A search for *tWZ* production at the ATLAS experiment

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The *tWZ* process

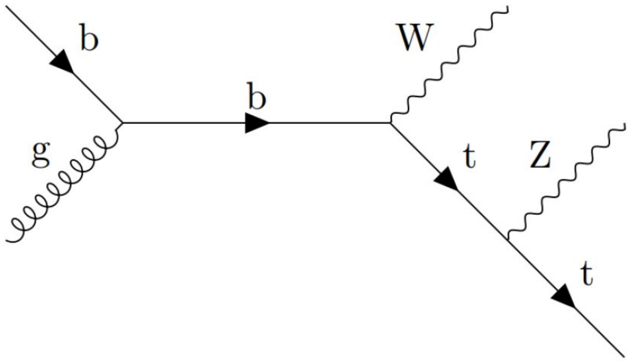
- Extremely rare unobserved SM process
- Used to constrain new physics theories
  - Particularly Standard Model effective field theory (SMEFT)
- Experimental signatures are 3 and 4 lepton with $Z \to \ell\ell$
- CMS found obs. significance of 3.5 (exp. 1.4)[1]

Question: Could *tWZ* be found with the ATLAS Run 2 *pp* dataset (L=140fb^{-1})?

Goal: Measure the cross section σ_{tWZ} and compare it with SM prediction

$\sigma_{tWZ} \cdot Br(Z \to \ell\ell) = 16.1$ fb

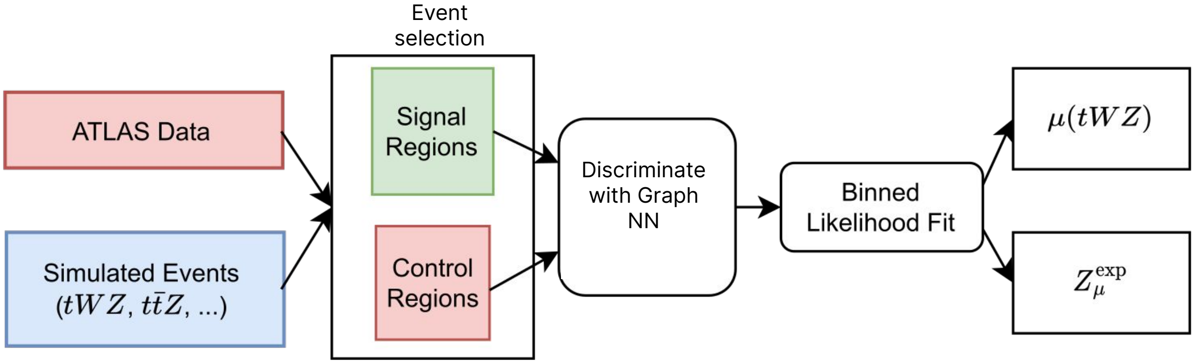
NLO+PS with DR1



Challenges

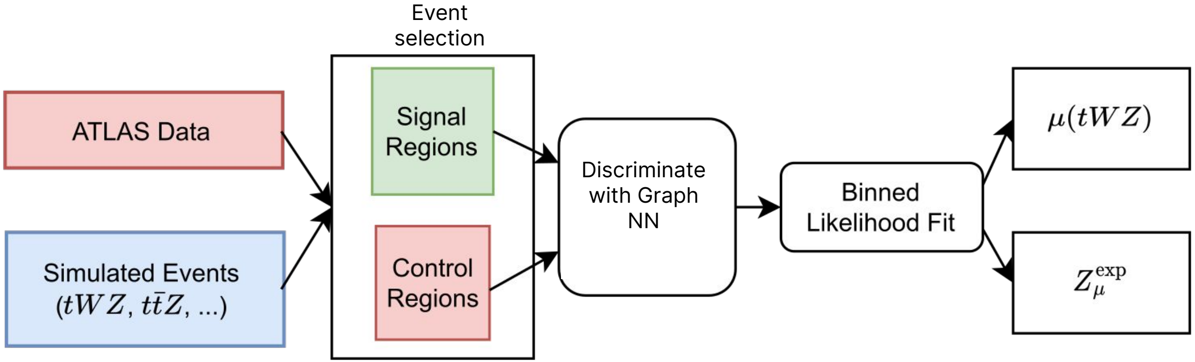
1. Large $t\bar{t}Z$ backgrounds
2. Considerable diagram interference with $t\bar{t}Z$

Analysis Overview



Signal Strength $\mu(tWZ) = \sigma_{Measured}/\sigma_{SM}$	$\mu(tWZ) \approx 0 \rightarrow$ no tWZ measured $\mu(tWZ) \approx 1 \rightarrow$ SM prediction
Expected Significance $Z^{exp} = \Phi^{-1}(1\text{-}p\_value)$	$Z_{\mu}^{exp} \geq 3\sigma \rightarrow$ Reject bkg only $Z_{\mu}^{exp} \geq 5\,\sigma \rightarrow$ Discovery

Analysis Overview



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3ℓ Channel

- Difficult to distinguish from 3ℓ backgrounds
- Backgrounds are trilepton $t\bar{t}Z$ and WZ+jets

4ℓ Channel

- Easier to distinguish but lower statistics
- Backgrounds are tetralepton $t\bar{t}Z$ and ZZ+jets

Signal and Control Regions

Trilepton Regions		
tWZ SR	$t\bar{t}Z$ CR	WZ CR
$N_\ell = 3$	$N_\ell = 3$	$N_\ell = 3$
1 Z Candidate	1 Z Candidate	1 Z Candidate
≥ 3 jets	≥ 4 jets	1 or 2 jets
1 b-tagged jet	≥ 2 b-tagged jet	1 b-tagged jet

Regions are defined based on number of physics objects in an event

Signal regions for signal events and Control regions to estimate background rates

Z candidate is an OSSF lepton pair within 10GeV of m_Z

Signal and Control Regions

Trilepton Regions		
tWZ SR	$t\bar{t}Z$ CR	WZ CR
$N_\ell = 3$ 1 Z Candidate ≥ 3 jets 1 b-tagged jet	$N_\ell = 3$ 1 Z Candidate ≥ 4 jets ≥ 2 b-tagged jet	$N_\ell = 3$ 1 Z Candidate 1 or 2 jets 1 b-tagged jet

Region: A classification for events for isolating a sample based on physical information

Signal regions for signal events and Control regions to estimate background rates

Tetralepton Regions				
tWZ OF SR	tWZ SF SR	tWZ 3T1L SR	$t\bar{t}Z$ CR	ZZb CR
$N_\ell = 4$ 1 Z Candidate ≥ 1 jet 1 b-jet Opp. Flavour Non-Z leptons	$N_\ell = 4$ 1 Z Candidate ≥ 1 jet 1 b-jet Same Flavour Non-Z leptons	$N_\ell = 3,\ N_{\ell,\text{not tight}} = 1$ 1 Z Candidate ≥ 1 jet 1 b-jet	$N_\ell = 4$ 1 Z Candidate ≥ 2 jet 2 b-jet	$N_\ell = 4$ 2 Z Candidate ≥ 1 jet 1 b-jet

Signal and Control Regions

Trilepton Regions		
tWZ SR	$t\bar{t}Z$ CR	WZ CR
$N_\ell = 3$	$N_\ell = 3$	$N_\ell = 3$
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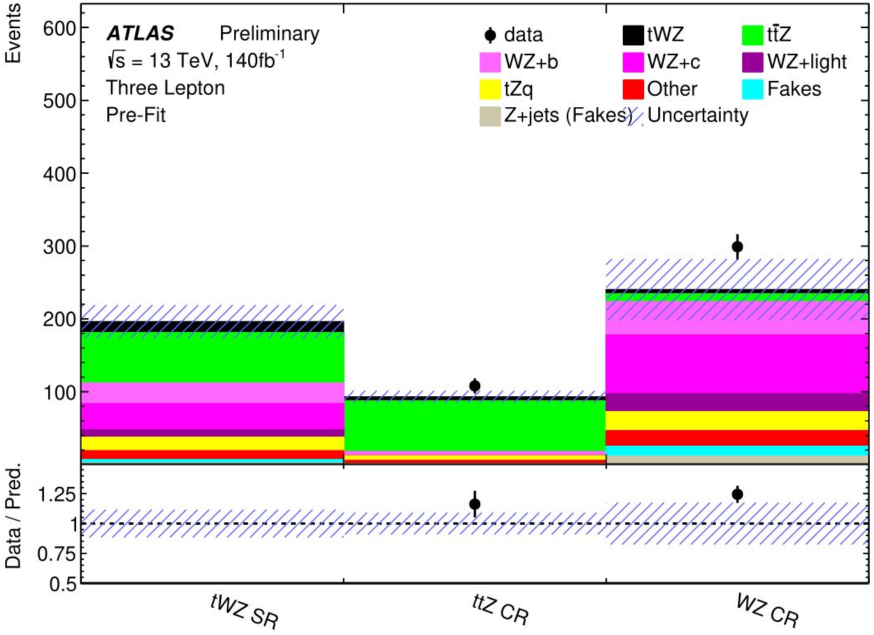
tWZ OF SR	tWZ SF SR	tWZ 3T1L SR	$t\bar{t}Z$ CR	ZZb CR
$N_\ell = 4$	$N_\ell = 4$	$N_\ell = 3$, $N_{\ell,\text{not tight}} = 1$	$N_\ell = 4$	$N_\ell = 4$
1 Z Candidate	1 Z Candidate	1 Z Candidate	1 Z Candidate	2 Z Candidate
≥ 1 jet	≥ 1 jet	≥ 1 jet	≥ 2 jet	≥ 1 jet
1 b-jet	1 b-jet	1 b-jet	2 b-jet	1 b-jet
Opp. Flavour Non-Z leptons	Same Flavour Non-Z leptons			

tWZ OF and *tWZ SF* defined based on the flavours of the two non-Z leptons

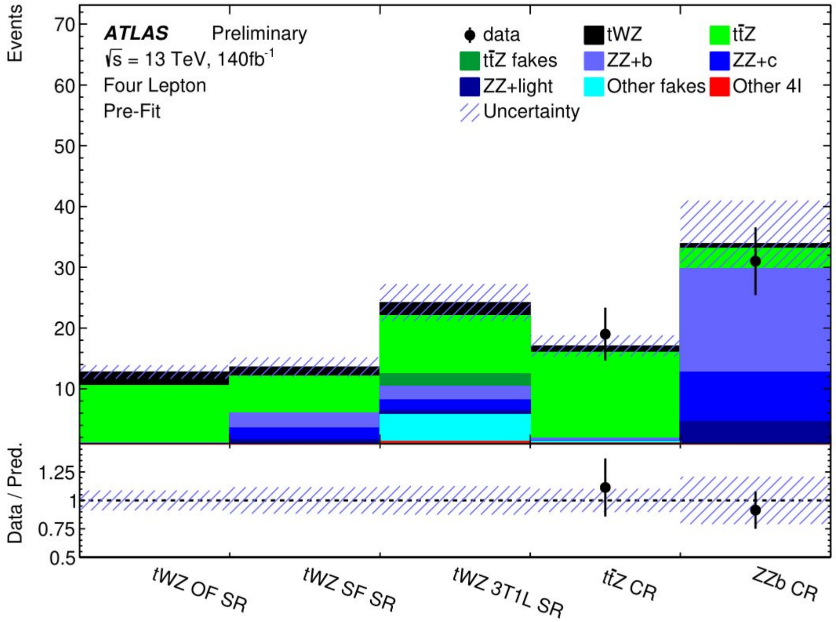
Region Summary

Trilepton



Poor modelling in WZ CR

Tetralepton



Large background contributions in SRs

Graph Neural Networks

A **graph** is a set of nodes with a set of edges between them.

A **GNN** is a neural network which uses graphs as input

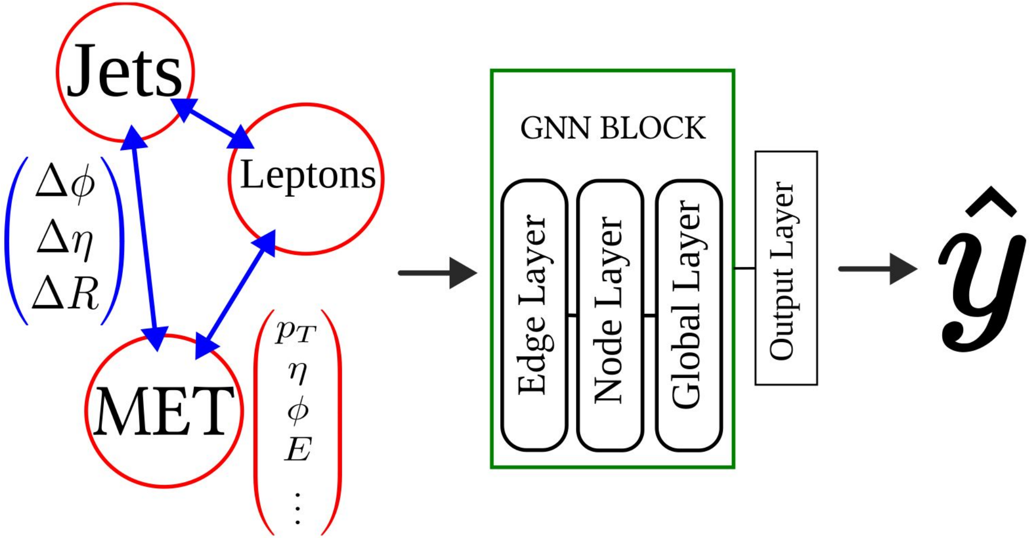
- **Benefits**
  - No ordering of objects
  - No limit on number of objects
- **Drawbacks**
  - Cost of graph construction
  - Less mature tooling

Graph construction from event

Nodes → Info about object

Edges → Angular difference between objects

Global → Graph-wide features



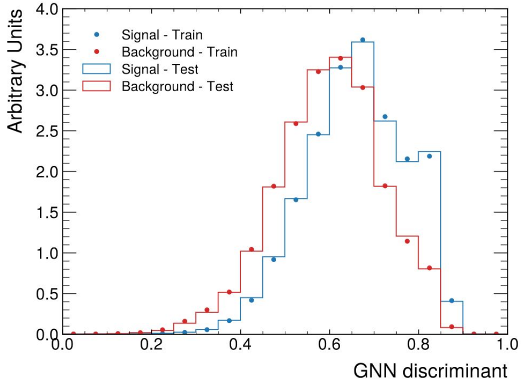
Signal/Background Discrimination with GNN

We want to define a variable to **discriminate *tWZ* events from background events** in our signal regions

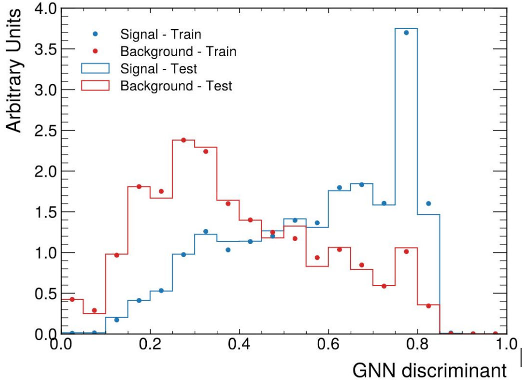
- Trained binary classification GNN models
  - Signal = 1 and Bkg = 0
- Separate models for trilepton and tetralepton channels

Tetralepton model shows better performance due to simpler background composition

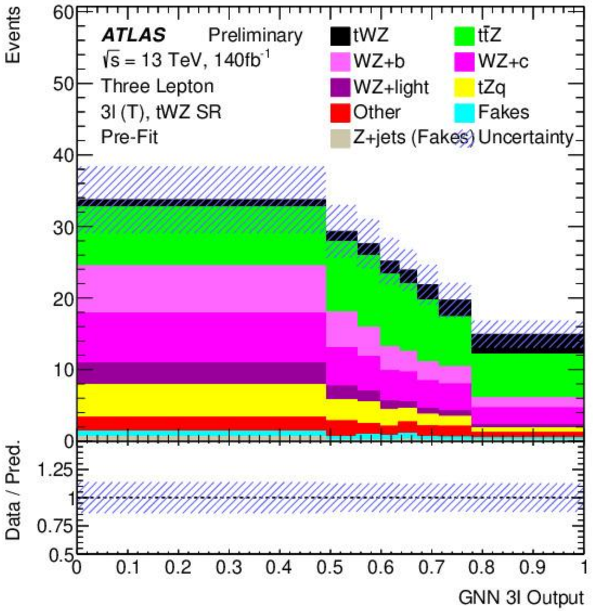
Trilepton Model



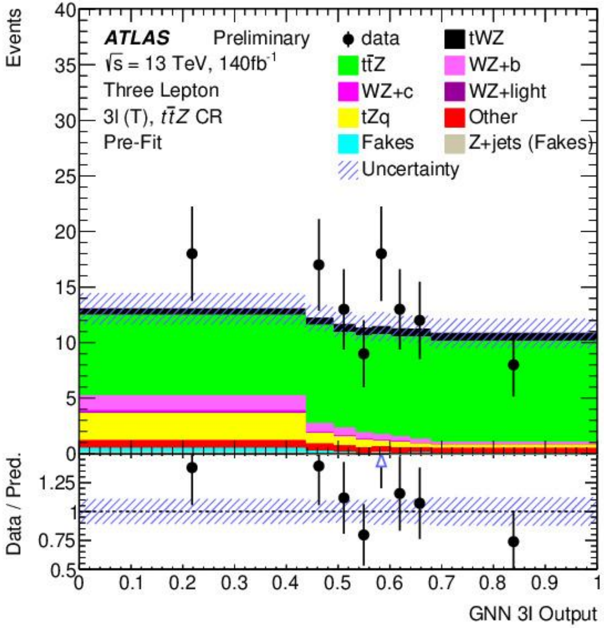
Tetralepton Model



Trilepton GNN Score



tWZ SR



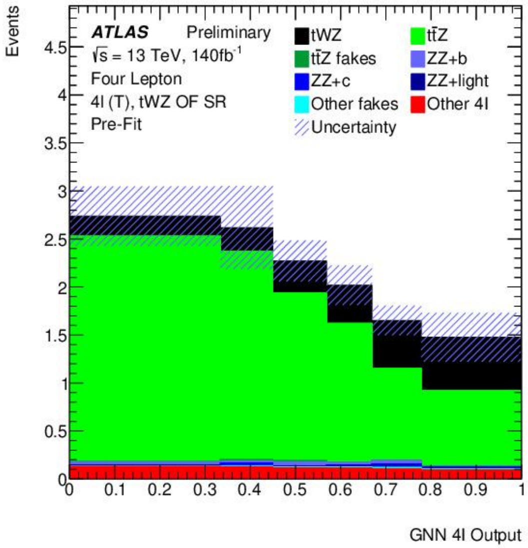
ttZ CR

GNN provides good separation in *tWZ* SR

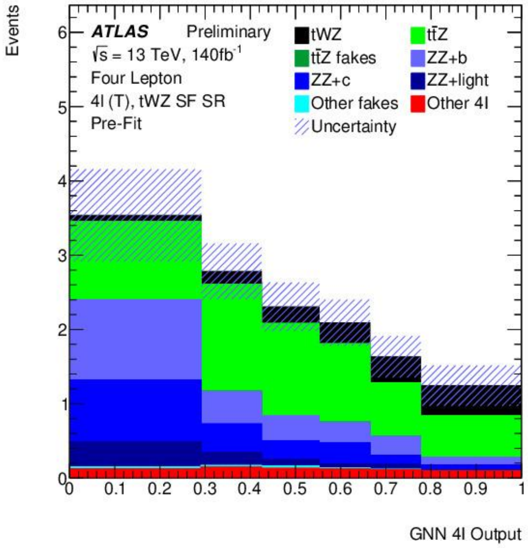
Generally good agreement between data and simulation in CR

Tetralepton GNN Score

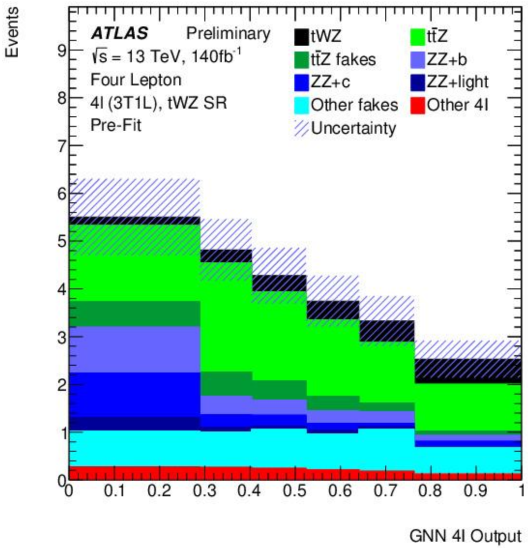
tWZ OF SR



tWZ SF SR



tWZ 3T1L SR

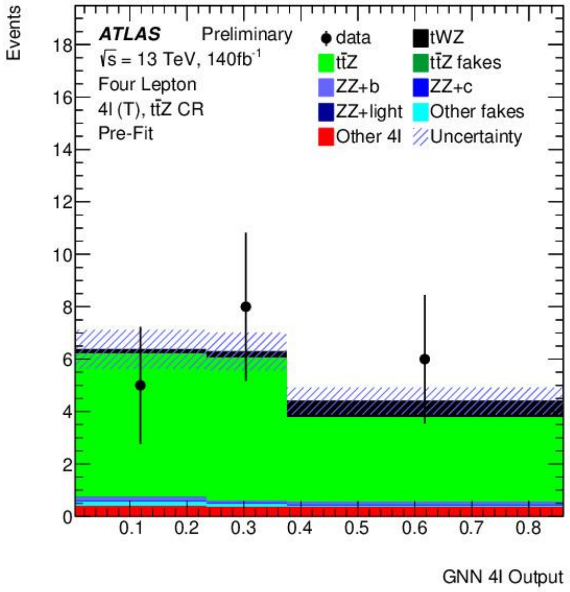


Great discrimination from the GNN

Low event counts in 4 lepton channel

Tetralepton GNN Score in CR

ttZ CR



Good agreement between data and simulation across CRs

Signal Extraction Method

- Performed a binned profile likelihood fit using μ *(tWZ)* as parameter of interest
- Nuisance Parameters
  - Experimental Systematic Uncertainties
  - Theoretical Systematic Uncertainties
- Fits are blinded (Asimov) to avoid bias

Experimental Uncertainties
Luminosity
Pileup
Jet Vertex Tagger
Jet Flavour Tagging
Object Energy Scale/Resolution
Lepton Scale Factors
and more

Theory Uncertainties
Cross section estimations
μ_R / μ_F scale variations
Alternative event generators
Parton Distribution Function

Blinded: The ATLAS data in all regions is replaced with Asimov dataset

Asimov Dataset: Toy dataset whose number of entries is the same as each bin is equal to the simulated value

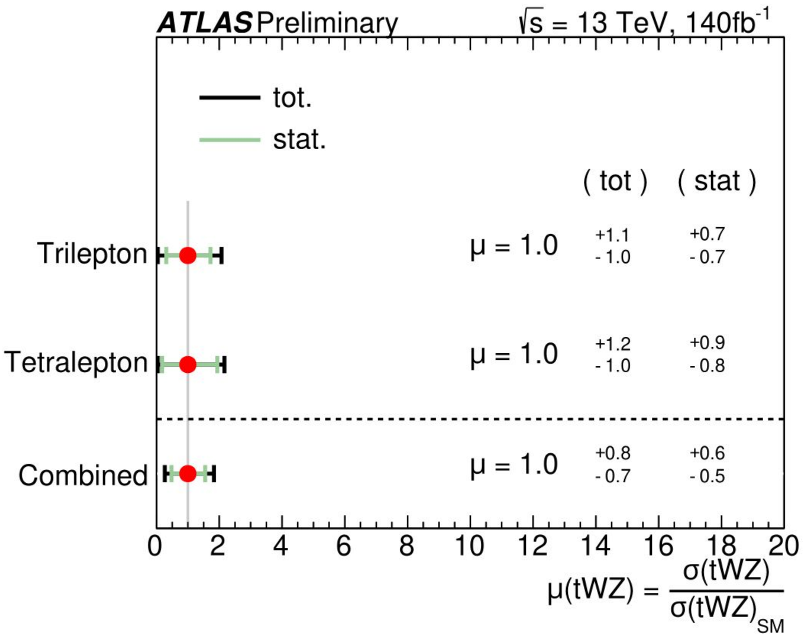
Blinded Results

- Similar sensitivity between 3 lepton and 4 lepton channels
- Combined result improves sensitivity
- Both statistically and systematically limited

$$\mu_{tWZ} = 1.00^{+0.56}_{-0.53}(\text{stat.})^{+0.54}_{-0.41}(\text{syst.})$$

Dominant Systematics

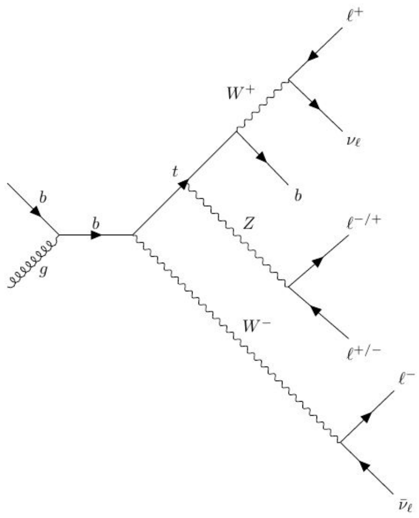
1. $t\bar{t}Z$ cross section normalisation
2. Jet Energy Resolution (JER)
3. PDF uncertainty of tWZ sample



$$Z^{\text{exp}} = 1.34\sigma$$

Summary

- tWZ process is a rare and never-before-observed process
- Difficult to measure due to large $t\bar{t}Z$ backgrounds and low number of events
- Explored both the trilepton and tetralepton channels
- GNN was used for S/B discrimination
- Measured an expected significance of $Z^{\text{exp}} = 1.34\sigma$
    - Similar to CMS



$$\mu_{tWZ} = 1.00^{+0.56}_{-0.53}(\text{stat.})^{+0.54}_{-0.41}(\text{syst.})$$

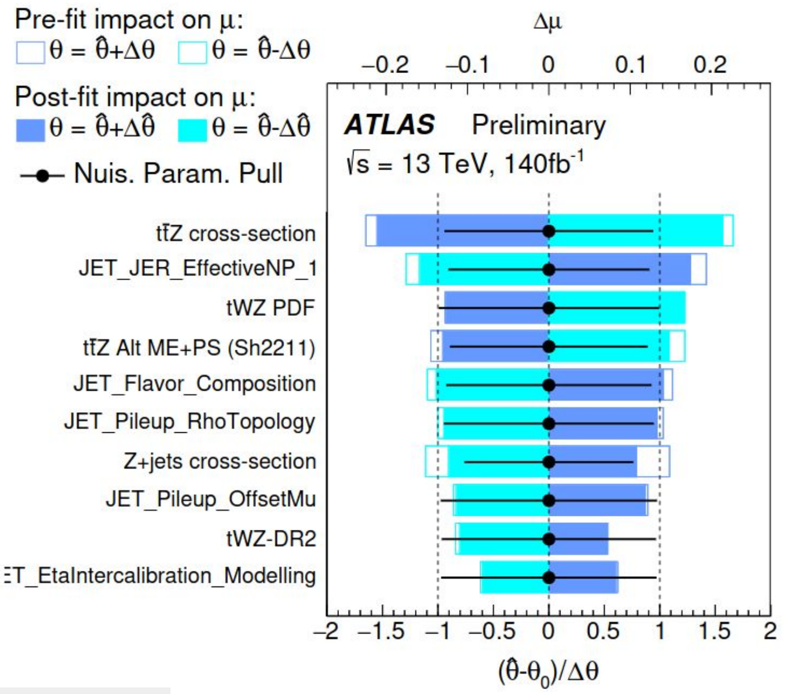
Both statistically and systematically limited

Backup

Investigating the Systematic Uncertainties

Impact: How much a systematic affects the fitted value of *μ(tWZ)*

Large impacts due to $t\bar{t}Z$ cross section estimation and jet modelling systematics



Blue is how much the value of *μ(tWZ)* changes when systematic varies (top axis)
Black is value of systematic post-fit (bottom axis)

Data and Simulation samples

ATLAS Full Run 2 proton proton collisions
at $\sqrt{s}$ = 13 TeV

Years	Luminosity (fb^{-1})
2015 + 2016	3.2 + 33.0
2017	44.3
2018	58.5
Total	139

Simulation Samples

tWZ-DR1
tWZ-DR2
$t\bar{t}Z$
ZZ
WZ
$t\bar{t}h$
$t\bar{t}$
VVV
$t\bar{t}\gamma$
+ others

Diagram removal (DR): Accounting for higher order $t\bar{t}Z$ diagrams

More systematics

Experimental Systematics
Luminosity
Pileup
Jet Vertex Tagger
Jet Flavour Tagging
Jet Energy Scale/Resolution
e/gamma Scale/Resolution
μ Scale/Resolution
E_T^{miss} Soft terms
Lepton Scale Factors
and more

Theory Systematics
Cross section estimations
muR/muF scale variations
Alternative event generators
PDF calculations

Trilepton Region Definitions

Baseline selections
$N_\ell = 3$
$p_T(\ell_1, \ell_2, \ell_3) > (30, 20, 14)$ GeV
p_T(jet) > 25 GeV, $\lvert\eta(\text{jet})\rvert < 2.5$, JVT > 0.5
$\lvert\eta(\ell_e)\rvert < 2.47$ excluding $1.37 < \lvert\eta(\ell_e)\rvert < 1.52$
$\lvert\eta(\ell_\mu)\rvert < 2.5$
All OSSF lepton pairs require $m_{\text{OSSF}} > 10$ GeV
1 Z Candidate (OSSF pair where $m_{ll} - m_Z < 10$ GeV

Regions

tWZ SR	$t\bar{t}Z$ CR	WZ CR
≥ 3 jets 1 b-tagged jet	≥ 4 jets ≥ 2 b-tagged jet	1 or 2 jets 1 b-tagged jet

Tetralepton Region Definitions

Baseline selections
$p_T(\ell_1, \ell_2, \ell_3, \ell_4) > (28, 18, 10, 10)$GeV
p_T(jet) > 20 GeV, $\lvert\eta(\text{jet})\rvert < 2.5$, JVT > 0.5
$\lvert\eta(\ell_e)\rvert < 2.47$ excluding $1.37 < \lvert\eta(\ell_e)\rvert < 1.52$
$\lvert\eta(\ell_\mu)\rvert < 2.5$
$\sum_\ell q_\ell = 0$
All OSSF lepton pairs require $m_{\text{OSSF}} > 10$ GeV

Regions

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≥ 1 jet	≥ 1 jet	≥ 1 jet	≥ 2 jet	≥ 1 jet
1 b-jet	1 b-jet	1 b-jet	2 b-jet	1 b-jet
Opp. Flavour	Same Flavour			
Non-Z leptons	Non-Z leptons			