First Study of Longitudinal-Longitudinal WZ Interactions using WZ events with the ATLAS Detector

US ATLAS SUPER Program
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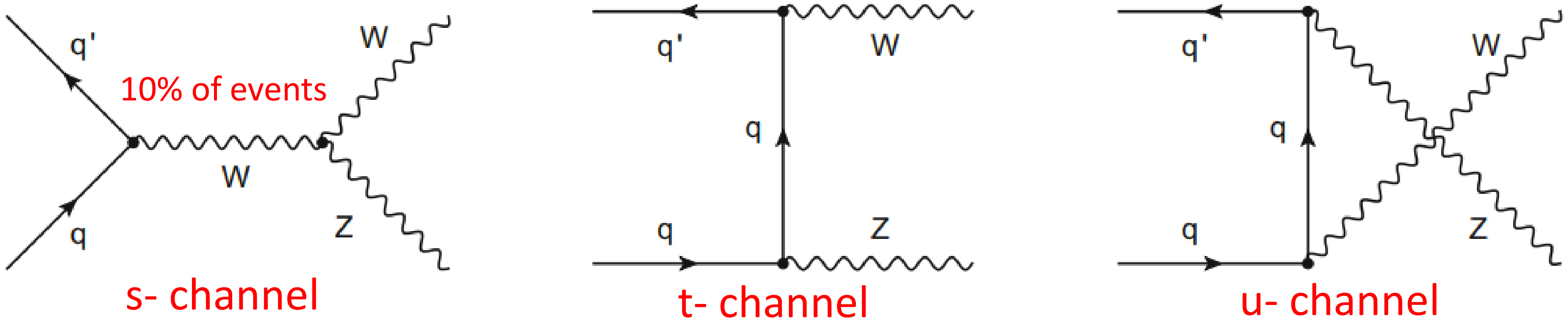
Introduction

- The Higgs Mechanism: Goldstone bosons from electroweak symmetry breaking (EWSB) become the longitudinal component of W/Z bosons
- Important to study longitudinal-longitudinal (LL) boson interactions ($W_L Z_L$) to gain a better understanding of the EWSB mechanism
- We are pioneering a first study of $W_L Z_L$ interactions using WZ → lvll events



$V_L V_L$ events have not been observed before

- Need to enhance s- channel contribution
- Need to reduce contribution from LT, TL, TT events
  - Longitudinal polarization of a boson occurs ~25%, so LL polarization occurs 6% of the time
- Our signal is 0.6% of inclusive WZ events, so we need to find methods to increase the signal to background ratio

Introduction: Selection Cuts

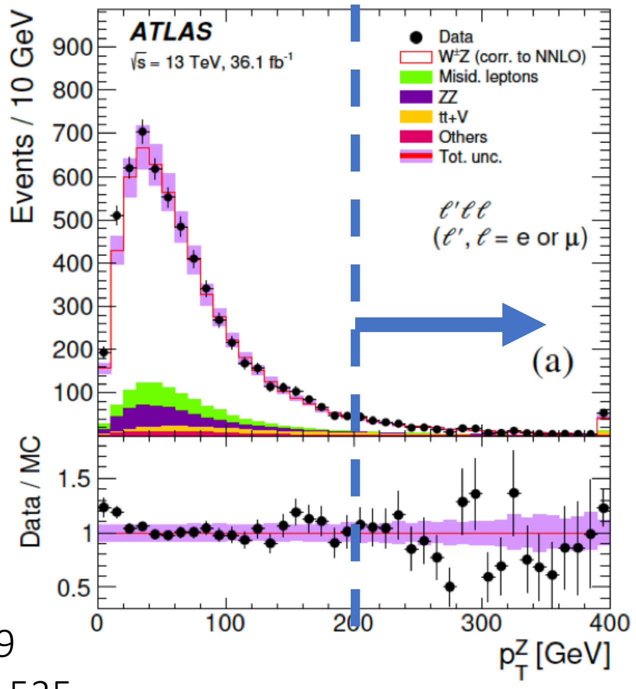
- To increase the fraction of LL events, only events passing the following cuts are selected for analysis:

Inclusive fiducial region → (Cut 1)

Cut 1 (lepton cuts)	lepton $p_T > 25$ GeV, $\|\eta\| < 2.5$, mET > 25 GeV
Cut 2	$p_T(Z) > 200$ GeV
Cut 3	$p_T(WZ) < 70$ GeV
Cut 4	$\|\cos\theta_W\| < 0.5$

LL-enhanced region ← (Cut 3)

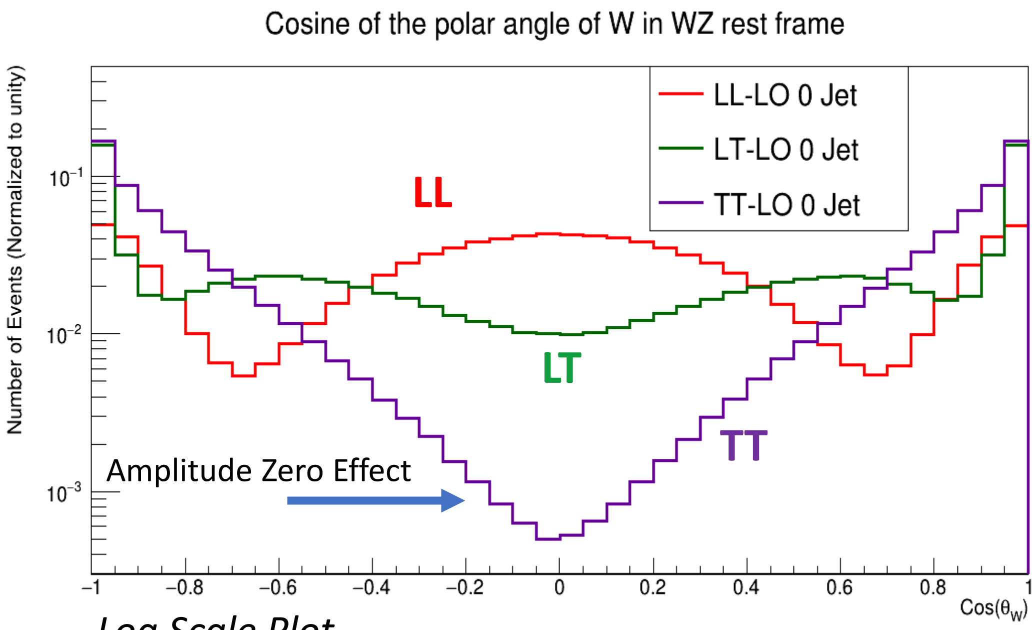
- Cut 2 on $p_T(Z)$ enhances s- channel contribution
  - We expect to have very few background events for the region with $p_T(Z) > 200$ GeV
  - Some theoretical studies can be found at Franceschini, Panico, Pomarol, Riva and Wulzer, JHEP 2018, 111 (2018), Liu and Wang, PRD, 99 (2019) 055001



ATLAS, EPJC 79 (2019) 535

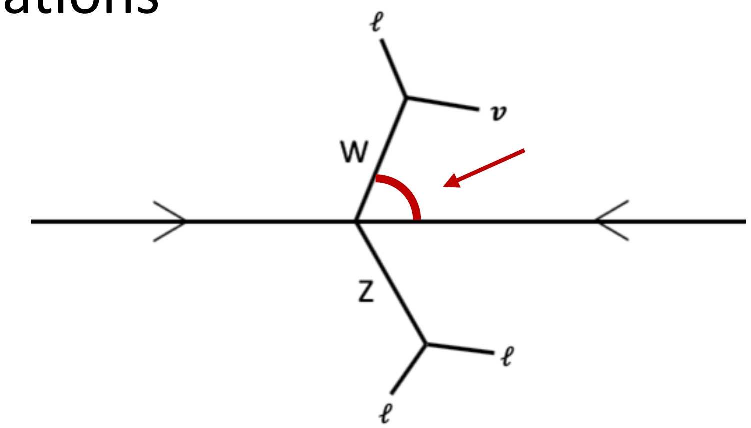
Introduction: Selection Cuts

- Cut 4 on $\cos\theta_W$ reduces LT and TT contributions
  - $\cos\theta_W$ is the W boson direction in the WZ rest frame w.r.t. the lab Z axis
  - LL fraction will be ~50% with $|\cos\theta_W| < 0.5$



Log Scale Plot
Events from initial truth-level study

- The reduction of TT contribution near $\cos\theta_W$~0 is due to the amplitude zero effect (Baur, Han and Ohnemus, PRL 72 (1994), 3941) ($\theta_V = \theta_W$)
- The LT contribution is also reduced due to strong gauge cancellations



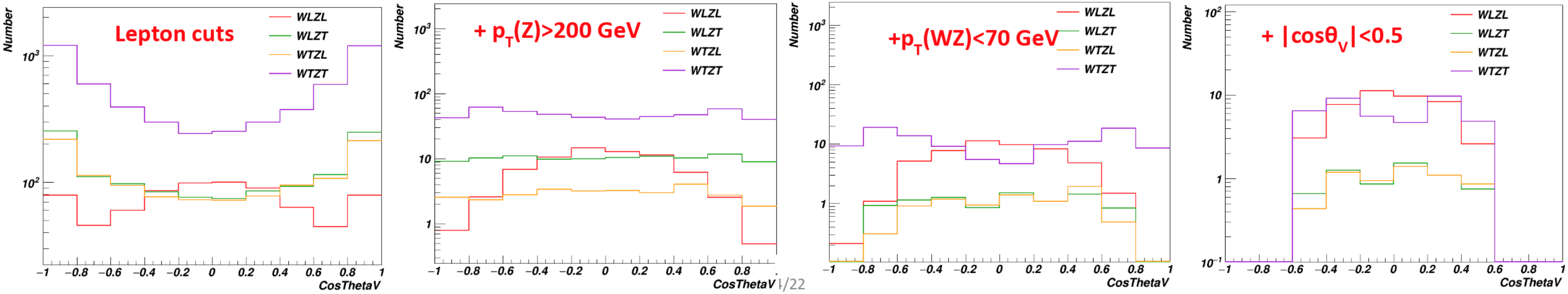
Introduction: Selection Cuts

- Results from initial truth-level studies (overall lepton detection efficiency of ~50% not included)

Number of Events Normalized to 150 fb^{-1} | Polarization Fraction

	LL	LT	TL	TT	Sum	fLL	fLT	fTL	fTT
No cuts	5436	12852	12032	79429	109750	0.05	0.12	0.11	0.72
Lepton cuts	1984	3361	3120	14576	23043	0.09	0.15	0.14	0.63
$p_T(Z)>200$ GeV	186	244	74	1152	1657	0.11	0.15	0.04	0.7
$p_T(WZ)<70$ GeV	135	26	23	299	484	0.28	0.05	0.05	0.62
$\lvert\cos\theta_W\rvert<0.5$	118	18	15	91	243	0.49	0.08	0.06	0.38

$\cos\theta_W$ Histograms:



Selection Cuts using Angular Variable Cosθ_W

- Calculation of cosθ_W requires neutrino p_Z (which cannot be reconstructed)
  - Wrote code to calculate met p_Z using W mass constraint:

$$(E_\ell + E_v)^2 - (P_\ell^x + P_v^x)^2 - (P_\ell^y + P_v^y)^2 - (P_\ell^z - P_v^z)^2 = m_W^2$$

- Detector effects also affect measurements required to calculate cosθ_W
  - Wrote code to smear electron/muon energy and momentum to mimic detector effects

Electron Smearing: $E = E_{original} + G_{random}\sigma_E$ $\quad p_T = p_{T,original}\,(E / E_{original})$

Muon Smearing: $p_T = p_{T,original} + G_{random}\sigma_{pT}$ $\quad E = E_{original}(p_T / p_{T,original})$

- How do these calculation methods affect resulting LL fraction
  - Tested on Monte Carlo generated events using MadGraph & Pythia merging (LO calculations)

Results: Selection Cuts using $\text{Cos}\theta_W$

Event Count and LL Fraction after all cuts applied:

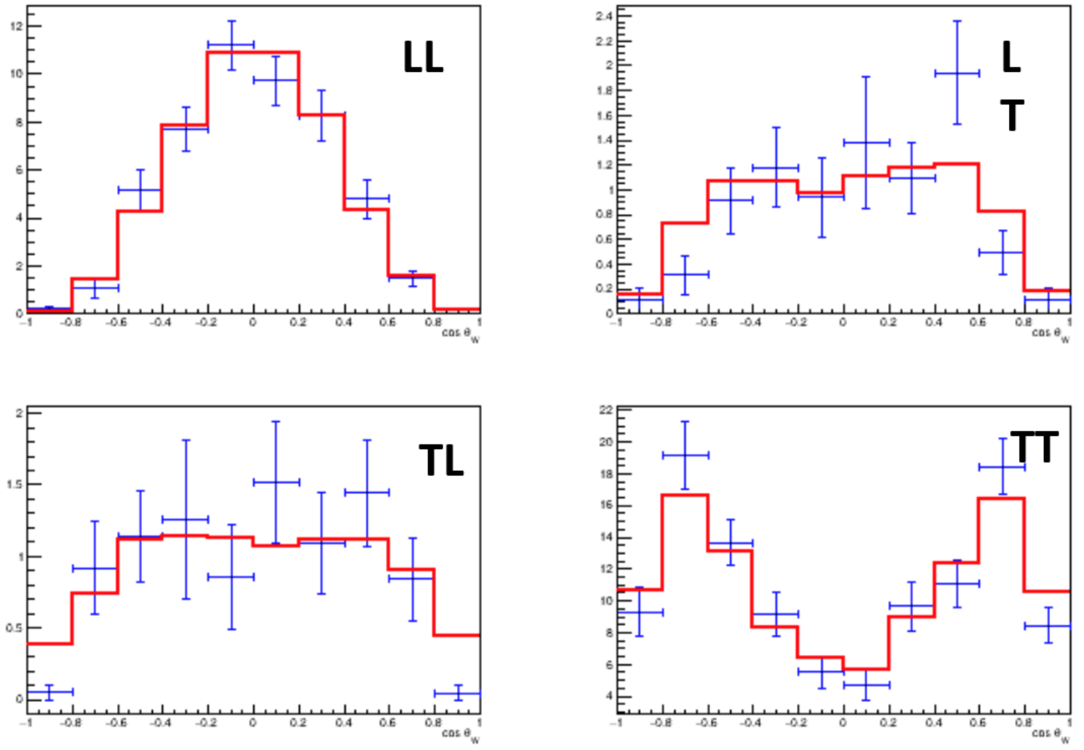
Calculation Method	LL	LT	TL	TT	LL fraction
Use truth neutrino information for all calculations	118.4	18.4	15	91.84	0.49
Use truth lepton & p_T(WZ) information to calculate metX, metY, use truth metZ	127.4	42.7	22.3	191.6	0.33
Same as above, now use W-mass constraint to calculate metZ	124.68	40.3	22.5	206.1	0.32
Same as above, add 2% smearing for electron and muon momenta	124.3	39.9	22.8	205.9	0.32
Same as above, add 10 GeV random smearing to metX, metY to emulate underlying event contribution	123.5	40.2	21.9	204.5	0.32

- Using calculation method for metX, metY results in decrease of LL fraction
- Smearing to mimic detector effects does not reduce LL fraction

Red: Truth-Level Information (row 1)

Blue: All experimental effects applied (row 5)

$\text{Cos}\theta_W$ Distributions:



Takeaways

- Calculation of metX, metY has the biggest effect, reducing LL fraction after cuts from 49% to 33%, while smearing to replicate detector effects and metZ calculation did not impact LL fraction (see rows 3-5)
- I will use the code I wrote to analyze a NLO sample in the future to compare results

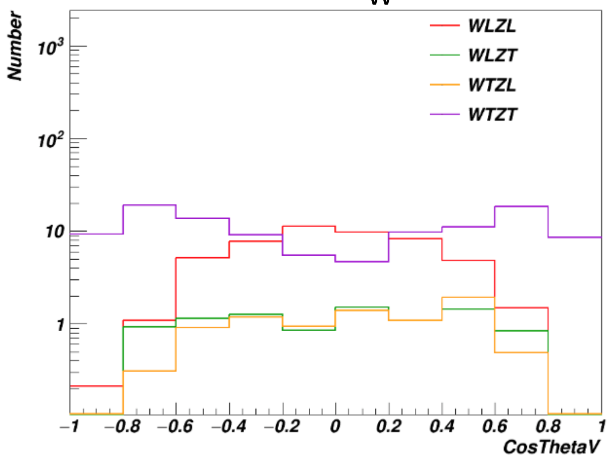
Multivariate Technique: XGBoost

- Develop binary classifier using XGBoost to further improve separation of LL events from other polarizations
  - XGBoost is a decision tree ensemble model created by Tianqi Chen [source]
- Angular Variables used as Features:
  - **$\cos\theta_W$**: W boson direction in the WZ rest frame wrt the lab Z axis
  - **$\cos\theta_{LepW}$**: lepton direction from the W decay in the W rest frame wrt the W direction in the lab frame
  - **$\cos\theta_{LepZ}$**: negatively-charged lepton direction from the Z decay in the Z rest frame wrt the Z direction in the lab frame
  - **ΔY(WZ)**: rapidity difference between W and Z bosons
  - **ΔY(3Z)**: rapidity difference between third lepton (from W decay) and Z boson
  - **ΔY(3N)**: rapidity difference between third lepton (from W decay) and the negatively-charged lepton from Z decay

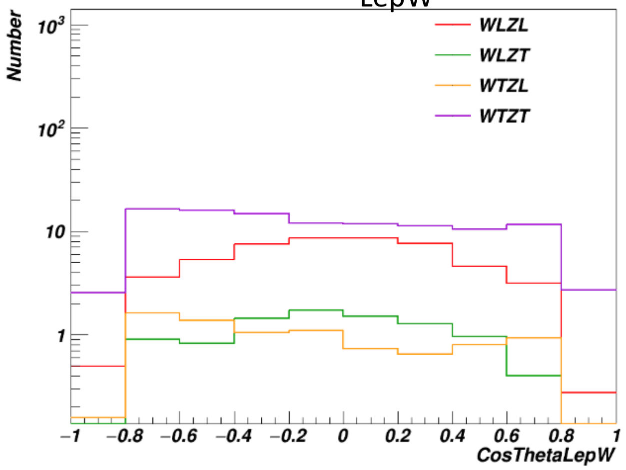
Multivariate Technique: XGBoost

- Plots of angular variable distributions are shown after pT(WZ) < 70 GeV cut

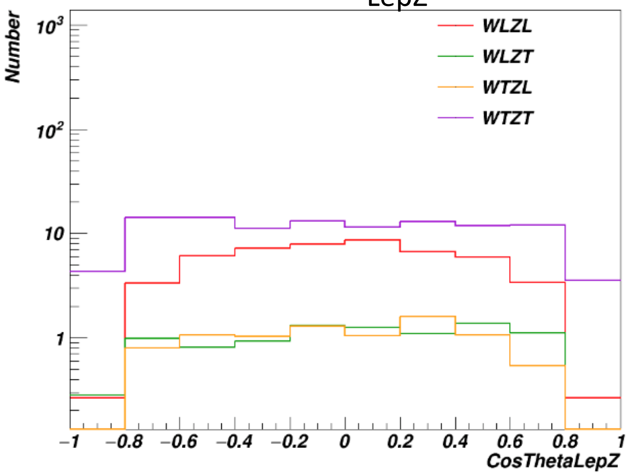
$Cos\theta_W$



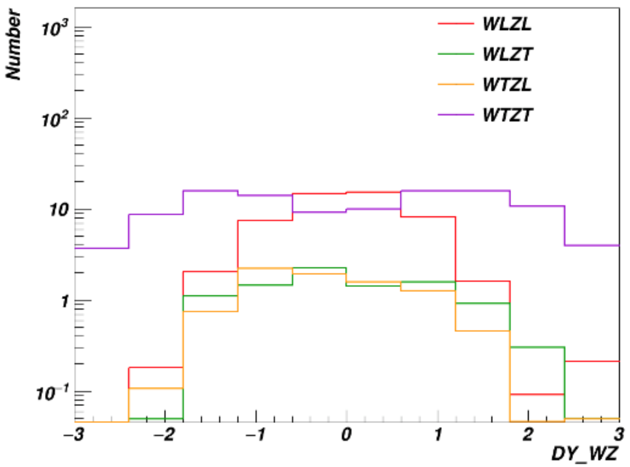
$Cos\theta_{LepW}$



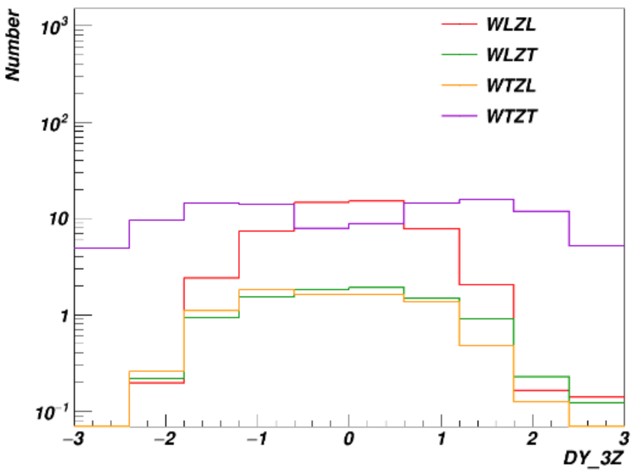
$Cos\theta_{LepZ}$



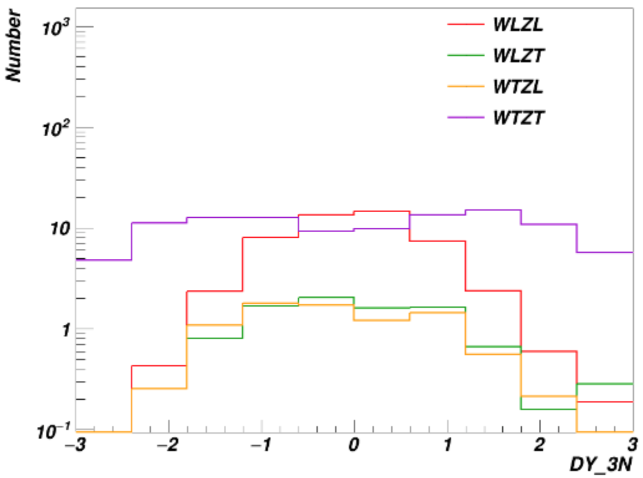
ΔY(WZ)



ΔY(3Z)



ΔY(3N)



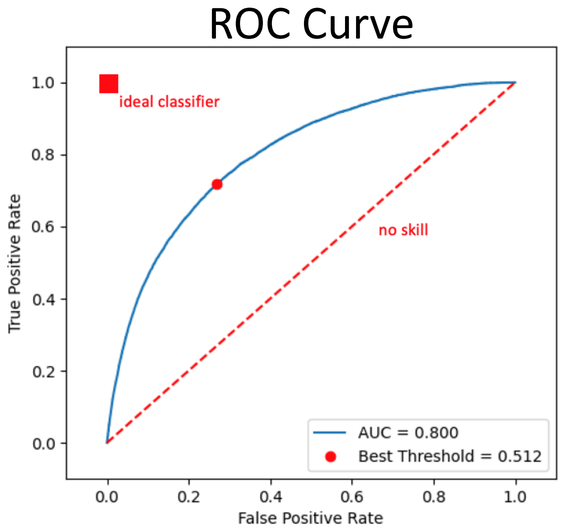
Multivariate Technique: XGBoost

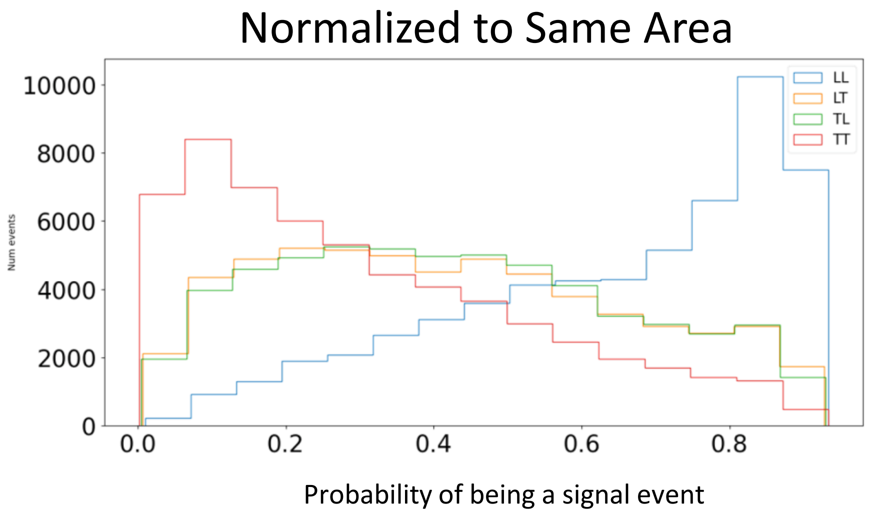
- Two different sets of events used to compare results
  - Truth-level events generated with Madgraph+Pythia
  - Reconstructed events from GEANT simulation
- Two different fiducial regions
  - Inclusive region: Only lepton cuts are applied
  - LL-enhanced region: All selection cuts except the $\cos\theta_W$ cut are applied
- Methods used to avoid overfitting:
  - Re-weighting of training events such that there is an equal contribution from signal (LL) and background (LT, TL, TT). Otherwise, training set is imbalanced.
  - Early stopping of boosting rounds: In each boosting round, XGBoost adds a new tree to the ensemble. If the AUC score hasn’t improved after 10 rounds, boosting stops and the model returns to the optimal solution

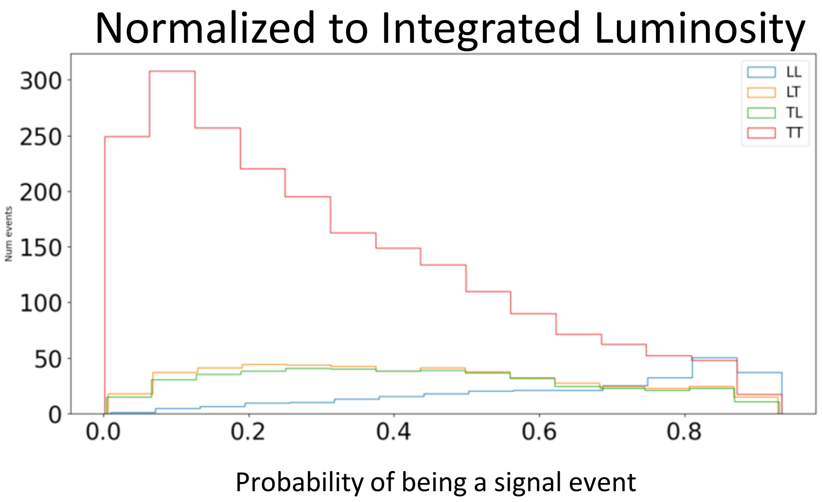
XGBoost Results: Truth-Level Events

<u>Inclusive Region</u>

AUC = 0.8

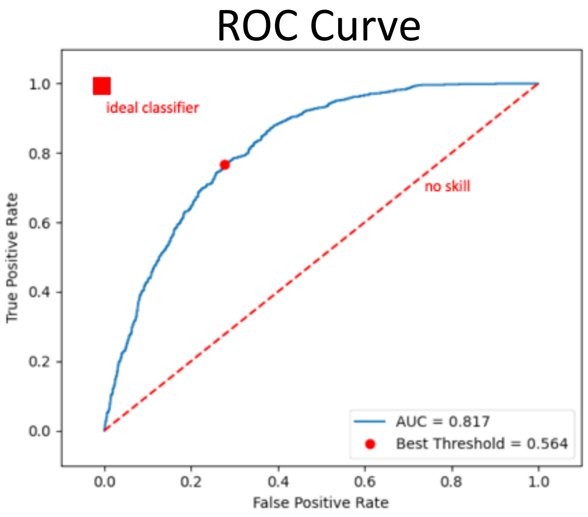


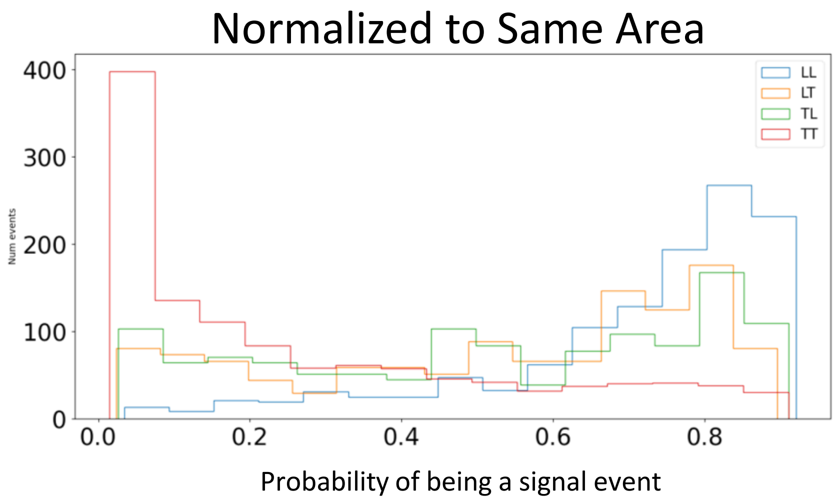


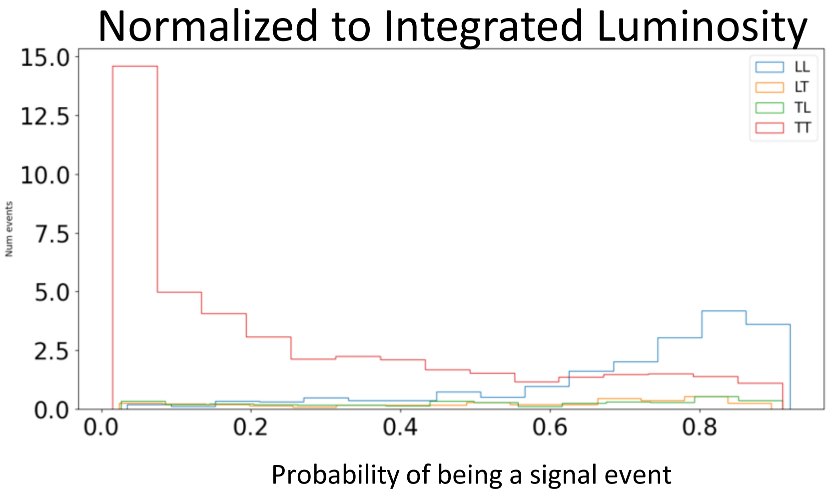


<u>LL-Enhanced</u>

AUC = 0.817



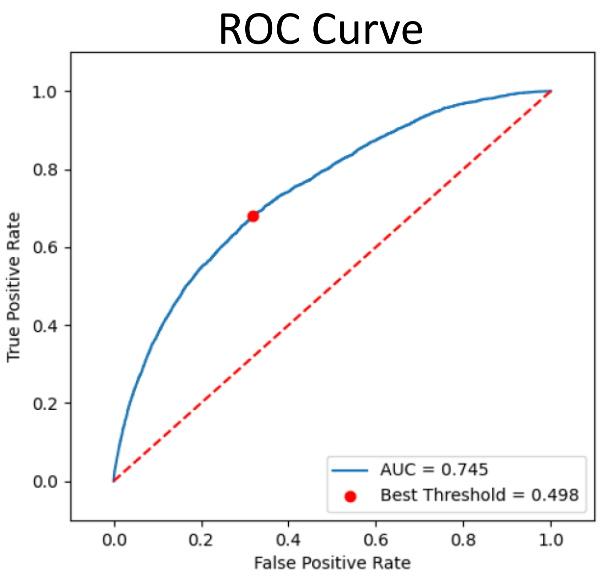


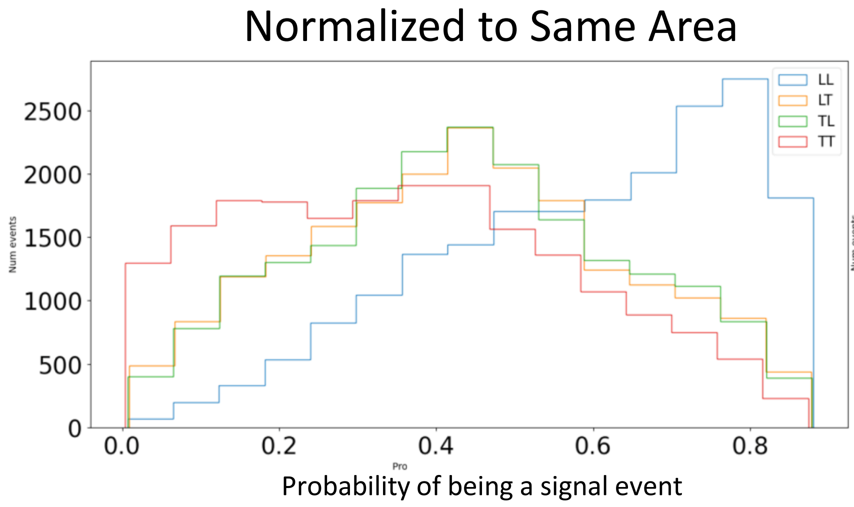


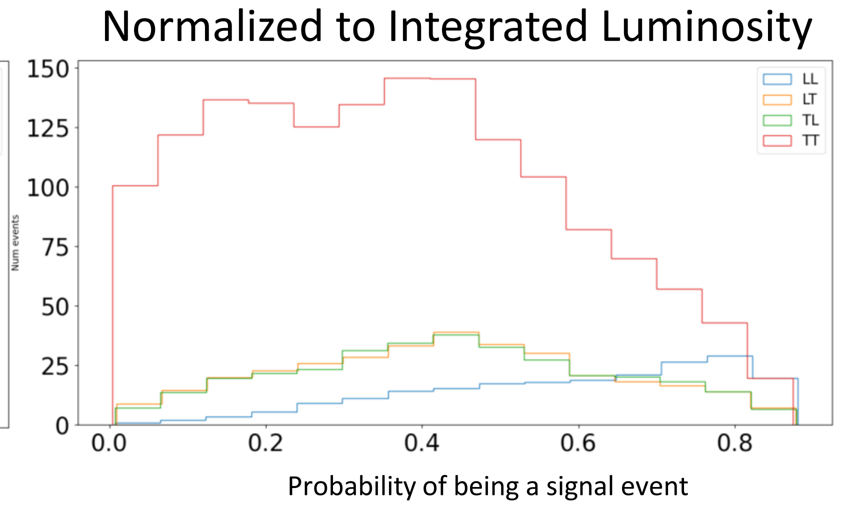
XGBoost Results: GEANT Events

Inclusive Region

AUC = 0.745

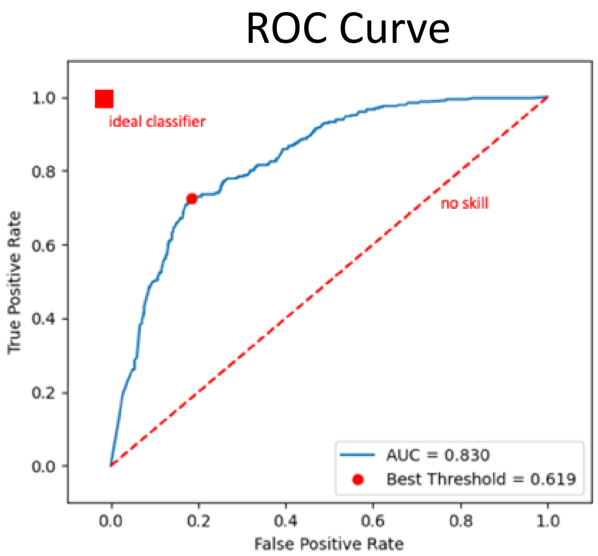


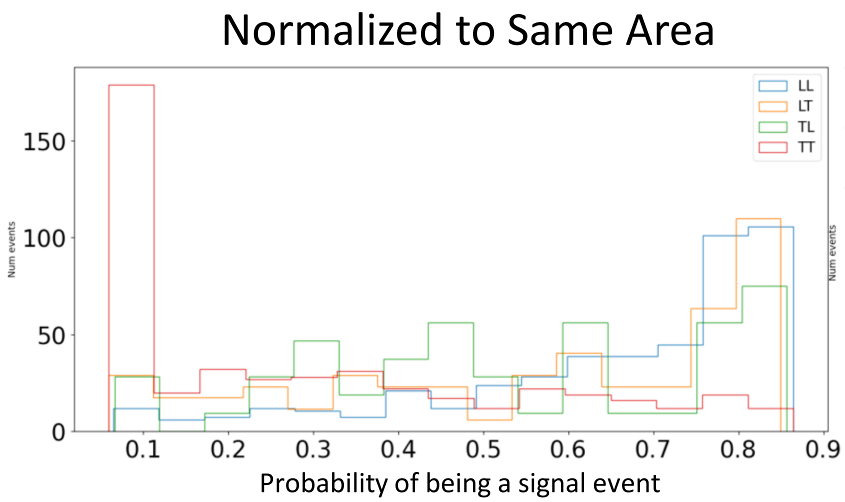


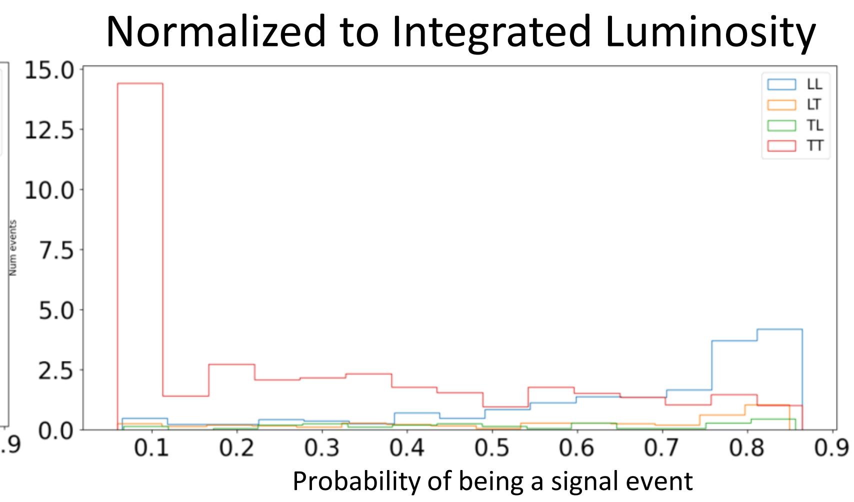


LL-enhanced

AUC = 0.83







Takeaways

- XGBoost can be used to further improve the separation between LL events and LT/TL/TT events for both regions using truth-level events and GEANT-simulated events
- Angular variables other than $\cos\theta_W$ turned out to have good separation powers as well
- We will compare probability distributions between data and simulation for various validation regions later to validate the XGBoost modelling

Current Work: LO vs NLO Comparison

- Comparing leading-order calculations with next-leading-order calculations for truth-level events
  - NLO Sherpa sample and LO Madgraph sample
- Using templates of $\cos\theta_W$ from different polarizations, perform fitting to extract the LL fraction from LO and NLO samples using TMinuit
  - Using code from previous work to calculate angular variables and prepare samples for fitting
- I will continue working with Professor Zhu in the fall semester to get a first evidence of non-zero $W_L Z_L$ fractions

Thank You!

Thank you to the US ATLAS SUPER Program for providing funding for my project this summer. I'm very grateful for the opportunity to do research within this community.