Diboson Polarization Measurements

Latest updates from ATLAS

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on behalf of the ATLAS collaboration

CNRS/IN2P3, IJCLab,

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What is diboson polarization?

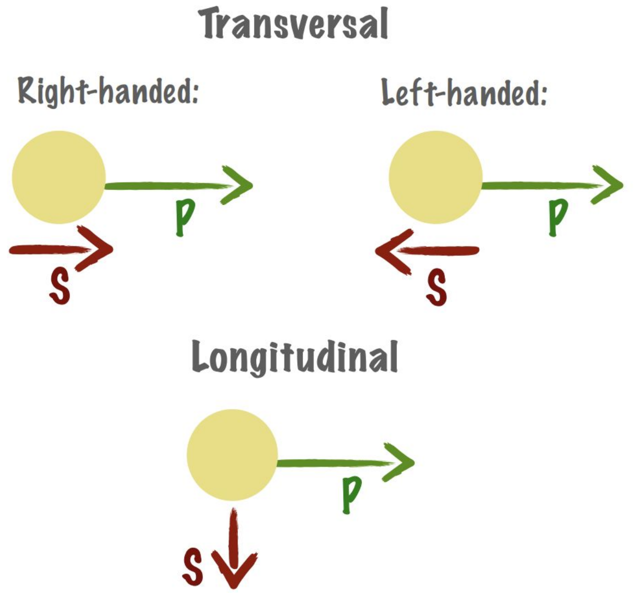
Polarization:

Polarization describes the alignment of a particle's spin with its momentum. Quantified using the helicity:

$$h = \vec{S} \cdot \frac{\vec{p}}{|p|}$$

Transversal polarization (T): the spin and momenta are (anti-)aligned (h = 1, -1)

Longitudinal polarization (L or 0): spin orthogonal to the momenta (h = 0)



Diboson polarization:

Refers to the study of the polarization states of pairs of bosons (e.g., WW, WZ, ZZ) produced in high-energy particle collisions, namely 00, 0T, T0, TT

What is diboson polarization?

Joint Polarization:

- Joint polarization involves the simultaneous consideration of the polarization states of two bosons produced in the same event.

- In diboson events, the polarizations of both bosons can be correlated → providing information about the vector boson couplings.

uncorrelated: $P(h_{V1}h_{V2}) = P(h_{V1}) \cdot P(h_{V2})$

correlated: $P(h_{V1}h_{V2}) \neq P(h_{V1}) \cdot P(h_{V2})$

- Joint polarization is described by a combined spin density matrix:

$$\rho_{\lambda_W \lambda'_W \lambda_Z \lambda'_Z} \equiv \frac{1}{C} \times \sum_{\mu_q \mu_{\bar{q}}} F^{(\mu_q \mu_{\bar{q}})}_{\lambda_W \lambda_Z} F^{(\mu_q \mu_{\bar{q}})*}_{\lambda'_W \lambda'_Z}$$

$$\text{where} \quad C = \sum_{\mu_q \mu_{\bar{q}} \lambda_W \lambda_Z} \left| F^{(\mu_q \mu_{\bar{q}})}_{\lambda_W \lambda_Z} \right|^2$$

$$\begin{aligned} f_{00} &= \rho_{0000} , \\ f_{TT} &= \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++} , \\ f_{0T} &= \rho_{00--} + \rho_{00++} , \\ f_{T0} &= \rho_{--00} + \rho_{++00} . \end{aligned}$$

Why study diboson polarization?

In standard model, the Higgs mechanism provides mass to the W and Z bosons through spontaneous symmetry breaking of the electroweak symmetry:

- Spontaneous breaking of a continuous symmetry gives rise to a massless Goldstone boson (ξ)
- By choosing a proper gauge, the Goldstone bosons is absorbed into the gauge fields → forming new massive gauge bosons
- None-zero mass indicates gauge fields with three polarization states (two transverse and one longitudinal)

$$\phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = e^{i\vec{\tau}\cdot\vec{\xi}/2v} \begin{pmatrix} 0 \\ (v+H)/\sqrt{2} \end{pmatrix}$$

$$U(\xi) = e^{-i\vec{\tau}\cdot\vec{\xi}/2v}$$

$$\phi' = U(\xi)\phi = \begin{pmatrix} 0 \\ (v+H)/\sqrt{2} \end{pmatrix} = \frac{1}{\sqrt{2}}(v+H)\chi$$

$$\vec{A}'_\mu = U(\xi)\vec{A}_\mu U(\xi)^{-1} - \frac{i}{g}(\partial_\mu U(\xi))U^\dagger(\xi)$$

Thus,

gauge boson polarization is strongly related to the electroweak theory in the standard model!

Why study diboson polarization?

What we can learn from diboson polarization study?

Validation of Theoretical Predictions:

- By studying diboson polarization, we can validate the Standard Model electroweak thoeries

Probing New physics:

- Discrepancies between observed polarization patterns and SM predictions could indicate beyond standard model (BSM) physics.
- New physics might behave differently with different polarization, which might have been overlooked by those unpolarized study

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

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high-energy behavior of amplitudes with different diboson helicity configurations, in the SM and in generic BSM (meaning the maximal effect that can be achieved with an insertion of any d = 6 operator) with cutoff scale M

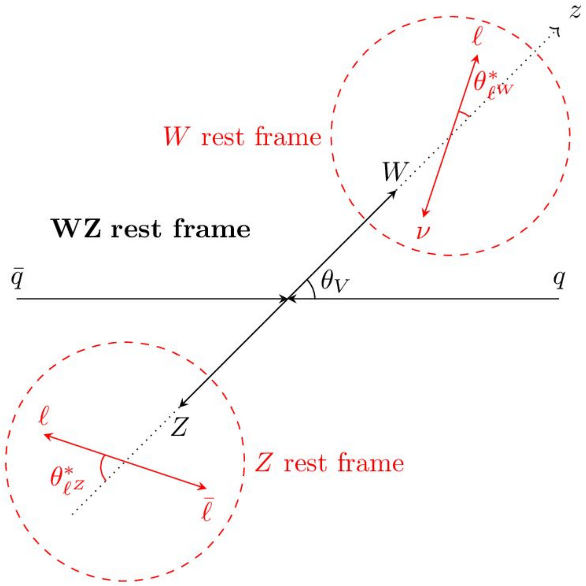
In addition to the single boson polairzation study, diboson joint polarization study provides an chance to inspect correlation between the helicity of interacting gauge bosons

How to study diboson polarization?

Angular variables between the bosons and the decay products are typically used to measure the weak bosons polarizations

- ➢ Choosing proper variables can effectively distinguish different polarizations
- ➢ Templates of different polarization process can be made utilizing the distribution of those variables

The fraction of each polarization state can be extracted by performing fits to data (with background subtracted) distributions using those polarized templates



Polarization measurements are frame dependent → For all measurements you need to define a frame

Variables sensitive to diboson polarization

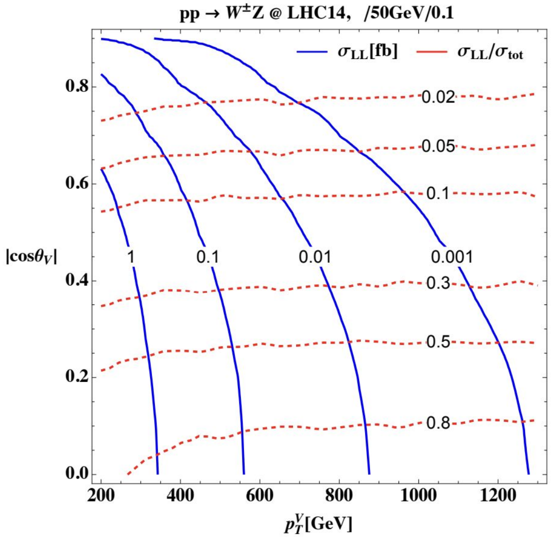
The vector boson scattering angle: θ_V

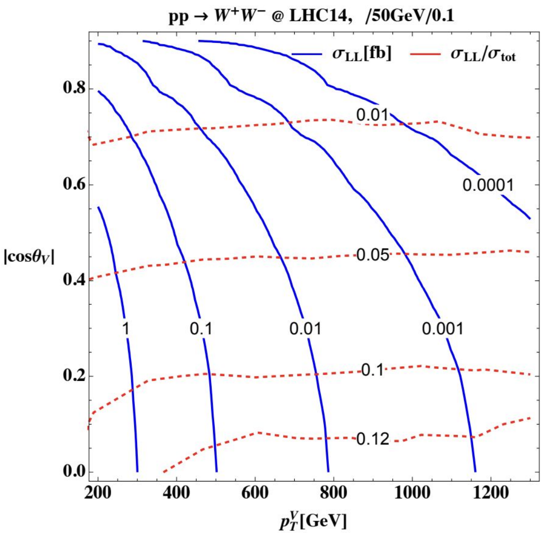
$$\frac{d^2\sigma_{WZ}^{LL}}{d^2\sigma_{WZ}^{TT}} \sim \frac{1}{8\cos^2\theta_V}\frac{1-\cos^2\theta_V}{1+\cos^2\theta_V} \qquad \frac{d^2\sigma_{WW}^{LL}}{d^2\sigma_{WW}^{TT}} \sim \frac{1}{8}\frac{(1-\cos^2\theta_V)^2}{(1+\cos^2\theta_V)^2}.$$

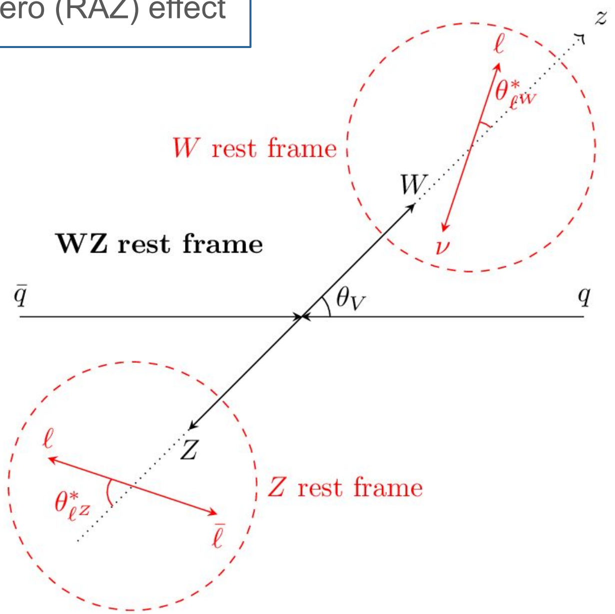
*Defined in the parton center-of-mass frame

[Phys. Rev. D 99, 055001 (2019)]

Radiation Amplitude Zero (RAZ) effect







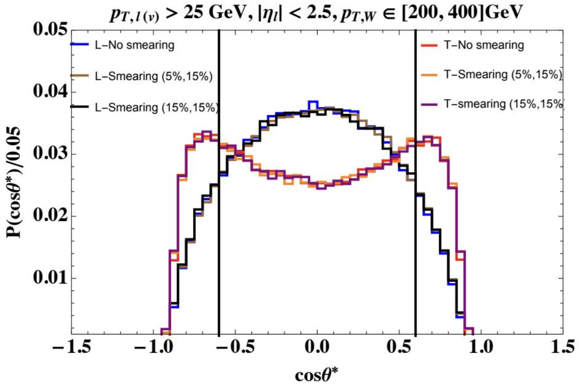
Variables sensitive to diboson polarization

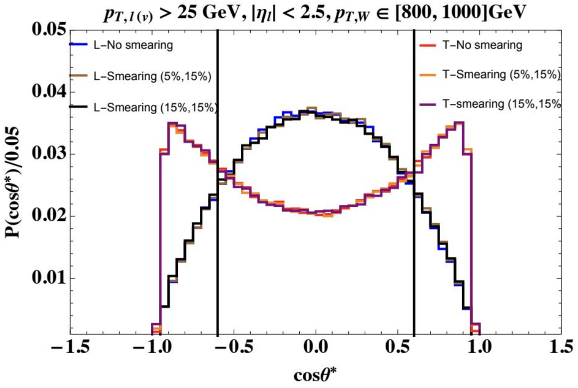
Child lepton decay angle of vector bosons: θ_ℓ^*:

$$\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta^*_{\ell Z}} = \frac{3}{8}f_L(1+2\alpha\cos\theta^*_{\ell Z}+\cos^2\theta^*_{\ell Z})+\frac{3}{8}f_R(1-2\alpha\cos\theta^*_{\ell Z}+\cos^2\theta^*_{\ell Z})+\frac{3}{4}f_0\sin^2\theta^*_{\ell Z}$$

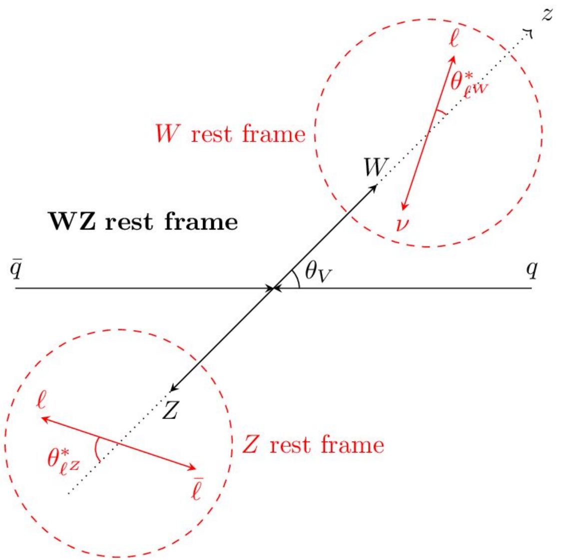
$$\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta^*_{\ell W}} = \frac{3}{8}f_L[(1-q_W\cdot\cos\theta^*_{\ell W})^2]+\frac{3}{8}f_R[(1+q_W\cdot\cos\theta^*_{\ell W})^2]+\frac{3}{4}f_0\sin^2\theta^*_{\ell W}$$

Phys. Rev. D 99, 055001 (2019)





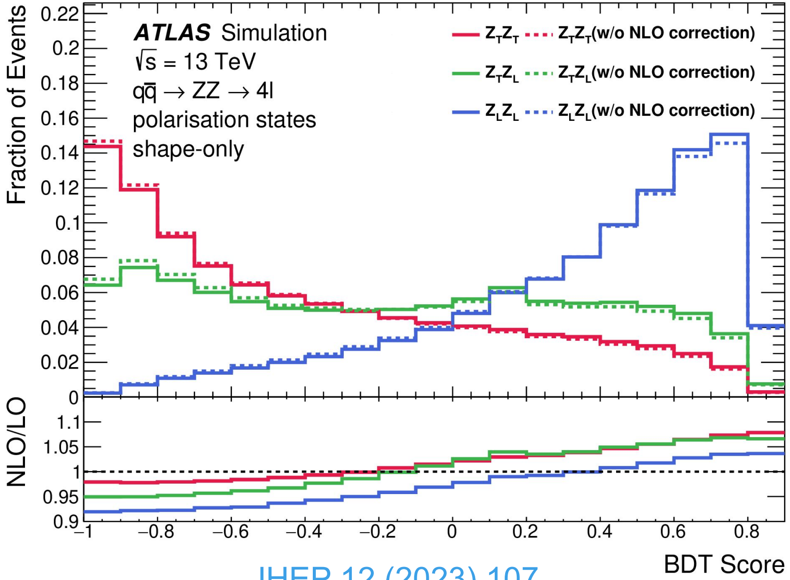
*Defined in the modified helicity frame as the angle between "the negatively (positively for W^+) charged lepton as seen in the $W(Z)$ rest frame" and "the direction of the $W(Z)$ which is given in the WZ centre-of-mass frame".



Variables sensitive to diboson polarization

MVA variables:

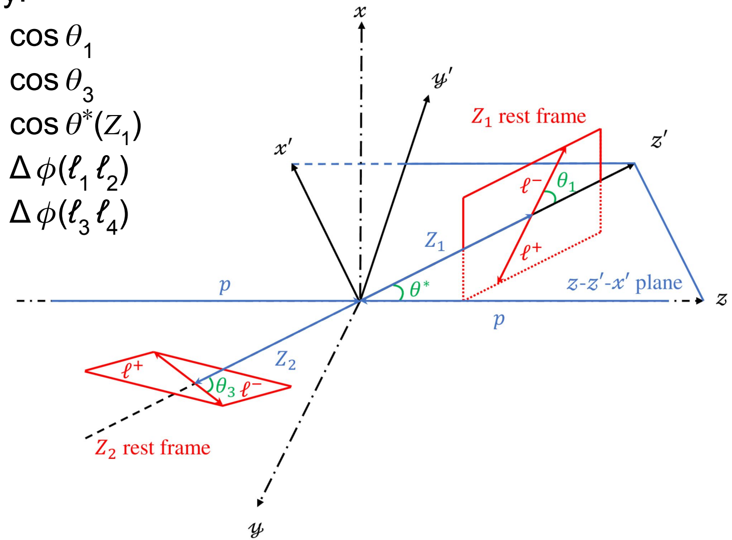
- ❑ BDT, DNN…
- ❑ In general provides better separating power than using single variable



[JHEP 12 (2023) 107]

Built by:

- ❑ $\cos\theta_1$
- ❑ $\cos\theta_3$
- ❑ $\cos\theta^*(Z_1)$
- ❑ $\Delta\phi(\ell_1\ell_2)$
- ❑ $\Delta\phi(\ell_3\ell_4)$



Polarized diboson samples

Recent developments make it possible to separate diboson production into different polarisations → Input templates for fitting!

Some available polarized samples:

- ❏ LO polarised $qq \rightarrow ZZ$ samples: MadGraph5_aMC@NLO 2.7.3, interfaced to Pythia 8.240 for parton shower, hadronisation, and underlying event
- ❏ LO polarised $qq \rightarrow WZ$ sample: MadGraph5_aMC@NLO 2.7.3, interfaced to Pythia 8.244 for parton shower, hadronisation and the underlying event

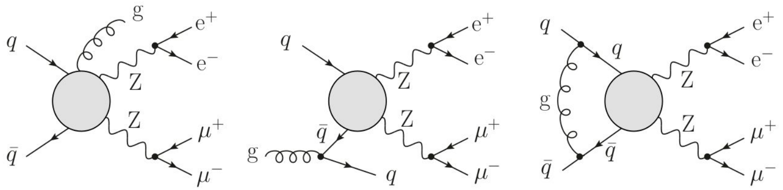
Currently polarized samples are only available at Leading Order (LO)

Official high-order corrections (k-factors) not yet available from ATLAS Metadata Interface (AMI) for polarized samples → High-order corrections are made by each analysis team

High order correction

High-order corrections include contributions from both real emissions (additional particles) and virtual particles (loops):

- To account for the real part of NLO QCD corrections, events were simulated with either 0,1 jets in the matrix element at LO, and merged with Pythia parton shower using the CKKW-L scheme
- Electroweak and virtual part corrections still missing.



Examples: NLO QCD real and virtual corrections to resonant ZZ production

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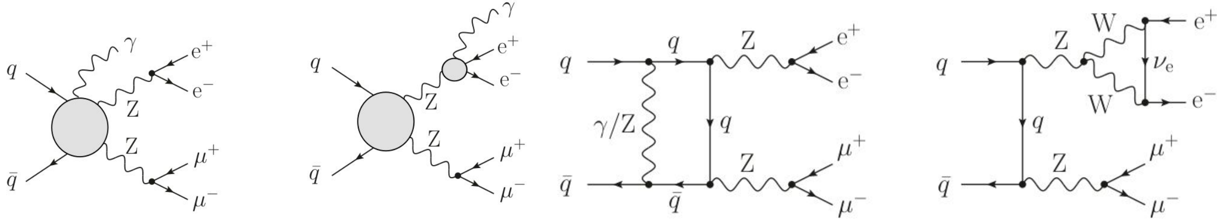


Examples: NLO electroweak real and virtual corrections to resonant ZZ production

High order correction

Several ways to achieve full (real+virtual, QCD+EWK+Other) NLO corrections:

- **Reweight NLO inclusive diboson sample to NLO polarized diboson samples using MVA method**
  - Reweighting factors obtained from LO polarized sample to LO inclusive sample
  - Four sets (00, 0T, T0, TT) of DNN-based event-by-event reweighting factors as functions of variables sensitive to polarization
  - Adopted by Phys. Lett. B 843 (2023) 137895
- **Reweight LO polarized sample (0+1 jet) to NLO polarized sample according to theoretical calculation (QCD+EWK+Other)**
  - Theorists provide NLO distribution in fiducial regions → compared with LO 0+1 distribution → k-factor!

$$k_{factor} = \frac{MoCaNLO^{Parton}_{Polarized}}{MadGraph01LO^{Particle}_{Polarized}} \times \frac{Sherpa\_NLO^{Particle}_{Inclusive}}{MoCaNLO^{Parton}_{Inclusive}}$$

Theoretical polarized NLO calculation (MoCaNLO) only available at parton level → reweight it to get particle level (after PS) values

LO 0+1j merged polarized distribution at particle level

  - Additional corrections (e.g, interference effect, higher order effects…) are also considered
  - Adopted by JHEP 12 (2023) 107 and Phys. Rev. Lett. 133 (2024) 101802 (as systematic uncertainty)

Analyses of diboson polarization

Measurements at LEP:

$e^-e^+ \to WW$:

OPAL @189 GeV 183 pb^{-1} [Eur. Phys. J. C 19, 229–240 (2001)]

DELPHI @189–209 GeV 520 pb^{-1} [Eur. Phys. J. C 63, 611 (2009)]

Measurements at the LHC:

$pp \to W^{\pm}W^{\pm}jj$

CMS @13TeV 137 fb^{-1} (VBS phase space) Phys. Lett. B 812 (2020) 136018 → The electroweak $W^{\pm}W^{\pm}$ production with at least one longitudinal W bosons measured with observed (expected) significance of 2.3 (3.1) standard deviations.

$pp \to ZZ$

ATLAS @13TeV 140 fb^{-1} (inclusive phase space) JHEP 12 (2023) 107 → Simultaneously longitudinal ZZ production measured with observed (expected) signifcances of 4.3 (3.8) standard deviations

$pp \to WZ$

CMS @13TeV 137 fb^{-1} (inclusive phase space) JHEP 07 (2022) 032 → Simultaneously longitudinal WZ production observed at the level of five standard deviations for the first time

ATLAS @13TeV 139 fb^{-1} (inclusive phase space) Phys. Lett. B 843 (2023) 137895 → Simultaneously longitudinal WZ production measured with observed (expected) significances of 7.1 (6.2) standard deviations

ATLAS @13TeV 140 fb^{-1} (high pT(Z) phase space) Phys. Rev. Lett. 133 (2024) 101802 Just published!

High pT(Z) WZ polarization and RAZ analysis

Studies of the energy dependence of diboson polarization fractions and the Radiation Amplitude Zero (RAZ) effect in WZ production with the ATLAS detector (Phys. Rev. Lett. 133 (2024) 101802)

RAZ effect: At leading-order, the dominant helicity amplitude with two transversely-polarized bosons is exactly zero when the scattering angle of the W boson in the WZ rest frame with respect to the incoming antiquark direction approaches 90°

$$|\mathcal{M}_{WZ}^{TT}|^2 = \frac{g^4}{32}\left(\frac{s}{t} - \frac{s}{u}\right)^2 \sin^2\theta_V(1+\cos^2\theta_V), \qquad |\mathcal{M}_{WZ}^{LL}|^2 = \frac{g^4}{16}\sin^2\theta_V.$$

RAZ effect behaves differently between different polarization states → inspires two topics of this analysis:

- ❏ WZ joint polarization fraction at 00 enhanced region
- ❏ Direct quantification of RAZ effect

High pT(Z) WZ polarization and RAZ analysis

Joint polarization fraction measurement:

Event selection starts from inclusive WZ region, and:

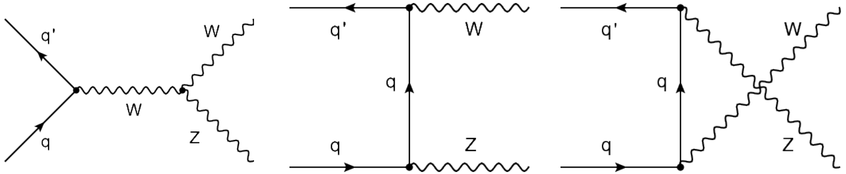
pT(Z) > 100 (200) GeV to select s-channel events

- At leading-order, WZ production is dominated by the TT polarization due to the presence of t- and u-channel
- t-channel significantly enhances the forward-scattering amplitude
- High pT(Z) cut tamed t-channel contribution and hence enhance 00 fraction! → A better chance to observe 00 polarization states and measure the low 00 fraction!
- s-channel → probing "joint" polarization fraction where both bosons come from the same vertex

pT(WZ) < 70 GeV to suppress jet multiplicity

- RAZ effect significant only at LO
- Reducing jet activity enhances RAZ effect, hence enhances separation power between polarization
- Achieved by requiring low pT(WZ)

s-channel t-channel u-channel

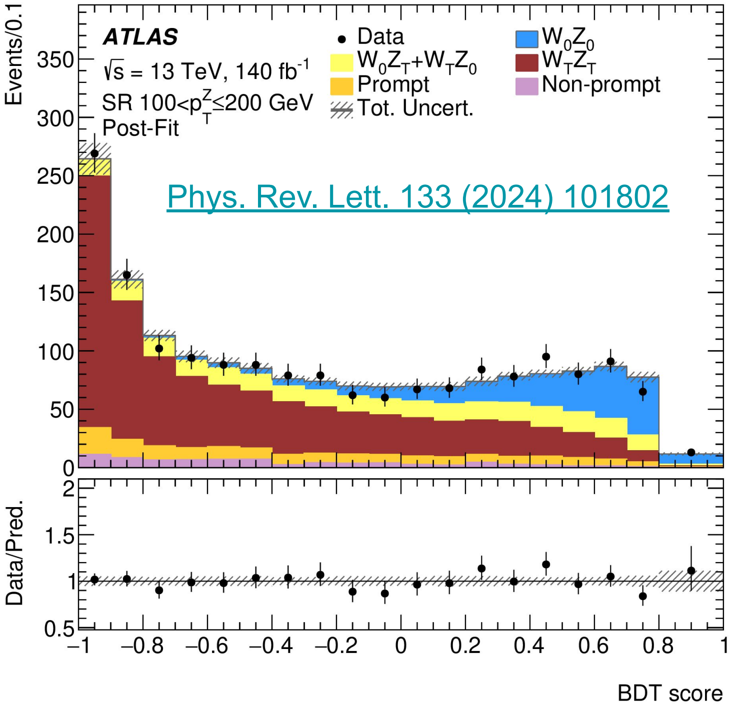


High pT(Z) WZ polarization and RAZ analysis

Use BDT variable to perform the fit and extract the joint polarization fraction

RAZ effect leads to a dip around 0 in the $\Delta Y\,(WZ)$ and $\Delta Y\,(\ell_W\, Z)$ distributions → contributing separation power to BDT

Variable
$\Delta Y(\ell_W Z)$
$p_T(WZ)$
$p_T^{\ell}(W)$
Subleading $p_T^{\ell}(Z)$
$E_{\mathrm{T}}^{\mathrm{miss}}$
$\cos\theta^{\ell}(Z)$
$\cos\theta^{\ell}(W)$



Phys. Rev. Lett. 133 (2024) 101802

High pT(Z) WZ polarization and RAZ analysis

Process	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
W_0Z_0	222 ± 5	47.6 ± 1.5
$W_0Z_T + W_TZ_0$	323 ± 12	23.7 ± 0.8
W_TZ_T	856 ± 31	124 ± 4
Prompt background	169 ± 18	24.1 ± 2.7
Non-prompt background	68 ± 29	2.8 ± 1.1
Total Expected	1640 ± 60	222 ± 8
Data	1740	236

The measured fractions are found to be consistent with the SM predictions.

A non-zero fraction of events where both bosons are longitudinally polarized is measured with an observed significance of 5.2σ (1.6σ) in the phase space with 100 < pT(Z) ≤ 200 GeV (pT(Z) > 200 GeV)

[Phys. Rev. Lett. 133 (2024) 101802]

	Measurement		Prediction		
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV		$100 < p_T^Z \leq 200$ 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_{00}	0.152 ± 0.006	0.234 ± 0.007
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_{0T}	0.120 ± 0.002	0.062 ± 0.002
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_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ	f_{TT}	0.619 ± 0.007	0.646 ± 0.008

High pT(Z) WZ polarization and RAZ analysis

Direct RAZ measurement:

RAZ effect leads to a dip around 0 in the ΔY (WZ) and ΔY ($\ell_W Z$) distributions → Makes it possible to quantify RAZ effect by measuring the depth of the dip in ΔY (WZ) and ΔY ($\ell_W Z$) distributions

- The RAZ effect only happens for $W\gamma$ and WZ production
- Observed in $W\gamma$ events at both $p\bar{p}$ and pp colliders.
- Never measured in WZ before → **This analysis is the first study of RAZ effect in WZ channel!**

$$\mathcal{D} = 1 - 2 \times N^{\mathrm{unf}}_{\mathrm{central}} / N^{\mathrm{unf}}_{\mathrm{sides}}$$

Difficulty to observe RAZ effect and the treatment in this analysis:

- 00, 0T and T0 events make the dip less significant

  →**Solution:** None-TT contributions are subtracted from data to check TT dip only. WZ 00, 0T, and T0 contributions are normalized to the SM predicted cross sections

- RAZ effect significant only at LO, higher order effects dilute the RAZ effect

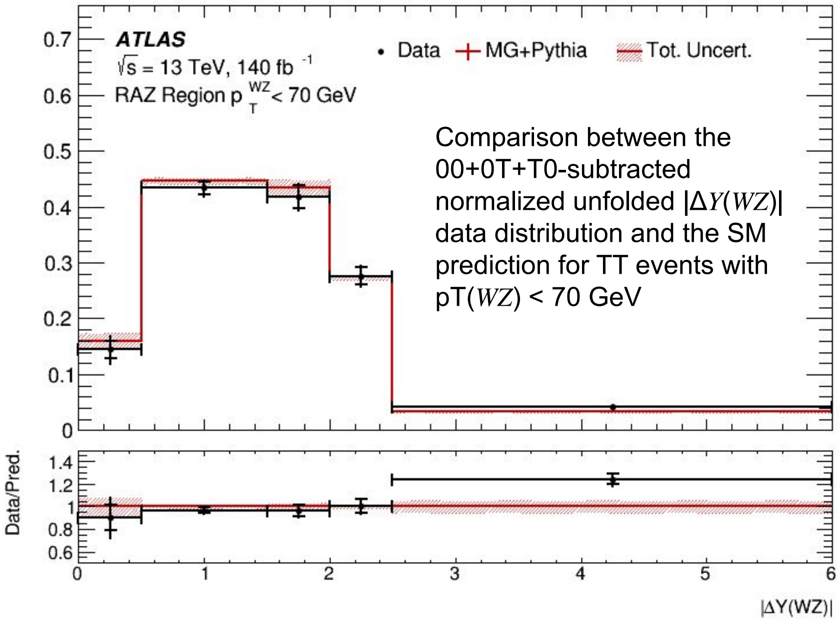
  →**Solution:** Requiring low pT(WZ) to suppress jet multiplicity and hence high-order effect → pT(WZ) < 20, 40, or 70 GeV is applied to define three regions to measure the depth

Unfolded $|\Delta Y$ ($\ell_W Z$)$|$ and $|\Delta Y$ (WZ)$|$ distributions are measured and compared to theoretical predictions

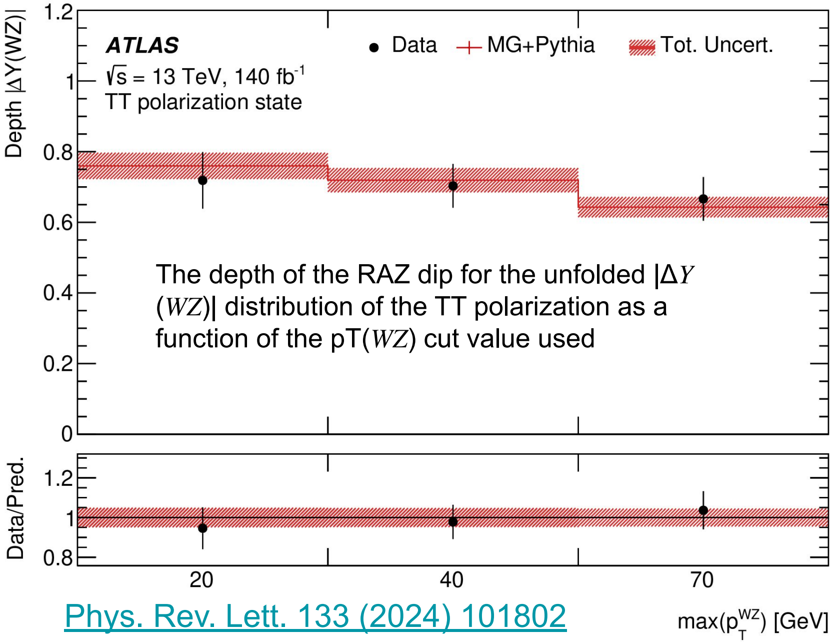
High pT(Z) WZ polarization and RAZ analysis

The depth of the RAZ dip, represented by the variable $\mathcal{D} = 1 - 2 \times N^{\text{unf}}_{\text{central}} / N^{\text{unf}}_{\text{sides}}$

where $N^{\text{unf}}_{\text{central}}$ ($N^{\text{unf}}_{\text{sides}}$) indicates the number of events with $|\Delta Y(WZ)| < 0.5$ ($0.5 < |\Delta Y(\ell_W Z)| < 1.5$) after the unfolding. A positive value of $\mathcal{D}$ indicates the existence of a dip.



Comparison between the 00+0T+T0-subtracted normalized unfolded $|\Delta Y(WZ)|$ data distribution and the SM prediction for TT events with pT(WZ) < 70 GeV



The depth of the RAZ dip for the unfolded $|\Delta Y(WZ)|$ distribution of the TT polarization as a function of the pT(WZ) cut value used

Phys. Rev. Lett. 133 (2024) 101802

Significant dips are observed in the $\Delta Y(\ell_W Z)$ and $\Delta Y(WZ)$ distributions!

Prospects for diboson polarization

Possible to probe not only the breaking of but also the restoration of electroweak symmetry through diboson polarization study

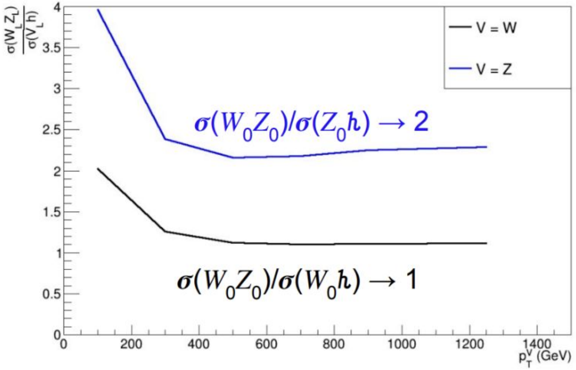
- Goldstone boson equivalence theorem (GBET): At high energy, the longitudinal degree of freedom of a massive vector boson is equivalent to the Goldstone boson (G)
- At high energy scales, the effects of symmetry breaking become less dominant → Restoration of electroweak symmetry!
  - In this limit the EW gauge bosons become massless. That is, only the transverse polarizations persist and the longitudinal polarizations are replaced by their associated Goldstone bosons
  - Symmetry of the terms involving $G^{\pm}$, G^0, and h

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}$$

In the Higgs mechanism, a massive W boson acquired its longitudinal component by absorbing a Goldstone boson from the Higgs sector. When the W is at rest, it is not so clear which polarization state comes from the original vector boson and which comes from the Higgs boson. However, for a highly boosted W, there is a clear distinction between the transverse and longitudinal polarization states. Then,

$$\mathcal{M}(X \to Y + W_0^+(p)) = \mathcal{M}(X \to Y + \pi^+(p))\ (1 + \mathcal{O}(m_W/E_W))$$

What can be observed at high energy:



Helicity cross sections (in fb)

p_T^V [GeV]	[0, 200]	[200, 400]	[400, 600]	[600, 800]	[800, 1000]	[1000, 1500]
$\sigma(W_0Z_0)$ (fb)	784	58.5	4.84	0.799	0.188	0.0749
$\sigma(W_0h)$ (fb)	387	46.5	4.30	0.726	0.169	0.0671
$\sigma(Z_0h)$ (fb)	198	24.5	2.24	0.367	0.0835	0.0327

p_T^V [GeV]	[0, 200]	[200, 400]	[400, 600]	[600, 800]	[800, 1000]	[1000, 1500]
$\sigma(W_0Z_0)/\sigma(W_0h)$	2.03	1.26	1.13	1.10	1.11	1.11
$\sigma(W_0Z_0)/\sigma(Z_0h)$	3.96	2.39	2.16	2.18	2.25	2.29

PHYS. REV. D 99, 055001 (2019)

Prospects for diboson polarization

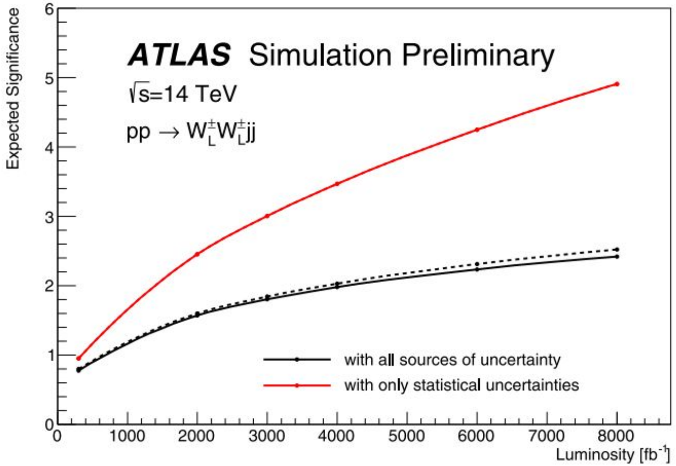
Prospects of VBS diboson polarization measurement in HL-LHC: [Reviews in Physics 8 (2022) 100071]

CMS:

- ❏ $W^{\pm}W^{\pm}jj$: The expected significance for an integrated luminosity of 3000 fb^{-1} is expected to reach 2.7 standard deviations, and exceed 3σ when combining CMS and ATLAS results.
- ❏ $ZZjj$: The expected significance for selecting the VBS $Z_L Z_L$ event fraction is 1.4σ with 3000 fb^{-1} at the CMS experiment. Comparable results are anticipated for the ATLAS experiment.

ATLAS:

- ❏ $W^{\pm}W^{\pm}jj$: The significance is expected to be 1.8σ.The expected precision of the measurement of the LL $W^{\pm}W^{\pm}$ scattering cross section is 47%.
- ❏ $W^{\pm}Zjj$: Different selections are tested, namely the nominal selection requiring m_{jj} > 500, 600, 1100 GeV, as well as two different BDT cuts. The luminosity is doubled to emulate the combination of the ATLAS and CMS data samples. The expected significance for the polarization signal is 0.5–3.5σ depending on the selection



Summary

- The study of diboson polarization is interesting for both validating standard model electroweak theory and probing BSM new physics
- New techniques makes it possible to better study diboson polarization
  - MC generation could provide polarized samples in LO, with NLO corrections available with helps from the theorists
  - Utilization of MVA methods provides better separation between different polarization states
- Multiple measurements of diboson polarization has been done with LEP and LHC. The latest ATLAS diboson polarization analysis was introduced today → First study of the energy-dependence of diboson polarization fractions in $WZ \to \ell\nu\ell\ell$ and the first study of the Radiation Amplitude Zero effect in WZ process
- Still rich physics potential to be discovered with diboson polarization
  - Prospects of VBS diboson polarization measurement in HL-LHC: Reviews in Physics 8 (2022) 100071

back up

High order correction

Formulation of reweighting LO polarized sample (0+1 jet) to NLO polarized sample according to theoretical calculation (QCD+EWK+Other)

$$k_{factor} = \frac{MoCaNLO^{Parton}_{Polarized}}{MadGraph01LO^{Particle}_{Polarized}} \times \frac{Sherpa\_NLO^{Particle}_{Inclusive}}{MoCaNLO^{Parton}_{Inclusive}}$$

Theoretical polarized NLO calculation (MoCaNLO) only available at parton level → reweight it to get particle level (after PS) values

LO 0+1j merged polarized distribution at particle level

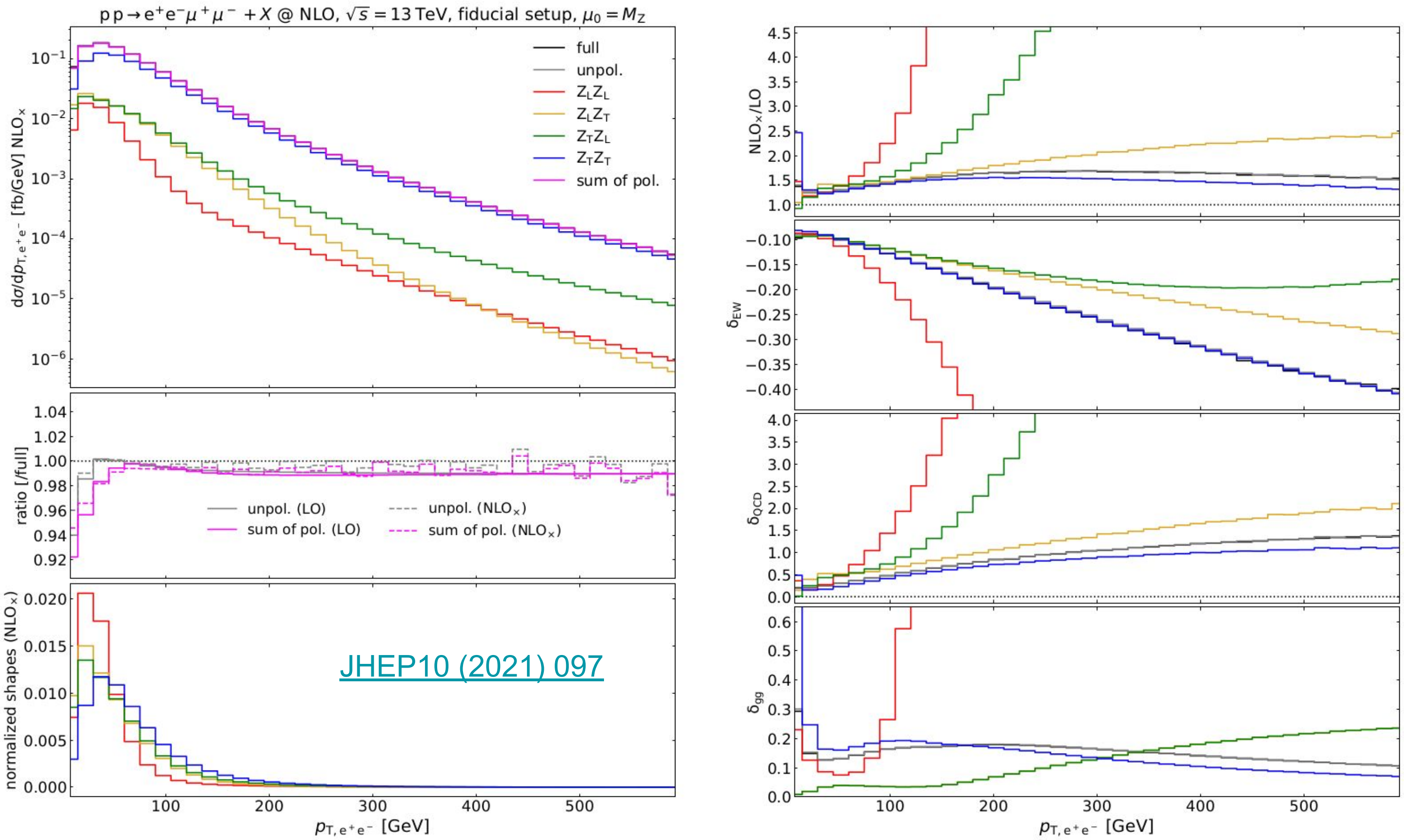
If the theory calculation for combined QCD+EWK+Other is not available, one can get QCD correction and EWK correction individually, then combine them in either additive way or multiplicative way:

$$\mathrm{d}\sigma_{\mathrm{NLO}_+} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}} + \delta_{\mathrm{EW}}\right) + \text{other corrections}$$

$$\mathrm{d}\sigma_{\mathrm{NLO}_\times} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}}\right)\left(1 + \delta_{\mathrm{EW}}\right) + \text{other corrections}$$

The difference can be taken as uncertainty

High order correction



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