Polarization measurements in CMS

COMETA-VBP 2024

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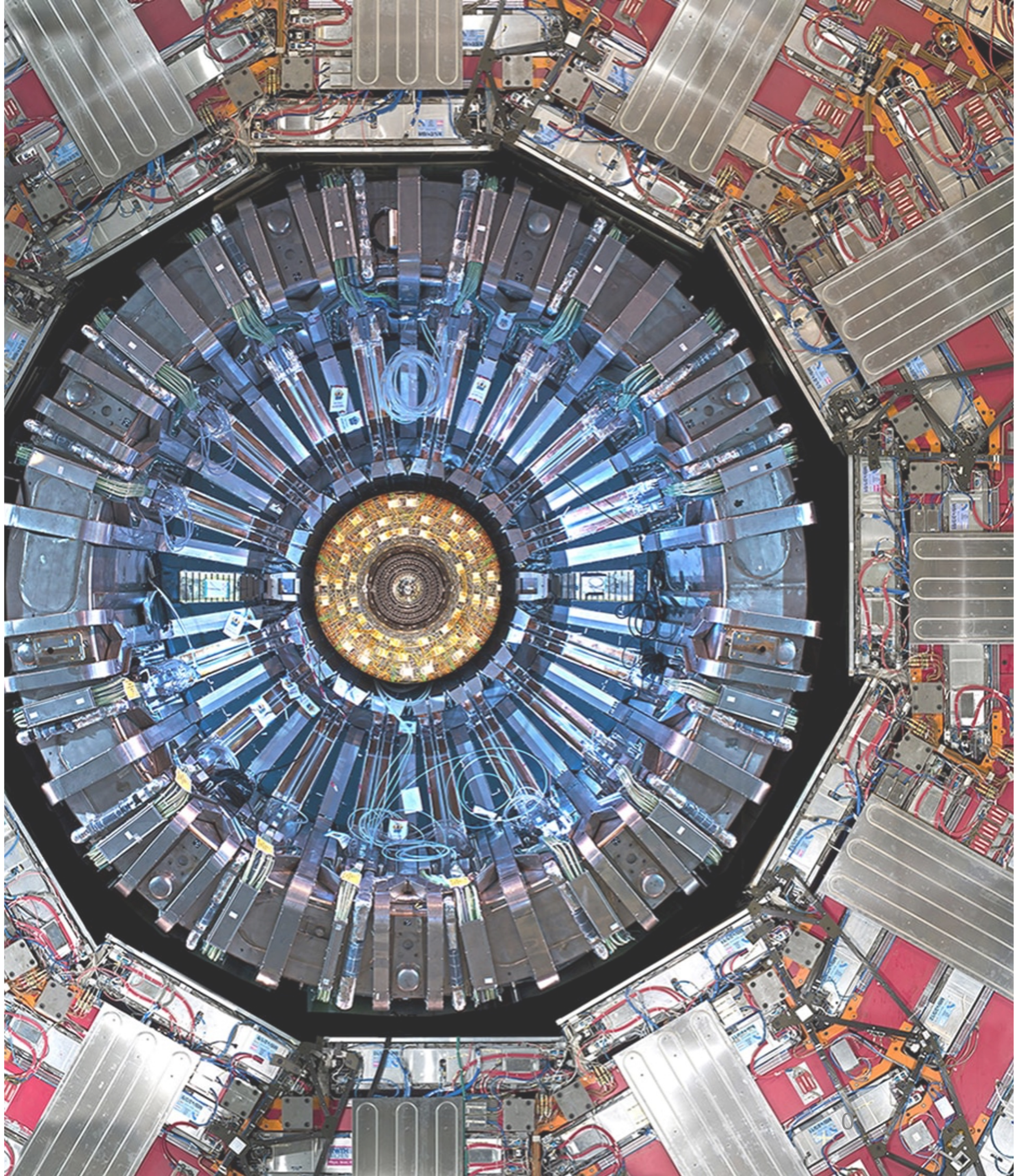

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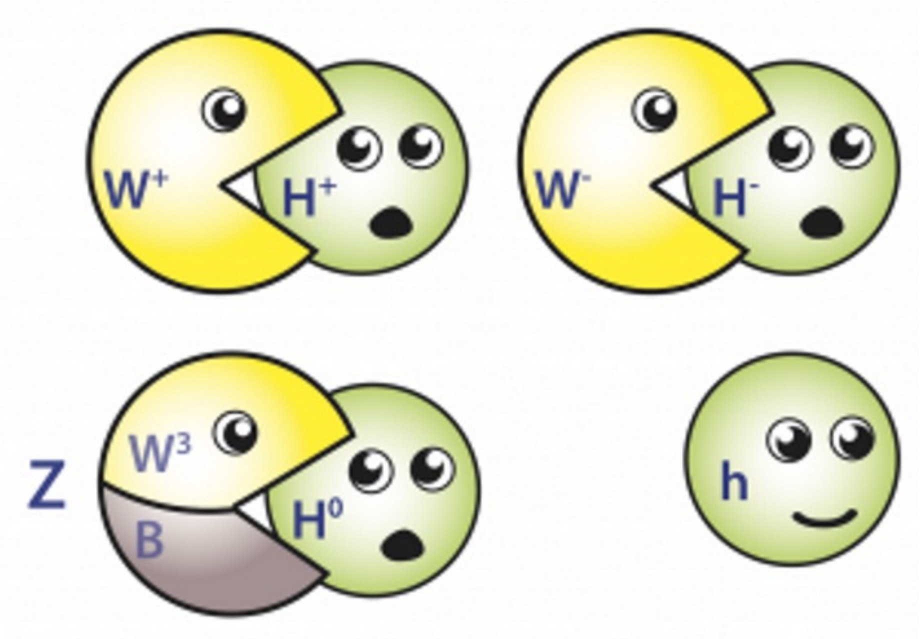
Introduction and motivation

The measurement of **vector boson polarization** represents important tests for the electroweak sector

The Higgs mass introduces important corrections to the **longitudinally polarized** di-boson productions

The measurement of longitudinally polarized boson is an important test to the **electroweak symmetry breaking** mechanism



Introduction and motivation

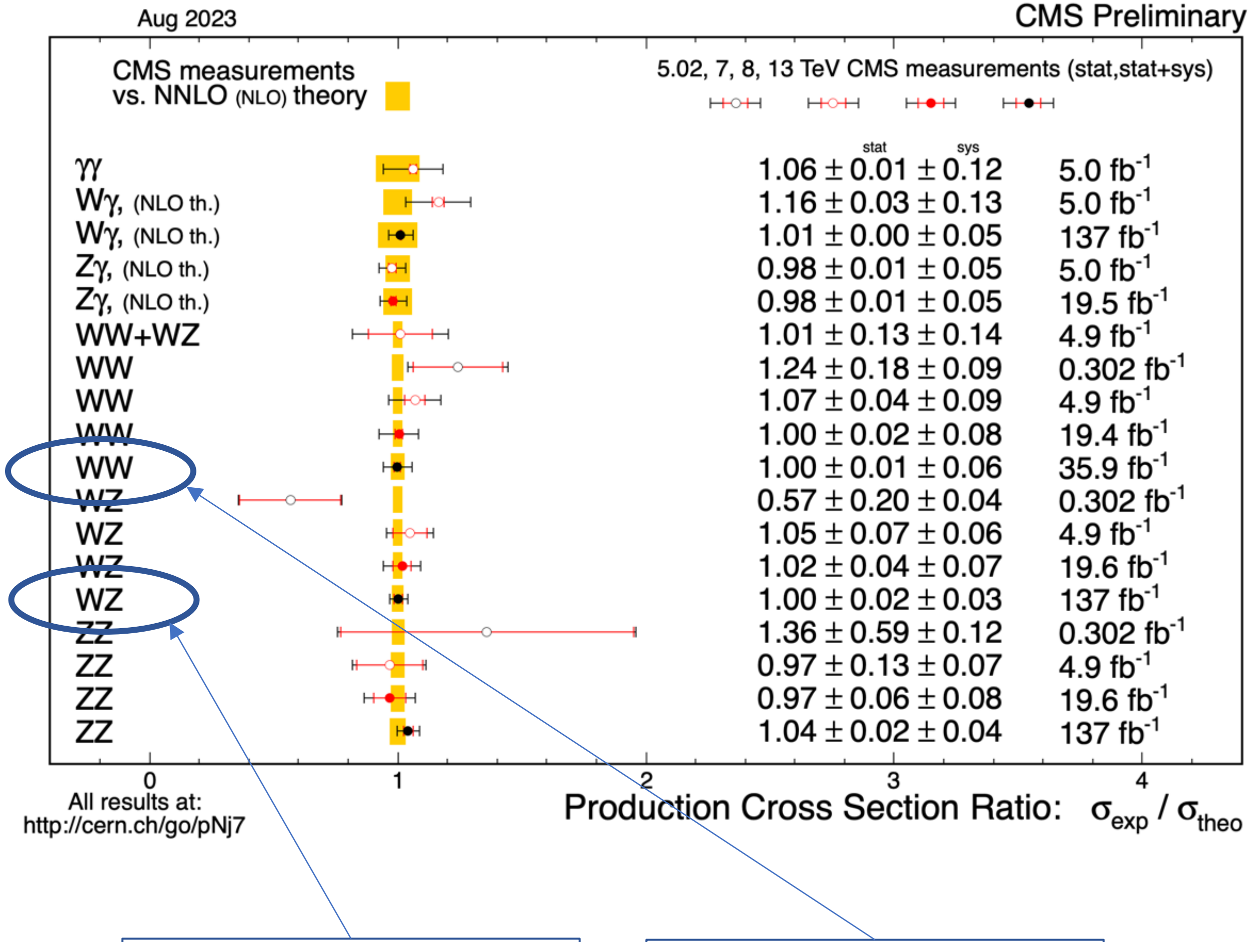
The measurement of **vector boson polarization** represents important tests for the electroweak sector

The Higgs mass introduces important corrections to the **longitudinally polarized** di-boson productions

The measurement of longitudinally polarized boson is an important test to the **electroweak symmetry breaking** mechanism

So far, **experimentally measuring polarization is a challenge** for many final states. E.g. neutrinos in the final state or large backgrounds

Due to these limits only a few analyses are performed, although the efforts are increasing in the last years



WZ Polarization
CMS-SMP-20-014

VBS Same-sign WW
CMS-SMP-20-006

What’s done? summary

Given that the number of results for vector boson polarization is not large, I will try to start a fruitful discussion about the experimental point of view

Let’s start asking ourselves a few important questions. **What’s done? What can be done? Why?**

Single boson production

- Z
- W

Di-boson production

- WW
- WZ
- Vγ
- ZZ

Tri-boson production

- WWW
- WWZ
- WZZ
- ZZZ
- V$\gamma\gamma$
- VVγ

Other bosonic channels

- Higgs → di-boson
- VBS → Single boson
- VBS → Di-boson

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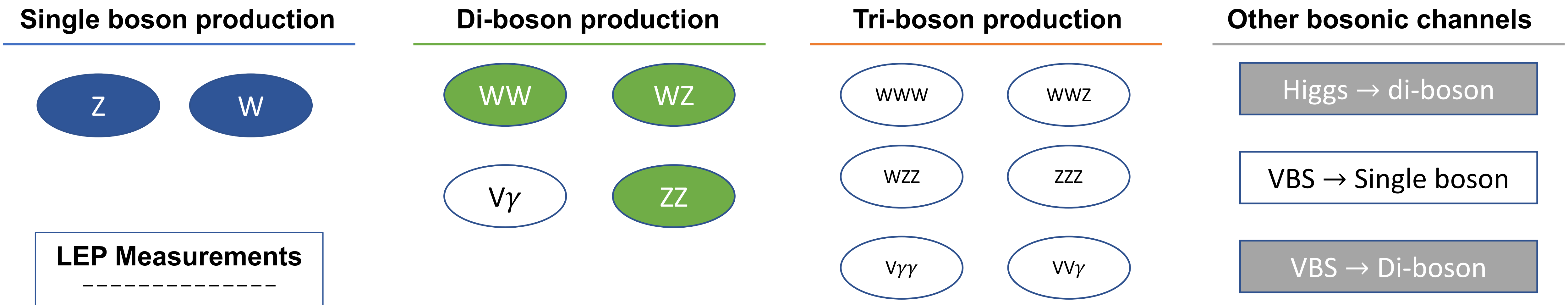

Single boson production

Z
W

Di-boson production

WW
WZ
$V\gamma$
ZZ

Tri-boson production

WWW
WWZ
WZZ
ZZZ
$V\gamma\gamma$
$VV\gamma$

Other bosonic channels

Higgs → di-boson
VBS → Single boson
VBS → Di-boson

LEP Measurements

Single boson
L3
OPAL
DELPHI

Di-boson
OPAL
DELPHI

CMS Measurements

WZ
CMS-SMP-20-014

VBS Same-sign WW
CMS-SMP-20-006

ATLAS Measurements

WZ
ZZ
VBF H → WW^* (POs)

Experimental challenges

What’s done? What can be done? Why?

The first need of an experimentalist is a reliable prediction/simulation

I will skip this topic since:

- A huge efforts has been made by the theoretical community to address a solution
- More and more results are been published at LO, NLO, etc.
- **A lot of talks will cover this topic during the workshop**

Polarised calculations with MulBos

Polarised calculations with STRIPPER

Polarised calculations with BBMC (and MoCaNLO)

Polarised calculations with SHERPA

Polarised calculations with POWHEG-BOX

Polarised calculations with MG5_aMC@NLO

ATLAS & CMS simulations

Experimental challenges

What’s done? What can be done? Why?

The polarization measurements are quite challenging for most of the final states. Let’s summarize the difficulties of the di-boson production modes, which are the most accessible for Run 2 and Run 3 data.

Di-boson production (LHC)

Process	Status	Challenge
$ZZ \to 4l$	ATLAS	Clean signal - Access to decay kinematics
$WZ \to 3l\nu$	CMS and ATLAS	Clean signal and high statistics - Access to decay kinematics
$WW \to 2l2\nu$	No	Clean signal and high statistics - No access to decay angles
$WW \to q\bar{q}2\nu$	No	Challenging backgrounds (Top, W+jets) - Access to decay angles

Experimental challenges

What's done? What can be done? Why?

The polarization measurements are quite challenging for most of the final states. Let's summarize the difficulties of the di-boson production modes, which are the most accessible for Run 2 and Run 3 data.

Other boson productions (LHC)

Process	Status	Challenge
$gg \rightarrow \mathrm{H}$	No	Medium statistics - Depending on the decay, access to decay kinematics
VBF $qq \rightarrow \mathrm{H\ jj}$	ATLAS	Low statistcs - Benefit from the jet to access polarization
VBS / VBF to di-boson	One CMS result	In general, low statistics

Experimental challenges

What's done? What can be done? Why?

The polarization measurements are quite challenging for most of the final states. Let's summarize the difficulties of the di-boson production modes, which are the most accessible for Run 2 and Run 3 data.

In general, I would say that:

- **Leptonic Z decays** provide the perfect scenario for polarization measurements
- **Leptonic W decays** are challenging for the separation of the polarization components
- **Hadronic W decays** can help with polarization. However, backgrounds are huge
- **Hadronic Z decays**, why if we have leptonic ones?

Machine learning can help here, but probably more efforts are needed

For VBS and Higgs is the same, but with lower statistics…

Experimental challenges

What's done? What can be done? Why?

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- **Hadronic Z deca** … we have leptonic ones?

…and longitudinal polarization even lower cross-sections

Machine learning can help here, but probably more efforts are needed

For VBS and Higgs is the same, but with lower statistics…

Measurements

WZ CMS-SMP-20-014

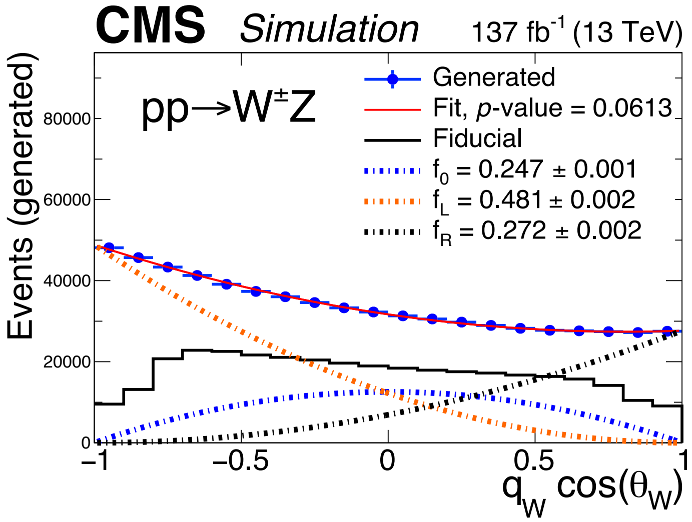
WZ: Polarization definition

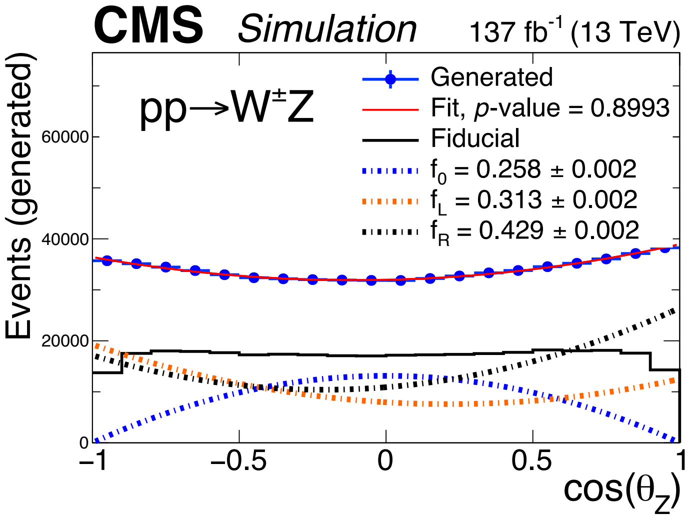
The reference frame is an important choice as it's not Lorentz invariant. For the CMS WZ analysis, the individual polarization of the W and Z boson is defined through this analytical expression:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_{W^\pm}} = \frac{3}{8}\left\{\left[1 \mp \cos\theta_{W^\pm}\right]^2 f_L^W + \left[1 \pm \cos\theta_{W^\pm}\right]^2 f_R^W + 2\sin^2\theta_{W^\pm} f_0^W\right\}$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_Z} = \frac{3}{8}\{[1+\cos^2\theta_Z - 2c\cos\theta_Z]\, f_L^Z + [1+\cos^2\theta_Z + 2c\cos\theta_Z]\, f_R^Z + 2\sin^2\theta_Z\, f_0^Z\}$$

Only valid at Gen. level, inclusive





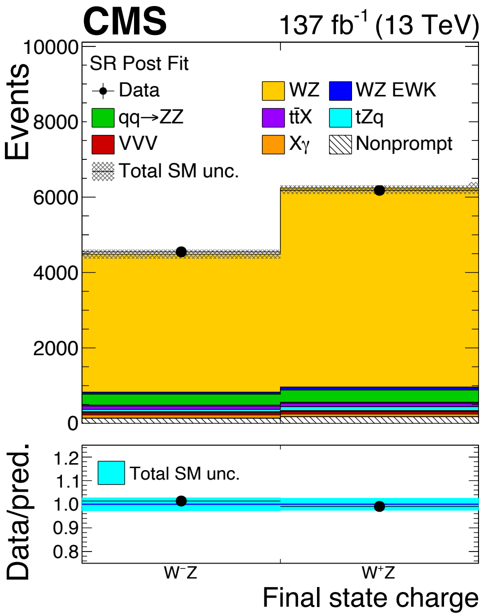
Fiducial ≠ Gen

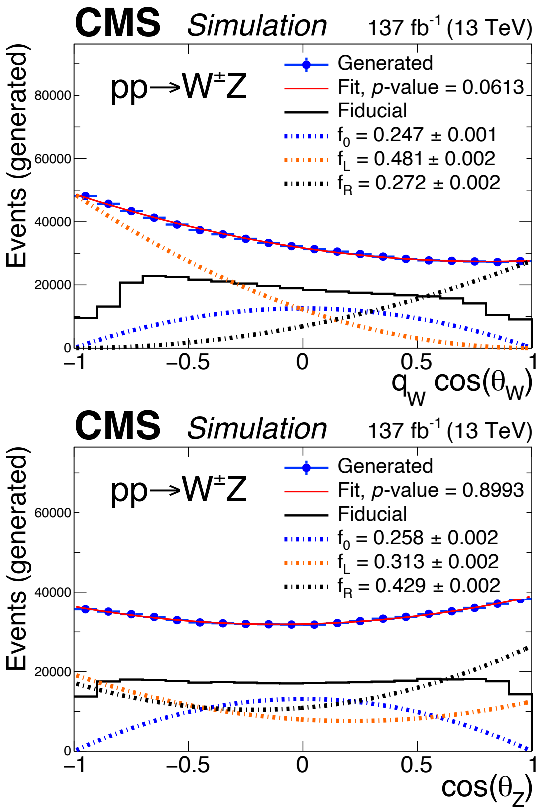
The chosen reference frame is the so-called Helicity (HE) frame, where *θ* is defined as the angle between the momentum of the lepton in the rest frame of the parent boson and the momentum of the boson in the laboratory frame.

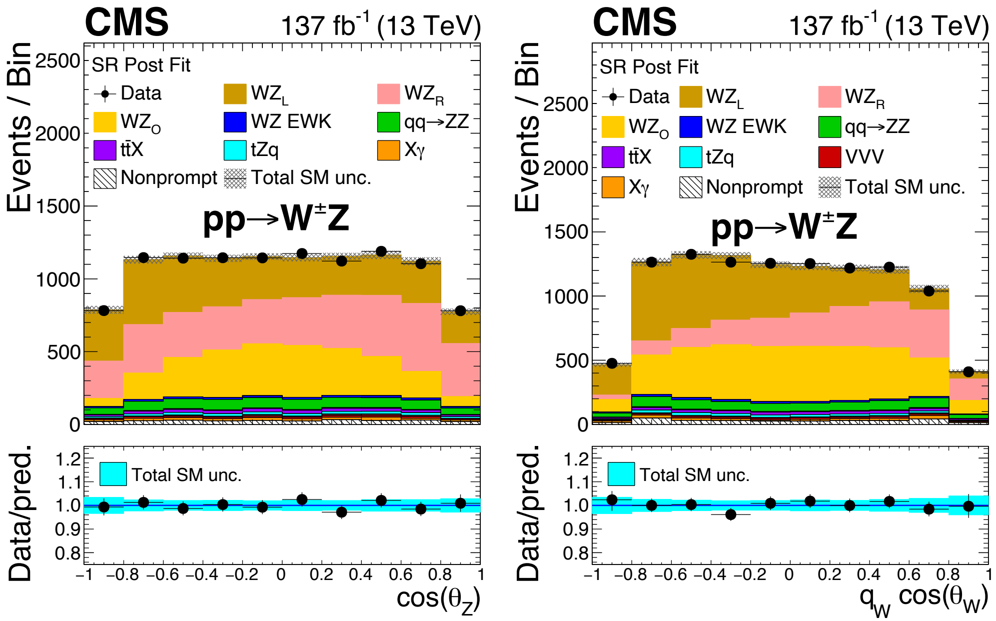
WZ: Polarized templates

To perform reliable polarization measurements, predictions are needed for the polarized templates

1. The analytical expressions are only valid at Gen. level, without any selection
2. Dedicated polarized samples are not produced using MonteCarlo (Many improvements on this topic in the last years)
3. The inclusive **WZ MC sample is divided, and reweighted** to match the polarization components





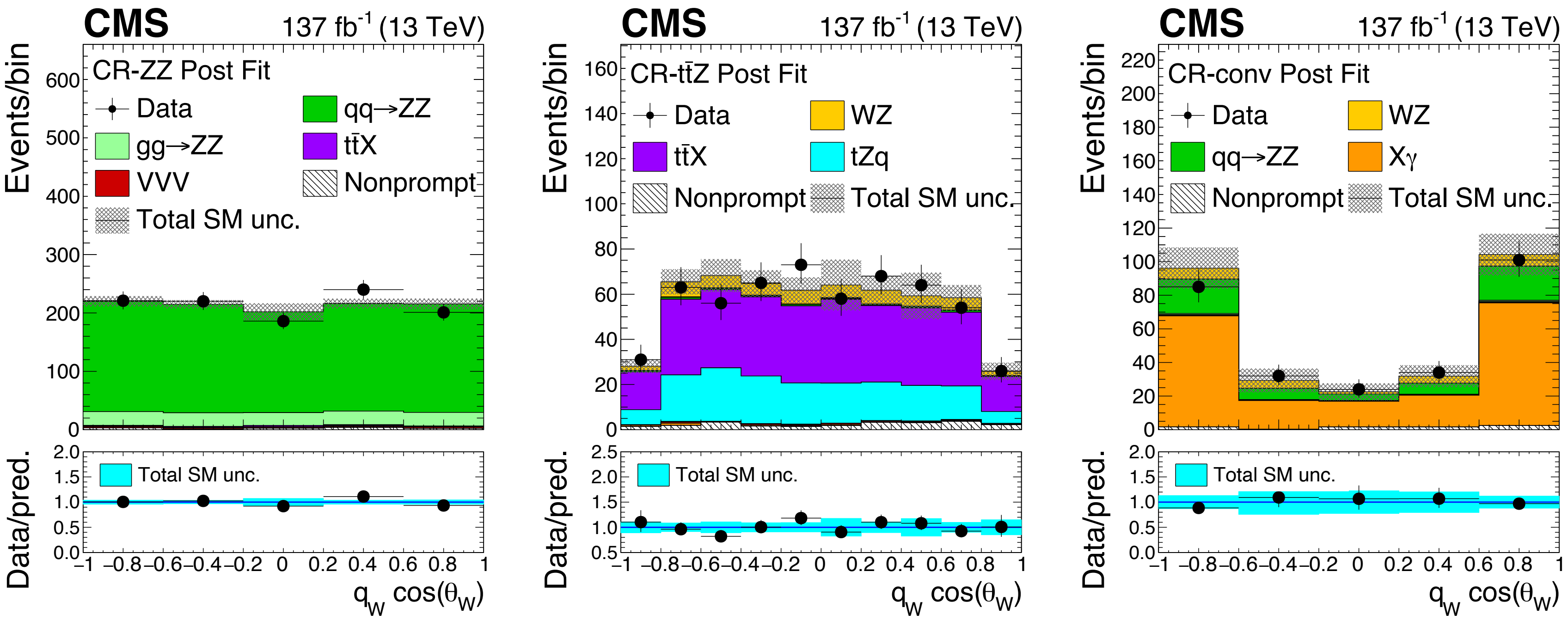


WZ: Analysis strategy

The same strategy as the inclusive WZ cross-section analysis is used. Several control regions are constructed and included in the fit to account precisely for the background normalization

- ZZ control region, ask for $\mathrm{N_l} = 4$ and remove p_T^{miss} cut
- $t\bar{t}Z$ and $t\bar{t}W$ control region, inverted b-Veto. At least one b-tagged jet
- Conversion control region $(V\gamma)$, remove Z mass requirement and invert the ones for p_T^{miss} and $M_{l_1^Z,l_2^Z,l^W}$

	Selection
Signal Region	$N_l = 3$
	$p_T^l > (25, 10, 25)$ GeV
	$N_{OSSF} \geq 1$
	$\left\lvert M_{l_1^Z,l_2^Z} - m_Z \right\rvert < 15$ GeV
	$p_T^{miss} > 30$ GeV
	$N_{b-tag} = 0$
	$M_{l_1^Z,l_2^Z,l^W} > 100$ GeV



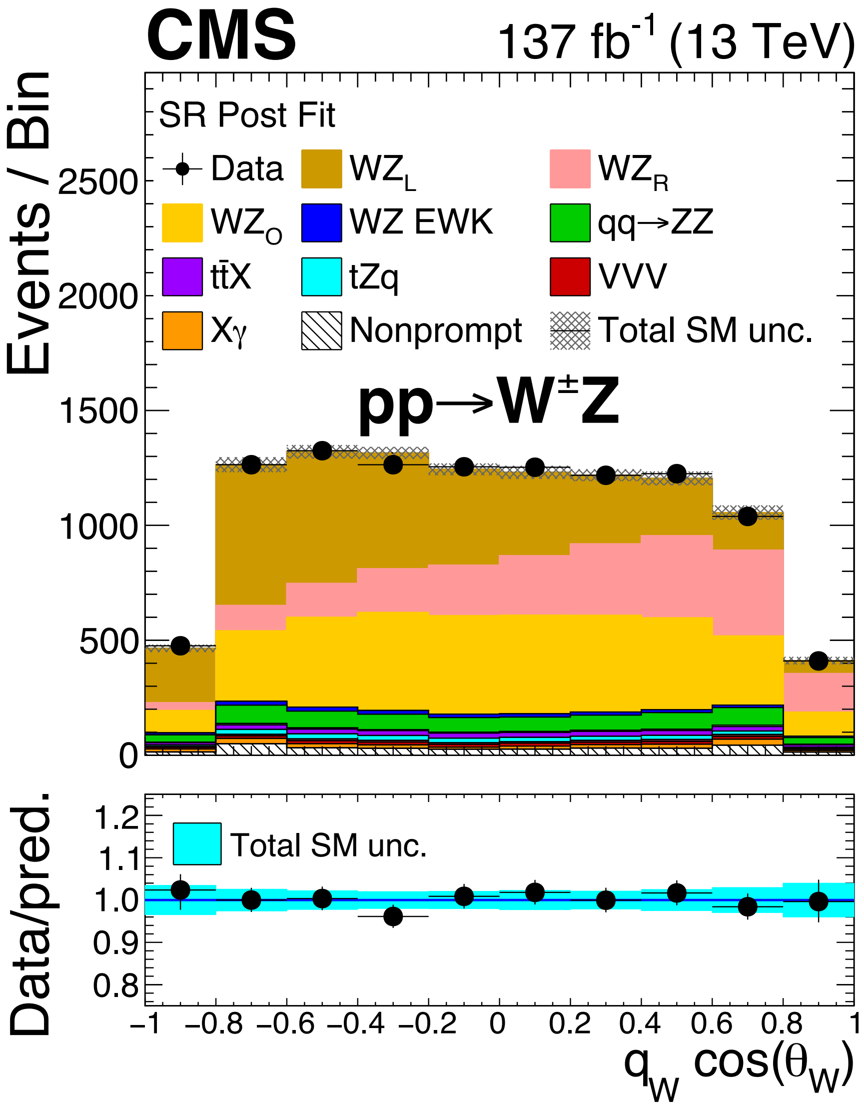
WZ: Analysis strategy

- **The fit is performed to the binned distribution of $\cos\theta_{Z/W}$**

- The p_T^{miss} and Φ^{miss} are used to reconstruct the W boson three-momentum. However, a tune is needed to better approximate the neutrino vector from the missing transverse energy.

- The longitudinal component of the MET is computed such that the Lepton+MET invariant mass is close to the W boson mass. In case of multiple numerical solutions, the lowest one for the p_L^{miss} is selected

- As expected, the limited resolution for the θ_W angle generates migration among bins. The effect is larger at high $|\cos\theta_W|$



Machine learning can probably help here

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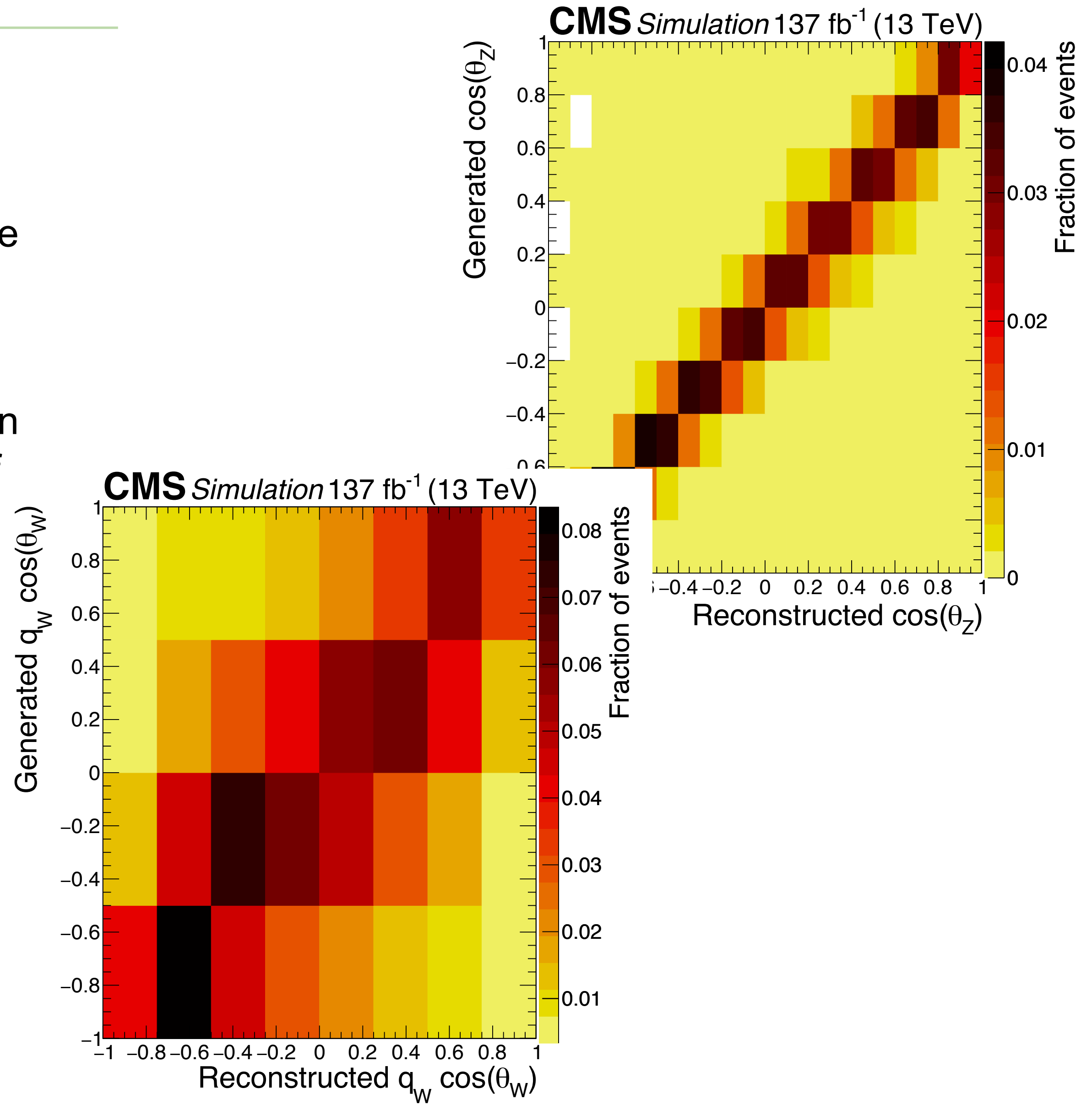

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- As expected, the limited resolution for the θ_W angle generates migration among bins. The effect is larger at high $|\cos\theta_W|$
- A joint extended binned likelihood fit is built. Three parameters in the fit:

$\boxed{\mu = \text{Normalization}}$ $\boxed{1 = f_0 + f_L + f_R}$ $\boxed{f_0}$ $\boxed{f_{LR} = f_L - f_R}$

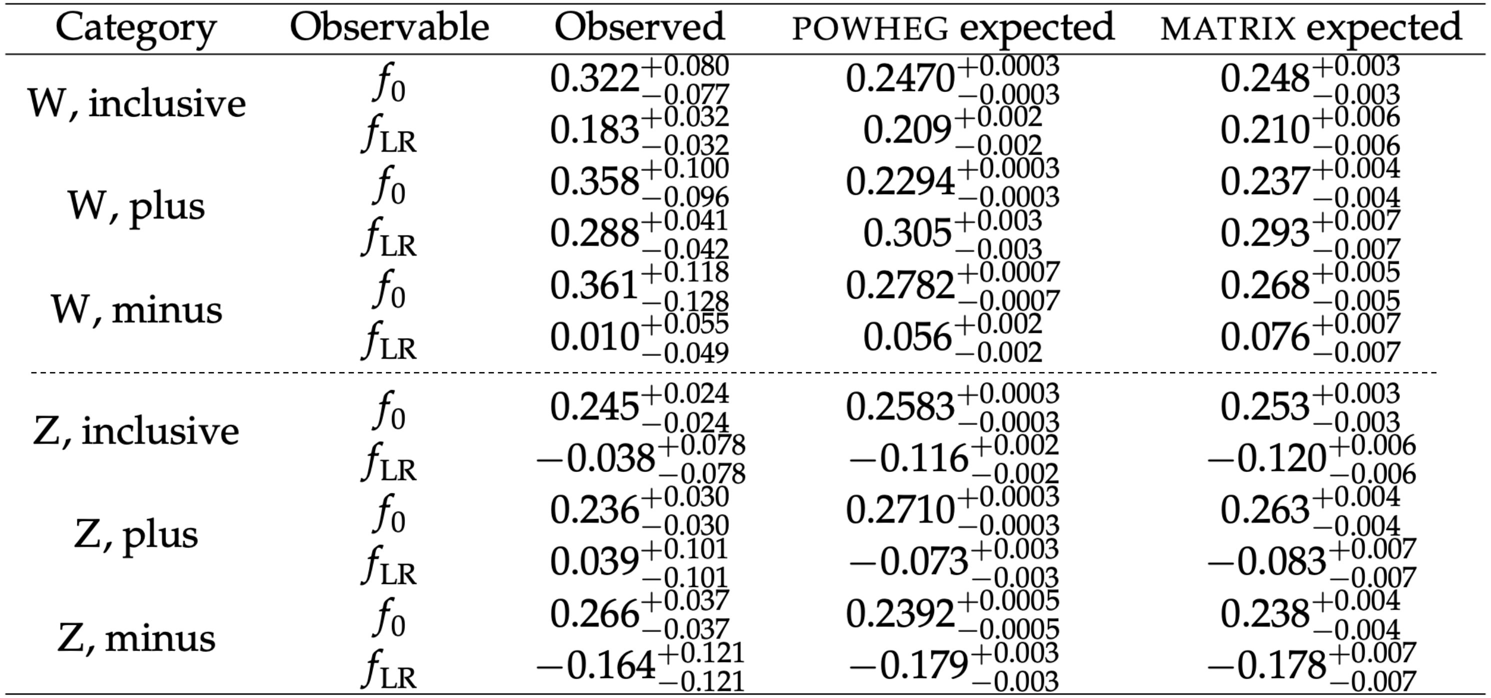
- The polarization fractions are measured for both **W and Z boson individually**

WZ: Results

The results from the binned likelihood fit are presented, in terms of the individual polarization fractions for the Z and W boson

The significance for the **W boson longitudinal** polarization is **5.6σ (4.3σ) observed (expected).** There is a much larger significance $(> 8\sigma)$ **for the Z boson longitudinal** polarization

Results in agreement with expected polarized fractions



Category	Observable	Observed	POWHEG expected	MATRIX expected
W, inclusive	f_0	$0.322^{+0.080}_{-0.077}$	$0.2470^{+0.0003}_{-0.0003}$	$0.248^{+0.003}_{-0.003}$
	f_{LR}	$0.183^{+0.032}_{-0.032}$	$0.209^{+0.002}_{-0.002}$	$0.210^{+0.006}_{-0.006}$
W, plus	f_0	$0.358^{+0.100}_{-0.096}$	$0.2294^{+0.0003}_{-0.0003}$	$0.237^{+0.004}_{-0.004}$
	f_{LR}	$0.288^{+0.041}_{-0.042}$	$0.305^{+0.003}_{-0.003}$	$0.293^{+0.007}_{-0.007}$
W, minus	f_0	$0.361^{+0.118}_{-0.128}$	$0.2782^{+0.0007}_{-0.0007}$	$0.268^{+0.005}_{-0.005}$
	f_{LR}	$0.010^{+0.055}_{-0.049}$	$0.056^{+0.002}_{-0.002}$	$0.076^{+0.007}_{-0.007}$
Z, inclusive	f_0	$0.245^{+0.024}_{-0.024}$	$0.2583^{+0.0003}_{-0.0003}$	$0.253^{+0.003}_{-0.003}$
	f_{LR}	$-0.038^{+0.078}_{-0.078}$	$-0.116^{+0.002}_{-0.002}$	$-0.120^{+0.006}_{-0.006}$
Z, plus	f_0	$0.236^{+0.030}_{-0.030}$	$0.2710^{+0.0003}_{-0.0003}$	$0.263^{+0.004}_{-0.004}$
	f_{LR}	$0.039^{+0.101}_{-0.101}$	$-0.073^{+0.003}_{-0.003}$	$-0.083^{+0.007}_{-0.007}$
Z, minus	f_0	$0.266^{+0.037}_{-0.037}$	$0.2392^{+0.0005}_{-0.0005}$	$0.238^{+0.004}_{-0.004}$
	f_{LR}	$-0.164^{+0.121}_{-0.121}$	$-0.179^{+0.003}_{-0.003}$	$-0.178^{+0.007}_{-0.007}$

WZ: Results

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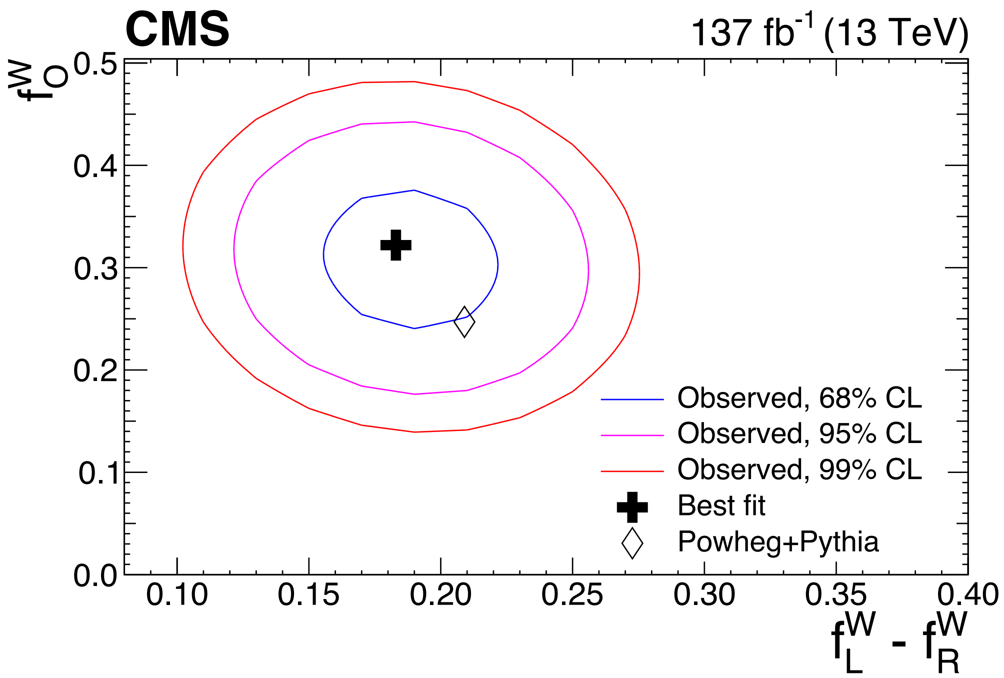
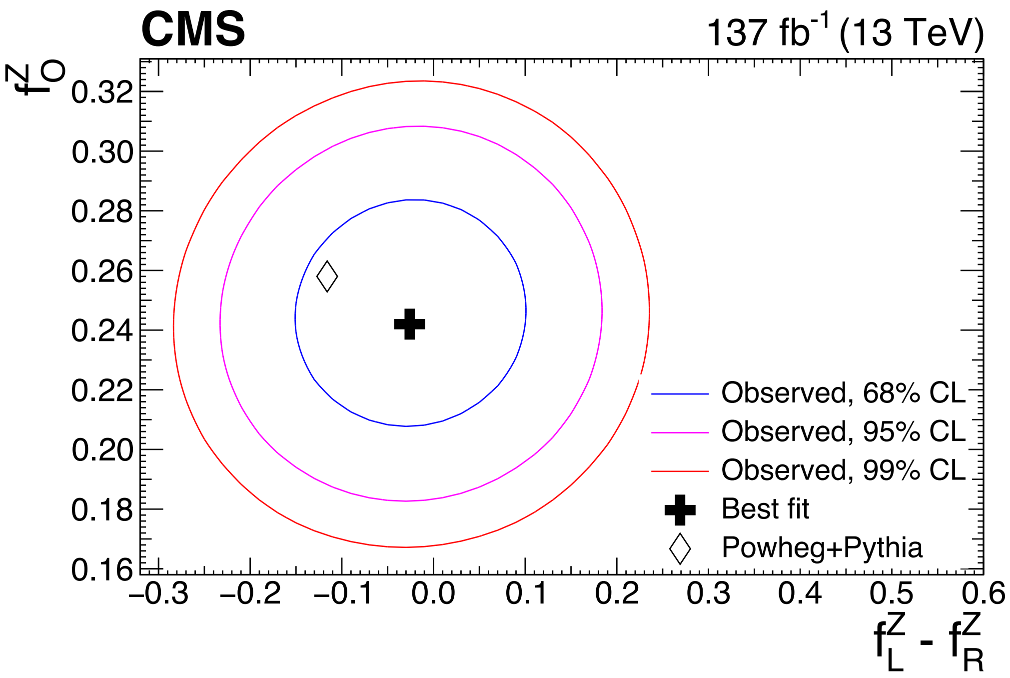




Measurements

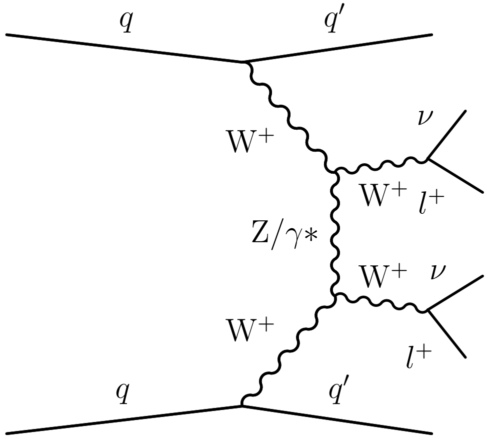
VBS WW CMS-SMP-20-006

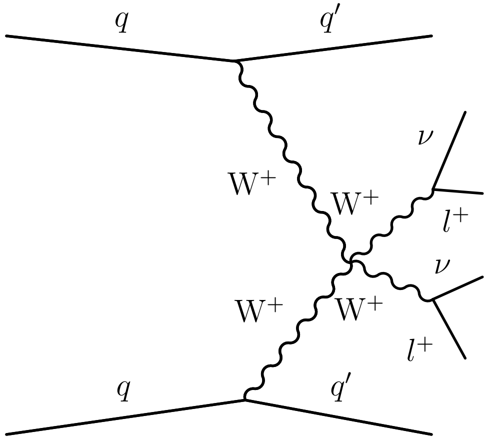
VBS WW: Introduction

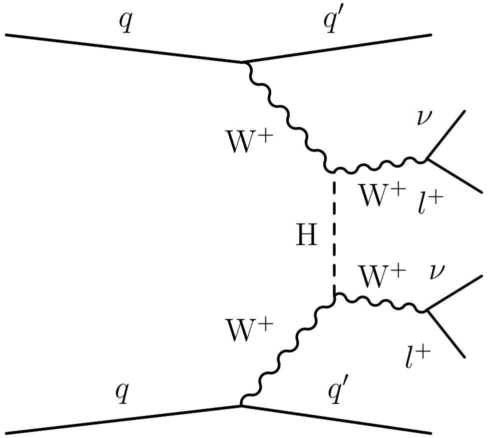
The analysis targets the **Vector Boson Scattering (VBS)** production of **same-sign W bosons**. Same-sign leptonic decay channel targeted

$$\mathbf{pp \rightarrow W^{\pm}W^{\pm}jj \rightarrow 2l2\nu_l\ jj}$$

The scattering of longitudinally polarized W boson is of particular interest due to the electroweak symmetry breaking, which predicts a suppression with the Higgs mediation







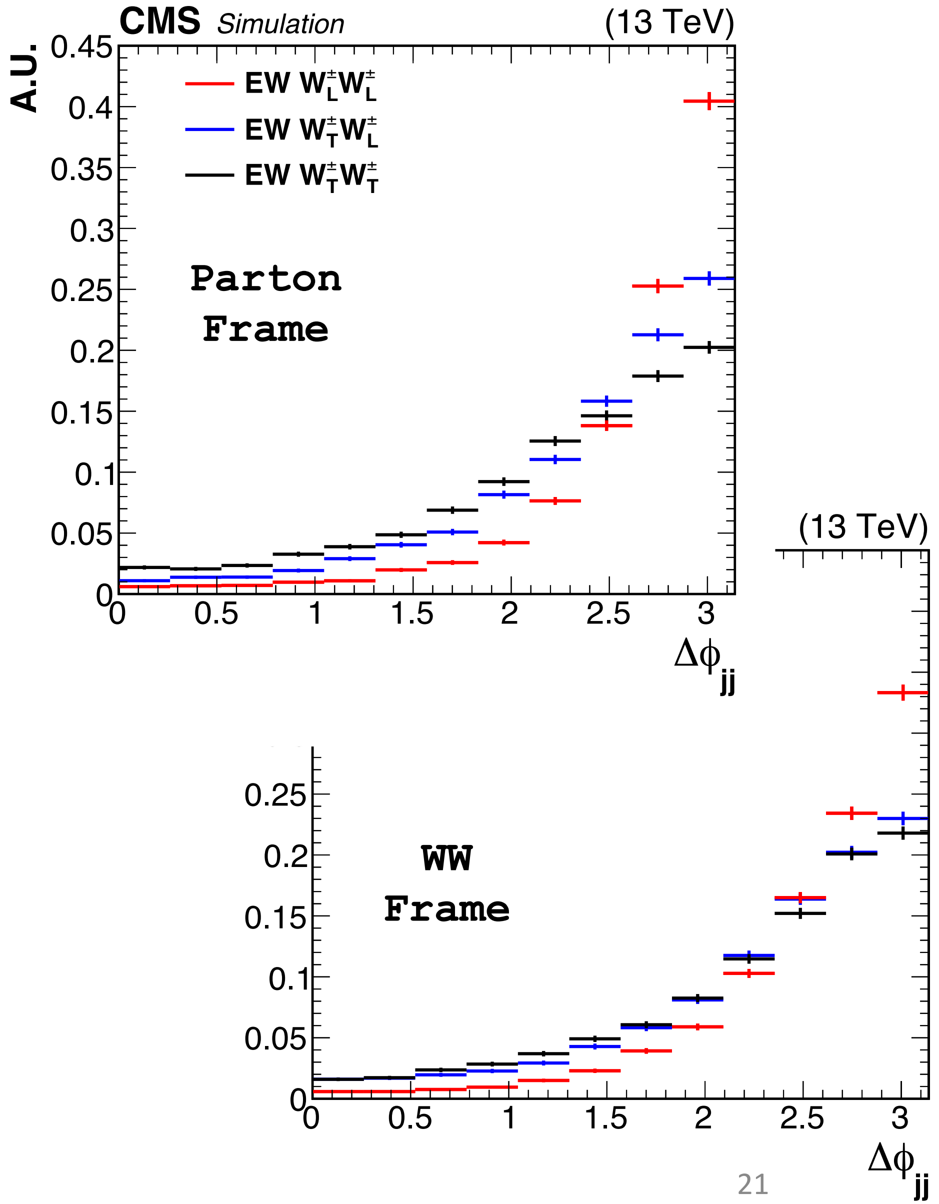
VBS WW: Polarization definition

Doubly polarized W-bosons are targeted

- Polarization samples are generated using **MADGRAPH5 aMC@NLO at LO** interfaced with **Pythia8**
- Validated using additional **Phantom** MC samples (Good agreement within stat. unc.)
- Results are presented in terms of two different reference frames: **WW pair frame** and **Parton frame**
- **Signals:**

$\boxed{pp \rightarrow W^{\pm}_{L}W^{\pm}_{L}jj}$ $\boxed{pp \rightarrow W^{\pm}_{T}W^{\pm}_{T}jj}$

$\boxed{pp \rightarrow W^{\pm}_{L}W^{\pm}_{T}jj}$ $\boxed{pp \rightarrow W^{\pm}_{T}W^{\pm}_{L}jj}$



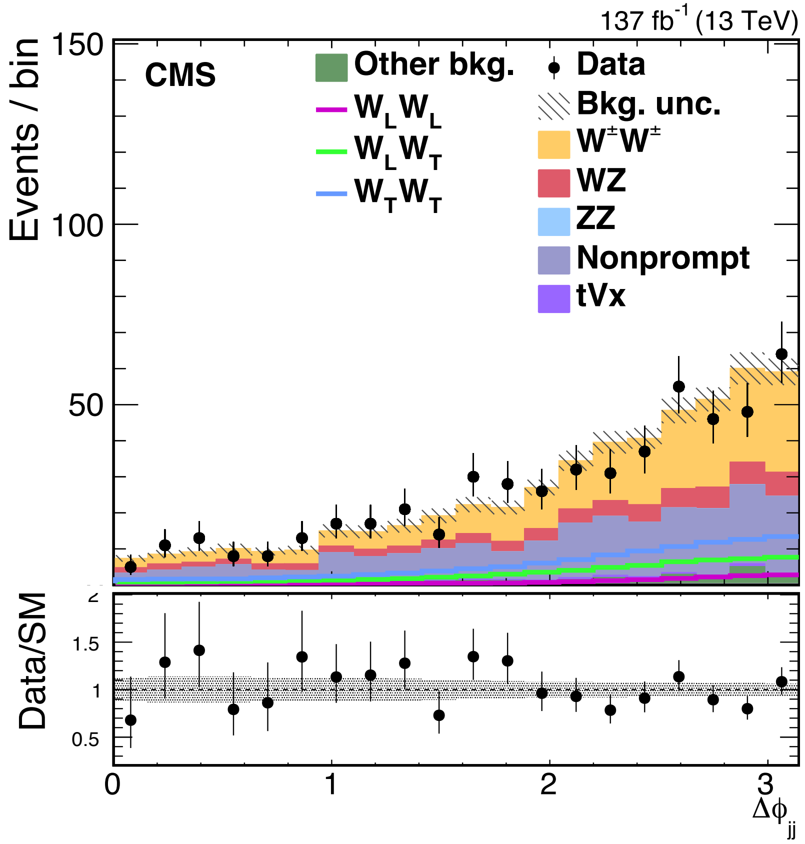
VBS WW: Analysis strategy

- An event selection is designed to create a **WW signal region**
- **Single lepton triggers** are used to select the events
- **Control regions** are constructed for the WZ and Non-prompt lepton backgrounds

Variable	Requirement
Leptons	Exactly 2 same-sign leptons, $p_{\mathrm{T}} > 25/20\,\mathrm{GeV}$
$p_{\mathrm{T}}^{\mathrm{j}}$	$>50\,\mathrm{GeV}$
$\lvert m_{\ell\ell} - m_{\mathrm{Z}} \rvert$	$>15\,\mathrm{GeV}$ (ee)
$m_{\ell\ell}$	$>20\,\mathrm{GeV}$
$p_{\mathrm{T}}^{\mathrm{miss}}$	$>30\,\mathrm{GeV}$
b quark veto	Required
$\mathrm{Max}(z_{\ell}^{*})$	<0.75
m_{jj}	$>500\,\mathrm{GeV}$
$\lvert \Delta\eta_{\mathrm{jj}} \rvert$	>2.5

Only electron channel, for charge-flip probability

$$\boxed{z_l^* = \frac{\left|\eta^l - \dfrac{(\eta^{j1} + \eta^{j2})}{2}\right|}{\Delta\eta_{jj}}}$$



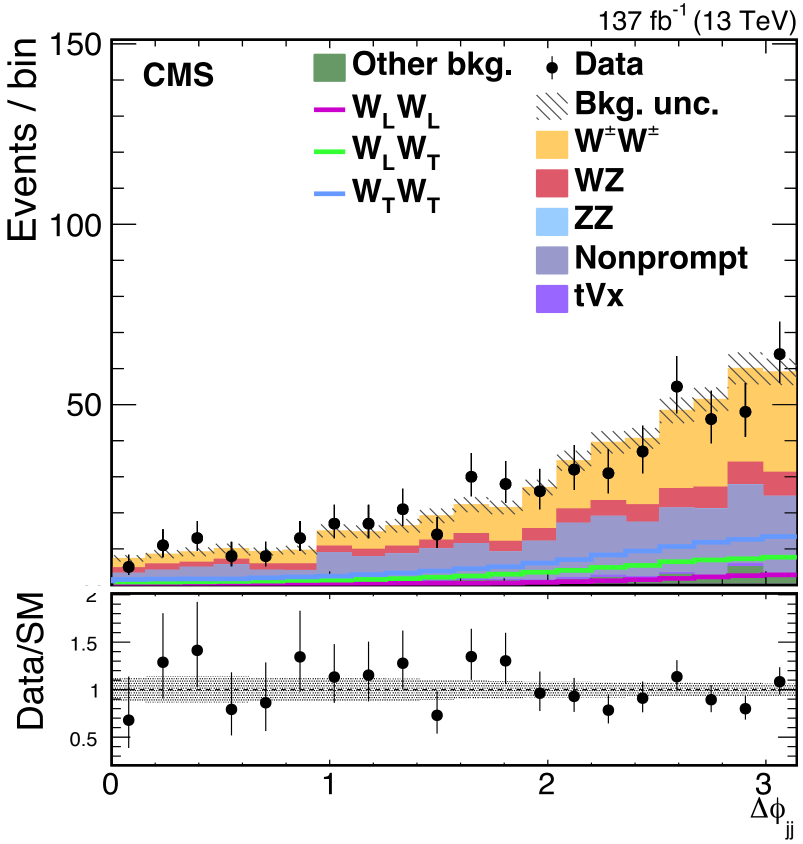
VBS WW: Analysis strategy

- The different polarizations account for slightly different angular kinematic observables but not enough to perform the analysis directly over one variable

- **Multivariate techniques** are used to solve the most challenging part of this analysis:

1. **Extract the signal** (VBS WW) over a large background

2. **Separate the polarization components**



Both lepton and jet kinematic variables used to train the BDTs

VBS WW: Analysis strategy

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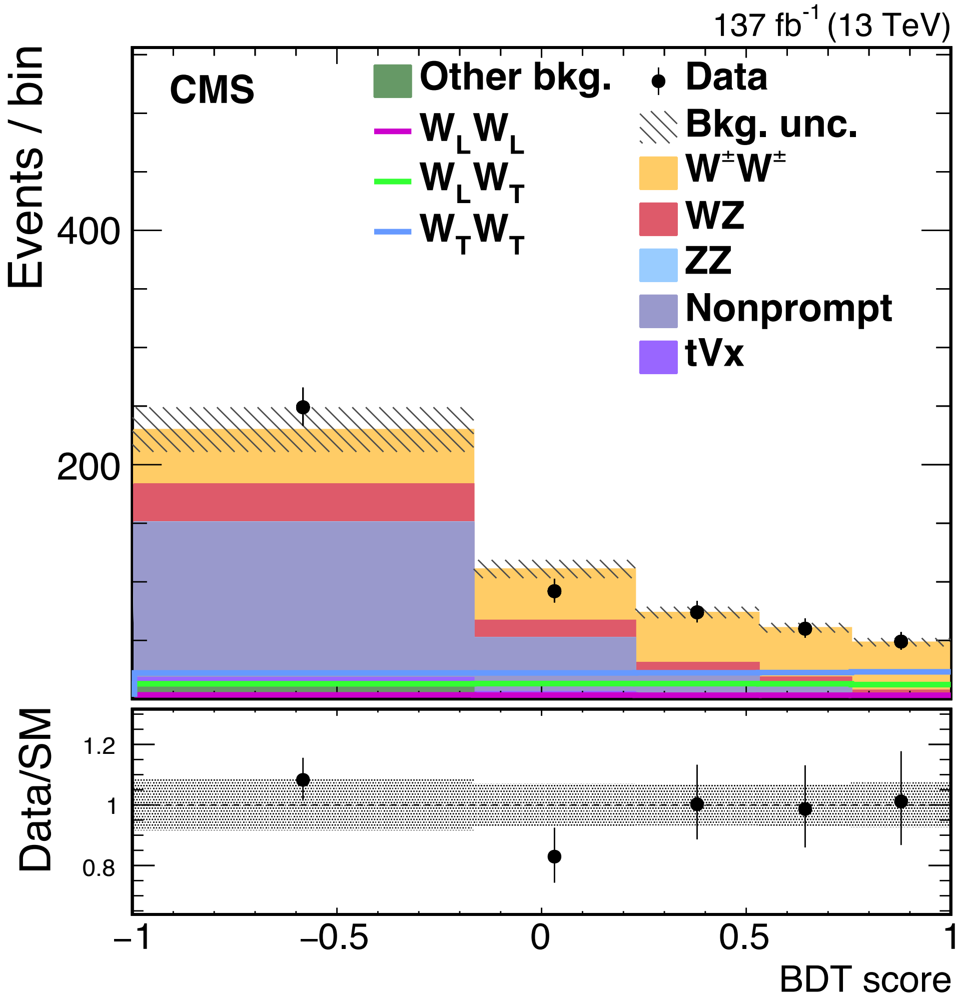
1. **Extract the signal** (VBS WW) over a large background

   "Inclusive BDT": Trained on WW as a signal vs Top quark simulated events that account for the Non-prompt background

2. **Separate the polarization components**



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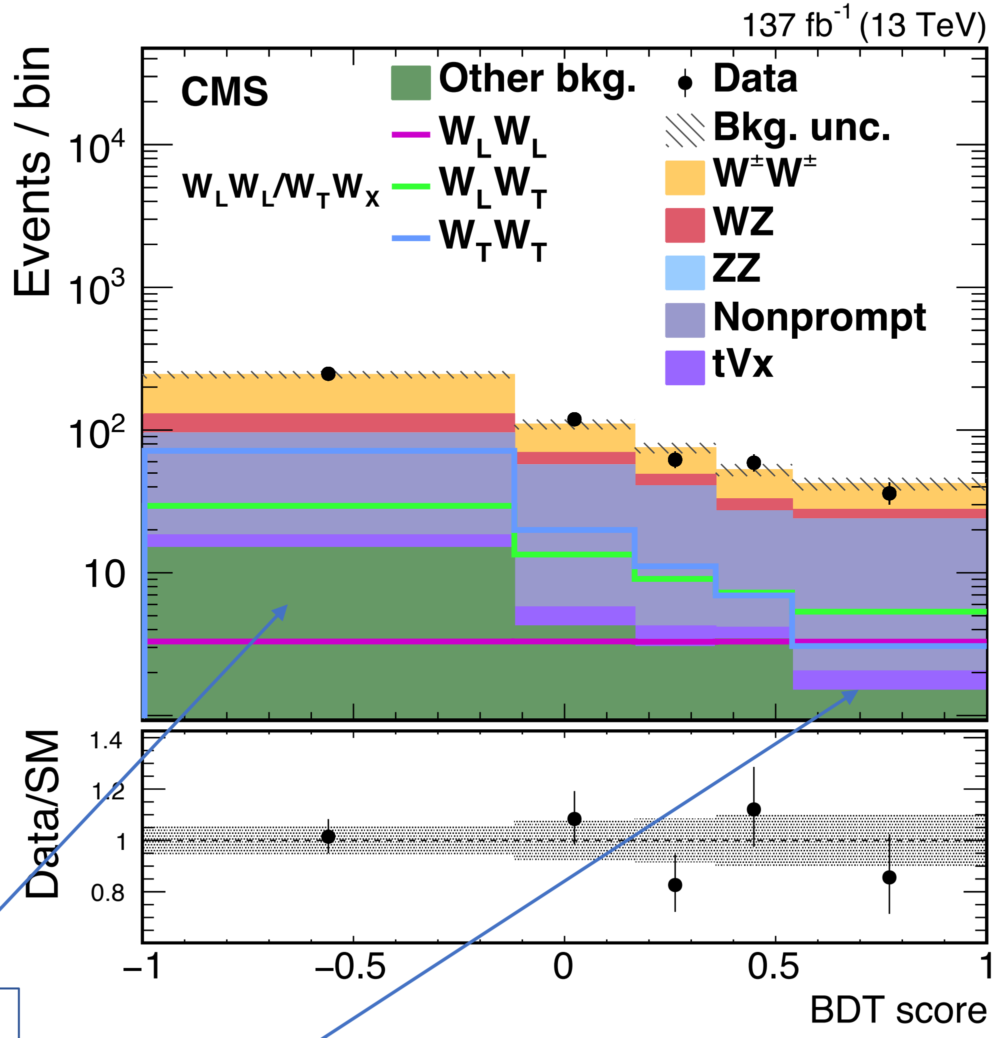
2. **Separate the polarization components**

   Two BDTs to separate the polarization components

   - $W^{\pm}_{L}W^{\pm}_{L}$ against all
   - $W^{\pm}_{T}W^{\pm}_{T}$ against all



$W^{\pm}_{T}W^{\pm}_{X}$ at low values

$W^{\pm}_{L}W^{\pm}_{L}$ at high values

VBS WW: Analysis strategy

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- **Multivariate techniques** are used to solve the most challenging part of this analysis:

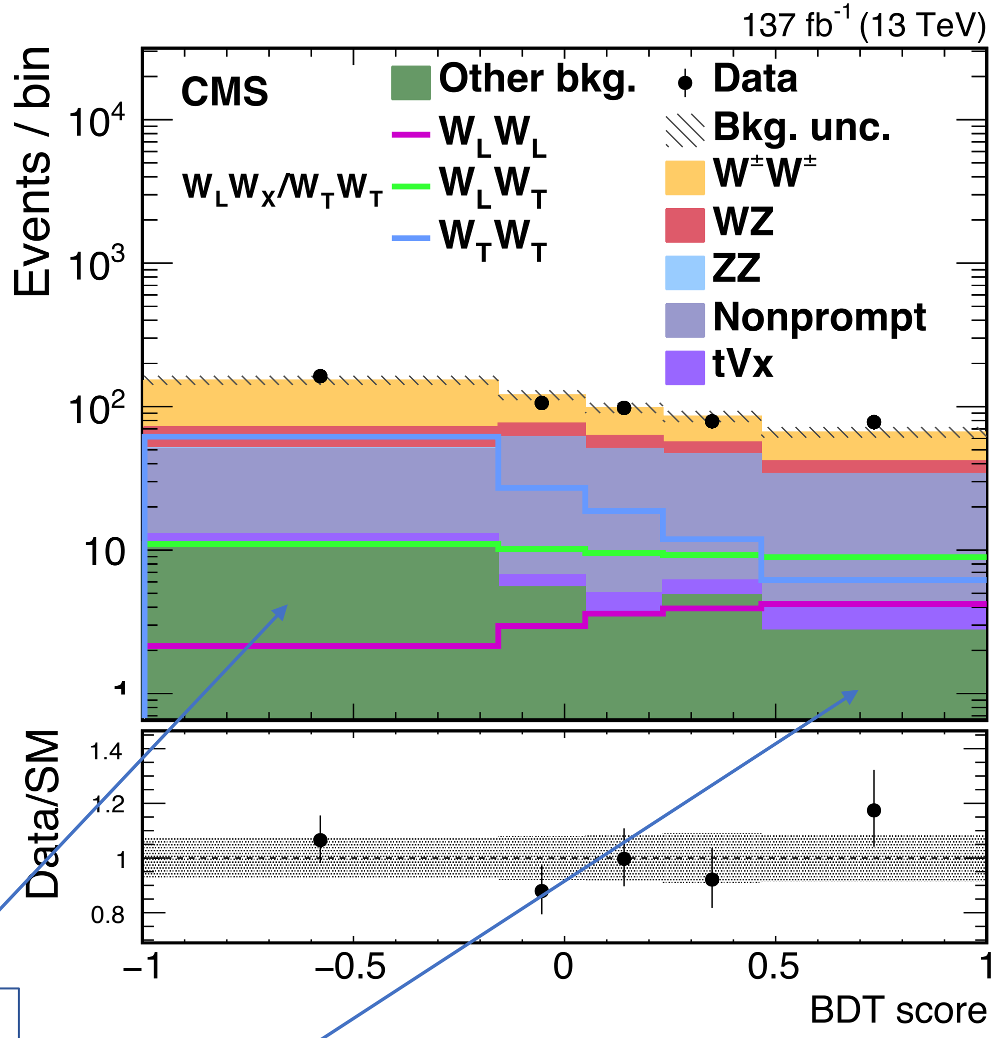
1. **Extract the signal** (VBS WW) over a large background

   "Inclusive BDT": Trained on WW as a signal vs Top quark simulated events that account for the Non-prompt background

2. **Separate the polarization components**

   Two BDTs to separate the polarization components

   - $W^\pm_L W^\pm_L$ against all
   - $W^\pm_T W^\pm_T$ against all



$W^\pm_L W^\pm_X$ at low values

$W^\pm_T W^\pm_T$ at high values

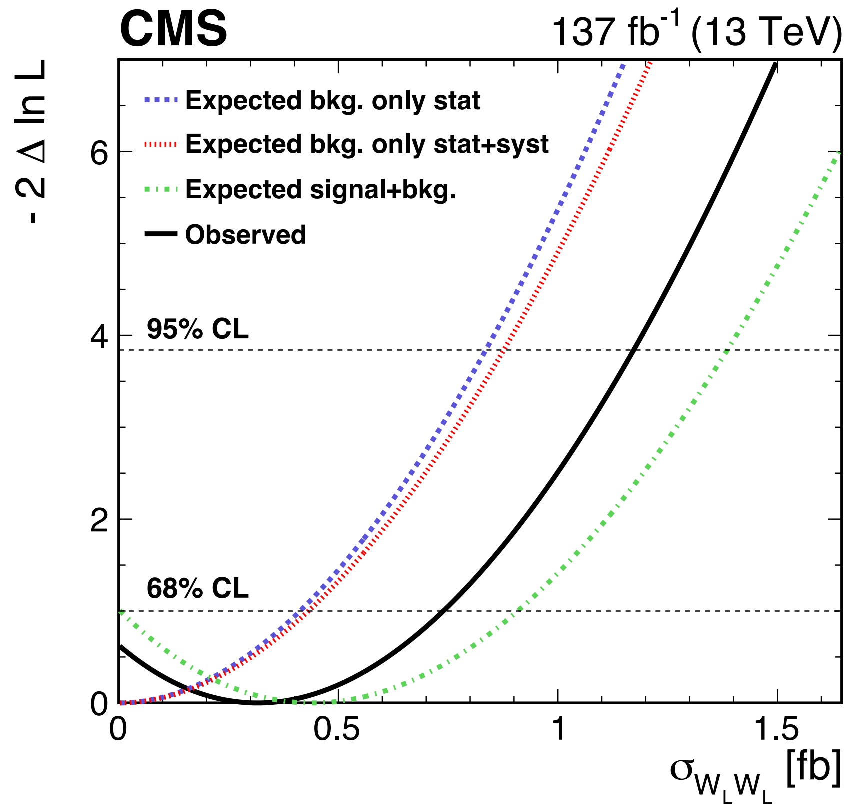
VBS WW: Analysis strategy

The “Inclusive” BDT and the polarization BDTs are combined to extract the double and individual polarization cross-section from a 2D binned likelihood fit

The cross-section for all the subprocesses is extracted simultaneously

- 2D histogram: $\mathbf{BDT_{Inclusive}}$ **vs** $\mathbf{BDT_{LL}}$ → **extract $W^{\pm}_{L}W^{\pm}_{L}$ and $W^{\pm}_{T}W^{\pm}_{X}$**
- 2D histogram: $\mathbf{BDT_{Inclusive}}$ **vs** $\mathbf{BDT_{TT}}$ → **extract $W^{\pm}_{T}W^{\pm}_{T}$ and $W^{\pm}_{L}W^{\pm}_{X}$**

Results provided for both **WW reference frame and Parton reference frame**

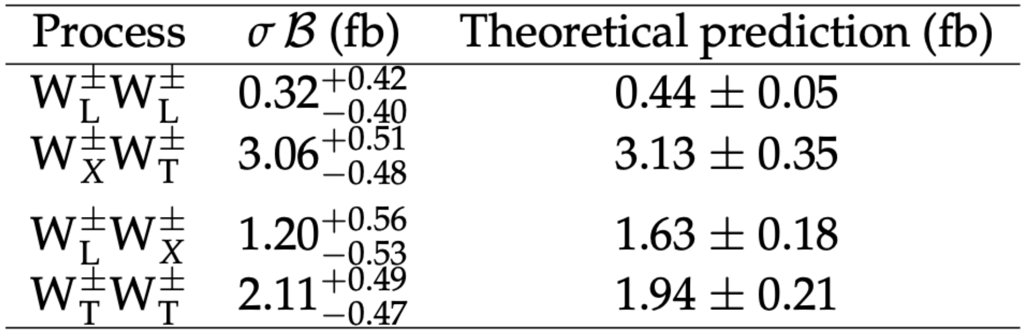


VBS WW: Results

The results are consistent with the SM expectation

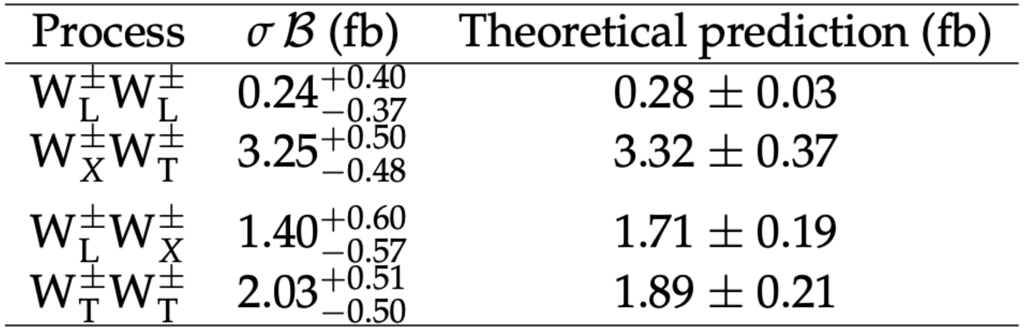
The significance for observing at least one **longitudinally** polarized W boson is computed to be $\mathbf{2.3\sigma}$ $(\mathbf{2.6\sigma})$ in the **WW (Parton)** frame

WW pair frame



Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.32^{+0.42}_{-0.40}$	0.44 ± 0.05
$W^\pm_X W^\pm_T$	$3.06^{+0.51}_{-0.48}$	3.13 ± 0.35
$W^\pm_L W^\pm_X$	$1.20^{+0.56}_{-0.53}$	1.63 ± 0.18
$W^\pm_T W^\pm_T$	$2.11^{+0.49}_{-0.47}$	1.94 ± 0.21

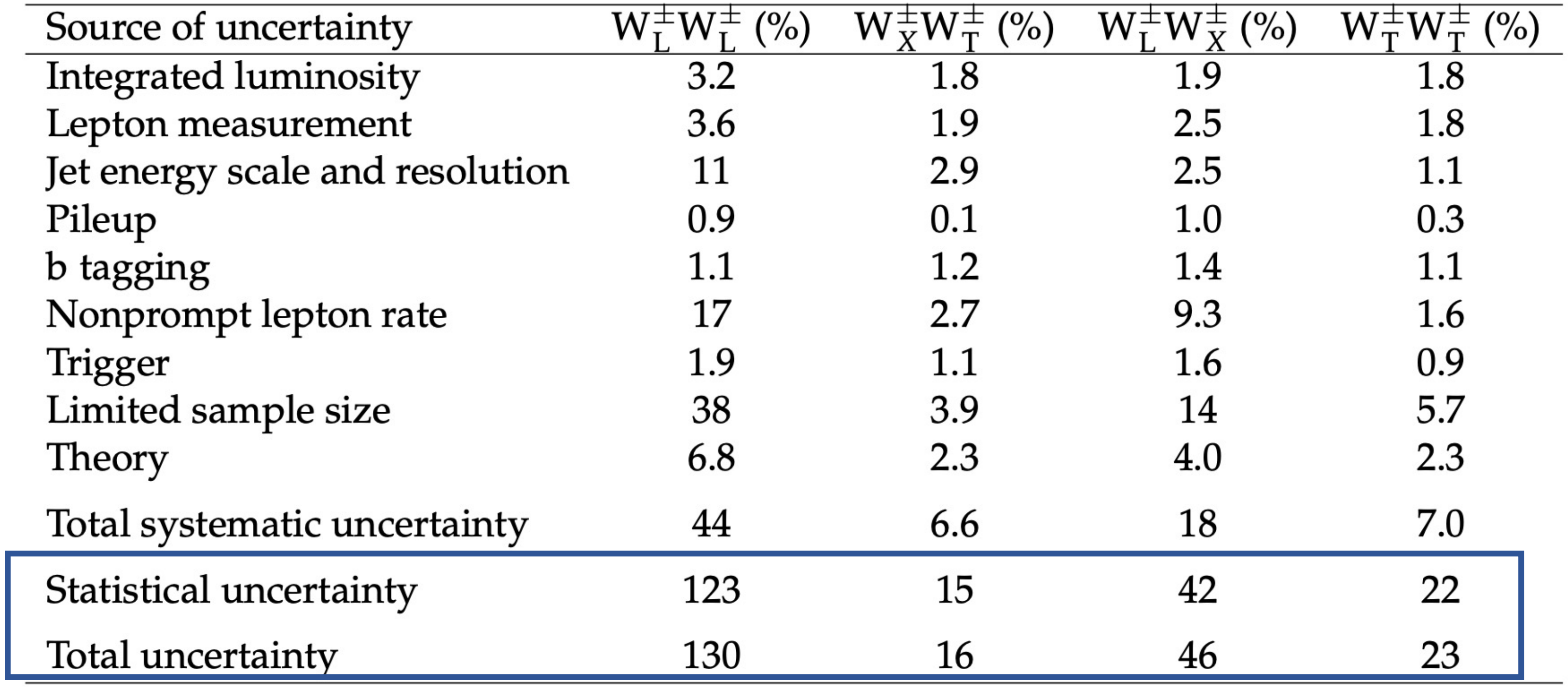
Parton frame



Process	$\sigma\mathcal{B}$ (fb)	Theoretical prediction (fb)
$W^\pm_L W^\pm_L$	$0.24^{+0.40}_{-0.37}$	0.28 ± 0.03
$W^\pm_X W^\pm_T$	$3.25^{+0.50}_{-0.48}$	3.32 ± 0.37
$W^\pm_L W^\pm_X$	$1.40^{+0.60}_{-0.57}$	1.71 ± 0.19
$W^\pm_T W^\pm_T$	$2.03^{+0.51}_{-0.50}$	1.89 ± 0.21

VBS WW: Uncertainty breakdown

- Similar uncertainty break for the two reference frames
- As expected, **the analysis is completely dominated by the statistical uncertainty**
- There is room for improvement with a future Run 3 datasets



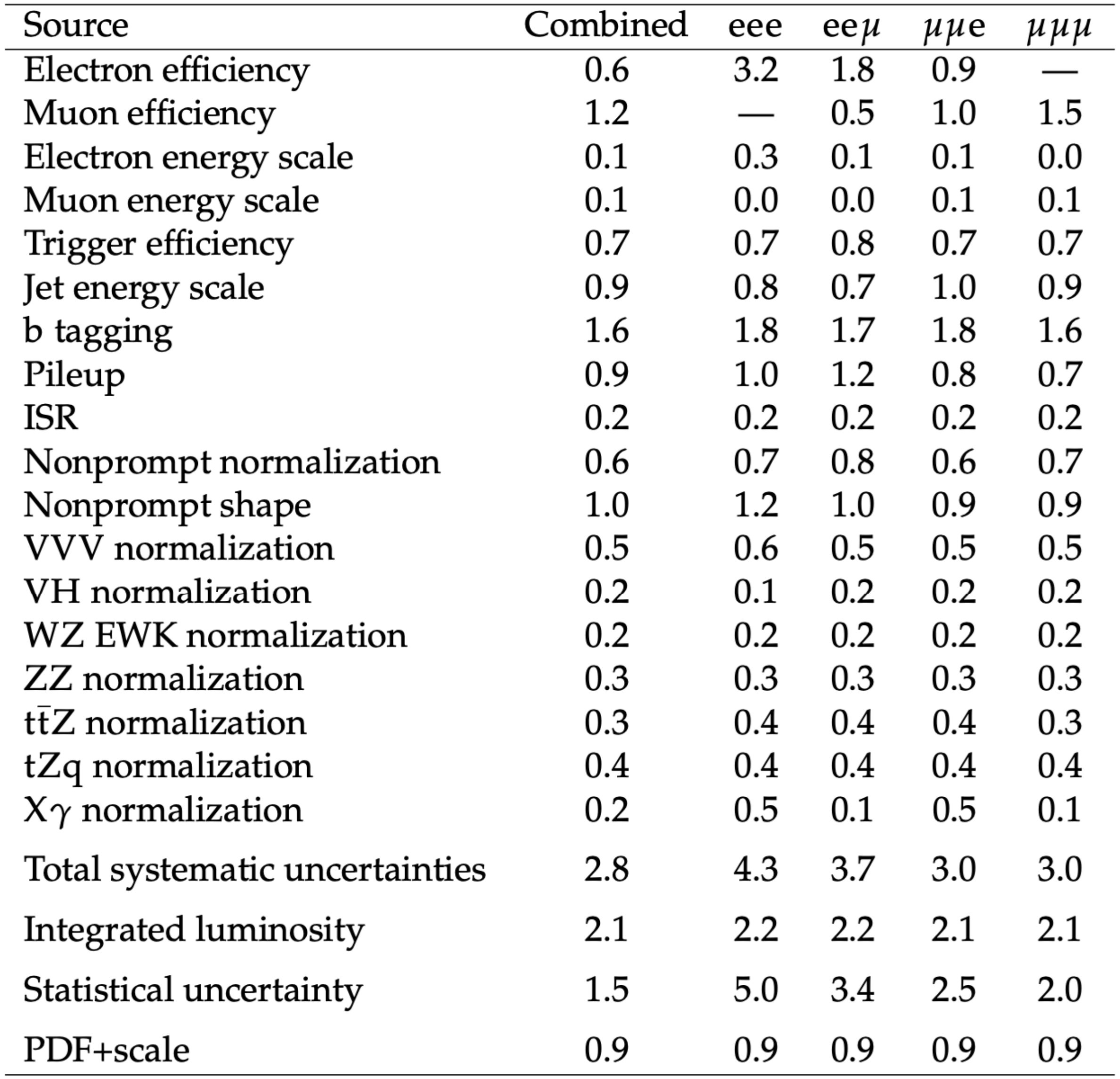
Source of uncertainty	$W^{\pm}_{L}W^{\pm}_{L}$ (%)	$W^{\pm}_{X}W^{\pm}_{T}$ (%)	$W^{\pm}_{L}W^{\pm}_{X}$ (%)	$W^{\pm}_{T}W^{\pm}_{T}$ (%)
Integrated luminosity	3.2	1.8	1.9	1.8
Lepton measurement	3.6	1.9	2.5	1.8
Jet energy scale and resolution	11	2.9	2.5	1.1
Pileup	0.9	0.1	1.0	0.3
b tagging	1.1	1.2	1.4	1.1
Nonprompt lepton rate	17	2.7	9.3	1.6
Trigger	1.9	1.1	1.6	0.9
Limited sample size	38	3.9	14	5.7
Theory	6.8	2.3	4.0	2.3
Total systematic uncertainty	44	6.6	18	7.0
Statistical uncertainty	123	15	42	22
Total uncertainty	130	16	46	23

Summary

- In the last years, **only a few measurements** have been delivered by CMS on vector boson polarization
- Lot of work published by the theory community on polarization recently
- I believe this can enhance the experimental measurements since a reliable theoretical prediction is the first stone for an experimental measurement
- **Machine learning may be a key in future measurements**
- **Stay tuned for new Run 2 and Run 3 results!**

BACKUP

WZ: Uncertainty breakdown



Source	Combined	eee	eeμ	$\mu\mu$e	$\mu\mu\mu$
Electron efficiency	0.6	3.2	1.8	0.9	—
Muon efficiency	1.2	—	0.5	1.0	1.5
Electron energy scale	0.1	0.3	0.1	0.1	0.0
Muon energy scale	0.1	0.0	0.0	0.1	0.1
Trigger efficiency	0.7	0.7	0.8	0.7	0.7
Jet energy scale	0.9	0.8	0.7	1.0	0.9
b tagging	1.6	1.8	1.7	1.8	1.6
Pileup	0.9	1.0	1.2	0.8	0.7
ISR	0.2	0.2	0.2	0.2	0.2
Nonprompt normalization	0.6	0.7	0.8	0.6	0.7
Nonprompt shape	1.0	1.2	1.0	0.9	0.9
VVV normalization	0.5	0.6	0.5	0.5	0.5
VH normalization	0.2	0.1	0.2	0.2	0.2
WZ EWK normalization	0.2	0.2	0.2	0.2	0.2
ZZ normalization	0.3	0.3	0.3	0.3	0.3
$t\bar{t}$Z normalization	0.3	0.4	0.4	0.4	0.3
tZq normalization	0.4	0.4	0.4	0.4	0.4
Xγ normalization	0.2	0.5	0.1	0.5	0.1
Total systematic uncertainties	2.8	4.3	3.7	3.0	3.0
Integrated luminosity	2.1	2.2	2.2	2.1	2.1
Statistical uncertainty	1.5	5.0	3.4	2.5	2.0
PDF+scale	0.9	0.9	0.9	0.9	0.9

VBS WW: Analysis strategy

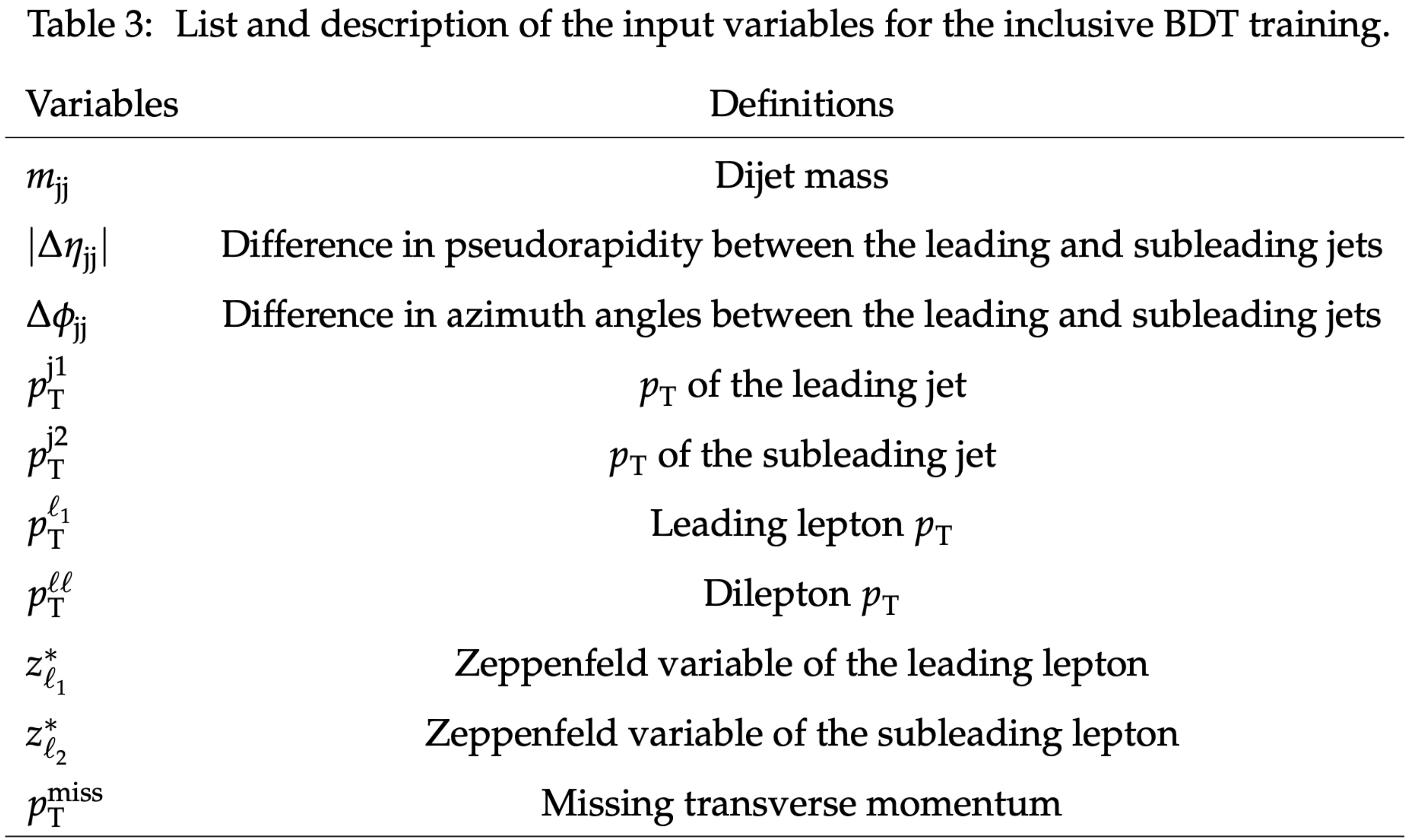


Table 3: List and description of the input variables for the inclusive BDT training.

Variables	Definitions
m_{jj}	Dijet mass
$\lvert\Delta\eta_{\mathrm{jj}}\rvert$	Difference in pseudorapidity between the leading and subleading jets
$\Delta\phi_{\mathrm{jj}}$	Difference in azimuth angles between the leading and subleading jets
$p_{\mathrm{T}}^{\mathrm{j1}}$	p_{T} of the leading jet
$p_{\mathrm{T}}^{\mathrm{j2}}$	p_{T} of the subleading jet
$p_{\mathrm{T}}^{\ell_1}$	Leading lepton p_{T}
$p_{\mathrm{T}}^{\ell\ell}$	Dilepton p_{T}
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
$p_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum