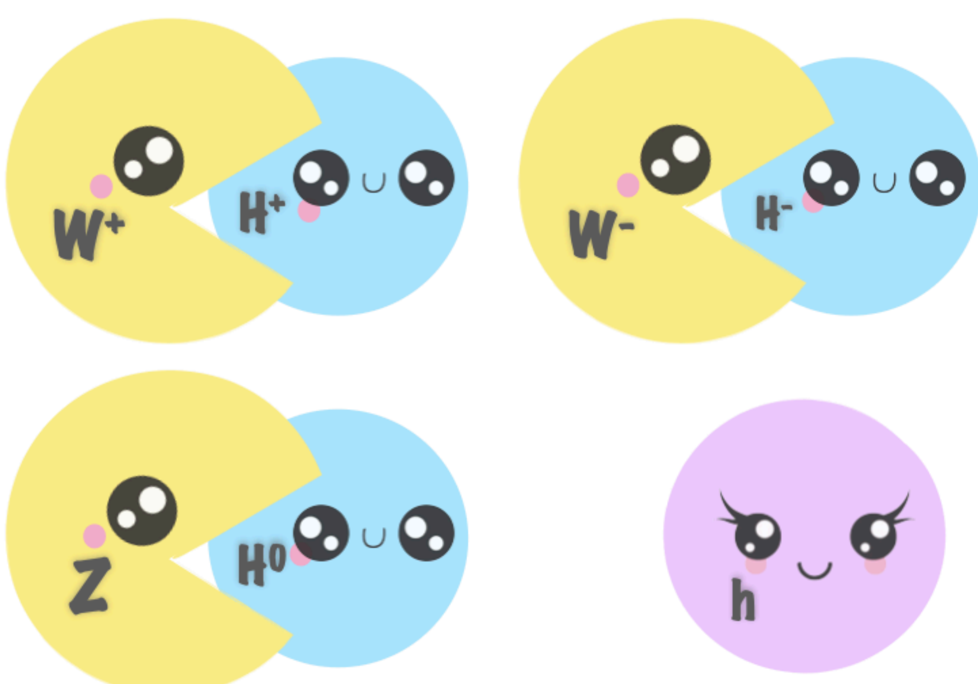
State-of-the-art of polarization measurements in multi-boson

Joany Manjarrés Ramos
on behalf of the ATLAS and CMS collaborations

Why weak boson polarization is interesting?

- Gauge boson polarization is strongly related to the structure of the electroweak sector
- The Higgs mechanism predicts the existence of Goldstone bosons, and those are eaten by the W^+, W^-, and Z respectively, providing them with a mass and their longitudinal polarization

Inspired by quantumdiaries.org



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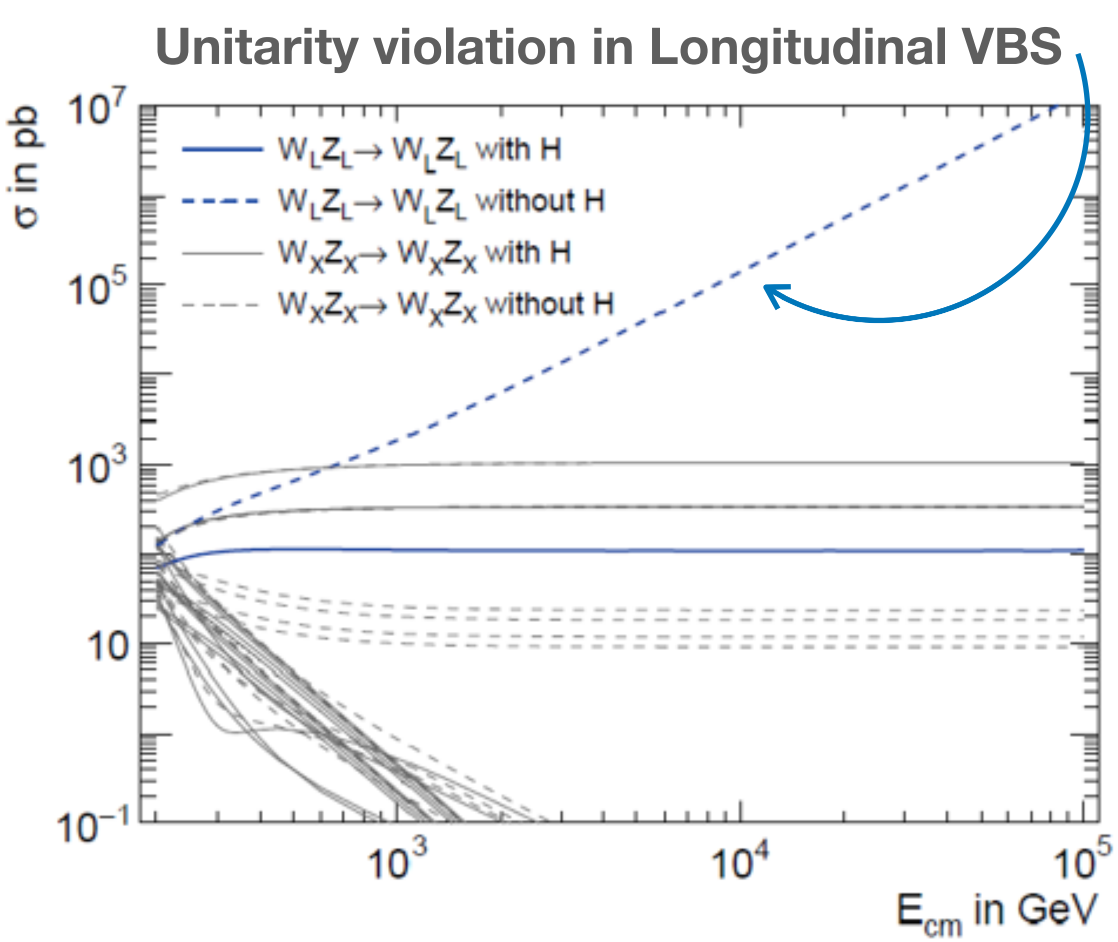

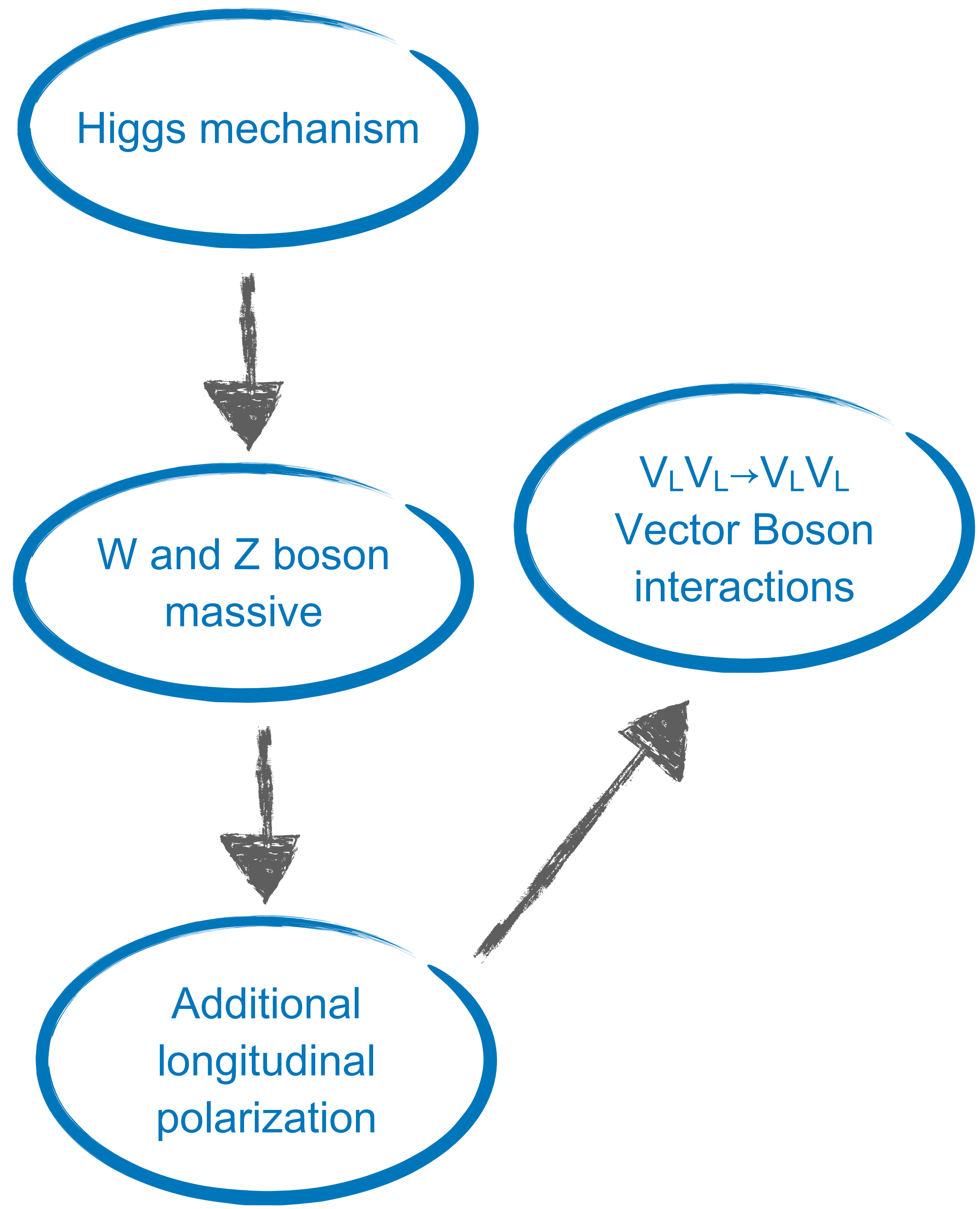

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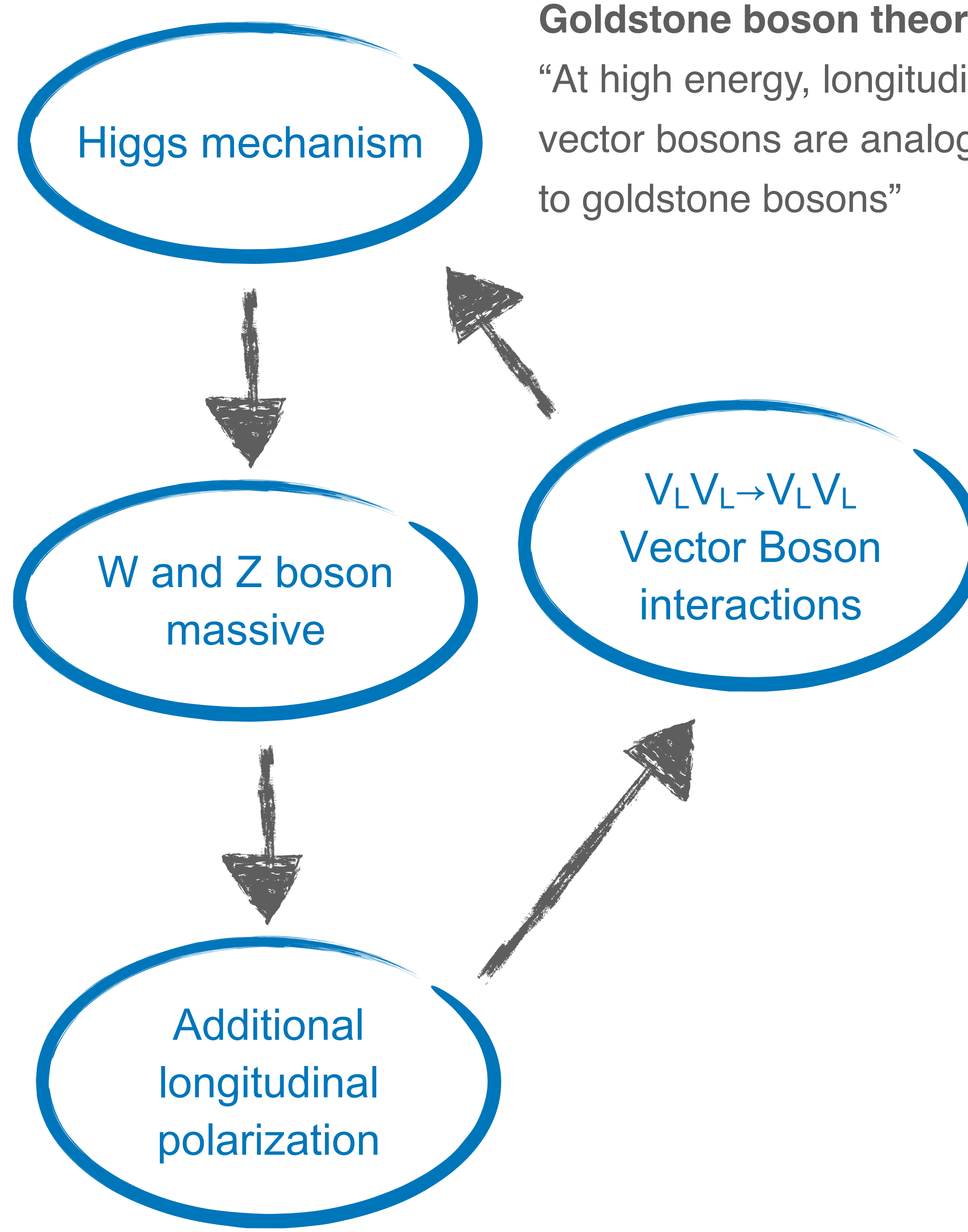
- **Important test of the EWSB**

Goldstone boson theorem
"At high energy, longitudinal vector bosons are analogous to goldstone bosons"



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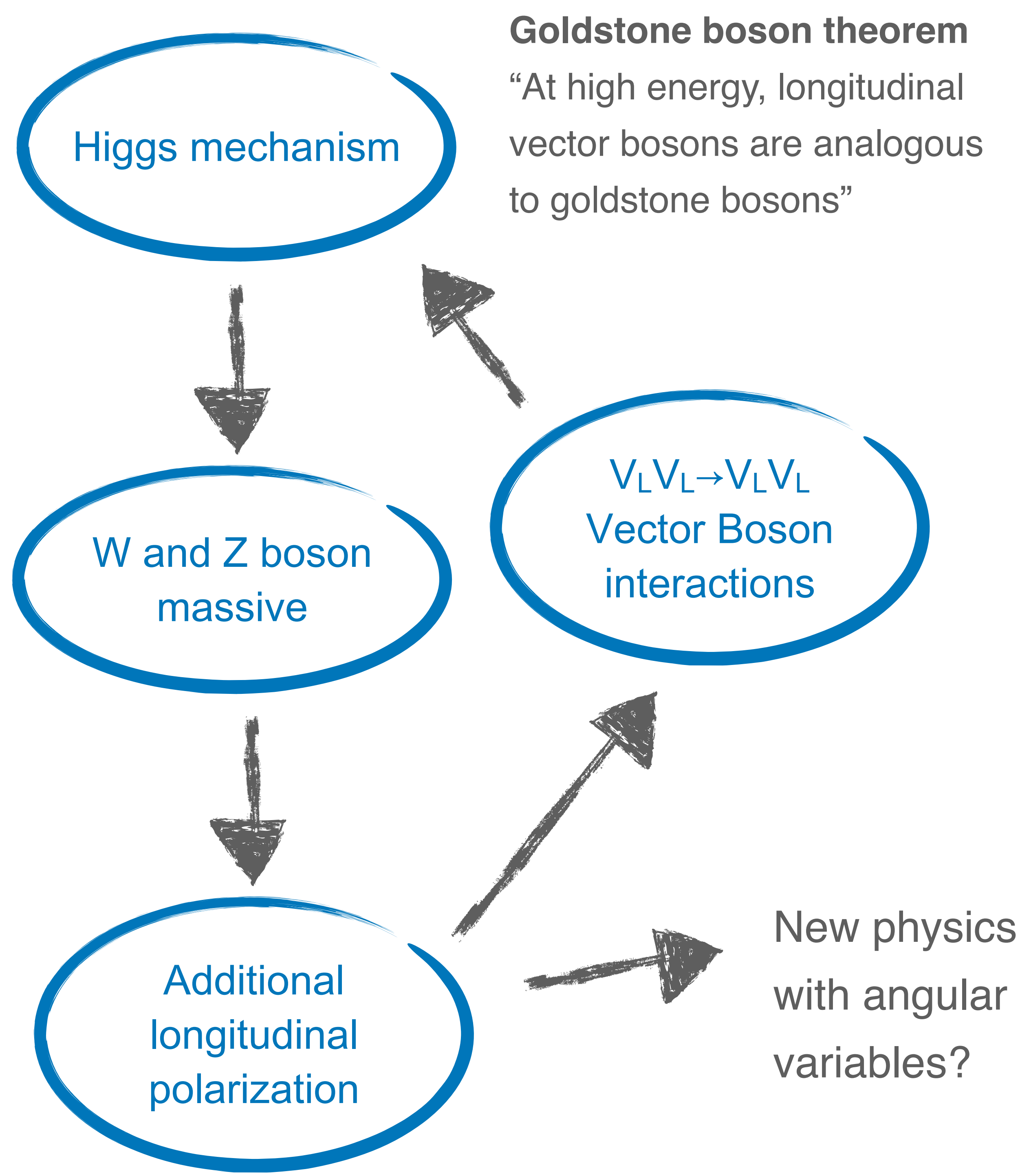
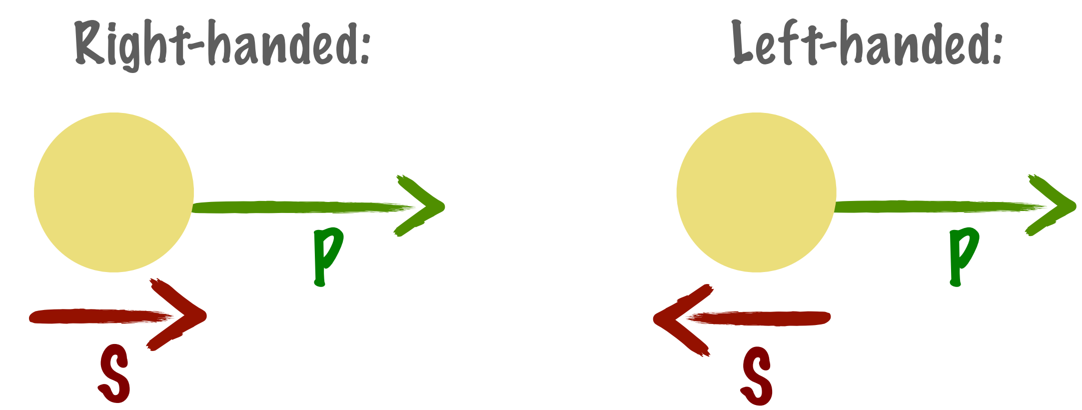
- **Important test of the EWSB**
- **Also New physics might couple preferentially to some polarization**



How to measure polarization?

What polarization means?

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



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

A caveat

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

How to measure polarization?

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

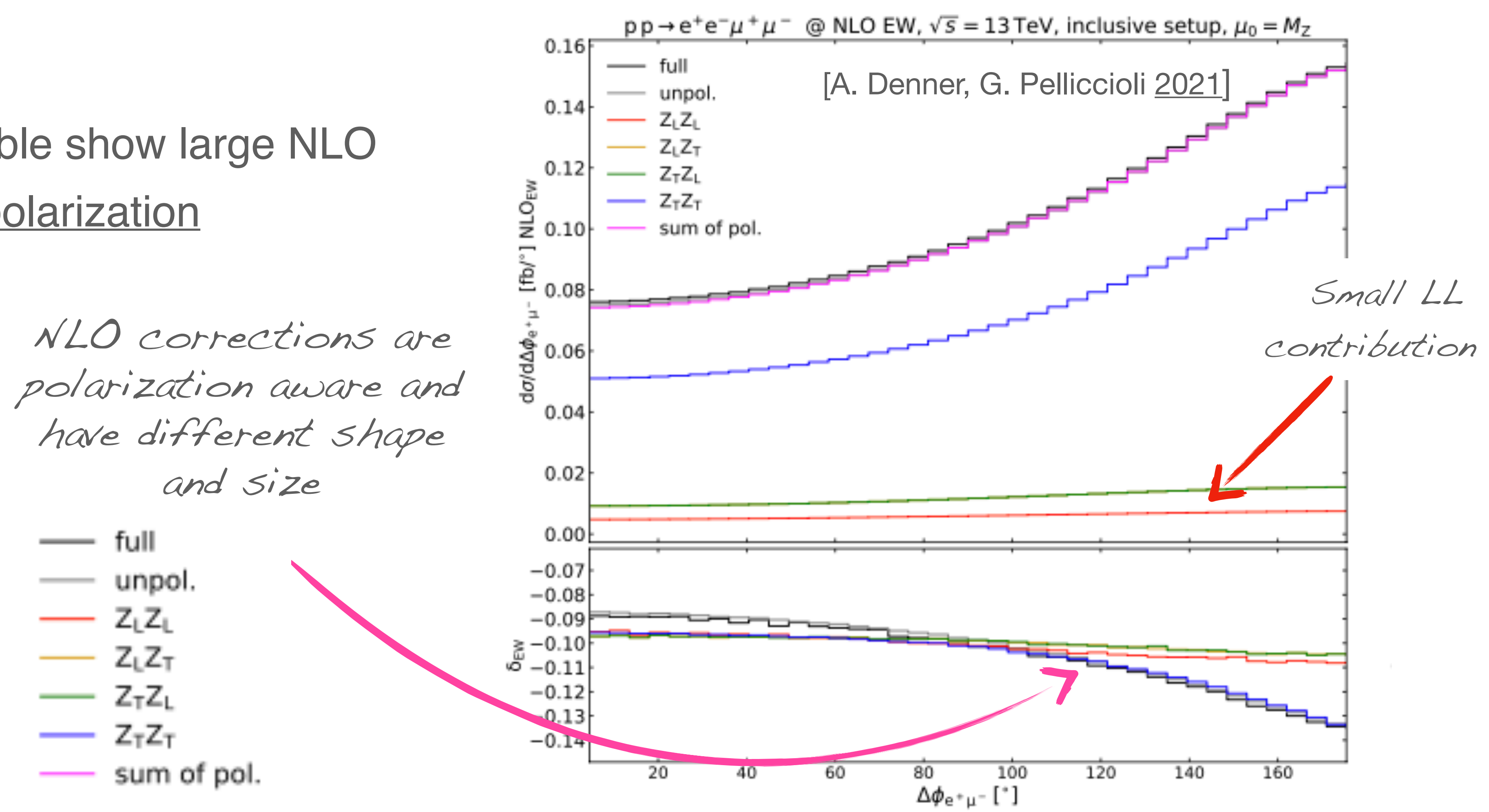
Polarized templates how?

Monte Carlo generators

- Several generators in the market:
  - PHANTOM: 2 → 6 processes @ LO+PS [A. Ballestrero et al. 2008, 2017]
  - Madgraph: arbitrary processes @ LO, PS matching, multi-jet merging [D. Buarque Franzosi et al. 2020]
  - POWHEG-BOX-RES: diboson processes @NLO QCD+PS [G. Pelliccioli, G. Zanderighi 2023]
  - Sherpa: arbitrary processes @nLO QCD, PS matching, multi-jet merging [MH, M. Schönherr, F. Siegert 2023]
- Madgraph has been so far the one used by the collaborations

Fix order calculations

- Fix order calculations available show large NLO QCD and EW electroweak polarization depended corrections



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Fix order calculations

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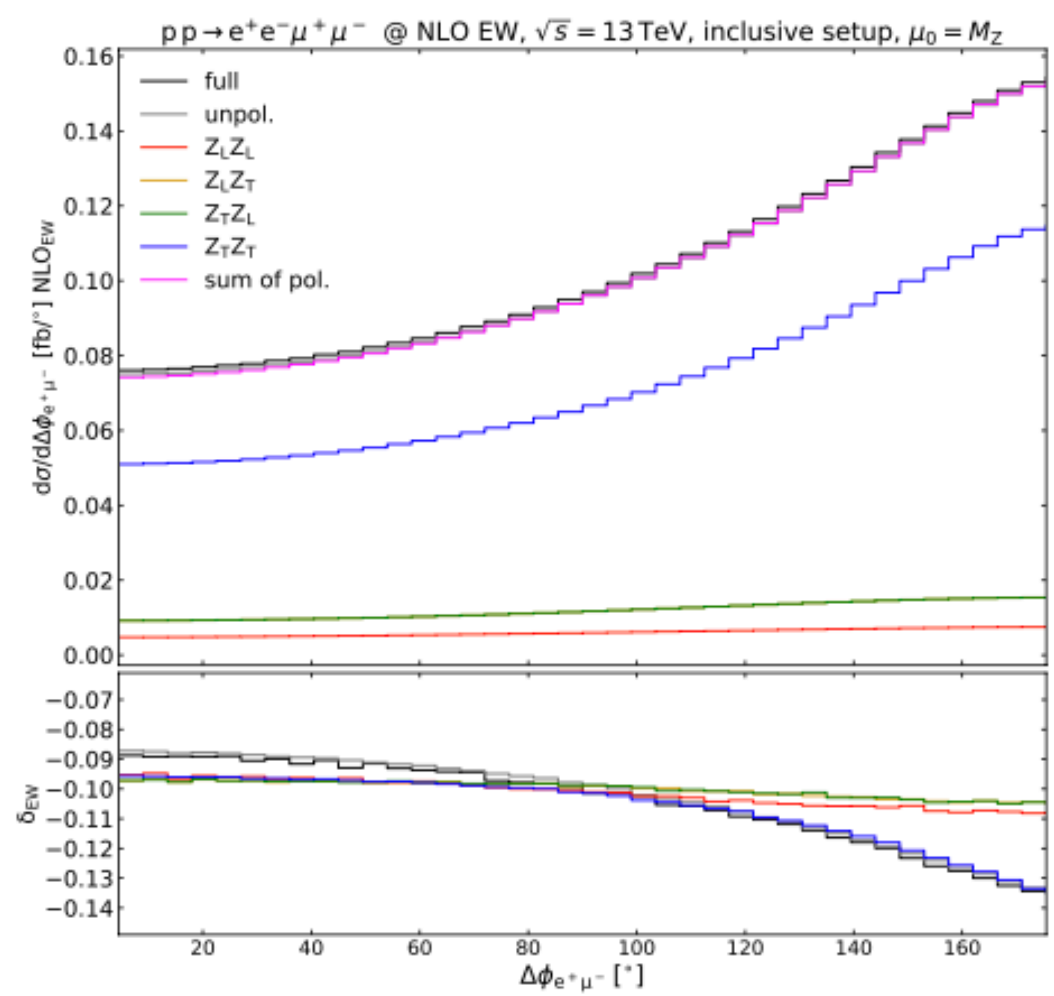
Getting polarised templates is a challenge!

MC simulations + multiple reweighing techniques used to include corrections from fix order calculations



The state-of-the-art

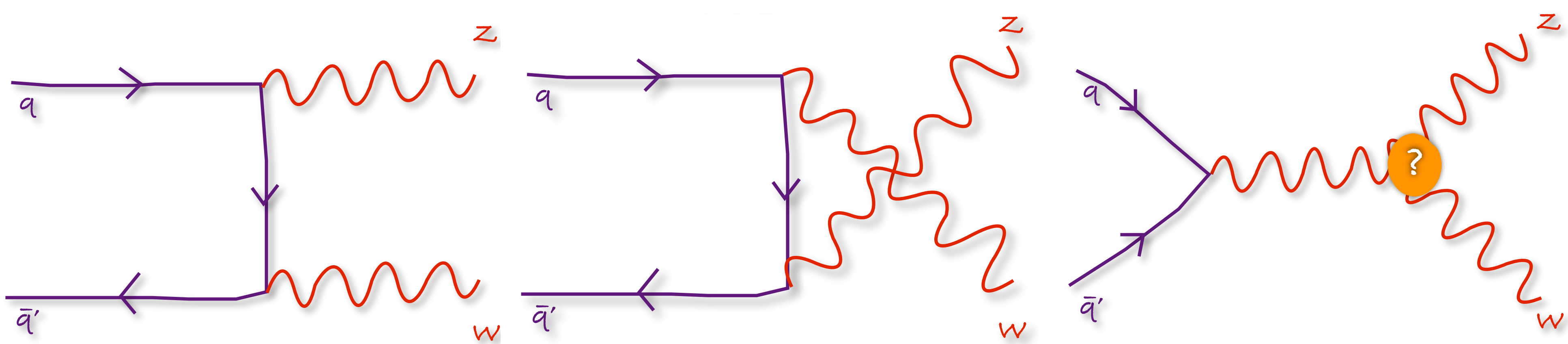
Measurements at LEP:

- Only diboson process accessible for such measurements $e^+e^- \rightarrow W^+W^-$
  - ***Single boson polarization measurements***: L3 [arXiv:0301027], OPAL [arXiv:0312047], DELPHI [arXiv:0801.1235]
  - ***Joint-polarization measurements***: OPAL [arXiv:0009021], DELPHI [arXiv:0908.1023]
- Never reached observation level sensitivity for longitudinal-longitudinal joint-polarization

Measurements at the LHC:

- Single and Joint- boson polarization measurements
- ***pp → W±Z***
  - CMS @13TeV 137 fb^{-1} (inclusive phase space) CMS-SMP-20-014
  - ATLAS @13TeV 139 fb^{-1} (inclusive phase space) Phys. Lett. B 843 (2023) 137895
  - ATLAS @13TeV 139 fb^{-1} (high p_T (Z) phase space) Submitted to PRL New!
- ***pp → ZZ***
  - ATLAS @13TeV 140 fb-1 (inclusive phase space) JHEP 12 (2023) 107
- ***pp → W±W±jj***
  - CMS @13TeV 137 fb^{-1} (VBS phase space) Phys. Lett. B 812 (2020) 136018

Polarization measurements in WZ



CMS Polarization in WZ measurement

JHEP 07 (2022) 032

- ***Single boson polarization*** measurement @13 TeV

The analysis target

- Singly-polarized final states:
  - "W polarization" : $W_L Z$, $W_R Z$, $W_0 Z$
  - "Z polarization" : WZ_L, WZ_R, WZ_0

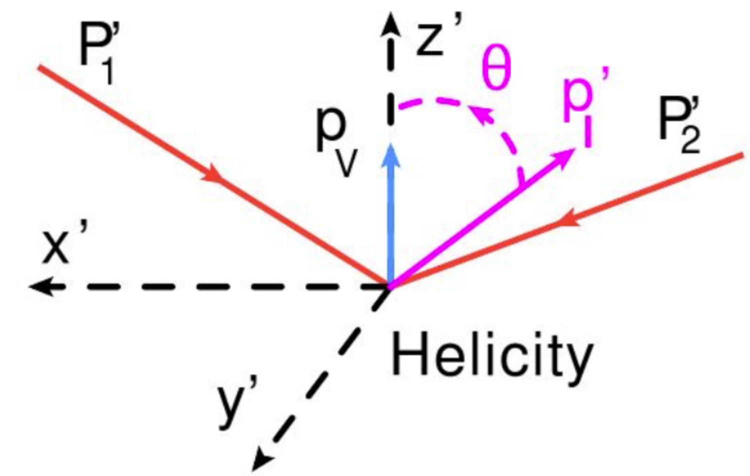
The frame

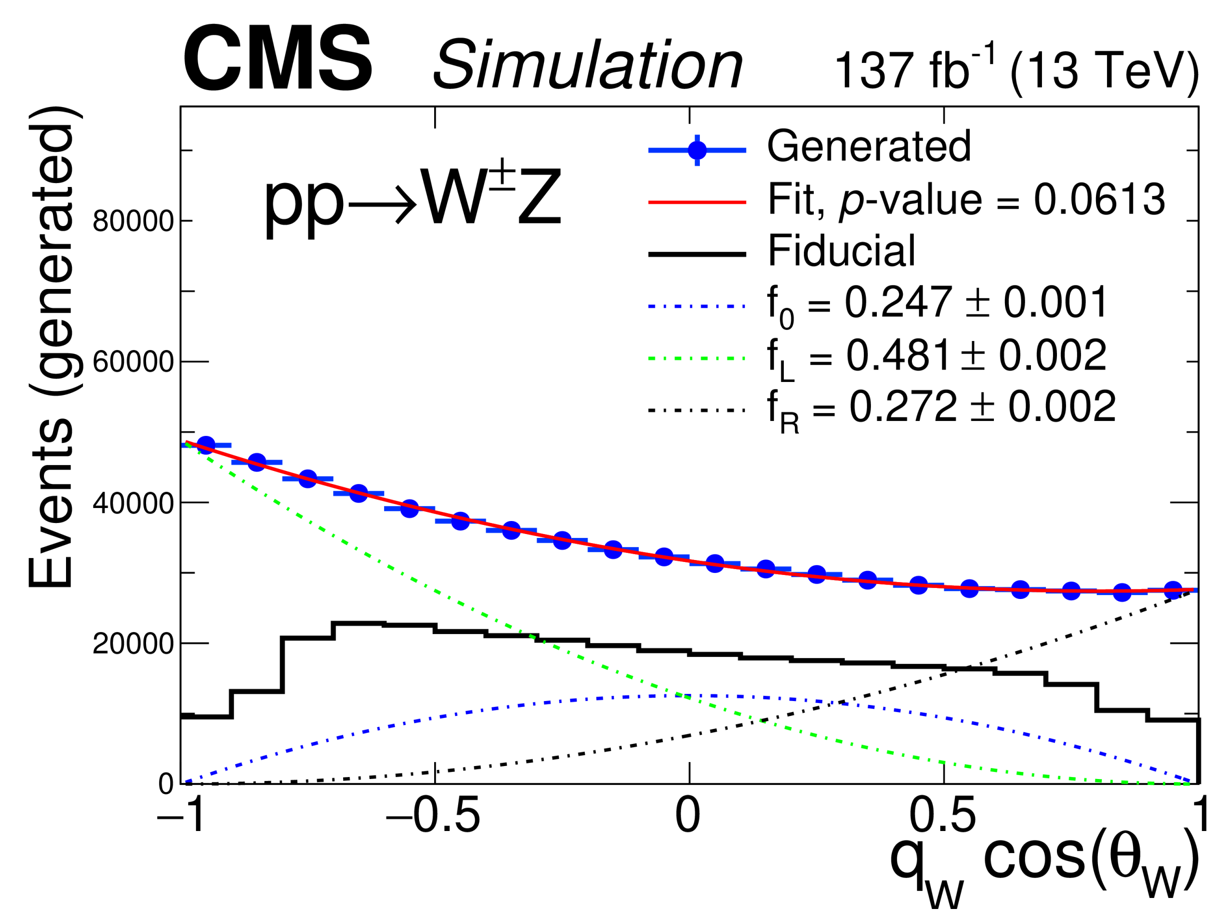
- The helicity frame defined in the centre-of mass of the measured gauge boson (W or Z) is used

How is the analysis performed?

- Polarization templates obtained by reweighting a POWHEG+Pythia sample based on the generator-level $\cos(\theta_V)$ distributions
- Cut-based SR selection, that exploits:
  - fully leptonic WZ decays: leptons p_T>25/10/25 GeV, p_T^{miss}>30 GeV
  - Z mass on-shell (15 GeV window)
  - W reconstructed using pdg mass constrain
- Three Control regions for ZZ, top and photon conversions

The frame:





WZ polarization extraction

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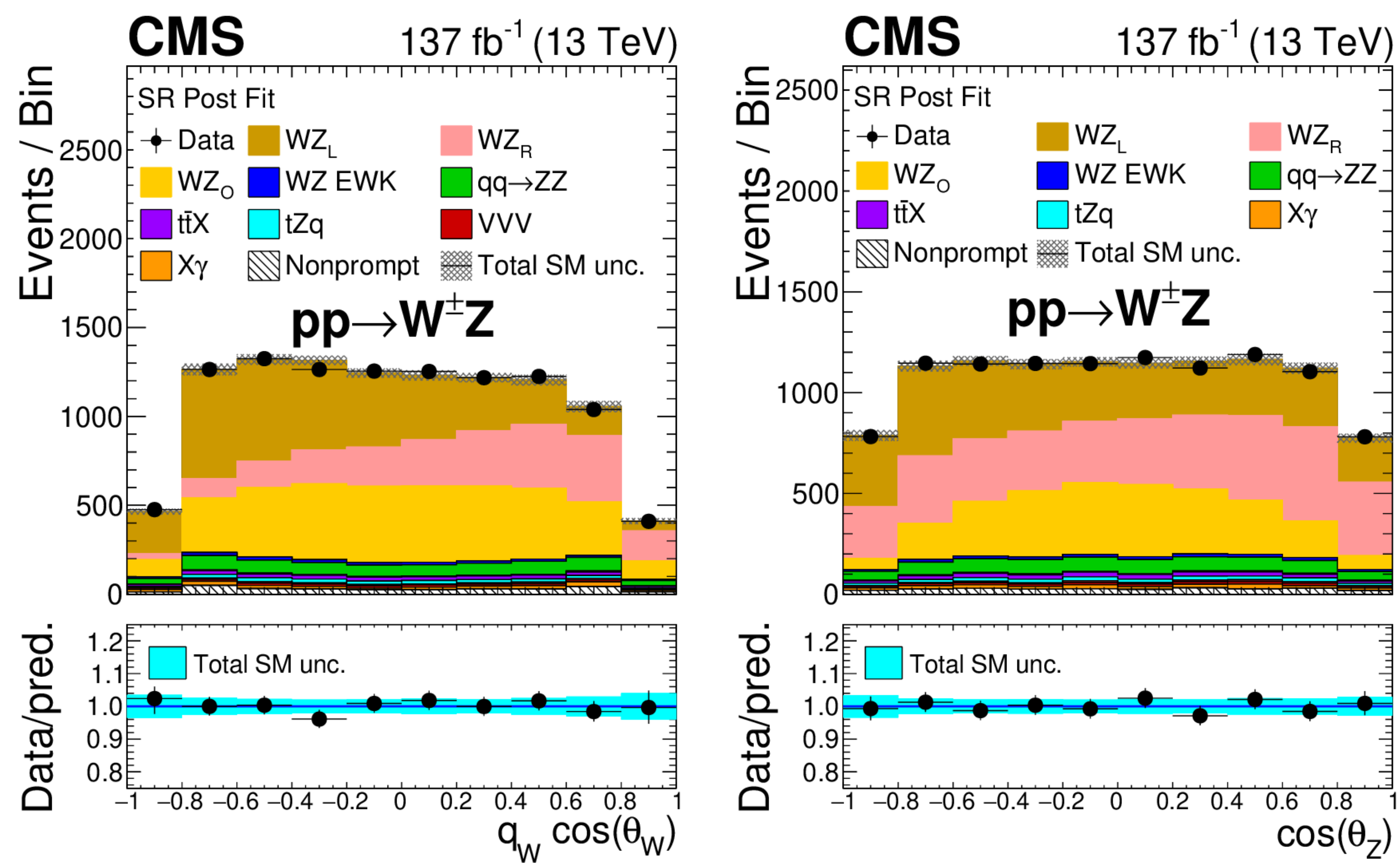
The statistical analysis

- The $\cos(\theta_V)$ distributions at the reconstructed level are fitted separately for W/Z production.
- Free parameters: μ (overall WZ cross-section), f0, and fL-fR are fitted simultaneously in all the measurements
- Simultaneous fit of SR and background CRs

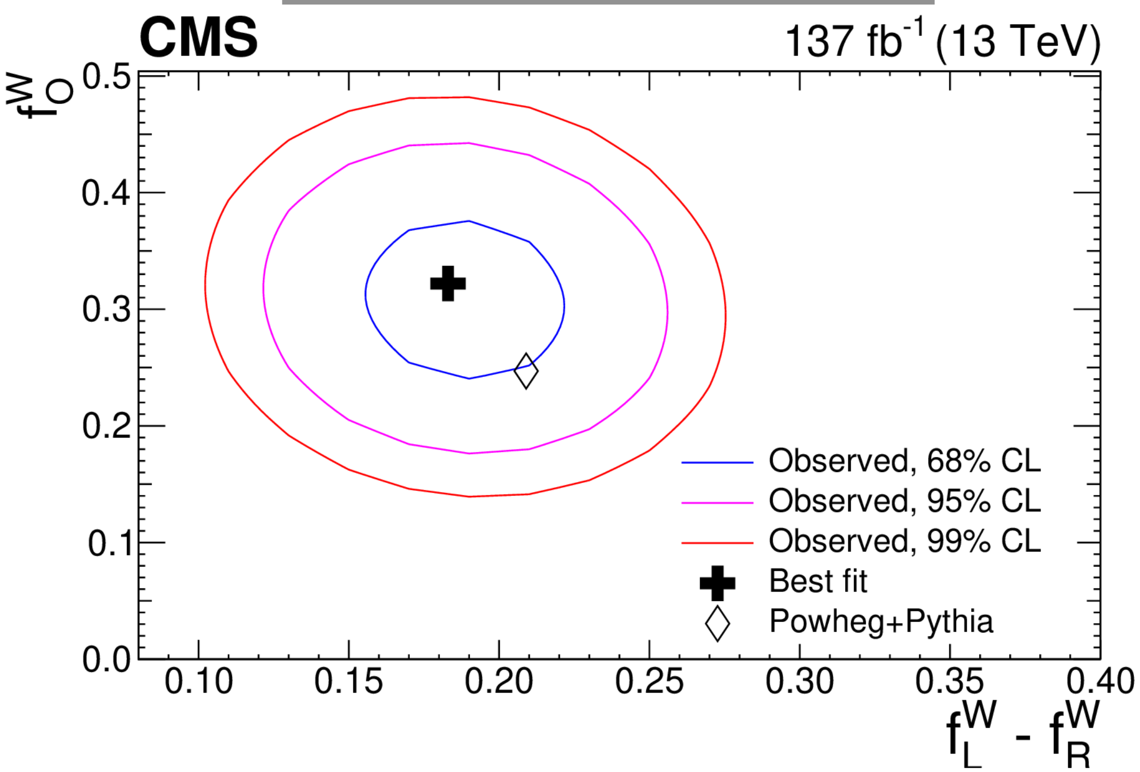


WZ polarization results

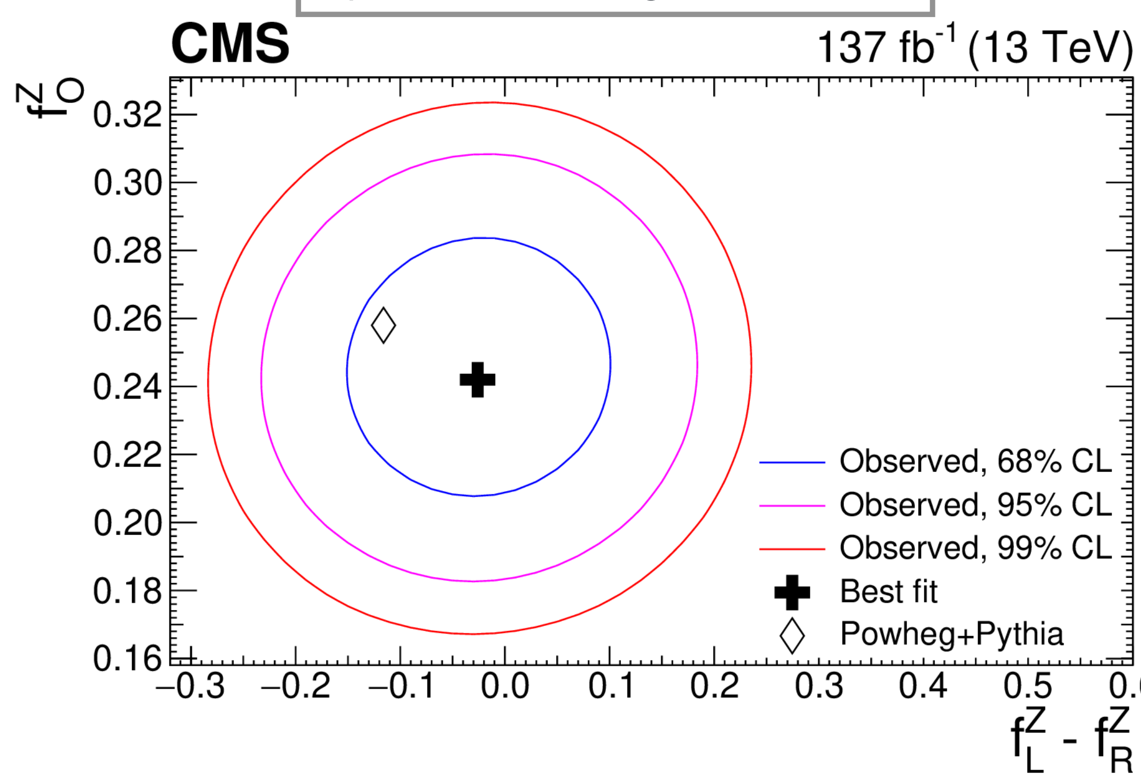
JHEP 07 (2022) 032

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

W polarization charge inclusive SR



Z polarization charge inclusive SR



- Overall results consistent between observations and predictions.
- 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.
- No strong correlation is found between the measured parameters on the fits

ATLAS Polarization in WZ measurement

[Phys. Lett. B 843 (2023) 137895]

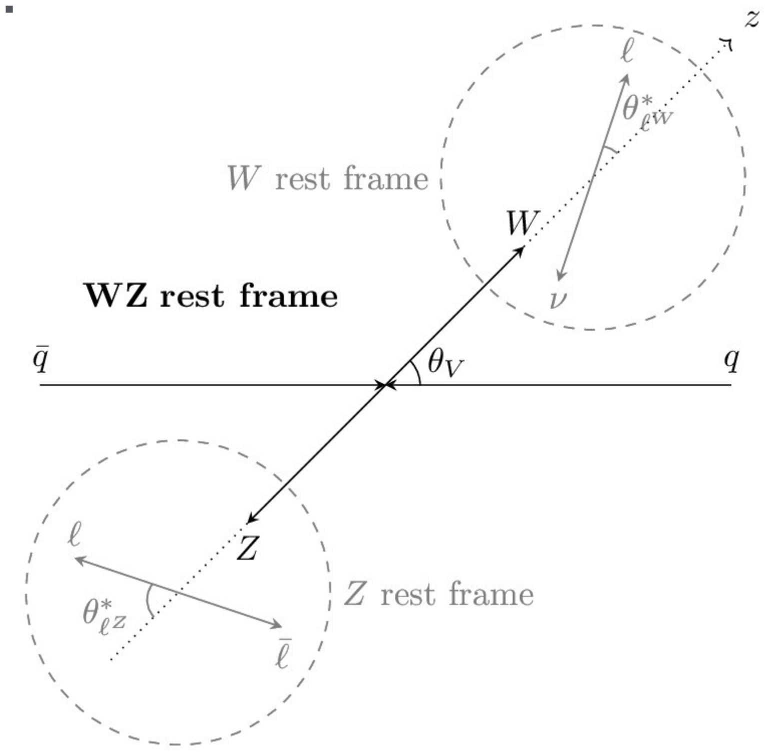
The analysis target

- Joint-polarizations: W_0Z_0, W_TZ_0, W_0Z_T , W_TZ_T
- Singly-polarized final states

The frame

- The WZ rest frame for single and joint polarizations as maximize the decorrelation of 00 and TT polarization modes

The frame:



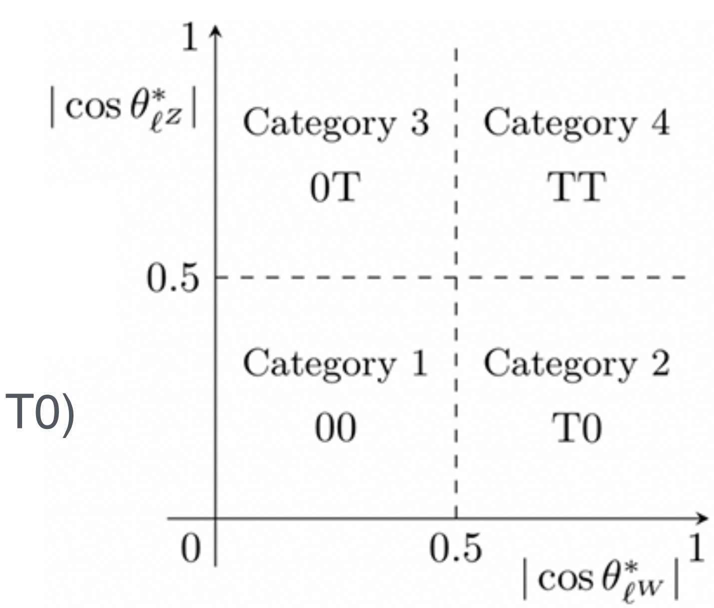
How is the analysis performed?

The templates challenge:

- Polarized templates available with Madgraph 2.7.3 at LO+real corrections → great! but insufficient, bias from 10% to 50% of the fraction values in this phase space
- Joint polarization templates at NLO-QCD obtained using several reweighing techniques
  - NLO-QCD at particle level available (MoCaNLO) [A. Denner and G. Pelliccioli arXiv:2010.07149]
  - Use DNN as a multi-dimensional reweigthing [arXiv:1907.08209]

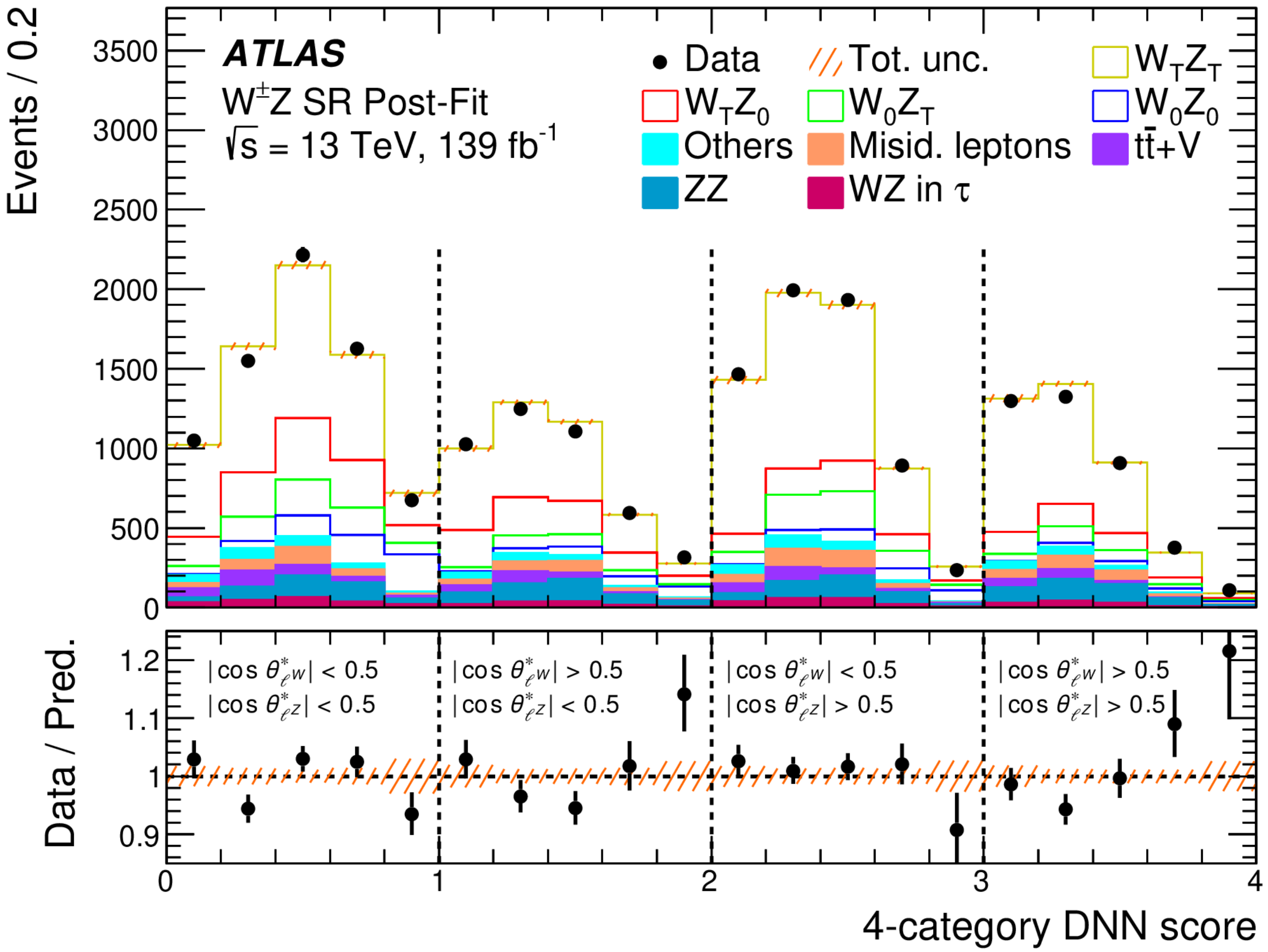
The joint-polarization extraction challenge:

- Four different polarizations fractions to extract
- DNN classifies each joint polarization state
- Events split in 4 categories based on cosθ* to discriminate mix states (0T, T0)



Joint-polarization WZ measurement

Phys. Lett. B 843 (2023) 137895



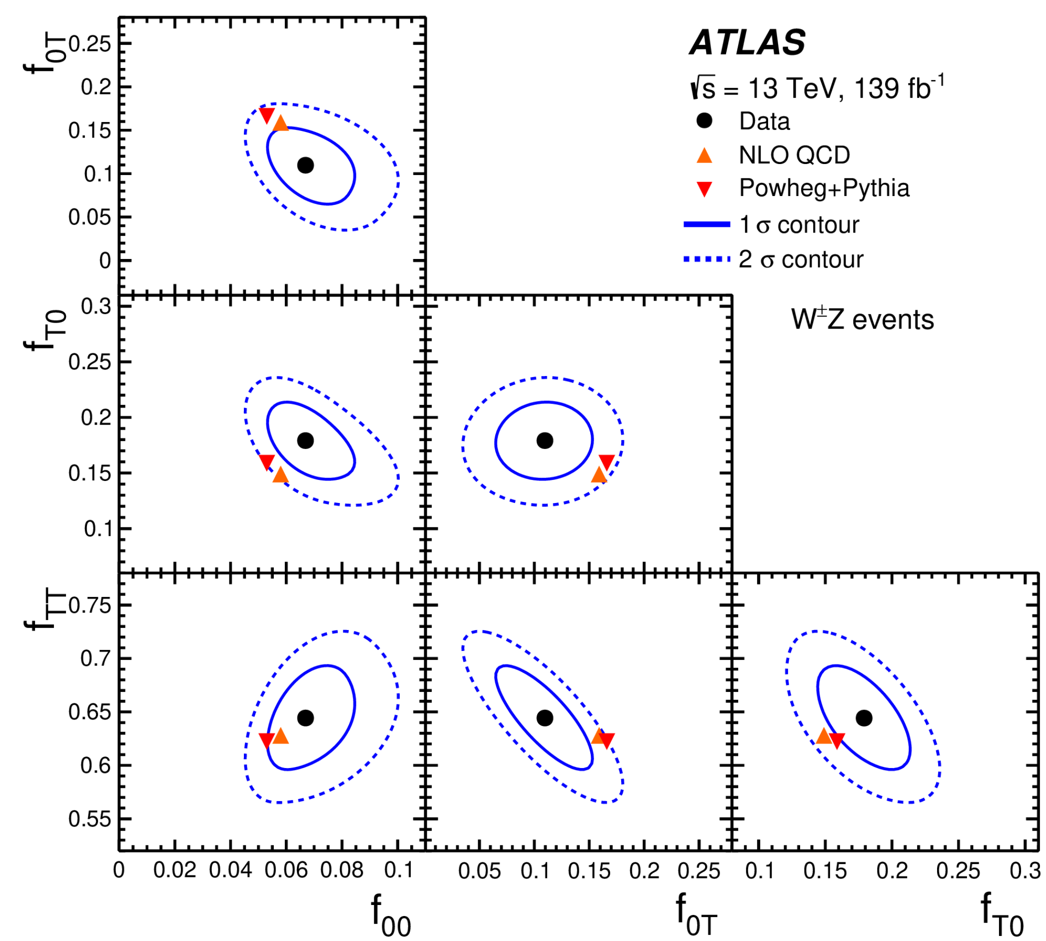
Statistical analysis

- Simultaneous fit of the 4 categories
- Statistical uncertainties at the same level as systematic uncertainties, mainly
  - Template modelling uncertainties **(Higher order QCD shape effects on polarization templates)**
  - QCD scale
  - E_T^{miss}/jets object reconstruction

First observation of joint polarisation states for diboson

- Significance on f_{00} at 7.1σ
- Significance on f_{TT} and f_{T0} >5σ

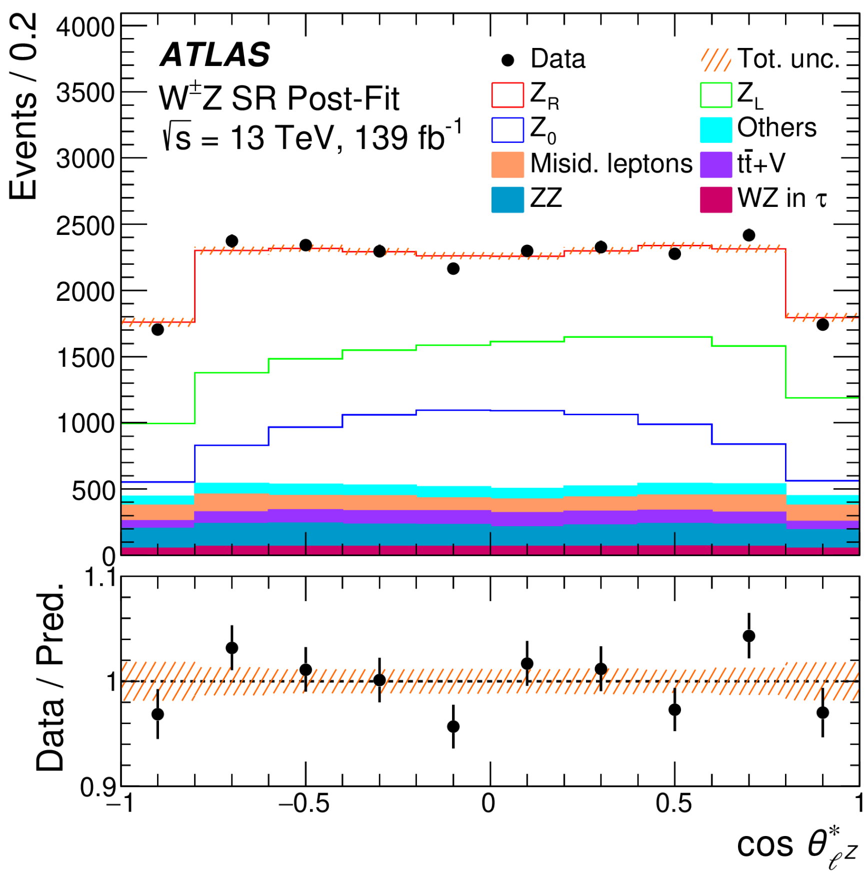
	Data	Powheg+Pythia	NLO QCD
		$W^{\pm}Z$	
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003
f_{T0}	0.179 ± 0.023	0.1465 ± 0.0017	0.149 ± 0.003
f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021	0.628 ± 0.004

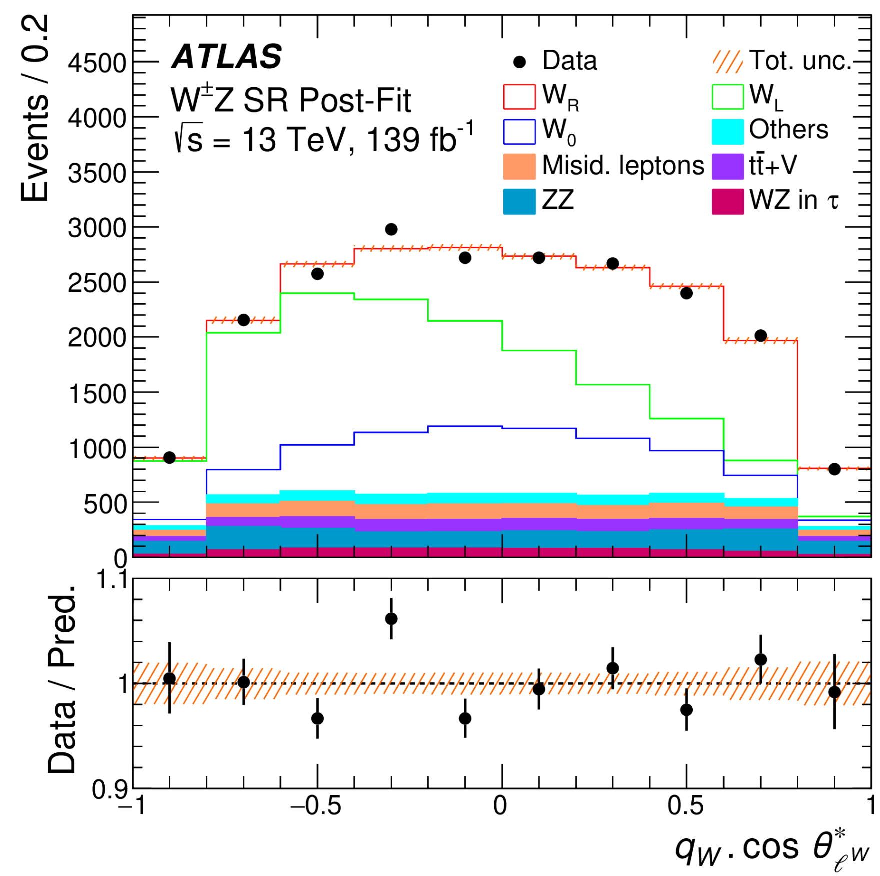


Single boson polarization WZ measurement

Phys. Lett. B 843 (2023) 137895

- Single Boson polarization: f_0 and f_L-f_R measured for W and Z boson
- Single Polarization templates using analytical reweighting agreed well with fitted templates with data
- f_0 measured with 5σ significance even in charge break-down





Are the polarization correlated?

- The spin correlations using $R_c = \frac{f_{00}}{f_0^W f_0^Z}$
- If uncorrelated $R_c = 1$ while SM (NLO QCD) predicts $R_c = 1.3$
- Measured $R_c = 1.54 \pm 0.35$ (Obs. Significance 1.6σ wrt $R_c = 1$ hypothesis)

	Data	POWHEG+PYTHIA
	$W^{\pm}Z$	
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017
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f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021

RAZ effect and energy dependence of WZ polarization fractions

Submitted to PRL

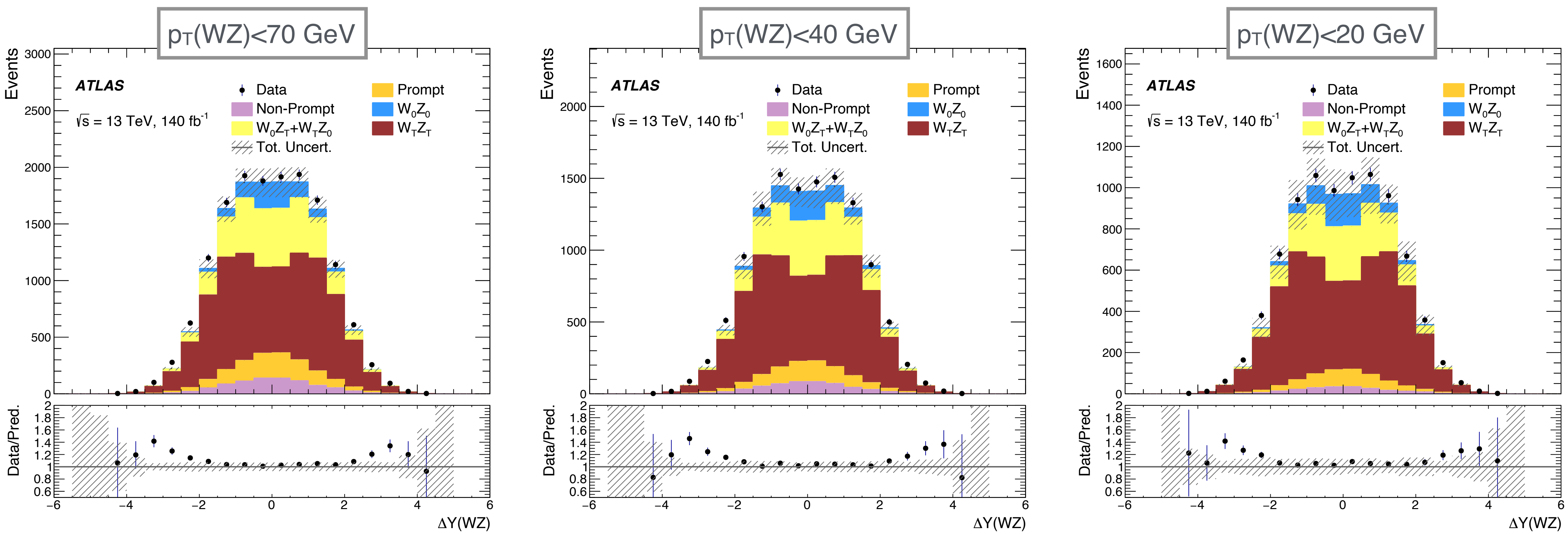
New!

The analysis target

- Radiation Amplitude Zero (RAZ) effect for WZ
- Joint-polarizations at high $p_T(Z)$: W_0Z_0, W_TZ_0, W_0Z_T , W_TZ_T

Radiation Amplitude Zero effect

- At LO strong gauge cancellations making a drop in the TT cross-section (true for WZ and Wγ [D0 result])
- Use a $p_T(WZ)$ cut to reduce the jet activity → tighter $p_T(WZ)$ cut → more LO like Phase Space!



- **Polarization modelling:** Madgraph LO 0+1j merged samples. Uncertainties by reweighing to NLO QCD+EW based on fix order predictions (G. Pellicciolo, Duc Ninh Le)

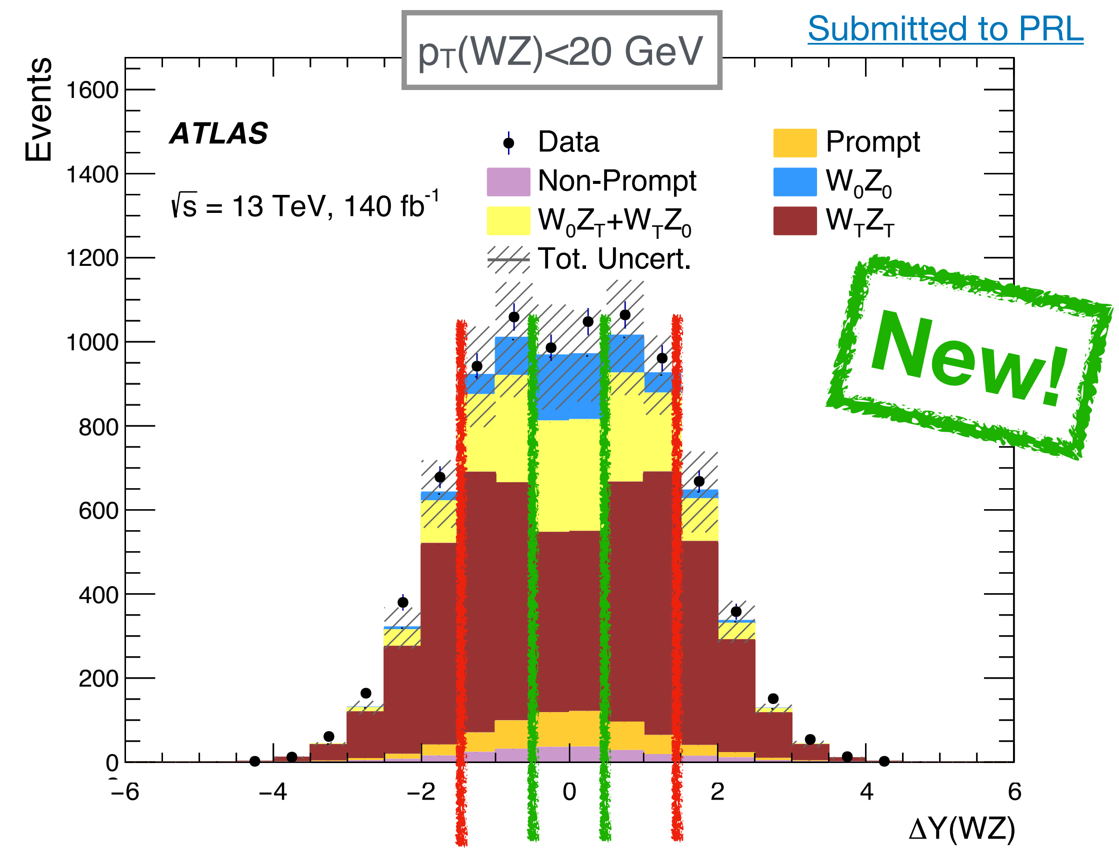
Radiation Amplitude Zero effect in WZ

Submitted to PRL

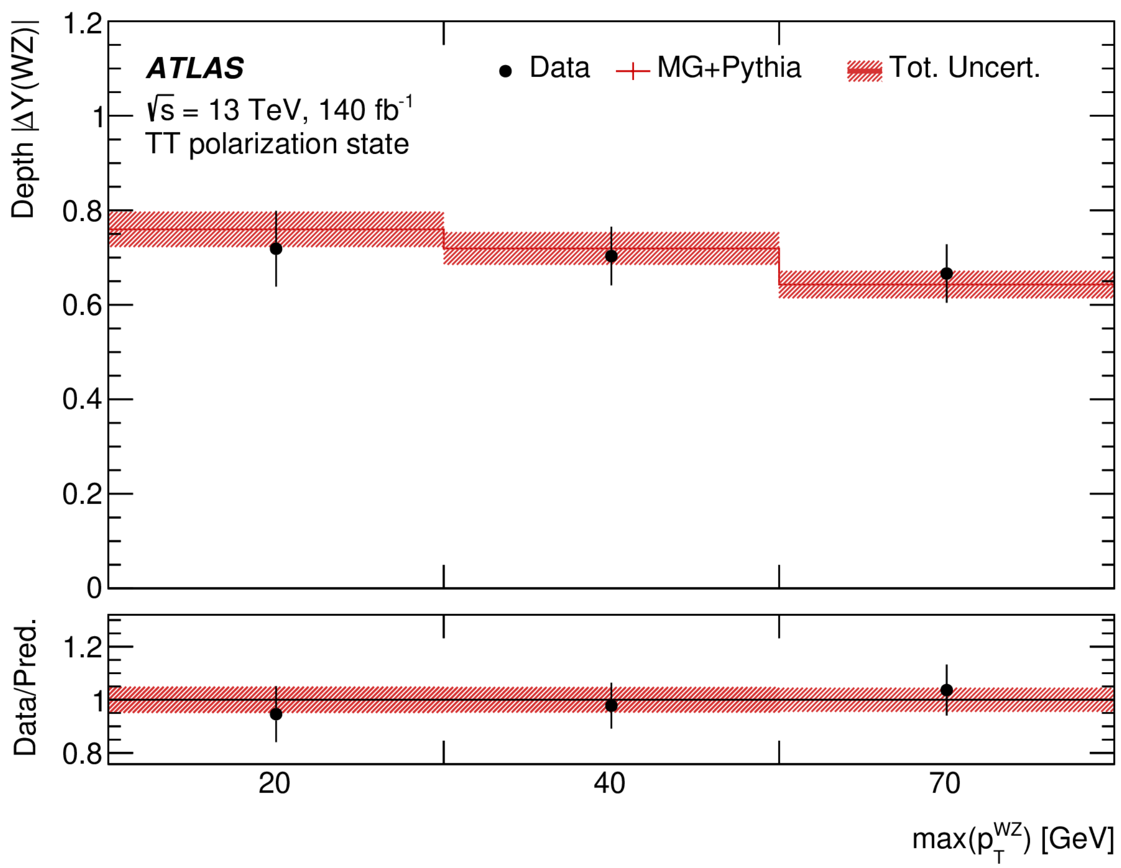
- Define a Depth variable to qualify how deep is the TT deep

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

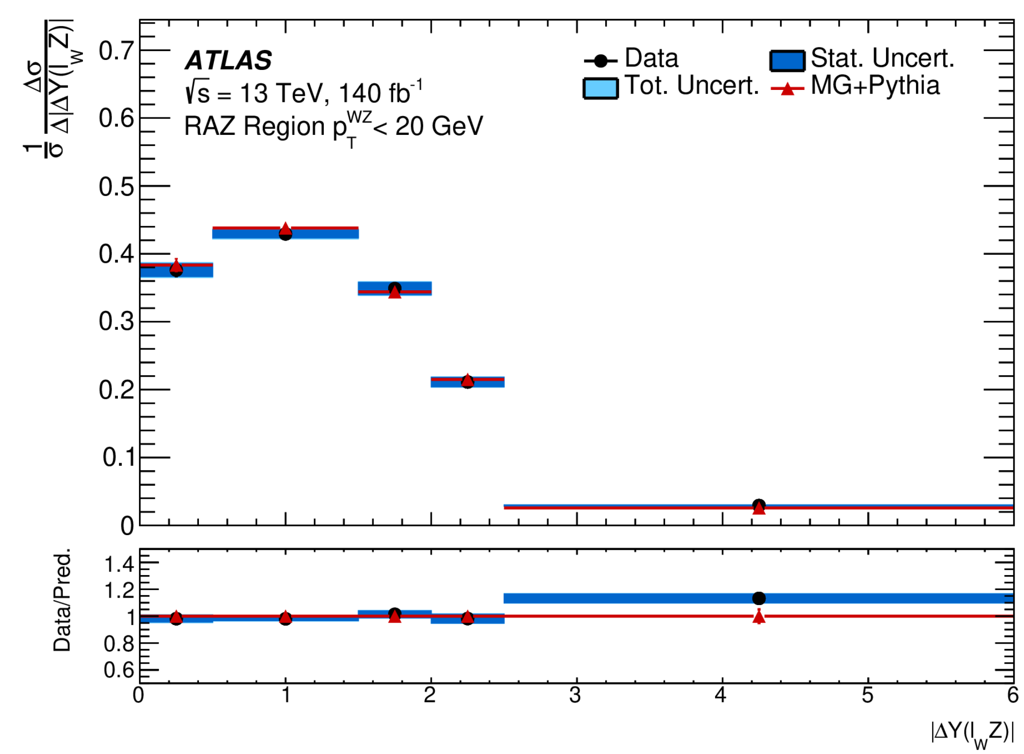
- D = 0 no deep
- D < 0 an excess
- D > 0 means there is a deep



- Calculated the depth using unfolded TT only distributions (00+0T+T0-subtracted) for different $p_T(WZ)$ cuts



- Unfolded angular variables (w.o subtracting any polarization state)



- **Depth variable well above 0 ! We see the RAZ deep !**

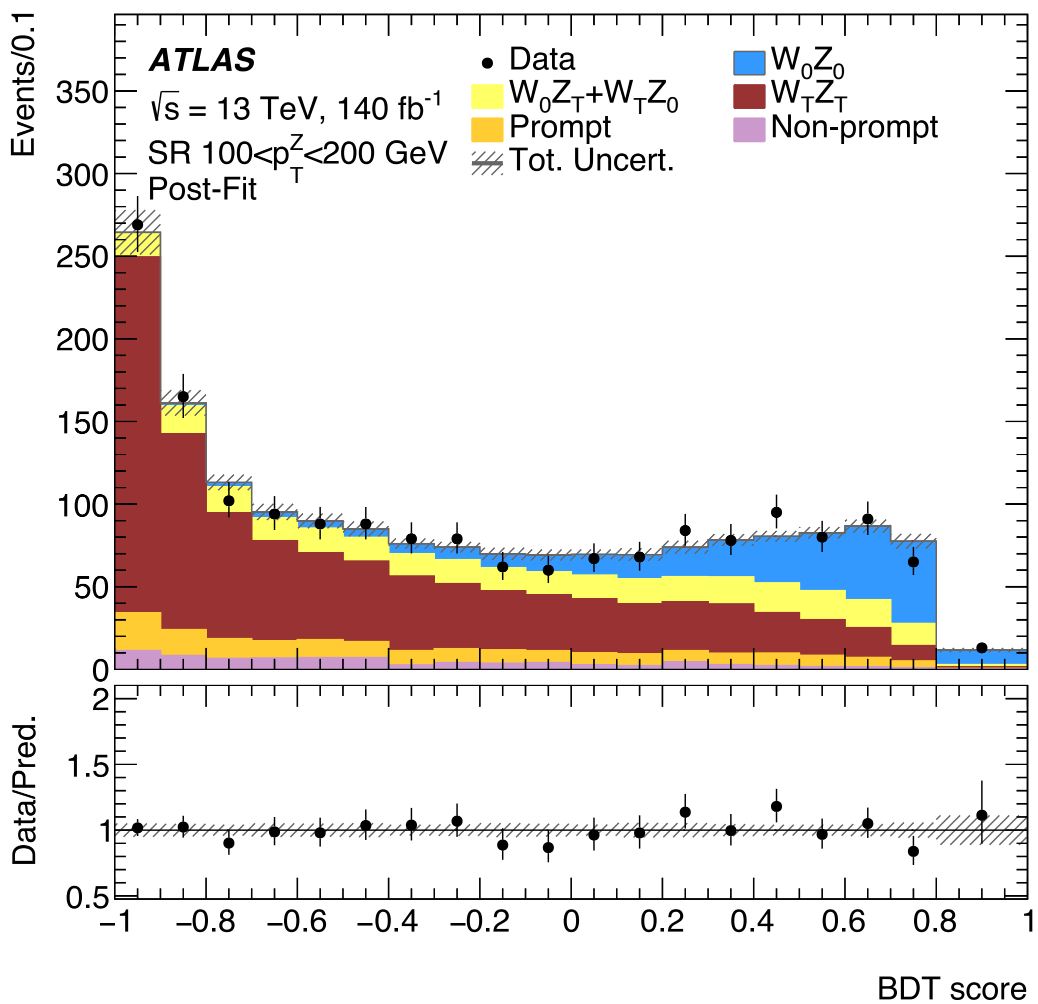
WZ join polarization - 00-enhaced region

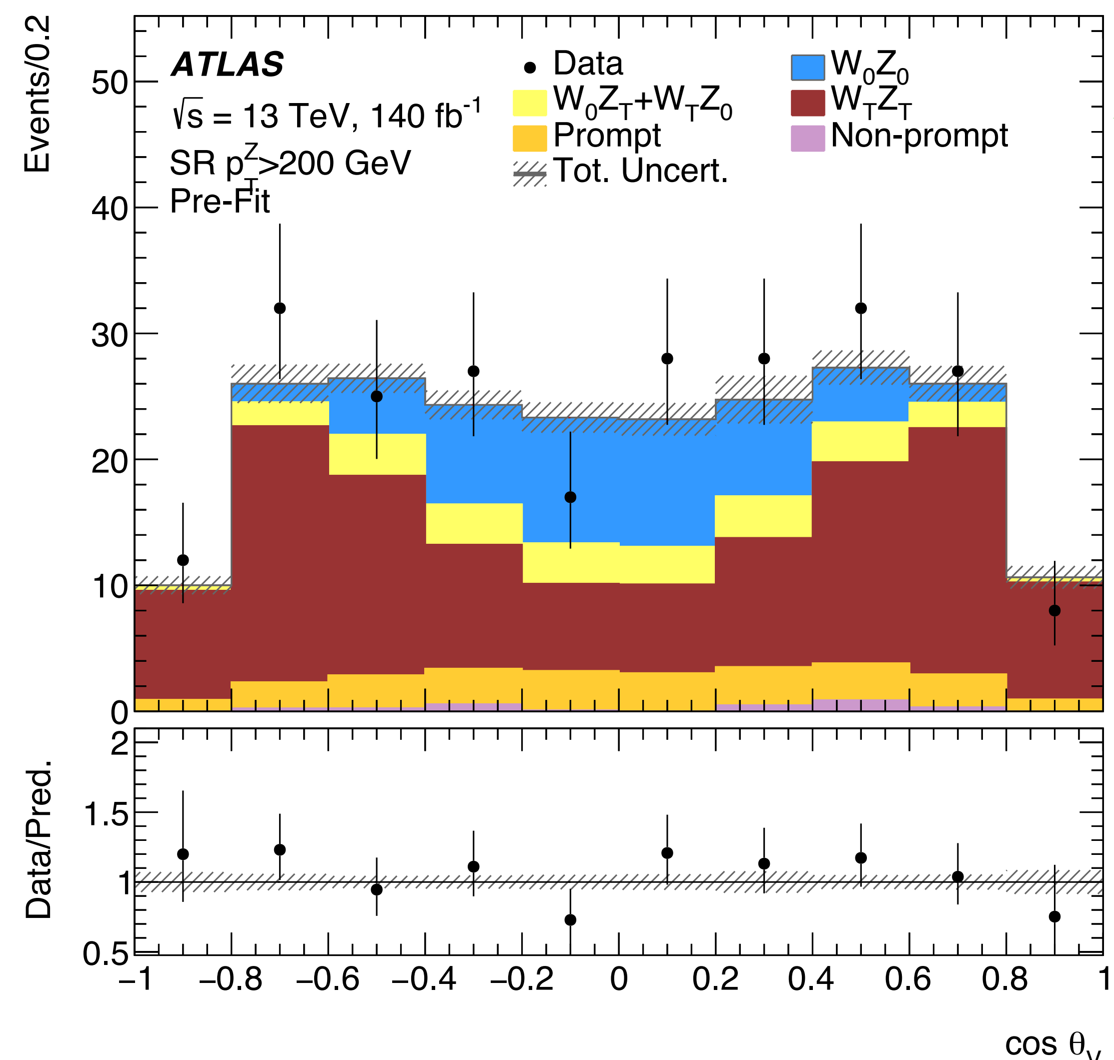
[Submitted to PRL]

- To increase the contribution of the longitudinal component we use $p_T(WZ)<70$ GeV and do the measurement in 2 $p_T(Z)$ bins [100,200] and [200, inf] GeV
- Double Longitudinal component increased up to 23%
- Relative s-channel contribution expected to be higher at high $p_T(Z)$
- To separate the polarization components dedicated BDT were trained for each $p_T(Z)$ bin

	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

New!





WZ join polarization - 00-enhaced region

Submitted to PRL

Statistical analysis

- Fit performed using 2 configurations (more free parameters less model dependent):
  - 3 parameters: 00, T0+0T and TT
  - 2 parameters: 00 vs T0+0T+TT
- Dominated by statistical uncertainties, but NLO EW and QCD uncertainties have the largest impact!

	Prediction	
	100 < p_T^Z ≤ 200 GeV	**p_T^Z > 200 GeV**
f_{00}	0.152 ± 0.006	0.234 ± 0.007
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f_{TT}	0.619 ± 0.007	0.646 ± 0.008

New!

3 free parameters

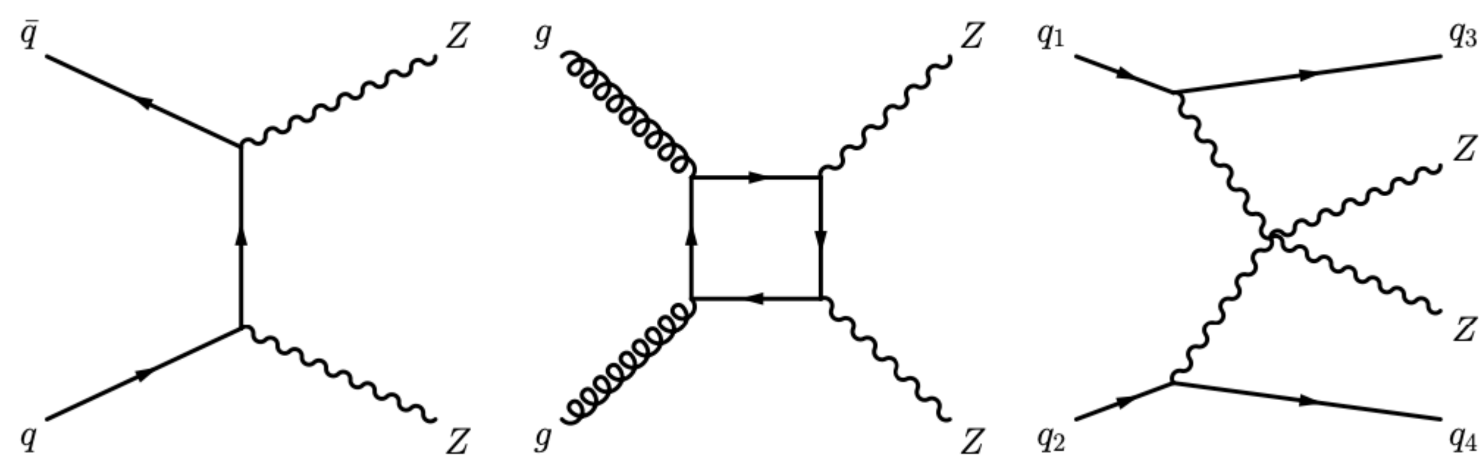
	Measurement	
	100 < p_T^Z ≤ 200 GeV	**p_T^Z > 200 GeV**
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (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

2 free parameters

	Measurement	
	100 < p_T^Z ≤ 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

- **We are able to reach observation/ evidence of double longitudinal bosons at high p_T (Z) !!** → approaching the regime where longitudinal bosons already behave as Goldstone bosons

Polarization measurement in ZZ

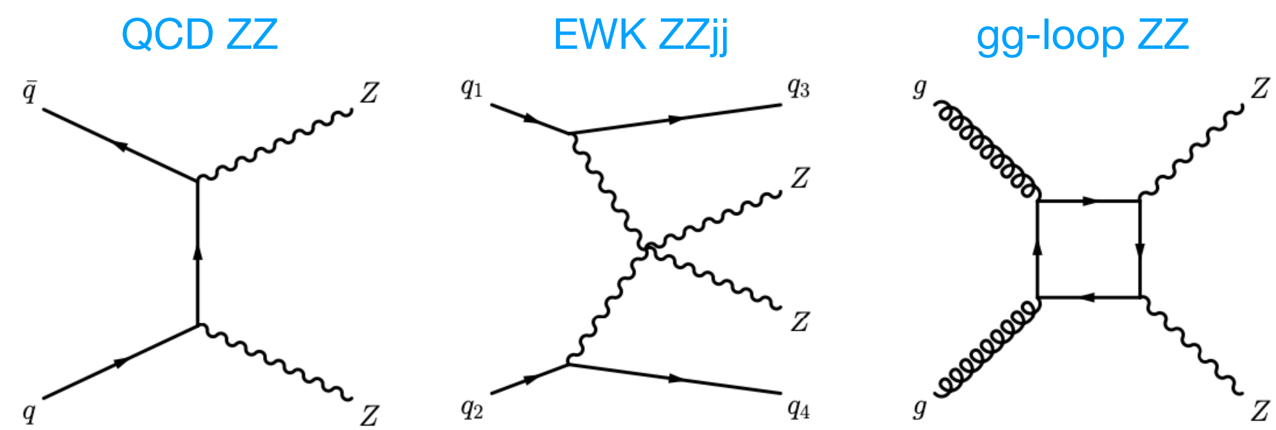


ATLAS ZZ →4ℓ Polarization

JHEP 12 (2023) 107

The analysis target

- Joint-polarizations: Z_LZ_L and $Z_LZ_{T+}Z_TZ_T$
- The frame: The centre-of-mass frame of the two Z bosons



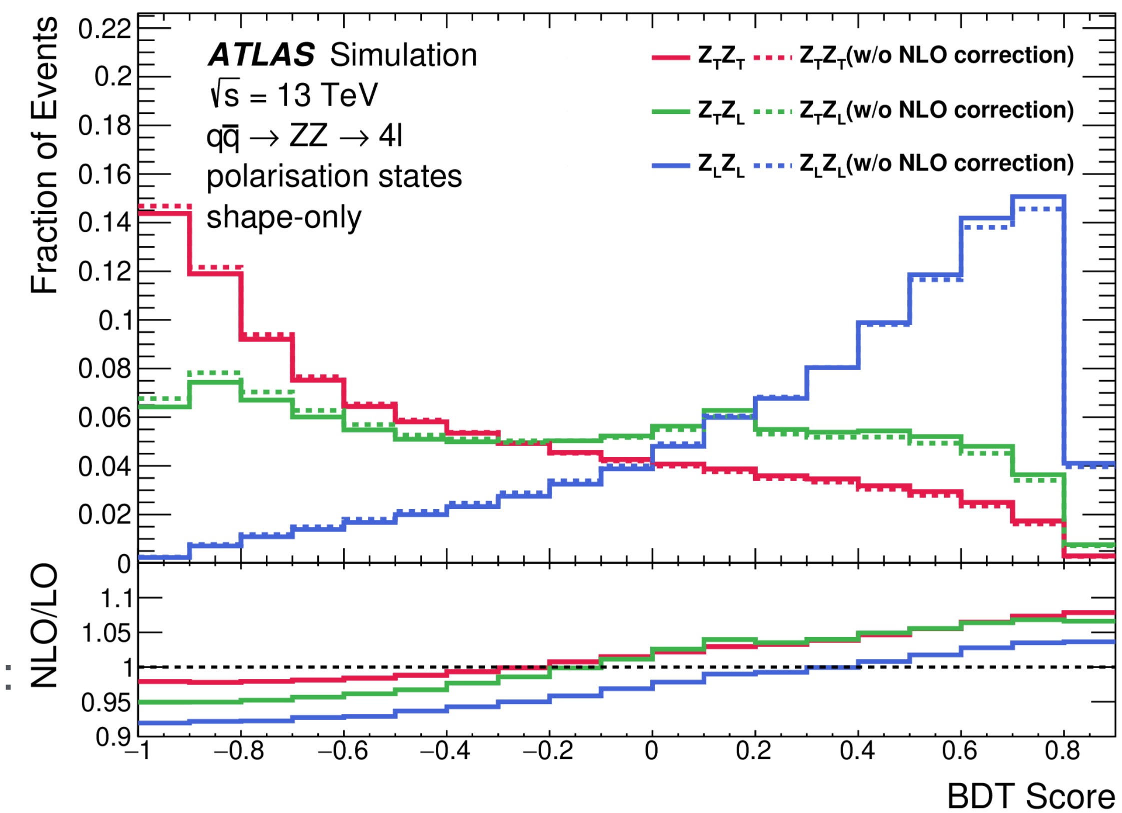
How is the analysis performed?

The joint-polarization extraction challenge:

- Boosted Decision Tree trained to discriminate Z_LZ_L vs Z_TZ_X
- Using the leptons and Z bosons angular variables

The templates challenge:

- Polarized templates available with Madgraph 2.7.3 for
  - QCD and EWK, but…
  - Not possible for the loop-induced gg
- NLO EW + QCD corrections and the loop-induced gg calculations are available for ZZ at particle level (MoCaNLO) [A. Denner and G. Pelliccioli JHEP10(2021)097]
- A three step reweighing method using 1D and 2D distributions to:
  - Incorporate NLO EW + QCD corrections to the Madgraph 2.7.3 simulation
  - Obtain polarized templates from the unpolarized Sherpa the loop-induced gg MC sample
  - Include interference effects among the polarization templates (non-negligible for some observables)



ATLAS ZZ →4ℓ Polarization

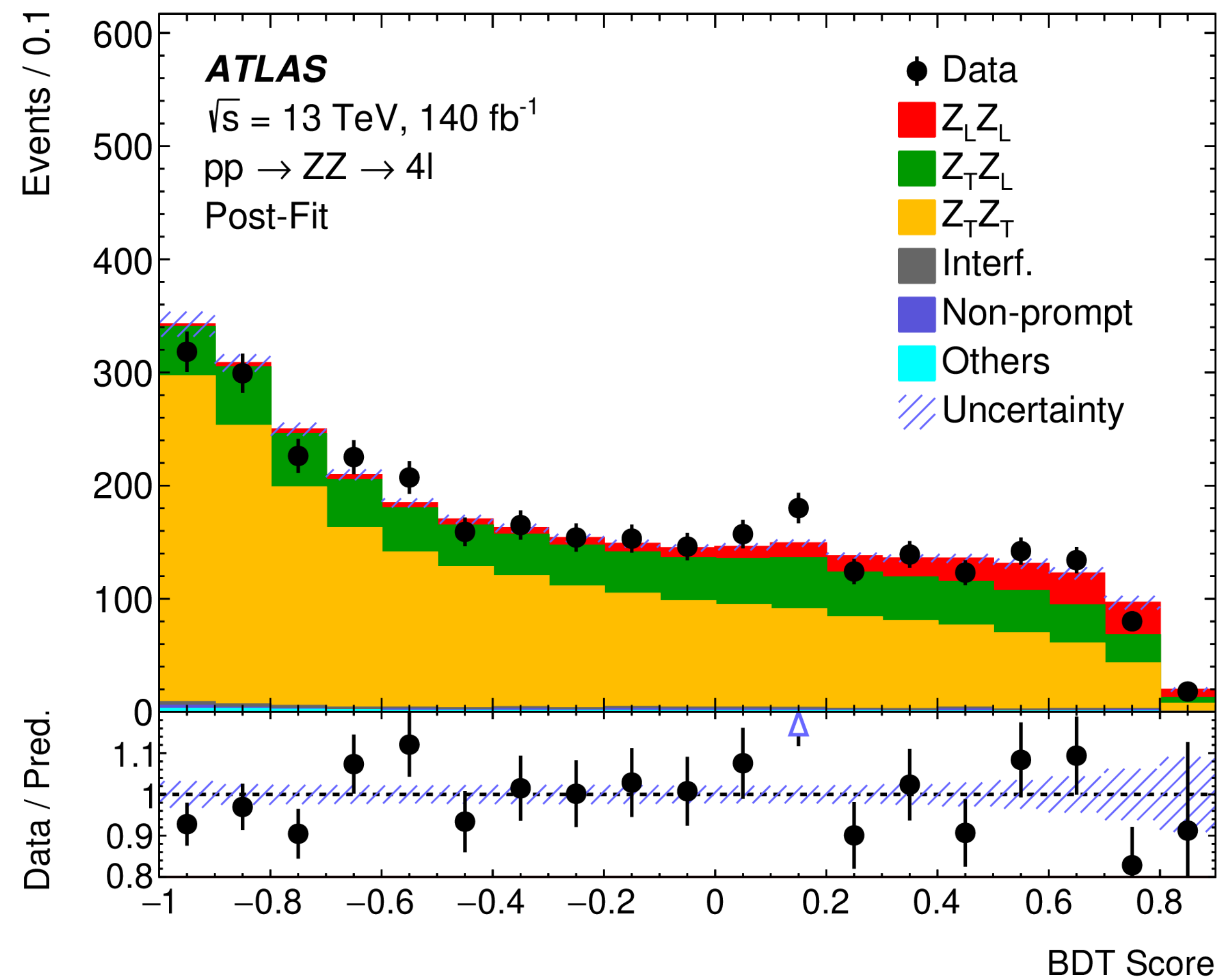
JHEP 12 (2023) 107

Evidence of longitudinally polarized bosons in ZZ!

- Fit using 2 free parameters Z_LZ_L vs Z_TZ_X
- **Evidence for Z_LZ_L with 4.3σ (3.8σ exp.)**
- Measured Z_LZ_L cross section in agreement with predictions $\sigma^{\text{pred.}}_{Z_LZ_L} = 2.10 \pm 0.09$ fb.

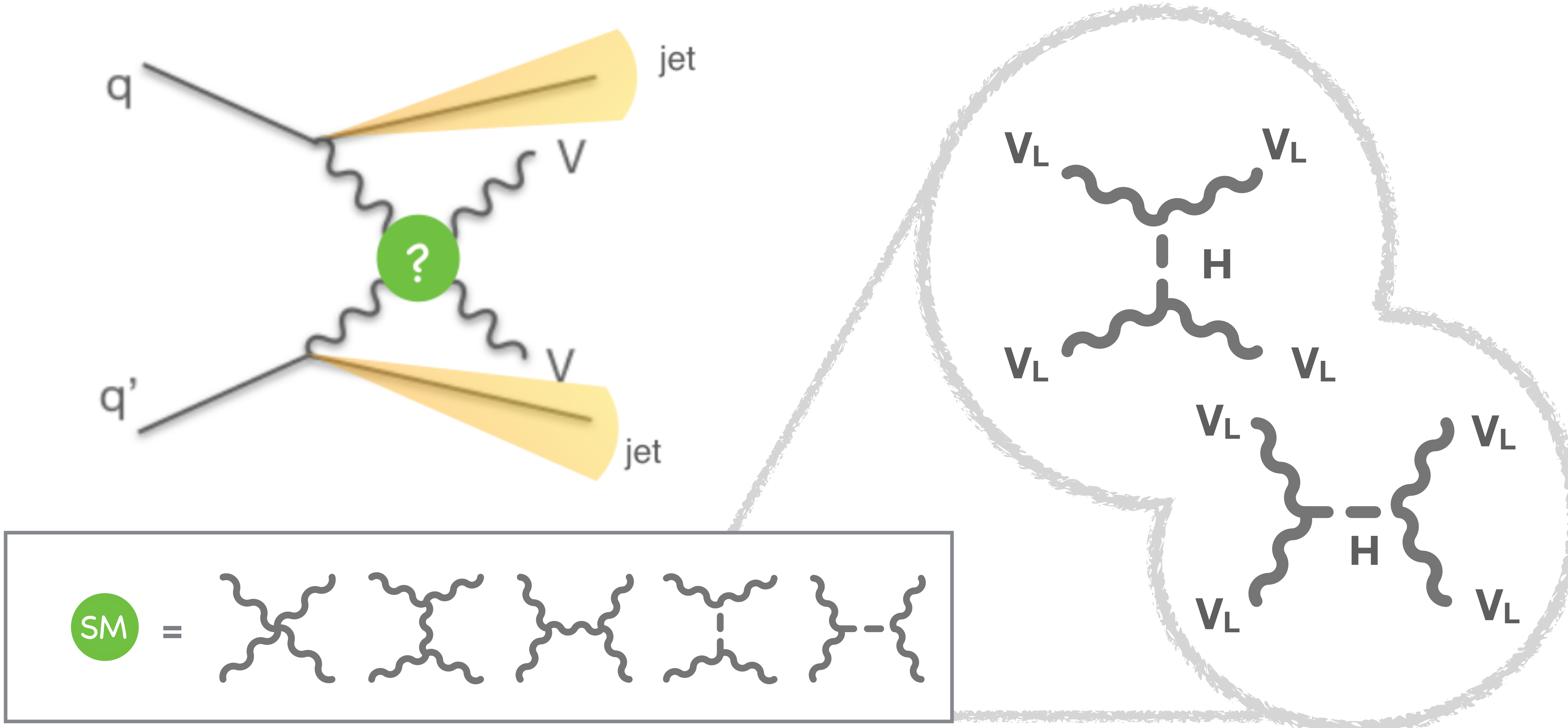
$$\sigma^{\text{obs.}}_{Z_LZ_L} = 2.45 \pm 0.56(\text{stat.}) \pm 0.21(\text{syst.})\ \text{fb}$$

Contribution	Relative uncertainty [%]
Total	24
Data statistical uncertainty	23
Total systematic uncertainty	8.8
MC statistical uncertainty	1.7
Theoretical systematic uncertainties	
$q\bar{q} \to ZZ$ interference modelling	6.9
NLO reweighting observable choice for $q\bar{q} \to ZZ$	3.7
PDF, α_s and parton shower for $q\bar{q} \to ZZ$	2.2
NLO reweighting non-closure	1.0
QCD scale for $q\bar{q} \to ZZ$	0.2
NLO EW corrections for $q\bar{q} \to ZZ$	0.2
$gg \to ZZ$ modelling	1.4
Experimental systematic uncertainties	
Luminosity	0.8
Muons	0.6
Electrons	0.4
Non-prompt background	0.3
Pile-up reweighting	0.3
Triboson and $t\bar{t}Z$ normalisations	0.1



- Modelling uncertainties coming from the reweighing procedure among the most important ones!

Polarization measurements in Vector Boson Scattering



Phys. Lett. B 812 (2020) 136018

VBS same sign WW polarization measurement

- First polarization measurement in VBS using @13 TeV (137 fb^{-1}, full run-2)

The analysis target

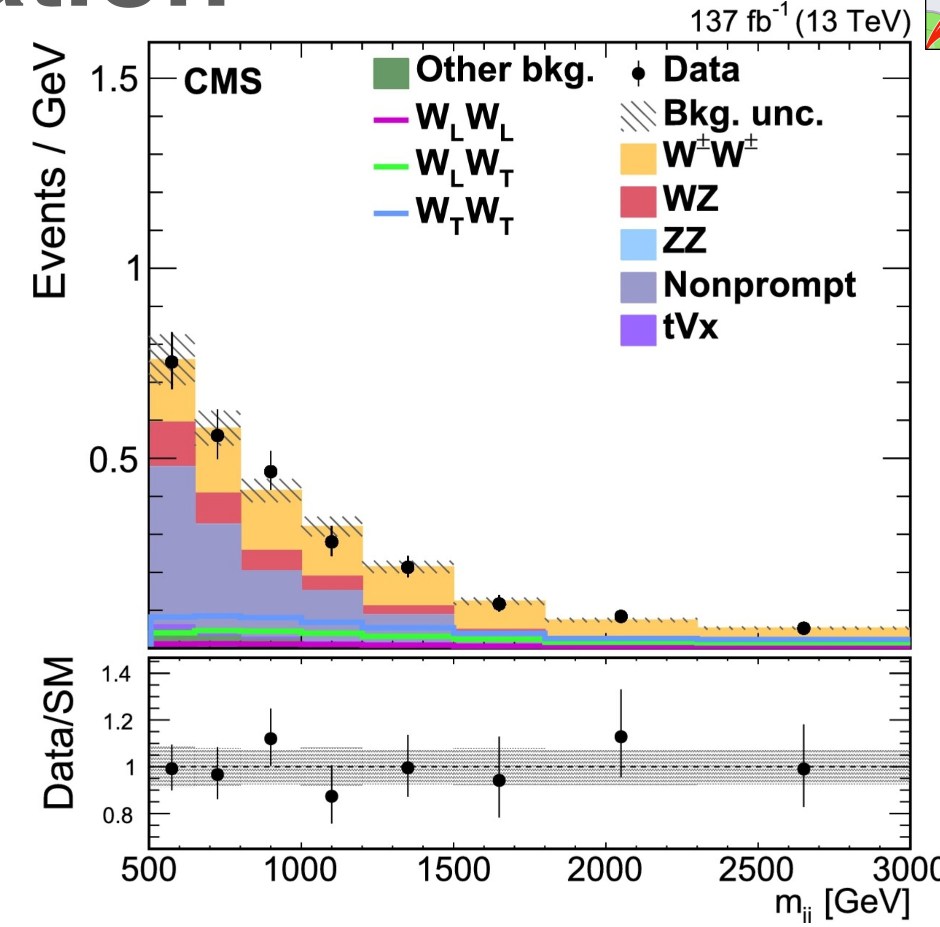
- doubly polarized final states: W_LW_L, W_TW_T, W_LW_T
- single boson longitudinal polarization: W_LW_X and W_TW_X production (any polarization for the second boson).

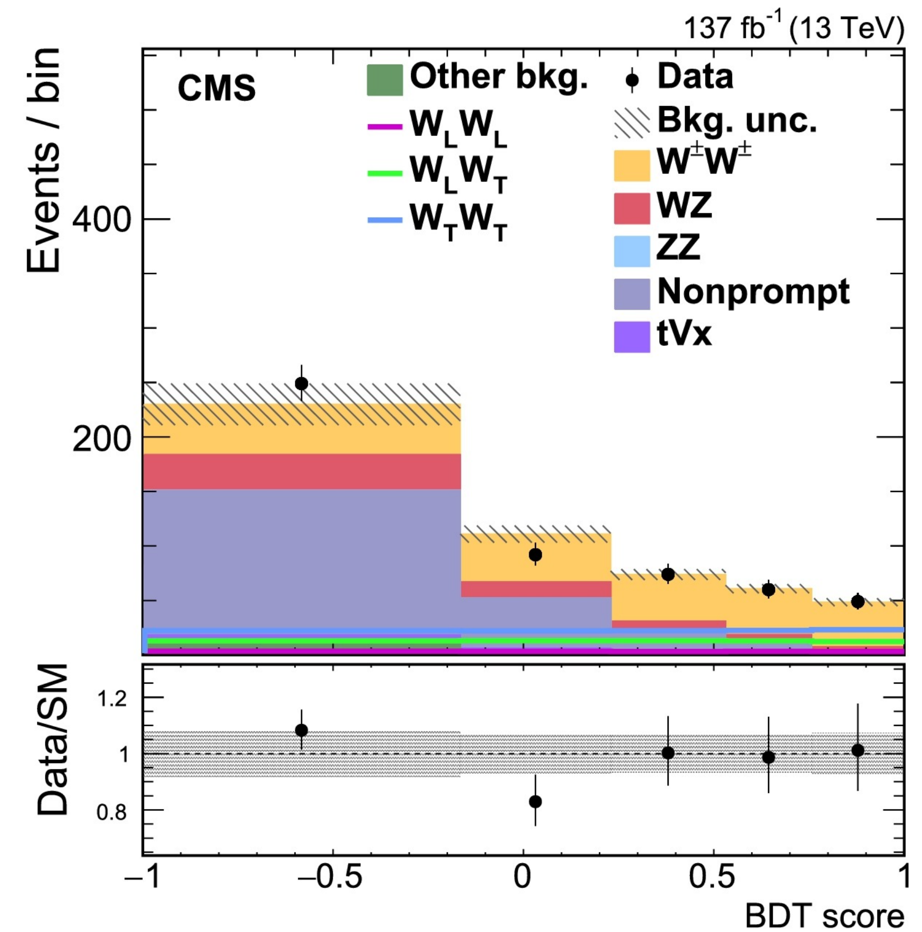
The challenge

- Separation Signal from Background (WZ, Nonprompt)
- Separation between the different polarization modes themselves.

How is the analysis performed?

- Polarization templates take directly from Madgraph
- Cut-based SR selection, that exploits:
  - VBS topology requires m_{jj}>500 GeV and lepton Zeppenfeld's .
  - fully leptonic W decays: leptons p_T>25/20 GeV, p_T^{miss}>30 GeV
- Three BDTs are trained:
  - Inclusive BDT: ssWW signal vs background
  - LL vs the rest: To extract W_LW_L and W_TW_X
  - TT vs the rest: To extract W_LW_X and W_TW_T





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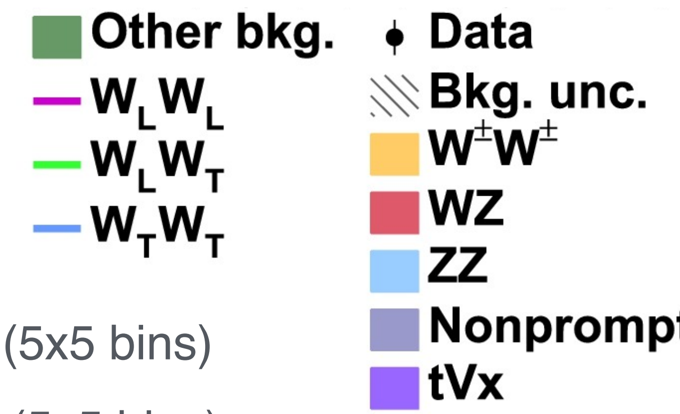
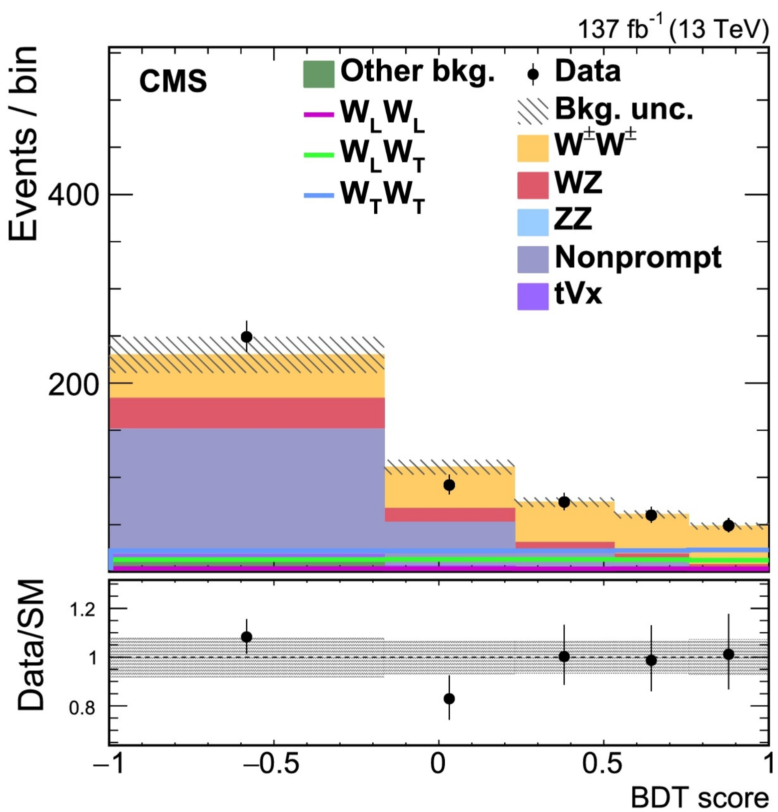


The statistical analysis

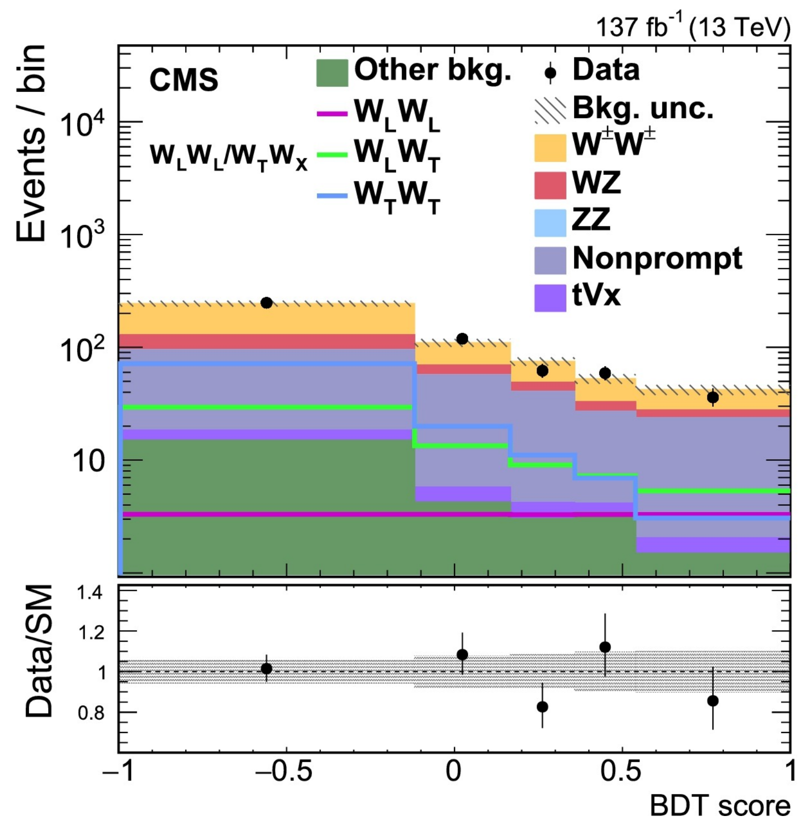
- Two fits performed depending on the signal hypothesis
  - To extract W_LW_L and W_TW_X cross sections: Inclusive BDT x “LL vs all” BDT (5x5 bins)
  - To extract W_TW_T and W_LW_X cross sections: Inclusive BDT x “TT vs all” BDT (5x5 bins)

Inclusive BDT



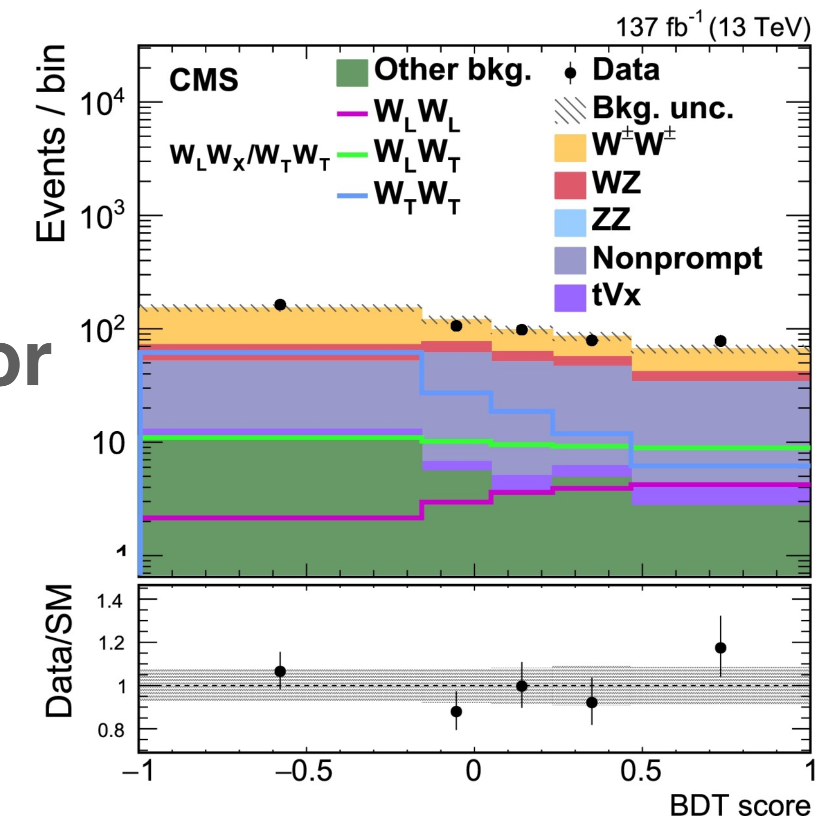
x

LL vs all BDT



or

TT vs all BDT



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The results

- Presented in the WW reference frame and in the incoming parton frame

Results in the WW reference frame

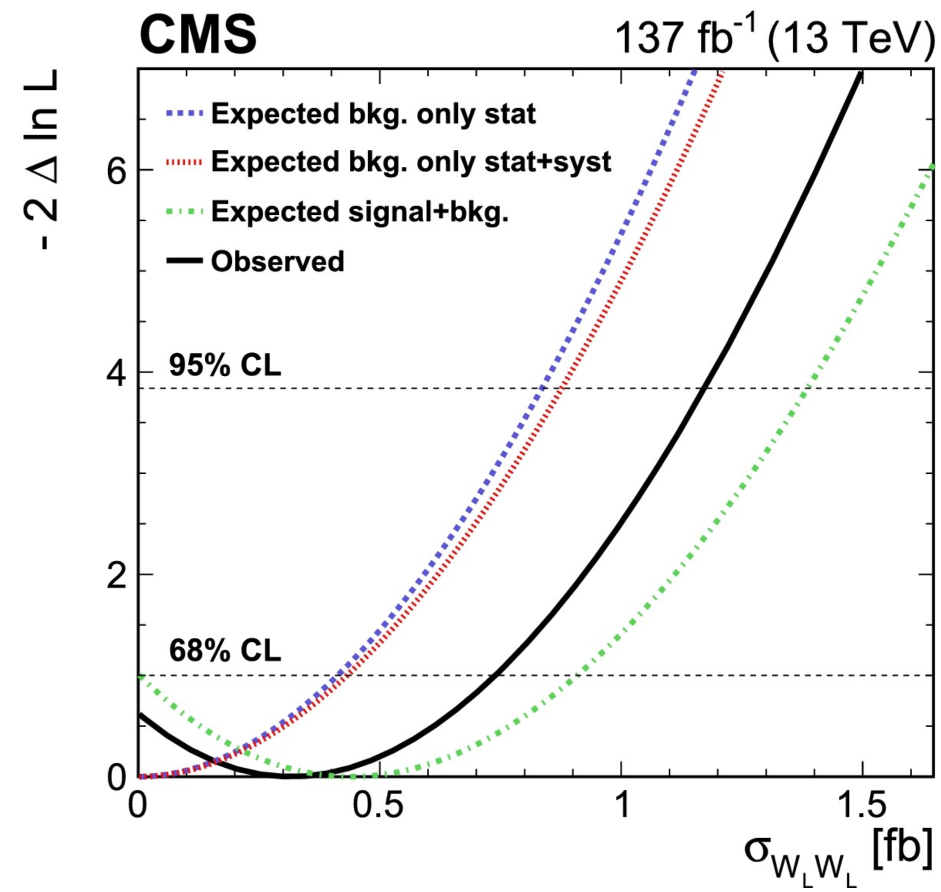
- Significance for LX production at 2.3σ (3.1σ expected)

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

Results in the incoming parton reference frame

- Significance for LX production at 2.6σ (2.9σ expected)

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

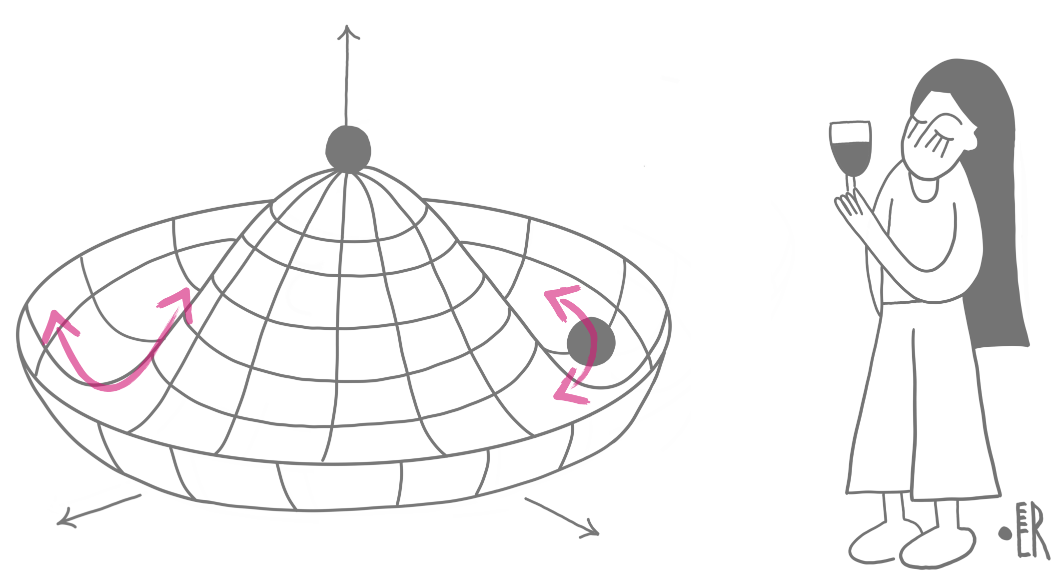


Uncertainties

- 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

Summary

- The measurements of Weak boson polarization are interesting!
    - they probe the ingredients of the EWSB
    - are an interesting corner to look for new physics
- With our current data we are already able to probe the polarization fractions in VV production.
    - Results include the first evidence or observation of double longitudinally polarized gauge bosons in VV production
    - Big limiting factor for our measurements is the modelling of the polarization templates! → theory community is actively working on the topic!
    - VBS 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!
- 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 of angular distributions are closely related and can be used for re-interpretations, combinations, etc… we have them for WZ, same-sign WWjj, WW, ZZ and Z VBF



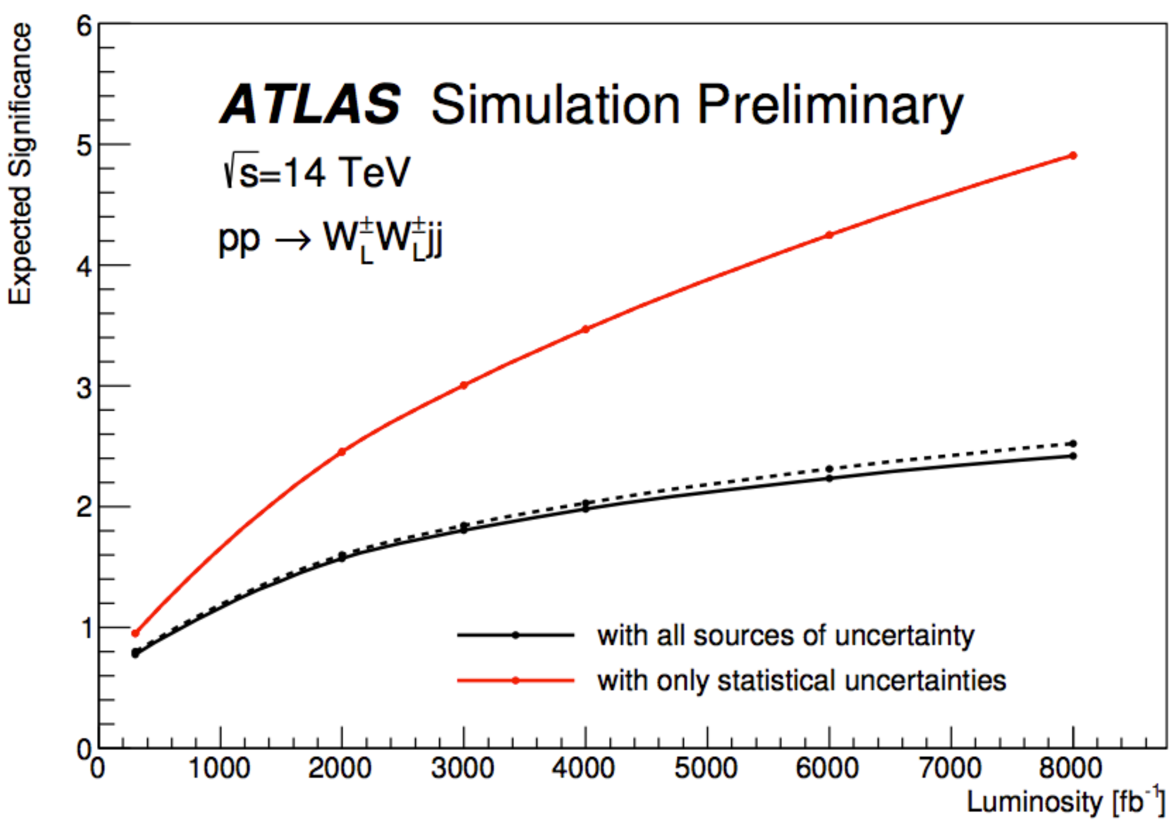
Do you want on polarization?

Polarization Workshop: https://indico.cern.ch/event/1371888/overview
MBI conference: https://indico.cern.ch/event/1383159/

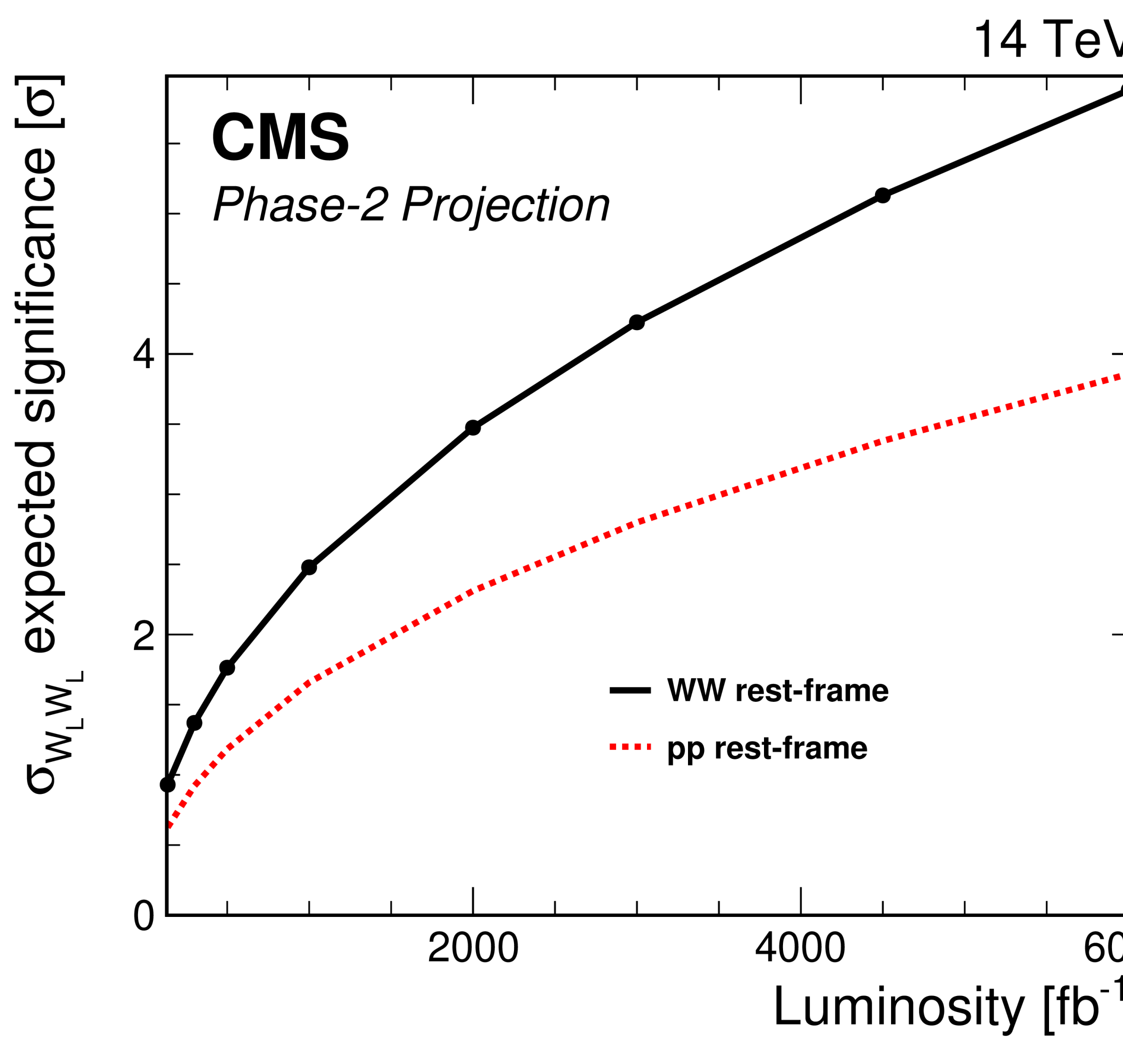
..and in the future

- Some projection studies for polarization measurements in the HL-LHC can be found in the Yellow Report (using the parton center of mass frame).
- A lot of new results expected as we take more and more data in the future!

ATL-PHYS-PUB-2018-052



- Simple cut-based analysis



CMS-PAS-FTR-21-001

- Almost the same analysis as presented before