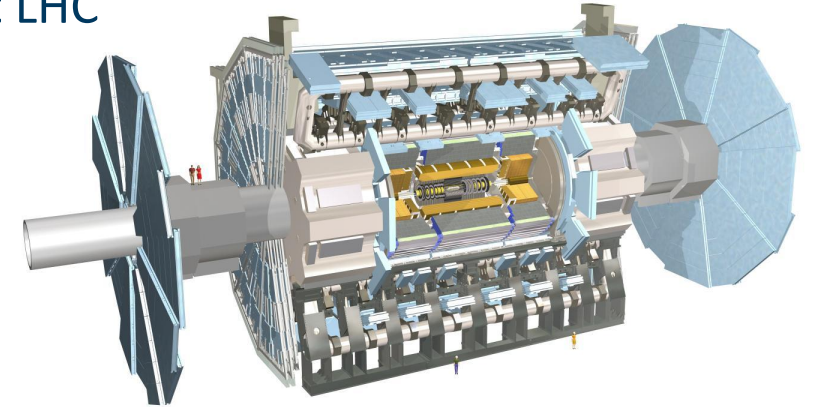
Motivation

- The Standard Model (SM) describes the fundamental particles and their interactions
 - ↳ however, the SM is incomplete, p.e.:
 - ↳ it does not explain the matter-antimatter asymmetry
 - ↳ it does not provide a candidate for dark matter
- The **top quark** may be a door for probing for new physics
 - ↳ is the heaviest elementary particle known
 - ↳ has by far the largest strong coupling to the Higgs boson



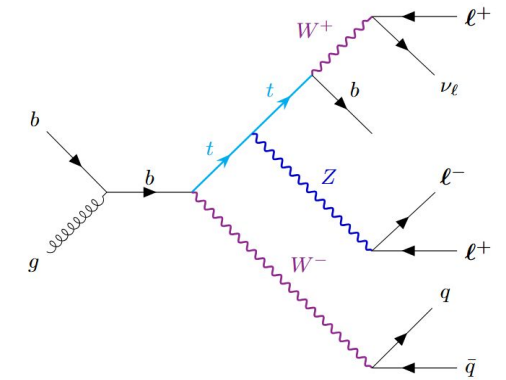
The ATLAS Detector at CERN

- The Large Hadron Collider (LHC) is the most energetic particle collider ever built
- The ATLAS detector is a general-purpose detector and the largest at LHC
 - ↳ allows for particle tracking and identification
 - ↳ provides precise measurements to test SM predictions and search for BSM physics
- Since it started operations in 2009, the LHC has undergone multiple operational runs:
 - ↳ Run 3 occurred from July 2022 to June 2026
 - ↳ Highest collision energy achieved: $\sqrt{s} = \mathbf{13.6\ TeV}$
 - ↳ This analysis used a Run 3 subset collected between 2022-2024, corresponding to $159\ \text{fb}^{-1}$.

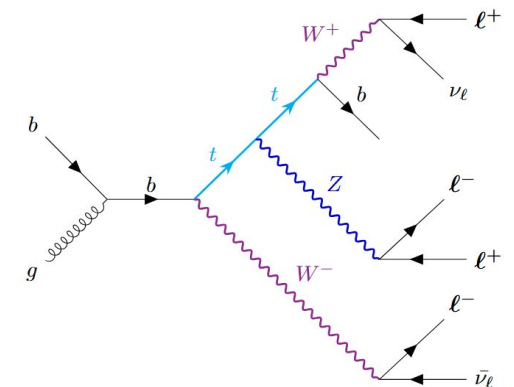


The tWZ process

- tWZ : rare process sensitive to the electroweak coupling of the top quark
 - ↳ Sensitive to 13 Standard Model Effective Field Theory (SMEFT) operators with different dependence than other top+boson processes ([JHEPO1\(2022\)100](#))
- The tWZ process has never been observed at the ATLAS experiment:
 - ↳ $\sigma = 148^{+10}_{-9}$ fb at $s = \sqrt{13.6}$ TeV (NLO MC)
 - ↳ Large background contributions (e.g. ttZ and WZ) and events with non-prompt leptons
 - ↳ The **three** and **four lepton** channels are the most sensitive.
 - For this talk I will focus on the three lepton channel, current four lepton channel results can be seen in the backup slides



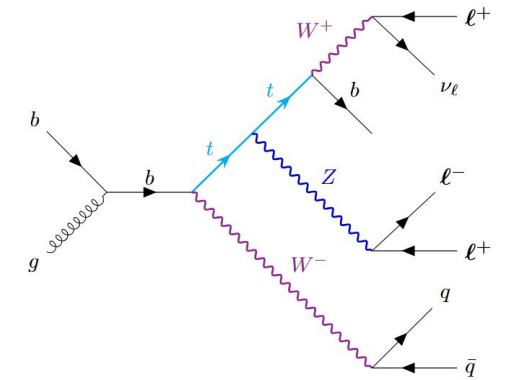
Three Lepton Channel (3L)



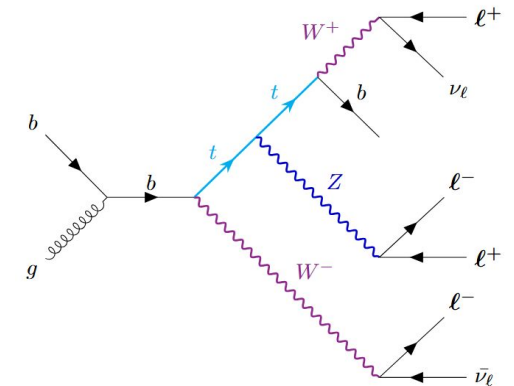
Four Lepton Channel (4L)

The tWZ process

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 - ↳ The **three** and **four lepton** channels are the most sensitive.
- Why now?
 - ↳ Data collected during Run 2 + Run 3 allows enough luminosity for such measurement
 - ↳ CMS measured cross section slightly larger than the SM prediction ([arXiv:2510.19080v1](#))
 - ↳ Motivates for an independent measurement from ATLAS Collaboration



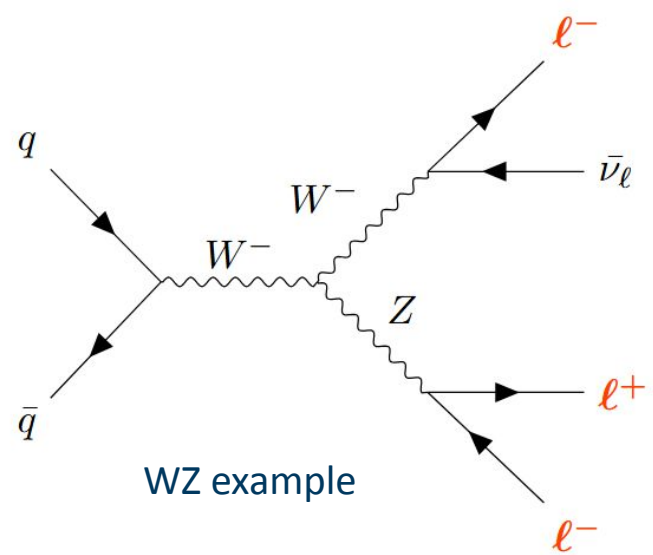
Three Lepton Channel (3L)



Four Lepton Channel (4L)

3 Lepton Channel

- Defined regions based on the number of leptons (prompt or fake), b-tagged jets and $m_{\ell\ell}$ requirements
- There were defined two different regions rich in tWZ - varying the cut on the p_T of the leptons.
- The regions rich in tWZ , ttZ and WZ will later be used to train machine learning methods.
- The regions rich in Z jets and tt contain fake leptons and are used as control regions for the fit.



	Regions used for training				
Variable	tWZ-3L Region	ttZ CR	WZ CR	Zjets CR	tt CR
$N_{\ell}(\ell = e, \mu)$	3 tight ID leptons			2 tight, 1 medium ID leptons	
$p_T(\ell_1, \ell_2, \ell_3)$	$> 28, 18, 10 \text{ GeV}$			$> 28, 18, 10 \text{ GeV}$	
N_{jets}	≤ 3	≥ 2		≥ 2	
$p_{T\text{jets}}$	$> 25 \text{ GeV}$			$> 25 \text{ GeV}$	
$N_{b\text{-jets}}$	1	≥ 2	0	1	1
E_T^{miss}	$> 30 \text{ GeV}$			$< 30 \text{ GeV}$	$> 30 \text{ GeV}$
$N_{Z\text{candidate}}, m_{l-l+} - m_Z < 10 \text{ GeV}$	1			1	0



3 Lepton Channel: CR distributions

- Distributions of the sum of pT of all jets (H_T) for the different CR:
 - For ttZ the expected events underestimate observed events
 - The remaining CR show good data-MC agreement

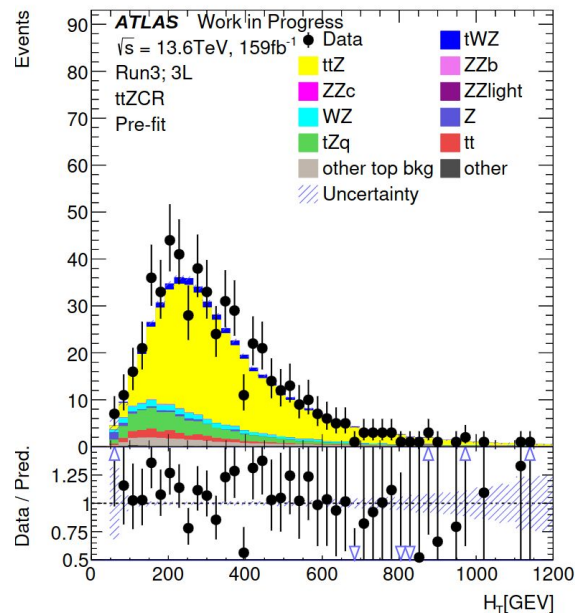
Other top background:

ttW, ttGamma, ttH, ttWW, ttt, tttt, tW

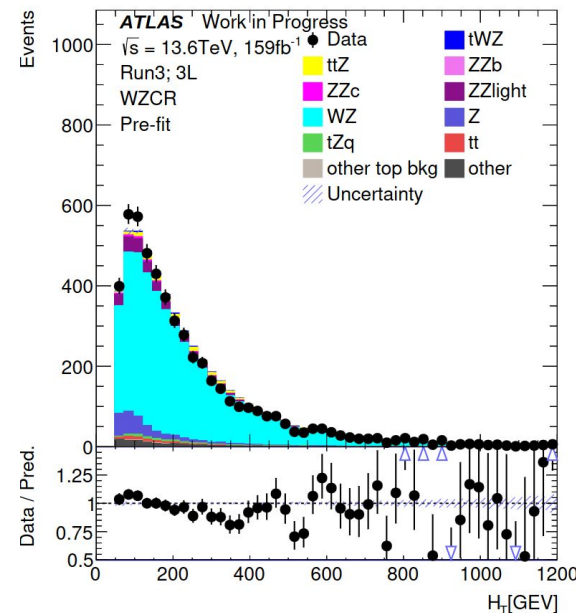
Other:

VVV, W, Vgamma, VH

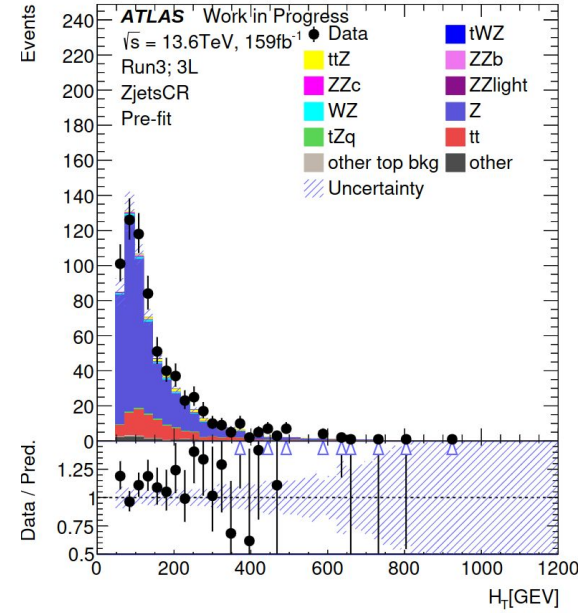
CR: ttZ
 H_T



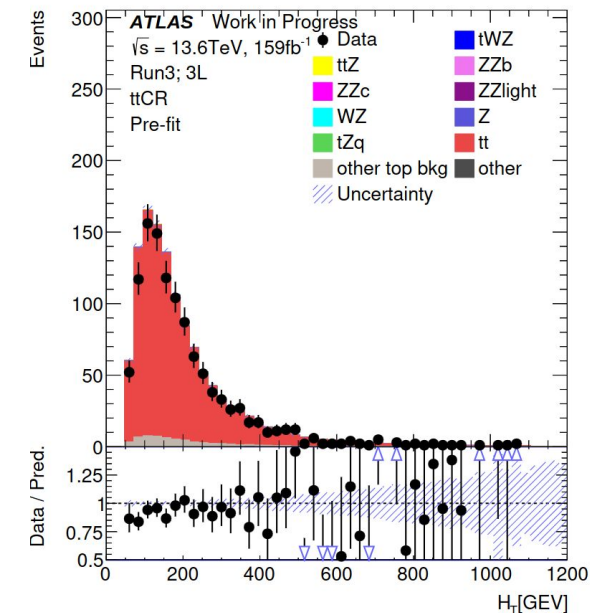
CR: WZ
 H_T



CR: Z+jets
 H_T



CR: tt
 H_T



DNN training: for 3L and 4L Channel

- The model is a 4-fold cross validation DNN Multi-classifier:
 - ↳ divide the events in 4 subsets and alternate their usage for each run
- Using Egor Antipov's training and evaluation setup.
- This structure is used for both 3L and 4L Channels.

Fold ↓ k th set →	0	1	2	3
0	train	train	validate	test/deploy
1	test/deploy	train	train	validate
2	validate	test/deploy	train	train
3	train	validate	test/deploy	train

by Egor Antipov

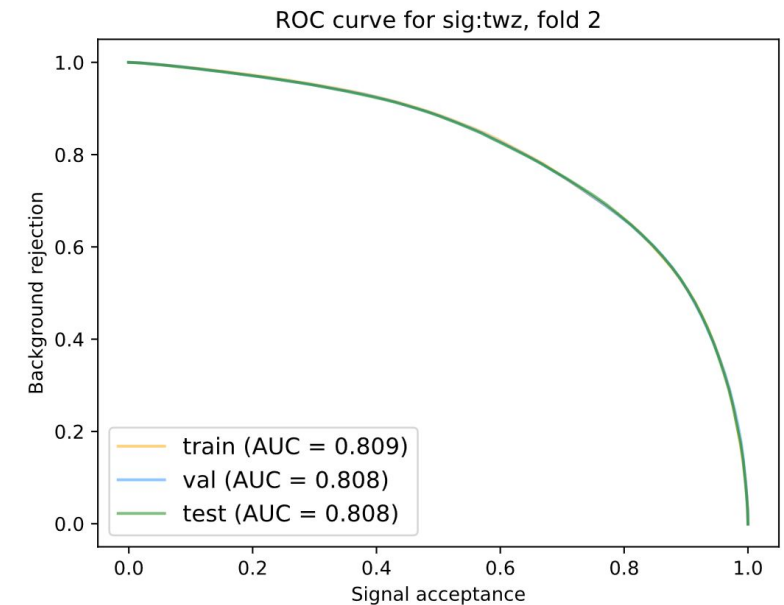
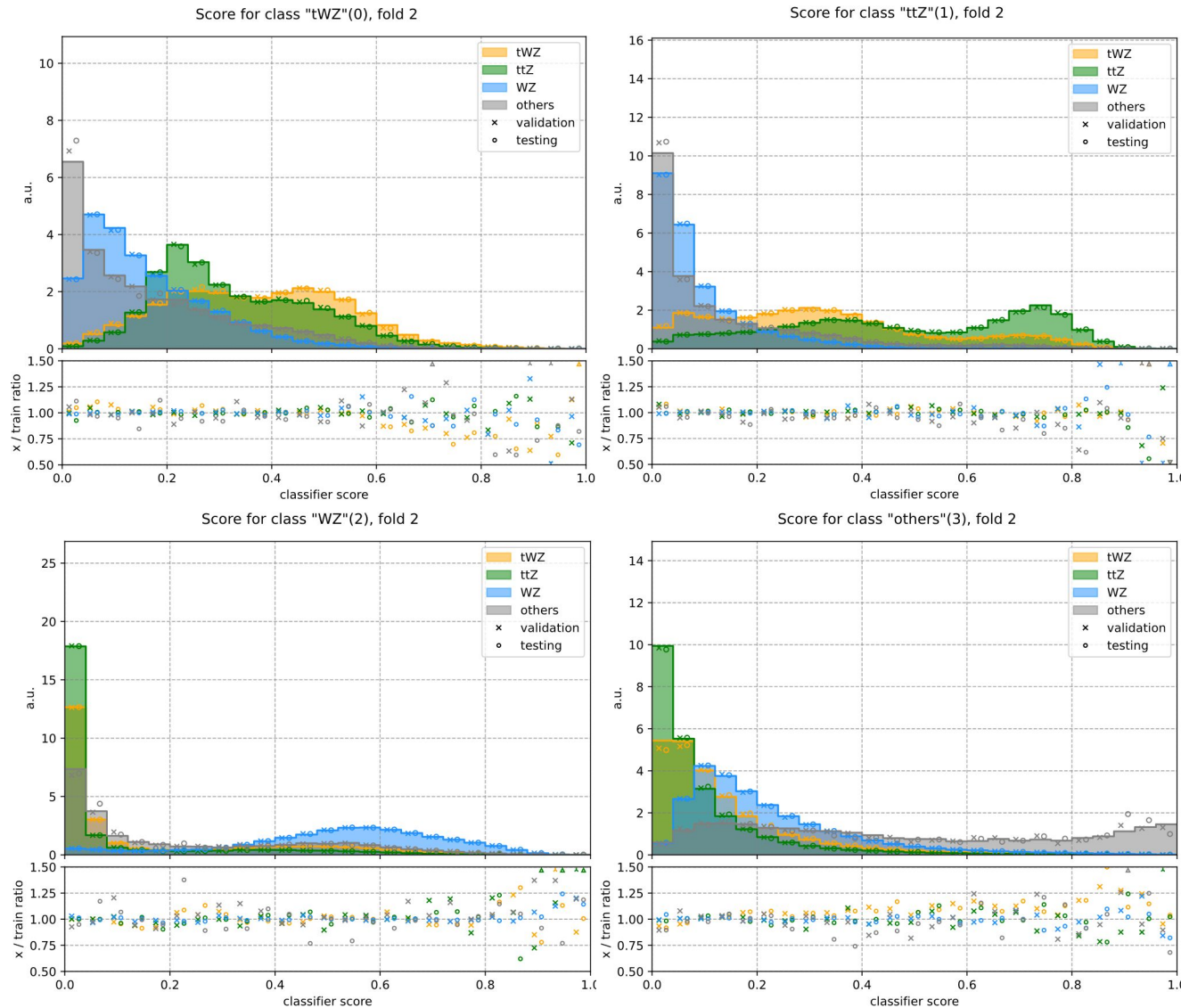
3 Lepton Channel: DNN model specificities

- 4 classes for the 3L Channel:
 - ↳ **signal: tWZ**
 - ↳ **3 background classes: ttZ , WZ and others**
- Model Architecture:
 - ↳ 41 input features
 - ↳ Normalization layer
 - ↳ 3 hidden Dense layers with 72, 36, and 18 nodes
 - ↳ 4-node softmax output layer
- Optimizer: Adam
- Initial learning rate: 10^{-3}
- Batch size: 64
- Early stopping: Validation loss, patience of 7 epochs
- Training with event weights

- nJets, nBJets
- missing transverse momentum (MET) and phi
- p_T, η, ϕ for three leading leptons
- p_T, η, ϕ for leading non-Z lepton
- p_T, η, ϕ for two leading jets
- p_T, η, ϕ for leading non-b-jet
- p_T, η, ϕ mass for leading Z candidate
- $\Delta\phi$ between MET and each of the three leading leptons
- $\Delta\phi$ and ΔR between leading b-jet and leading Z candidate
- $\sum p_T$ (Z candidates)
- $\sum p_T$ (leptons)
- $\sum p_T$ (jets)
- $\sum p_T$ (leptons) + $\sum p_T$ (jets)
- $\sum p_T$ (b-tagged jets)
- $\sum p_T$ (leptons) + $\sum p_T$ (jets) + MET
- Second-smallest value of $|172.5 - m(\text{b-jet, lepton})|$

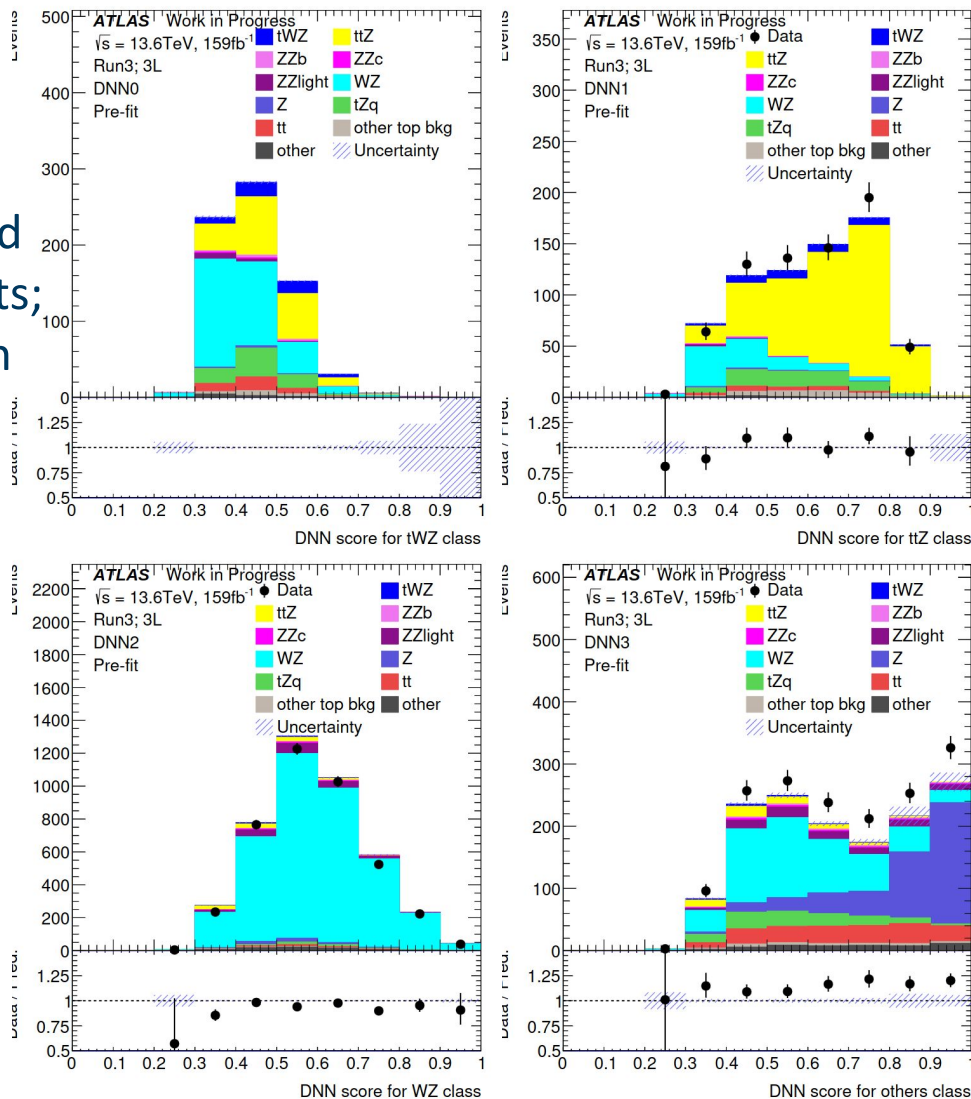
3 Lepton Channel: DNN model training and evaluation

- Here presenting the results for the third fold - the remaining folds presented similar results.



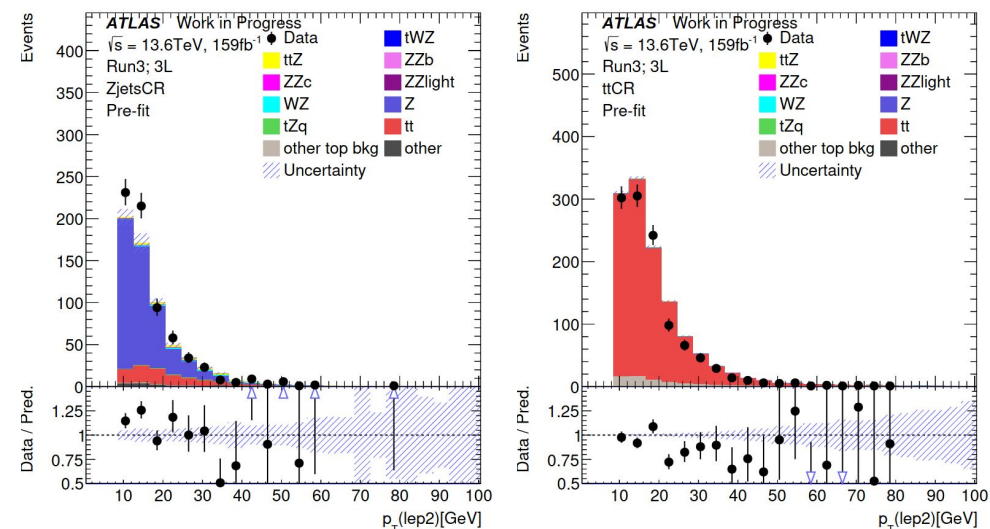
3 Lepton Channel: Distributions used on the fit

The tWZ region is still strongly affected by ttZ and WZ events; further optimization of the classifier is needed



- Here presenting the distributions used for the fit

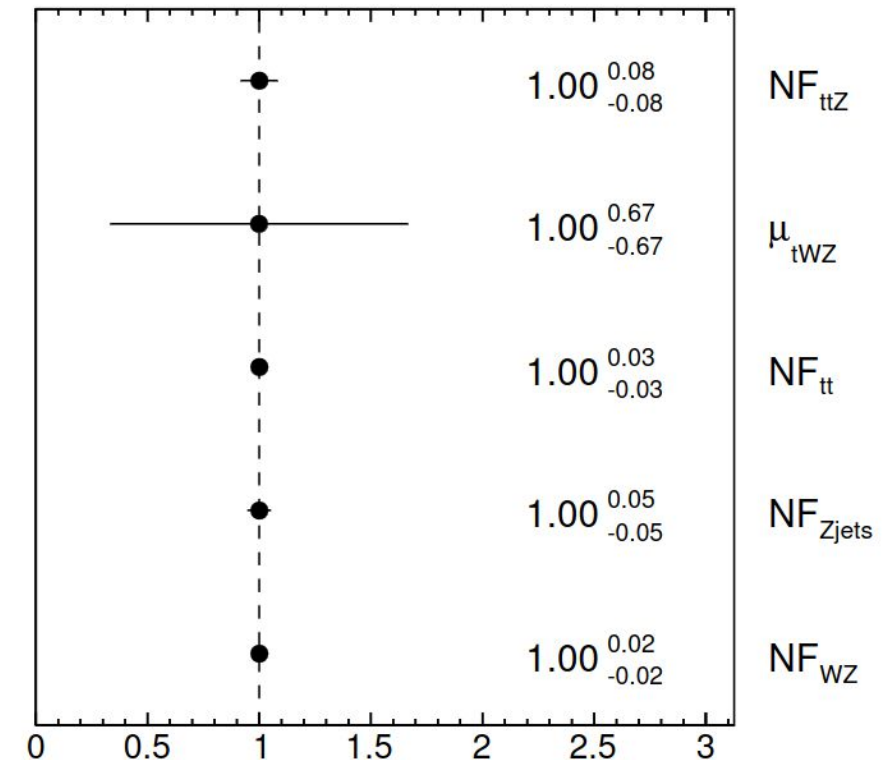
- the 4 DNN outputs for each class
- p_T of the 3rd lep for the Zjets and tt CR



3 Lepton Channel: Asimov fits

- Asimov fits using the previously presented distributions
 - ↳ DNN outputs for each class
 - ↳ p_T of the 3rd lep for the tt and Zjets CR
- Only statistical uncertainties considered
- Extracting the signal strength ($\mu = \frac{\sigma}{\sigma_{SM}}$) for tWZ, ZZ, ttZ, tt and WZ simultaneously
- **Expected significance: 1.56 σ**

ATLAS Work in Progress



Summary

- First tWZ production measurement at ATLAS is ongoing
 - ↳ Final goal: combined measurement of Run 2 and Run 3 data for the three and four lepton channels
- Multi-class analysis using DNN for signal and background separation
 - ↳ New optimization strategies being discussed, including introduction of new physics-motivated features for training
- Next Steps:
 - ↳ Include systematic uncertainties
 - ↳ Proceed with cross-section measurement
 - ↳ Combine results with Run 2

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Thank You

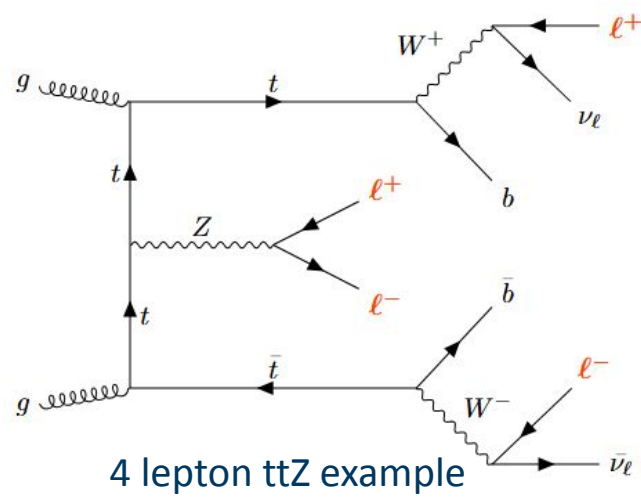
57. Herbstschule HEP



Backup slides

4 Lepton Channel

- Defined regions based on the number of leptons (prompt or fake), b-tagged jets and $m_{\ell\ell}$ requirements
- There were defined three different regions rich in tWZ - separating event with opposite flavour (OF) and same flavour (SF) leptons, as well as relaxing the lepton identification
- All regions are used for the ML model training

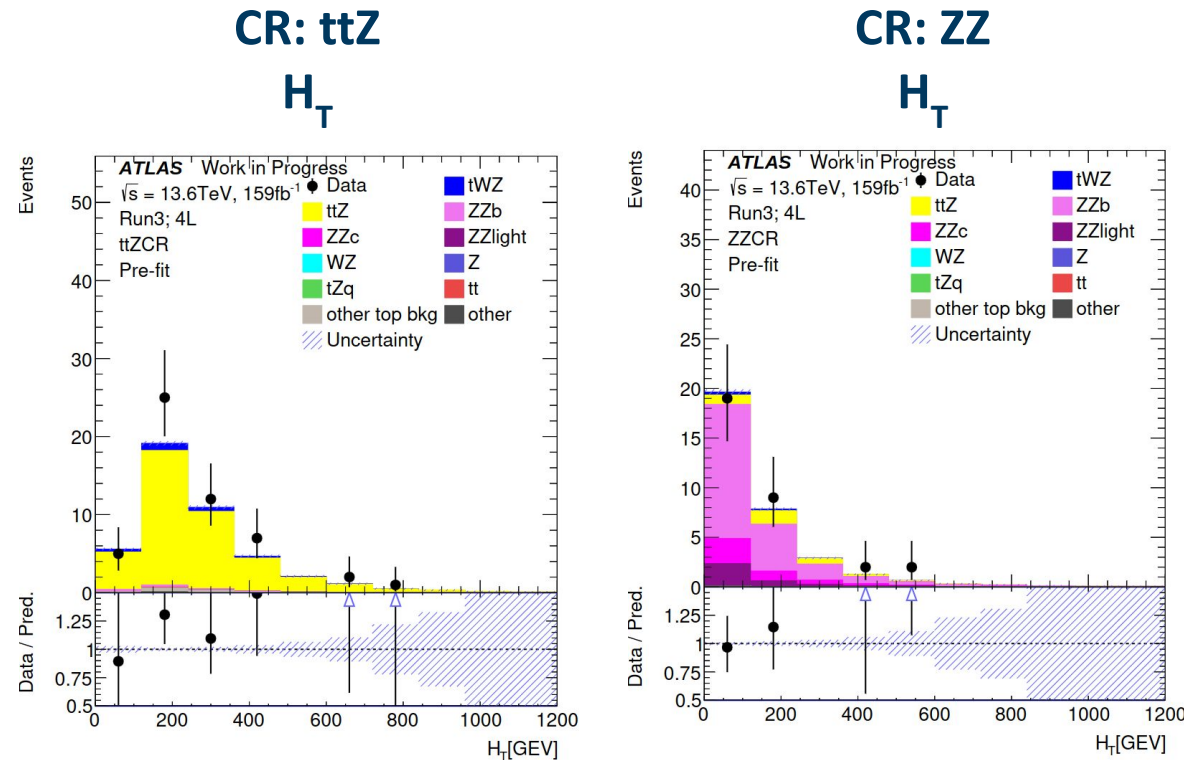


Variable	All regions used for training				
	tWZ OF Region	tWZ SF Region	tWZ Loose Region	ttZ CR	ZZ CR
$N_{\ell}^{\text{tight}}(\ell = e, \mu)$	4	4	3	4	4
N_{ℓ} (loose & not tight)	–	–	1	–	–
$p_T(\ell_1, \ell_2, \ell_3, \ell_4)$		$> 28, 18, 10, 10$ GeV			
N_{jets}	1	1	1	≥ 2	≥ 1
$p_{T\text{jets}}$	> 25 GeV	> 25 GeV	> 25 GeV	> 20 GeV	
$N_{b\text{-jet}}$	1	1	1	2	1
$N_{Z\text{candidate}}, m_{l-l^+} - m_Z < 10$ GeV	1	1	1	1	2
Lepton flavour	Opp. flavour non-Z leptons	Same flavour non-Z leptons	-	-	-



4 Lepton Channel: CR distributions

- Distributions of the sum of pT of all jets (H_T) for the different CR:
 - ↳ For ttZ the expected events underestimate observed events, in agreement with the 3L channel
 - ↳ ZZ showing good data-MC agreement.



4 Lepton Channel: DNN model specificities

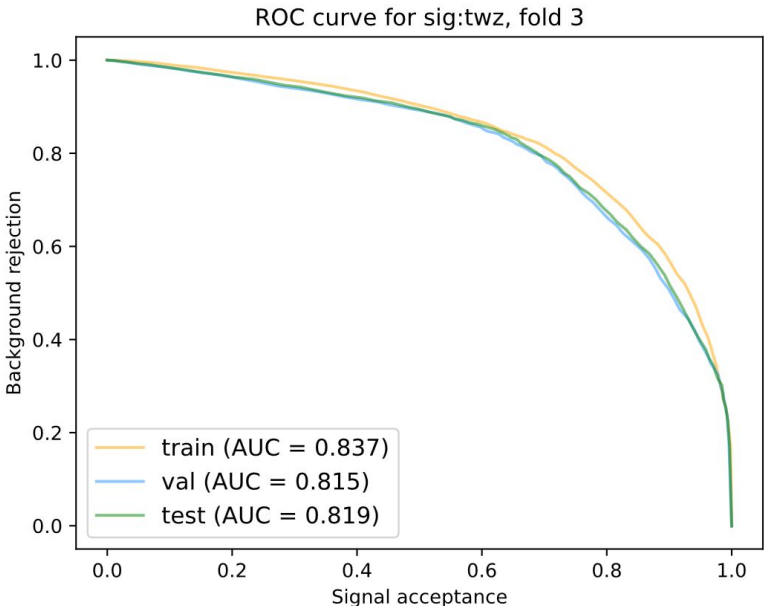
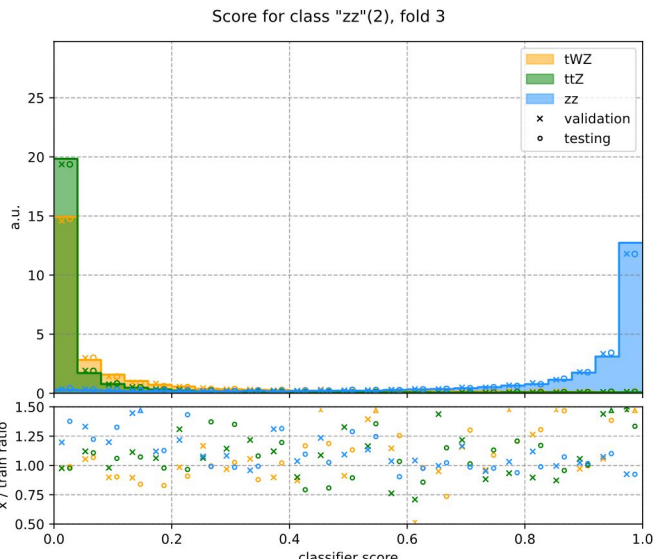
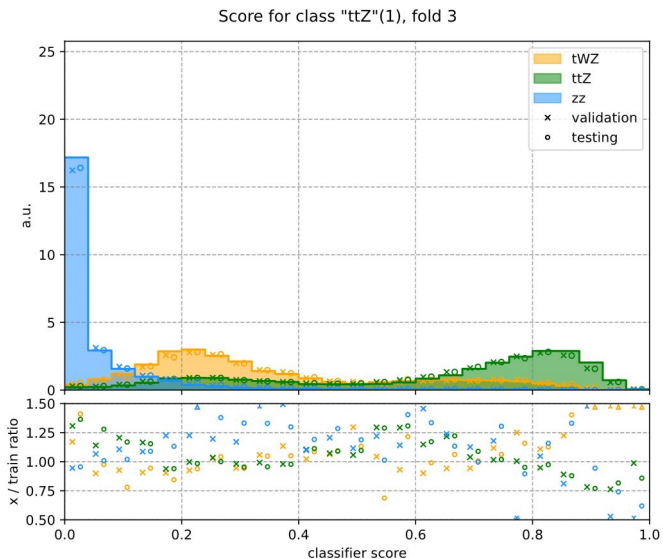
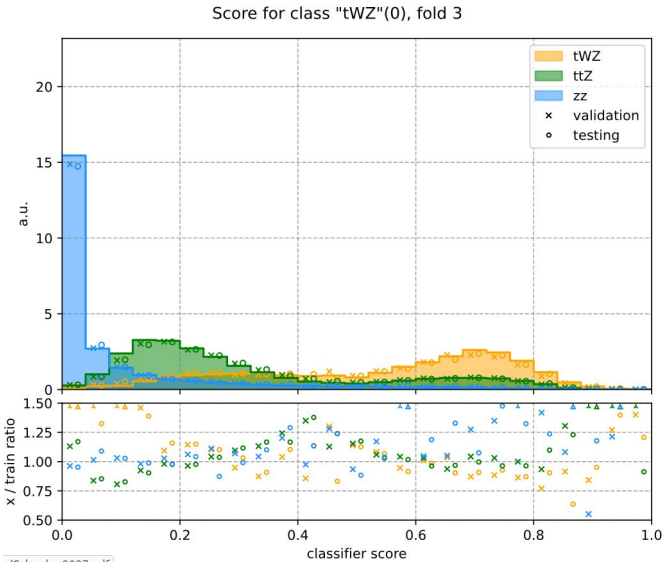
- **3 classes** for the 4L Channel:
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 - ↳ **2 background classes: ttZ and ZZ**
 - Model Architecture:
 - ↳ 42 input features
 - ↳ Normalization layer
 - ↳ 3 hidden Dense layers with 72, 36, and 18 nodes
 - ↳ 4-node softmax output layer
 - Optimizer: Adam
 - Initial learning rate: 10^{-3}
 - Batch size: 32
 - Early stopping: Validation loss, patience of 10 epochs
 - Training with event weights
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- nJets, nBJets and nZCandidates
- missing transverse momentum (MET) and phi
- p_T, η, ϕ for four leading leptons
- p_T, η, ϕ for leading non-Z lepton
- p_T, η, ϕ for leading b-jet
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- $\Delta\phi$ between MET and each of the three leading leptons
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- $\sum p_T$ (Z candidates)
- $\sum p_T$ (leptons)
- $\sum p_T$ (jets)
- $\sum p_T$ (leptons) + $\sum p_T$ (jets)
- $\sum p_T$ (b-tagged jets)
- $\sum p_T$ (leptons) + $\sum p_T$ (jets) + MET
- Second-smallest value of $|172.5 - m(\text{b-jet, lepton})|$

4 Lepton Channel: DNN model training and evaluation

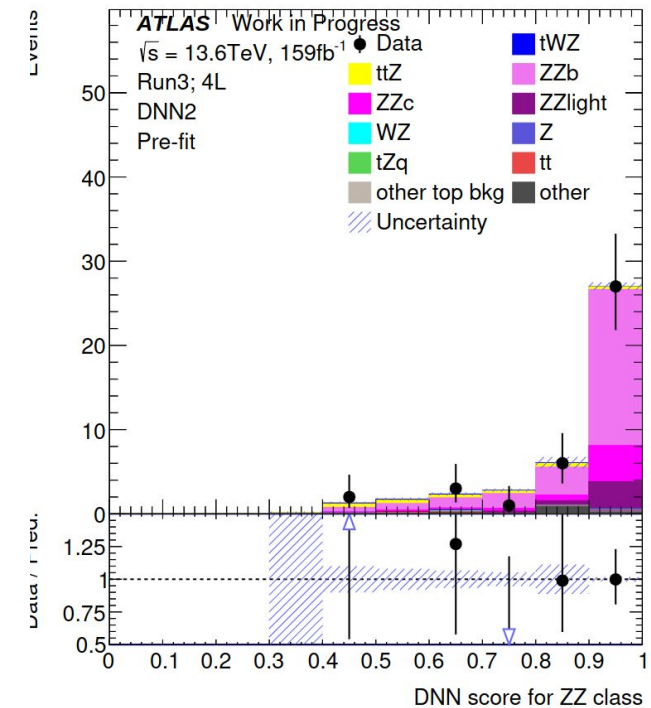
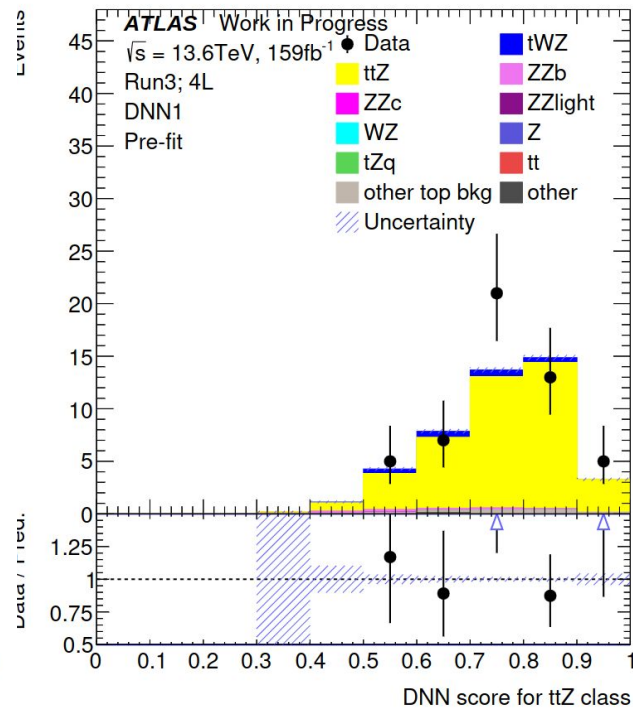
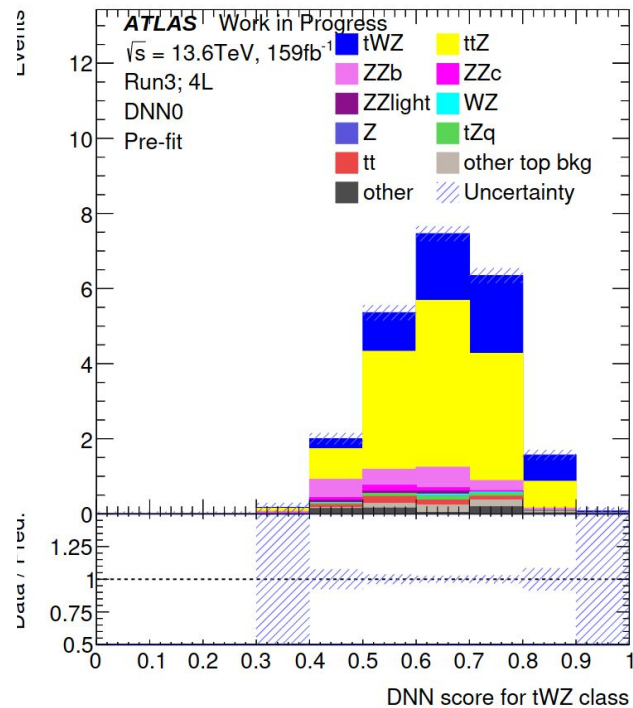
- Here presenting the results for the fourth fold - the remaining folds presented similar results.

It is clear the model classifies ZZ accurately; however requires optimization for tWZ and ttZ separation



4 Lepton Channel: Distributions used on the fit

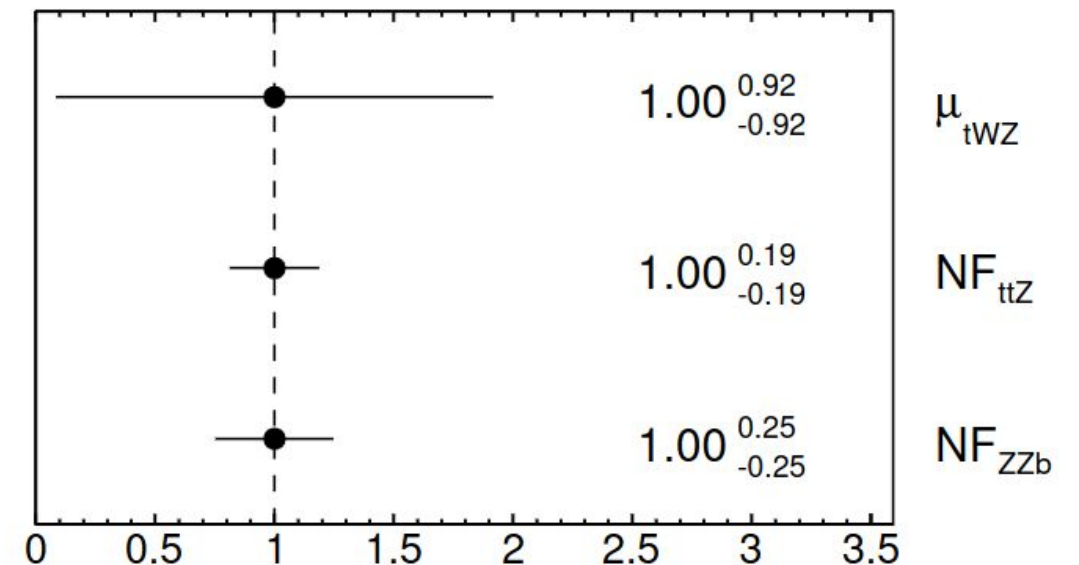
- Here presenting the distributions used for the fit
 - the 3 DNN outputs for each class



4 Lepton Channel: Asimov fits

- Asimov fits using the previously presented distributions
 - ↳ DNN outputs for each class
- Only statistical uncertainties considered
- Extracting the signal strength for tWZ , ttZ and ZZb simultaneously
- **Expected significance: 1.23σ**

ATLAS Work in Progress



Previous CMS results [arxiv:2510.19080](https://arxiv.org/abs/2510.19080)

- The first observation of single top quark production in association with a W and a Z boson in proton-proton collisions was reported. The analysis used:
 - ↳ Data at center-of-mass energies of 13 and 13.6 TeV
 - ↳ Total integrated luminosity of 200 fb⁻¹
- The signal was established with a statistical significance of 5.8 σ , with 3.5 expected, compared to the background-only hypothesis.