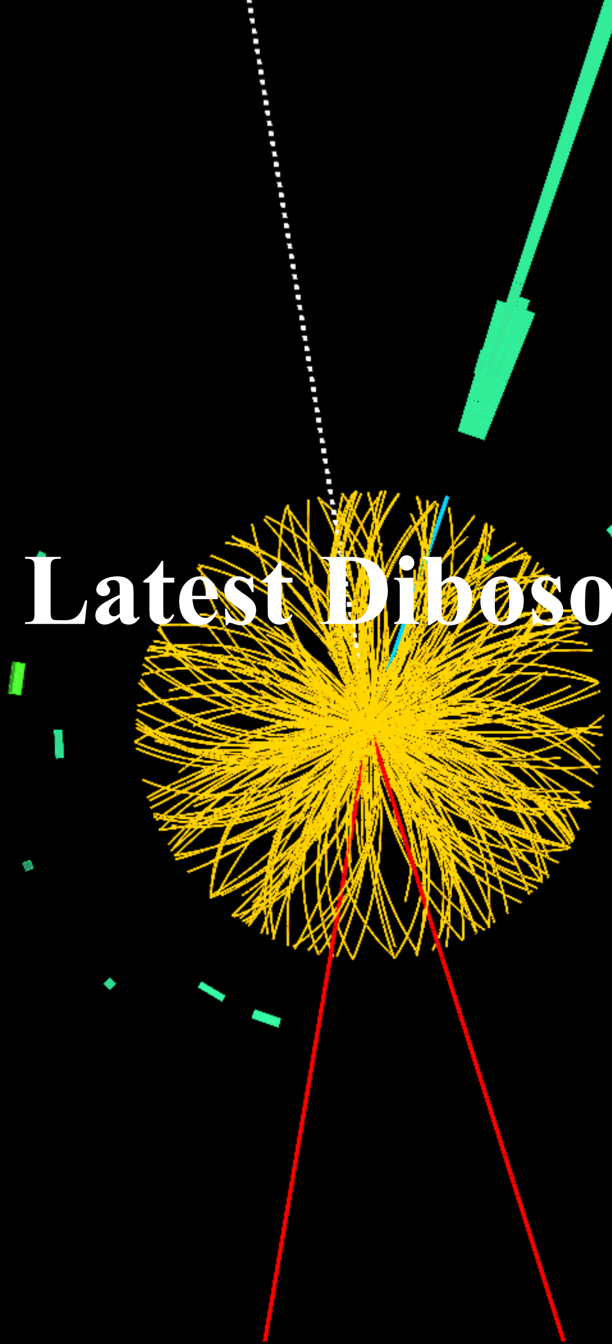
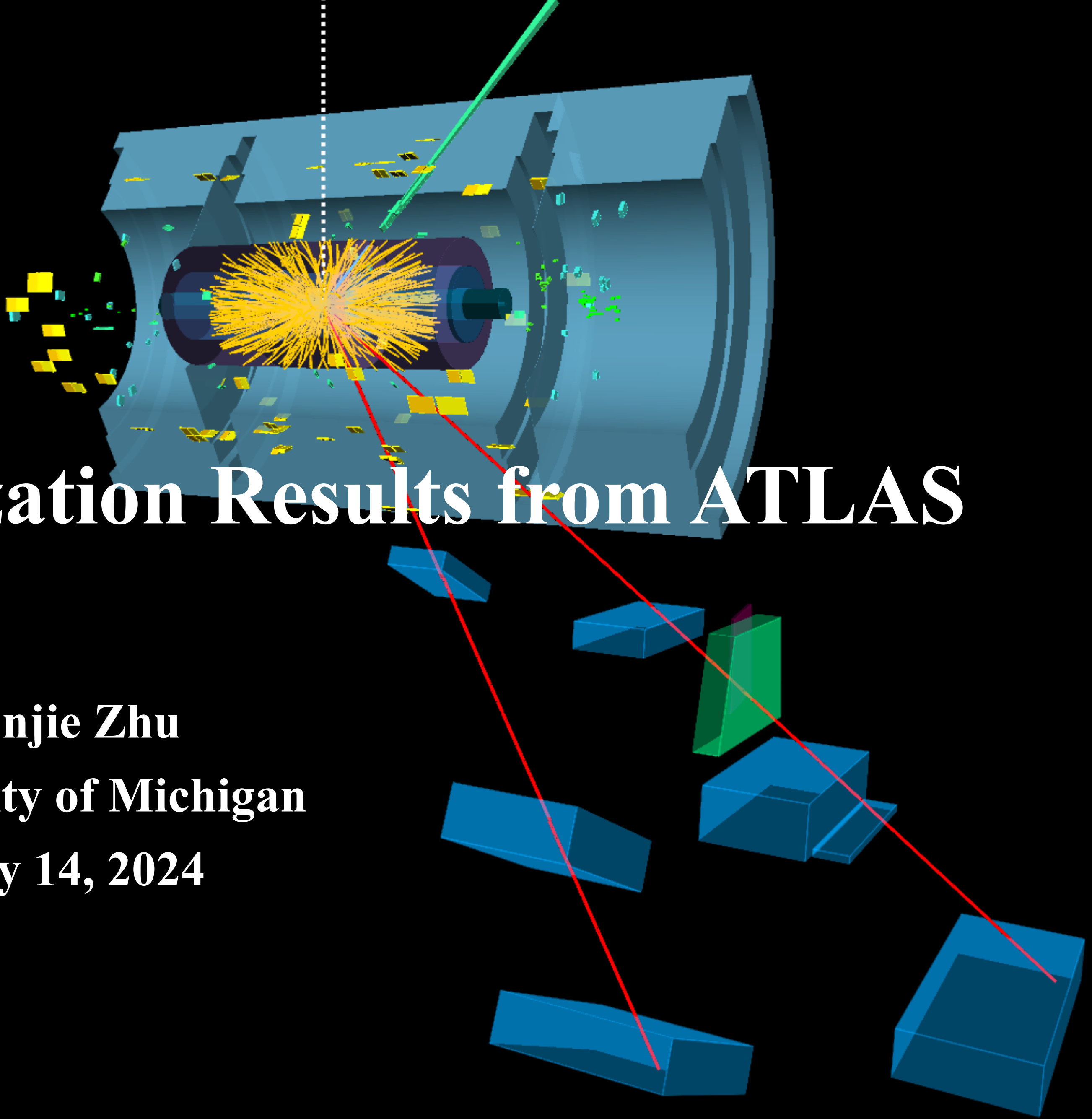




Latest Diboson Polarization Results from ATLAS

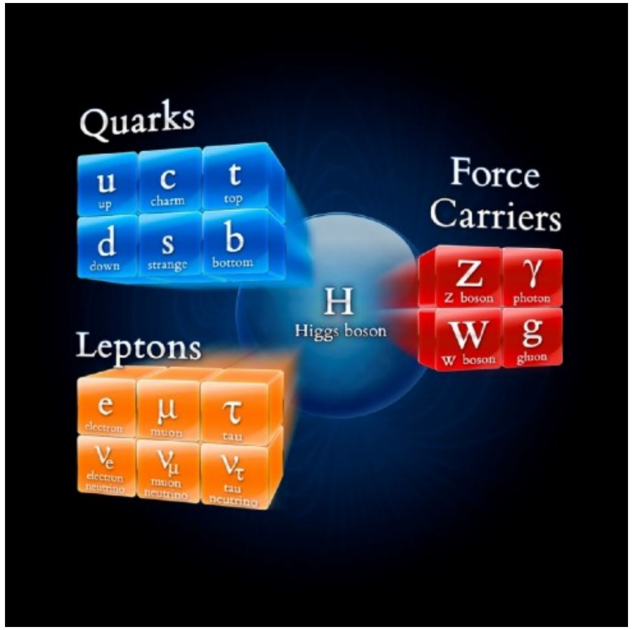
Junjie Zhu

University of Michigan

May 14, 2024

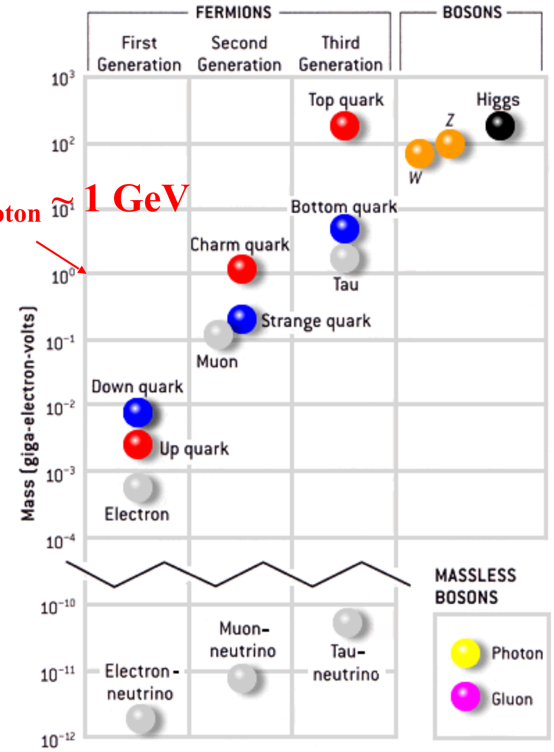
Periodic table of SM particles

- All known elementary particles:
  - 12 matter particles – spin-½ fermions
  - 4 force carrier particles – spin-1 bosons (vector bosons)
    - Electromagnetic (γ), weak (W^+/W^-, Z) and strong (g)
    - Electromagnetic and weak forces are unified to electroweak force
  - 1 Higgs particle – spin-0 boson (scalar boson)

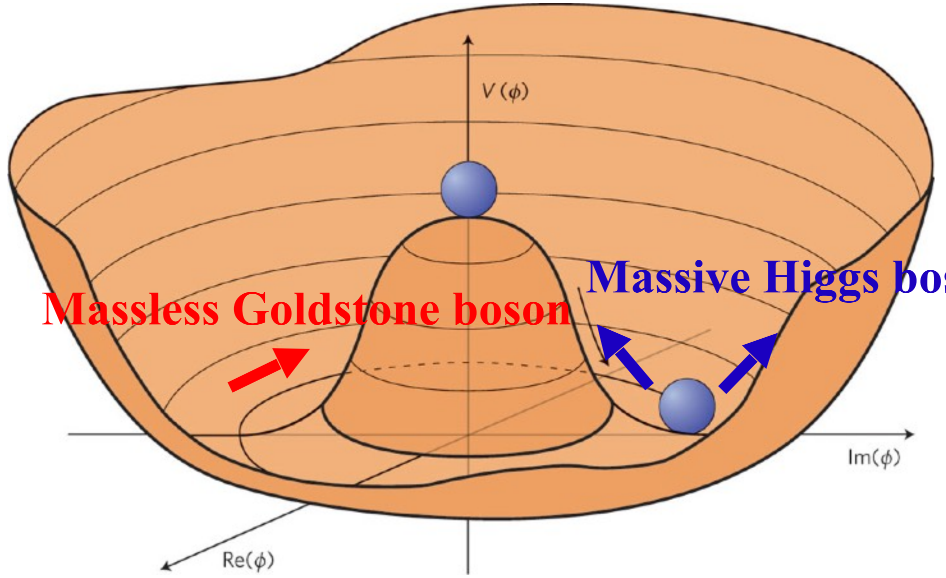


- Mass puzzles:
  - Different particles have different masses, and their masses are dramatically different
  - W, Z and γ are electroweak force carriers, but have different masses
  - According to symmetries in the SM, all particles should be massless

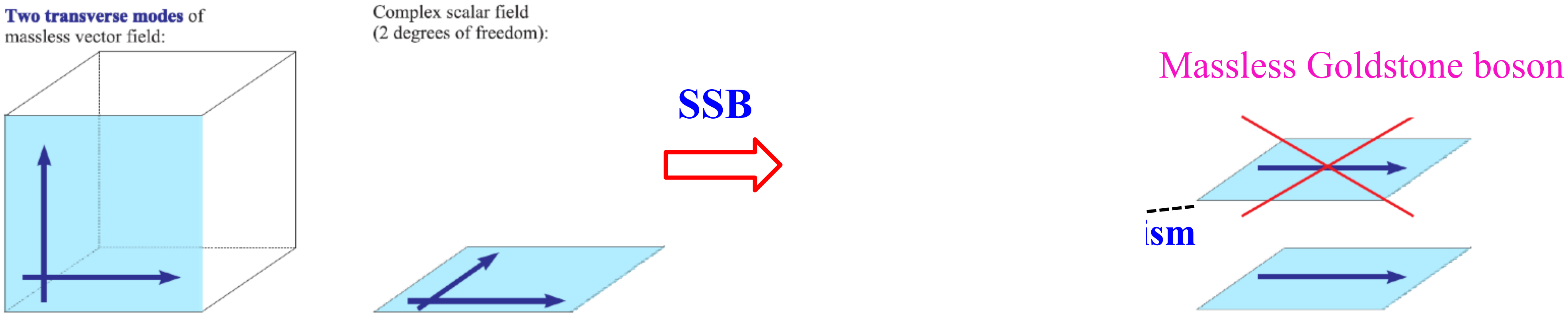
$m_{proton} \sim 1$ GeV



Spontaneous symmetry breaking and the Higgs mechanism



Consider an example of a complex Higgs field (2 DOFs) with a non-zero vev



Massless vector boson Higgs field Massive vector boson Higgs boson

Only massive particles can have longitudinal modes → the original massless vector boson now becomes massive

Spontaneous symmetry breaking and Higgs mechanism

4 massless vector bosons (W^+, W^-, Z, γ)

$$4 \times 2 + 4$$

2 transverse modes

4 DOFs for the Higgs sector
(the real Higgs field is a weak isospin doublet)

1 massive Higgs boson and 3 massless Goldstone bosons after SSB

⇒ **Higgs mechanism:** Massless Goldstone bosons are "eaten" by massless vector bosons and become their longitudinal modes

3 massive bosons (W^+, W^-, Z)   Massless γ the Higgs boson

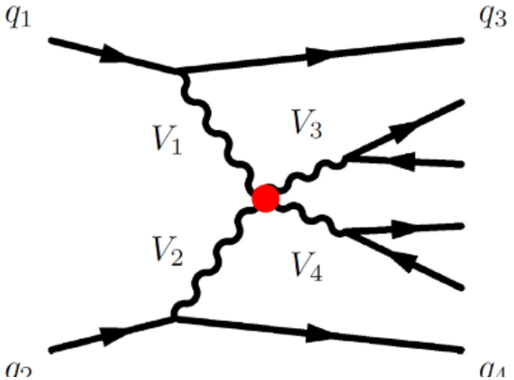
$$3 \times 3 + 2 + 1$$

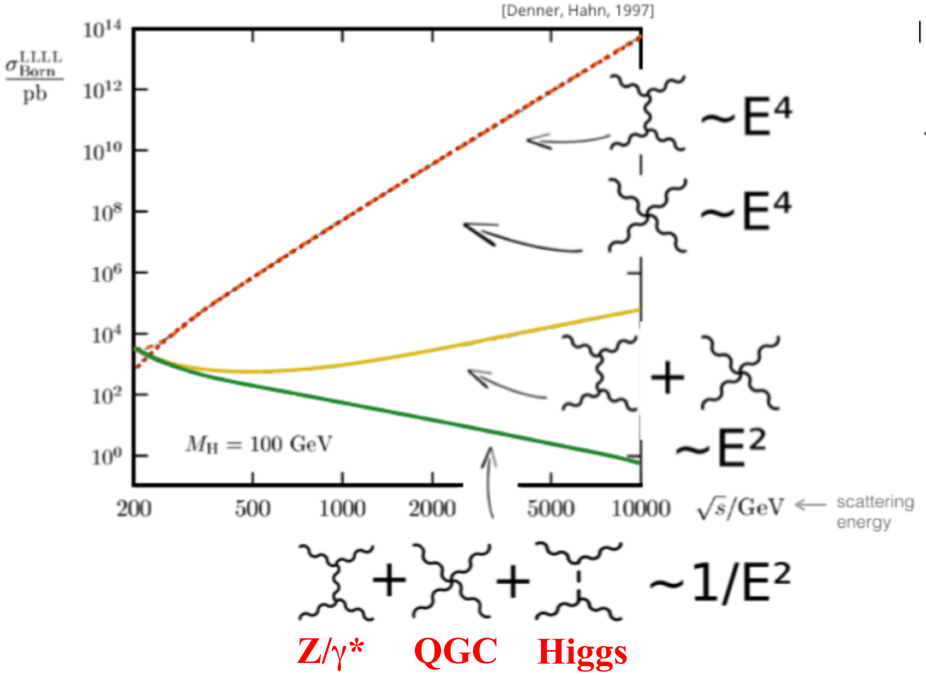
2 transverse modes +
1 longitudinal mode

- Masses of matter particles (Fermions) come from the Yukawa coupling between the particle and the Higgs field

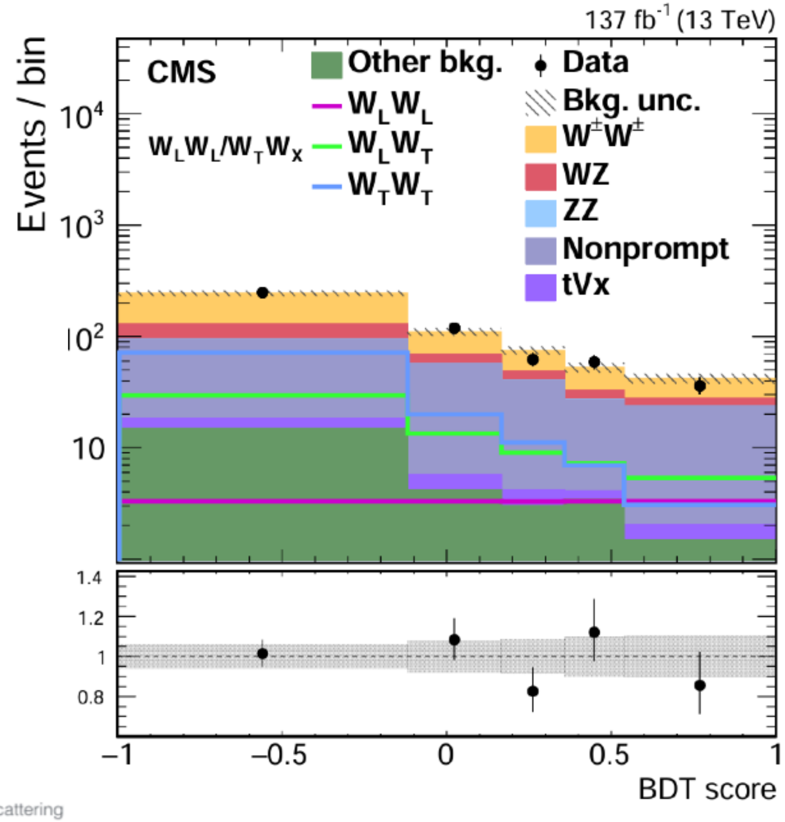
Vector boson scattering

- Studies of polarized electroweak bosons are gaining interest in both experimental and theoretical communities these days: mainly VBS and diboson (VV, VH) processes
- VBS: unitarity conservation in scattering of the longitudinal modes of W/Z bosons ($V_L V_L \to V_L V_L$)





PLB 812 (2021) 136018



16 W_LW_L events expected with a total background of 506 events

Diboson polarization measurements at ATLAS:

- pp → ZZ (140 fb^{-1}, 13 TeV)
  - Inclusive phase space (JHEP 12 (2023) 107)
- pp → WZ (140 fb^{-1}, 13 TeV)
  - Inclusive phase space (PLB 843 (2023) 137895)
  - High-energy phase space and Radiation Amplitude Zero (arXiv:2402.16365, submitted to PRL)

Sensitivity to new physics

- New physics might couple preferentially to some polarization states
- LL events are often more sensitive to new physics
  - High-energy behavior of amplitudes with different diboson helicity configurations:

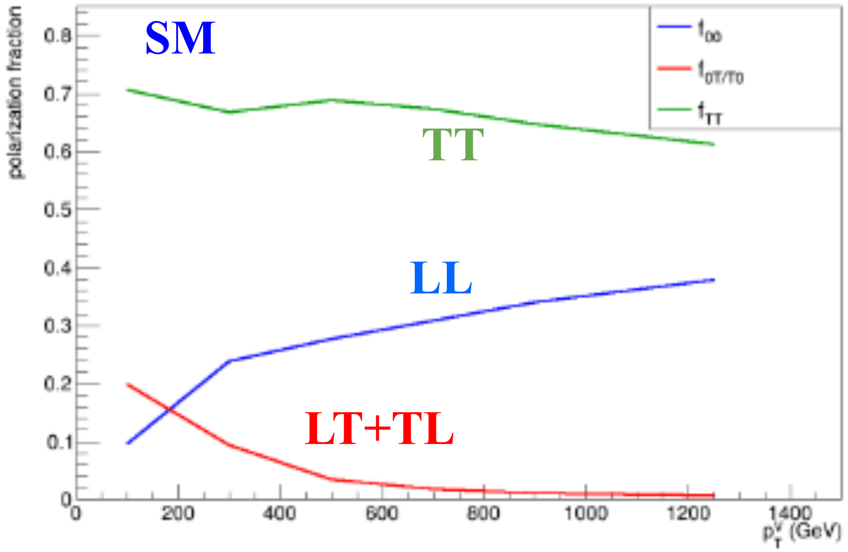
		SM	BSM
LL	$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
TL	$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
TT	$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
	$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

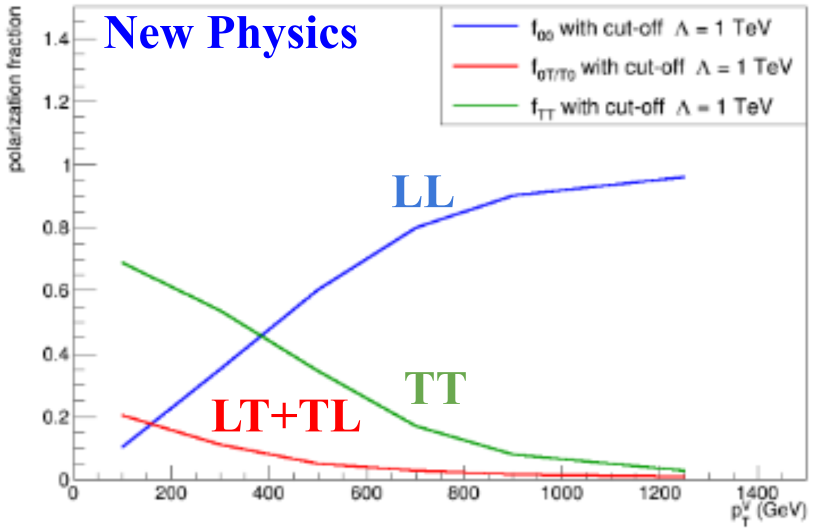
JHEP 2018, 111 (2018)

Dim-6 EFT operator

$1/E^2$ dependence in SM, E^2 dependence with BSM

PRD 99, 055001 (2019)

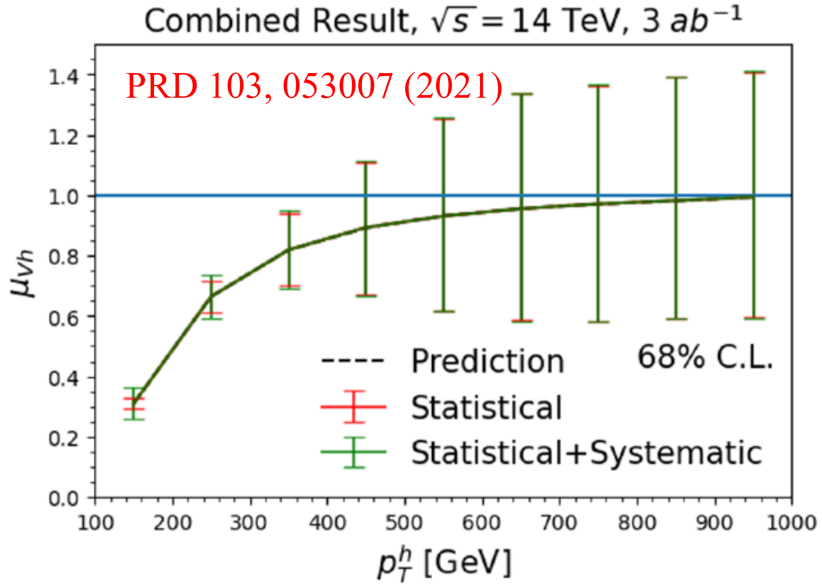


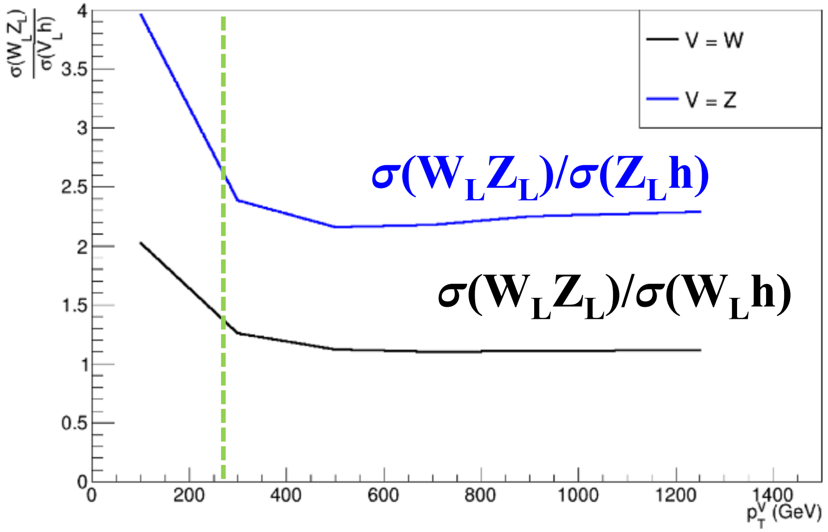


Interesting to measure f_{LL} at high energies

"Electroweak restoration" and Goldstone boson equivalence theorem

- The LHC is exploring physics at the scale electroweak symmetry is broken
- Possible to probe not only the breaking of but also the restoration of electroweak symmetry





- At high energies, SM particles are essentially massless, equivalent to the Higgs vev going to zero → EW symmetry is restored
- Measure unfolded pp→Wh and pp→Zh cross sections as a function of the Higgs boson p_T
- Compare to the theoretical calculation of pp→G^0h and derive μ_{VH}

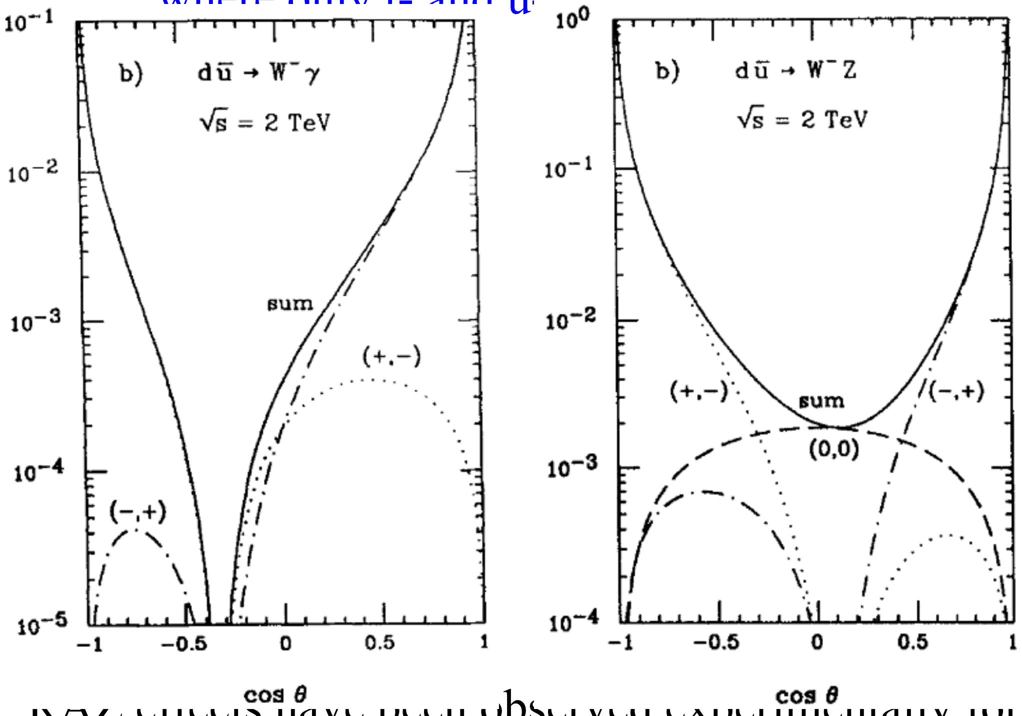
- At high energies, the longitudinal mode of a massive vector boson is equivalent to the Goldstone boson (Goldstone boson equivalence theorem)
- $\sigma(W_L Z_L)/\sigma(W_L h) \to 1$ and $\sigma(W_L Z_L)/\sigma(Z_L h) \to 2$

- EW symmetry restoration ←→ convergence of the Goldstone boson equivalence theorem
- Interesting to measure $\sigma(W_L Z_L)$, $\sigma(W_L h)$, $\sigma(Z_L h)$, and their ratios at high energies

Radiation amplitude zero

- RAZ: due to destructive interferences between different Feynman diagrams, the production cross section is exactly 0 at LO for the following angles:
  - $f_1\bar{f}_2 \rightarrow W\gamma$: $\cos\theta = \frac{Q_1 + Q_2}{Q_1 - Q_2}$ (PRL 43, 746 (1979))
  - $f_1\bar{f}_2 \rightarrow WZ$: $\cos\theta_0 = \frac{\alpha}{\beta}\left(\frac{g_-^{f_1} + g_-^{f_2}}{g_-^{f_1} - g_-^{f_2}}\right)$ (PRL 72, 3941 (1994)) for $\mathcal{M}$ $(\pm,\mp)$

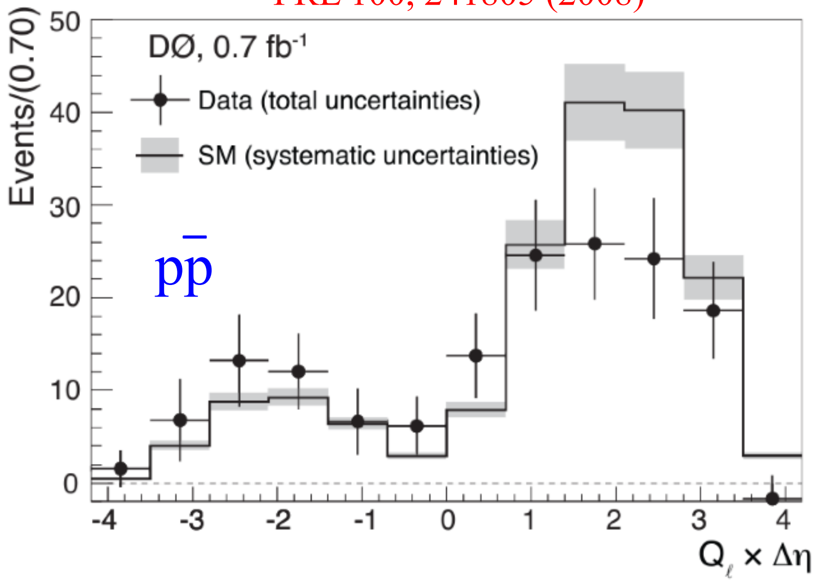
    where only t- and u-channels contribute



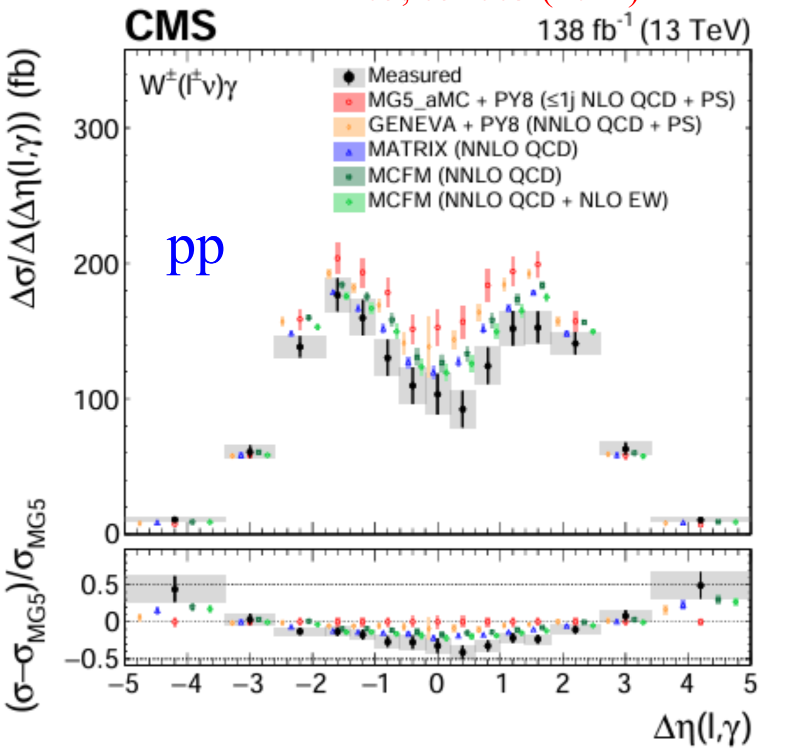
PRL 72 (1994) 3941

θ is the angle between the W boson and the incident fermion (d)

PRL 100, 241805 (2008)



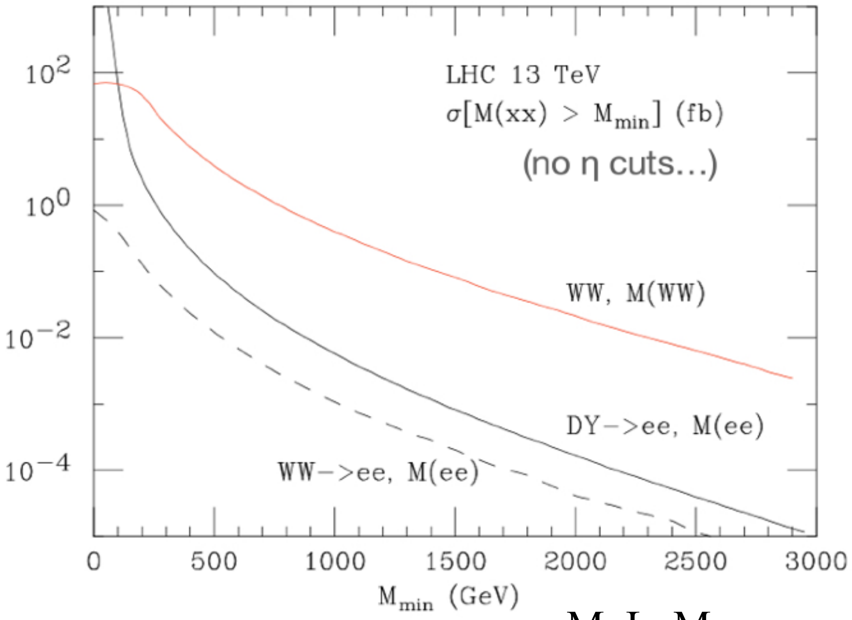
PRD 105, 052003 (2022)



- RAZ effects have been observed experimentally for Wγ by D0 and CMS
- Hard to observe this effect in WZ production, need to select TT events
- Higher-order corrections and non-SM couplings would eliminate the RAZ effect

Energy vs accuracy

- Diboson processes are in general important processes to study at LHC
  - Clean final states
  - Relatively large cross sections at high energies
  - Precise measurements to test SM predictions and higher-order corrections
  - Higgs measurements with $H\rightarrow WW^*$, $H\rightarrow ZZ^*$, $H\rightarrow\gamma\gamma$, $H\rightarrow Z\gamma$
  - Sensitive to new physics (aTGC, resonances, …)
    - LEP: a precision of 0.1% at 100 GeV can set a new physics scale of Λ^2=10 TeV^2
    - LHC: to set the same new energy scale, only need to have a precision of 10% at 1 TeV

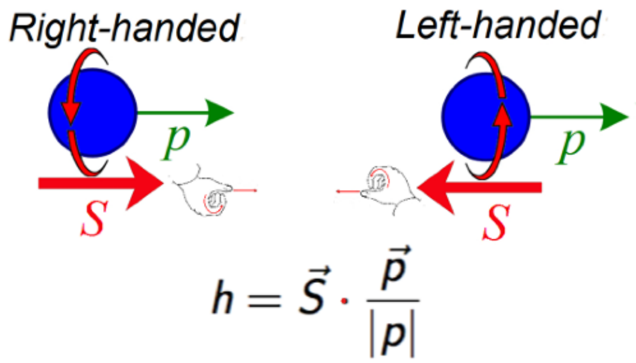


M. L. Mangano

How to measure the polarization of a weak boson

Polarization of a particle:

- Polarization describes the alignment of a particle's spin with its momentum. Quantified using the helicity variable:
  - Transversal polarization (T or ±): the spin and momentum are (anti-)aligned (h=1, -1)
  - Longitudinal polarization (L or 0): spin in parallel with the momentum (h=0)

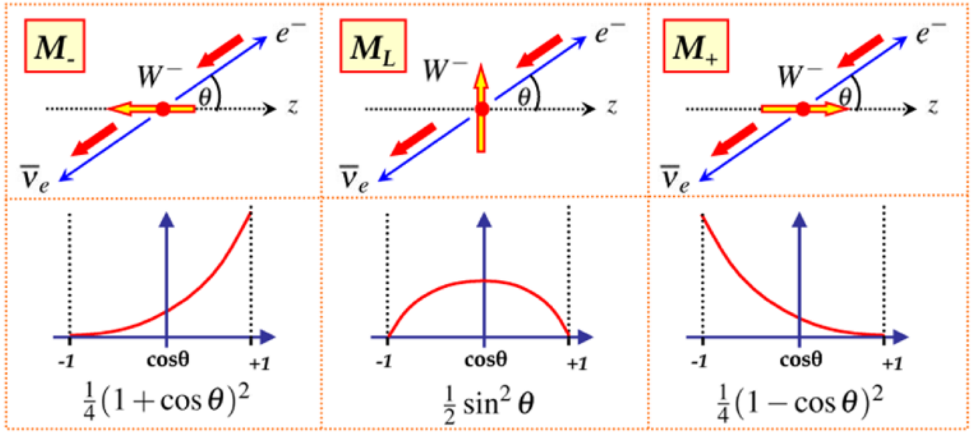


A caveat:

- Polarization measurements are frame dependent
- For all measurements we need to define a frame (there is not an universally preferred frame)

How to measure the polarizations of the weak bosons?

- Weak bosons are their own polarimeters
- Parity violation in weak interactions → polarization has effects on the decay products
- Angular variables between the bosons and the decay products are typically used to measure the weak boson polarizations
- Perform fits to data distributions using **polarized templates**

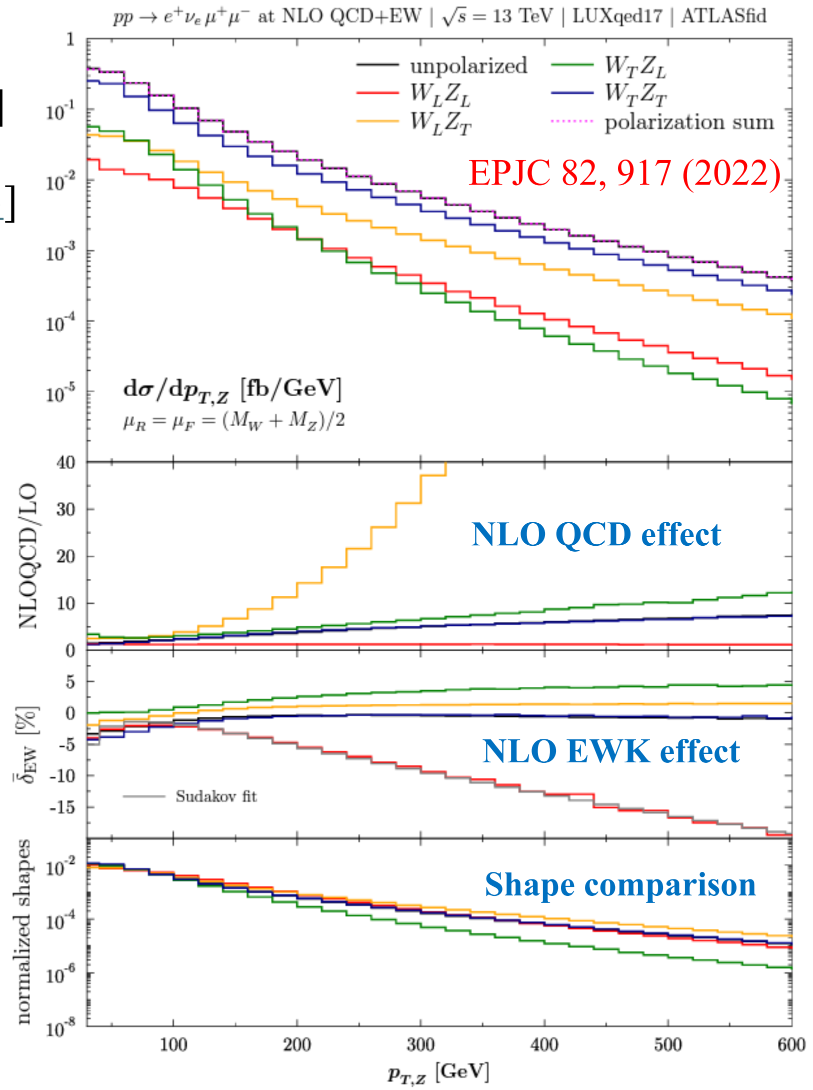


Left-handed Longitudinal Right-handed

Polarized samples

Monte Carlo generators (LO QCD calculations so far)

- PHANTOM: 2 → 6 processes @LO+PS [Ballestrero et al. 2008]
- MadGraph: arbitrary processes @ LO, PS matching, multi-jet merging (Franzosi et al. 2019]
- POWHEG-Box-RES: diboson processes @NLO QCD+PS [Pelliccioli et al. 2023]
- Sherpa: arbitrary processes @nLO QCD, PS matching, multi-jet merging [Hoppe et al. 2023]
- MadGraph has been the one used by ATLAS to generate polarized samples



Fixed order calculations

- The interference effect is often on the order of a few percent
- Large NLO QCD and electroweak corrections:
  - QCD corrections: 1.3 – 2.7 depending on polarization states and the frame used
  - EW corrections: often negative and its magnitude increasing with energy due to the double and single-Sudakov logarithms in the virtual contribution
- No MC event generation

Getting polarized templates is a challenge

- Reweighting technique and/or MC generators are used to include higher-order effects and to estimate systematic uncertainties

Inclusive ZZ polarization measurement

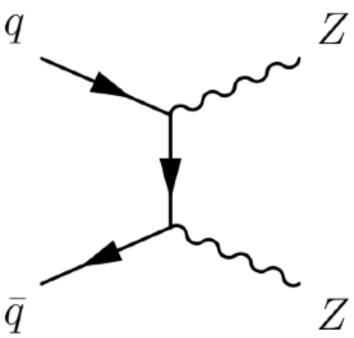
JHEP 12 (2023) 107

Event selection

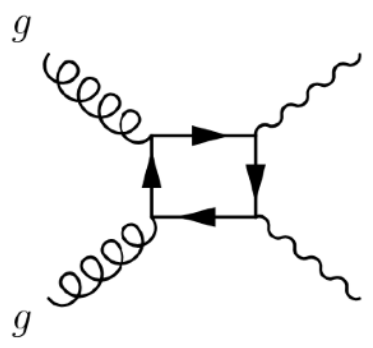
- Four isolated charged leptons with two SFOS lepton pairs consistent with the decay of a Z boson, and m_{4l}>180 GeV

Category	Requirement
Event Preselection	Fire at least one lepton trigger ≥1 vertex with 2 or more tracks
Four-lepton signature Lepton kinematics	At least 4 leptons (e, μ) $p_T > 20$ GeV for leading two leptons
Lepton separation J/ψ-Veto	$\Delta R_{ij} > 0.05$ for any two leptons $m_{ij} > 5$ GeVfor all SFOS pairs
Trigger matching	Baseline leptons matched to at least one lepton trigger
Quadruplet formation	At least one quadruplet with 2 Same-Flavor, Opposite-Sign (SFOS) pairs (the quadruplet having the smallest $\lvert m_{Z_1} - m_{Z_{pole}}\rvert + \lvert m_{Z_2} - m_{Z_{pole}}\rvert$ is chosen)
On-shell ZZ pair	$m_{4l} > 180$ GeV
On-shell Z boson	$\lvert m_{ij} - m_Z\rvert$<10 GeV

qq-initiated



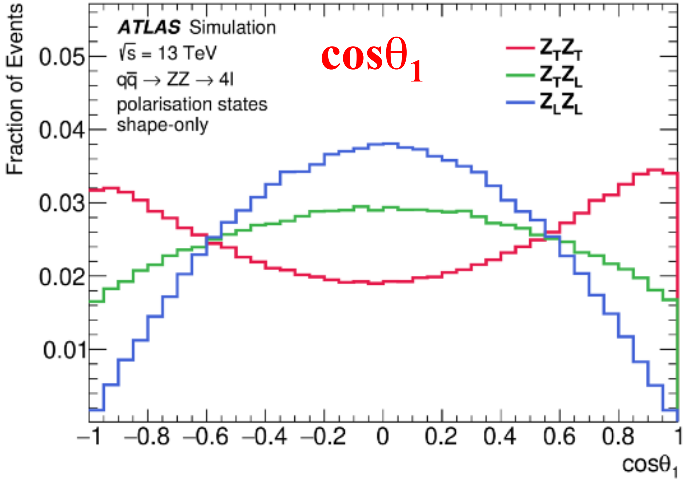
gg-initiated

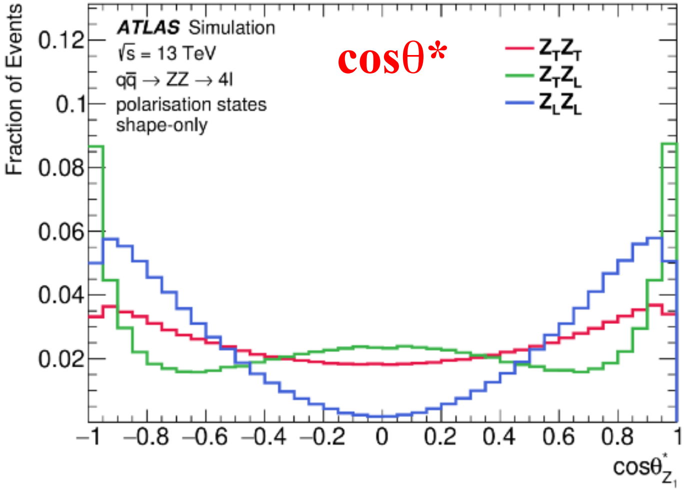


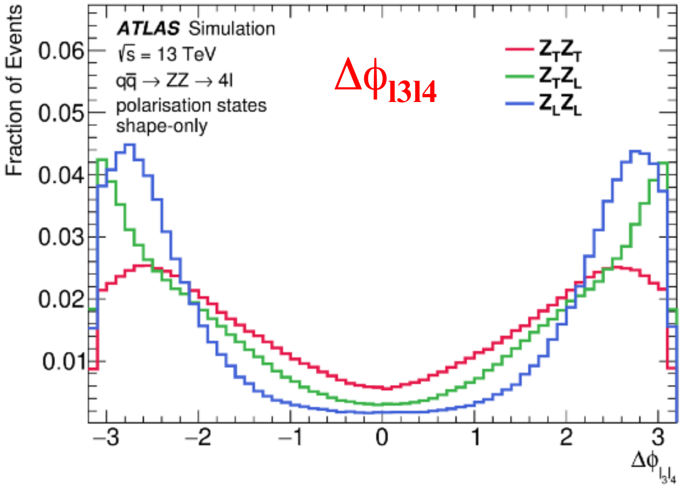
ZZ	$Z_L Z_L$	189.3	±	8.7	~6%
	$Z_T Z_L$	710	±	29	~23%
	$Z_T Z_T$	2170	±	120	~70%
	Interference	33.7	±	2.8	~1%
Non-prompt		18.7	±	7.1	
Others		20.0	±	3.7	
Total		3140	±	150	
Data		3149			

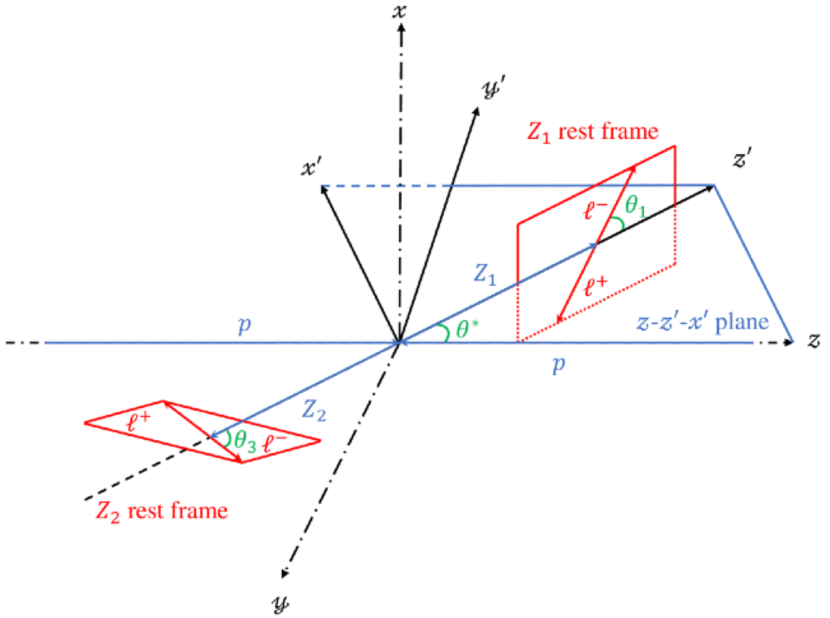
Variables used for polarization measurements

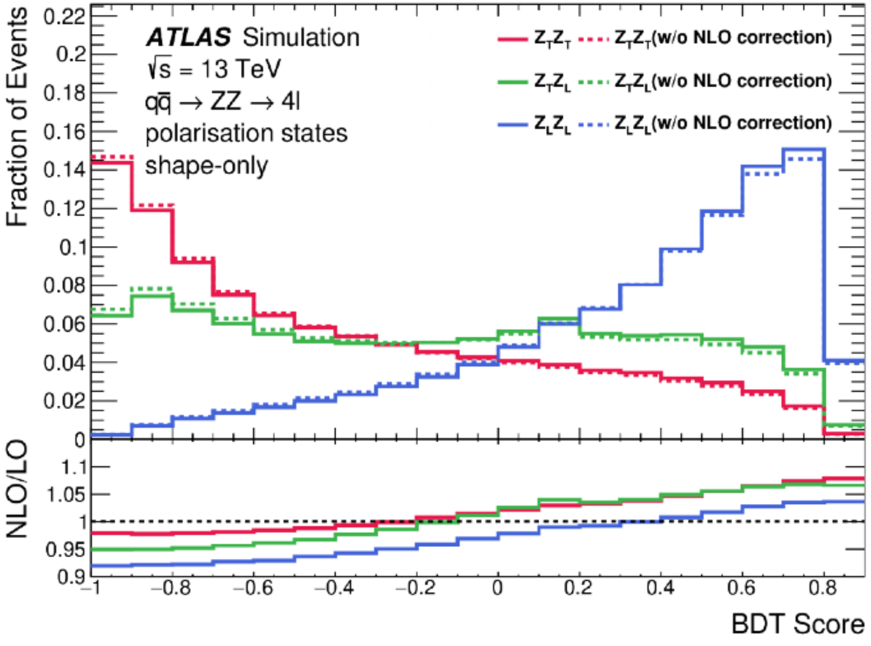
- The ZZ rest frame is used
- Five angular variables ($\cos\theta_1$, $\cos\theta_3$, $\cos\theta^*_{Z1}$, $\Delta\phi_{l1l2}$, and $\Delta\phi_{l3l4}$) are used to train a BDT variable to separate Z_LZ_L from Z_TZ_X







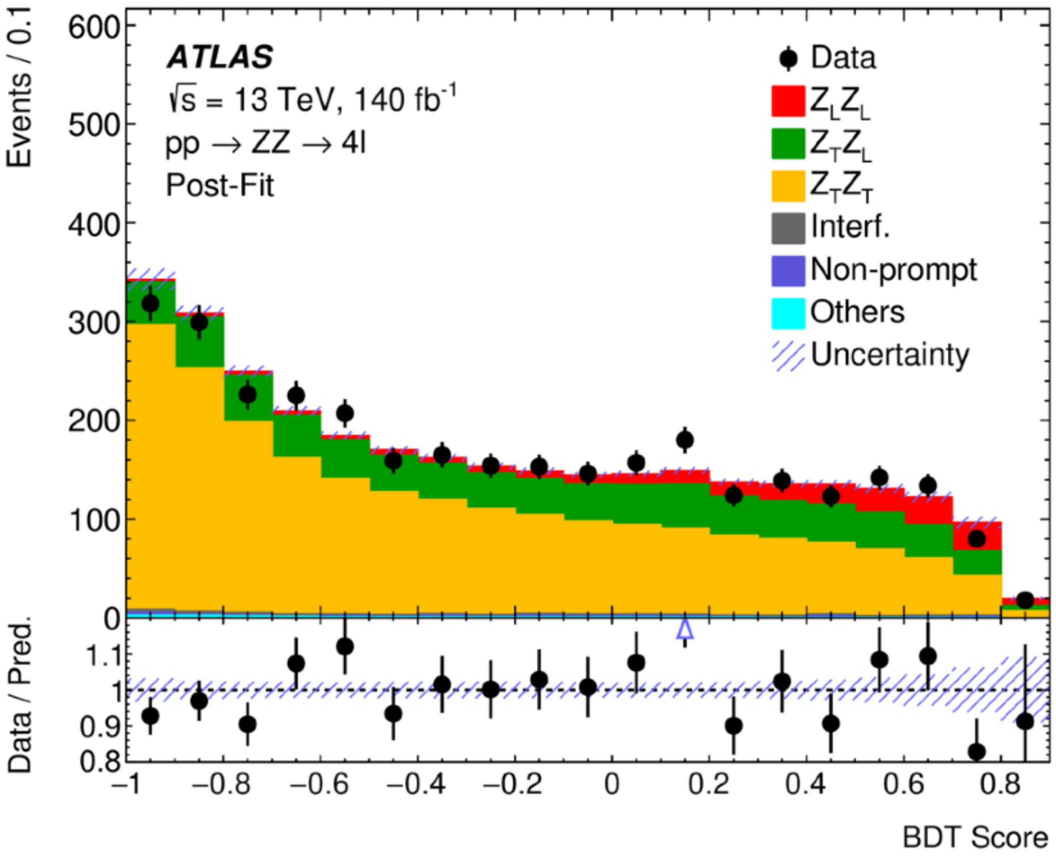




Template fitting

Template challenges:

- Polarized templates available with MadGraph for qq-initiated and EW ZZjj but not for gg-initiated diagrams
- NLO EW+QCD corrections and the gg-initiated contributions are available for ZZ at particle level with MoCaNLO (arXiv:2107.06579)
- A reweighting method using 1D and 2D distributions to:
  - Incorporate NLO EQ+QCD corrections to the MadGraph simulation for each polarization state
  - Obtain polarized templates from the unpolarized Sherpa gg-initiated MC sample
  - Include the interference effects among different polarization states



Fitting for joint polarization fractions:

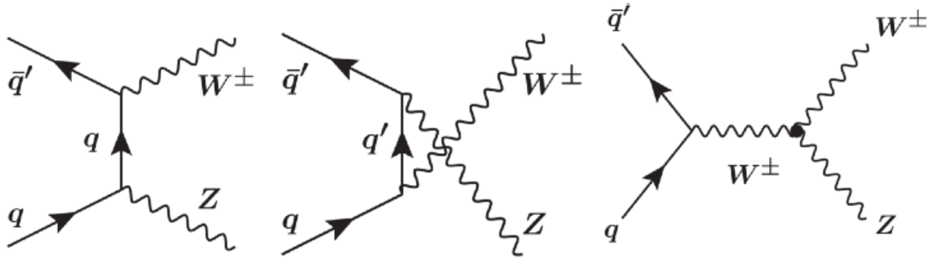
- Fitted using two parameters: μ_{LL} and μ_{TX}
- Obs. significance on μ_{LL} at 4.3σ (3.8σ expected) → First evidence of $Z_L Z_L$ production
- $Z_L Z_L$ cross section measured to be 2.45±0.56(stat)±0.21(syst) fb, consistent with the prediction of 2.10±0.09 fb

Inclusive WZ polarization measurement

PLB 843 (2023) 137895

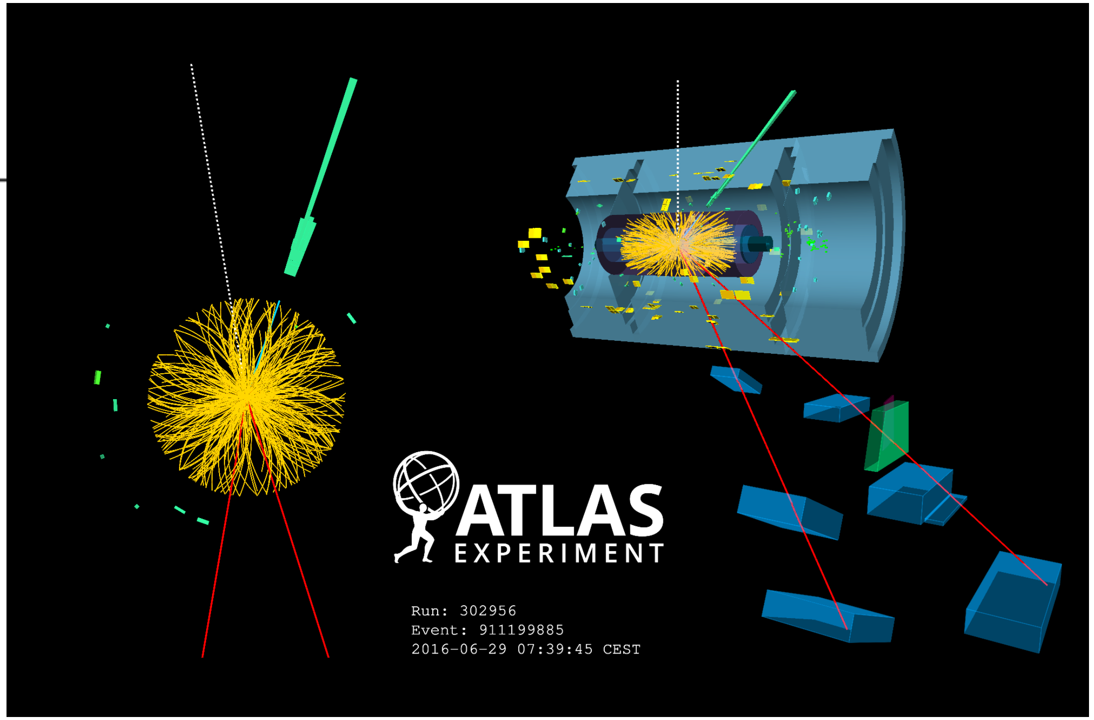
Event selection

- Three isolated charged leptons with an SFOS lepton pair consistent with the decay of a Z boson



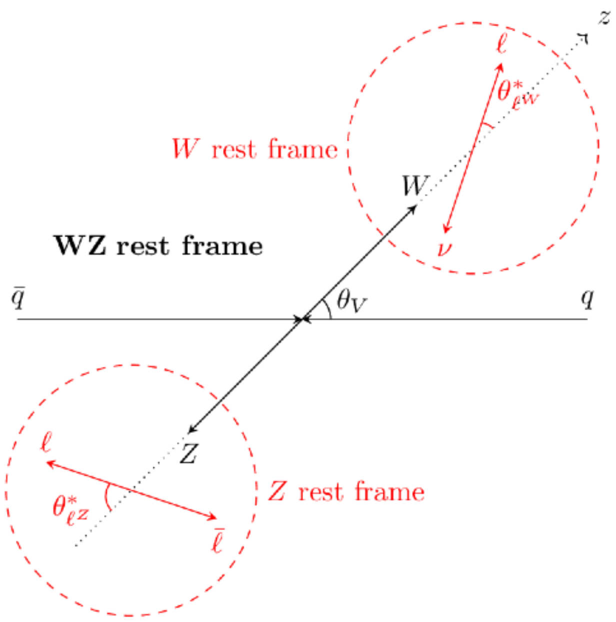
Trigger	At least one of five single lepton triggers fired
Leading lepton p_{T}	$p_{\mathrm{T}}^{\mathrm{lead}} > 27\,\mathrm{GeV}$
Event cleaning	Reject corrupted or incomplete events and events with non-collision background jet
Primary vertex	Hard scattering vertex with at least two tracks
ZZ veto	Strictly less than 4 baseline leptons
N leptons	Exactly 3 leptons passing the Z-lepton selection
Z leptons	2 same flavor oppositely charged leptons passing Z-lepton selection
Mass window	$\lvert m_{\ell\ell} - M_Z \rvert < 10\,\mathrm{GeV}$
W lepton	Remaining lepton passes W-lepton selection
W transverse mass	$m_{\mathrm{T}}^{W} > 30\,\mathrm{GeV}$

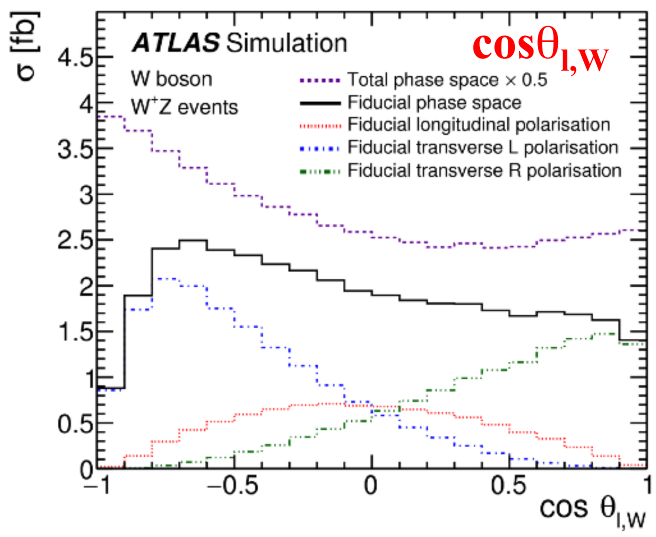
WZ in τ	620 ± 60	
ZZ	1420 ± 120	~10%
$t\bar{t} + V$	870 ± 130	
Misid. leptons	1170 ± 230	~5%
Others	800 ± 90	
W_0Z_0	920 ± 40	~6%
W_0Z_{T}	2670 ± 50	~32%
$W_{\mathrm{T}}Z_0$	2670 ± 60	
$W_{\mathrm{T}}Z_{\mathrm{T}}$	10200 ± 230	~62%
Total MC	21400 ± 500	
Data	21936	

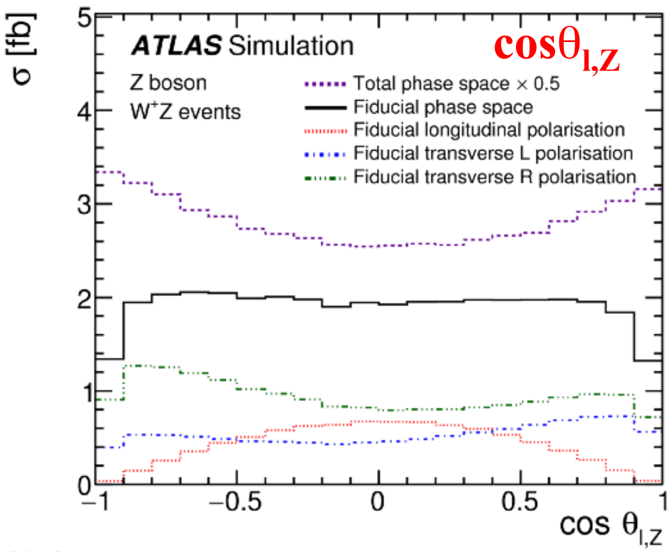


Discriminating variables used

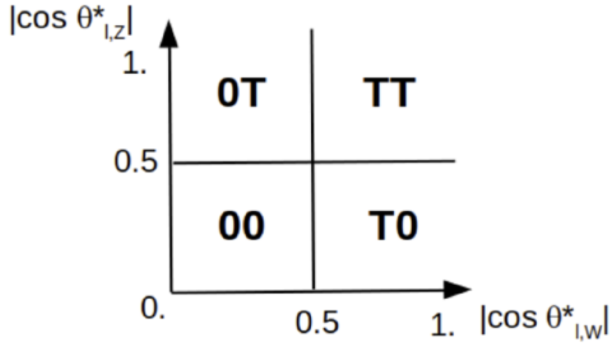
- The WZ rest frame is used
- A DNN score variable trained with eight kinematic variables (ΔY_{lZ}, $\Delta\phi(l_W, l_\nu)$, $\Delta\phi(l^1_Z, l^2_Z)$, p_T^{WZ}, W lepton p_T, two Z lepton p_T, and MET)
- The DNN score is trained separately in each of the four categories based on $|\cos\theta_{l,W}|$ and $|\cos\theta_{l,Z}|$

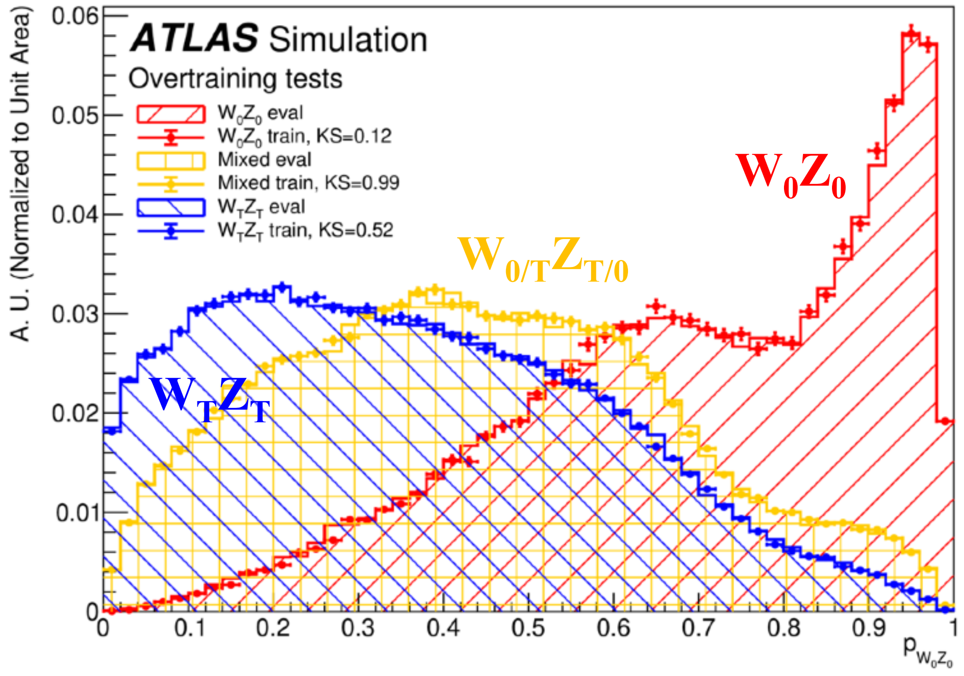






Blue: left-handed
Green: right-handed
Red: longitudinal





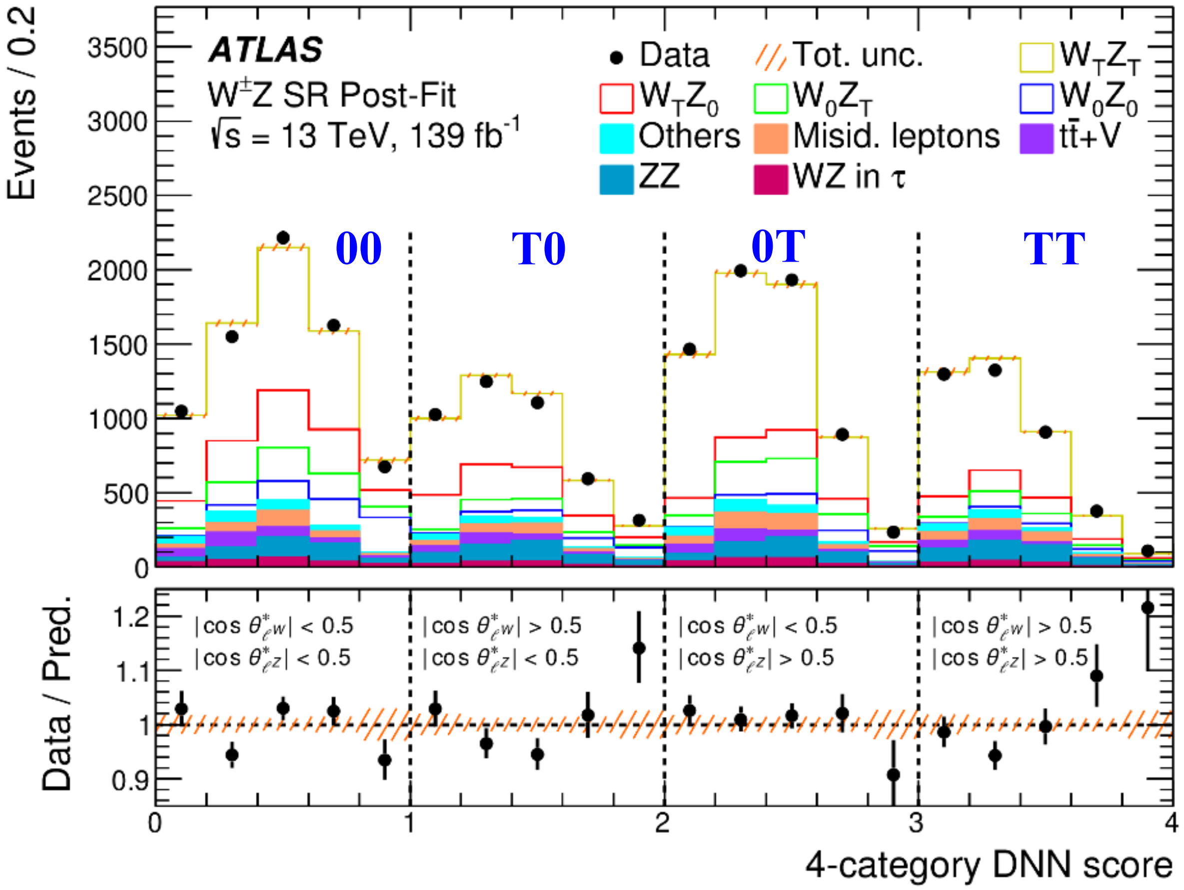
Templates and fitting

Template challenges:

- Polarized templates available with MadGraph at LO+real corrections → great, but insufficient, bias from 10% to 50% of the fraction values in this phase space
- Polarized templates at NLO QCD are obtained using a multi-dimensional reweighting technique with a classification DNN output [arXiv:1907.08209]:
  - For a given event *x* (12 selected kinematic variables describing the event), figure out the probabilities for it to be in 00, 0T, T0, and TT states using LO polarized MadGraph samples
  - These probabilities are then applied as weights to NLO unpolarized POWHEG samples

Fitting for joint polarization fractions:

- Four different polarization fractions (f_{00}, f_{0T}, f_{T0}, and f_{TT}) to extract
- DNN score classifies each joint polarization state
- Simultaneous fit performed in 4 categories based on $|\cos\theta_{l,W}|$ and $|\cos\theta_{l,Z}|$



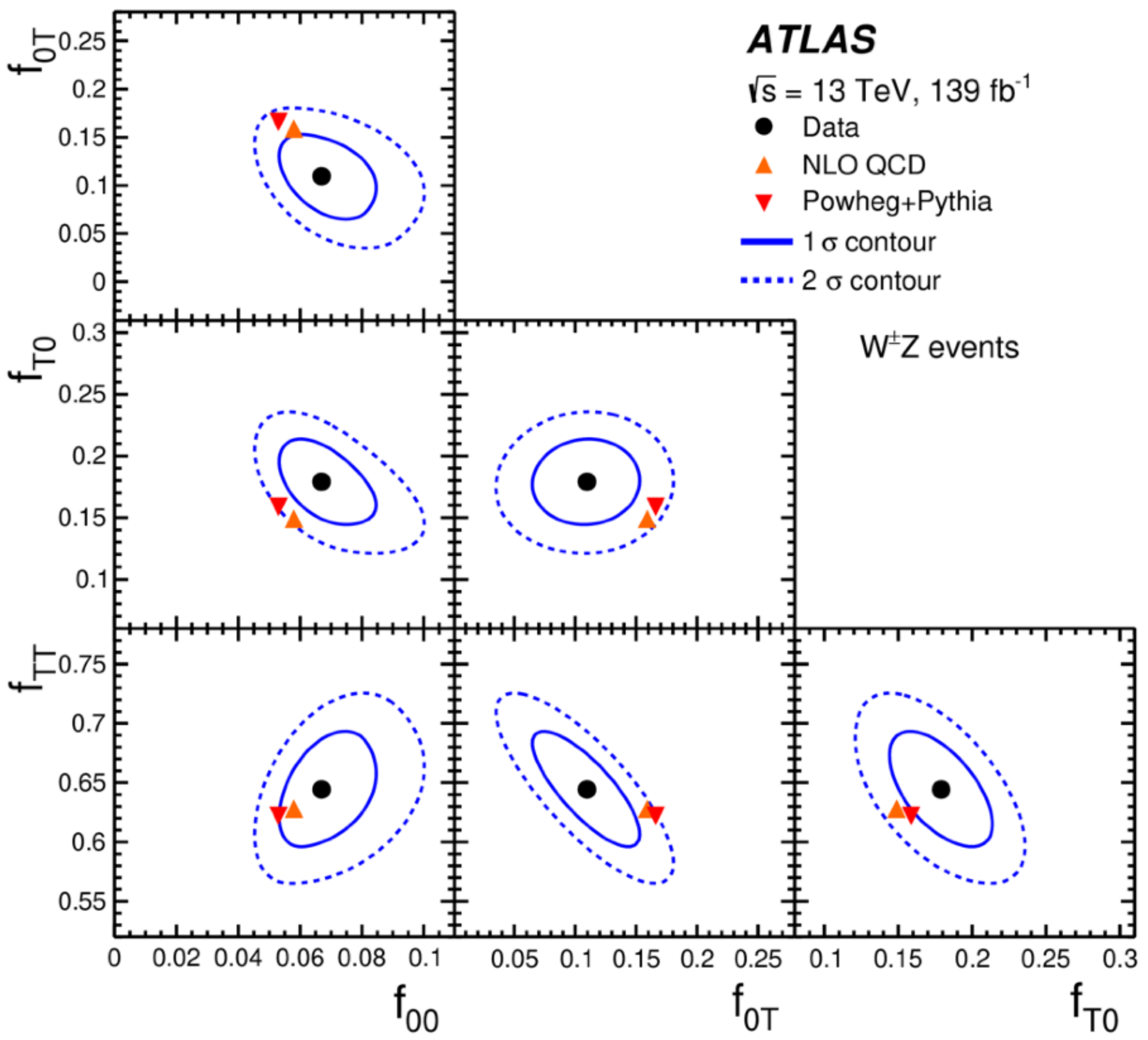
Fitted results

	Data			Powheg+Pythia			NLO QCD		
				$W^{\pm}Z$					
f_{00}	0.067	±	0.010	0.0590	±	0.0009	0.058	±	0.002
f_{0T}	0.110	±	0.029	0.1515	±	0.0017	0.159	±	0.003
f_{T0}	0.179	±	0.023	0.1465	±	0.0017	0.149	±	0.003
f_{TT}	0.644	±	0.032	0.6431	±	0.0021	0.628	±	0.004

- Stat and syst uncertainties are comparable
- Dominant systematic uncertainty comes from modeling
- Obs. significance on f_{00} at 7.1σ (6.2σ expected)
- Obs. significance on f_{0T} (3.4σ), f_{T0}(7.1 σ) and f_{TT} (11σ)
- First observation/evidence of WZ in different polarizations

- Joint polarization fractions are also measured for W^+Z and W^-Z processes separately

- Individual boson helicity fractions are also measured
- The measured values agree with the SM predictions and the multiplications are consistent with the measured joint helicity fractions when neglecting interference among polarization states ($f_{00} \approx f_0^W \times f_0^Z$)

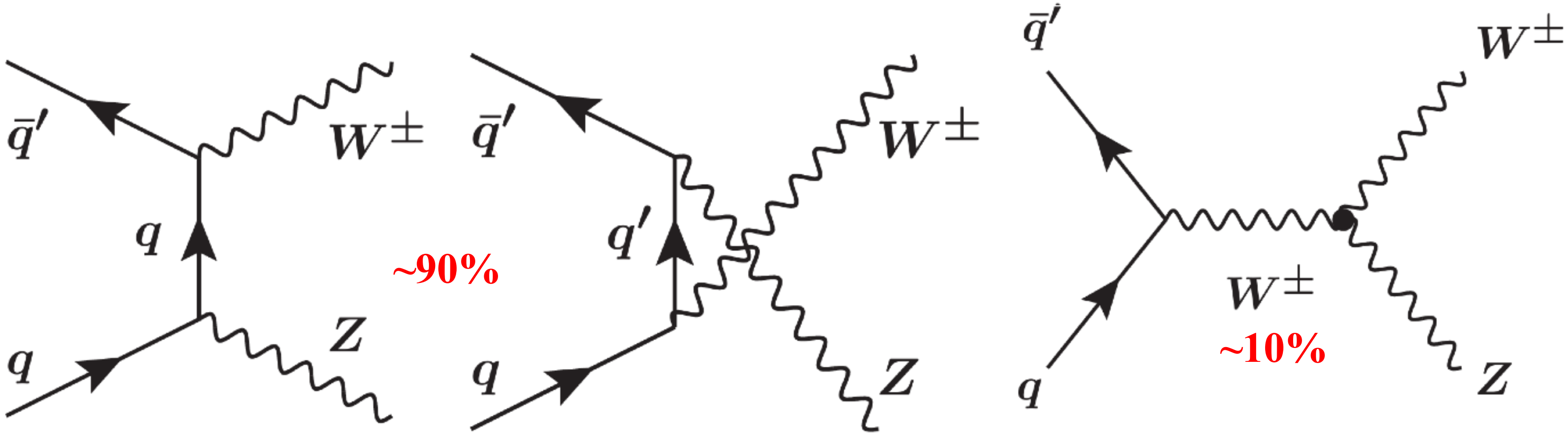


High-p_T WZ polarization measurement and Radiation Amplitude Zero

arXiv:2402.16365

Introduction

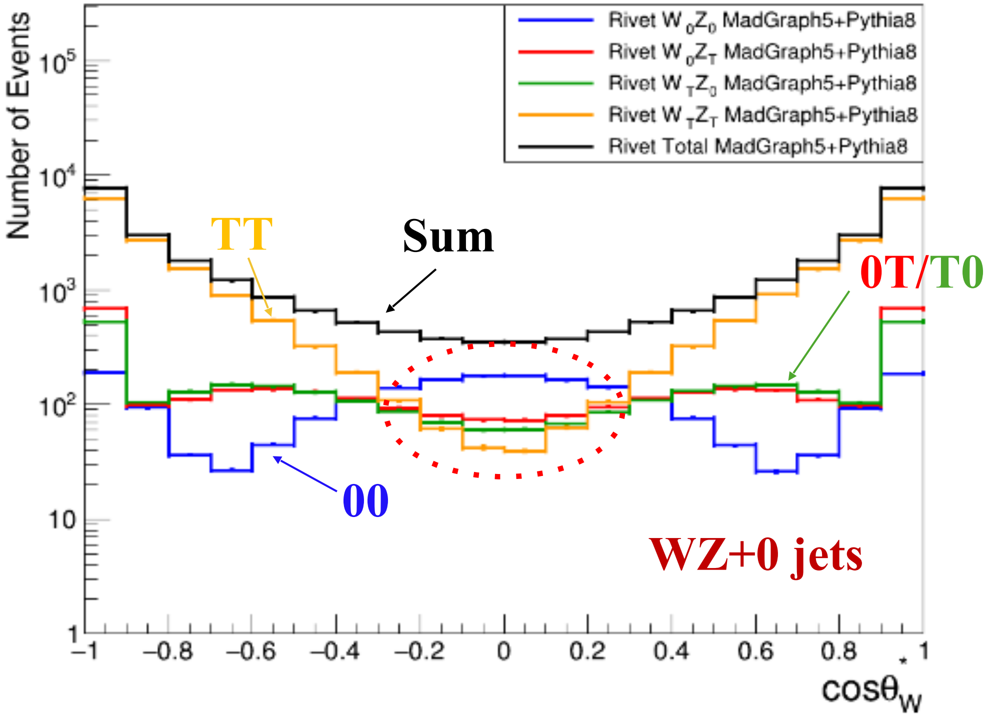
- Inclusive WZ and ZZ polarization measurements are dominated by t- and u-channel production ($f_{00} \approx f_0^W \times f_0^Z$)
- Interesting measurements with:
  - Events produced in the s-channel where two longitudinally-polarized vector bosons interacting with each other
  - Cross-section/fraction measurements for different polarization states at high energies

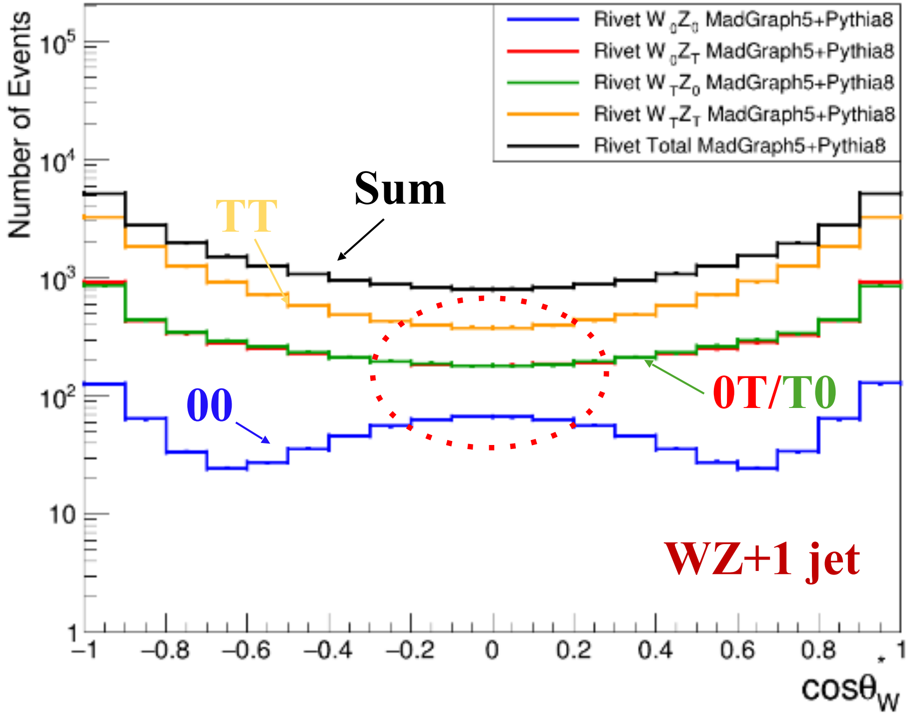


- Challenges:
  - Only ~10% of events produced in the s-channel
  - Both bosons are longitudinally polarized is ~6% → 10% × 6%=0.6%
  - The signal size is ~0.6% of inclusive diboson production

Reasons to choose the WZ → lvll channel

- Experimental side: large cross sections, most kinematical variables can be calculated (neutrino p_z calculated using the W mass constraint), small reducible background expected
- Theoretical side: Radiation Amplitude Zero
  - At LO expect to have exact zero for $\sigma(W_T Z_T)$ in the region with the boson scattering angle $\cos\theta_W \sim 0$
  - Strong gauge cancellations for the 0T and T0 amplitudes
  - This results in a lower cross section for TT+0T+T0 than 00 for $\cos\theta_W \sim 0$
  - RAZ effect happens only at LO



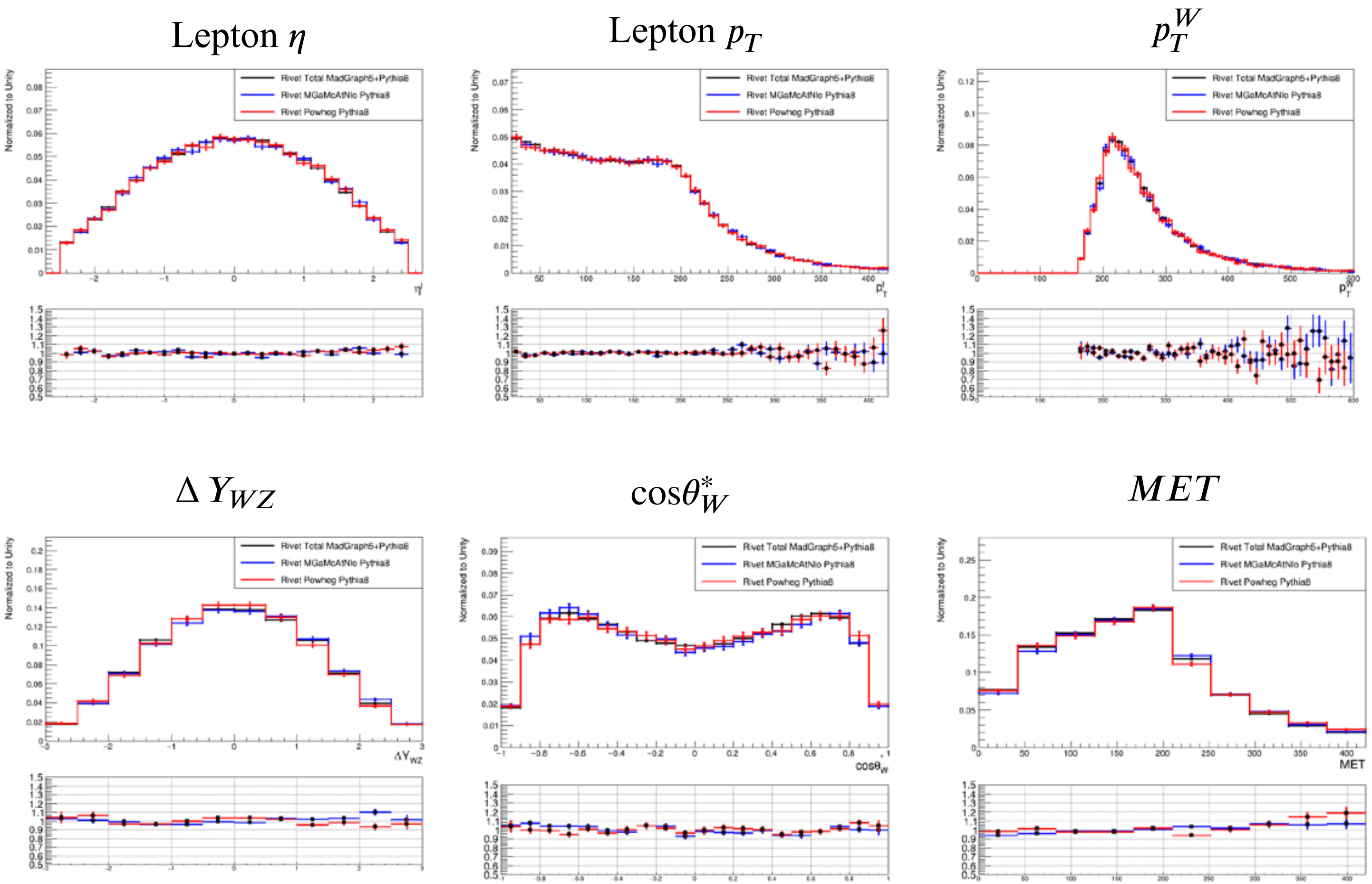


Polarized WZ samples

- LO WZ+0 jets and WZ+1 jet events generated with MadGraph
- Pythia is used to perform parton shower and merge these two samples to emulate the NLO effect
- Separate samples generated for events with $p_T(Z)<150$ GeV and $p_T(Z)>150$ GeV to have more statistics at high p_T
- Samples with e/μ and τ in the final state are generated separately
- Negligible interference effects

- Sum of polarized events are compared with inclusive NLO QCD events
- Comparison of merged LO MadGraph predictions with NLO EWK+QCD calculations for each polarization state
- Good agreement observed for all comparison plots

MadGraph Sum of different diboson polarizations LO + Pythia8
MadGraph aMC@NLO – NLO + Pythia8
Powheg+Pythia8



Event selection

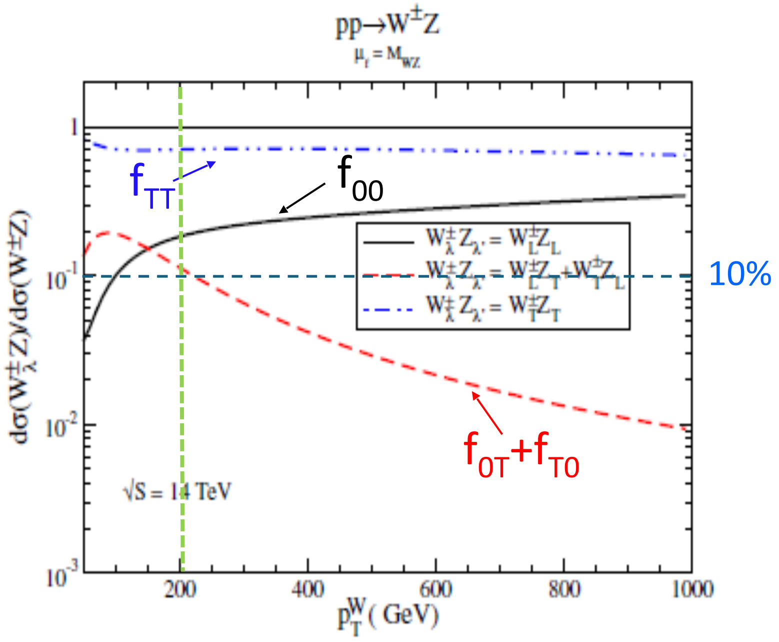
Inclusive WZ event selection	
Event cleaning	Reject LAr, Tile and SCT corrupted events and incomplete events
Primary vertex	Hard scattering vertex with at least two tracks
Triggers in 2015	`HLT_e24_lhmedium_L1EM20VH || HLT_e60_lhmedium || HLT_e120_lhloose` `HLT_mu20_iloose_L1MU15 || HLT_mu50`
Triggers in 2016–2018	`HLT_e26_lhtight_nod0_ivarloose || HLT_e60_lhmedium_nod0 || HLT_e140_lhloose_nod0` `HLT_mu26_ivarmedium || HLT_mu50`
ZZ veto	Less than 4 baseline leptons
N leptons	Exactly three leptons passing the Z lepton selection
Leading lepton p_T	$p_T^{lead} > 25$ GeV (in 2015) or $p_T^{lead} > 27$ GeV (in 2016-2018)
Z leptons	Two same flavor oppositely charged leptons passing the Z-lepton selection
Z lepton invariant mass	$\|m_{\ell\ell} - M_Z\| < 10$ GeV
W lepton	Remaining lepton passes the W-lepton selection
W transverse mass	$m_T^W > 30$ GeV
ΔR	$\Delta R(\ell_Z^-, \ell_Z^+) > 0.2$, $\Delta R(\ell_Z, \ell_W) > 0.3$

Signal regions

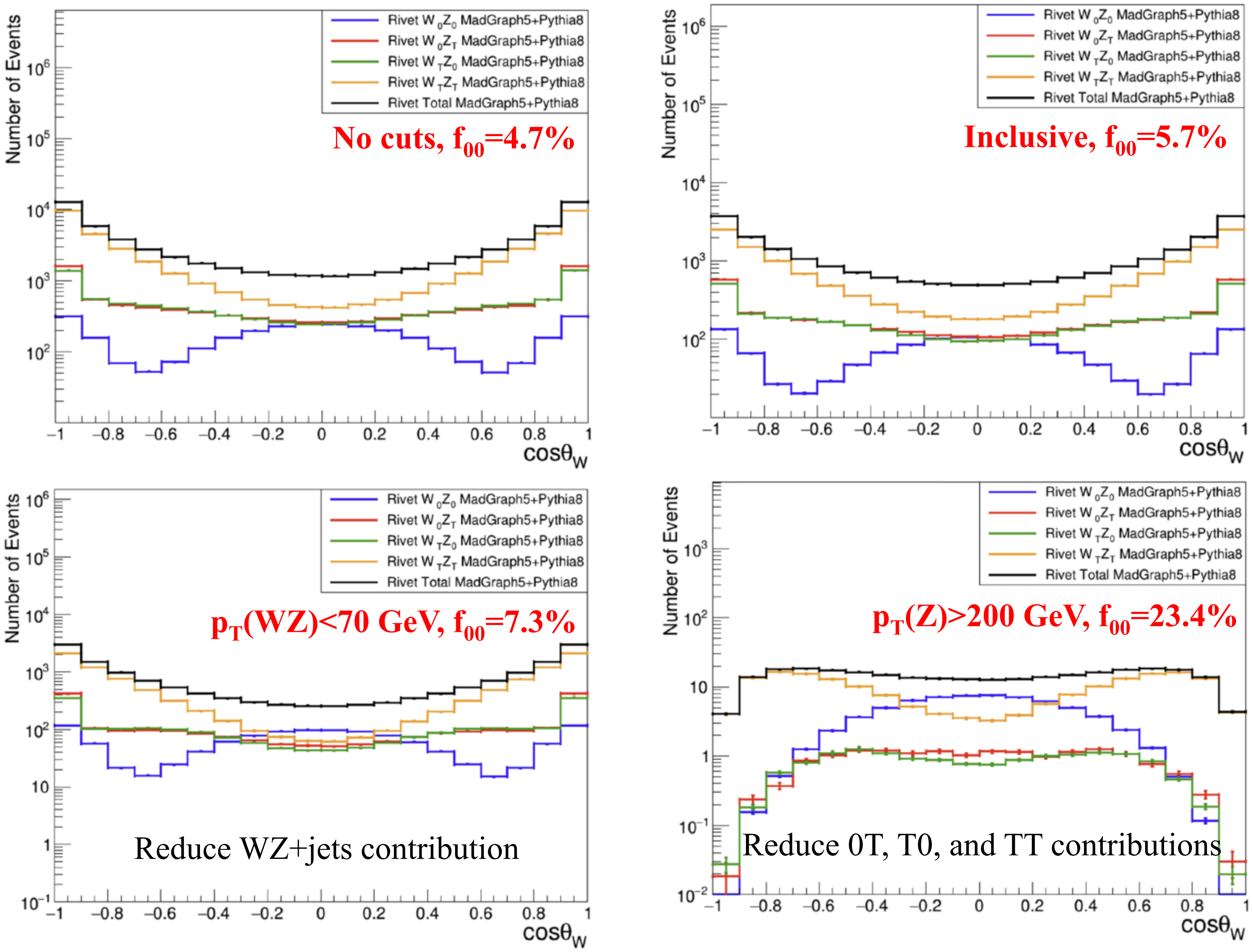
	Radiation Amplitude Zero	00-enhanced region 1	00-enriched region 2
Pass inclusive WZ event selection	✓	✓	✓
Transverse momentum of the Z boson (p_T^Z)	-	[100, 200] GeV	> 200 GeV
Transverse momentum of the WZ system (p_T^{WZ})	< 20, 40, 70 GeV	< 70 GeV	< 70 GeV

Same requirements as used by the inclusive WZ polarization measurement

- Inclusive: events with three isolated leptons
- Low-$p_T(WZ)$: $p_T(WZ)$<70 GeV to reduce WZ+jets events → increase the RAZ effect
- High $p_T(Z)$: 100<$p_T(Z)$<200 GeV (or $p_T(Z)$>200 GeV) to select s-channel events

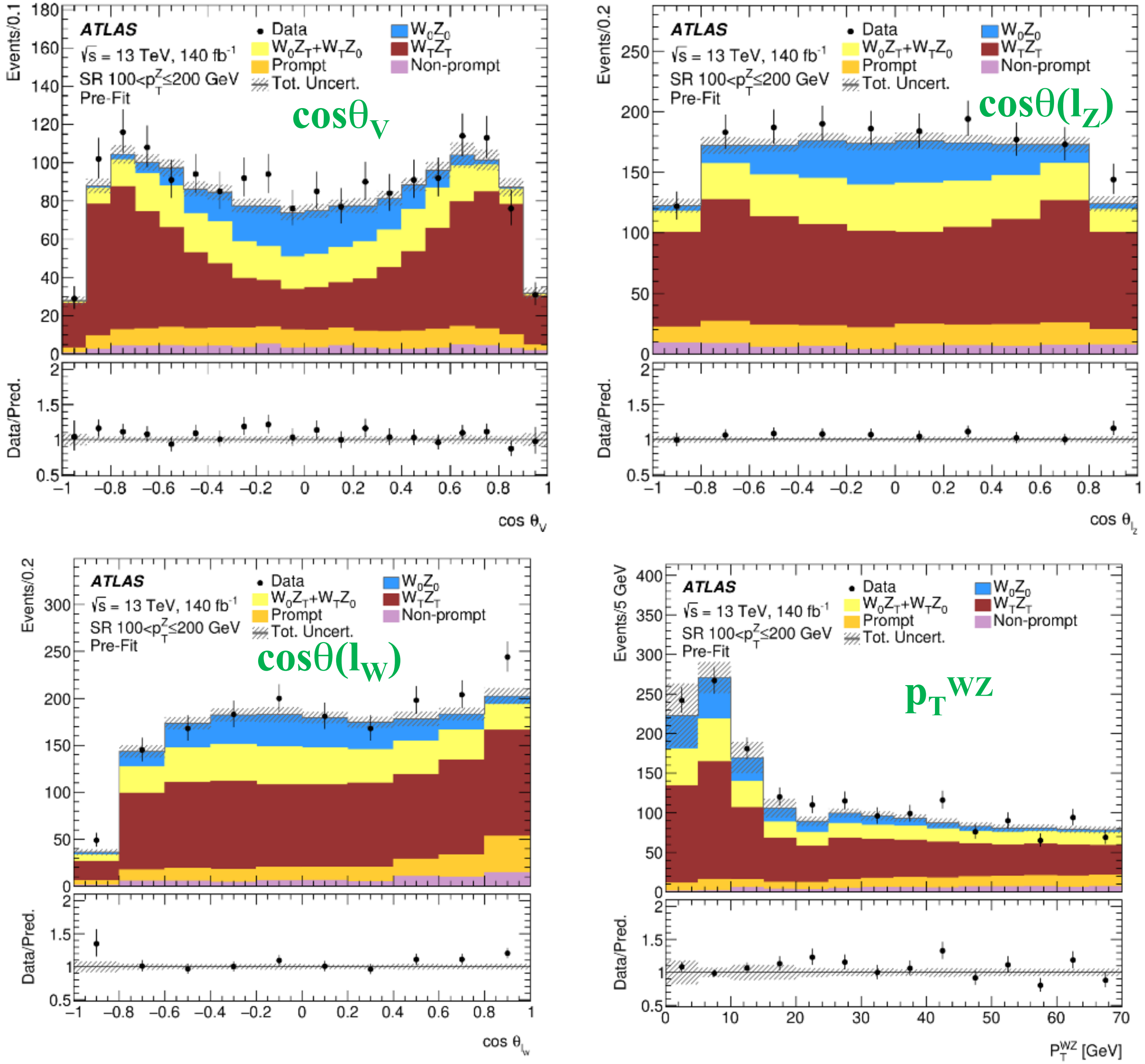


00-enhanced signal regions

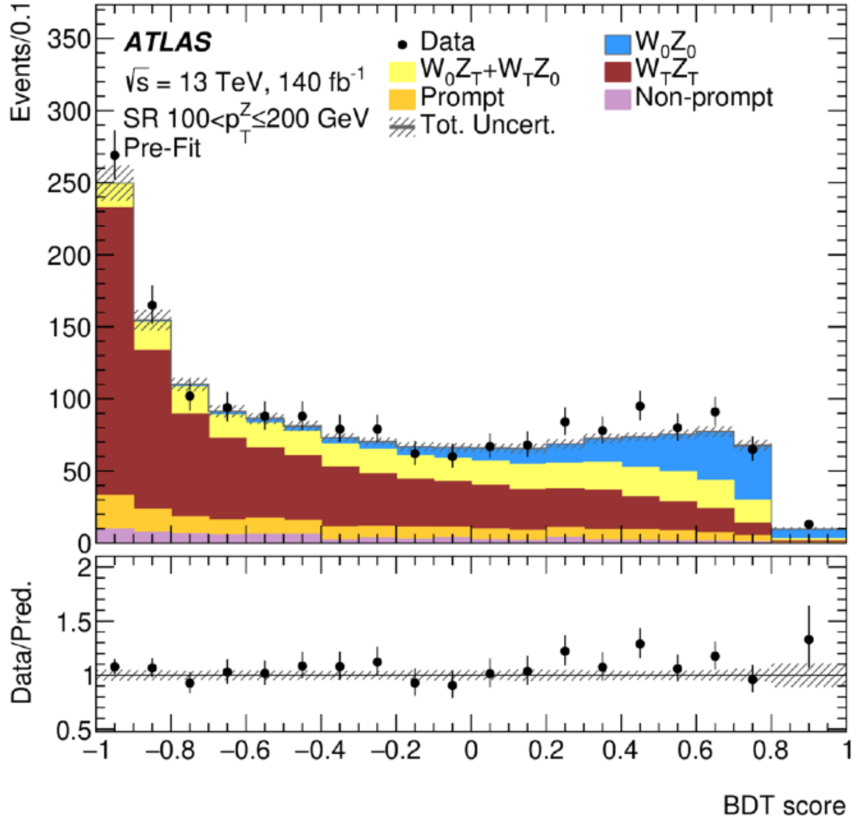


Blue: 00
Red: 0T
Green: T0
Orange: TT

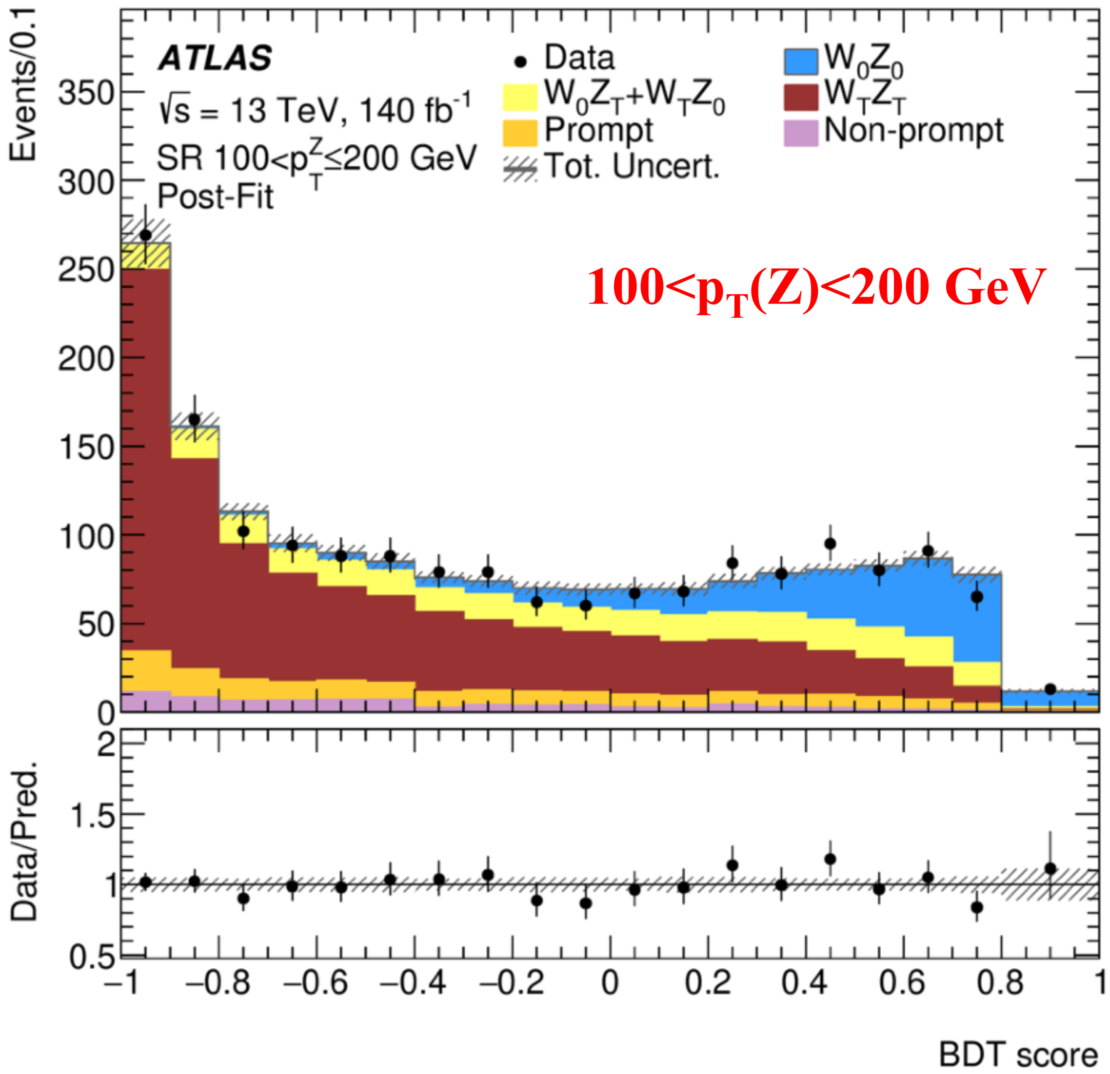
BDT

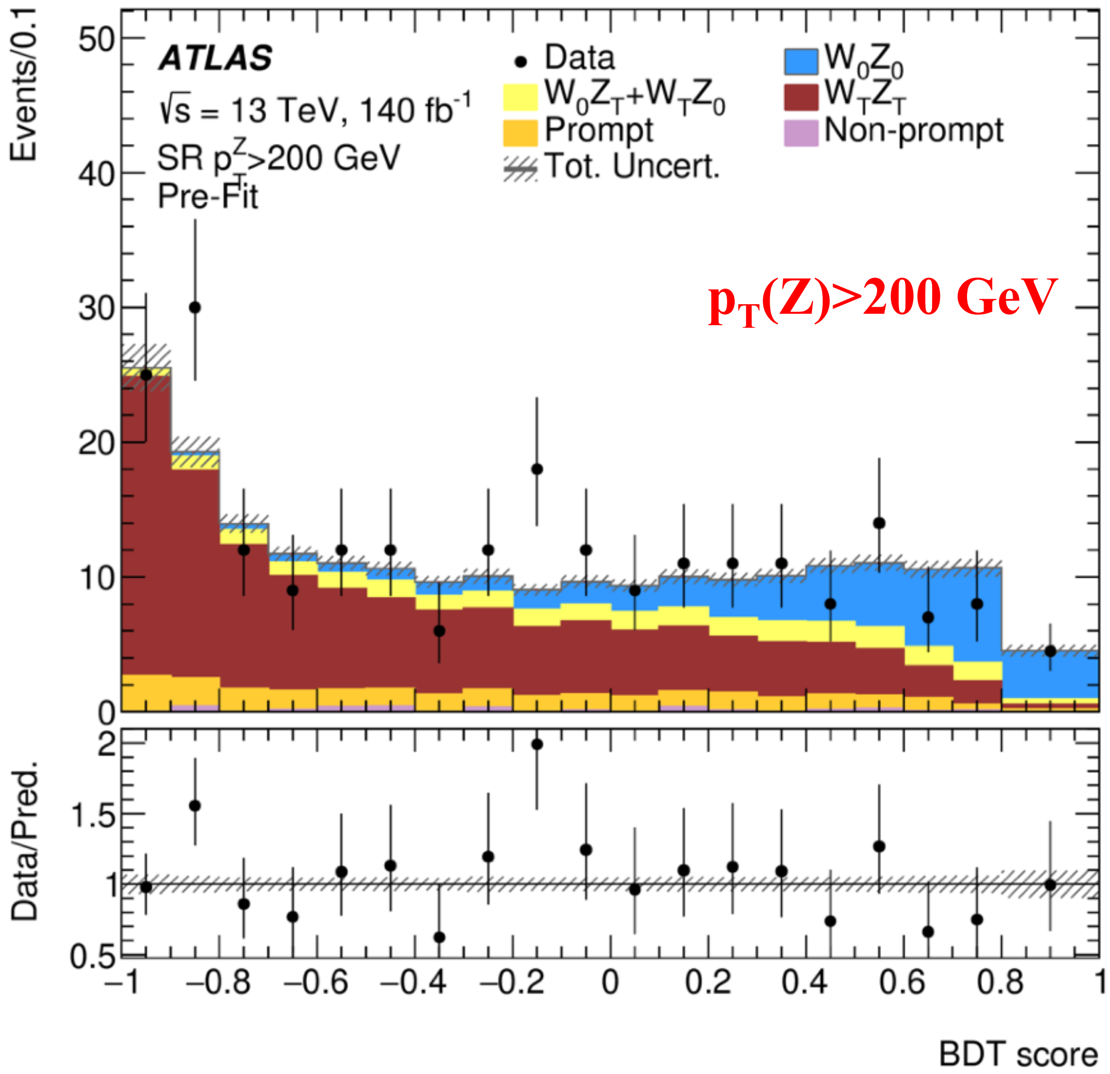


- A BDT discriminant is trained using seven kinematical variables to separate 00 from other polarization states
- Separate BDT variable trained for each 00-enhanced signal region
- Pre-fit plots are shown



Fitting results





Results

Process	$100 < p_T^Z \leq 200$ GeV		$p_T^Z > 200$ GeV	
	Pre-fit	Post-fit	Pre-fit	Post-fit
W_0Z_0	222 ± 5	290 ± 60	47.6 ± 1.5	28 ± 19
$W_0Z_T + W_TZ_0$	323 ± 12	280 ± 140	23.7 ± 0.8	50 ± 40
W_TZ_T	856 ± 31	920 ± 100	124 ± 4	132 ± 29
Prompt background	169 ± 18	166 ± 18	24.1 ± 2.7	24.2 ± 2.7
Non-prompt background	68 ± 29	80 ± 40	2.8 ± 1.1	2.8 ± 1.1
Total Expected	1640 ± 60	1740 ± 40	222 ± 8	236 ± 15
Data	1740		236	

Two-parameter fit: f_{00} and N_{tot}

	Measurement	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.17 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.01}_{0.02}$ (syst)	$0.16 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.02}_{0.03}$ (syst)
f_{XX}	$0.83 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.02}_{0.01}$ (syst)	$0.84 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.03}_{0.02}$ (syst)
f_{00} obs (exp) sig.	7.7 (6.9) σ	3.2 (4.2) σ

Three-parameter fit: f_{00}, f_{0T+T0}, and N_{tot}

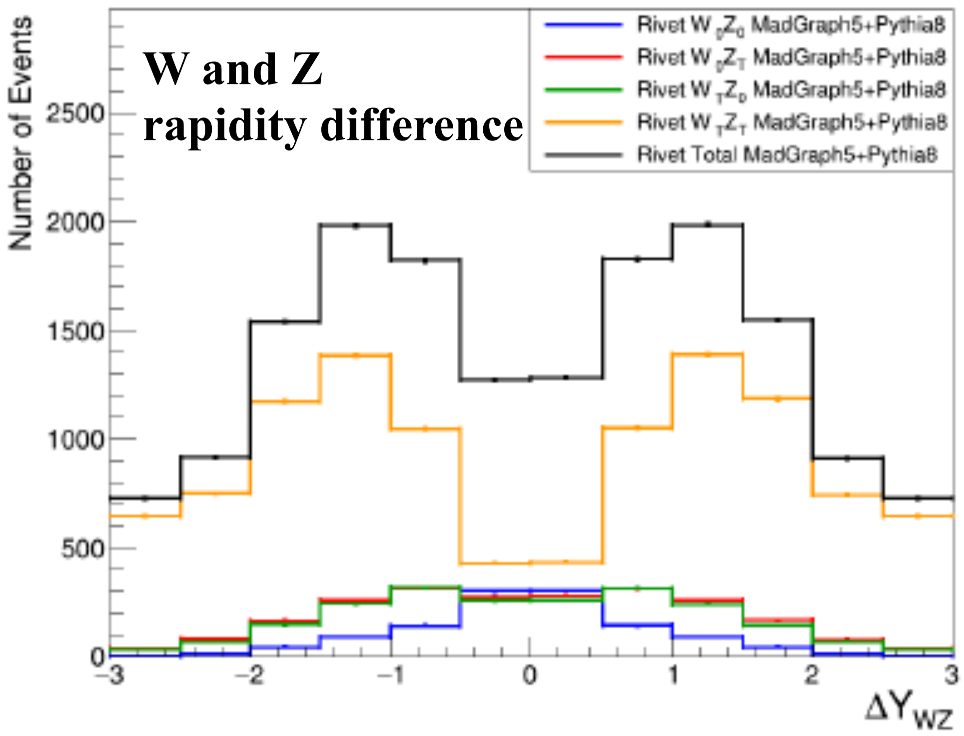
	Measurement	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ

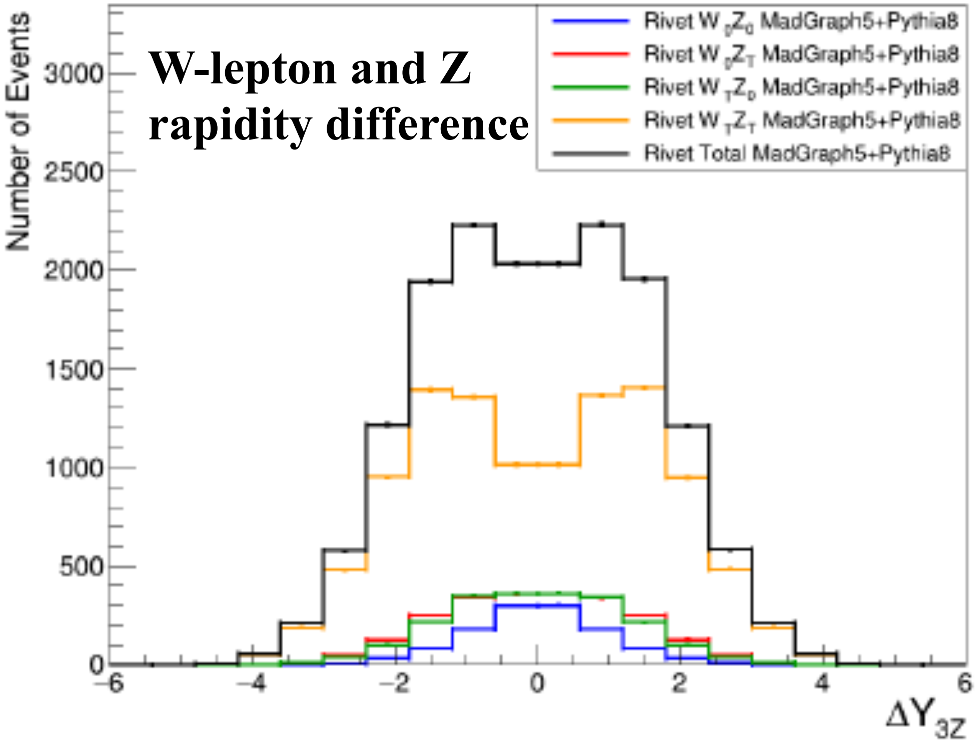
	Prediction	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{TT}	0.619 ± 0.007	0.646 ± 0.008

- First observation/evidence of joint longitudinally-polarized bosons at high energies → approaching the regime where longitudinal bosons behave as Goldstone bosons
- These signal regions are dominated by s-channel events where two bosons directly interact with each other

Radiation amplitude zero

- Result of destructive interferences between different Feynman diagrams
- Theorists were pessimistic about the observation of RAZ in WZ production due to the polarization of the W boson (arXiv: hep-ph/9506286)
- New MadGraph versions allow us to generate WZ events in different polarization states
- A dip observed in $\Delta\eta(l, \gamma)$ for Wγ production, similarly we expect to see a dip in ΔY_{WZ} and ΔY_{lZ} distributions
- Larger dip expected in the ΔY_{WZ} distribution



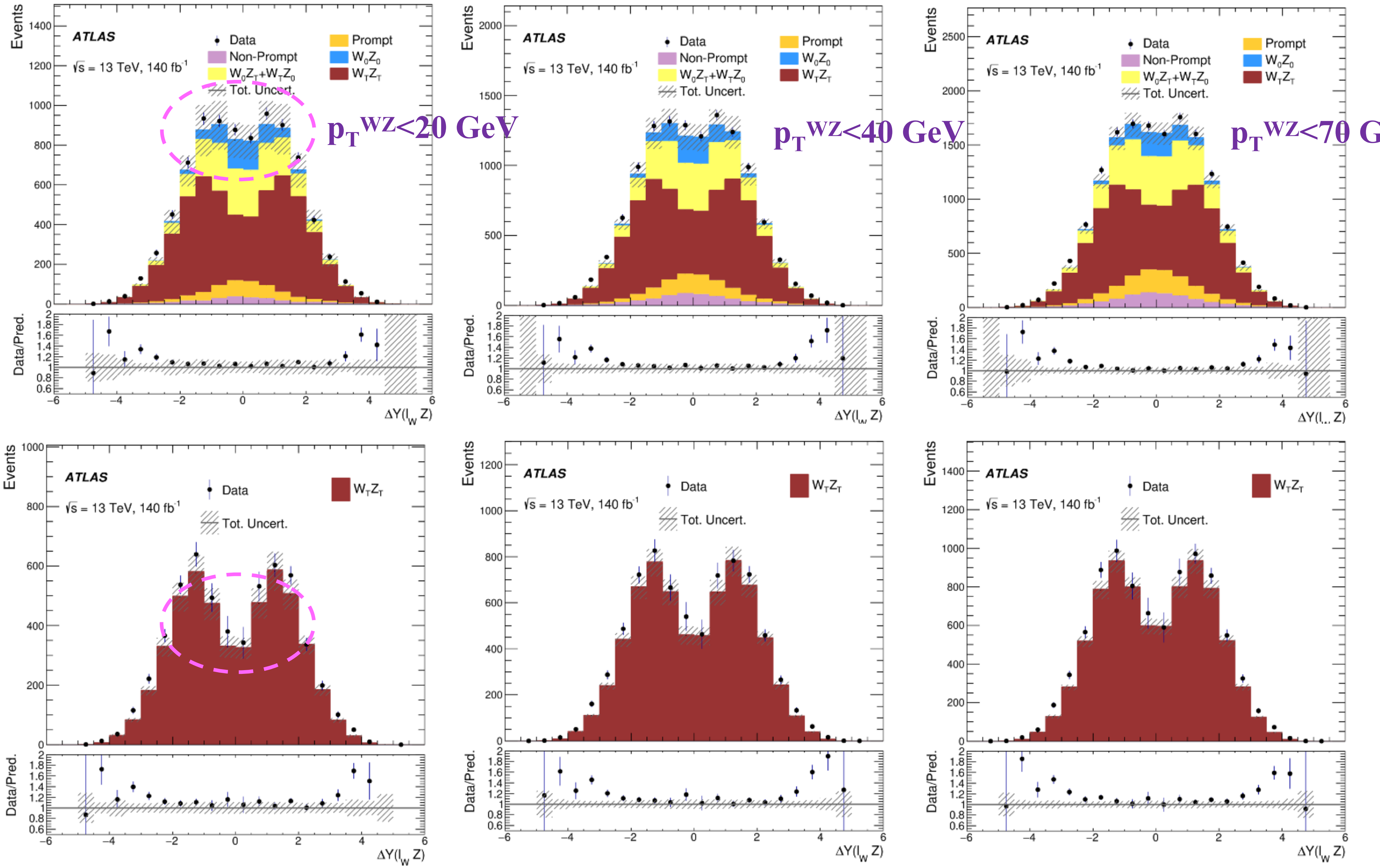


Blue: 00
Red: 0T
Green: T0
Orange: TT

TT, T0, 0T and 00 contributions are not stacked together

Peak structure: 00, T0, and 0T
Dip structure: TT

RAZ effect for different $p_T(WZ)$ [$\Delta Y(l_W Z)$]



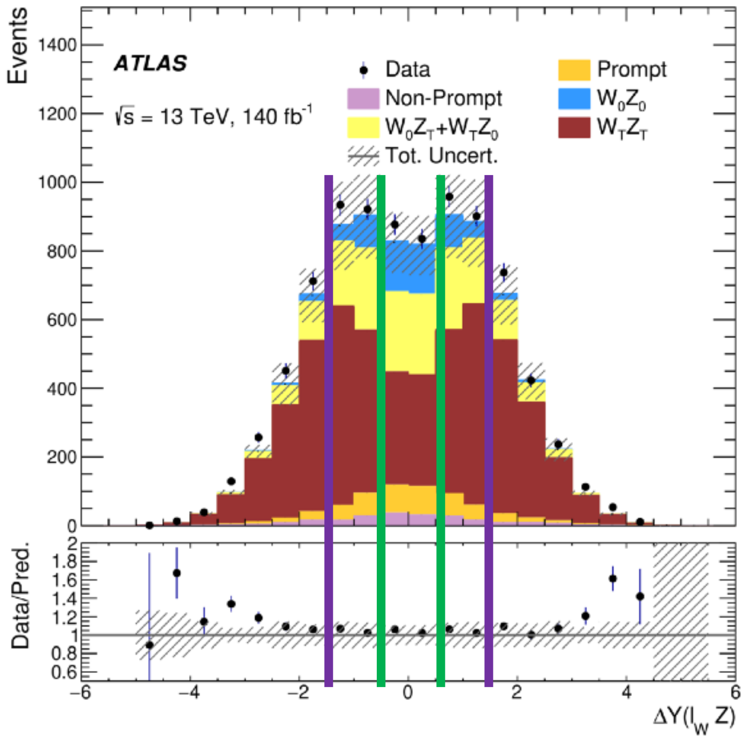
Inclusive events with contributions from all polarization states

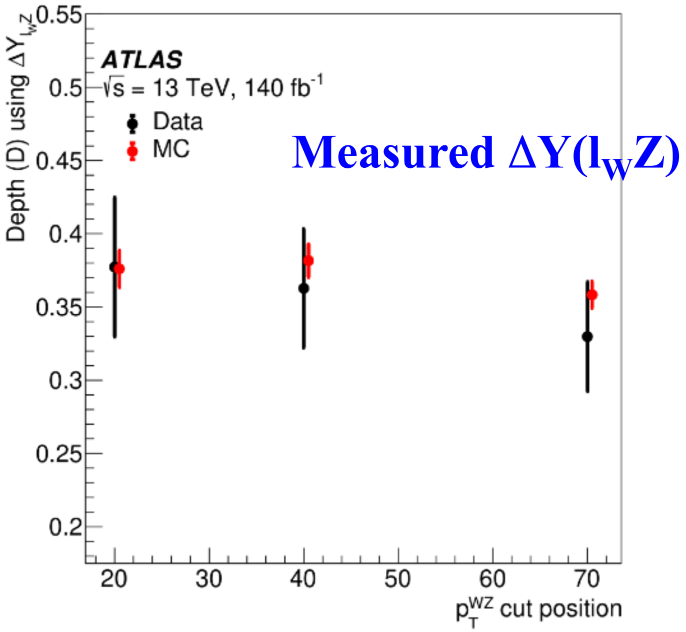
TT-only events and contributions from 00, 0T, and T0 are removed

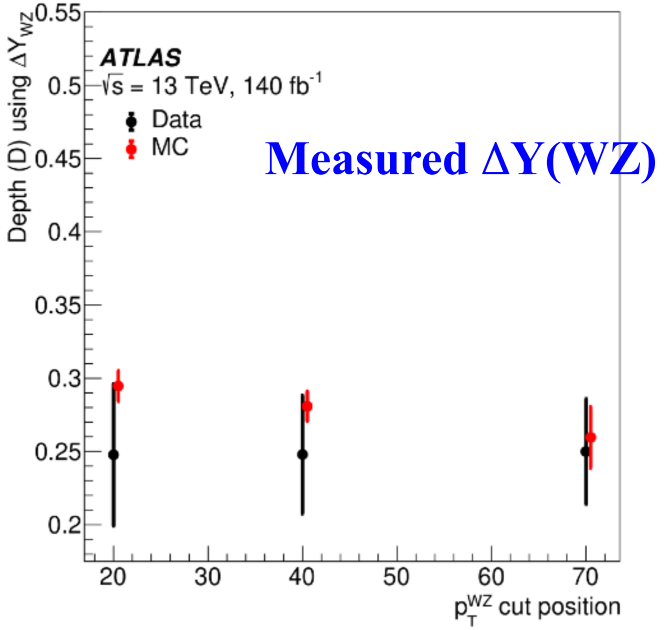
Quantify the depth of the dip

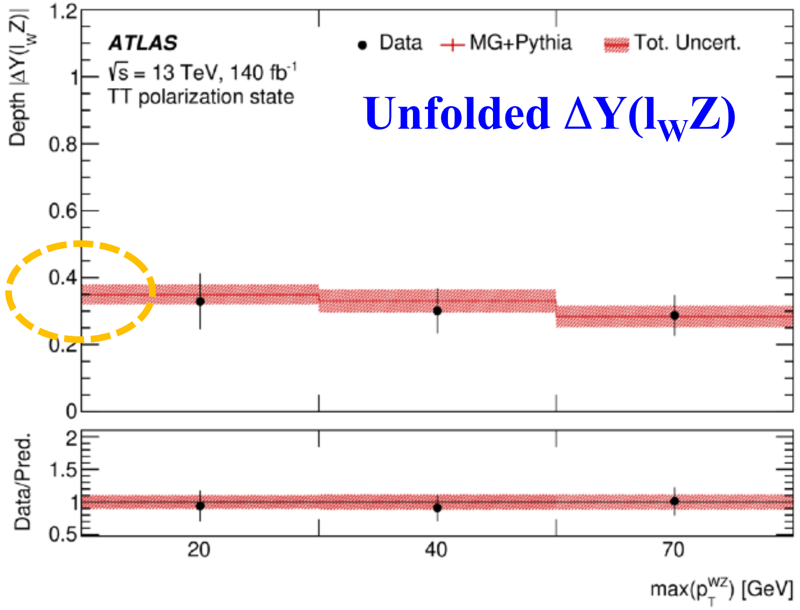
$$D = 1 - 2 \times \frac{N_{\mathrm{unf}}^{\mathrm{central}}}{N_{\mathrm{unf}}^{\mathrm{sides}}}$$

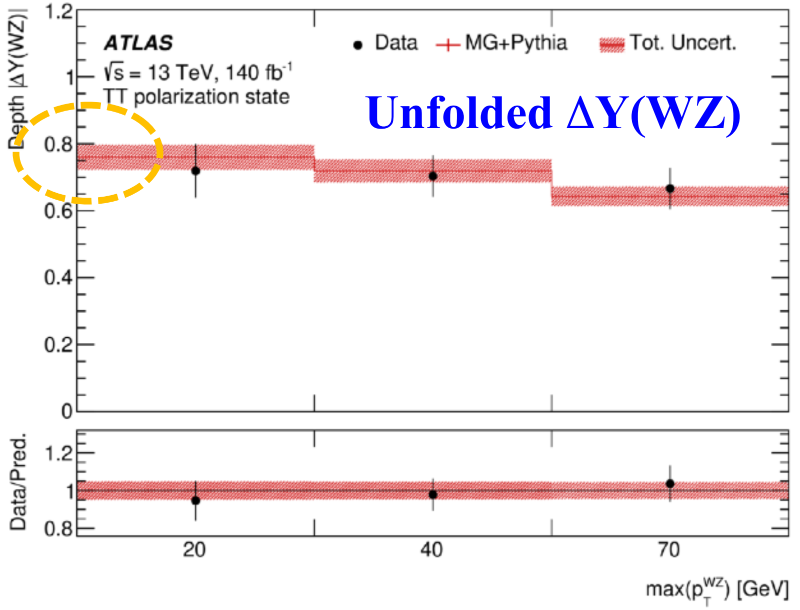
D=0, flat
D>0, dip structure
D<0, peak structure











Conclusions

- Diboson polarization measurements are interesting:
  - Probe the ingredients of the Higgs mechanism (interactions of longitudinal components of W and Z bosons, Goldstone bosons, restoration of electroweak symmetry breaking, …)
  - Perform precise measurements to test the SM gauge structure and higher-order corrections, constraints on the scale of new physics
  - Direct search for physics beyond the SM (new physics often sensitive to longitudinal components)
  - Increasing interests in both experimental and theoretical communities since ~2018

- With our current data we are already able to probe the polarization fractions in VV production:
  - First evidence/observation of double longitudinally-polarized vector bosons in VV production (inclusive WZ, inclusive ZZ, high-p_T WZ s-channel events)
  - First observation of RAZ in WZ production with two transversely-polarized bosons
  - Large systematic uncertainty on measurements due to the modelling of polarized templates! → the theory community is actively working on these topics
  - VBS production still severely limited by data statistics, but already showing promise in same-sign WW production
  - VH polarization fractions are also interesting to measure
  - More results on polarization measurements of diboson (VV, VH), ratios of $V_L V_L / V_L H$, VBS polarization, H→ZZ* polarization and entanglement measurements are expected

Some recent theoretical publications on polarized bosons

Poncelet's talk at the MBI2022 workshop

- Polarised VBS (so far LO):

W boson polarization in vector boson scattering at the LHC,
Ballestrero, Maina, Pellicciioli 1710.09339
Polarized vector boson scattering in the fully leptonic WZ and ZZ channels at the LHC,
Ballestrero, Maina, Pellicciioli 1907.04722
Automated predictions from polarized matrix elements
Buarque Franzosi, Mattelaer, Ruiz, Shil 1912.01725
Different polarization definitions in same-sign WW scattering at the LHC,
Ballestrero,Maina, Pellicciioli 2007.07133

- Polarized Diboson NLO QCD / NLO EW : WW / WZ / ZZ

Fiducial polarization observables in hadronic WZ production: A next-to-leading order QCD+EW study,
Baglio, Le Duc 1810.11034
Anomalous triple gauge boson couplings in ZZ production at the LHC and the role of Z boson polarizations,
Rahama, Singh 1810.11657
Polarization observables in WZ production at the 13 TeV LHC: Inclusive case,
Baglio, Le Duc 1910.13746
Unravelling the anomalous gauge boson couplings in ZW+- production at the LHC and the role of spin-1 polarizations,
Rahama, Singh 1911.03111
Polarized electroweak bosons in W+W- production at the LHC including NLO QCD effects,
Denner, Pellicciioli 2006.14867
NLO EW and QCD corrections to polarized ZZ production in the four-charged-lepton channel at the LHC,
Denner, Pellicciioli 2107.06579
Breaking down the entire spectrum of spin correlations of a pair of particles involving fermions and gauge bosons,
Rahama, Singh 2109.09345
NLO QCD predictions for doubly-polarized WZ production at the LHC,
Denner, Pellicciioli 2010.07149
Doubly-polarized WZ hadronic cross sections at NLO QCD+EW accuracy,
Duc Ninh Le, Baglio 2203.01470
Doubly-polarized WZ hadronic production at NLO QCD+EW: Calculation method and further results
Duc Ninh Le, Baglio, Dao 2208.09232

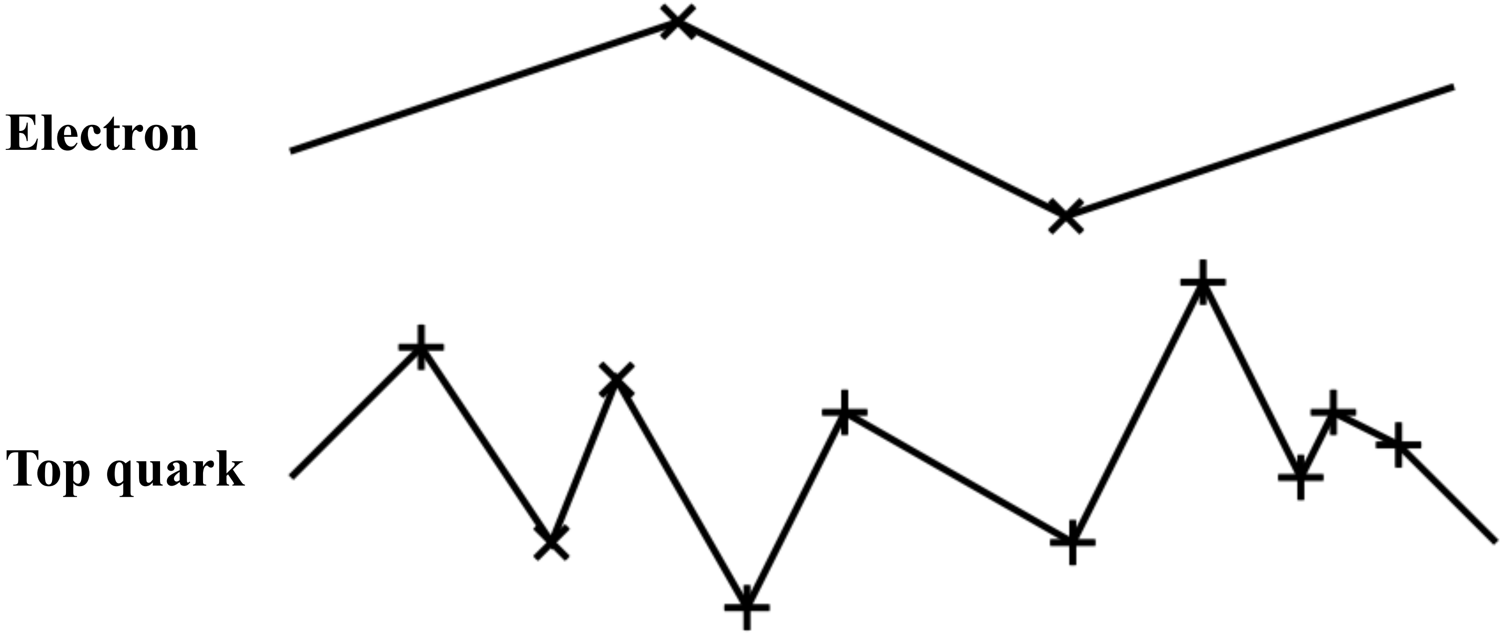
- Polarized Diboson NNLO QCD

NNLO QCD study of polarised W+W- production at the LHC,
Poncelet, Popescu 2102.13583

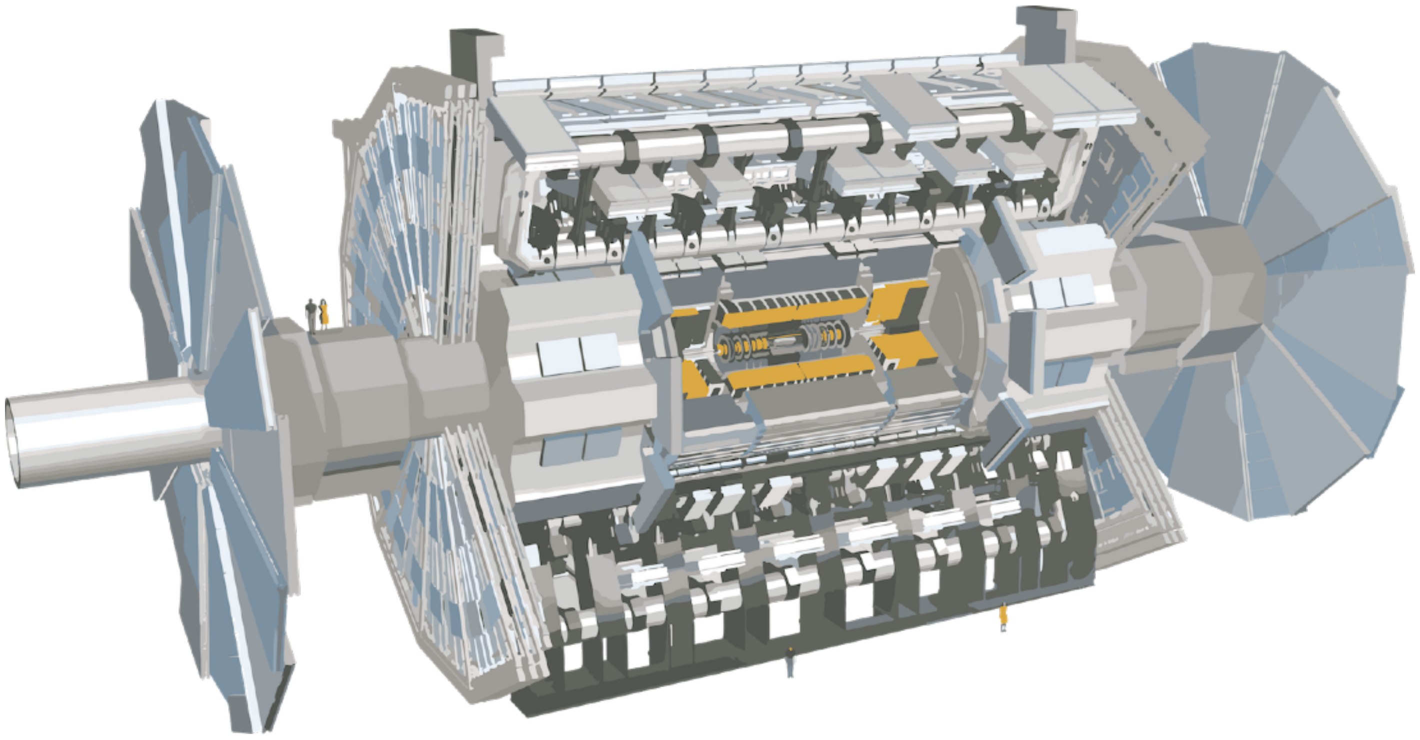
BACKUP

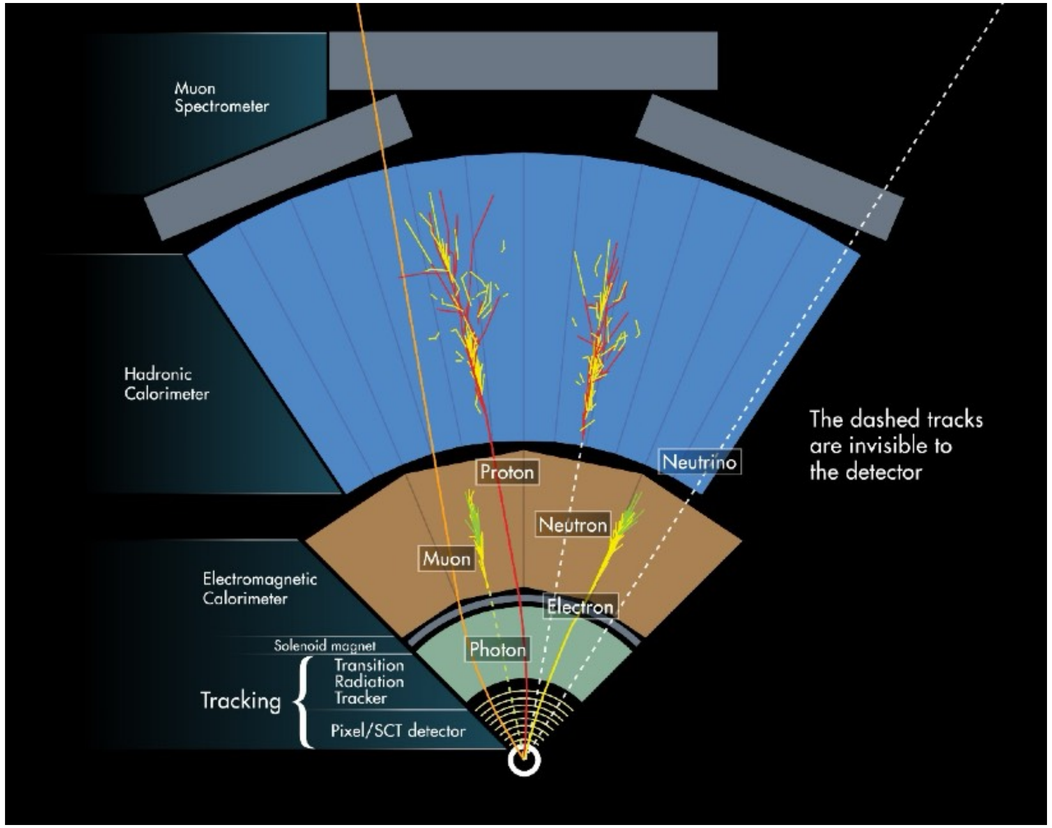
Fermion masses

- Masses of matter particles (Fermions) come from the Yukawa coupling between the particle and the Higgs field
  - Space is filled with the Higgs field
  - Matter particles interact with the Higgs field, “slow down” and appear to be massive
- The coupling depends on the mass of the particle, Higgs likes to couple to heavy particles



ATLAS detector





DNN Reweighting method hypotheses

- HP.1: A DNN can be trained to classify events belonging to two samples, S_A and S_B, in a way that its output can be interpreted as the likelihood of an event to belong to S_A and the complementary to unity of its output as the event likelihood to belong to S_B. Under such assumption, it is possible to define a weight function $w(x)=DNN(x)/[1-DNN(x)]$ that can reweight events from S_B to match S_A, where x is a vector of observables used as DNN inputs.
- HP.2: The underlying probability density function (pdf) to generate diboson polarized samples at NLO can be factorized as:

$$pdf_{NLO}(x, i, j) \propto pdf_{LO}(x) \times pdf(x, i, j) \times pdf_{LO \rightarrow NLO}(x)$$

where x is a vector of observables fully describing a generated event

i, j = L, T are the W and Z polarization states

  - the underlying *pdf* generating the polarized MadGraph sample is proportional to $pdf_{LO}(x) \times pdf(x, i, j)$
  - the *pdf* generating the unpolarized NLO WZ inclusive POWHEG sample is proportional to $pdf_{LO}(x) \times pdf_{LO \rightarrow NLO}(x)$
  - Such factorization implies that the $pdf(x, i, j)$, which generates the polarization states, does not depend on the generation order

DNN Reweighting method

- Step 1: train a set of four DNNs, DNN(i, j), to discriminate each (i, j) polarization MadGraph sample at LO from the sum of LO polarized MadGraph samples (unpolarized sample). The set of four weight functions defined as in HP.1 can then be interpreted as HP.2 *pdf(x, i, j)*:

  $$w(x, i, j) = DNN_{(i,\,j)}(x)/[1-DNN_{(i,\,j)}(x)] \propto pdf_{LO}(x) \times pdf(x, i, j)/pdf_{LO}(x) \propto pdf(x, i, j)$$

- Step 2: Applying *w(x, i, j)* to the NLO unpolarized POWHEG sample to produce NLO polarized samples

DNN Reweighting validation

- *w(x, i, j)* can be applied to the sum of LO polarized MadGraph samples to reproduce the LO polarized MadGraph samples, this is to validate HP.1
- An independent weight function can be derived by training one DNN to discriminate the NLO unpolarized POWHEG sample from the sum of LO polarized MadGraph samples (unpolarized). The corresponding weight function defined as in HP.1 can then be interpreted as HP.2 $pdf_{LO\rightarrow NLO}(x)$:

$$w(x) = DNN(x)/[1-DNN_{(i,j)}(x)] \propto pdf_{LO}(x) \times pdf_{LO\rightarrow NLO}(x)/pdf_{LO}(x) \propto pdf_{LO\rightarrow NLO}(x)$$

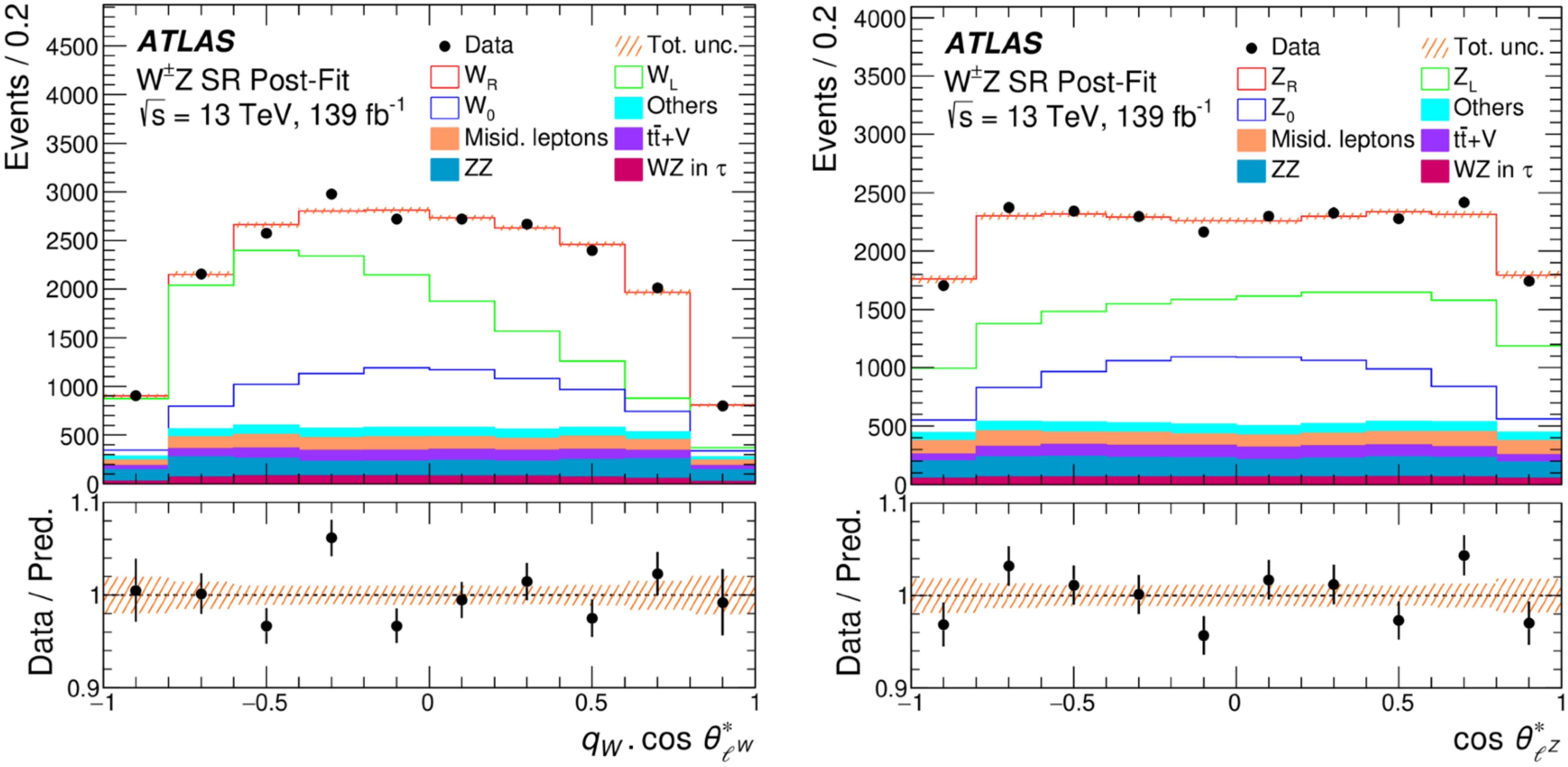
If such w(x) is applied to the sum of LO polarized MadGraph samples, HP.1 can again be tested by comparing the reweighted unpolarized MadGraph NLO sample against the NLO unpolarized POWHEG sample

- If *w(x)* shown above is applied to the LO polarized MadGraph samples, an alternative set of NLO polarized samples can be obtainted and HP.2 can be validated by comparing the two sets of reweighted polarized samples, the former being the NLO reweighting of LO polarized MadGraph samples and the latter being the polarization reweighting of NLO inclusive POWHEG sample

Inclusive WZ diboson polarization uncertainties

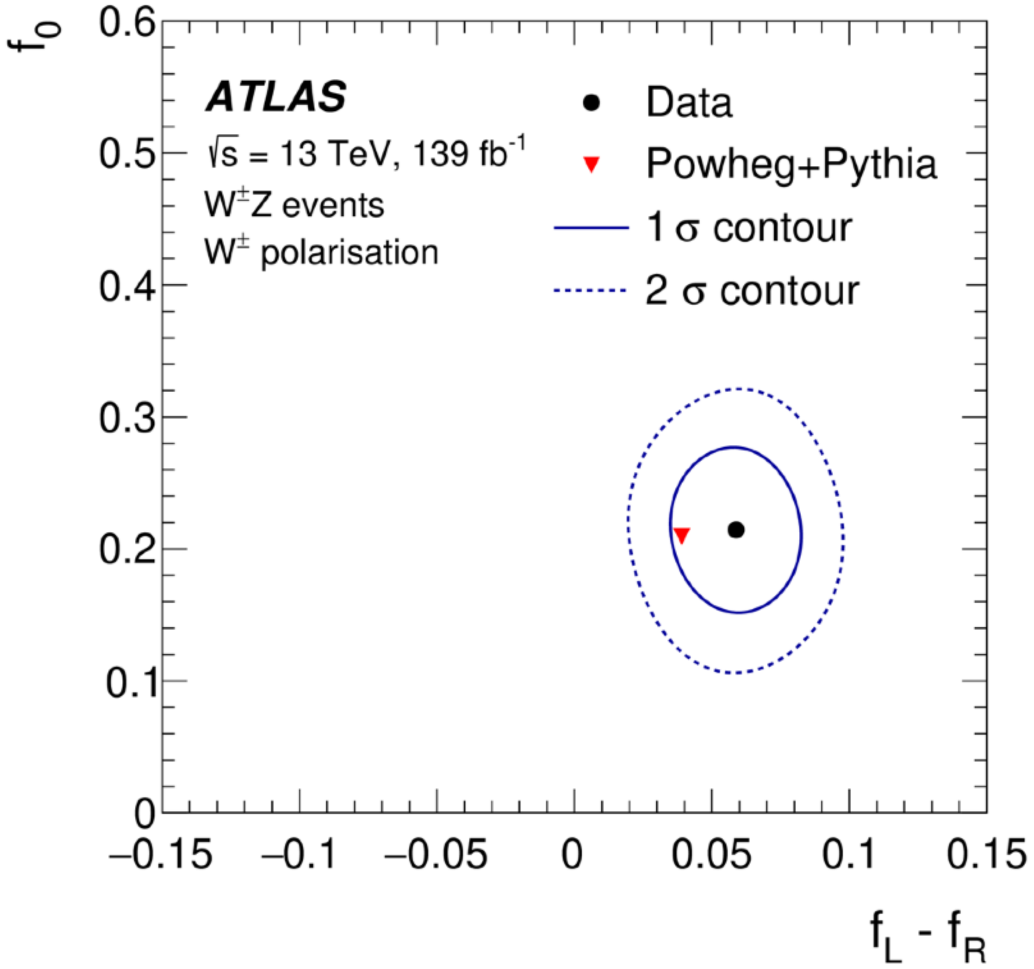
	f_{00}	$f_{0\mathrm{T}}$	$f_{\mathrm{T}0}$	f_{TT}
Relative uncertainty [%]				
e energy scale and id. efficiency	0.34	0.6	0.8	0.31
μ energy scale and id. efficiency	0.8	0.23	0.23	0.13
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	3.3	1.3	1.2	0.4
Pile-up	0.6	0.17	0.4	0.15
Misidentified lepton background	2.3	1.6	0.8	0.26
ZZ background	0.9	0.17	0.32	0.07
Other backgrounds	3.0	1.6	1.3	0.4
Parton Distribution Function	0.5	1.8	0.09	0.5
QCD scale	0.19	8	0.9	2.0
Modelling	9	4	2.9	1.2
Total systematic uncertainty	14	15	8	4
Luminosity	0.35	0.24	0.15	0.05
Statistical uncertainty	13	10	12	3.0
Total	19	18	14	5

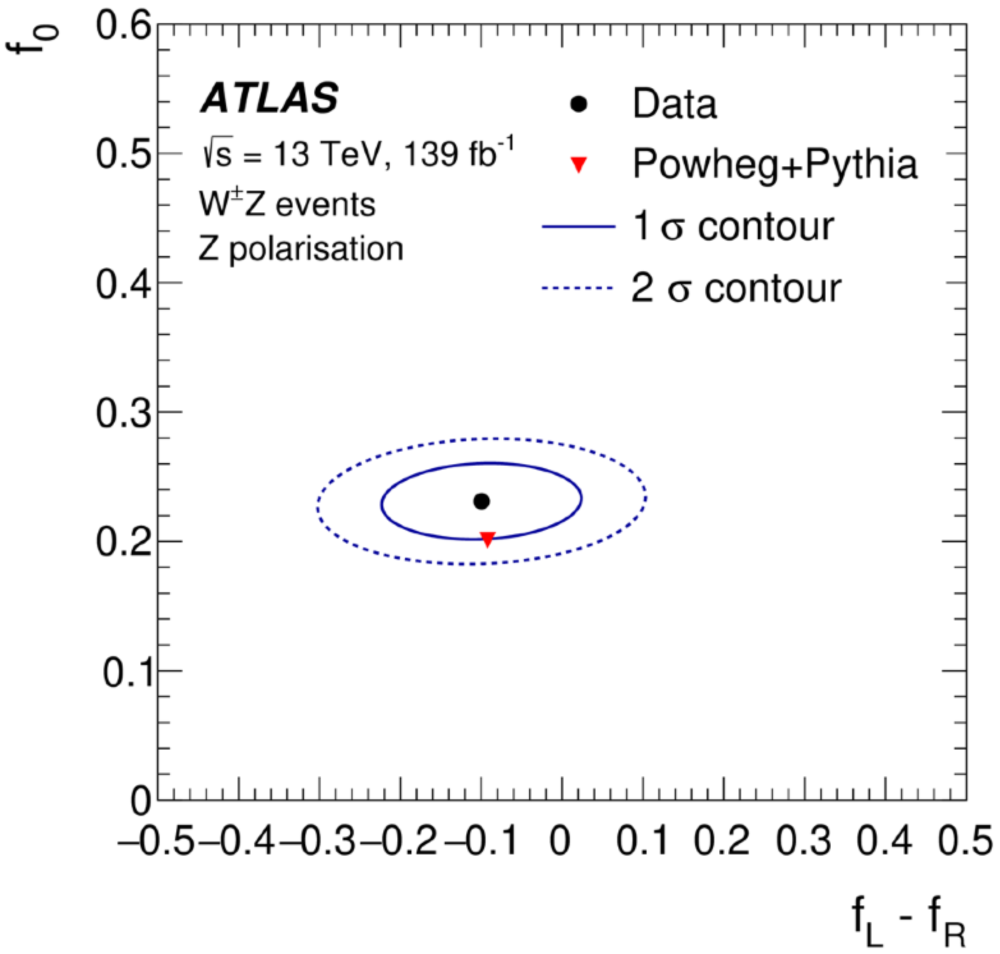
Post-fit data/MC comparison



All four categories of $\cos\theta_{l,W}$ and $\cos\theta_{l,Z}$ are summed together

Single boson polarization results (Inclusive WZ)





High-energy behavior of amplitudes with different polarizations

		SM	BSM	
LL	$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$	
TL	$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$	
TT	$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$	negligible contribution, $1/E^2$ dependence in SM
	$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1	

The results of the table can be understood as follows. Maximal helicity violating (MHV) amplitudes $q\bar{q} \to V_\pm V_\pm$ are suppressed in the SM massless limit [20, 21], and scale like m_W^2/E^2 for finite mass; MHV selection rules don't apply in BSM, where they grow therefore unsuppressed. On the other hand, $q\bar{q} \to V_\pm V_\mp$ are not suppressed in the SM at high-energy, but don't receive contributions from $d = 6$ operators [19, 22]. The suppression of SM amplitudes with one longitudinal only can be understood as a consequence of the symmetry under which all the SM doublets (Higgs and fermions) change sign, namely $H \to -H$, $Q_L \to -Q_L$ and $L_L \to -L_L$. This operation corresponds to the "$g_L = -\mathbb{1}$" element of $\mathrm{SU}(2)_L$, which is part of the SM gauge group and hence it is respected both by the SM and the BSM Lagrangian. Since the symmetry is only broken by the Higgs VEV v, it produces a selection rule that controls whether even or odd powers of v (actually, of m_W) are present in the amplitudes [23]. Transversely polarized vector bosons are even under the symmetry, while longitudinal polarizations are odd because they are related to the Goldstone components of the Higgs doublet through the Equivalence Theorem.[4] The amplitudes for producing one transverse and one longitudinal state (or a Higgs) are odd, hence they scale like m_W/E and $m_W E/M^2$, respectively, in the SM and in the $d = 6$ EFT, as the table shows.

Radiation amplitude zero for Wγ

arXiv:hep-ph/9506286

In fact, it is not difficult to see what is happening for some simple cases. Take $d\bar{u} \to W^-\gamma$ as an example. There are three Feynman diagrams to contribute at the Born level: a t-channel diagram with an amplitude proportional to Q_u/t, a u-channel diagram proportional to Q_d/u, and an s-channel diagram proportional to $Q_{W^-}/(s - M_W^2)$, where $t = (p_d - p_W)^2 = -\frac{1}{2}(s - M_W^2)(1 - \cos\theta)$. Notice the charge relation in the Standard Model $Q_d - Q_u = Q_{W^-}$, and the kinematical relation $s - M_W^2 = -t - u$, one can easily cast the amplitude into the form

$$\mathcal{M} \sim (\frac{Q_u}{t} + \frac{Q_d}{u})F(\sigma_i, \lambda_i, p_i), \qquad (2)$$

Radiation amplitude zero for WZ

arXiv:hep-ph/9506286

symmetry, such as the Standard Model (SM). It is conceivable that the radiation of a Z-boson may have some similarity to that of a photon. For the case of $d\bar{u} \to W^- Z$, the amplitude can be written as [13]

$$\mathcal{M} \sim X F_X(\sigma_i, \lambda_i, p_i) + Y F_Y(\sigma_i, \lambda_i, p_i), \tag{3}$$

where X and Y are combinations of coupling factors

$$X = \frac{s}{2}\left(\frac{g_-^{f_1}}{u} + \frac{g_-^{f_2}}{t}\right), \quad Y = g_-^{f_1}\,\frac{M_Z^2\, s}{2\,u\,(s - M_W^2)}\,, \tag{4}$$

with the left-handed neutral current couplings $g_-^{f_1} - g_-^{f_2} = Q_W \cot\theta_{\rm w}$, and $F_{X,Y}(\sigma_i, \lambda_i, p_i)$ contain the spin dependent part and is roughly proportional to the product of the vector-boson wave functions $\epsilon_{\rm w}^* \cdot \epsilon_{\rm z}^*$. It is obvious that without the Y-term, the helicity amplitudes would factorize. In this case, all amplitudes would simultaneously vanish for $g_-^{f_1}/u + g_-^{f_2}/t = 0$, analogous to the $W\gamma$ case in Eq. 2. Since Y is directly proportional to M_Z^2, one may naively expect full factorization when $M_Z^2 \ll s$. In fact, in the high energy limit, only three helicity amplitudes remain non-zero:

$$\mathcal{M}(\lambda_{\rm w} = \pm, \lambda_{\rm z} = \mp) \longrightarrow \frac{1}{\sin\theta}\,(\lambda_{\rm w} - \cos\theta)\left[(g_-^{f_1} - g_-^{f_2})\cos\theta - (g_-^{f_1} + g_-^{f_2})\right],$$

$$\mathcal{M}(\lambda_{\rm w} = 0, \lambda_{\rm z} = 0) \longrightarrow \frac{1}{2}\sin\theta\,\frac{M_Z}{M_W}\,(g_-^{f_2} - g_-^{f_1})\,. \tag{5}$$

While the dominant amplitudes $\mathcal{M}(\pm, \mp)$ fully factorize in the high energy limit, $\mathcal{M}(0,0)$ behaves differently. This can be traced to the special energy-dependence of the polarization

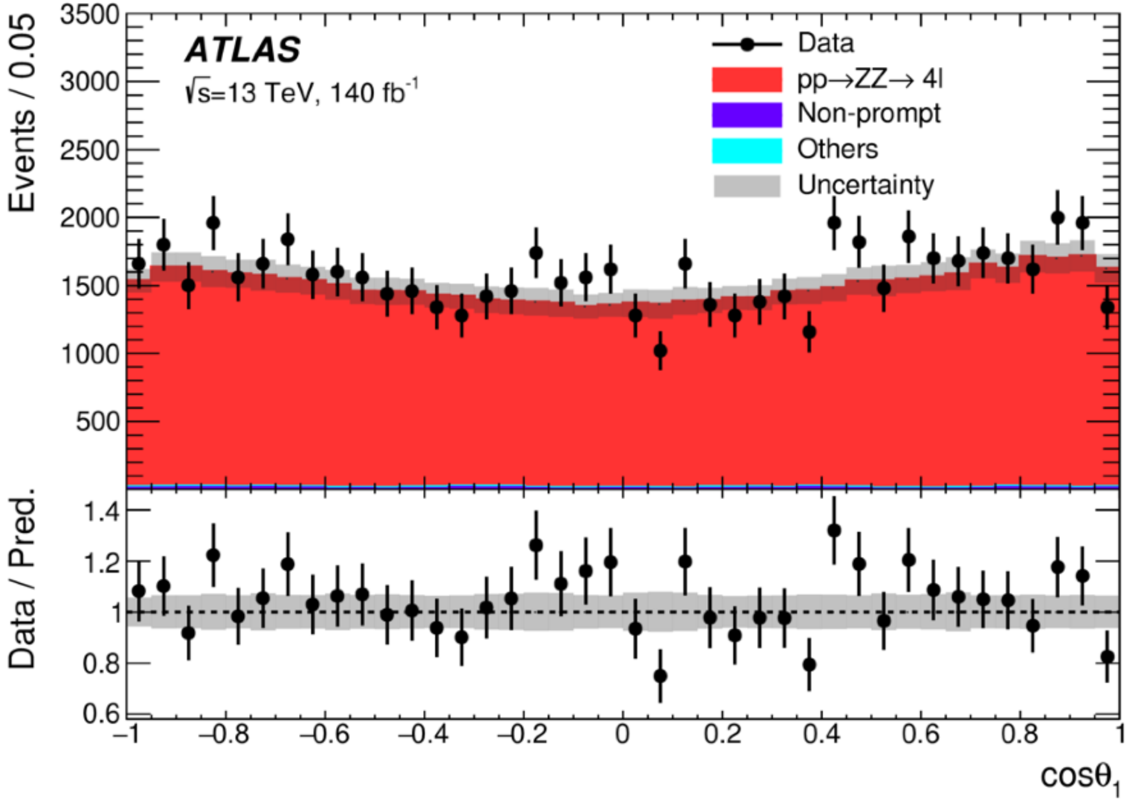
Event yields at the truth level

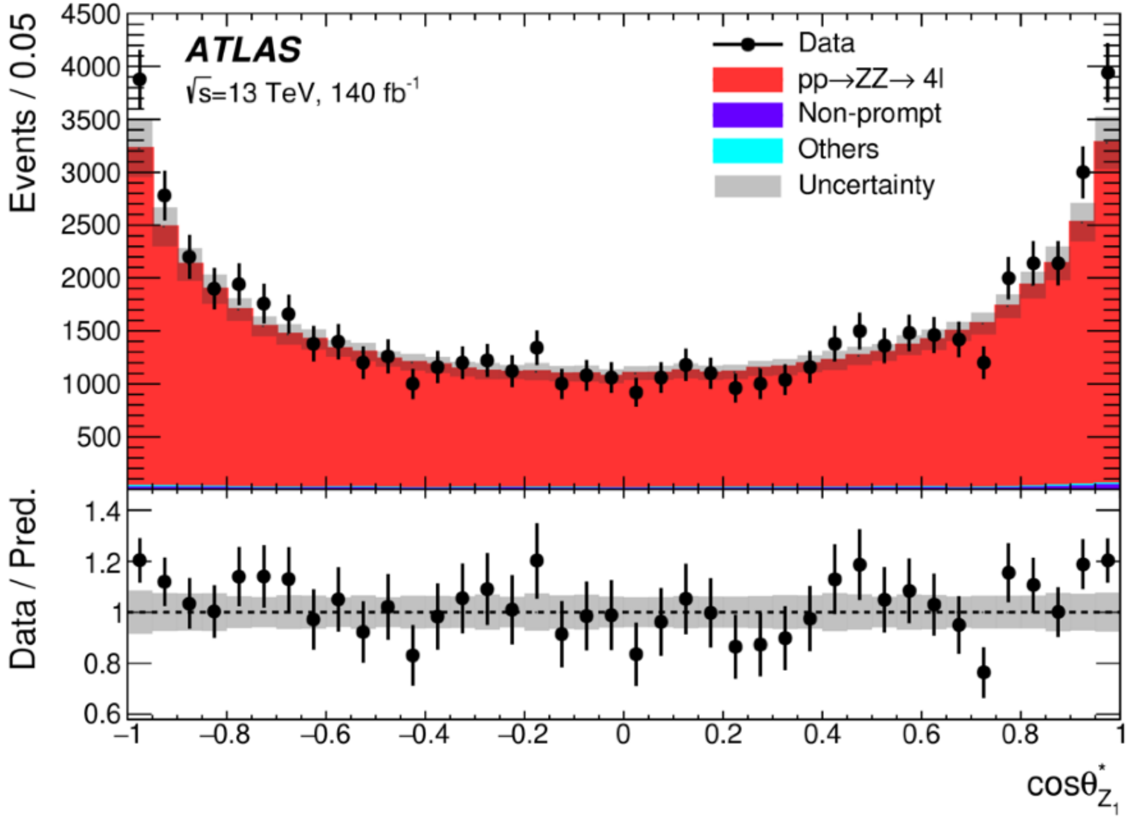
Selection cut	Polarization	Cross-section (pb)	No. of expected events			Fraction
			Total	0-jet	1-jet	
Without any cuts	W_0Z_0	0.0229	3214	2127	1103	4.7%
	W_0Z_T	0.0701	9825	3333	6511	14.3%
	W_TZ_0	0.0678	9496	3029	6482	13.8%
	W_TZ_T	0.330	46259	25472	20834	67.2%
Inclusive phase-space	W_0Z_0	0.00978	1370	888.9	490.5	5.7%
	W_0Z_T	0.0280	3924	1229	2698	16.4%
	W_TZ_0	0.0264	3699	1130	2566	15.5%
	W_TZ_T	0.106	14873	7415	7487	62.3%
$p_T^{WZ} < 70$ GeV	W_0Z_0	0.00875	1226	887	347	7.3%
	W_0Z_T	0.0165	2306	1228	1082	13.8%
	W_TZ_0	0.0155	2175	1129	1041	13.0%
	W_TZ_T	0.0785	10992	7403	3598	65.8%
$p_T^Z > 200$ GeV	W_0Z_0	0.000485	68	43	25	23.7%
	W_0Z_T	0.000119	17	8	9	5.8%
	W_TZ_0	0.000107	15	7	8	5.2%
	W_TZ_T	0.00133	187	88	99	65.2%
$p_T^Z > 100$ GeV	W_0Z_0	0.00258	361	252	109	16.1%
	W_0Z_T	0.00176	246	118	127	11.0%
	W_TZ_0	0.00160	224	116	110	10.0%
	W_TZ_T	0.0100	1407	703	701	62.9%
$100 < p_T^Z \leq 200$ GeV	W_0Z_0	0.00210	293	209	85	15.1%
	W_0Z_T	0.00164	229	111	118	11.8%
	W_TZ_0	0.00149	209	109	102	10.7%
	W_TZ_T	0.00867	1220	615	602	62.4%

Variables used in the BDT training

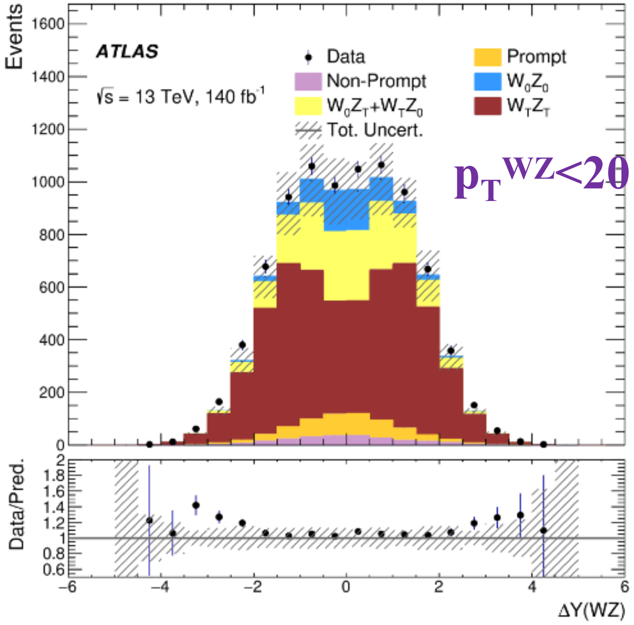
Training variable	Definition
$\Delta Y(\ell_W Z)$	Rapidity difference between the W lepton and Z boson
p_T^{WZ}	Transverse momentum of the WZ system
$p_T(\ell_W)$	Transverse momentum of the W lepton
$p_T(\ell_2^Z)$	Transverse momentum of the subleading Z lepton
E_T^{miss}	Missing transverse momentum
$\cos\theta_{\ell_Z}$	Cosine of the angle of the Z lepton in the WZ rest frame w.r.t the z-axis
$\cos\theta_{\ell_W}$	Cosine of the angle of the W lepton in the WZ rest frame w.r.t. the z-axis

ZZ Post-fit data/MC comparison

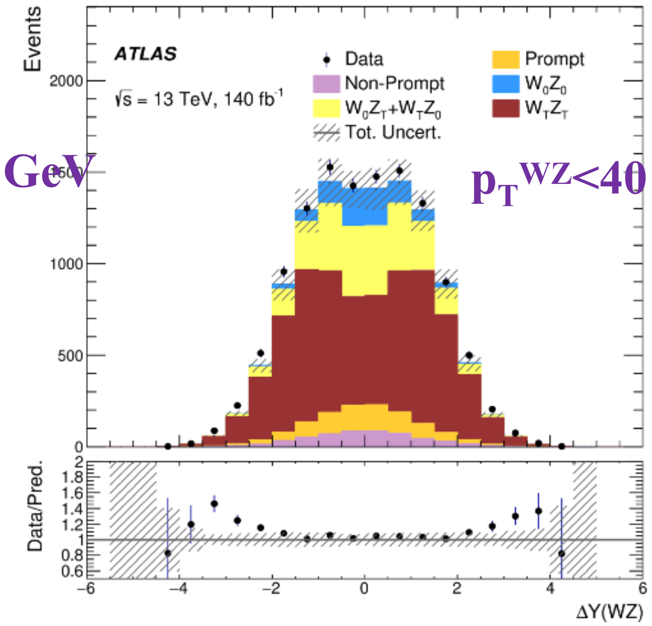




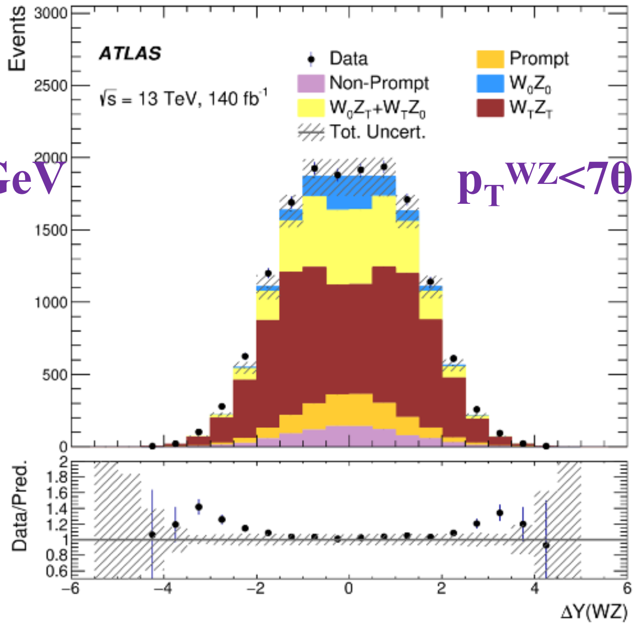
RAZ effect for different $p_T(WZ)$ [$\Delta Y(WZ)$]



p_T^{WZ}<20 GeV

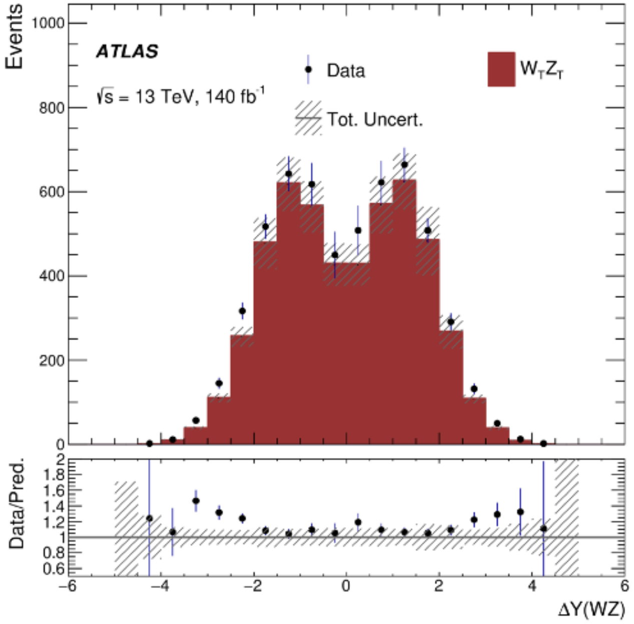


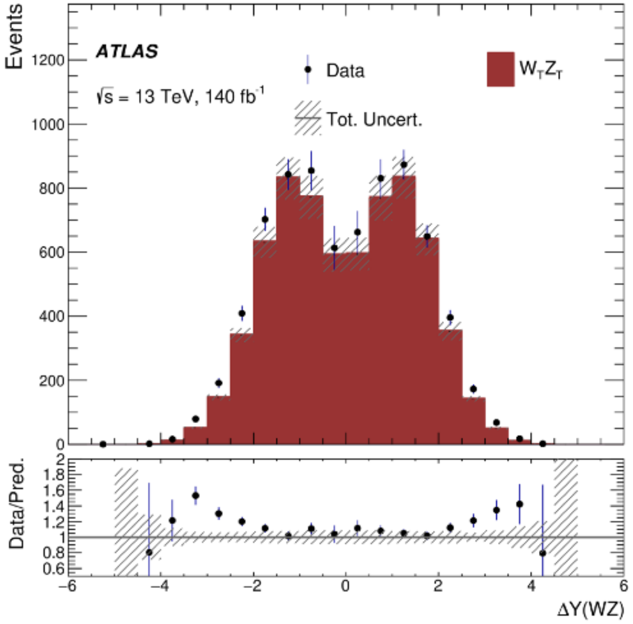
p_T^{WZ}<40 GeV

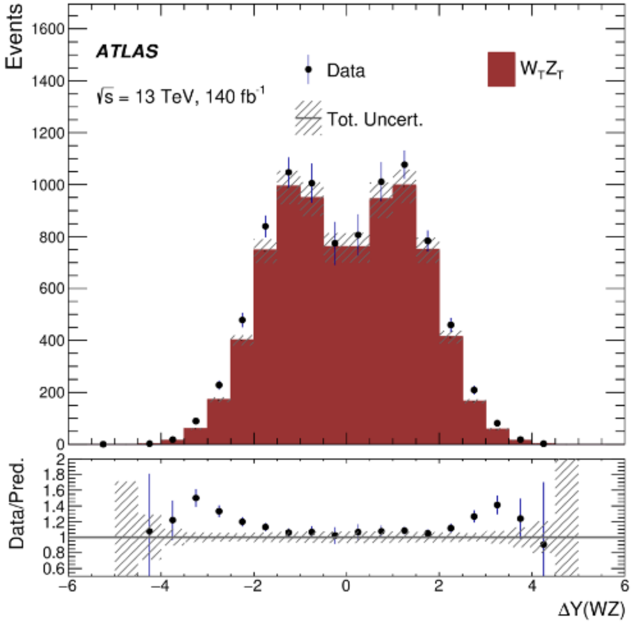


p_T^{WZ}<70 GeV

Inclusive events with contributions from all polarization states





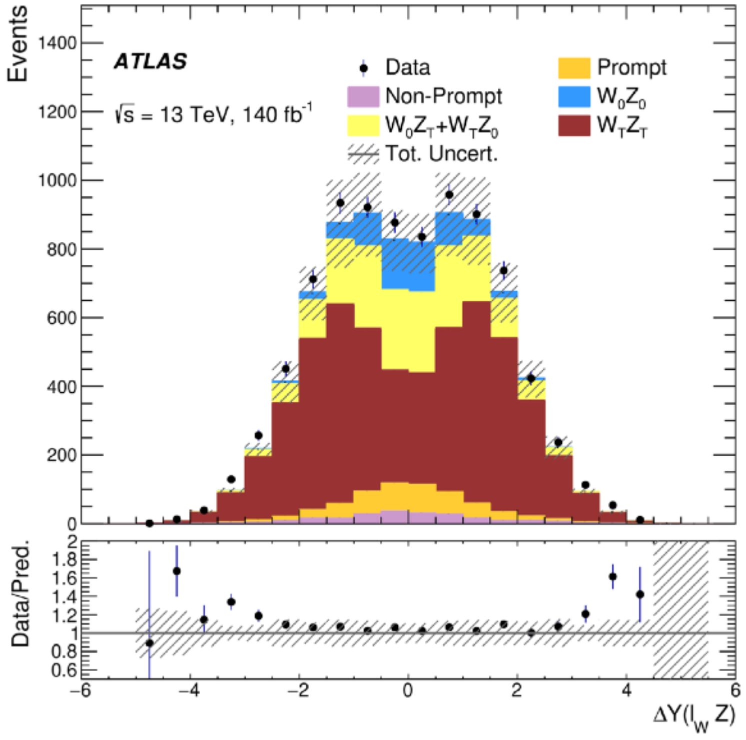


TT-only events and contributions from 00, 0T, and T0 are removed

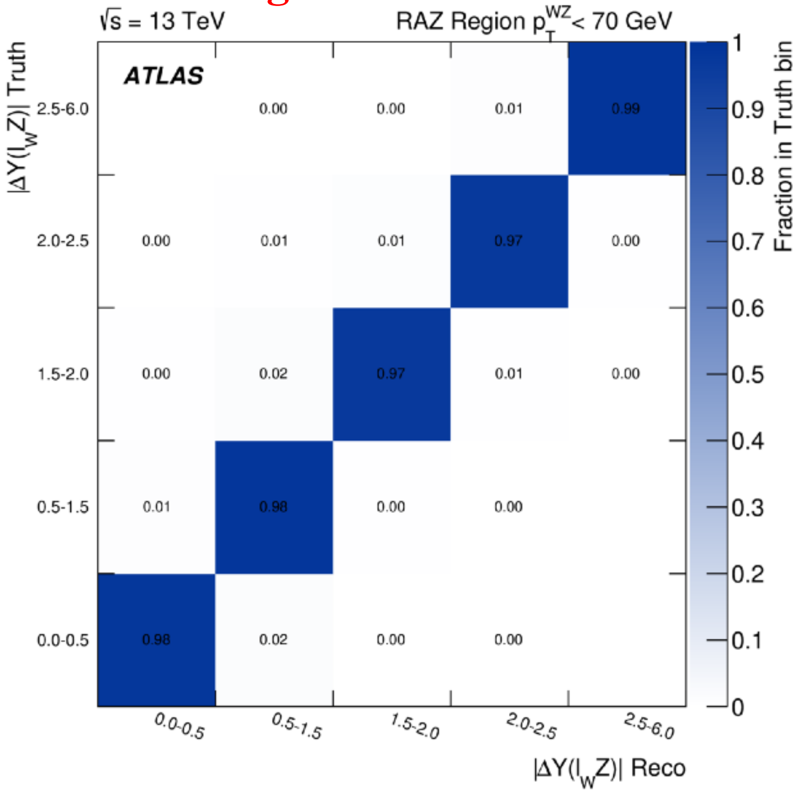
Unfolded ΔY(l_WZ) distributions

p_T(WZ)<20 GeV

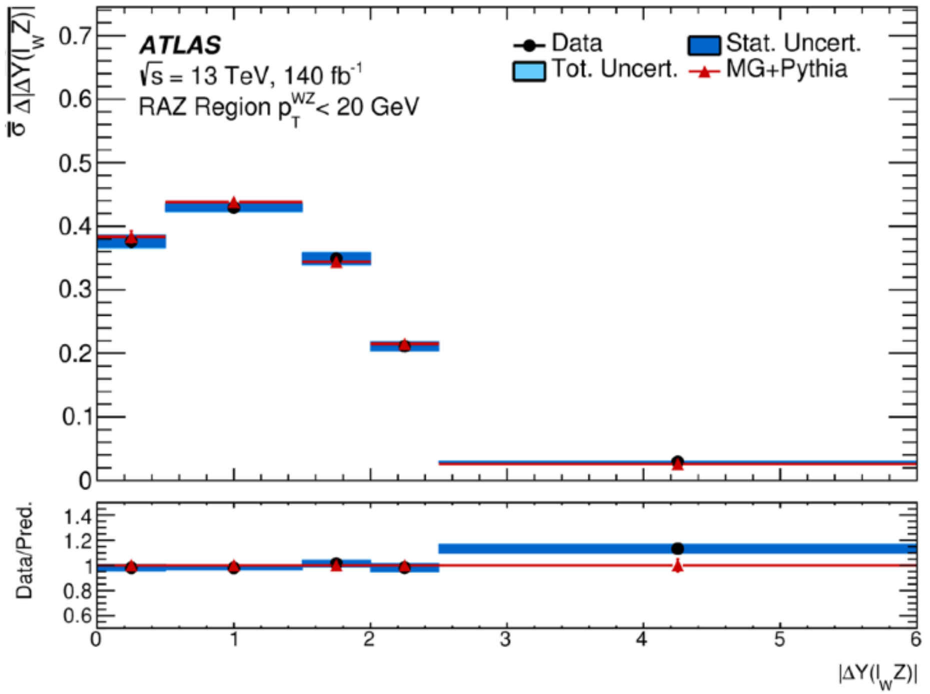
Raw distribution



Migration matrix



Unfolded distribution



- Unfolded both |ΔY(WZ)| and |ΔY(l_WZ)| distributions for 12 different cases:
  - For inclusive events with three p_T(WZ) cuts
  - For TT-only events with three p_T(WZ) cuts
- In general good agreement found between unfolded distributions and theoretical predictions

LEP measurements

arXiv:1708.09043