TECHNISCHE UNIVERSITÄT DRESDEN

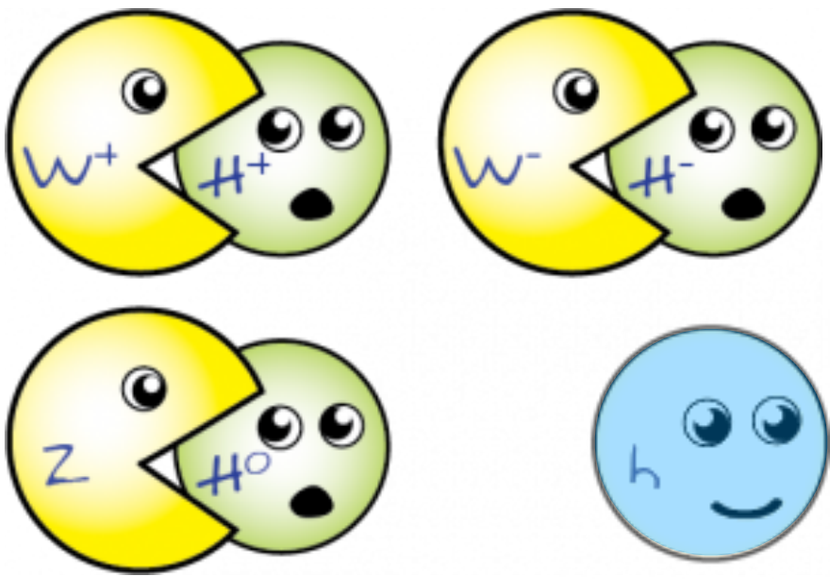
# Polarized Weak Bosons at the LHC

Joany Manjarrés Ramos
on behalf of the ATLAS and CMS collaborations

# Why weak boson polarization is interesting?

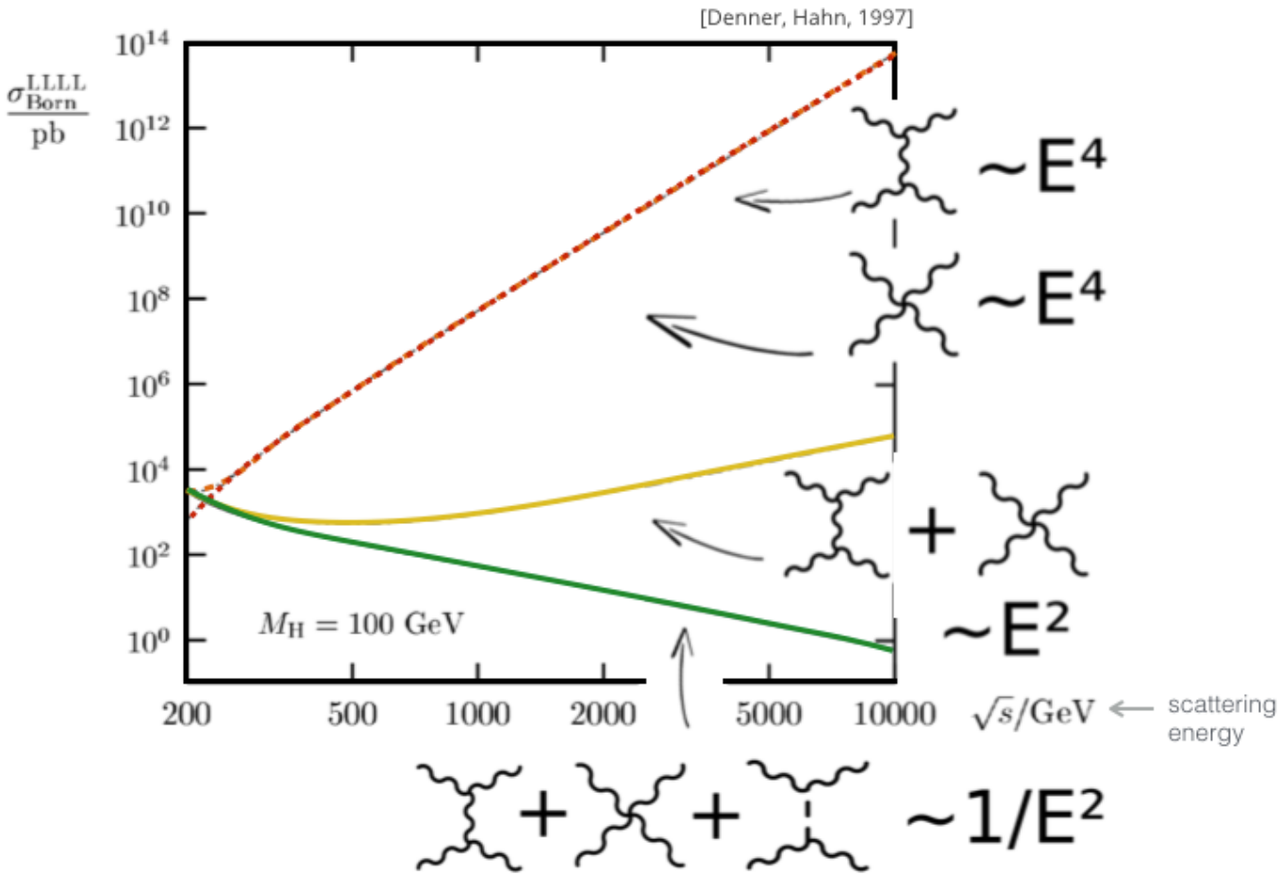
- Gauge boson polarization is strongly related to the structure of the electroweak sector
- The Higgs mechanism predicts the existence of Goldstone bosons, and those are eaten by the $W^+$, $W^-$, and Z respectively, providing them with a mass and their longitudinal polarization

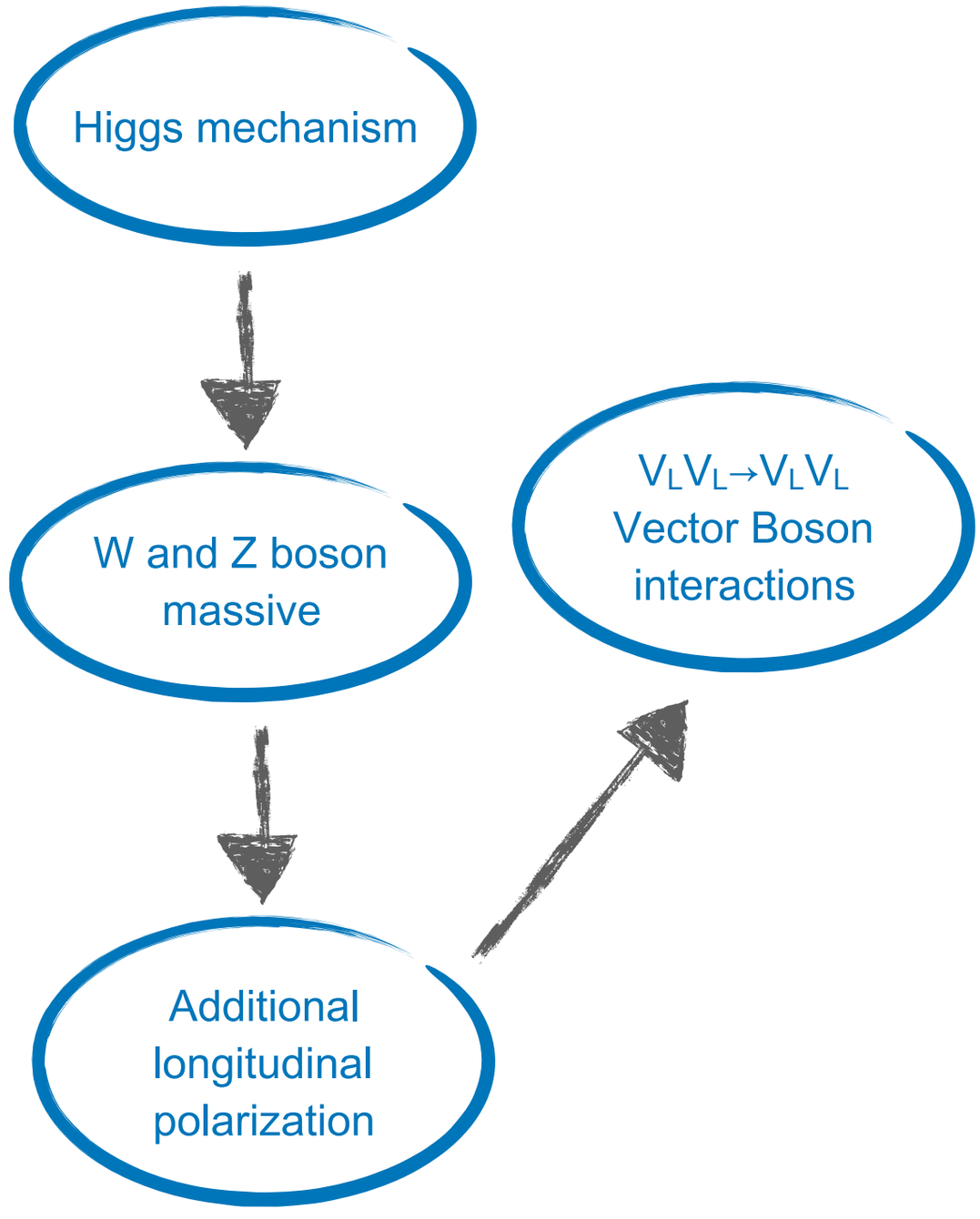

quantumdiaries.org



# 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

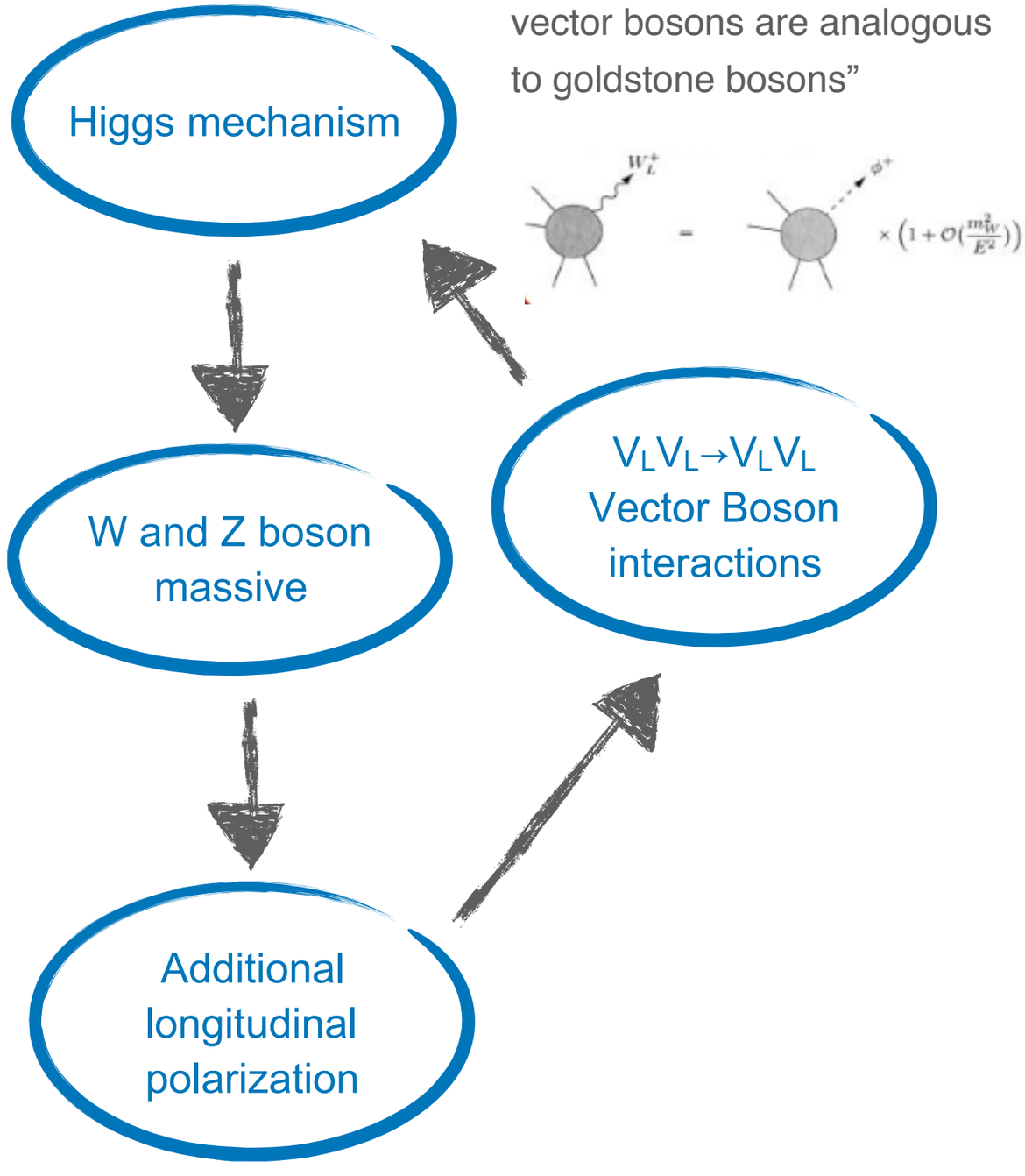


# Why weak boson polarization is interesting?

- 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
- **Important test of the EWSB**

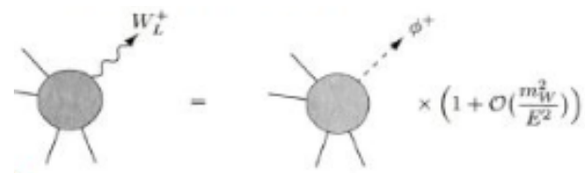
**Goldstone theorem**
"At high energy, longitudinal vector bosons are analogous to goldstone bosons"



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

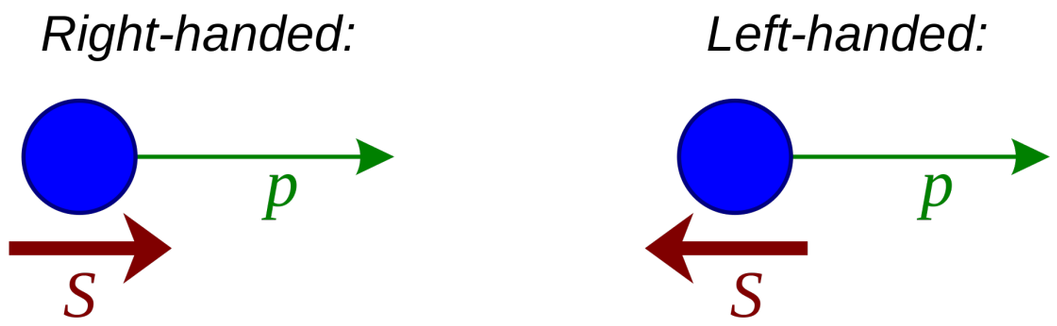
**Goldstone theorem**
"At high energy, longitudinal vector bosons are analogous to goldstone bosons"



# 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): 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

# Polarization measurements using top quarks

- ATLAS @13TeV, 139 $fb^{-1}$, Single top polarization, arXiv:2202.11382
- CMS+ATLAS @8TeV, W boson polarization in top quarks, JHEP 08 (2020) 051

# Single Top quark polarization

arXiv:2202.11382

- ATLAS measurement of all the top-quark polarization components @ 13 TeV (139 $fb^{-1}$).

**Why top quark polarization in this talk?**

- Single top quarks are always produced via the left-handed electroweak interaction
- This impacts the produced top quark's spin direction and, in turn, the spin of its decay products

**How is the analysis performed?**

- The top-quark polarization can be assessed from the angular distributions of its decay products in the top-quark rest frame.
- Event selection built to focus on the t-channel and the *W* leptonic decay:
  - Exactly 2 jets. With exactly one b-tagged
  - Exactly one tight charged lepton (e,μ) ($p_T > 30$ GeV)
  - $E_T^{miss} > 35$ GeV; $m_T(W) > 60$ GeV; Additional multi-jet rejecting cut.

Two Signal Regions (top & anti-top)

- Contains 50% t-channel signal; 25% ttbar, 15% W+jets

Two control regions

- ttbar & W+jets

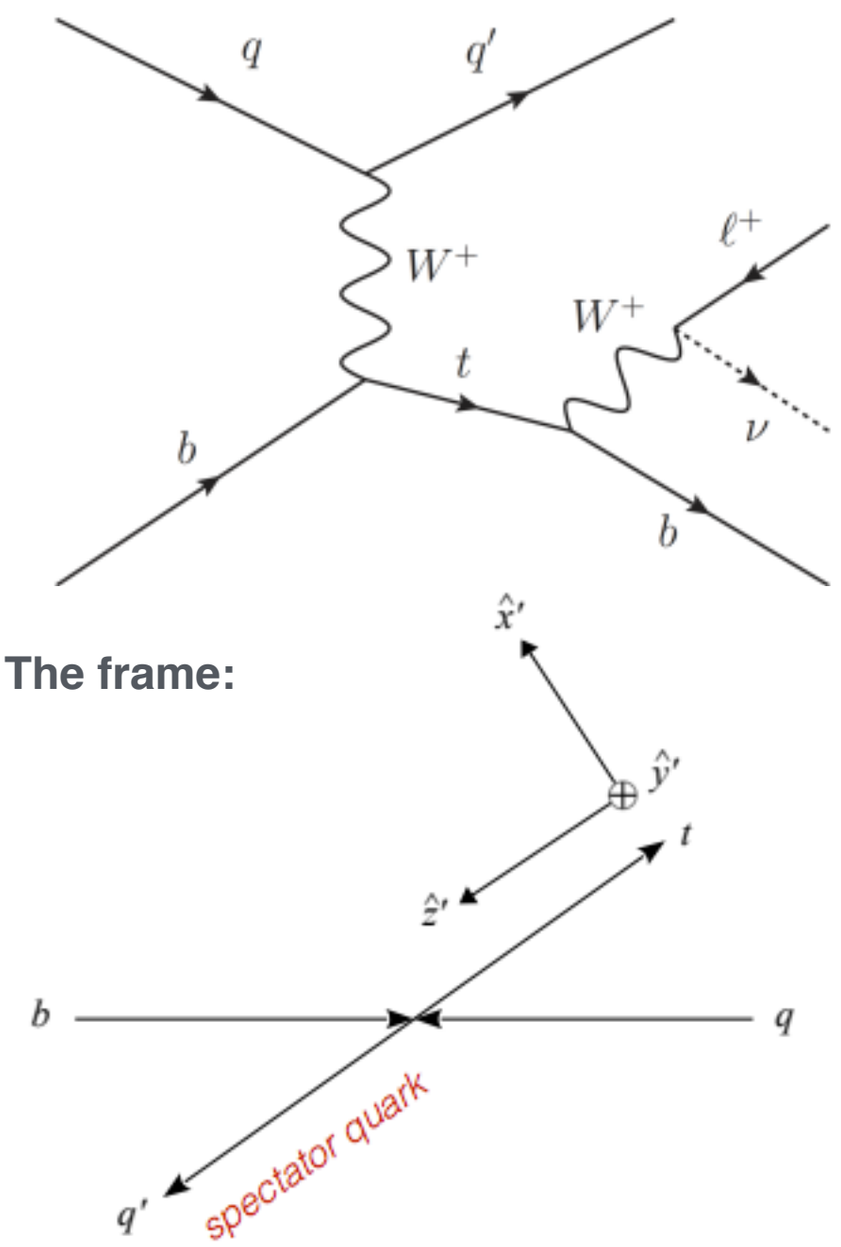



Figure: At LO single top quarks are produced with their spin aligned along the direction of the down-type quarks (spectator quark). Reference system is the top rest frame.

# The top polarization components

- The $\theta_{li}$ polar angle of the charged-lepton w.r.t the $i^{th}$ axis (i=$x'$,$y'$,$z'$ ), this give us the three different polarisation components $\{P_{x'}, P_{y'}, P_{z'}\}$

**The Statistical analysis:**

- The signal: 6 simulated templates with fully polarized states ($P_{x,y,z} = \pm 1$)
- Profile likelihood fit in 4 regions: 2 signal regions (top & antitop) + 2 control regions:
  - SR 8-bin splitting based on the octant variable (Slice the phase space depending on the sign of cos $\theta_c$)
  - CRs 2-bin splitting based on lepton charge
- The free parameters:
  - 3 normalisations ($t\bar{t}$, W+jets & t-channel signal)
  - 6 top & antitop polarization components
- The systematics uncertainties:
  - mainly dominated by jet-energy resolution

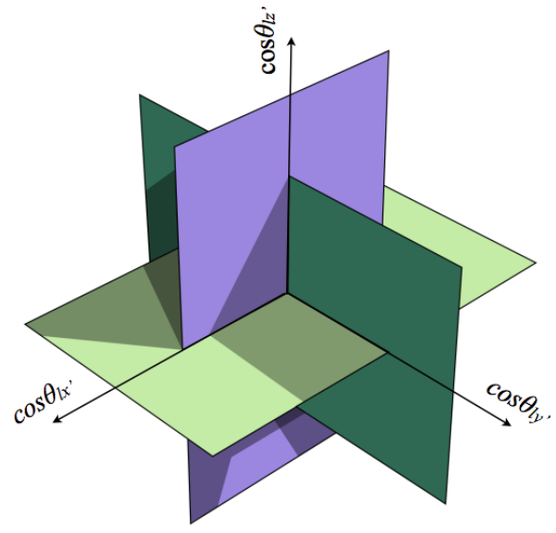
Fit results

| Parameter | Extracted value | (stat.) |
|---|---|---|
| $t$-channel norm. | $+1.045 \pm 0.022$ | ($\pm 0.006$) |
| $W$+ jets norm. | $+1.148 \pm 0.027$ | ($\pm 0.005$) |
| $t\bar{t}$ norm. | $+1.005 \pm 0.016$ | ($\pm 0.004$) |
| $P^{t}_{x'}$ | $+0.01 \pm 0.18$ | ($\pm 0.02$ ) |
| $P^{\bar{t}}_{x'}$ | $-0.02 \pm 0.20$ | ($\pm 0.03$ ) |
| $P^{t}_{y'}$ | $-0.029 \pm 0.027$ | ($\pm 0.011$) |
| $P^{\bar{t}}_{y'}$ | $-0.007 \pm 0.051$ | ($\pm 0.017$) |
| $P^{t}_{z'}$ | $+0.91 \pm 0.10$ | ($\pm 0.02$ ) |
| $P^{\bar{t}}_{z'}$ | $-0.79 \pm 0.16$ | ($\pm 0.03$ ) |

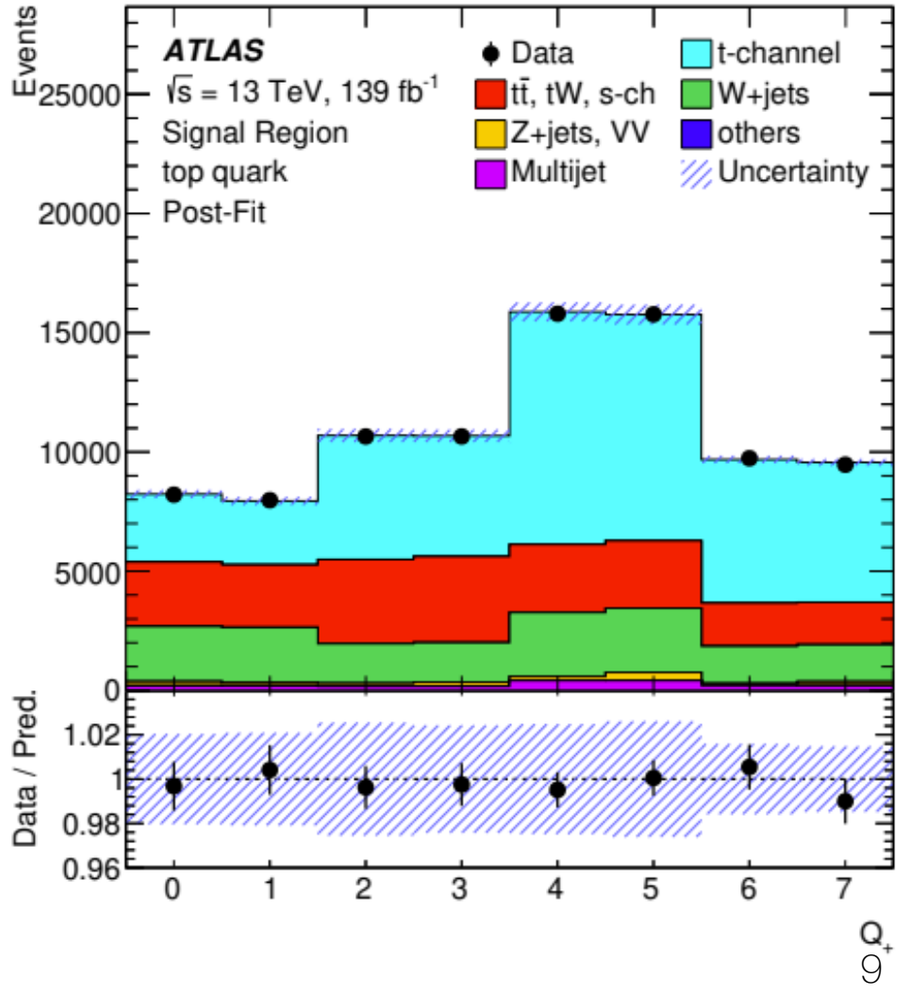
ATLAS EXPERIMENT

arXiv:2202.11382

Octant variable Q definition



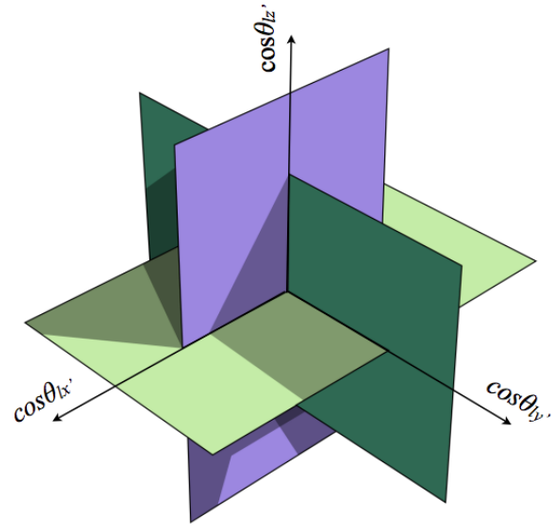

Octant variable in the top quark signal region



# The top polarization components

- The $\theta_{li}$ polar angle of the charged-lepton w.r.t the $i^{th}$ axis (i=$x'$,$y'$,$z'$ ), this give us the three different polarisation components $\{P_{x'}, P_{y'}, P_{z'}\}$

Octant variable Q definition



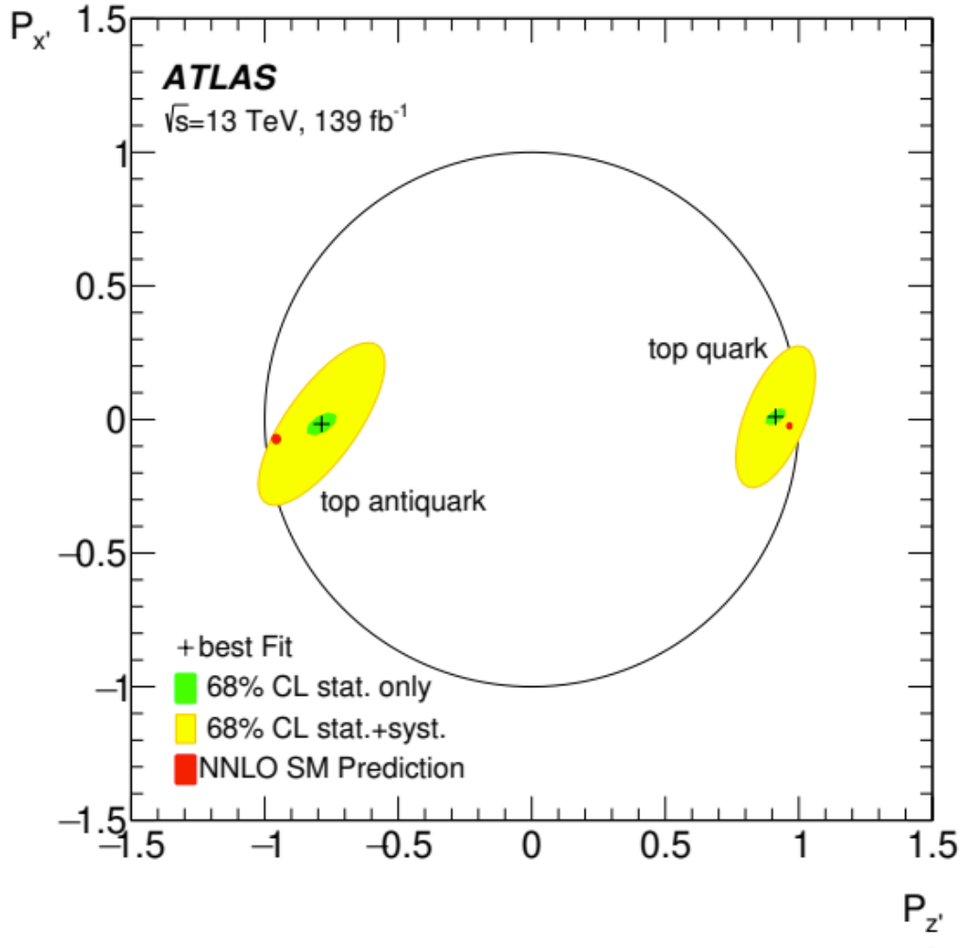

arXiv:2202.11382

**The Statistical analysis:**

- The signal: 6 simulated templates with fully polarized states ($P_{x,y,z}$ = ±1)
- Profile likelihood fit in 4 regions: 2 signal regions (top & antitop) + 2 control regions:
  - SR 8-bin splitting based on the octant variable (Slice the phase space depending on the sign of cos $\theta_{li}$)
  - CRs 2-bin splitting based on lepton charge
- The free parameters:
  - 3 normalisations ($t\bar{t}$, W+jets & t-channel signal)
  - 6 top & antitop polarization components
- The systematics uncertainties:
  - mainly dominated by jet-energy resolution

Fit results

| Parameter | Extracted value | (stat.) |
|---|---|---|
| $t$-channel norm. | +1.045 ± 0.022 | ( ± 0.006) |
| $W$+ jets norm. | +1.148 ± 0.027 | ( ± 0.005) |
| $t\bar{t}$ norm. | +1.005 ± 0.016 | ( ± 0.004) |
| $P^{t}_{x'}$ | +0.01 ± 0.18 | ( ± 0.02 ) |
| $P^{\bar{t}}_{x'}$ | −0.02 ± 0.20 | ( ± 0.03 ) |
| $P^{t}_{y'}$ | −0.029 ± 0.027 | ( ± 0.011) |
| $P^{\bar{t}}_{y'}$ | −0.007 ± 0.051 | ( ± 0.017) |
| $P^{t}_{z'}$ | +0.91 ± 0.10 | ( ± 0.02 ) |
| $P^{\bar{t}}_{z'}$ | −0.79 ± 0.16 | ( ± 0.03 ) |

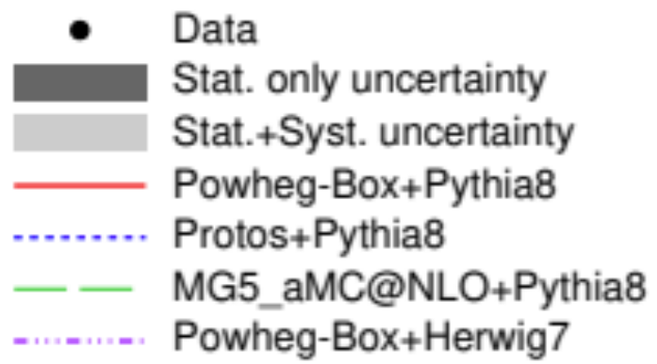



- Agreement with SM MC predictions (stat.): $P_x^t$ = 0.040 ± 0.012, $P_z^t$ = 1.024 ± 0.015; $P_x^{\bar{t}}$ = -0.070 ± 0.016, $P_z^{\bar{t}}$ = -0.967 ± 0.020 ($P_y$ is expected to be 0 from CP symmetry).

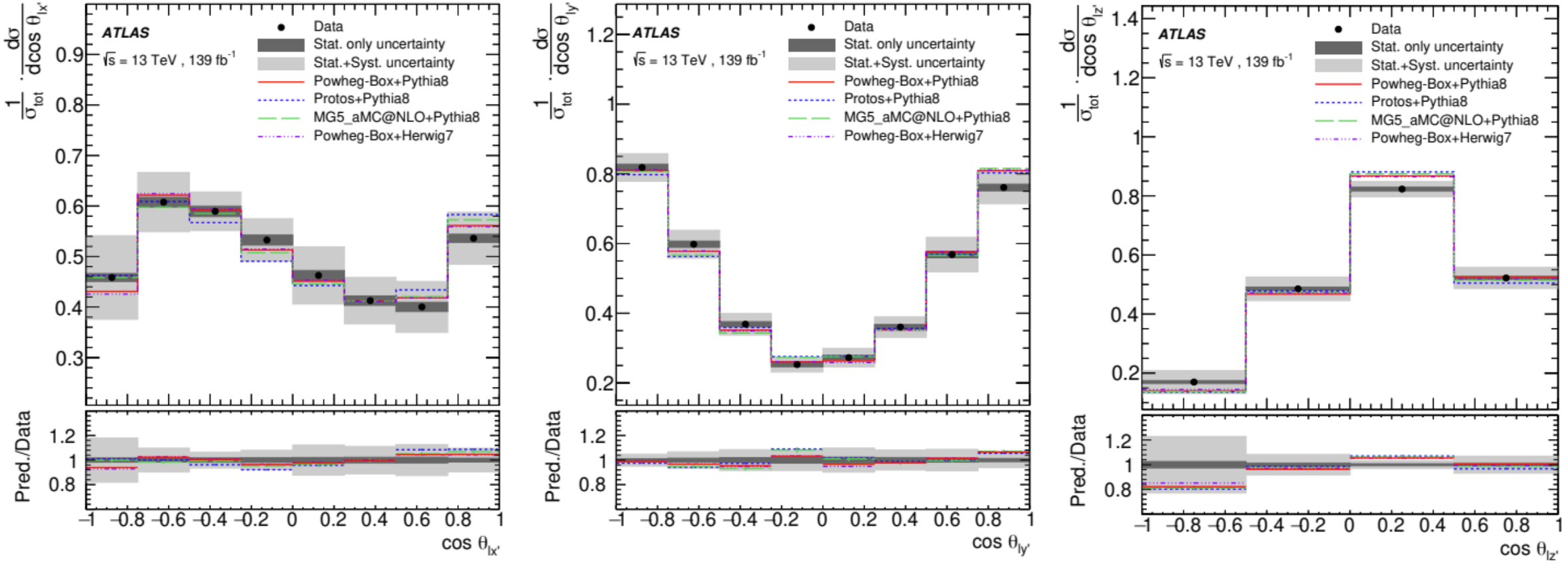
# Angular differential cross sections

arXiv:2202.11382

- Angular distributions might be sensitive to new physics effects in the *tWb* vertex (EFT interpretation)
- The normalisations of the W+jets and top-quark backgrounds and the t-channel signal are constrained with a maximum likelihood fit to the data in the signal and control regions.
- After background subtraction the distributions are unfolded to the particle-level in a fiducial region
- Systematics: Mainly dominated by jet-energy resolution, jet-energy scale and t-channel modelling




Unfolded angular variables for top and anti-top

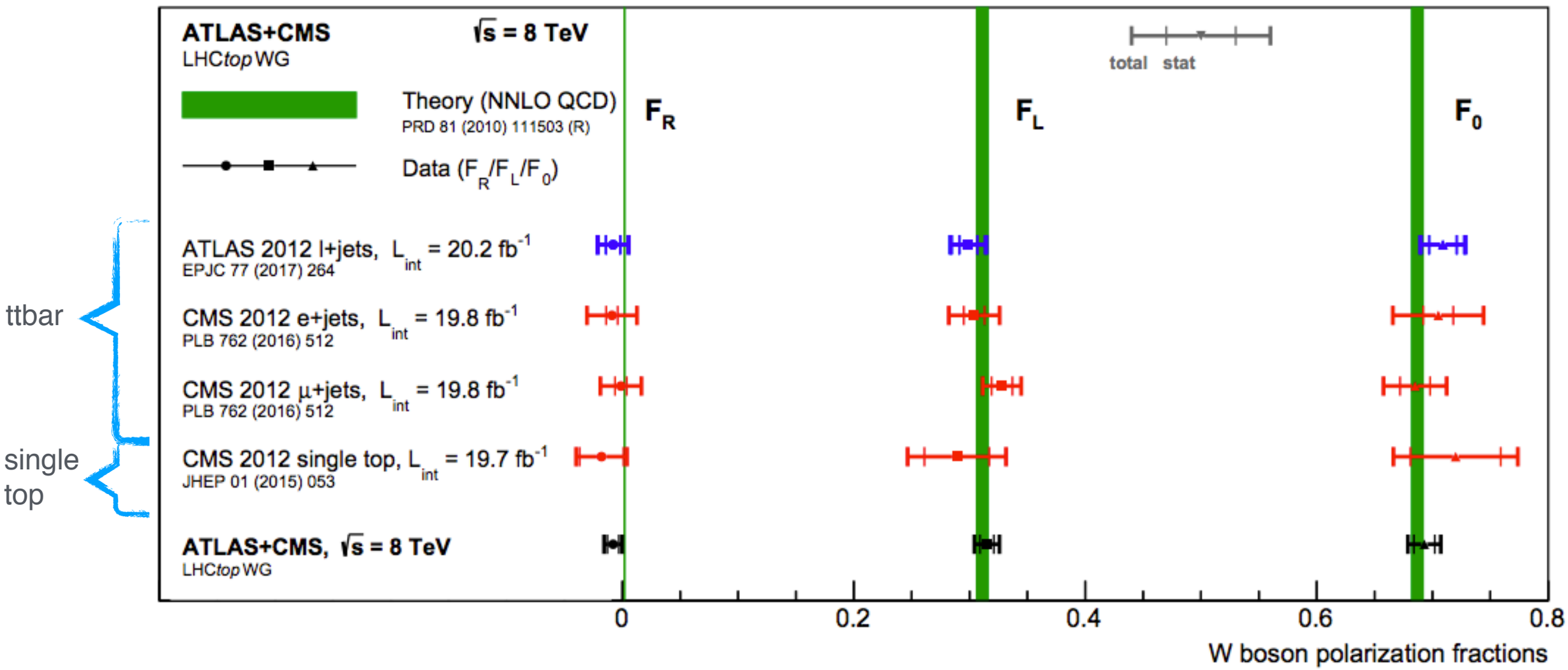



- The results are interpreted in an EFT context to set limits on Wilson coefficients.

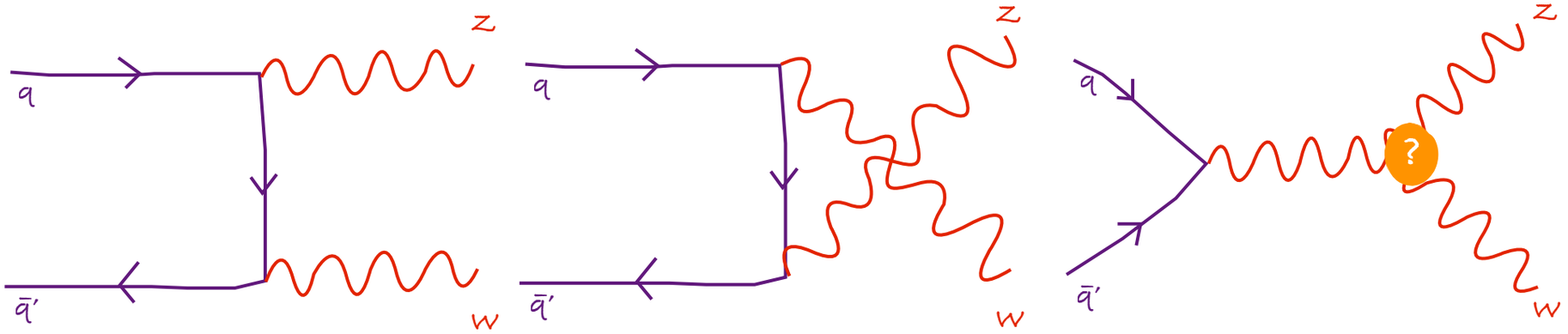
# Combination of top polarization measurements

JHEP 08 (2020) 051

- Combination of measurements of the W boson polarization in top quark decays @8 TeV (including single top and ttbar)




- The results are consistent with the standard model predictions at next-to-next-to-leading-order precision in perturbative quantum chromodynamics




# Polarization measurements in WZ

- CMS @13TeV 137 $fb^{-1}$ CMS-SMP-20-014
- ATLAS @13TeV 36 $fb^{-1}$ Eur. Phys. J. C 79 (2019) 535

# CMS Polarization in WZ measurement

CMS-SMP-20-014

- Single boson polarization measurement @13 TeV

**The analysis target**

- Singlely-polarized final states:
  - “W polarization” : $W_LZ$, $W_RZ$, $W_0Z$
  - “Z polarization” : $WZ_L$, $WZ_R$, $WZ_0$

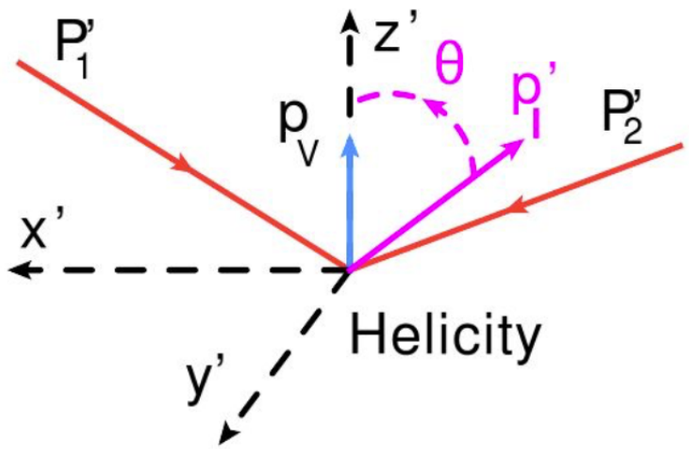
**The frame**

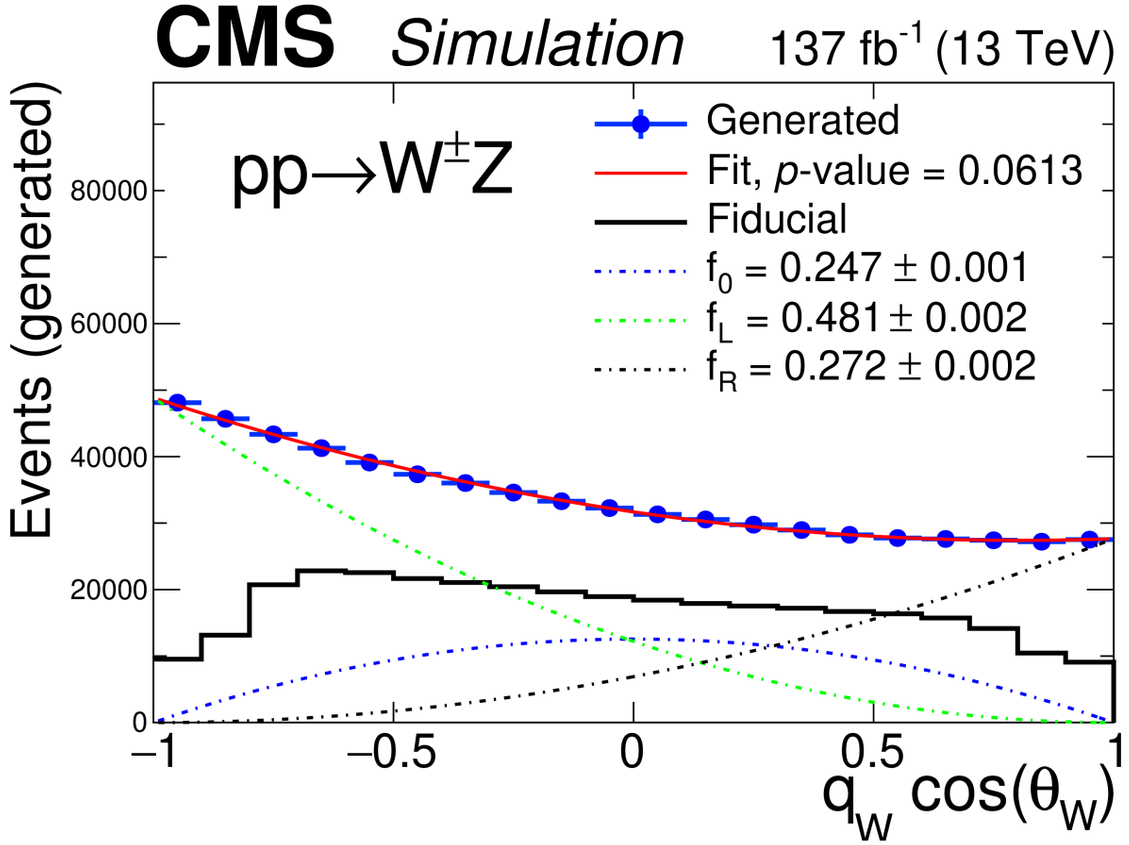
- The helicity frame defined in the centre-of mass of the measured gauge boson (W or Z) is used

**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:**



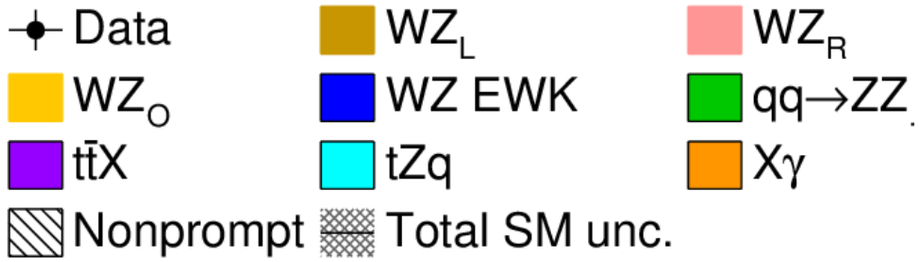



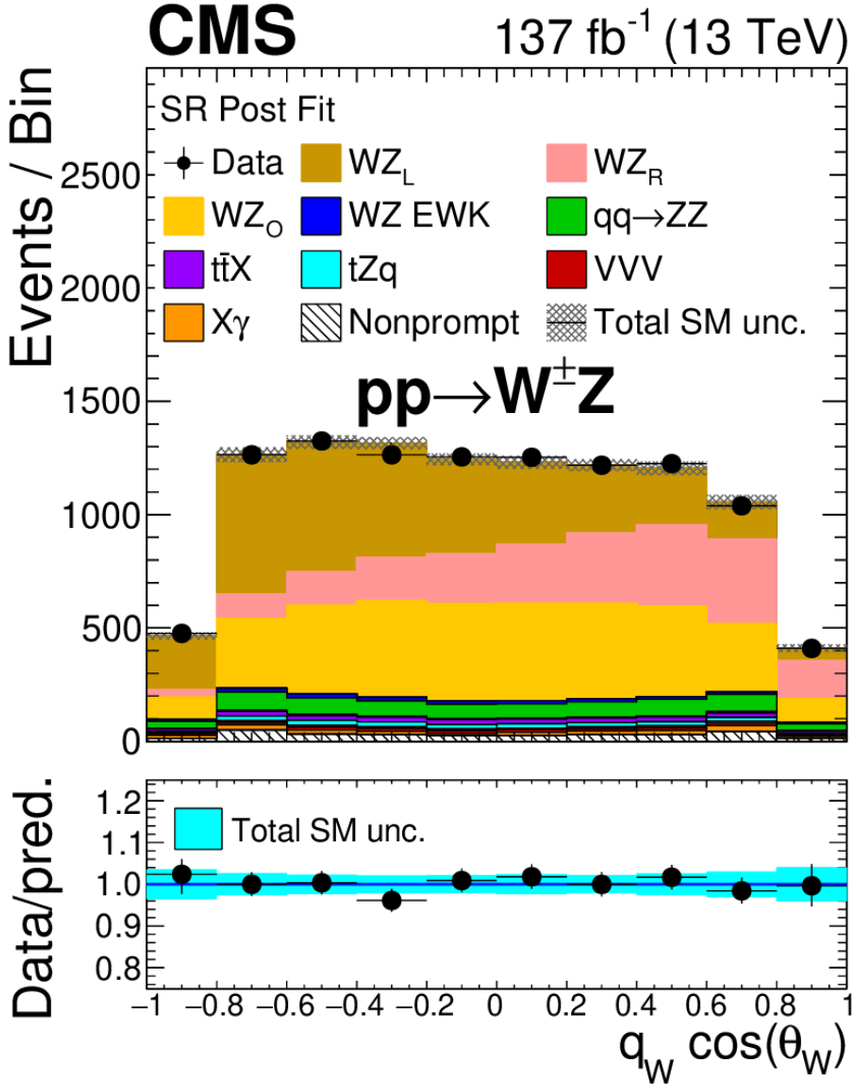
# WZ polarization extraction

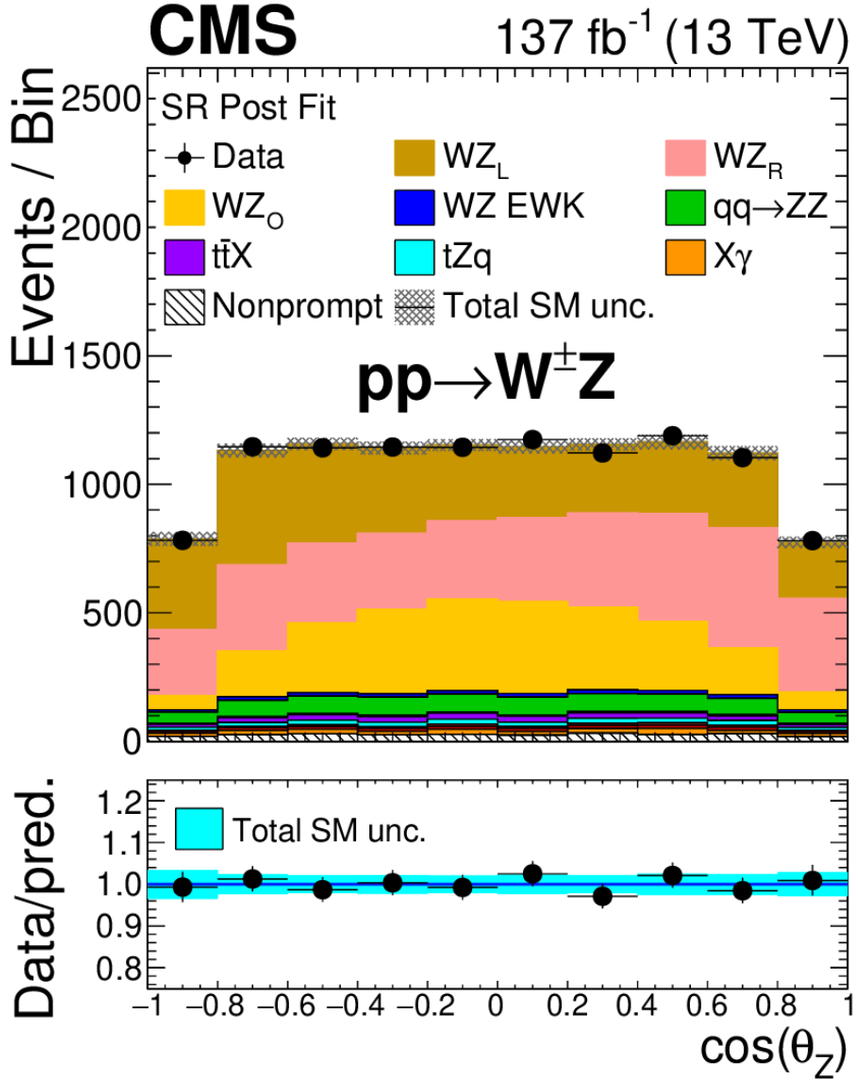
CMS-SMP-20-014


**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



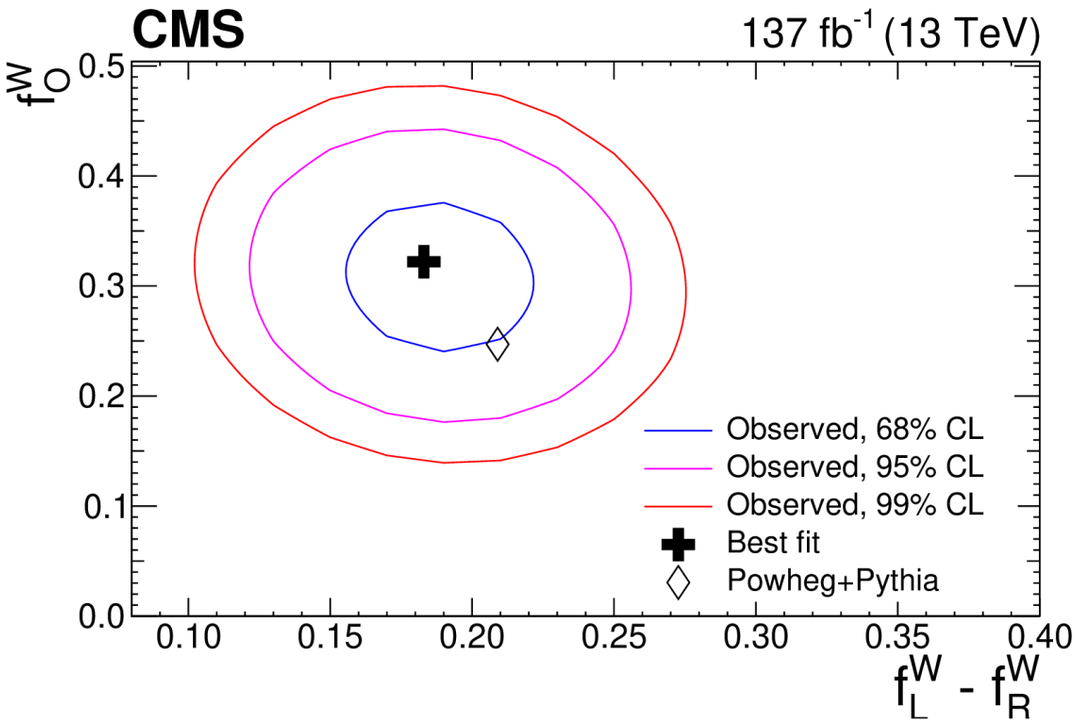



# WZ polarization results

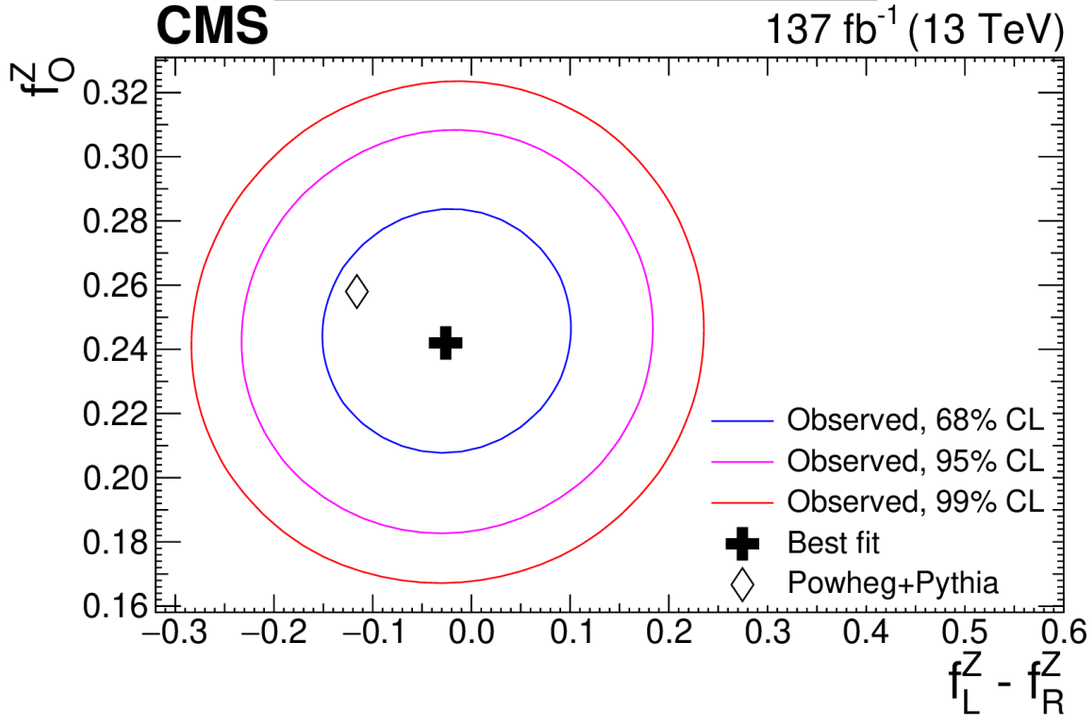
CMS-SMP-20-014

- 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

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

- Very similar analysis to the CMS one

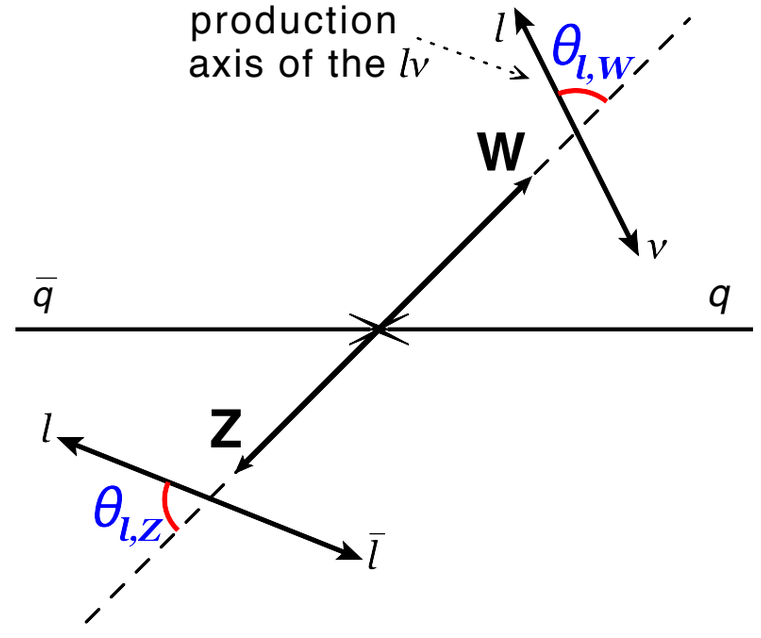
**The analysis target**

- Singly-polarized final states:
  - "W polarization" : $W_LZ$, $W_RZ$, $W_0Z$
  - "Z polarization" : $WZ_L$, $WZ_R$, $WZ_0$

**The frame**

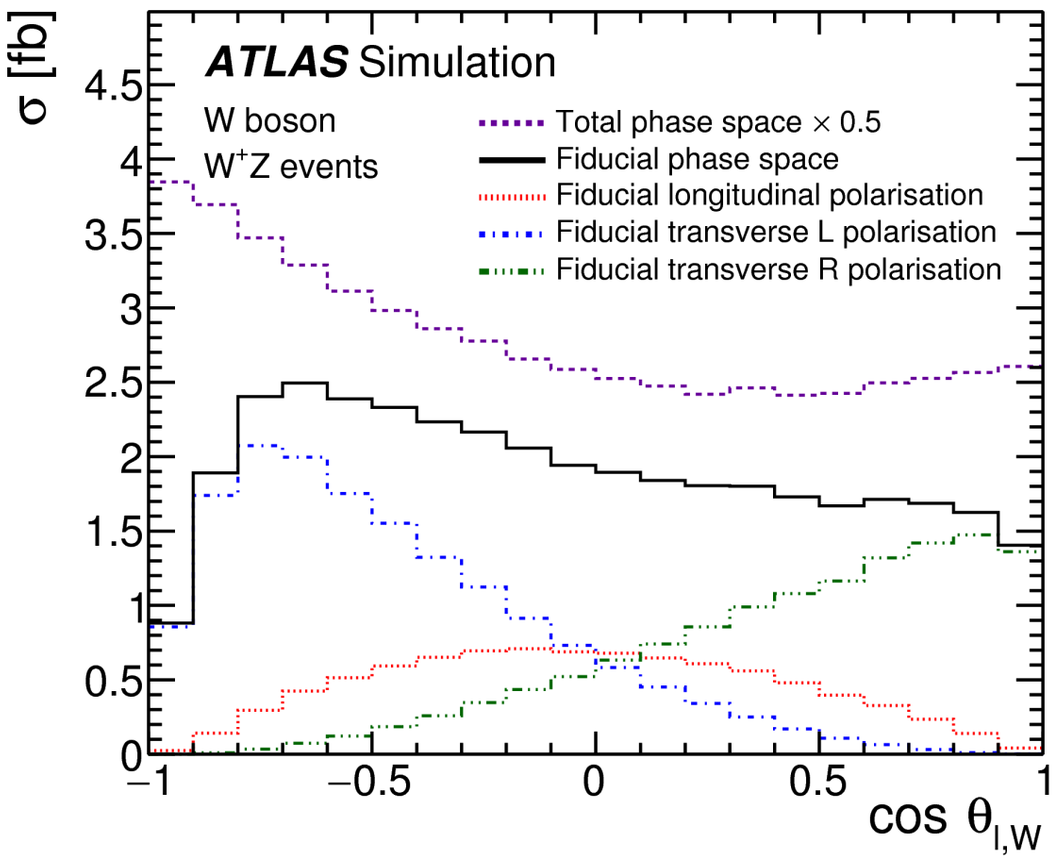
- The "modified" helicity frame with the WZ system at rest

**The frame:**




**How is the analysis performed?**

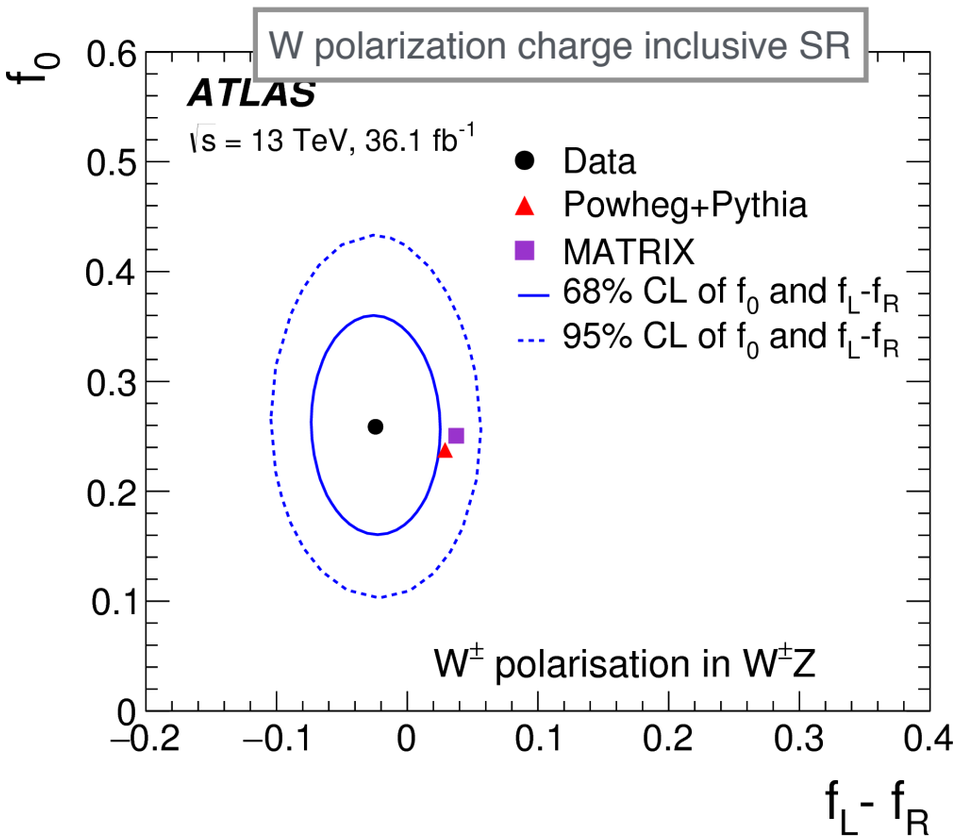
- Polarization templates obtained by reweighting a POWHEG+Pythia sample based on the generator-level $\cos(\theta_V)$ distributions
- Cut-based SR selection, that exploits:
  - fully leptonic WZ decays: leptons $p_T$>27/20 GeV
  - Z mass on-shell (10 GeV window)
  - W reconstructed using pdg mass constrain

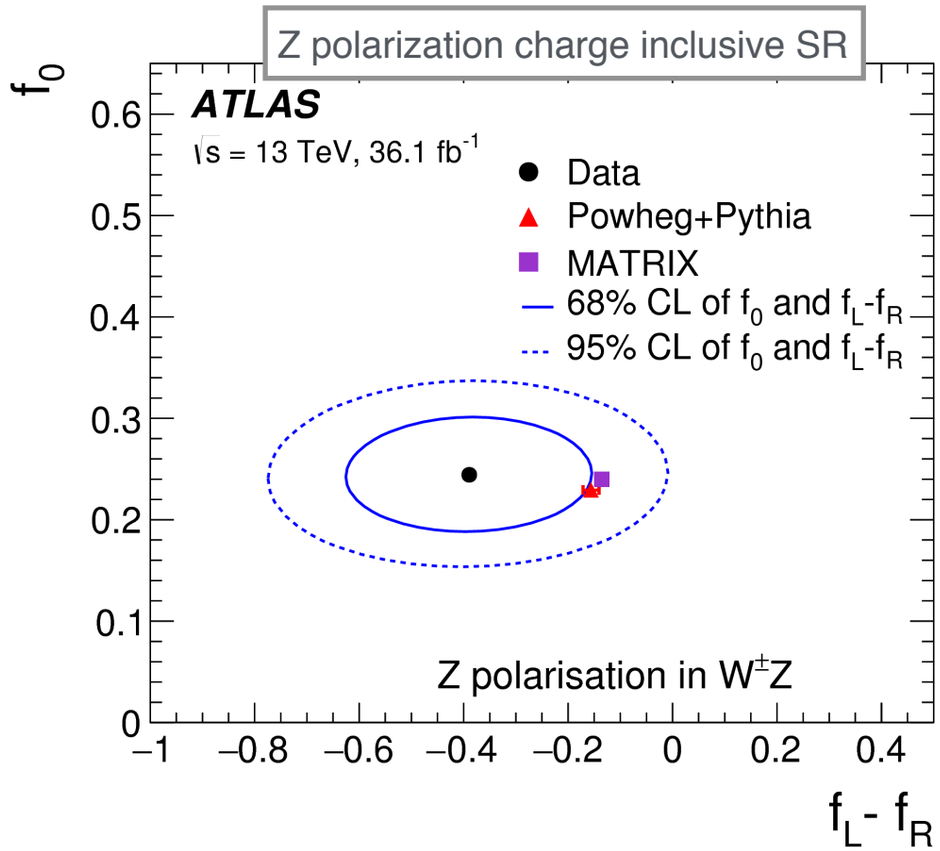


# WZ polarization results

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

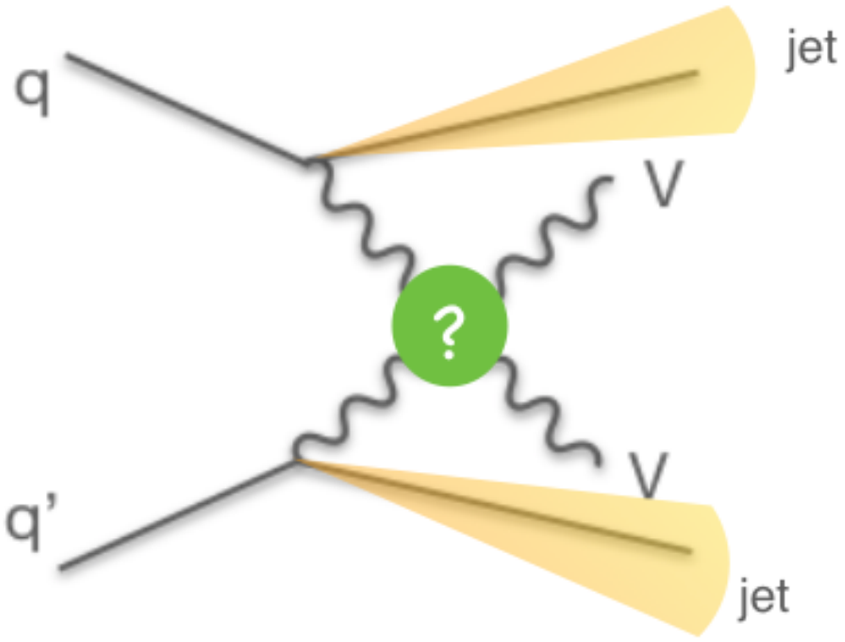
- All results are provided in the charge-inclusive and both charged ($W^+Z$, and $W^-Z$) final states.

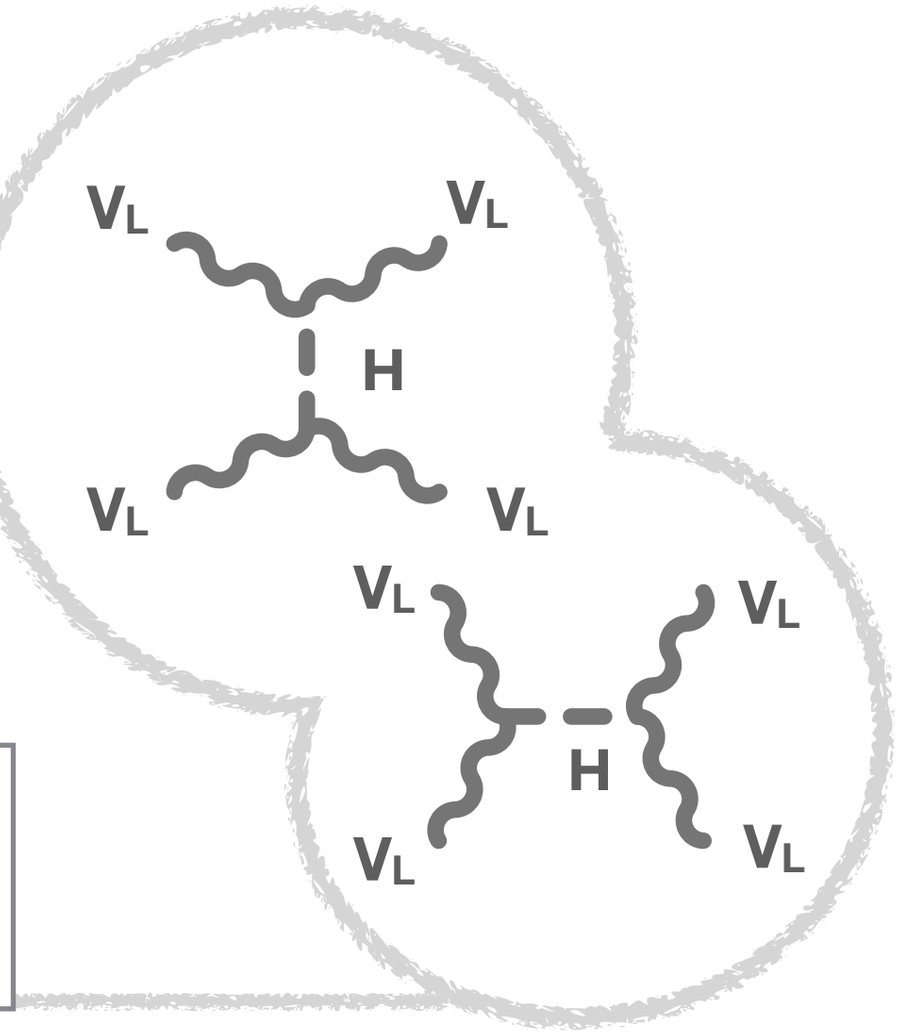


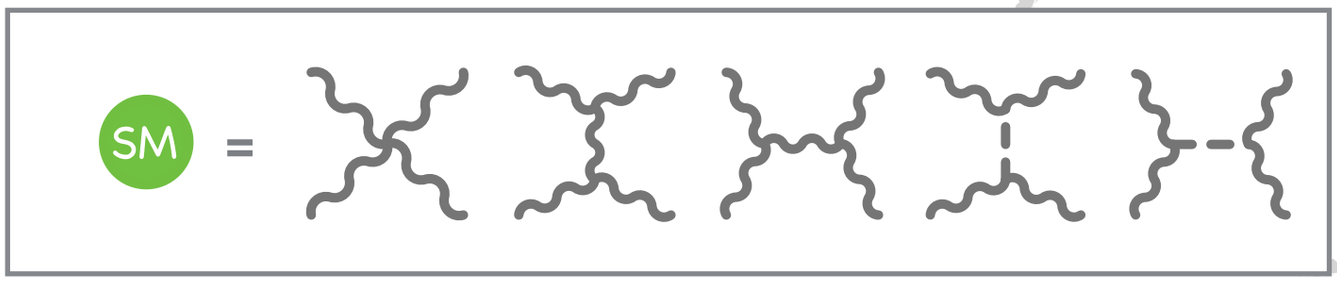




- Overall results consistent between observations and predictions.
- Evidence for the presence of **longitudinally polarized W bosons of 4.2σ (3.8σ expected)**. Observation of longitudinally polarized Z bosons at a 6.5σ significance (6.1σ expected)

# Polarization measurements in Vector Boson Scattering



# VBS same sign WW polarization measurement

Phys. Lett. B 812 (2020) 136018

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

**The analysis target**

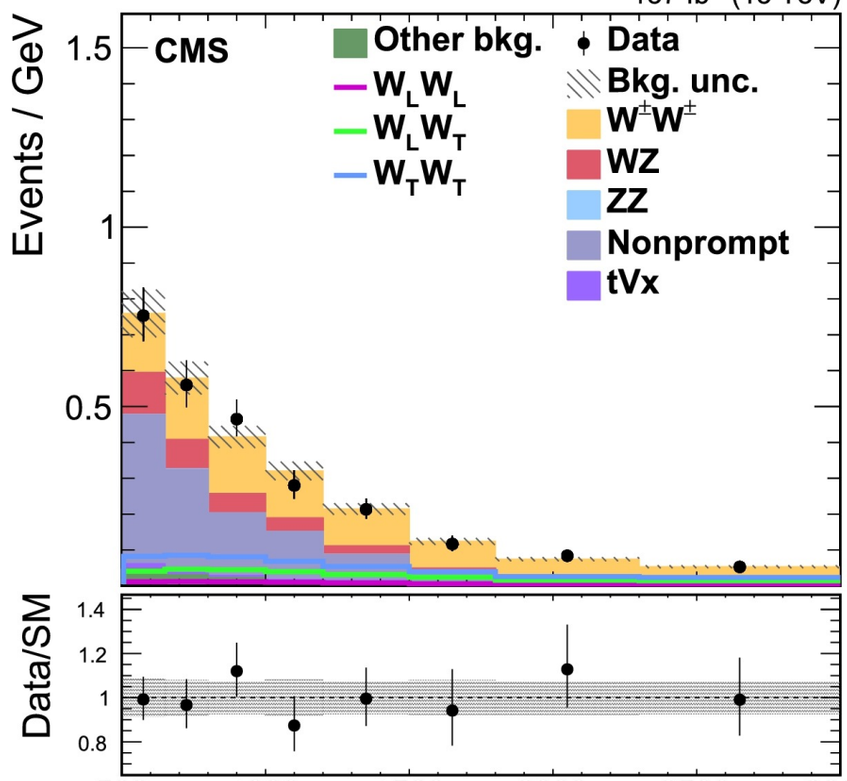
- doubly polarized final states: $W_LW_L$, $W_TW_T$, $W_LW_T$
- single boson longitudinal polarization: $W_LW_X$ and $W_TW_X$ production (any polarization for the second boson).

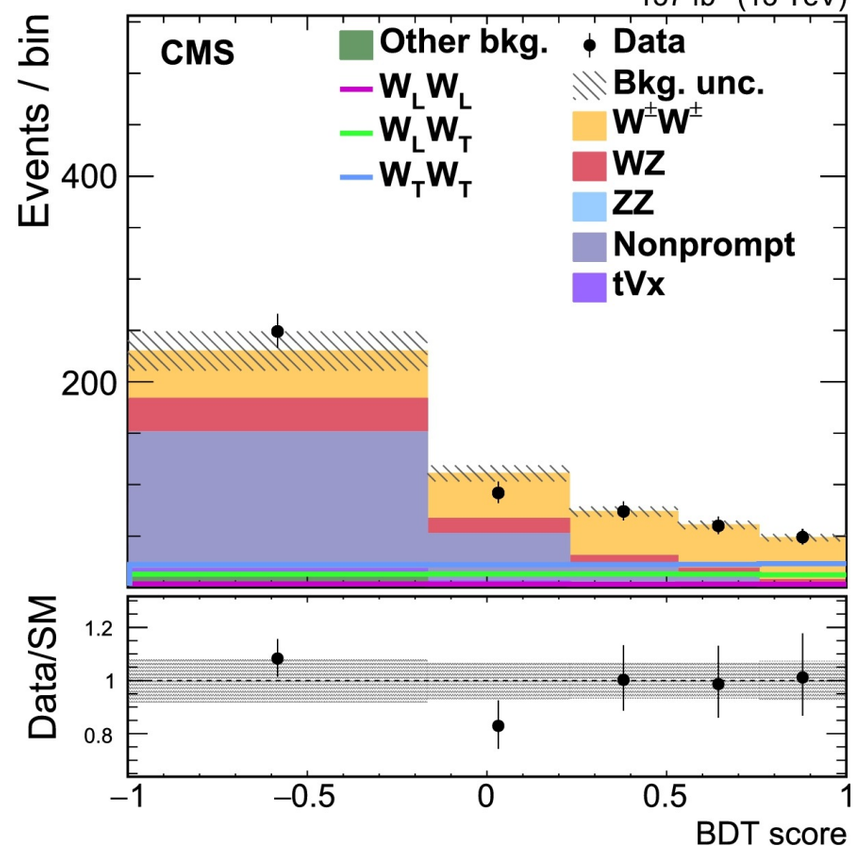
**The challenge**

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

**How is the analysis performed?**

- Starts with a cut-based SR selection, that exploits:
  - VBS topology requires $m_{jj}$>500 GeV and Zeppenfeld's production.
  - 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 $W_TW_T$
- Polarization templates from MAdgraph



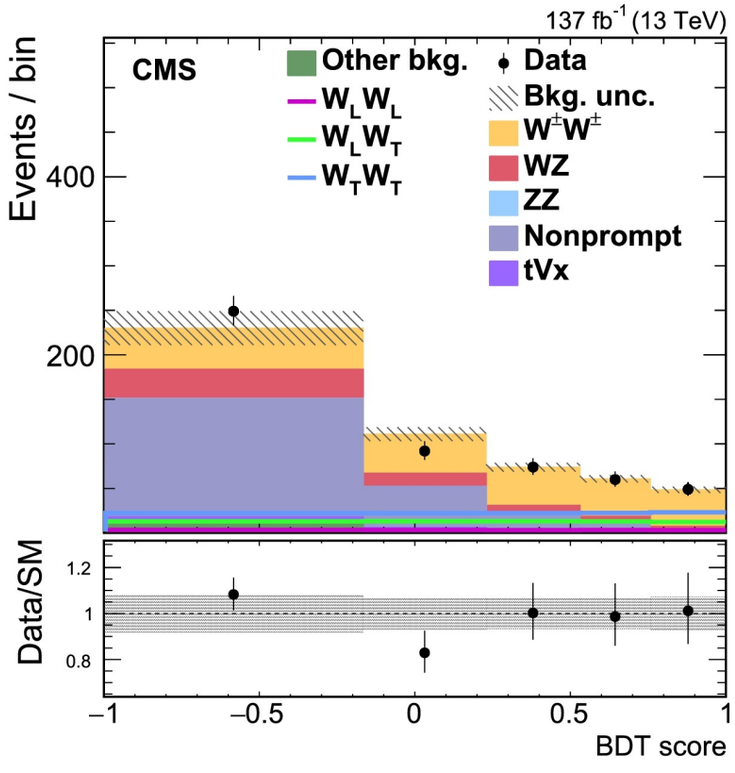
# VBS same sign WW polarization measurement

Phys. Lett. B 812 (2020) 136018

**The statistical analysis**

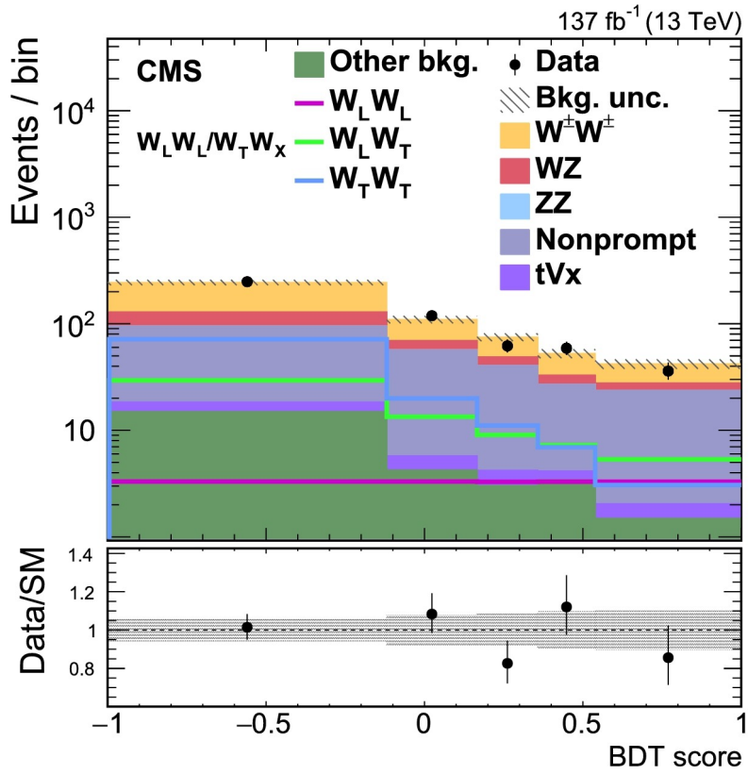
- Two fits performed depending on the signal hypothesis
  - To extract $W_LW_L$ and $W_TW_X$ cross sections: Inclusive BDT x “LL vs all” BDT (5x5 bins)
  - To extract $W_TW_T$ and $W_LW_X$ cross sections: Inclusive BDT x “TT vs all” BDT (5x5 bins)

Inclusive BDT



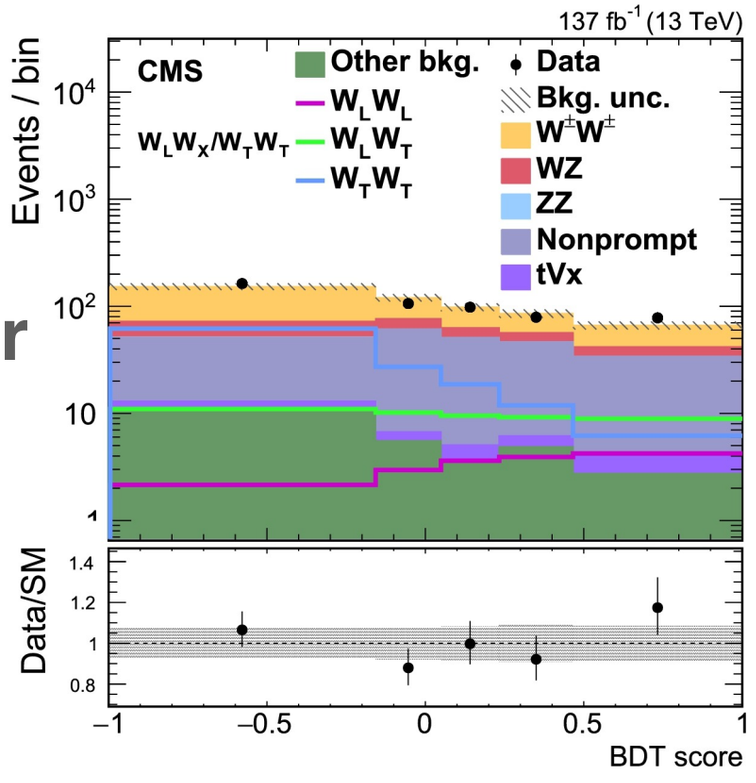

x

LL vs all BDT




or

TT vs all BDT



# VBS same sign WW polarization measurement

Phys. Lett. B 812 (2020) 136018

## The results

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

Results in the WW reference frame

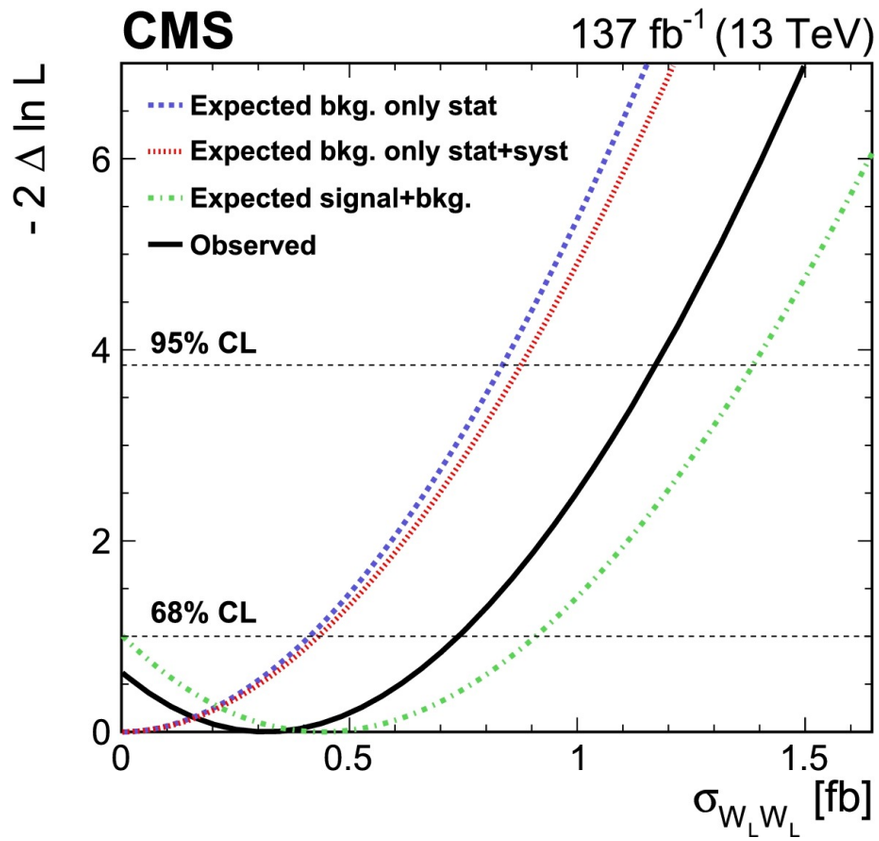
- Significance for LX production at 2.3σ (3.1σ expected)

| Process | $\sigma\,\mathcal{B}$ (fb) | Theoretical prediction (fb) |
|---|---|---|
| $W_L^\pm W_L^\pm$ | $0.32^{+0.42}_{-0.40}$ | $0.44 \pm 0.05$ |
| $W_X^\pm W_T^\pm$ | $3.06^{+0.51}_{-0.48}$ | $3.13 \pm 0.35$ |
| $W_L^\pm W_X^\pm$ | $1.20^{+0.56}_{-0.53}$ | $1.63 \pm 0.18$ |
| $W_T^\pm W_T^\pm$ | $2.11^{+0.49}_{-0.47}$ | $1.94 \pm 0.21$ |

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) |
|---|---|---|
| $W_L^\pm W_L^\pm$ | $0.24^{+0.40}_{-0.37}$ | $0.28 \pm 0.03$ |
| $W_X^\pm W_T^\pm$ | $3.25^{+0.50}_{-0.48}$ | $3.32 \pm 0.37$ |
| $W_L^\pm W_X^\pm$ | $1.40^{+0.60}_{-0.57}$ | $1.71 \pm 0.19$ |
| $W_T^\pm W_T^\pm$ | $2.03^{+0.51}_{-0.50}$ | $1.89 \pm 0.21$ |

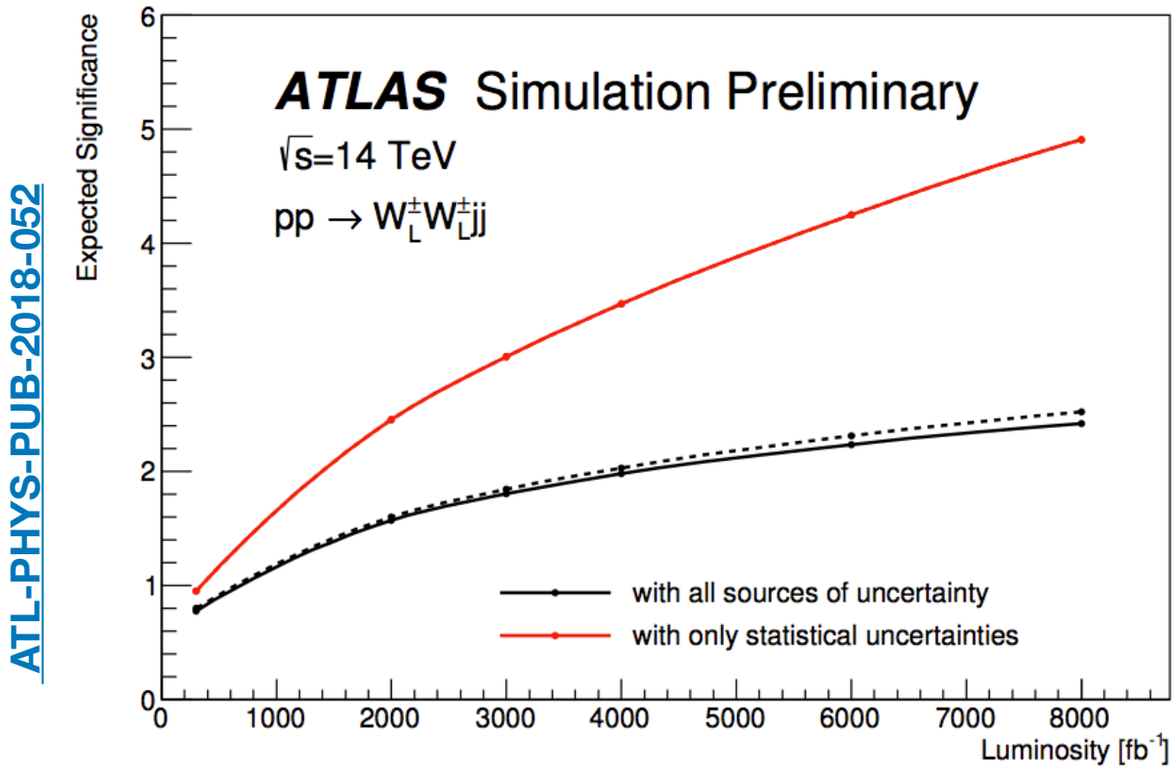



## Uncertainties

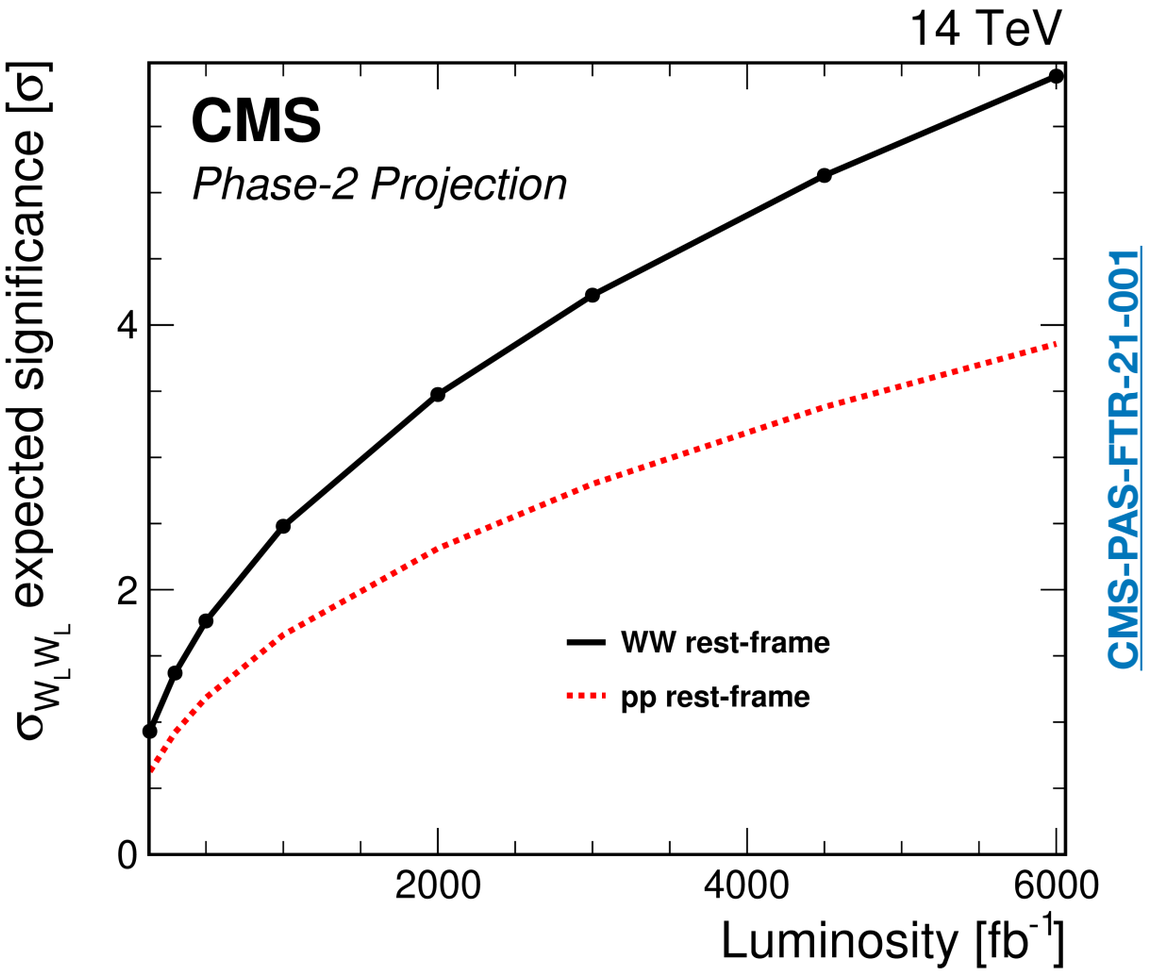
- Very strongly dominated by statistical uncertainty, significant improvements are to be expected from Run III and the HL-LHC before systematics start to become a significant issue

# ..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!




- Simple cut-based analysis




- Almost the same analysis as presented before

# 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
- Results on top quark polarization and first results for gauge boson polarization in WZ and WWjj production were presented.
- With our current data we are already able to probe the polarization fractions in 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!
- 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 WW, ZZ and Z VBF