Universität Siegen | HEP Experimental High Energy Physics | CPPS Center for Particle Physics Siegen

FSP ErUM

ATLAS EXPERIMENT

color meets flavor

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

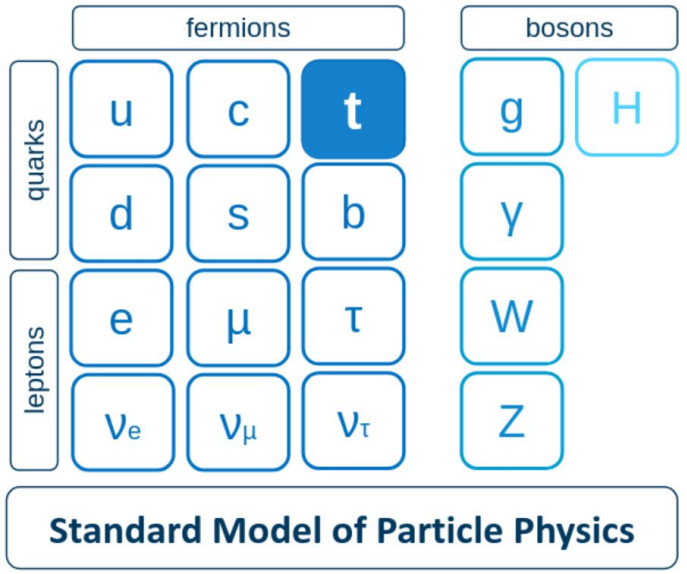
September 2026

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 *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) (arXiv:1209.6215)
  - ↳ 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

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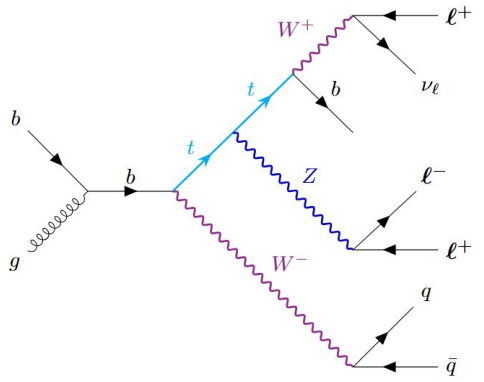
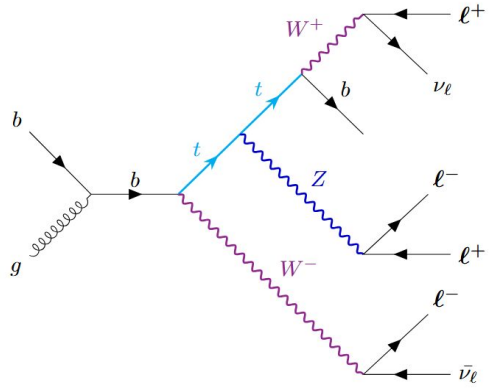


Three Lepton Channel (3L)



Four Lepton Channel (4L)

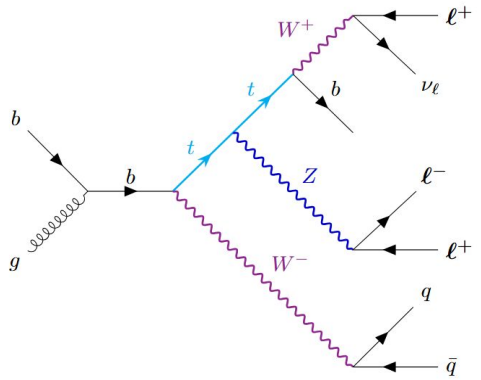
The *tWZ* process

- ***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)

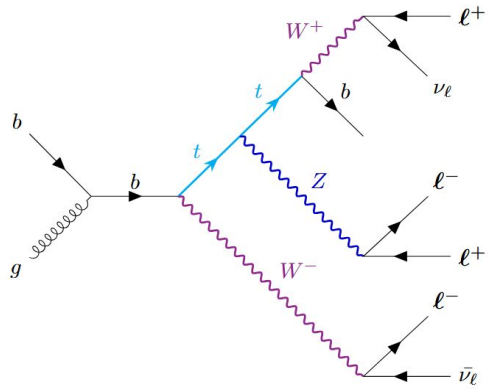
- **Why now?**
  - ↳ Data collected during Run 2 + Run 3 allows enough luminosity for such measurement
  - ↳ CMS measured cross section slightly larger than the SM prediction (arXiv:2510.19080v1)

    measured: $\sigma = 248 \pm 52$ fb at $s = \sqrt{13}$ TeV ; $\sigma = 244 \pm 74$ fb at $s = \sqrt{13.6}$ TeV (arXiv:1405.0301)

    prediction: $\sigma = 136^{+9}_{-8}$ fb at $s = \sqrt{13}$ TeV ; $\sigma = 148^{+10}_{-9}$ fb at $s = \sqrt{13.6}$ TeV (arXiv:1209.6215)
  - ↳ Motivates for an independent measurement from ATLAS Collaboration



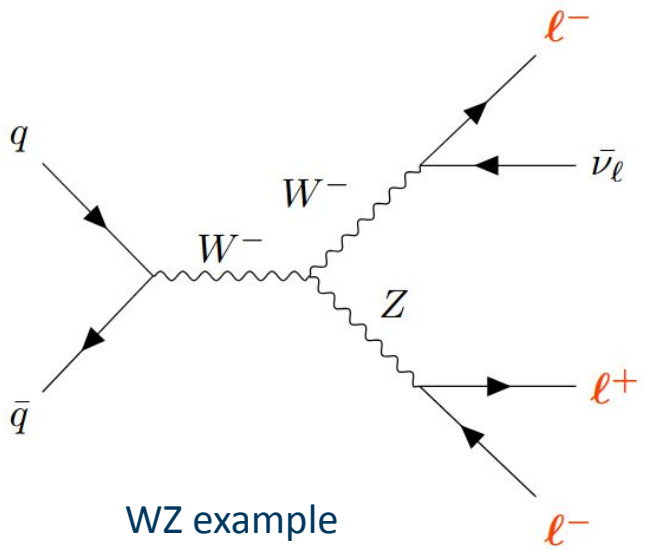
Three Lepton Channel (3L)



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
- The regions rich in tWZ, ttZ and WZ are used to train machine learning methods.
- The regions rich in Zjets and tt contain fake leptons and are used as control regions for the fit.



WZ example

	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 GeV			$>$ 28, 18, 10 GeV	
N_{jets}	≤ 3	≥ 2		≥ 2	
$p_{T\text{jets}}$	$>$ 25 GeV			$>$ 25 GeV	
$N_{b\text{-jets}}$	1	≥ 2	0	1	1
E_T^{miss}	$>$ 30 GeV			$<$ 30 GeV	$>$ 30 GeV
$N_{Z\text{candidate}}$, $\lvert m_{l^-l^+} - m_Z \rvert < 10\,\text{GeV}$	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:

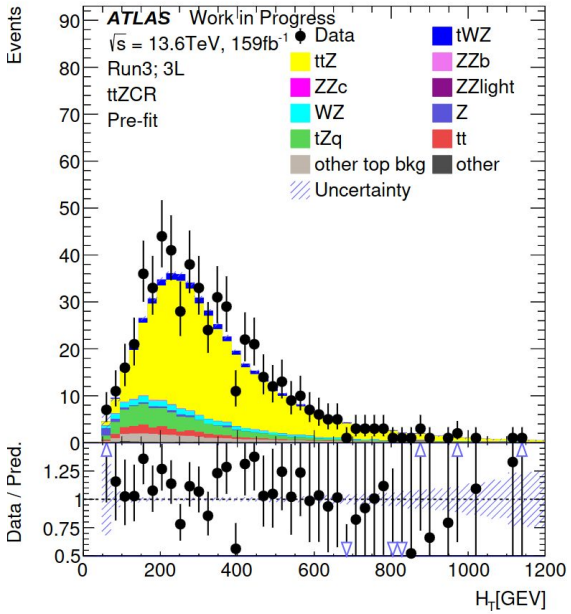
ttW, ttGamma, ttH, ttWW, ttt, tttt, tW

Other:

VVV, W, Vgamma, VH

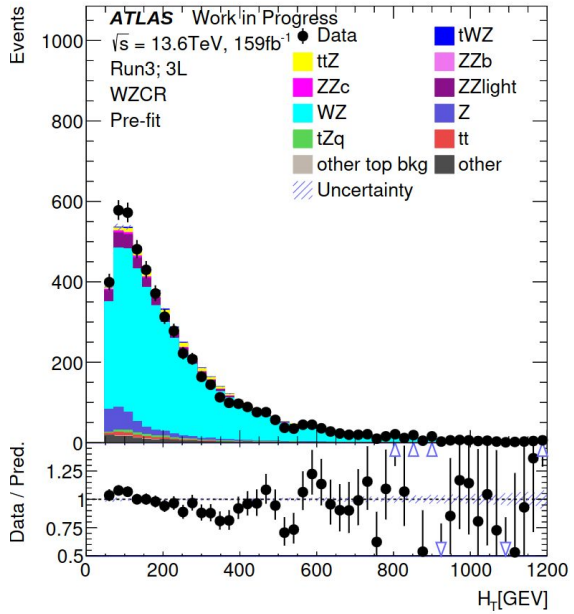
CR: ttZ

H_T



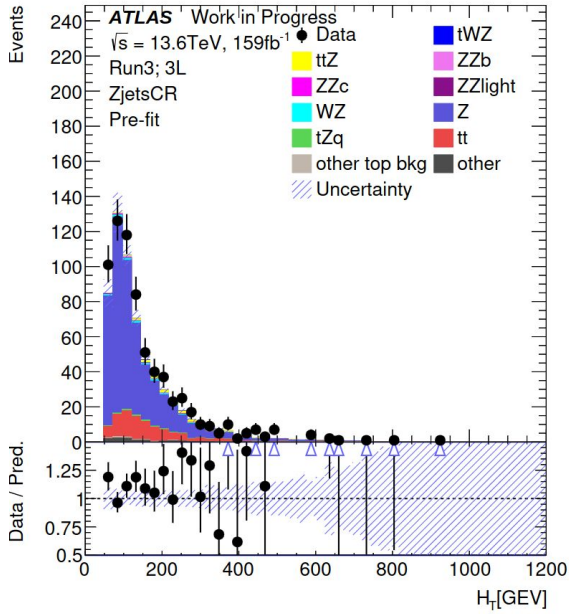
CR: WZ

H_T



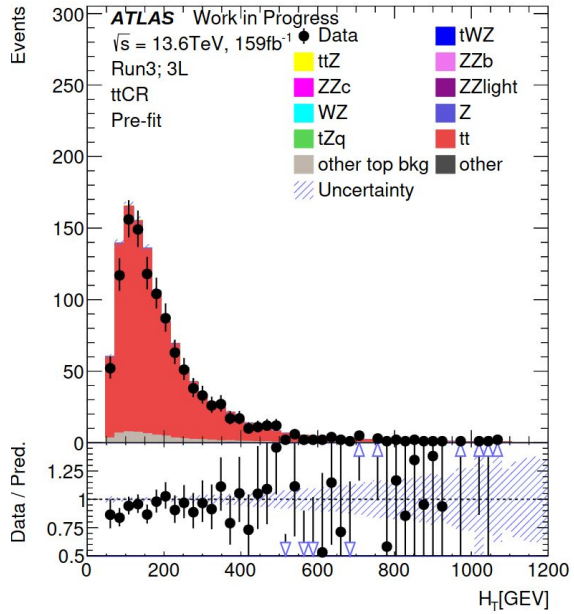
CR: Z+jets

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
- 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

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- nJets, nBJets
- missing transverse momentum (MET) and phi

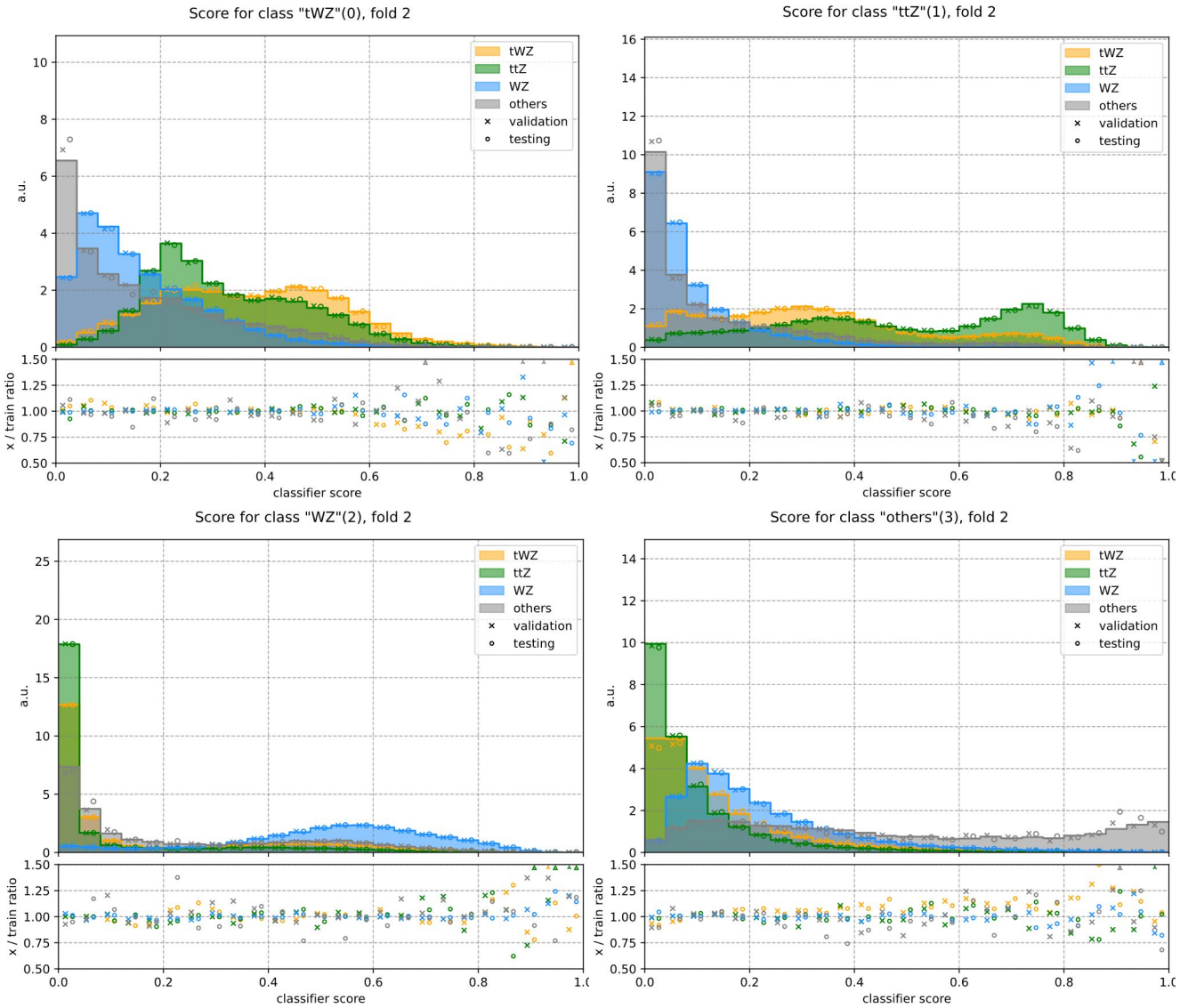
- p_T, η, ϕ for three leading leptons
- p_T, η, ϕ for leading non-Z lepton
- p_T, η, ϕ for two leading jets
- p_T, η, ϕ for leading non-b-jet
- p_T, η, ϕ mass for leading Z candidate

- $\Delta\phi$ between MET and each of the three leading leptons
- $\Delta\phi$ and ΔR between leading b-jet and leading Z candidate

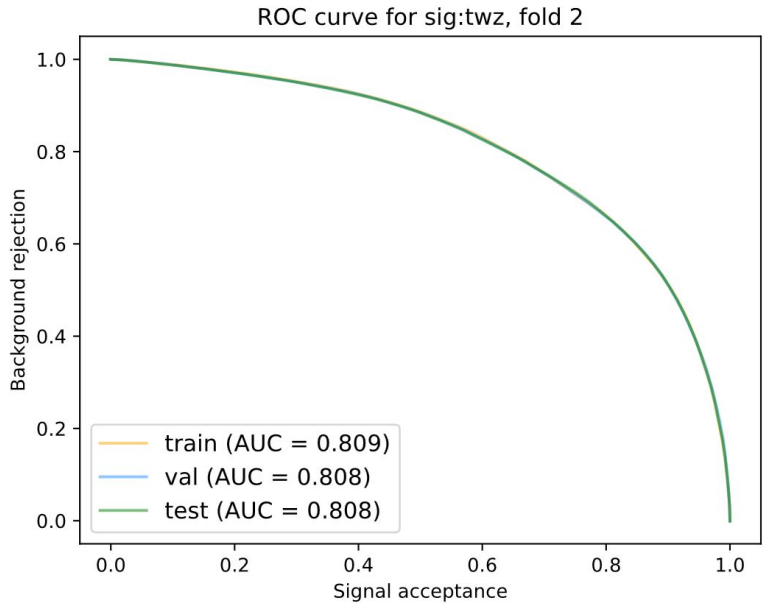
- $\sum p_T$ (Z candidates)
- $\sum p_T$ (jets)
- $\sum p_T$ (b-tagged jets)
- $\sum p_T$ (leptons)
- $\sum p_T$ (leptons) + $\sum p_T$ (jets)
- $\sum p_T$ (leptons) + $\sum p_T$ (jets) + MET

- Second-smallest value of $|172.5 - m(\text{b-jet, lepton})|$

3 Lepton Channel: DNN model training and evaluation

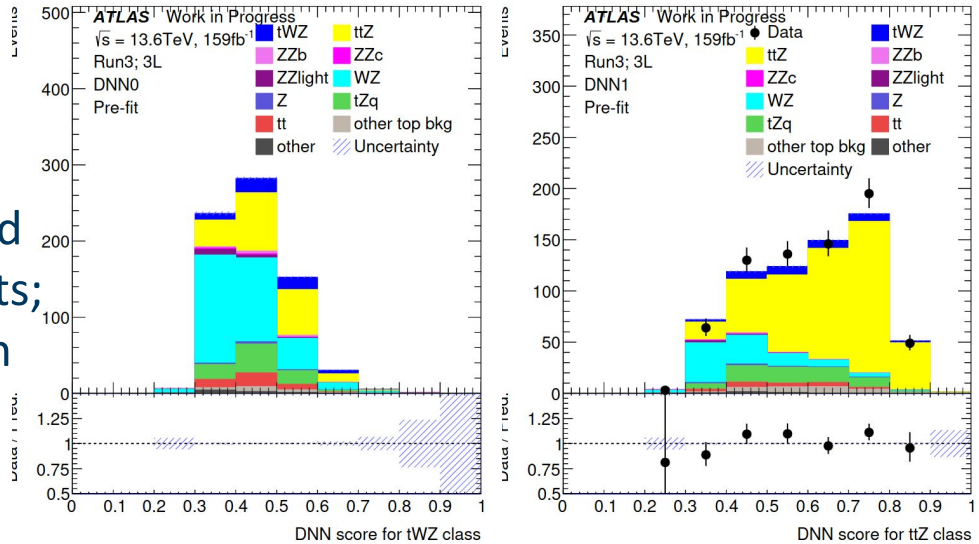


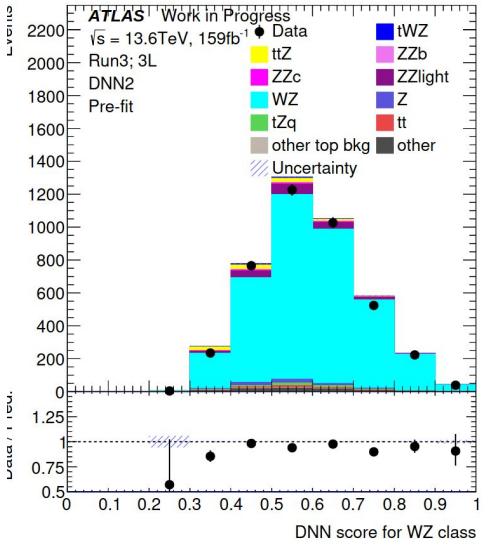
- Here presenting the results for the third fold - the remaining folds presented similar results.

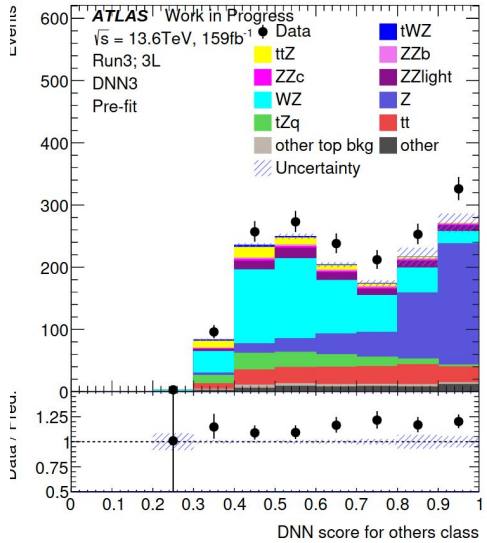


3 Lepton Channel: Distributions used on the fit

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: Distributions used on the fit

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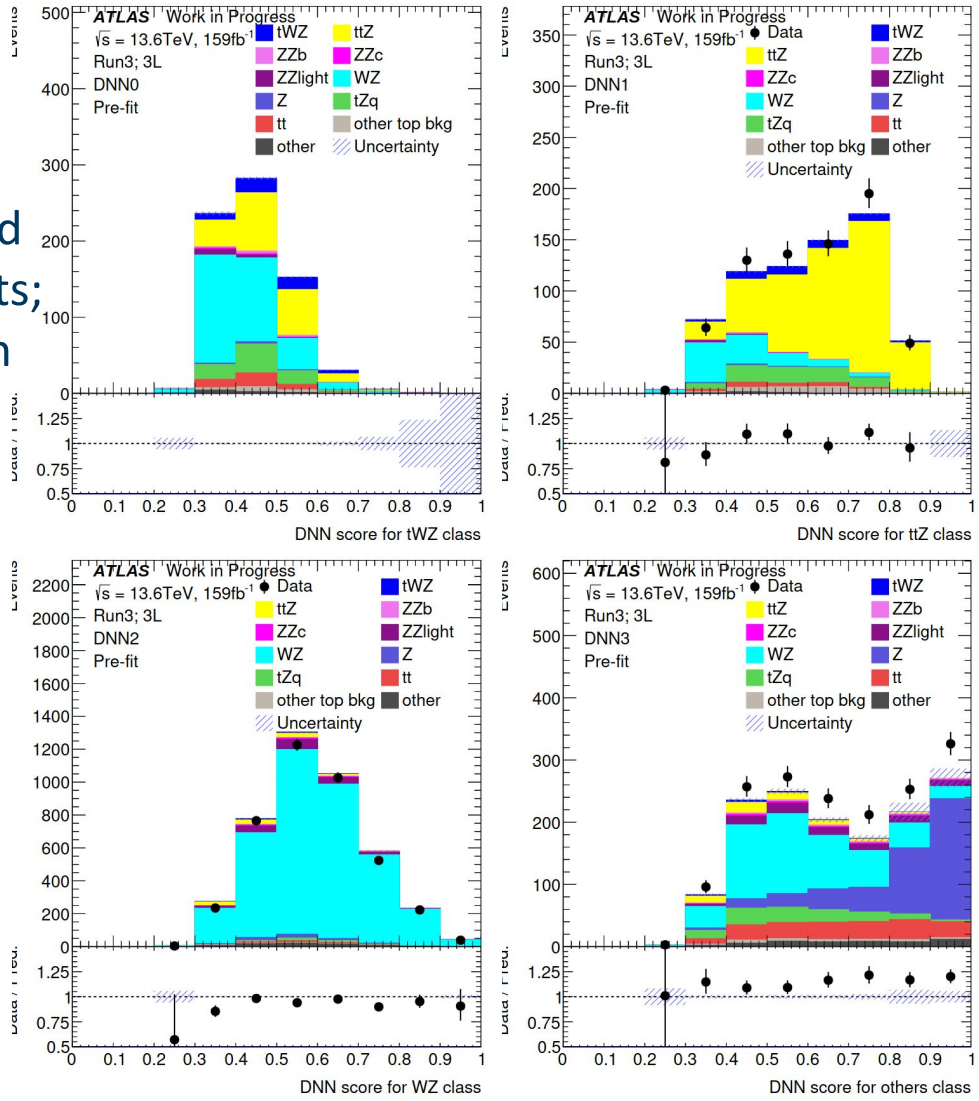

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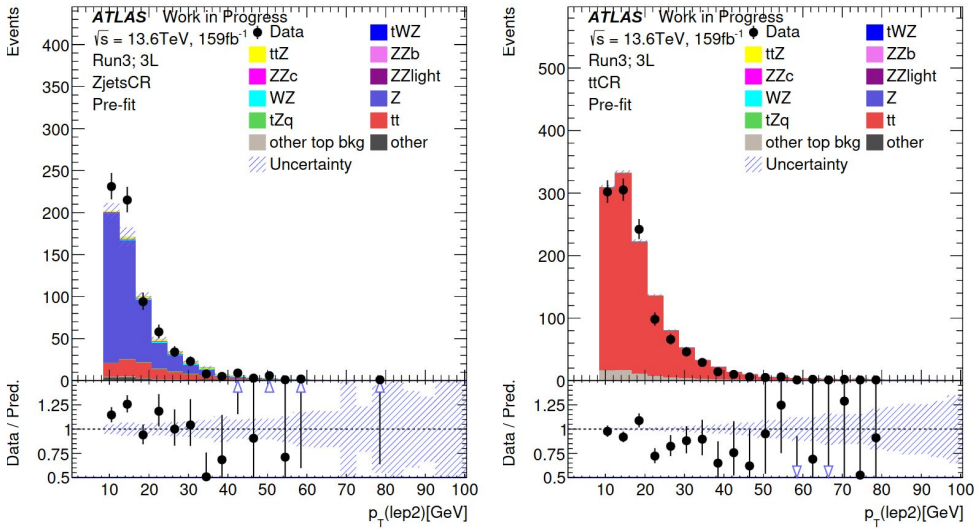
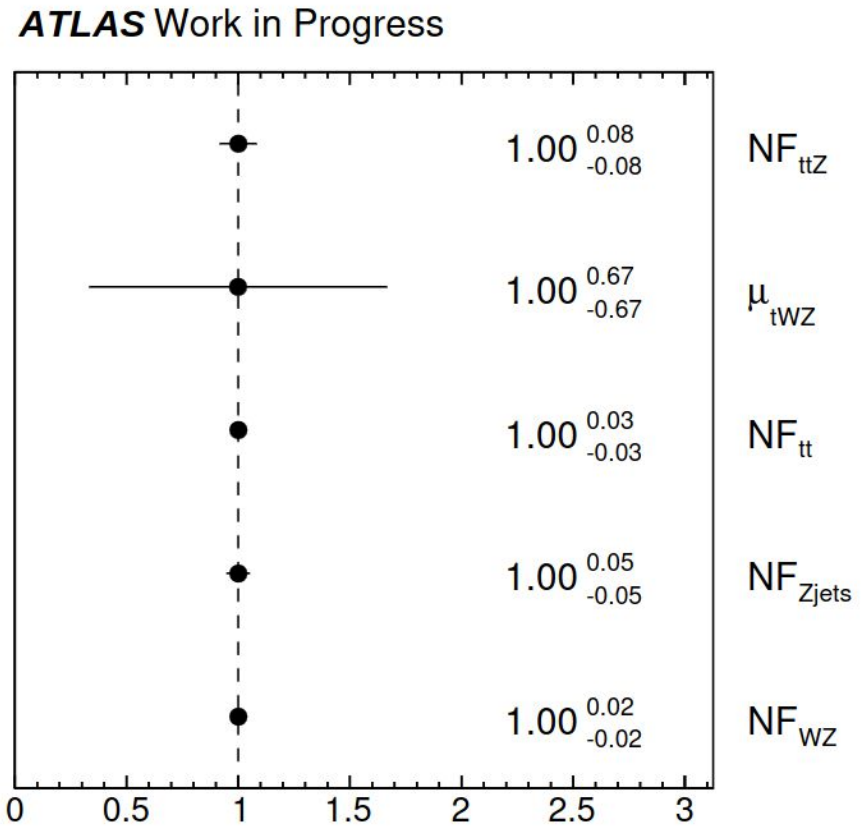


3 Lepton Channel: Asimov fits

- 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**



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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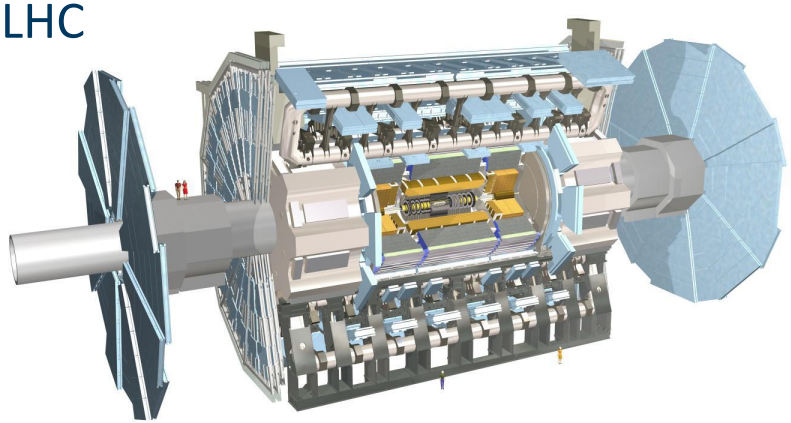
Thank You

57. Herbstschule HEP

Backup slides

The ATLAS Detector at CERN

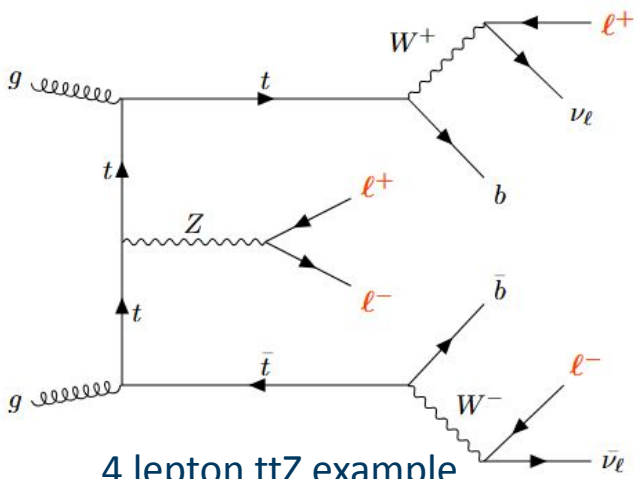
- The Large Hadron Collider (LHC) is the most energetic particle collider ever built
- The ATLAS detector is a general-purpose detector and the largest at LHC
  - ↳ allows for particle tracking and identification
  - ↳ provides precise measurements to test SM predictions and search for BSM physics



- 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: $\sqrt{s}$ **= 13.6 TeV**
  - ↳ This analysis used a Run 3 subset collected between 2022-2024, corresponding to 159 fb^{-1}.

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



4 lepton ttZ example

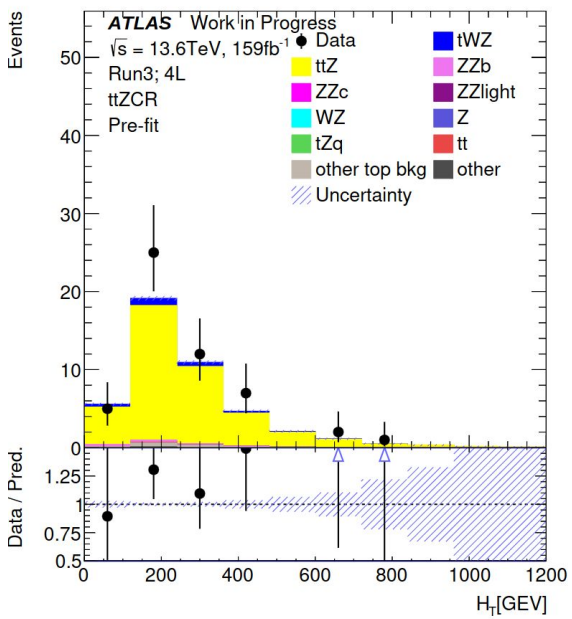
	All regions used for training				
Variable	**tWZ OF Region**	**tWZ SF Region**	**tWZ Loose Region**	**ttZ CR**	**ZZ CR**
$N_\ell^{\text{tight}}(\ell = e, \mu)$	4	4	3	4	4
N_ℓ (loose & not tight)	–	–	1	–	–
$p_T(\ell_1, \ell_2, \ell_3, \ell_4)$	$> 28, 18, 10, 10$ GeV				
N_{jets}	1	1	1	≥ 2	≥ 1
$p_{T\text{jets}}$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

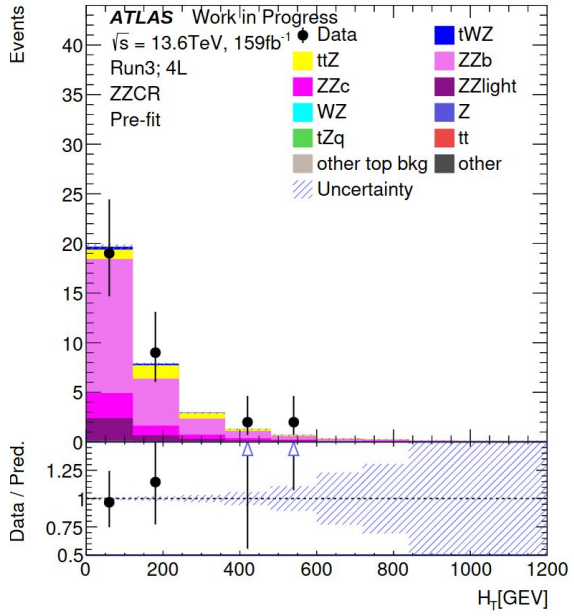
CR: ttZ

H_T



CR: ZZ

H_T



4 Lepton Channel: DNN model specificities

- **3 classes** for the 4L Channel**:**
  - ↳ **signal: tWZ**
  - ↳ **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

- nJets, nBJets and nZCandidates
- missing transverse momentum (MET) and phi

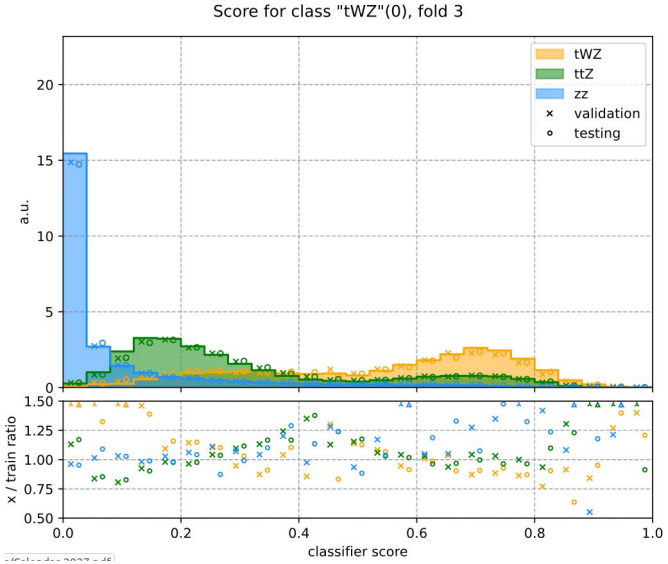
- p_T, η, ϕ for four leading leptons
- p_T, η, ϕ for leading non-Z lepton
- p_T, η, ϕ for leading b-jet
- p_T, η, ϕ for leading non-b-jet
- p_T, η, ϕ mass for leading Z candidate

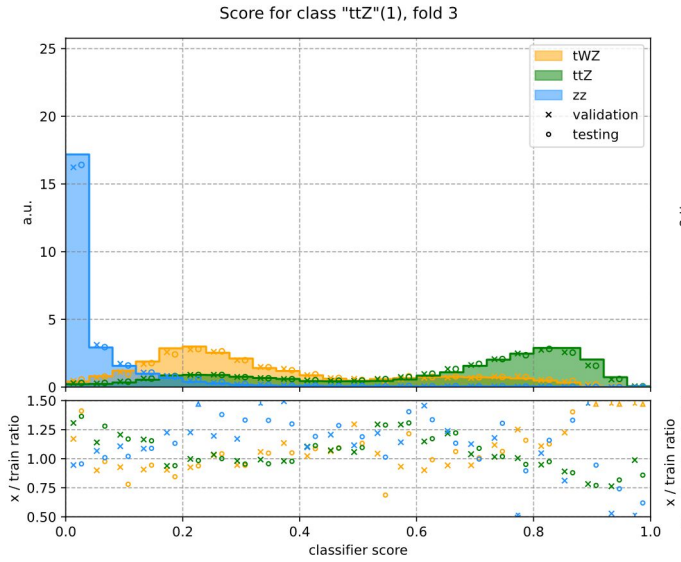
- Δϕ between MET and each of the three leading leptons
- Δϕ and ΔR between leading b-jet and leading Z candidate

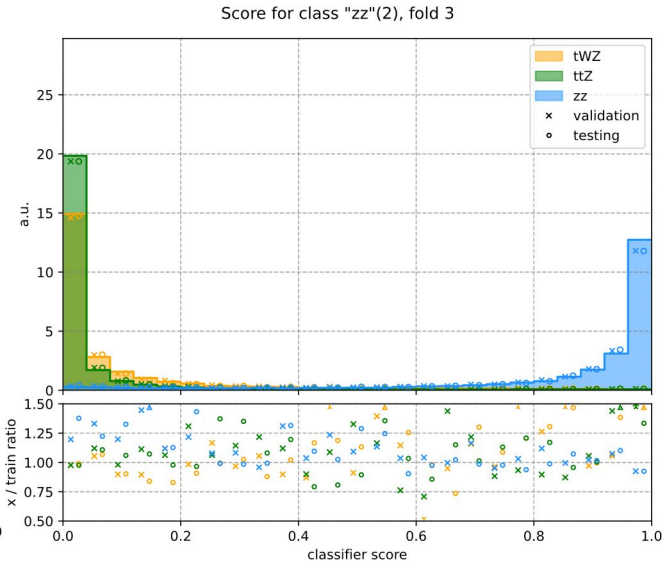
- $\sum p_T$ (Z candidates)
- $\sum p_T$ (jets)
- $\sum p_T$ (b-tagged jets)
- $\sum p_T$ (leptons)
- $\sum p_T$ (leptons) + $\sum p_T$ (jets)
- $\sum p_T$ (leptons) + $\sum p_T$ (jets) + MET

- Second-smallest value of |172.5 - m(b-jet, lepton)|

4 Lepton Channel: DNN model training and evaluation

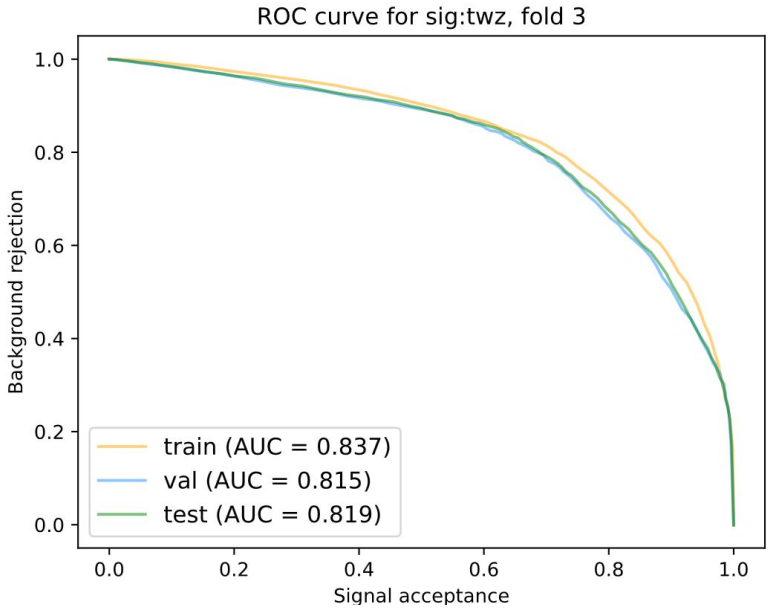






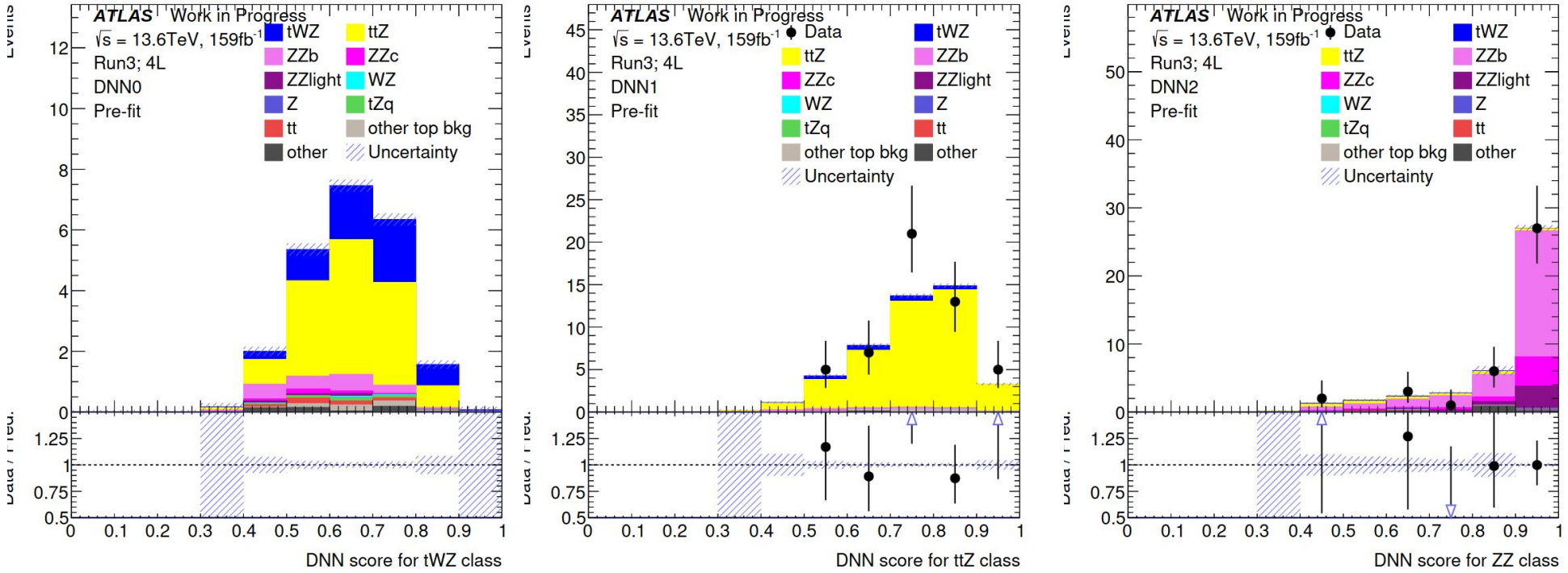
It is clear the model classifies ZZ acuractly; however requires optimization for tWZ and ttZ separation

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



4 Lepton Channel: Distributions used on the fit

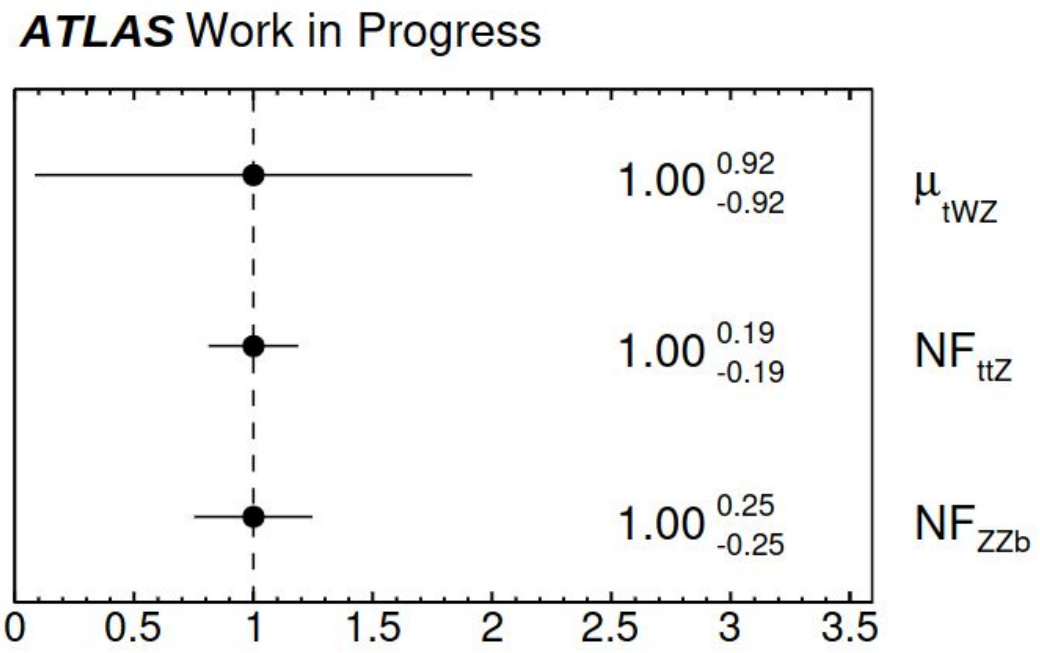
- Here presenting the distributions used for the fit
  - ↳ the 3 DNN outputs for each class



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: 1.23 σ**



Previous CMS results arxiv: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.

Trigger and Preselection

- Current preselection conditions and Object definitions
  - ↳ Study of the possibility of the use of dilepton trigger (ee, μμ, eμ) undergoing.

Preselection	Condition
Trigger	Single electron and muon triggers
Number of loose leptons	≥ 3
Number of jets	≥ 1 with $p_T > 20$ GeV

Electron and Muon Identification

Table 2: Definition of the electron isolation selection criteria. All working points use a cone size of $\Delta R = 0.2$ for calorimeter isolation, and $\Delta R_{\text{max}} = 0.3$ or 0.2 for track isolation. $p_{\text{T}}^{\text{varcone30}}$ uses a variable cone size and is defined in Equation 1.

Selection criteria	Calorimeter isolation	Track isolation
HighPtCaloOnly	$E_{\text{T}}^{\text{cone20}} < \max(0.015 \times p_{\text{T}}, 3.5\ \text{GeV})$	–
TightTrackOnly_VarRad	–	$p_{\text{T}}^{\text{varcone30}}/p_{\text{T}} < 0.06$
TightTrackOnly_FixedRad	–	$p_{\text{T}}^{\text{varcone30}}/p_{\text{T}} < 0.06$ for $E_{\text{T}} < 50$ GeV
		$p_{\text{T}}^{\text{cone20}}/p_{\text{T}} < 0.06$ for $E_{\text{T}} > 50$ GeV
Tight_VarRad	$E_{\text{T}}^{\text{cone20}}/p_{\text{T}} < 0.06$	$p_{\text{T}}^{\text{varcone30}}/p_{\text{T}} < 0.06$
Loose_VarRad	$E_{\text{T}}^{\text{cone20}}/p_{\text{T}} < 0.20$	$p_{\text{T}}^{\text{varcone30}}/p_{\text{T}} < 0.15$

https://arxiv.org/pdf/2308.13362