A search for tWZ production with the ATLAS detector

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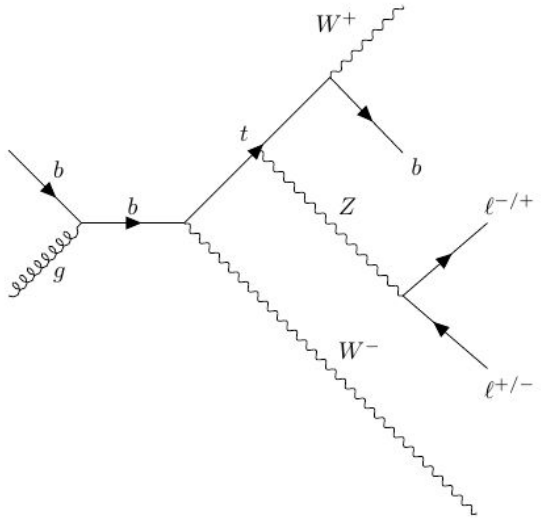
The tWZ process

$\sigma_{tWZ} \cdot Br(Z \to \ell\ell) = 16.06$ fb

$N_{Run2} \approx 9$ events

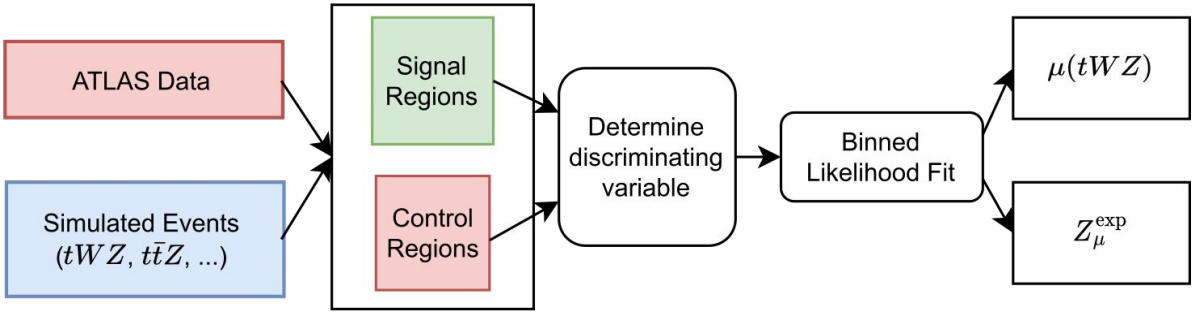
- tWZ process is the electroweak production of a top quark and an associated W and Z boson
- The rates of tWZ production is dependent on top electroweak couplings
- Top EW couplings is an area of interest for beyond SM theories
- Could be used to constrain new theories



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

1. Particularly rare process
2. Considerable diagram overlaps with $t\bar{t}Z$

Analysis Overview



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

3ℓ Channel (B Warren)

- Requires 1 hadronically and 1 leptonically decaying W bosons
- Difficult to distinguish from 3ℓ backgrounds
- Backgrounds are $t\bar{t}Z$ and WZ
- Being updated with latest calibrations and samples

4ℓ Channel (J Reich)

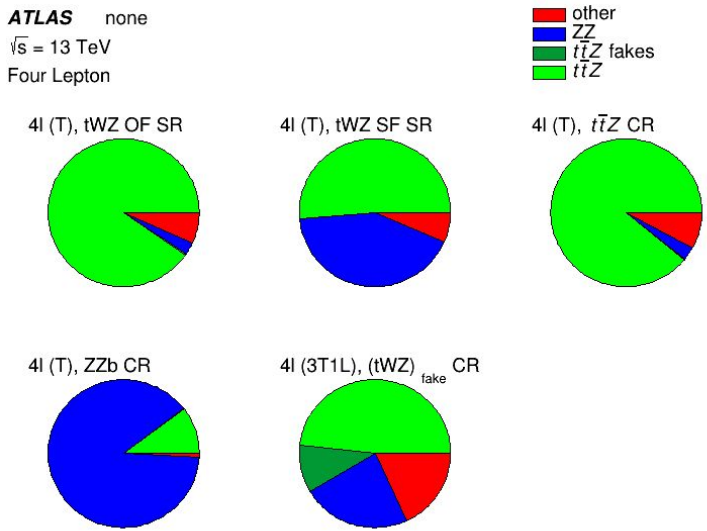
- Requires 2 leptonically decaying W bosons
- Easier to distinguish but lower statistics
- Backgrounds are $t\bar{t}Z$ and ZZ
- Updated results available and will be the focus

Signal and Control Regions for 4ℓ Channel

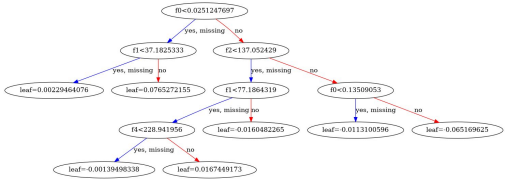
Name	Samples of interest	Variable
tWZ Opp. Flav. SR	tWZ	BDT Discr.
tWZ Same Flav. SR	tWZ Captures ZZ background	BDT Discr.
tt̄Z CR	tt̄Z	BDT Discr.
ZZb CR	ZZ	Sum. p_T of leptons, jets and E_T^{miss} (SMT)
tWZ fake CR	Fake leptons in tt̄Z sample	Loose lepton p_T

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

Signal regions for signal and Control regions for background



Signal/Background Discrimination



ATLAS EXPERIMENT

We want to define variable to differentiate tWZ events and background events in our SR regions

Two Neutrino Scanning Method (2vSM)

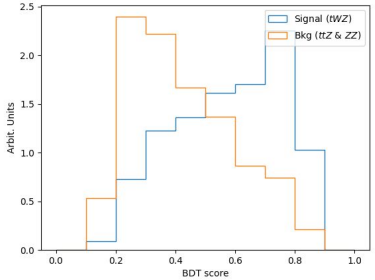
- Discriminate tWZ from $t\bar{t}Z$ using $t\bar{t}$ system
- Reconstruct top quarks and E_T^{miss} for various possible neutrino kinematics
- Find maximum ω_{2vSM}
- Produces score between 0 and 1
- Larger score means more likely to have a $t\bar{t}$ system

$$\omega_{2vSM} = Pr(m_1)\ Pr(m_2)\ Pr(\Delta E_x^{miss})\ Pr(\Delta E_y^{miss})$$

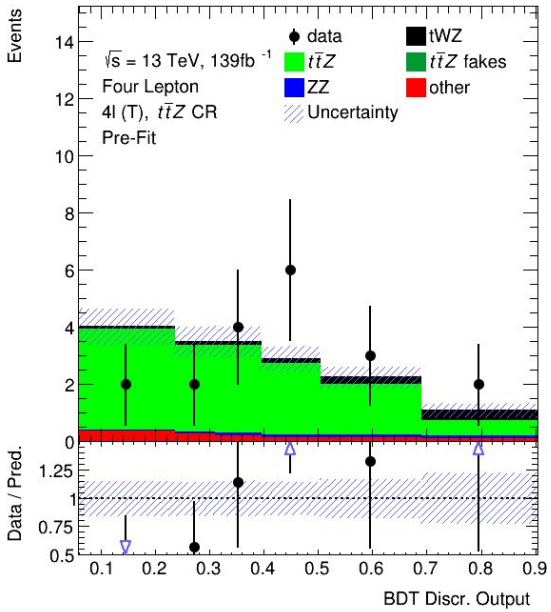
Event level Boosted Decision Tree (BDT)

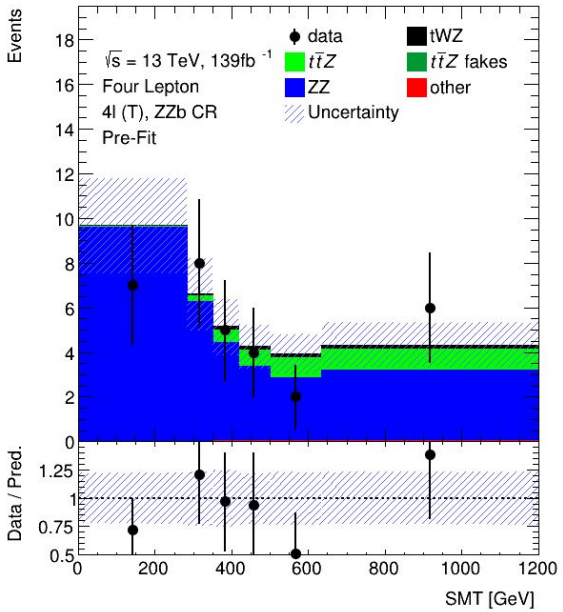
- Gives a score from 0 to 1 for each event
- Inputs
  - Maximum ω_{2vSM}
  - Sum of jet p_T
  - Sum of b-jet p_T
  - Sum of lepton p_T
  - $\Delta\eta$ between 2 non-Z leptons
- Trained on tWZ, $t\bar{t}Z$ and ZZ
- ω_{2vSM} has the largest feature importance

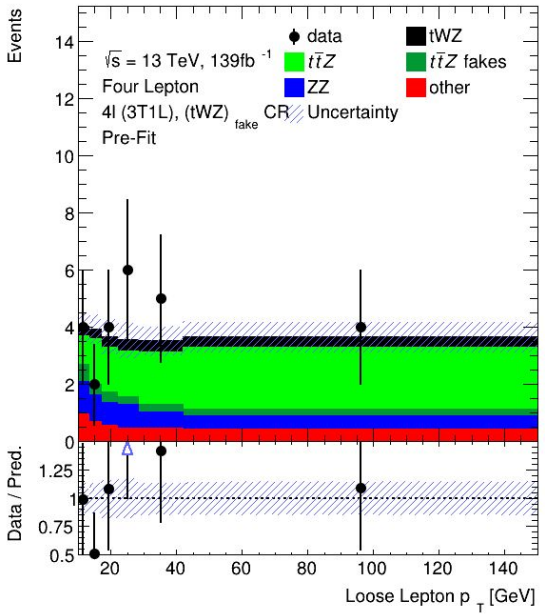
dmlc XGBoost



Control Regions







Generally good agreement between data and sim. across CRs

Low samples numbers due to 4 lepton channel

Extraction Method

- Performed a binned maximum likelihood fit using μ(tWZ) as parameter of interest
- Nuisance Parameters
  - Statistical uncertainties on bins
  - Experimental Systematic Uncertainties
  - Theoretical Systematic Uncertainties
- Fits are blinded (Asimov) to avoid bias
- The fit is performed using fully blinded and partially blinded datasets

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

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

Partially Blinded: Asimov dataset used in SR regions but ATLAS data used in CR

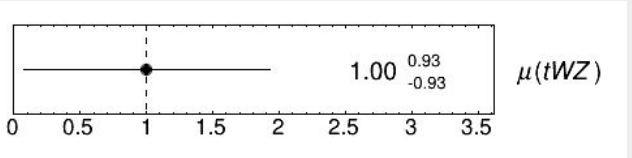
Experimental Systematics
Luminosity
Pileup
Jet Vertex Tagger
Jet Flavour Tagging
Object Scale/Resolution
Lepton Scale Factors
and more

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

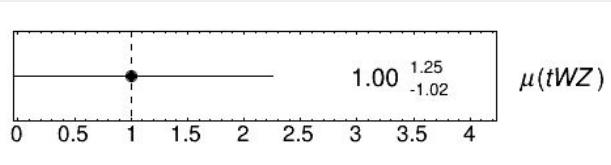
Blinded Results for 4ℓ Channel

- Uncertainties are statistically dominated due to low event numbers
- Additional regions could provide more events

Fully Blinded



(Stat. only)



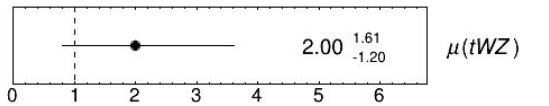
(Stat. + Sys.)

- Agreement with SM in partially blinded fit

$\mu_{exp}=2.61^{+1.46}_{-0.73}$

Partially Blinded

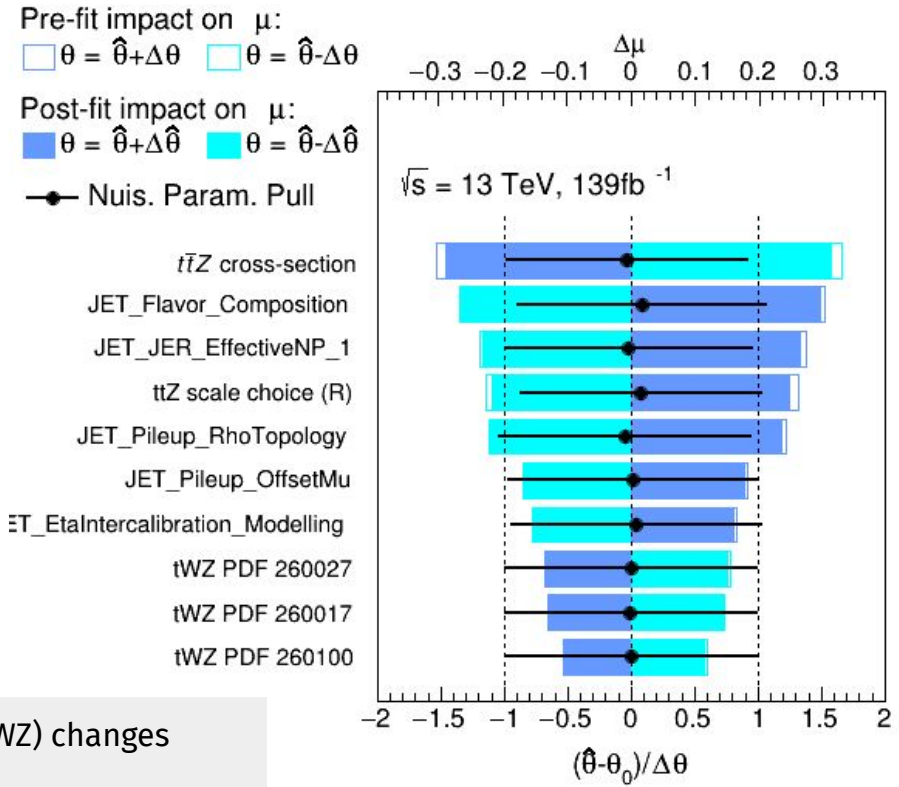
$Z_{\mu}^{exp} = 0.95\sigma$



(Stat. + Sys.)

Investigating the Systematic Uncertainties

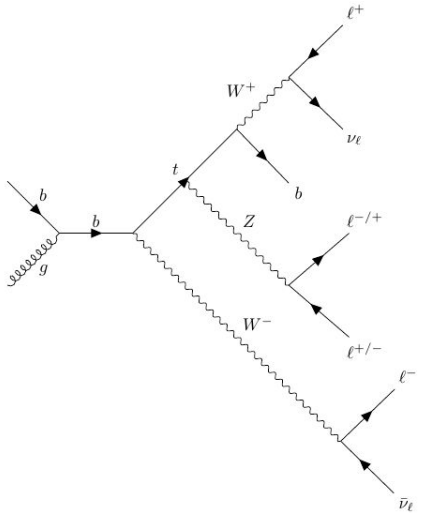
Large impacts due to tt̄Z cross section estimation and jet modelling systematics



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

Summary

- tWZ is a rare never before measured process that may be relevant for constraining BSM theories
- Difficult to measure due to large $t\bar{t}Z$ backgrounds
- Measurement in 4ℓ channel produced an expected significance of $Z_{\mu}^{exp} = 0.95\sigma$
- Channel is dominated by statistical uncertainty



Future Plans

- Combine 3ℓ and 4ℓ channel for simultaneous fit
- Define additional regions in 4ℓ to increase total events
- Perform kinematic reconstruction of top using ML for better signal/background discrimination

Backup

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

Region Definitions

Baseline selections

$$N_\ell = 4$$
$$p_T(\ell_1, \ell_2, \ell_3, \ell_4) > (28, 18, 10, 10)\ \text{GeV}$$
$$p_T(\text{jet}) > 20\ \text{GeV},\ |\eta(\text{jet})| < 4.5,\ \text{jvt} > 0.5$$
$$|\eta(\ell_e)| < 2.47 \text{ excluding } 1.37 < |\eta(\ell_e)| < 1.52$$
$$|\eta(\ell_\mu)| < 2.5$$
$$\sum_{i=1}^{4} \text{charge}(\ell_i) = 0$$
$$\text{All OSSF lepton pairs require } m_{\text{OSSF}} > 10\ \text{GeV}$$

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ttZ CR	1 Z Candidate Jets ≥ 2 b-jets = 2	BDT Discr.
ZZb CR	2 Z Candidate Jets ≥ 1 b-jets = 1	Sum. p_T of leptons, jets and E_T^{miss} (SMT)
tWZ fake CR	3 tight and 1 loose lepton 1 Z Candidate Jets ≥ 2 b-jets = 2	Loose lepton p_T

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

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