Measurements of gauge boson polarization in diboson production

Multi-Boson Interactions 2021

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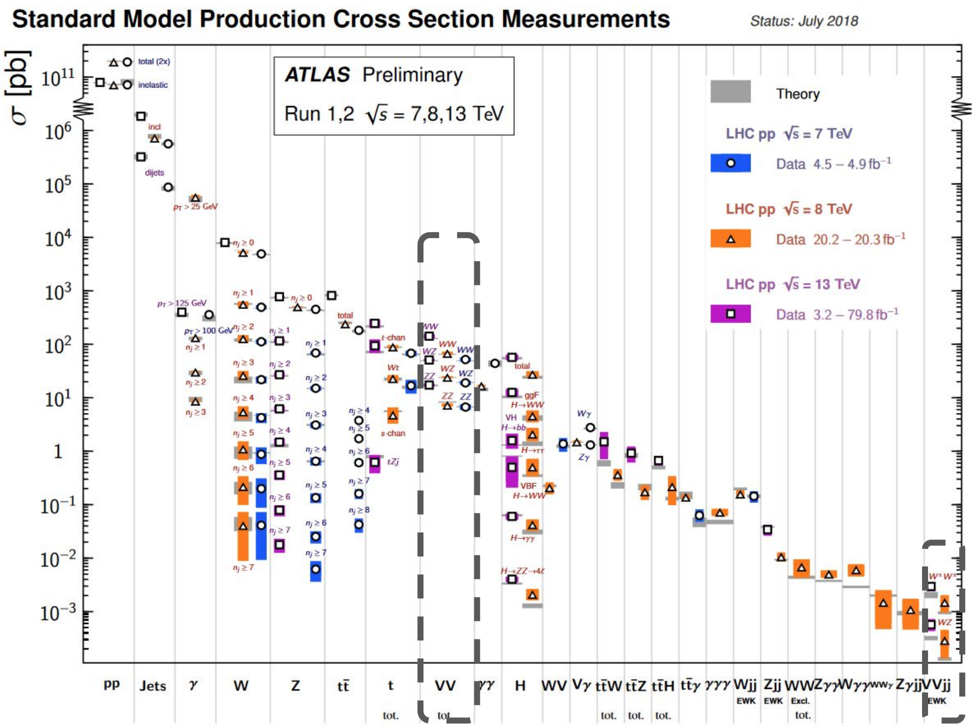
Motivation & Introduction

⇢ Gauge boson polarization is strongly related to the structure of the electroweak sector.

⇢ An important test in diboson production, as the Higgs introduces significant corrections in longitudinal VV scattering.

⇢ Measurements were strongly limited by available statistics, due to the low cross-sections of VV (/EWK VV) production. With the Run II of the LHC we start to reach sensibility to these quantities.



⇢This talk focuses on three available results in boson polarization in diboson production:

- Eur. Phys. J. C 79 (2019) 535 WZ production (ATLAS, 2015+2016 data)
- CMS-PAS-SMP-20-014 WZ production (CMS, Run II data)

Comparable up to a degree (*), as ATLAS result was earlier and with less data.

- Phys. Lett. B 812 (2020) 136018 Same-Sign EWK WW production (CMS, Run II data)

WZ production

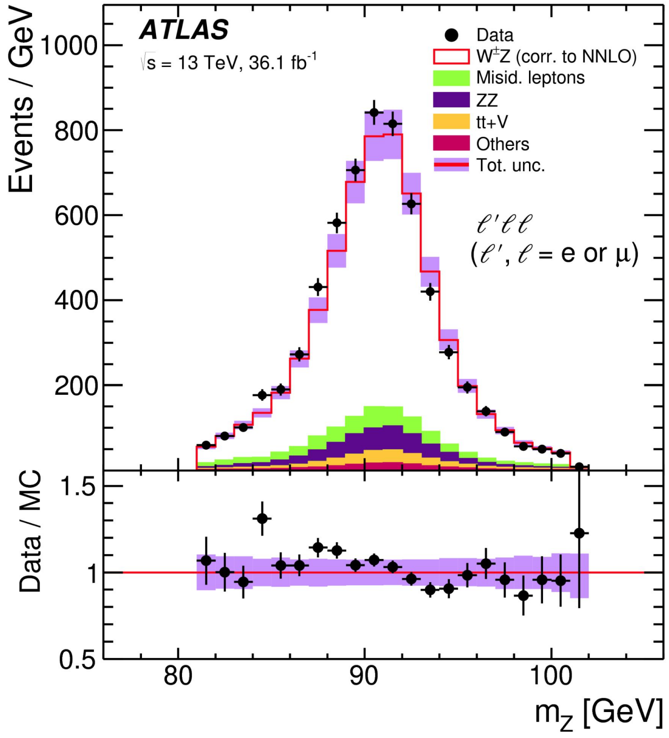
[Eur. Phys. J. C 79 (2019) 535]

WZ (ATLAS) - Event selection

⇢ The ATLAS measurement is based on a multileptonic selection. Also related to the needs of other WZ cross section measurements performed in the same analysis.

- ⇢ 3 light leptons with an opposite-sign same flavour pair
- ⇢ OSSF pair with closest mass to m_Z are "Z leptons".
- ⇢ Remaining lepton is "W lepton".

$p_{T,l1} > 27$ GeV	Based on trigger requisites
$p_{T,W} > 20$ GeV	Reduce non prompt bkg.
$m_T^W > 30$ GeV, $\lvert M_{Z1,Z2} - m_Z \rvert < 10$ GeV	On shell Z, and an energetic neutrino from W

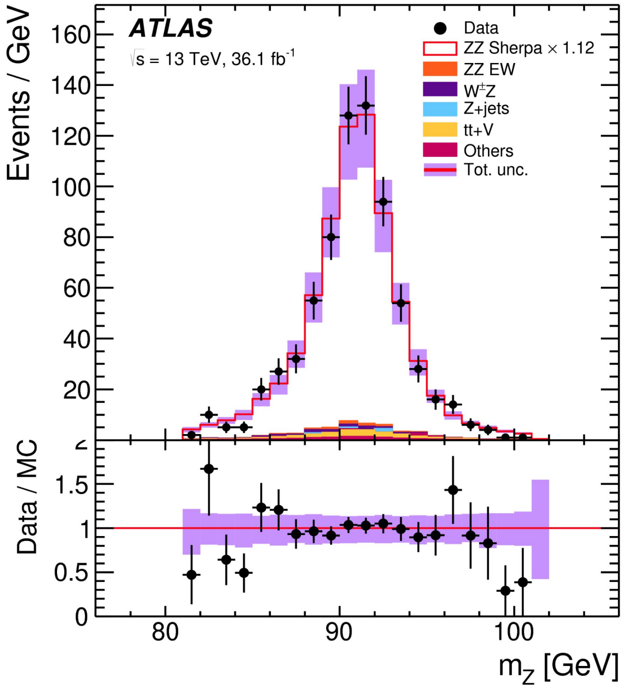


The selection results in a pure SR

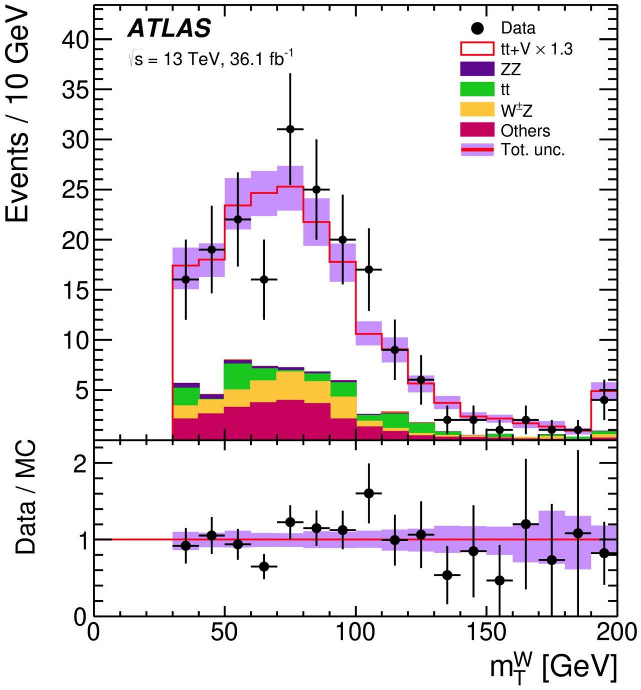
WZ (ATLAS) - Background estimation

Eur. Phys. J. C 79 (2019) 535

- Non-prompt background process is estimated using data-driven (matrix element) techniques.
- Control regions are defined to study ZZ and ttV production and derive normalization scale factors.



Four lepton control region targeting ZZ production



Control region targeting ttV production by requiring two b tagged jets

WZ (ATLAS) - Polarization modelling I

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⇢ Measurements of the polarization are performed in the "modified" helicity frame with the WZ system at rest.

⇢ The key observable is the "polarization angle" θ_V.

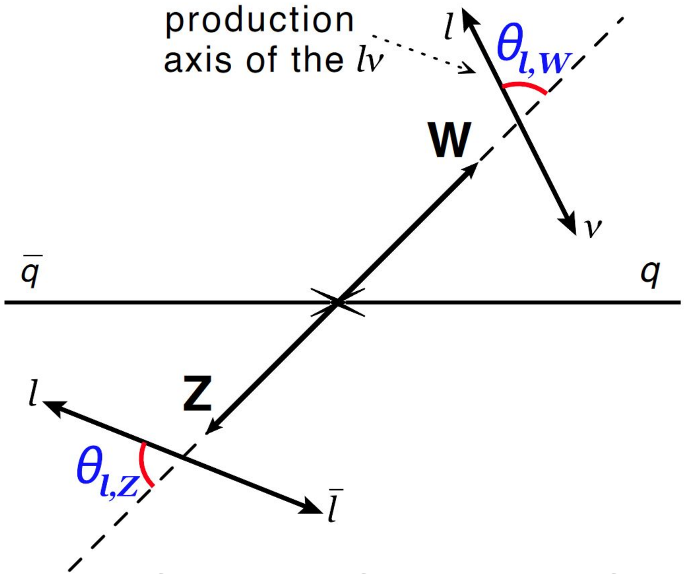
⇢ At LO in EWK, a quadratic dependance of the differential cross-section with respect to $\cos(\theta_V)$ is expected:

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

$$\frac{d\sigma}{\sigma d\cos\theta^{Z}} = \frac{3}{8}\left[(1 + \cos^2(\theta^{Z}) + 2c\cos(\theta^{Z})) f_L^Z + (1 + \cos^2(\theta^{Z}) - 2c\cos(\theta^{Z})) f_R^Z + 2\sin^2(\theta^{Z}) f_0^Z\right]$$

⇢ f_0 (longitudinal), and f_L, and f_R (transversal) polarization fractions are the measurable quantities. By construction they add up to 1.

⇢ The polarization fractions are frame-dependant quantities, and so **the frame needs to be fixed**.



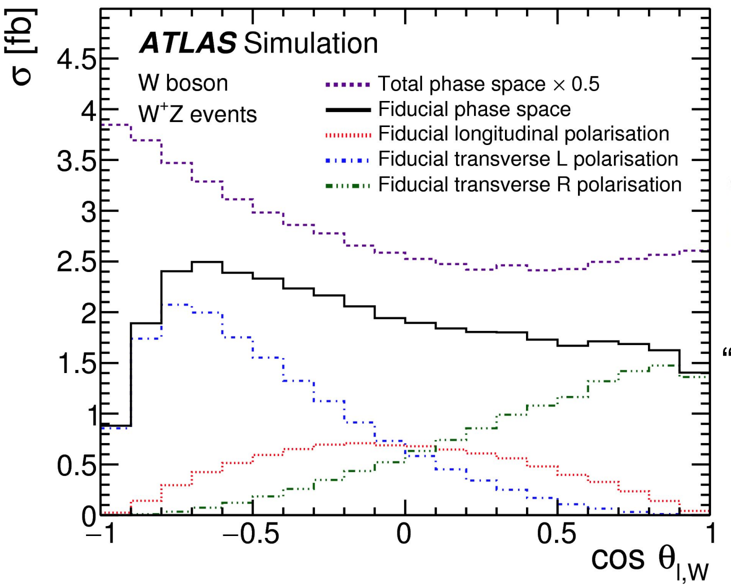
Modified helicity frame: the lab frame is boosted to the WZ frame
-Then rotated such that the W (Z) boson goes along the Z axis
-Then boosted such that the W (Z) is at rest
- θ is then the angle between the lepton and the Z axis.

WZ (ATLAS) - Polarization modelling II

[Eur. Phys. J. C 79 (2019) 535]

⇢ The quadratic relation can't be used directly at the reconstructed level, as fiducial lepton p_T and η requirements tend to be more inefficient at high $|\cos(\theta_V)|$.

⇢ Instead, polarized samples are built for W_LZ, W_RZ, W_0Z, WZ_L, WZ_R, and WZ_0 production.



⇢ Weights are based on the $\cos(\theta_V)$ variable computed at the generator level. I.e., for left-handed W bosons:

$$\frac{\frac{3}{8}(1 \mp \cos\theta_{\ell,W})^2}{\frac{3}{8} f_L^{\text{gen.}}(1 \mp \cos\theta_{\ell,W})^2 + \frac{3}{8} f_R^{\text{gen.}}(1 \pm \cos\theta_{\ell,W})^2 + \frac{3}{4} f_0^{\text{gen.}} \sin^2\theta_{\ell,W}}$$

"Expected" (SM) polarization fractions

Gen-level polarization angle

⇢ The reweighting is performed for all events in a POWHEG+Pythia8 sample to build "polarized" samples.

⇢ Reweighting is done in bins of boson p_T and Y.

WZ (ATLAS) - Fitting strategy

Eur. Phys. J. C 79 (2019) 535

⇢ The $\cos(\theta_V)$ distributions are built at the reconstructed level using the tagged final state leptons to reconstruct the W/Z bosons. These distributions are fitted to extract the pol. fractions.

⇢ p_T^{miss} is used as a proxy of the neutrino's four-momentum. And a W mass constraint is applied to reconstruct the W.

⇢ Three independent parameters are included into the fits:

⇢ Overall WZ normalization.

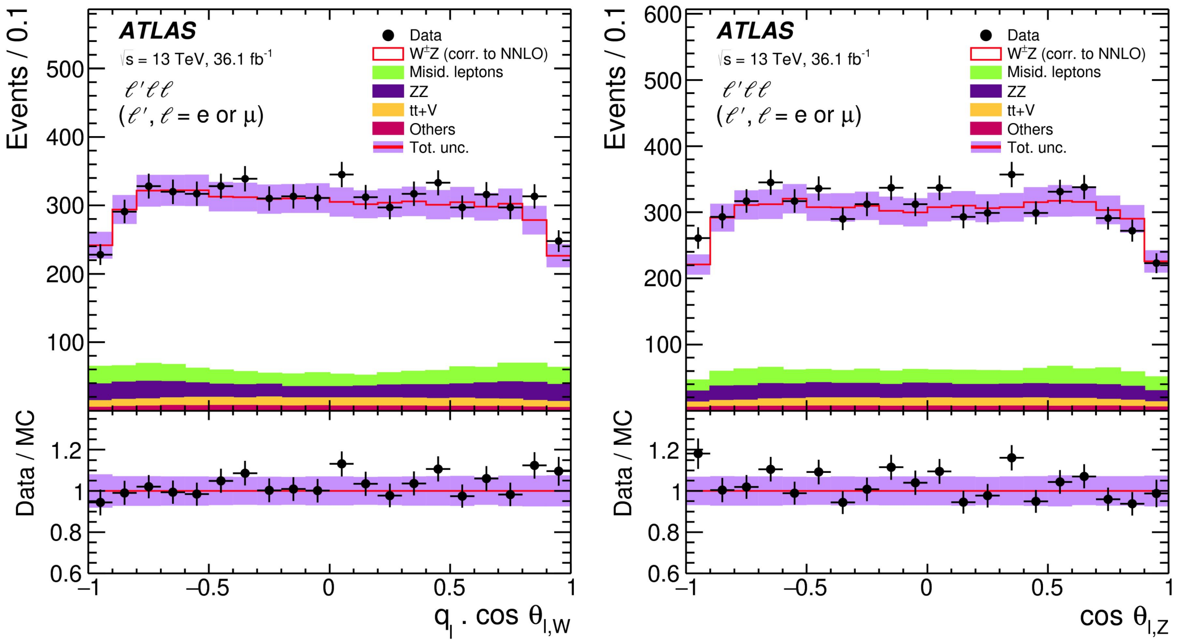
⇢ Longitudinal fraction ($\mathbf{f_0}$).

⇢ Difference in transversal fractions ($\mathbf{f_L - f_R}$).

As f_0, f_L, f_R are bounded by

$$f_0 + f_L + f_R = 1$$

They can't all float simultaneously



WZ (ATLAS) - Results I

Eur. Phys. J. C 79 (2019) 535

⇢ Results are obtained for the polarization fractions for both vector bosons in each of the charged final states separately ($W^{\pm}Z$, $W^{+}Z$, and $W^{-}Z$).

	f_0			$f_L - f_R$		
	Data	POWHEG+PYTHIA	MATRIX	Data	POWHEG+PYTHIA	MATRIX
W^+ in W^+Z	0.26 ± 0.08	0.233 ± 0.004	0.2448 ± 0.0010	-0.02 ± 0.04	0.091 ± 0.004	0.0868 ± 0.0014
W^- in W^-Z	0.32 ± 0.09	0.245 ± 0.005	0.2651 ± 0.0015	-0.05 ± 0.05	-0.063 ± 0.006	-0.034 ± 0.004
$W^\pm$ in $W^\pm Z$	0.26 ± 0.06	0.2376 ± 0.0031	0.2506 ± 0.0006	-0.024 ± 0.033	0.0289 ± 0.0022	0.0375 ± 0.0011
Z in W^+Z	0.27 ± 0.05	0.225 ± 0.004	0.2401 ± 0.0014	-0.32 ± 0.21	-0.297 ± 0.021	-0.262 ± 0.009
Z in W^-Z	0.21 ± 0.06	0.235 ± 0.005	0.2389 ± 0.0015	-0.46 ± 0.25	0.052 ± 0.023	0.0468 ± 0.0034
Z in $W^\pm Z$	0.24 ± 0.04	0.2294 ± 0.0033	0.2398 ± 0.0014	-0.39 ± 0.16	-0.156 ± 0.016	-0.135 ± 0.006

⇢ An observed **significance** for the presence of **longitudinally polarized W bosons of 4.2σ** is obtained (3.8σ expected). First **evidence** of them in diboson production. **Observation of longitudinally polarized Z bosons** at a 6.5σ significance (6.1σ expected).

⇢ POWHEG predictions include QCD+scale uncertainties. MATRIX ones only scale effects.

⇢ Overall agreement between measurements and predictions, but with some differences up to 2σ for f_L - f_R measurements. Still, the precision for these parameters is relatively low.

WZ (ATLAS) - Results II

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⇢ The precision of the measurements is very **strongly dominated by statistical uncertainties**, as shape differences in $\cos(\theta_V)$ already provide great separation between polarized final states.

	$W^{\pm}$ in $W^{\pm}Z$		Z in $W^{\pm}Z$	
	f_0	$f_L - f_R$	f_0	$f_L - f_R$
e energy scale and id. efficiency	0.0024	0.0004	0.005	0.0021
μ momentum scale and id. efficiency	0.0013	0.0027	0.0018	0.008
E_T^{miss} and jets	0.0024	0.0010	0.0017	0.005
Pile-up	0.005	0.00009	0.0014	0.005
Misid. lepton background	0.031	< 0.001	0.007	0.019
ZZ background	0.009	0.0004	0.0007	0.0012
Other backgrounds	0.0012	0.0005	0.0018	0.005
QCD scale	0.0008	0.0013	0.0004	0.008
PDF	0.0011	0.0009	0.00004	< 0.00001
Modelling	0.004	0.007	0.0015	0.0028
Total systematic uncertainty	0.033	0.008	0.009	0.024
Luminosity	0.0015	< 0.0001	< 0.0001	0.0008
Statistics	0.06	0.032	0.04	0.15
Total	0.06	0.033	0.04	0.16

WZ (ATLAS) - Results III

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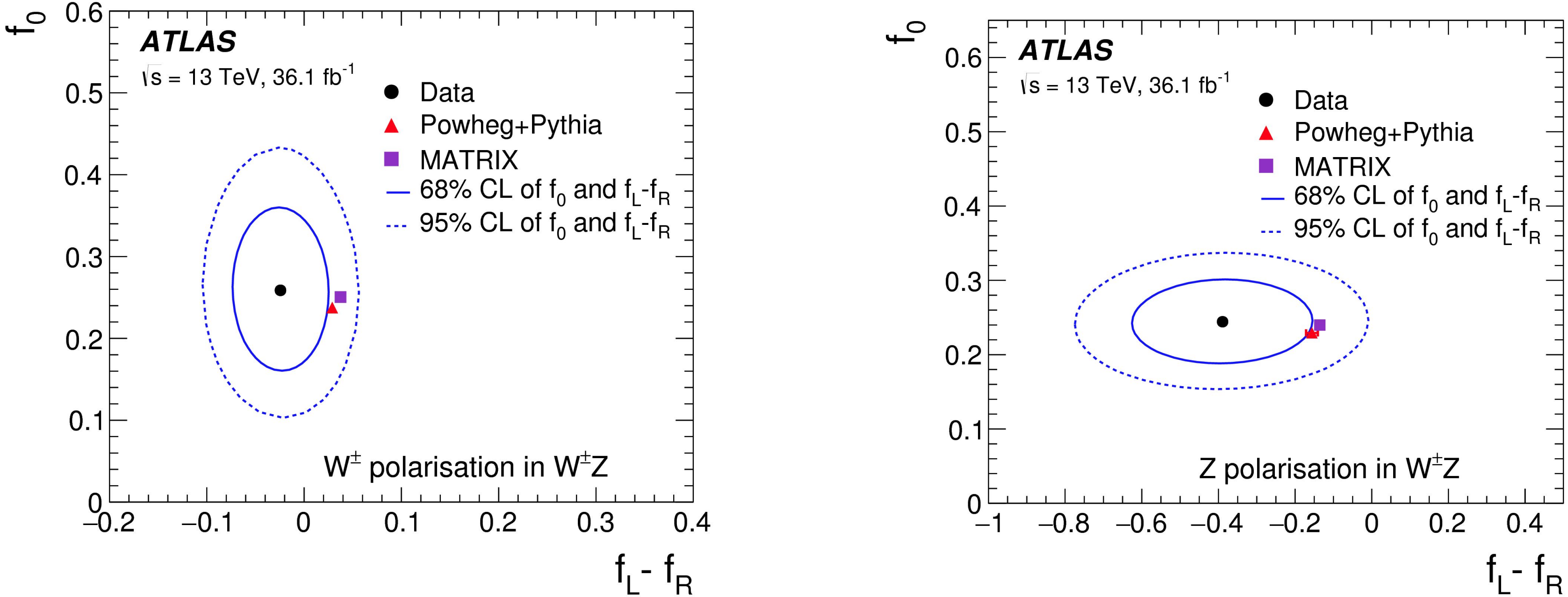
⇢ Additional results are provided as 2D scans in the polarization fraction parameters, in all cases the overall WZ normalization (μ) is free-floating. Shown for the charge-inclusive case.

⇢ Good consistency is found between the SM (POWHEG+Pythia, MATRIX) predictions and the experimental measurements of the polarization fractions, at the ~1σ level.



WZ (CMS) - Event selection

CMS-PAS-SMP-20-014

⇢ The CMS measurement is also based on a multileptonic selection. Related to the needs of the inclusive cross-section measurement (see Andrew's talk):

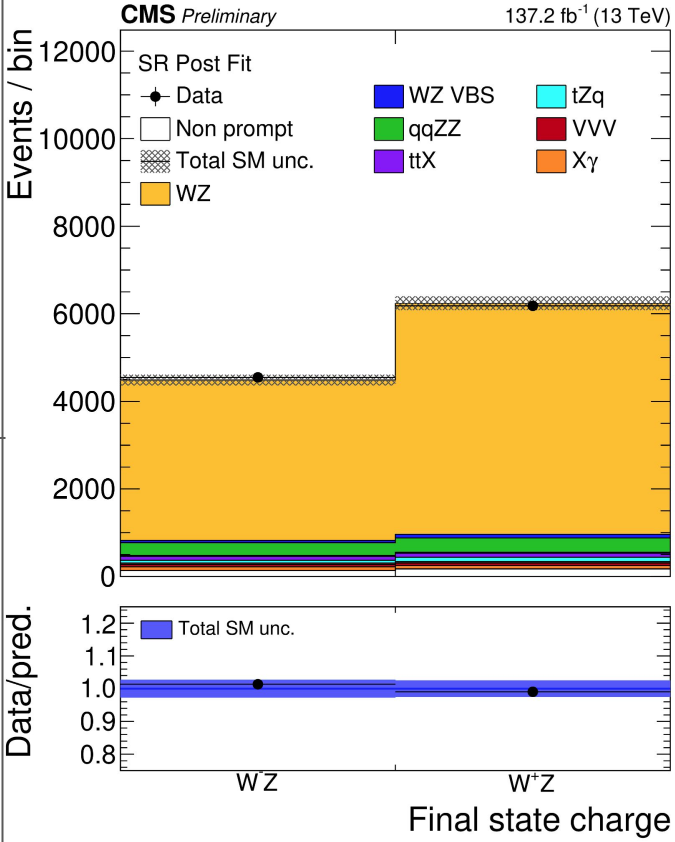
- ⇢ 3 light leptons with an opposite-sign same flavour pair
- ⇢ OSSF pair with closest mass to m_Z are "Z leptons".
- ⇢ Remaining lepton is "W lepton".

$p_{T,Z1} > 25$ GeV , $p_{T,Z2} > 10$ GeV , $p_{T,W} > 25$ GeV | Based on trigger requisites

$p_T^{miss} > 30$ GeV, $|M_{Z1,Z2} - m_Z| < 15$ GeV | On shell Z, and an energetic neutrino from W

$M_{lll} > 100$ GeV | Anti-Zγ requirement to avoid Z->3l events

$N_{b\ tag} = 0$ | Anti-top requirement to reduce the ttX backgrounds

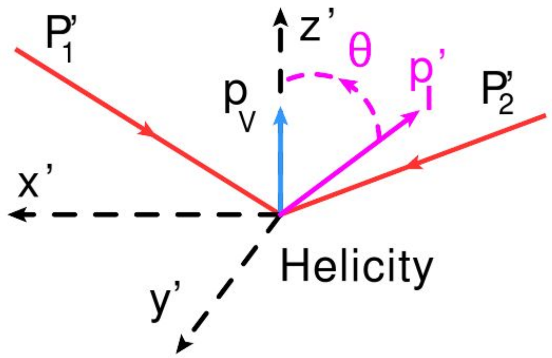


The selection results in a pure SR

WZ (CMS) - Polarization modelling I

CMS-PAS-SMP-20-014

⇢ The helicity frame defined in **the centre-of mass of the measured gauge boson (W or Z)** is used to perform the measurements of the gauge boson polarization fractions. Slightly different from the one used by ATLAS' measurement.



Helicity frame:
-The frame is rotated such that the W (Z) boson goes along the Z axis
-Then boosted such that the W (Z) is at rest
- θ is then the angle between the lepton and the Z axis.

⇢ Effectively "two different frames" for the W and Z polarization studies, which are two independent sets of measurements.

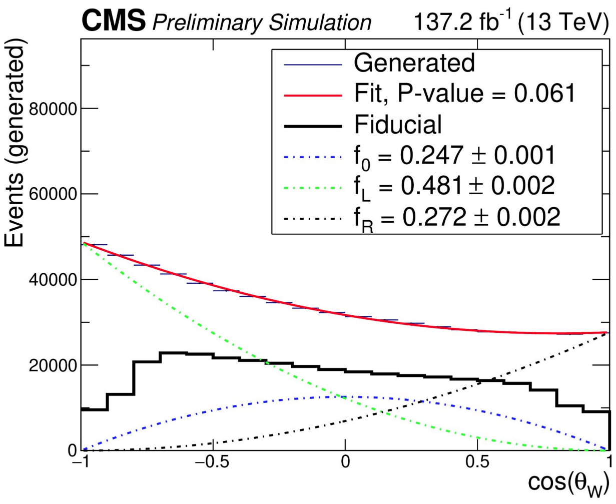
⇢ Only singly-polarized final states are studied:

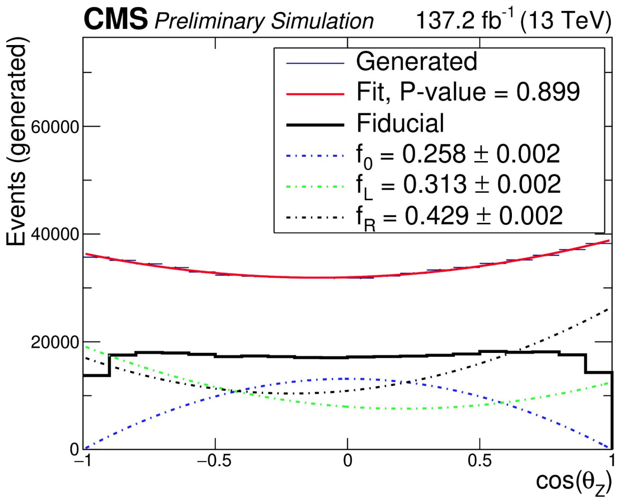
- ⇢ In the "W polarization" W_LZ, W_RZ, W_0Z, final states with inclusive Z polarization are considered.
- ⇢ In the "Z polarization" WZ_L, WZ_R, WZ_0, final states with inclusive W polarization are tested.

WZ (CMS) - Polarization modelling II

CMS-PAS-SMP-20-014

⇢ The procedure is very similar to the one introduced by ATLAS, based on the **reweighting of a POWHEG+Pythia sample** based on the generator-level $\cos(\theta_V)$ distributions to obtain “pure” polarized samples (W_LZ, W_RZ, W_0Z, WZ_L, WZ_R, WZ_0).





Two independent reweightings applied: for W and Z polarization

⇢ Fits are performed for an **inclusive selection of events** (requiring $60 < m_Z < 120$ GeV).

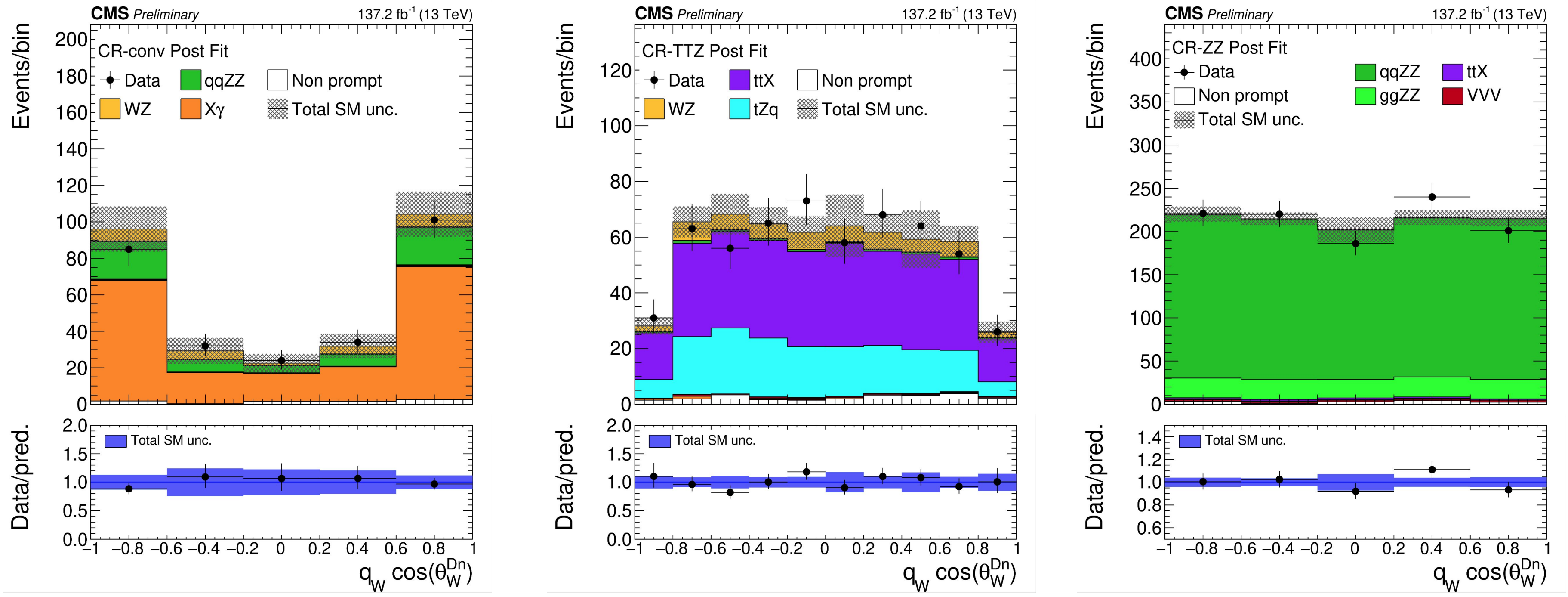
⇢ As before, **fiducial requirements “break” the quadratic dependance,** significant losses at very high/very low $\cos(\theta_V)$.

WZ (CMS) - Background estimation

CMS-PAS-SMP-20-014

⇢ Several background CR are defined to study the behaviour of the main background processes.

⇢ "cos(θ_V)" is shown at the reconstructed level, with W and Z kinematics reconstructed from the final state leptons. For the W boson, p_T^{miss} is used as a proxy of the neutrino's p_T and a constraint to the W mass is applied.



Inverted p_T^{miss}, $M_{Z1,Z2}$, M_{lll} requirements

Inverted $N_{b\text{-tag}}$ requirements

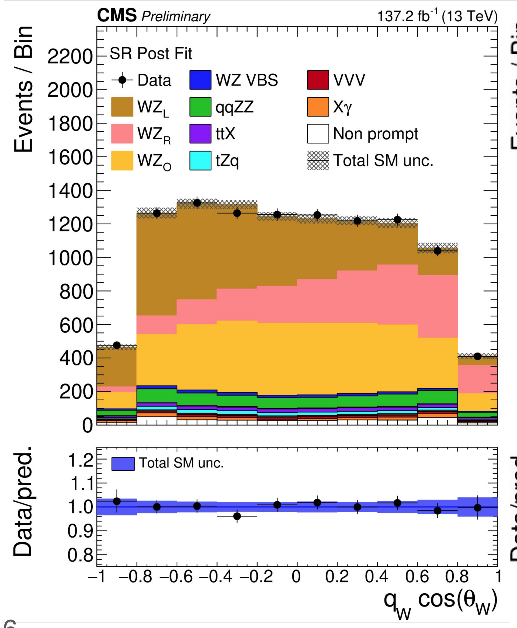
Requiring an additional lepton instead of p_T^{miss}

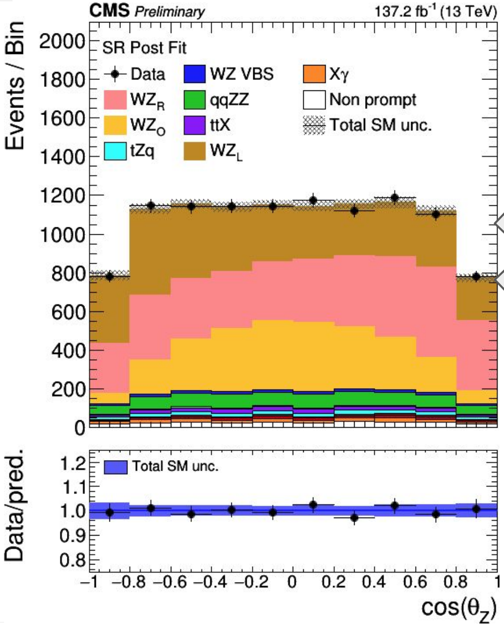
WZ (CMS) - Fitting strategy I

CMS-PAS-SMP-20-014

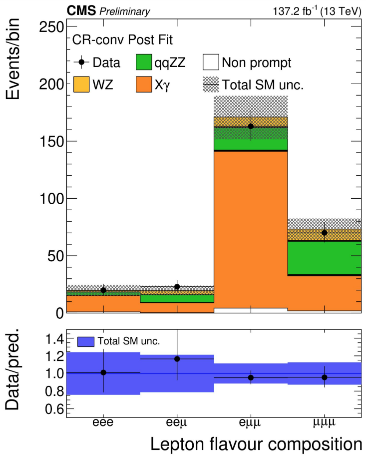
⇢ The $\cos(\theta_V)$ distributions at the reconstructed are fitted separately for W/Z production.

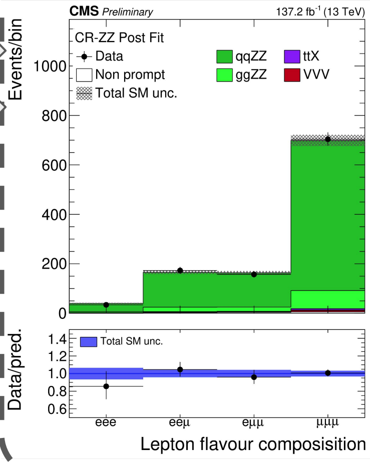
⇢ μ (overall WZ cross-section), f_0, and f_L-f_R are fitted simultaneously in all the measurements.

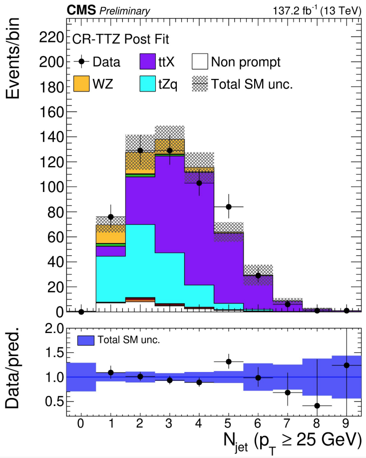




⇢ Background CR distributions are included into the fit (see the talk on the inclusive WZ cross section).





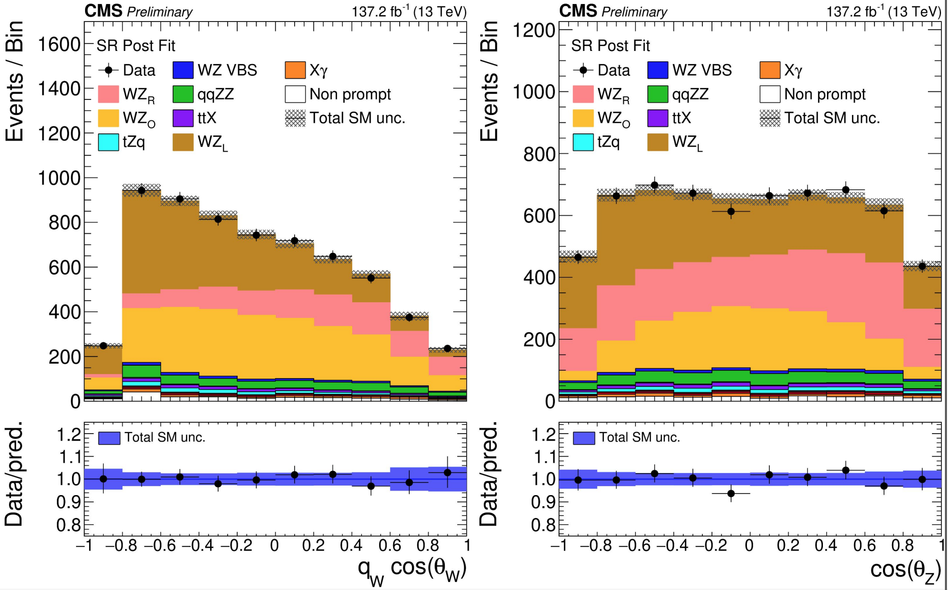


WZ (CMS) - Fitting strategy II

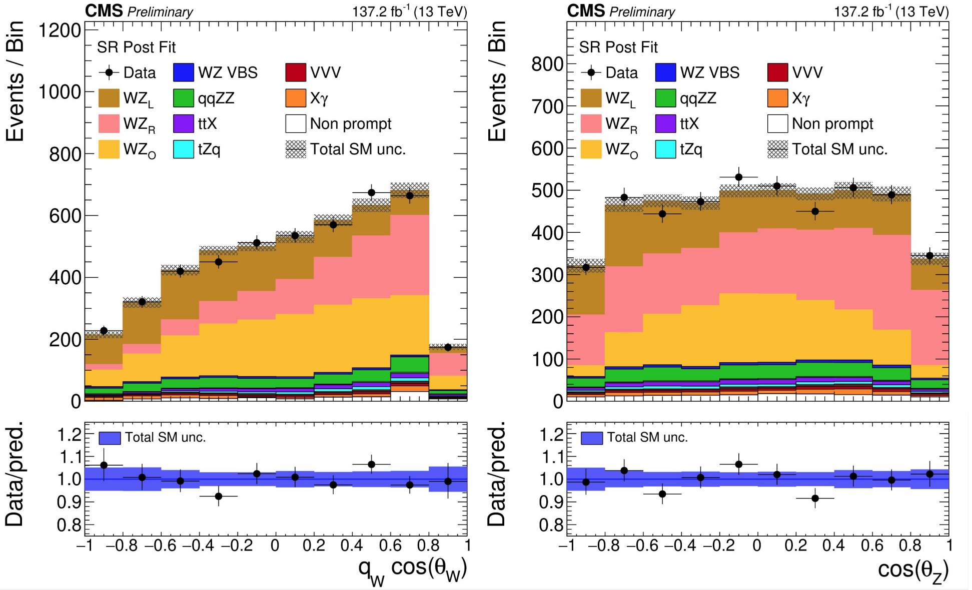
[CMS-PAS-SMP-20-014](CMS-PAS-SMP-20-014)

⇢ All results are provided in the charge-inclusive and both charged (W^+Z, and W^-Z) final states.

⇢ For W boson polarization, greater “mixing” of polarizations appear due to the reduced resolution on the W 4-momentum from p_T^{miss}, slightly reducing sensitivity.



W^+Z production



W^-Z production

WZ (CMS) - Results I

CMS-PAS-SMP-20-014

Boson and charge	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}	$-0.164^{+0.121}_{-0.121}$	$-0.179^{+0.003}_{-0.003}$	$-0.178^{+0.007}_{-0.007}$

⇢ Overall results consistent between observations and predictions.

⇢ POWHEG expectations show PDF uncertainties

⇢ MATRIX expectations include uncertainties related to precision on the fitting procedure.

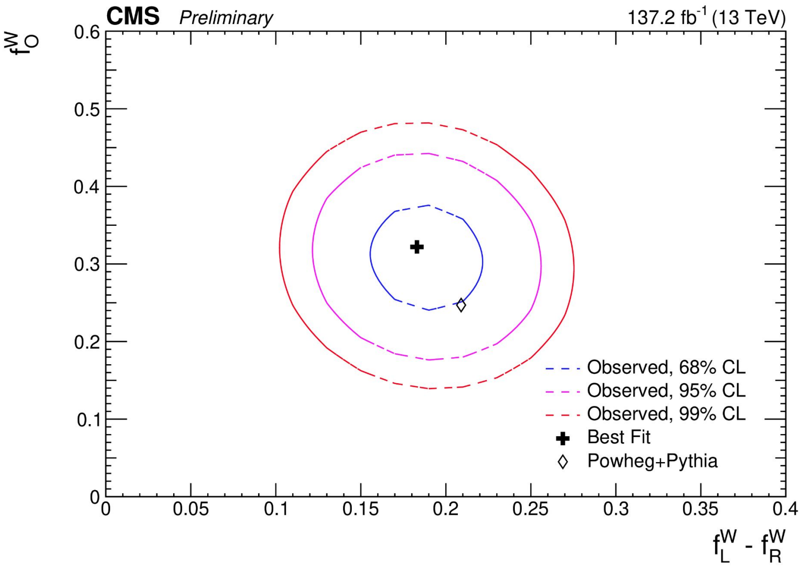
⇢ Observed **significance for the presence of longitudinally polarized W bosons of 5.6σ** (4.3σ expected). Way **over the observation mark (>8σ) for Z bosons**.

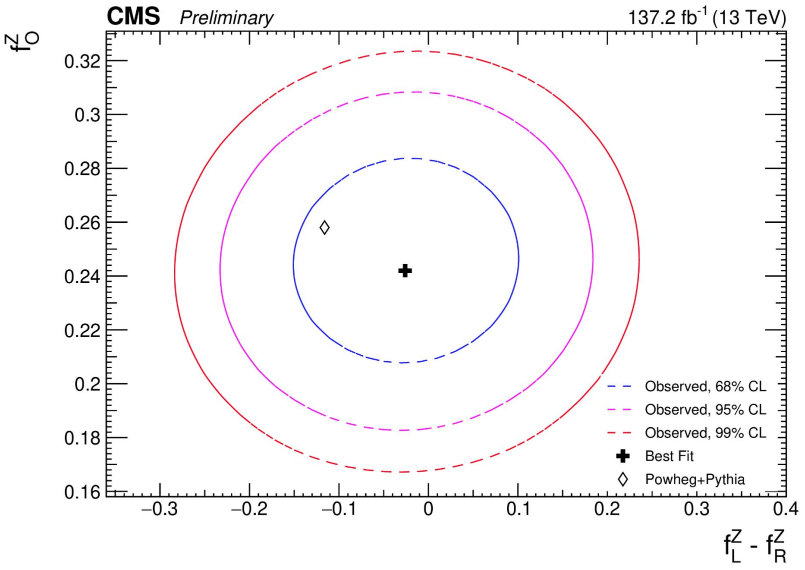
WZ (CMS) - Results II

⇢ Additional results are provided as 2D scans in the polarization fraction parameters, in all cases the overall WZ normalization (μ) is free-floating. Shown for the charge-inclusive case.

⇢ Good consistency is found between the SM (POWHEG+Pythia) predictions and the experimental measurements of the polarization fractions.

⇢ No strong correlation is found between the measured parameters on the fits.





VBS Same-Sign WW production

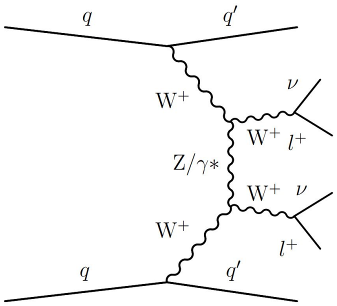
SS VBS WW (CMS) - Introduction

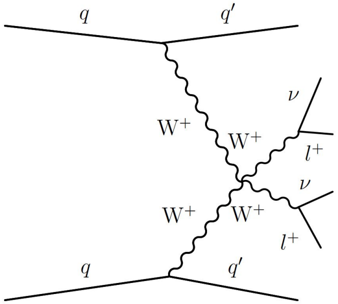
Phys. Lett. B 812 (2020) 136018

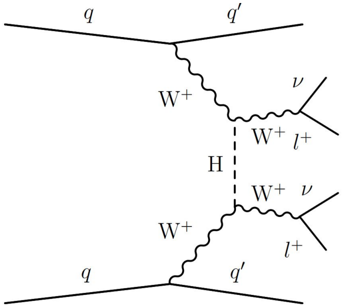
⇢ The only measurement of gauge boson polarization in VBS production, which can target diagrams with intermediate Higgs mediation instead of the quadruple gauge coupling.

⇢ The analysis uses all data from the Run II to target **doubly polarized final states**: W_LW_L, W_TW_T, W_LW_T. Cancellations expected for the L-L scattering contributions due to the Higgs presence can be thoroughly tested.

⇢ Measurements are also provided for W_LW_X and W_TW_X production (any polarization for the second boson).



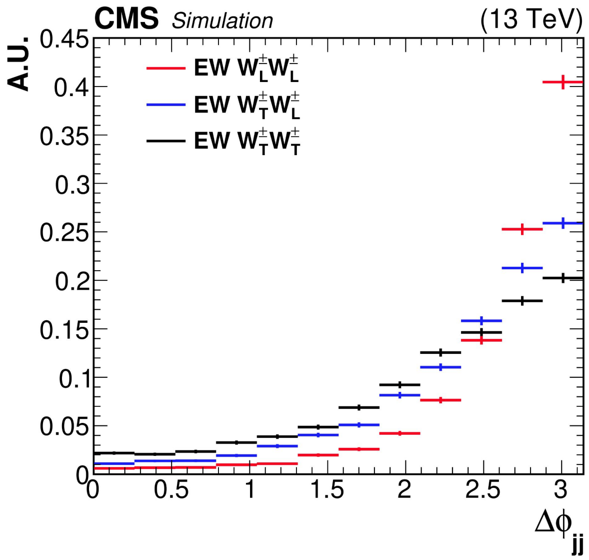


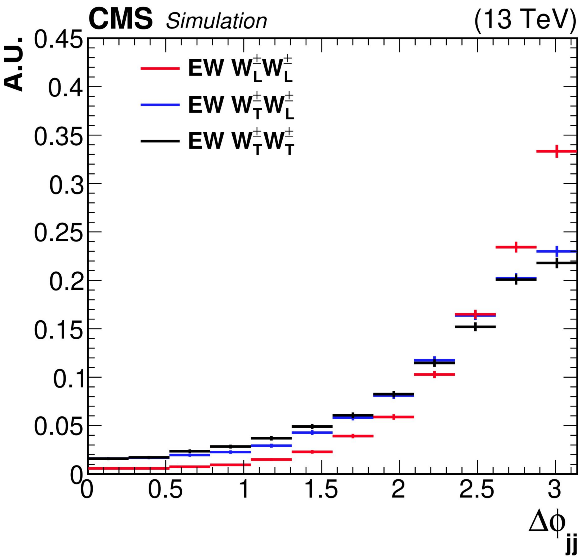


SS VBS WW (CMS) - Modelling

Phys. Lett. B 812 (2020) 136018

⇢ Dedicated simulated samples are produced for the polarized EWK WW signals (W_LW_L, W_TW_T, and W_LW_T) using MADGRAPH5 aMC@NLO interfaced with Pythia8.





⇢ All results are presented in two different helicity frames:

- ⇢ "**WW frame**": based on the centre of mass frame of the WW pair (left plot).
- ⇢ "**Parton frame**": based on the centre of mass frame of the incoming partons (right plot).

⇢ Results are compared with others obtained from PHANTOM, showing reasonable agreement in the regions used for the signal extraction.

SS VBS WW (CMS) - Event selection

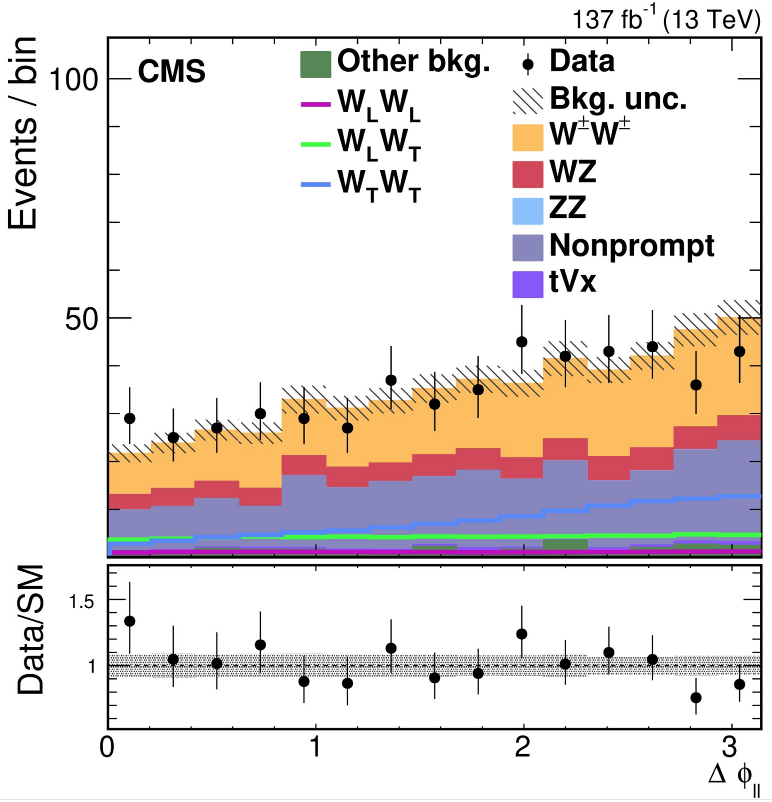
Phys. Lett. B 812 (2020) 136018

⇢ Event selection targeting WW (two same-sign leptons, minimal p_T^{miss}), EWK (requirements on jets and Zeppenfeld's z) production.

⇢ Lepton p_T requisites based on the leptonic triggers.

⇢ Final selection becomes the **WW SR** where all the measurements are performed.

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



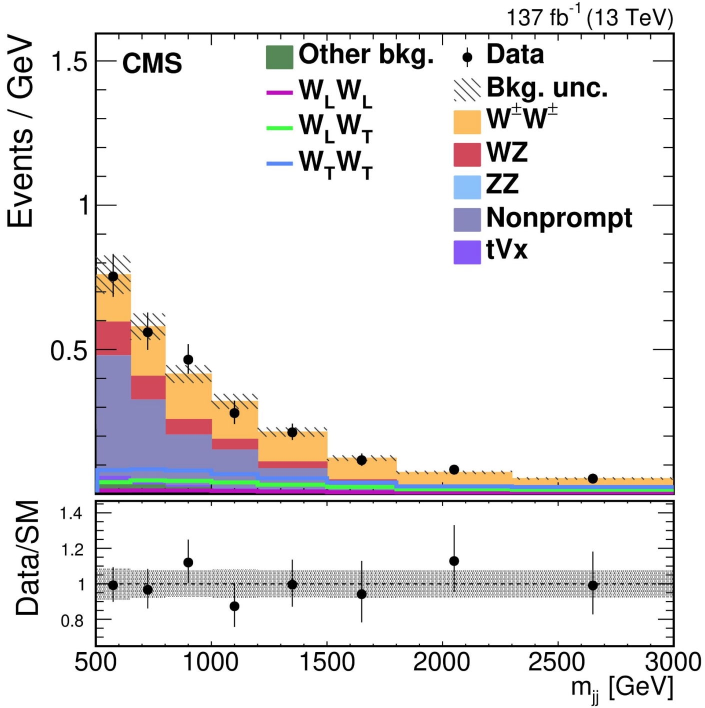
Background presence is significant still after the selection

SS VBS WW (CMS) - Signal extraction I

Phys. Lett. B 812 (2020) 136018

⇢ Two challenges appear when trying to extract the different signal contributions:

1) Separation from **comparatively big backgrounds** (non-prompt, WZ).
2) Separation between **the different polarization modes themselves**.



⇢ Each one is tackled through the usage of a dedicated BDT discriminant trained to solve it, using as input lepton and jet kinematics:

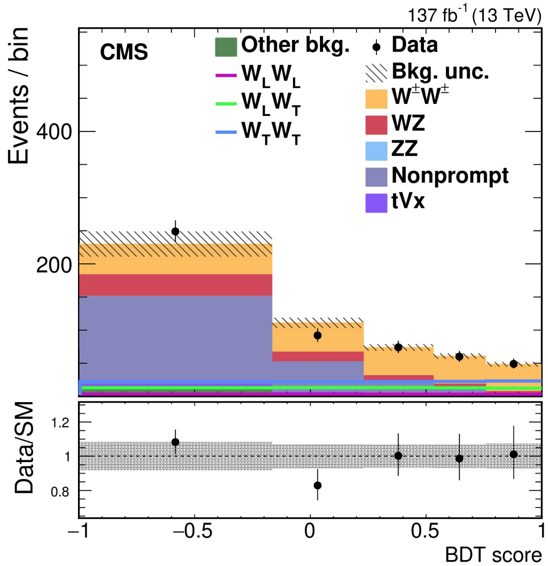
1) "Inclusive BDT": trained to separate WW from other SM backgrounds.
2) "Signal BDT": trained to separate the different kinds of signals between themselves.

⇢ The final signal extraction uses a **2D fit** based on a binning of both BDTs.

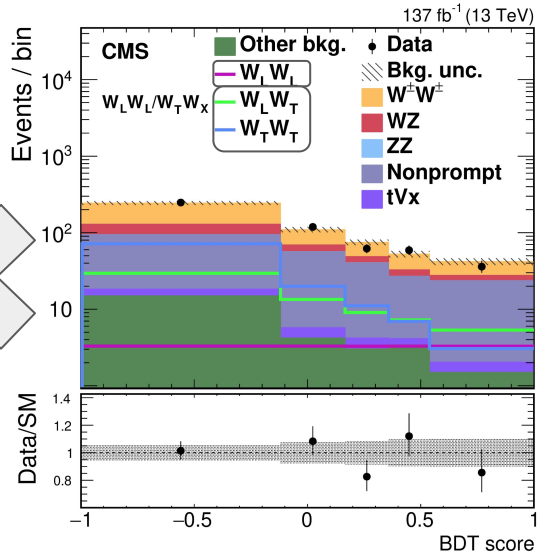
SS VBS WW (CMS)- Signal extraction II

Phys. Lett. B 812 (2020) 136018

- The fits are done separately twice:
  - Inclusive BDT x “LL vs all” BDT (5x5 bins): to extract W_LW_L and W_TW_X cross sections.
  - Inclusive BDT x “TT vs all” BDT (5x5 bins): to extract W_TW_T and W_LW_X cross sections.
- In both cases, the cross sections for each subprocess are fitted simultaneously.

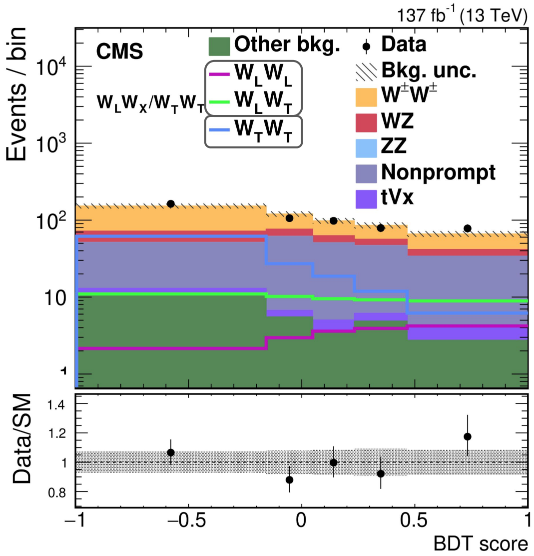


“Inclusive BDT”



“LL vs all” BDT

or



“TT vs all” BDT

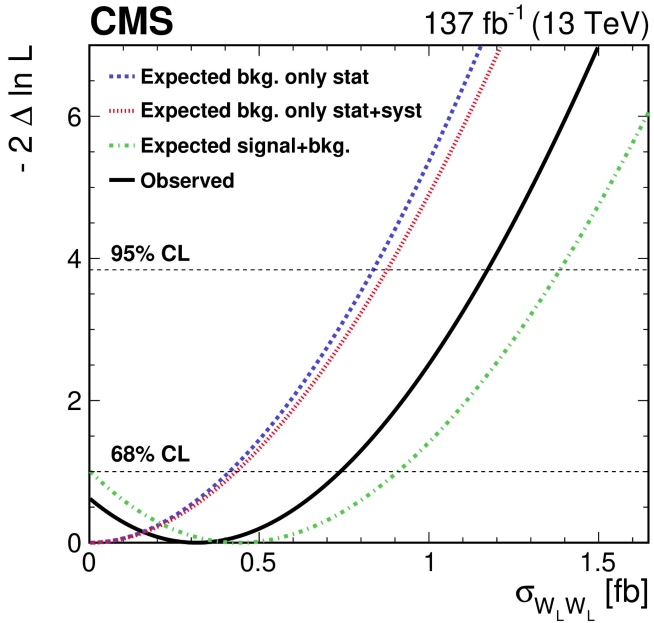
Same-Sign VBS WW (CMS) - Results I

Phys. Lett. B 812 (2020) 136018

⇢ The results in the **WW reference frame** are consistent with predictions within uncertainties (ranging 16-130%).

⇢ Significance for LX production at 2.3σ (3.1σ expected), still quite dependant on available statistics.

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



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

⇢ Similarly, in the **incoming parton frame** measurements and predictions are consistent.

⇢ Significances for L-X presence in the frame at the 2.6σ (2.9σ expected).

Same-Sign VBS WW (CMS) - Results II

Phys. Lett. B 812 (2020) 136018

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

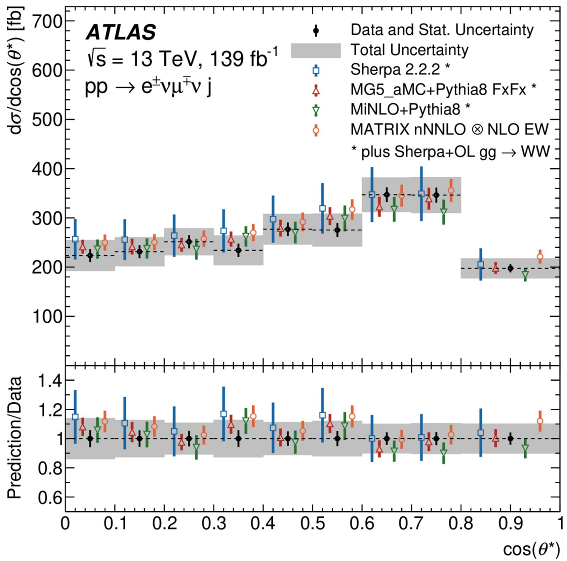
⇢ Uncertainty sources in **the WW frame**, split by source. Similar to the ones on the other.

⇢ Very strongly dominated by statistical uncertainty, significant improvements are to be expected from Run III and the HL-LHC before systematics start to become a significant issue.

Some final thoughts

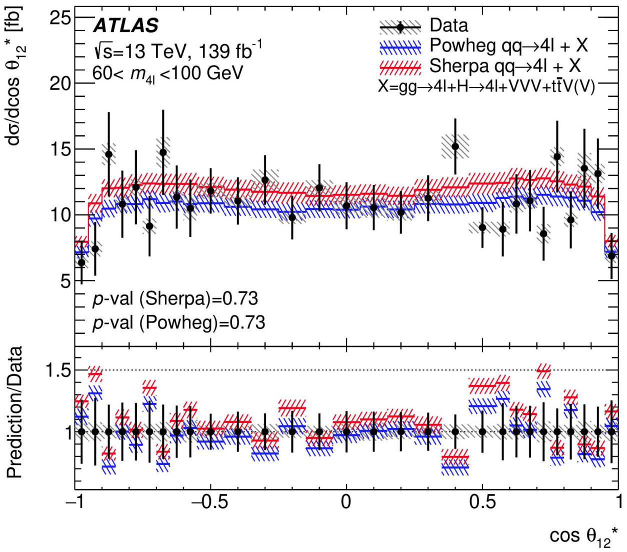
Related measurements now...

⇢ While other ATLAS and CMS measurements don't provide direct interpretations on the polarization of the gauge bosons, closely related results are often provided. Differential cross section measurements are closely related to the polarization measurements. Check [Andrew's talk](#)!



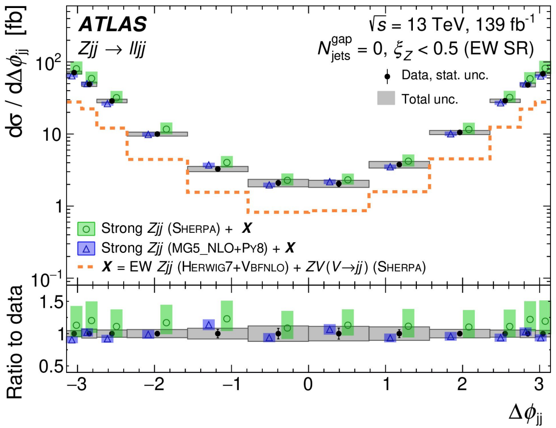
JHEP 06 (2021) 003

WW+1jet measurement



JHEP 07 (2021) 005

pp→4l differential measurements



Eur. Phys. J. C 81 (2021) 163

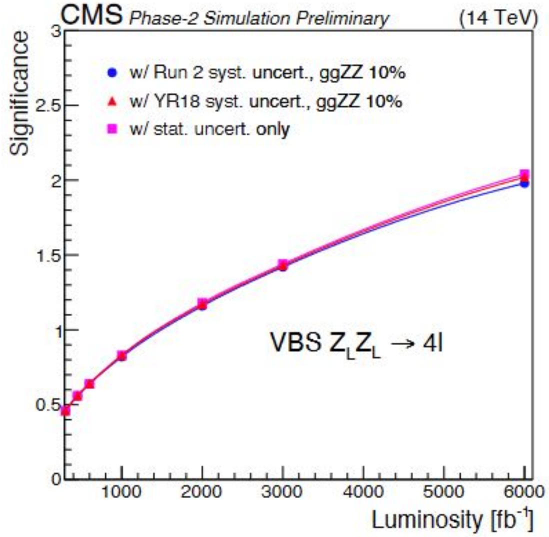
Zjj differential measurements

⇢ And, of course, also in the single boson production mode!

...and in the future

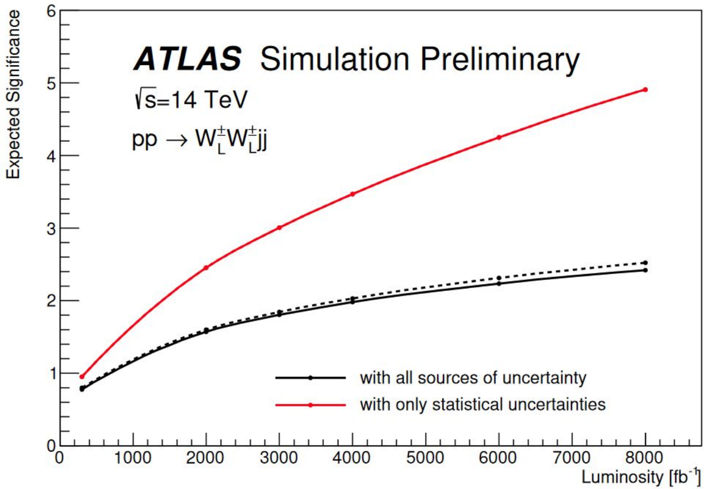
⇢ A reminder from the YR studies ([CERN Yellow Rep.Monogr. 7 (2019) 1-220](#)): possibilities to study longitudinal gauge boson scattering into the future.

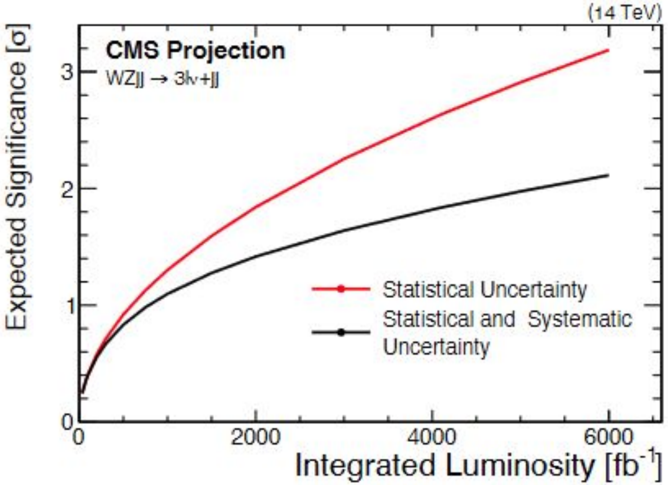
⇢ A lot of new results expected as we take more and more data in the future!



CMS-PAS-FTR-18-014

ATLAS-PHYS-PUB-2018-052





CMS-PAS-FTR-18-038

Summary

⇢ Results for gauge boson polarization in WZ and WW production has been presented:

⇢ With our current data we are already able to probe the polarization fractions in inclusive VV production.

⇢ Results include the first evidence + observation of longitudinally polarized gauge bosons in WZ production.

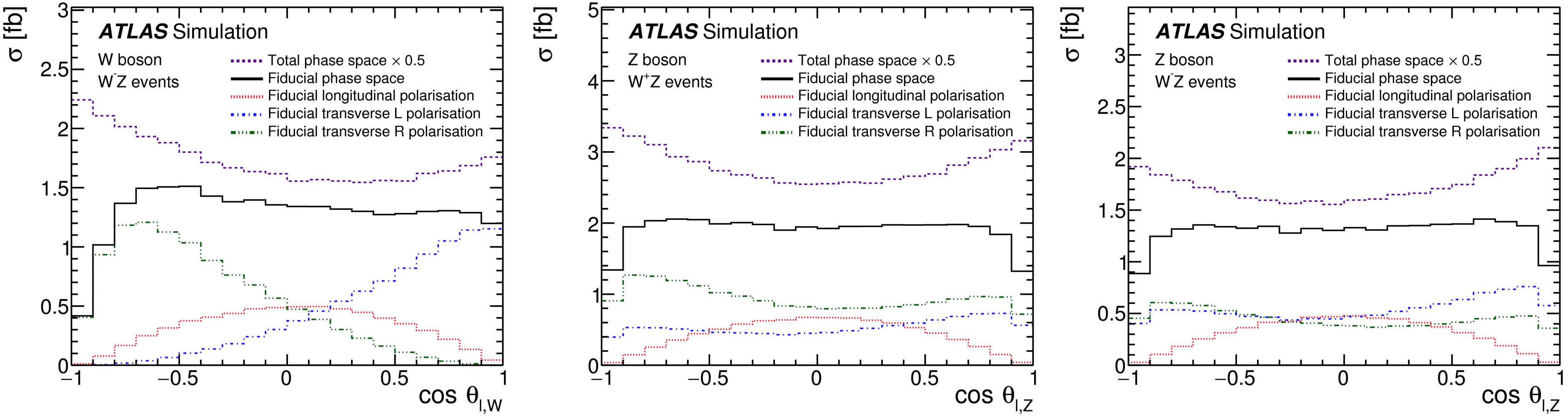
⇢ EWK production still severely limited by data statistics, but already showing promise in same-sign WW production. A lot can be expected as we gather more data!

Back-Up

WZ (ATLAS) - Polarization modelling

Eur. Phys. J. C 79 (2019) 535

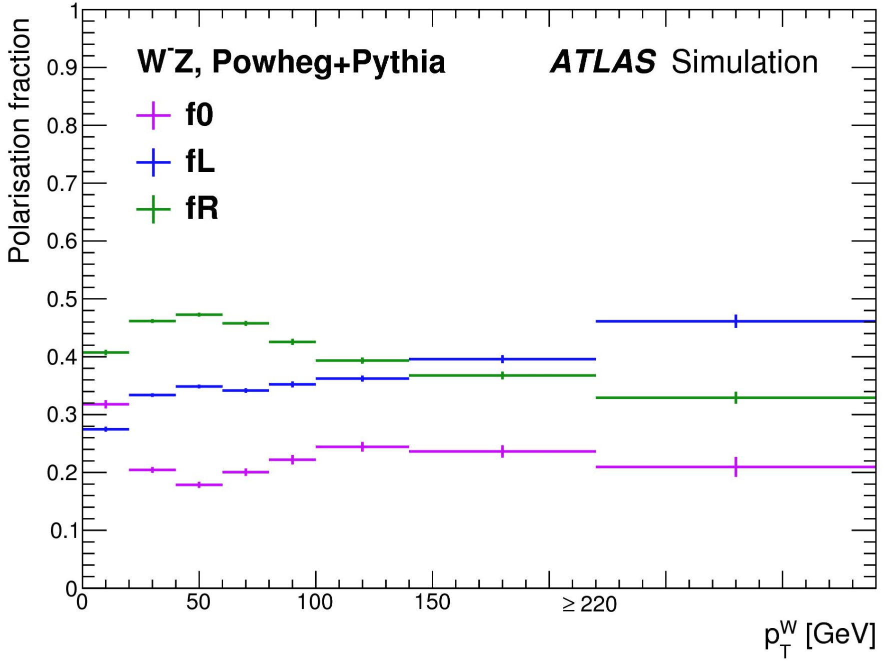
⇢ Other bosons and final states:

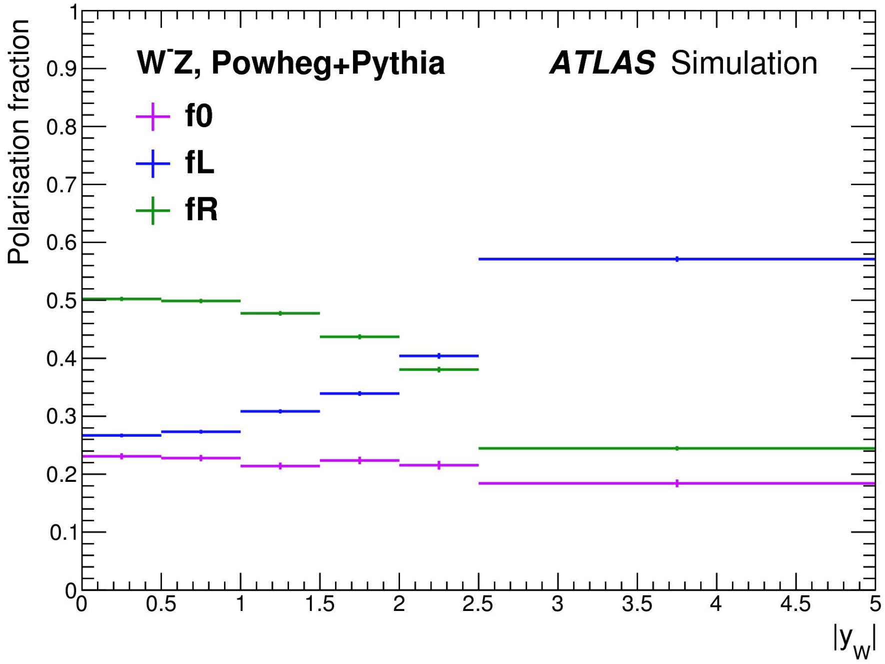


WZ (ATLAS) - Helicity fraction vs p_T/Y

Eur. Phys. J. C 79 (2019) 535

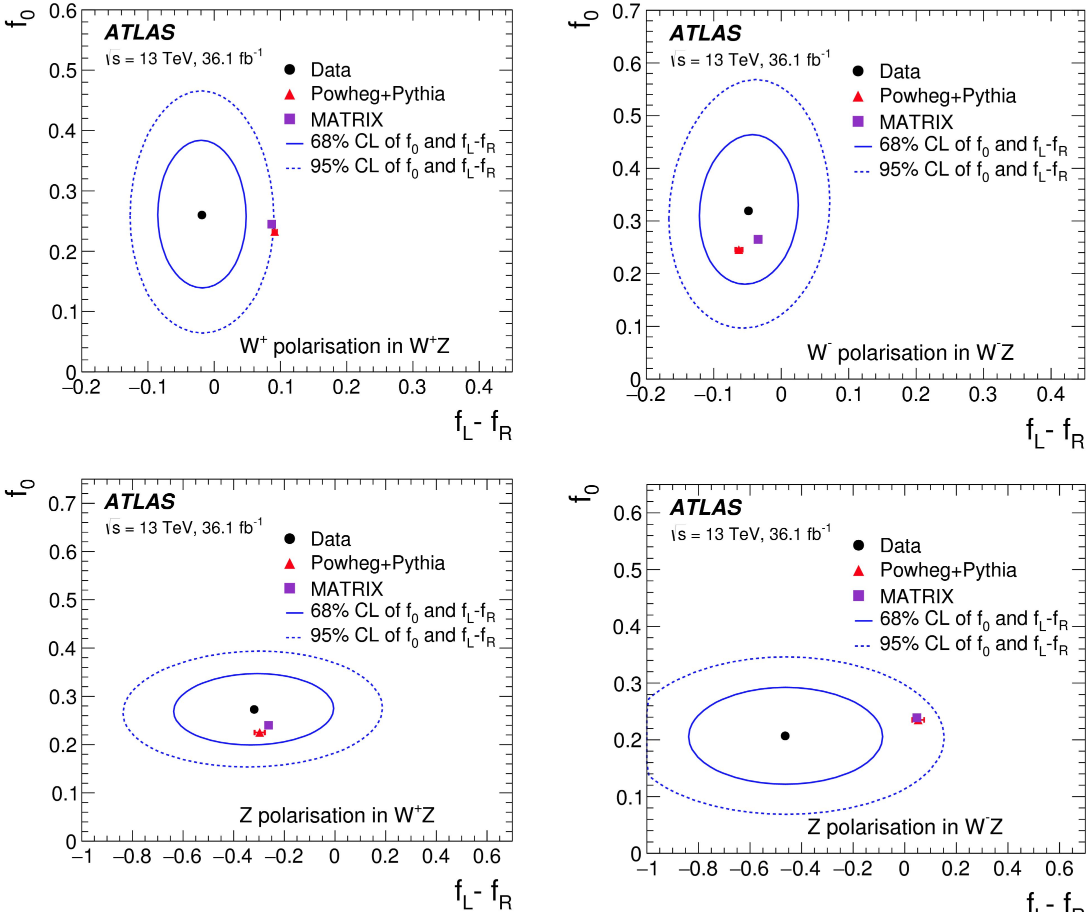
⇢ For each p_T/Y bin and boson, helicity fractions are fitted separately.





WZ (ATLAS) - Other 2D fits

Eur. Phys. J. C 79 (2019) 535

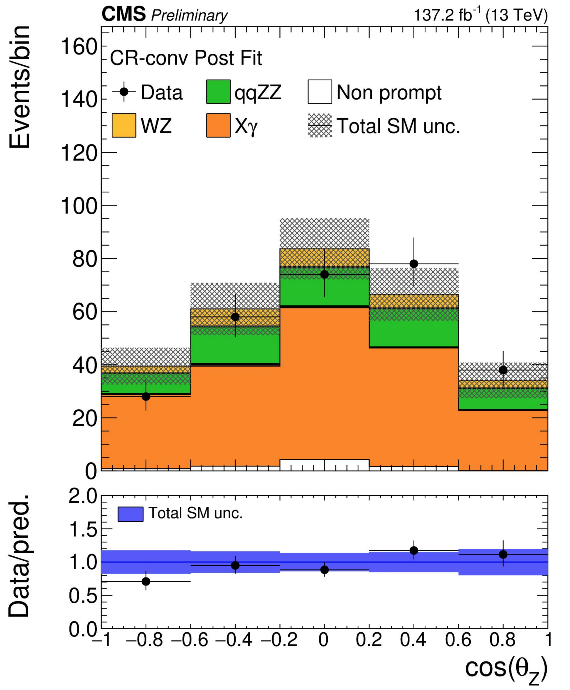


WZ (CMS) - Background estimation

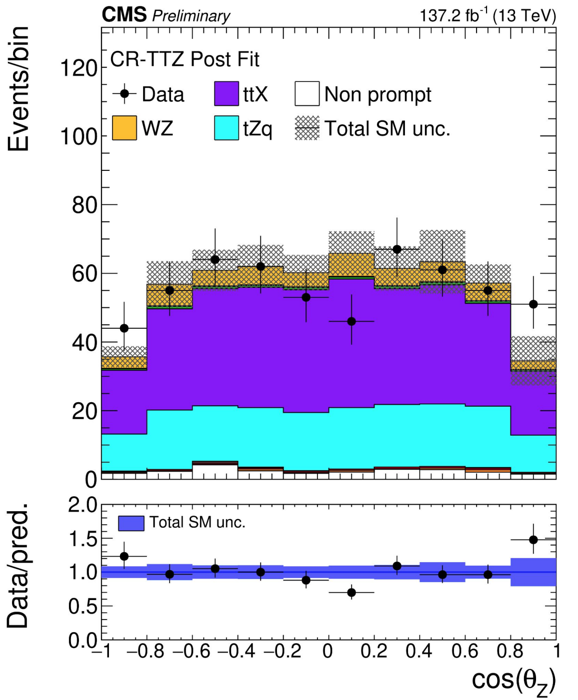
CMS-PAS-SMP-20-014

- Several background CR are defined to study the behaviour of the main background processes.
- "cos(θ_V)" is shown at the reconstructed level, with W and Z kinematics reconstructed from the final state leptons.

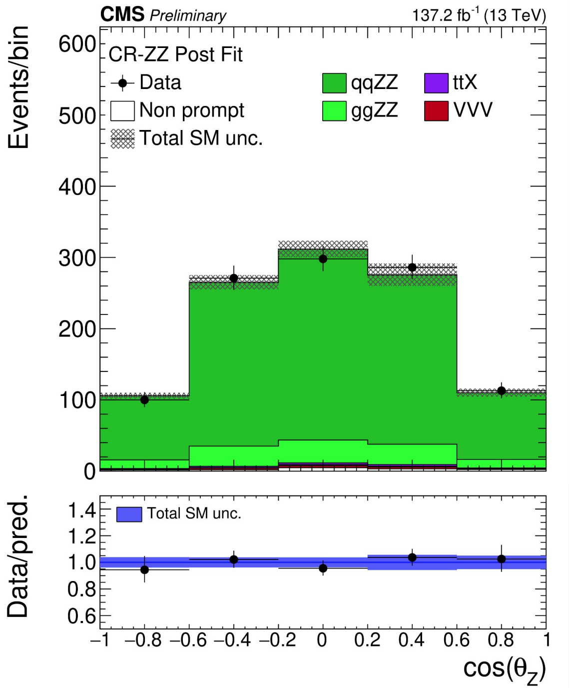
For the W boson, p_T^{miss} is used as a proxy of the neutrino's p_T and a constraint to the W mass is applied.



Inverted p_T^{miss}, $M_{Z1,Z2}$, M_{lll} requirements



Inverted $N_{b\text{-}tag}$ requirements



Requiring an additional lepton instead of p_T^{miss}

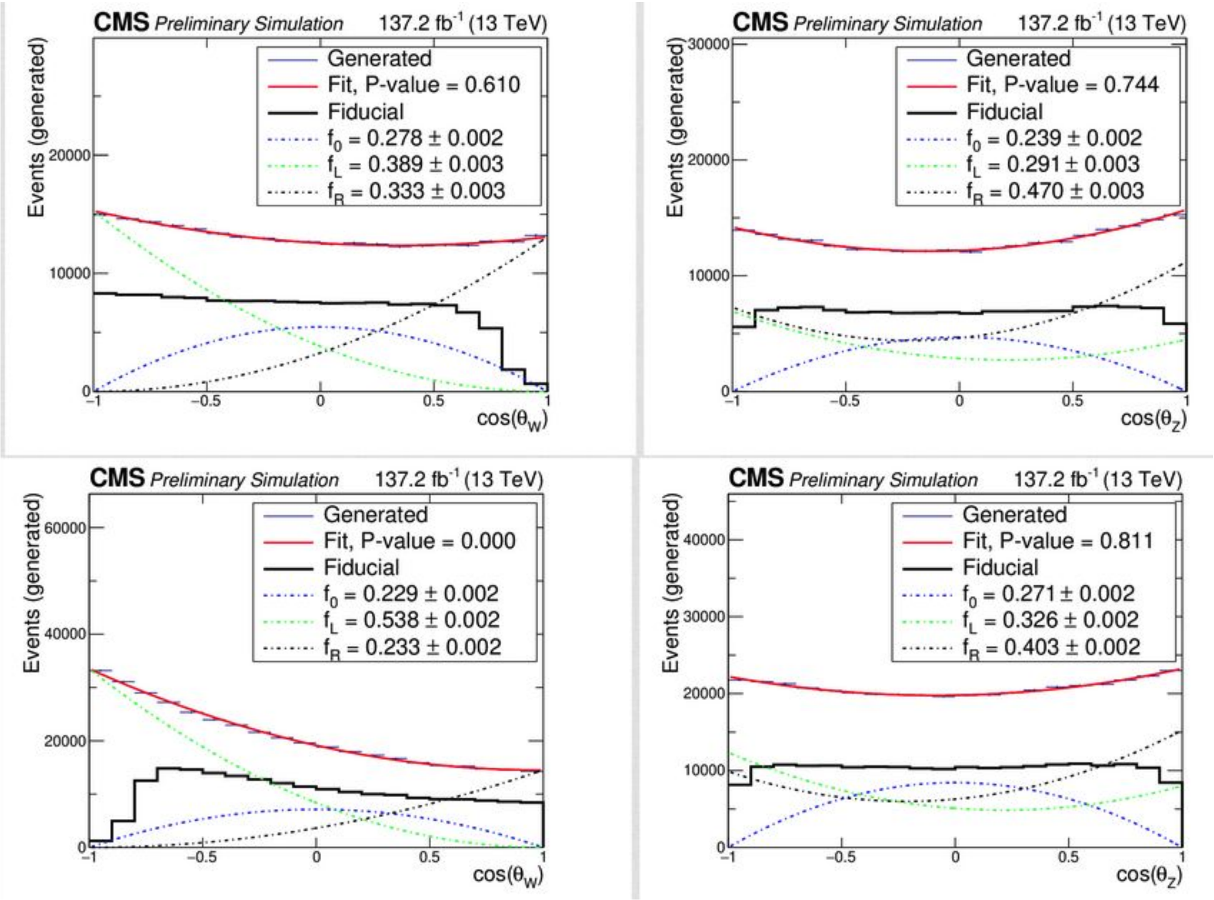
WZ (CMS) - Input systematics

CMS-PAS-SMP-20-014

Source	2016	2017	2018	Correlation scheme	Processes
Electron efficiency	$0-3.3$	$0-3.0$	$0-2.8$	Partially correlated	All MC
Muon efficiency	$0-2.4$	$0-2.1$	$0-2.0$	Partially correlated	All MC
Muon energy scale	$0-5$	$0-5$	$0-5$	Correlated	All MC
Electron energy scale	$0-5$	$0-5$	$0-5$	Correlated	All MC
Trigger efficiency	$-1.0/0.6$	$-0.7/0.6$	$-0.7/0.6$	Partially correlated	All MC
Jet energy scale	0.9	0.7	1.1	Partially correlated	All MC
B-tagging (heavy)	1.0	0.7	0.9	Correlated	All MC
B-tagging (light)	0.5	0.4	0.3	Correlated	All MC
Pileup	0.9	0.8	0.8	Correlated	ALL MC
ISR	$0.2-20$	$0.2-20$	$0.2-20$	Correlated	WZ
Nonprompt norm.	30	30	30	Correlated	nonprompt
VVV norm.	50	50	50	Correlated	VVV
VH norm.	25	25	25	Correlated	VH
WZ VBS norm.	20	20	20	Correlated	WZ VBS
ZZ	Free	Free	Free	Correlated	ZZ
$t\bar{t}Z$ norm.	Free	Free	Free	Correlated	$t\bar{t}X$
tZq norm.	Free	Free	Free	Correlated	tZq
$X\gamma$ norm.	Free	Free	Free	Correlated	$X\gamma$
Luminosity	2.5	2.3	2.5	Partially correlated	All MC
Statistical uncertainties	By bin	By bin	By bin	Decorrelated	All MC
Theoretical (PDF + Scale)	0.9	0.9	0.9	Correlated	WZ

WZ (CMS) - Other polarization fraction fits

[CMS-PAS-SMP-20-014](CMS-PAS-SMP-20-014)



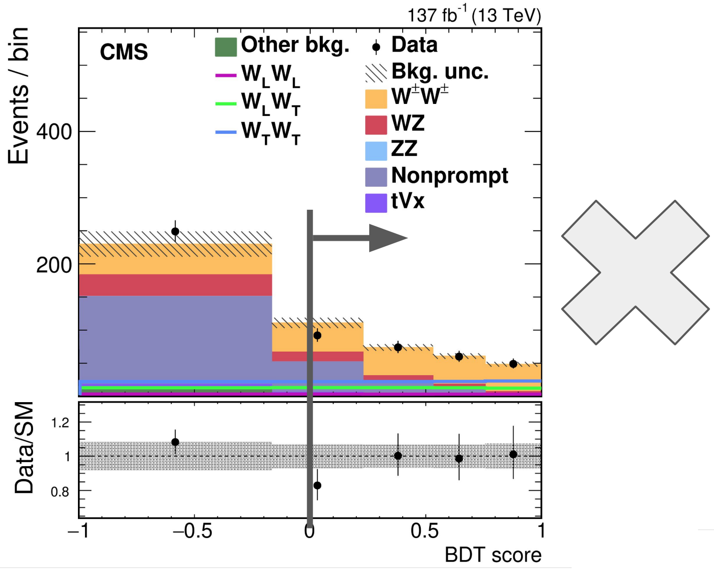
Minus charge

Plus charge

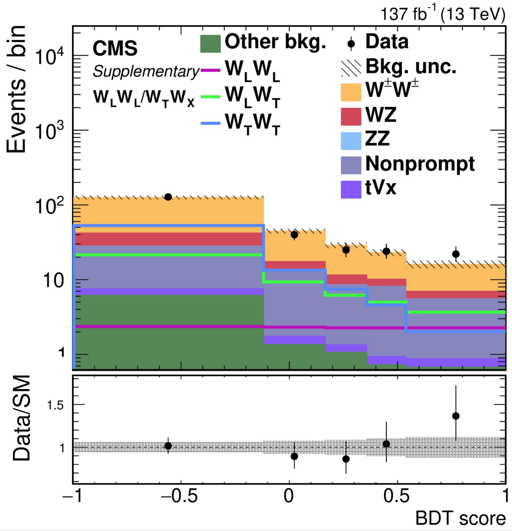
SS VBS WW (CMS)- Signal extraction

Phys. Lett. B 812 (2020) 136018

⇢ Same plots as in main slide, with additional cuts applied to the inclusive BDT at score > 0 when representing the others:

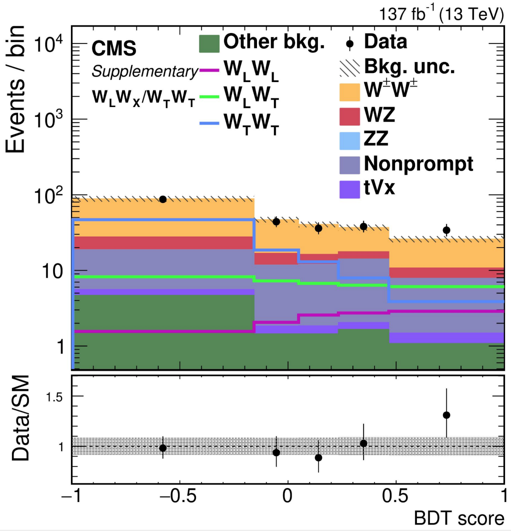


"Signal BDT"



"LL vs all" BDT

or



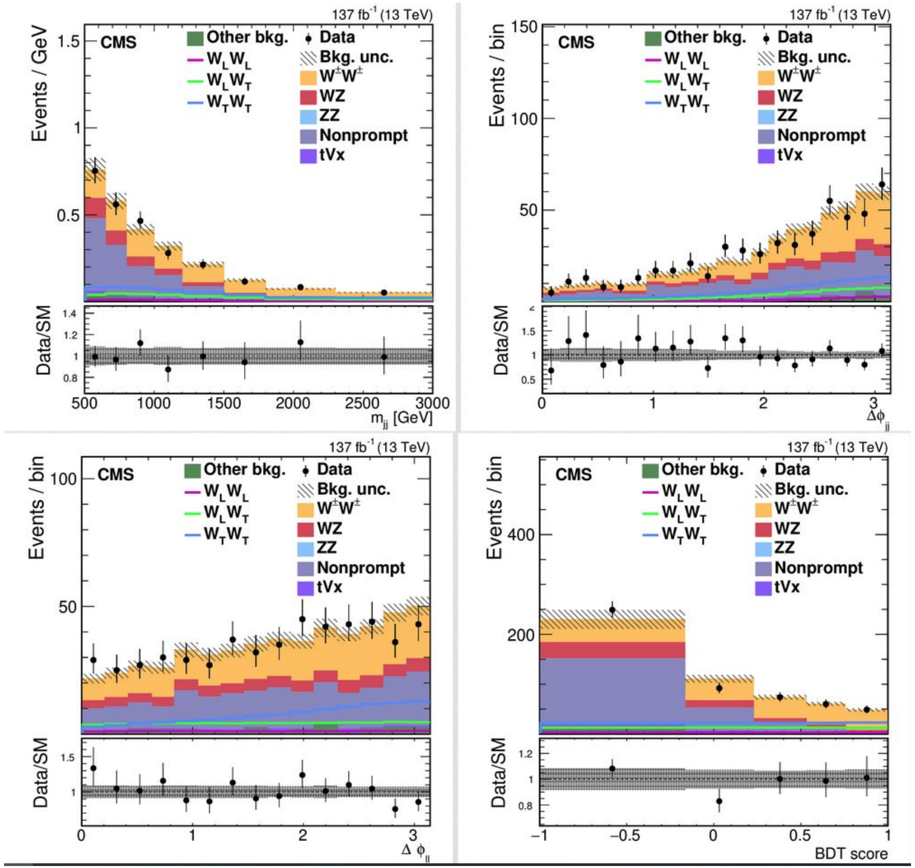
"TT vs all" BDT

SS VBS WW (CMS)- Inclusive BDT

Phys. Lett. B 812 (2020) 136018

⇢ Training variables and data/MC agreement in the WW SR.

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

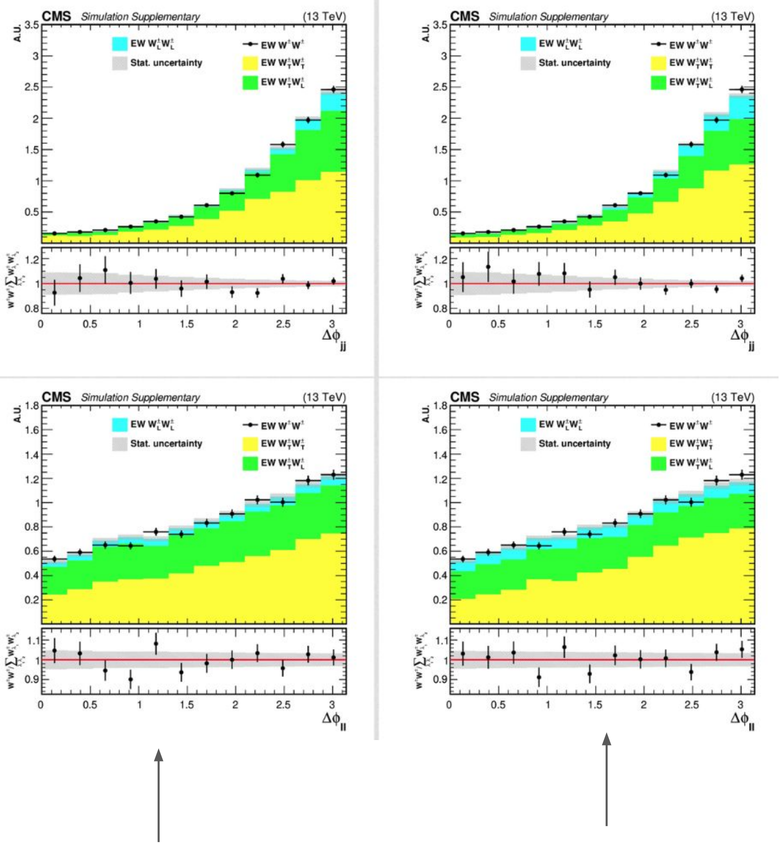


SS VBS WW (CMS)- Signal BDT

[Phys. Lett. B 812 (2020) 136018](#)

⇢ Training variables and separation observed at the generator level between fractions.

Variables	Definitions
$\Delta\phi_{jj}$	Difference in azimuthal angle between the leading and subleading jets
p_T^{j1}	p_T of the leading jet
p_T^{j2}	p_T of the subleading jet
$p_T^{\ell_1}$	Leading lepton p_T
$p_T^{\ell_2}$	Subleading lepton p_T
$\Delta\phi_{\ell\ell}$	Difference in azimuthal angle between the two leptons
$m_{\ell\ell}$	Dilepton mass
$p_T^{\ell\ell}$	Dilepton p_T
m_T^{WW}	Transverse WW diboson mass
$z^*_{\ell_1}$	Zeppenfeld variable of the leading lepton
$z^*_{\ell_2}$	Zeppenfeld variable of the subleading lepton
$\Delta R_{j1,\ell\ell}$	ΔR between the leading jet and the dilepton system
$\Delta R_{j2,\ell\ell}$	ΔR between the subleading jet and the dilepton system
$(p_T^{\ell_1} p_T^{\ell_2})/(p_T^{j1} p_T^{j2})$	Ratio of p_T products between leptons and jets
p_T^{miss}	Missing transverse momentum



WW frame

Parton frame

Same-Sign VBS WW (CMS) - Results III

Phys. Lett. B 812 (2020) 136018

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	3.3	1.8	1.9	1.8
Lepton measurement	3.9	1.9	2.3	1.8
Jet energy scale and resolution	13	2.1	1.4	1.6
Pileup	1.5	0.1	0.2	0.1
btagging	1.2	1.2	1.0	1.3
Nonprompt rate	15	2.5	8.6	1.5
Trigger	1.2	1.2	1.4	1.0
Limited sample size	37	3.7	10	6.0
Theory	13	2.2	5.6	2.4
Total systematic uncertainty	44	6.1	15	7.5
Statistical uncertainty	148	14	39	24
Total uncertainty	155	15	42	25

⇢ Uncertainty sources in **the parton frame**, split by source.

⇢ Near identical to those in the WW frame, completely dominated by statistics.