

# Measurement of WZ single and double polarization with the CMS experiment at CERN

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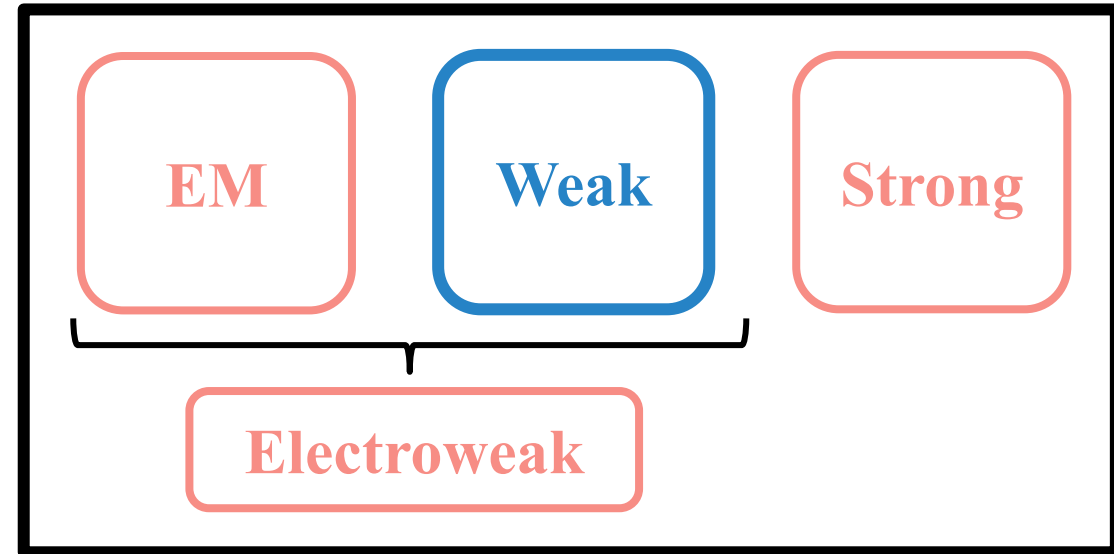


# Standard Model (SM)

## Particles

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> Higgs boson
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	<b>Scalar bosons</b>
<b>QUARKS</b>	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	<b>Gauge bosons</b>
	0.511 $\text{MeV}/c^2$	105.7 $\text{MeV}/c^2$	1.777 $\text{GeV}/c^2$	91.2 $\text{GeV}/c^2$	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	
<b>LEPTONS</b>	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	80.4 $\text{GeV}/c^2$	
	0	0	0	$\pm 1$	
	1/2	1/2	1/2	1	

## Interactions



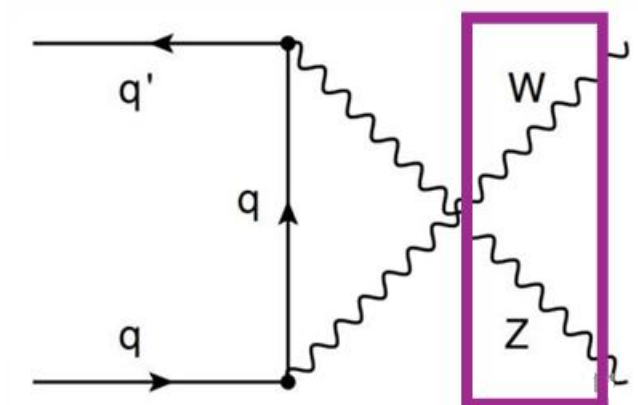
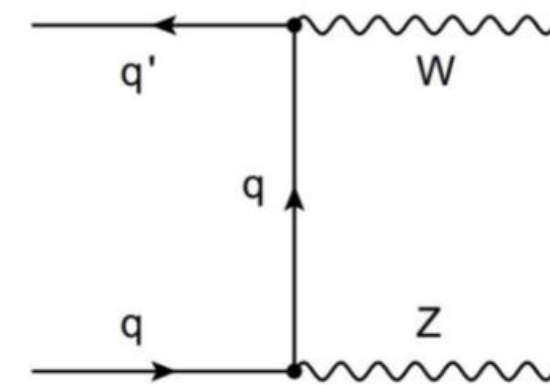
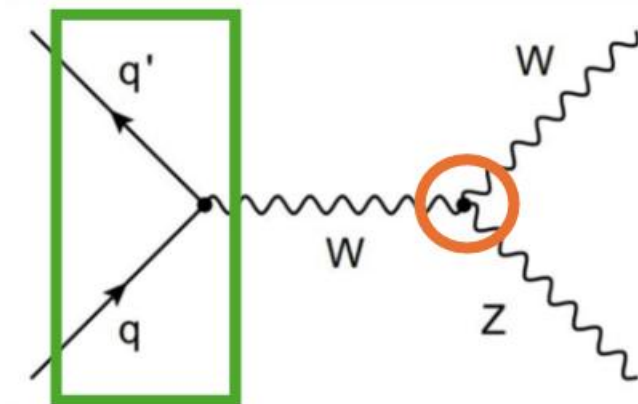
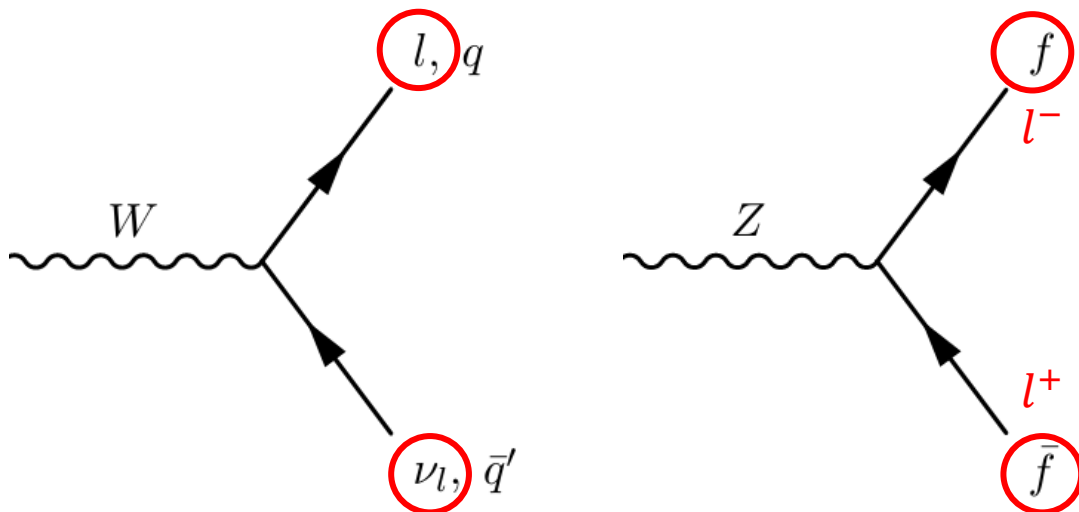
- Weak intermediate bosons
- Massive Gauge bosons

# WZ production

WZ is a process of interest for SMP and BSMP

- Sensitive to charge asymmetries
- Direct access to Trilinear Gauge Couplings and anomalies
- Boson polarization (final state leptons)

Multileptonic final state



# Large Hadron Collider (LHC)

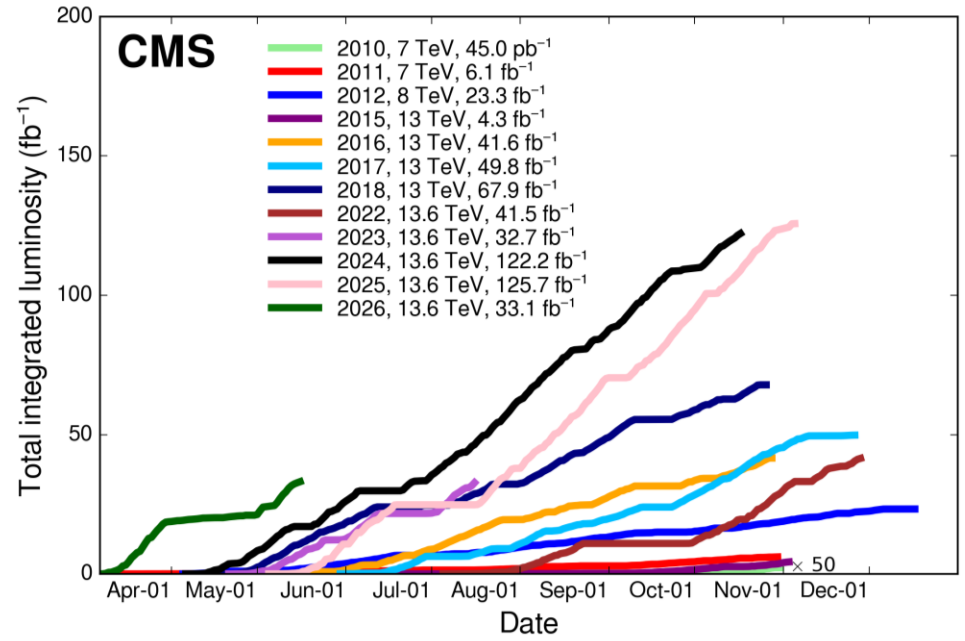
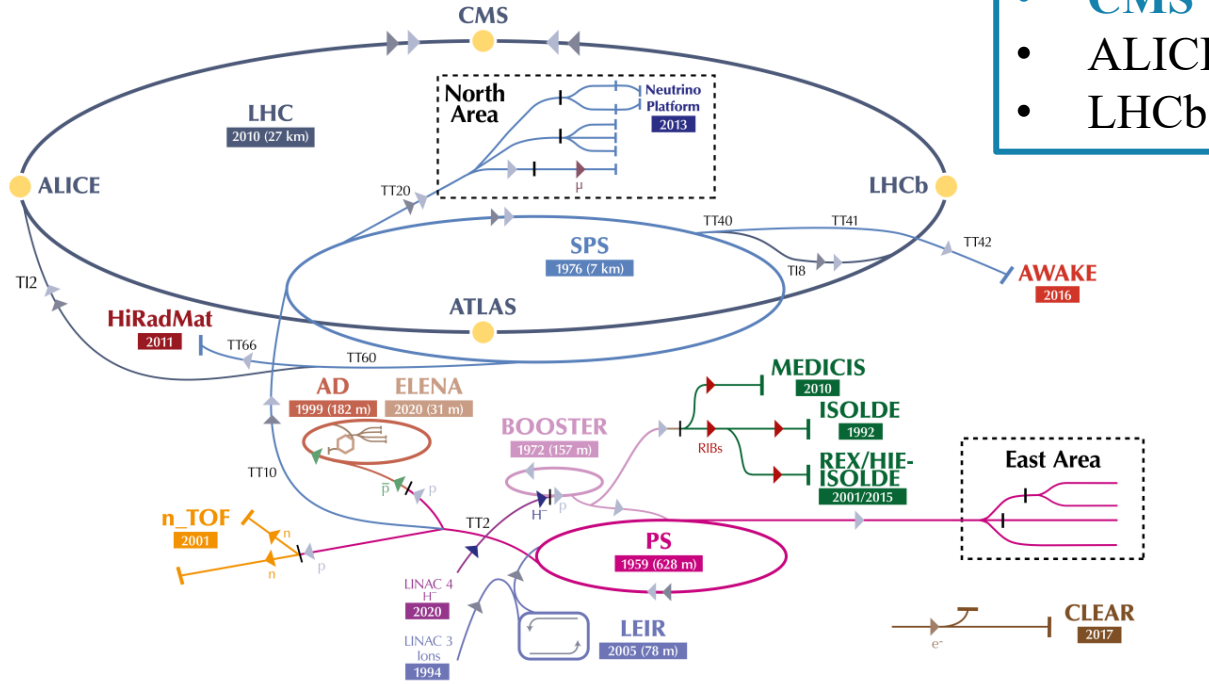
The CERN accelerator complex  
*Complexe des accélérateurs du CERN*

## Detectors:

- ATLAS
- CMS
- ALICE
- LHCb

Proton – proton collisions with center-of-mass energy of:

- Run 1 (2009-2013):  $\sqrt{s} = 7 - 8 \text{ TeV}$
- Run 2 (2015-2018):  $\sqrt{s} = 13 \text{ TeV}$
- **Run 3 (2022-2026):  $\sqrt{s} = 13.6 \text{ TeV}$**



$\blacktriangleright$   $\text{H}^-$  (hydrogen anions)  $\blacktriangleright$  p (protons)  $\blacktriangleright$  ions  $\blacktriangleright$  RIBs (Radioactive Ion Beams)  $\blacktriangleright$  n (neutrons)  $\blacktriangleright$   $\bar{p}$  (antiprotons)  $\blacktriangleright$   $e^-$  (electrons)  $\blacktriangleright$   $\mu$  (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKEfield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive Experiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n\_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

# Compact Muon Solenoid (CMS)

Tracker

Electromagnetic Calorimeter (ECAL)

Hadronic Calorimeter (HCAL)

Soleoid

Muon chambers

## Trigger system:

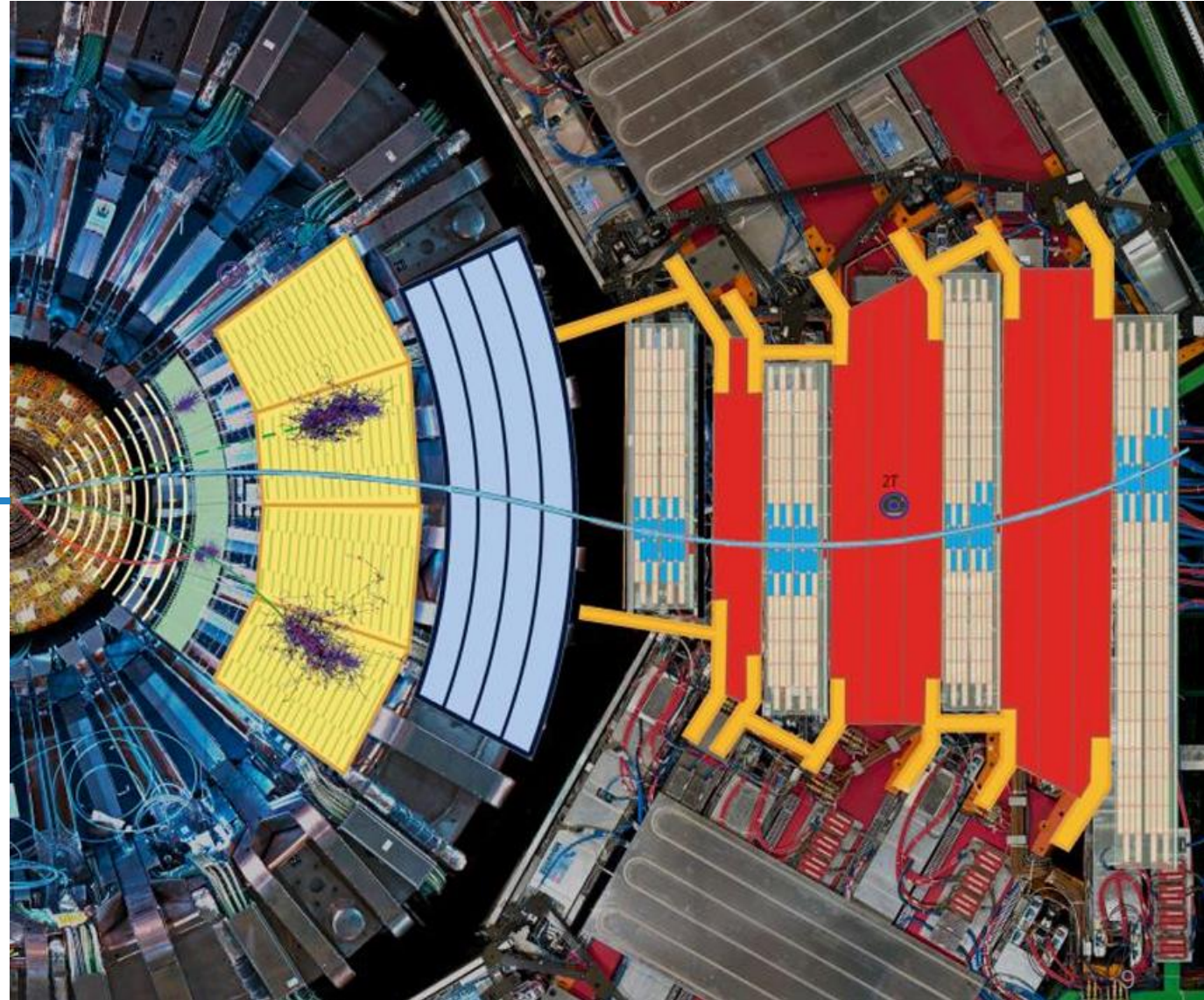
Initial data (40 MHz)



Level 1 trigger (10 kHz)

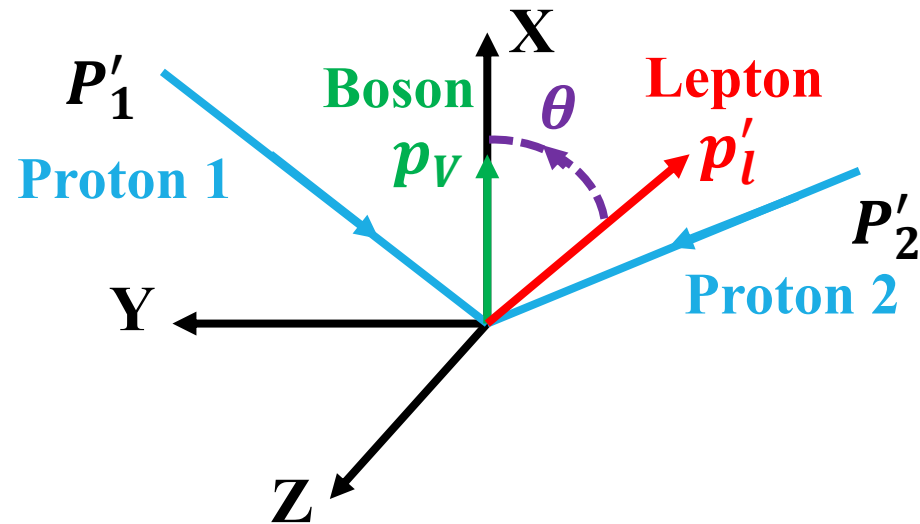


High level trigger (1 kHz)



# Polarization

- Studied in terms of the polarization angle  $\rightarrow \theta$  between **W (Z) boson** and  **$l^{(-)}$**



- **Single polarization**  $\rightarrow$  Measure W and Z polarization independently
- **Double polarization**  $\rightarrow$  Measure W and Z polarization at the same time

## Previous measurements of WZ polarization

- |       |                                                                                                                                                                                                                                                            |
|-------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| CMS   | <ul style="list-style-type: none"><li>• Full Run 2 data <a href="#">JHEP07 (2022) 032 (SMP-20-014)</a> <math>\rightarrow</math> WZ inclusive and differential cross section, <b>single polarization</b>, charge asymmetry and EFT interpretation</li></ul> |
| ATLAS | <ul style="list-style-type: none"><li>• Full Run 2 data (<a href="#">Phys. Lett. B 843 (2023) 137895</a>) <math>\rightarrow</math> WZ differential cross section, <b>single and double polarization</b></li></ul>                                          |

# Single polarization

- Following relation hold for  $\theta$ :

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

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

- Where  $f_L, f_R, f_0$  are the polarization fractions

- $f_L$  (left),  $f_R$  (right) → Transversal polarizations
- $f_0$  → Longitudinal polarization

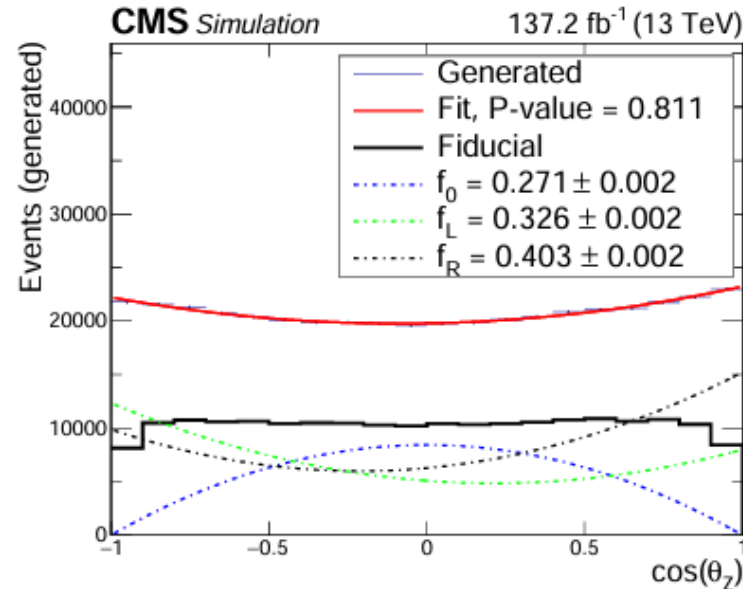
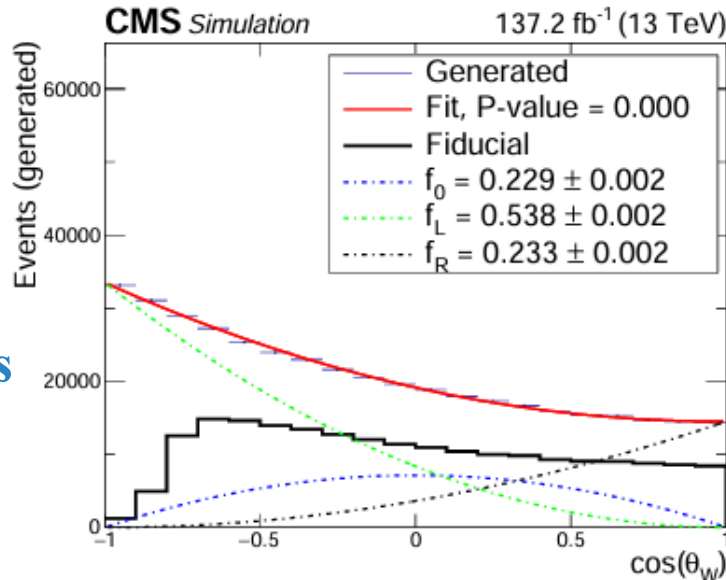
$$f_L + f_R + f_0 = 1$$

Due to  $Z$  coupling to fermions of different chiralities

$$c = \frac{c_L^2 - c_R^2}{c_L^2 + c_R^2}$$

- $c_L = -\frac{1}{2} + \sin^2 \theta_{eff}$
- $c_R = \sin^2 \theta_{eff}$

Plots from Run 2 analysis



Estimation of  $f_L, f_R, f_0$  value according to the SM → Fit to a quadratic function of  $\cos(\theta)$

# Double polarization

- The idea is to measure both the W and Z polarization at the same time → Can be longitudinal (0) or transversal (L, R) polarized too
- But equations become more complicated ...

$$\frac{d^2\sigma}{d\cos(\theta_Z)d\cos(\theta_W)} = 4f_{00}\sin^2(\theta_W)\sin^2(\theta_Z) + 2f_{0L}\sin^2(\theta_W)(1 - 2c\cos(\theta_Z) + \cos^2(\theta_Z)) + 2f_{0R}\sin^2(\theta_W)(1 + 2c\cos(\theta_Z) + \cos^2(\theta_Z)) + 4f_{L0}(1 \mp \cos^2(\theta_W))\sin^2(\theta_Z) + 2f_{LL}(1 \mp \cos^2(\theta_W))(1 - 2c\cos(\theta_Z) + \cos^2(\theta_Z)) + 2f_{LR}(1 \mp \cos^2(\theta_W))(1 + 2c\cos(\theta_Z) + \cos^2(\theta_Z)) + 4f_{R0}(1 \pm \cos^2(\theta_W))\sin^2(\theta_Z) + 2f_{RL}(1 \pm \cos^2(\theta_W))(1 - 2c\cos(\theta_Z) + \cos^2(\theta_Z)) + 2f_{RR}(1 \pm \cos^2(\theta_W))(1 + 2c\cos(\theta_Z) + \cos^2(\theta_Z))$$

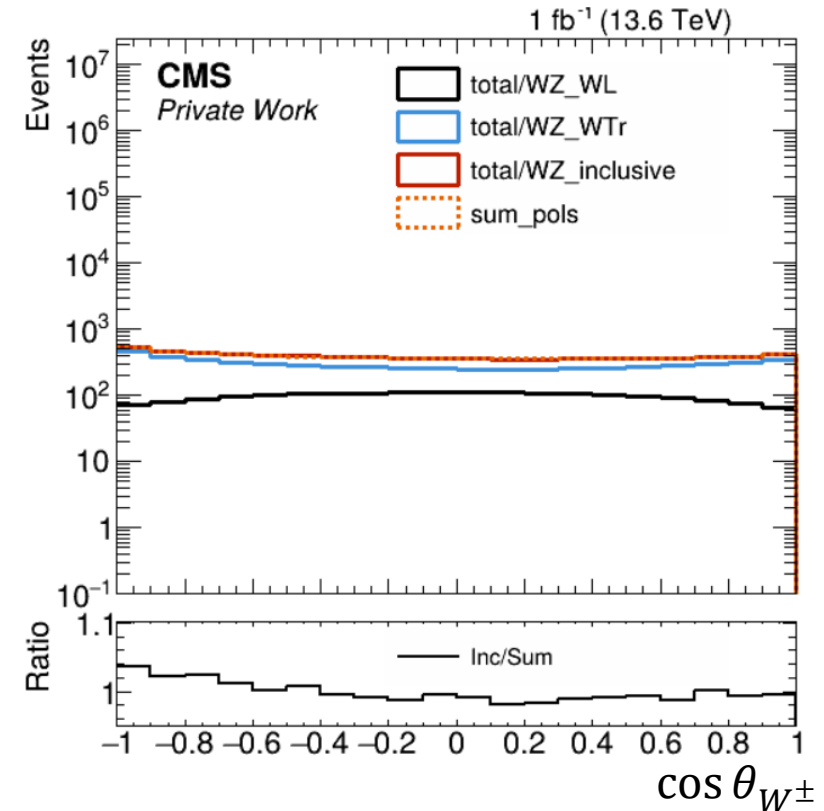
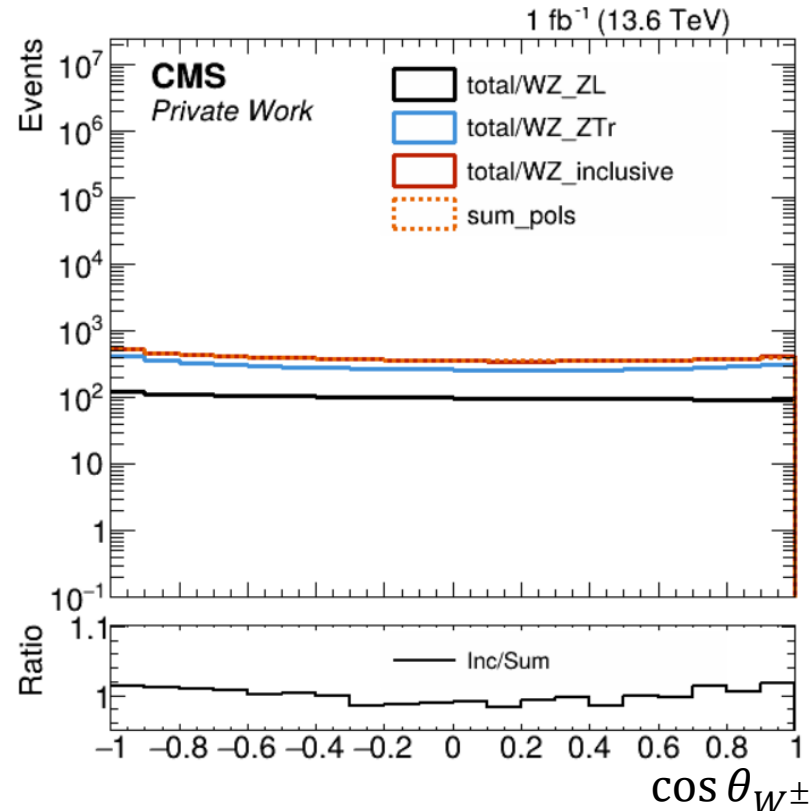
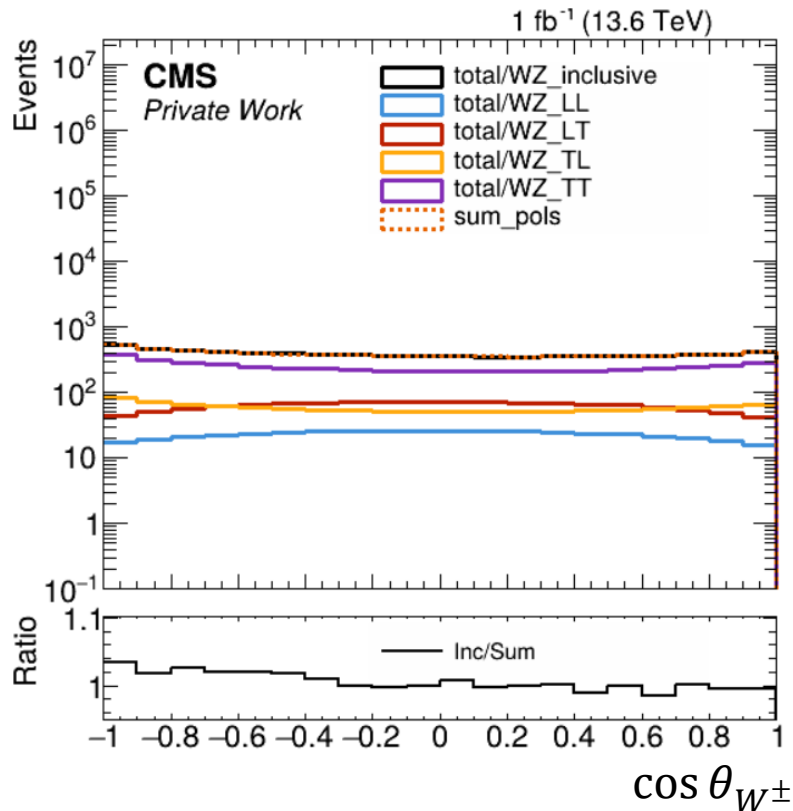
- Where the polarization fractions are  $f_{ij}$ ,  $i \in \{0, L, R\}$ ,  $j \in \{0, L, R\}$ , verifying

$$\sum_{i,j} f_{ij} = 1$$

- To simplify, we consider 4 polarization modes → 00, 0T, T0, TT  
Grouping L and R into a single category T

# What comes next?

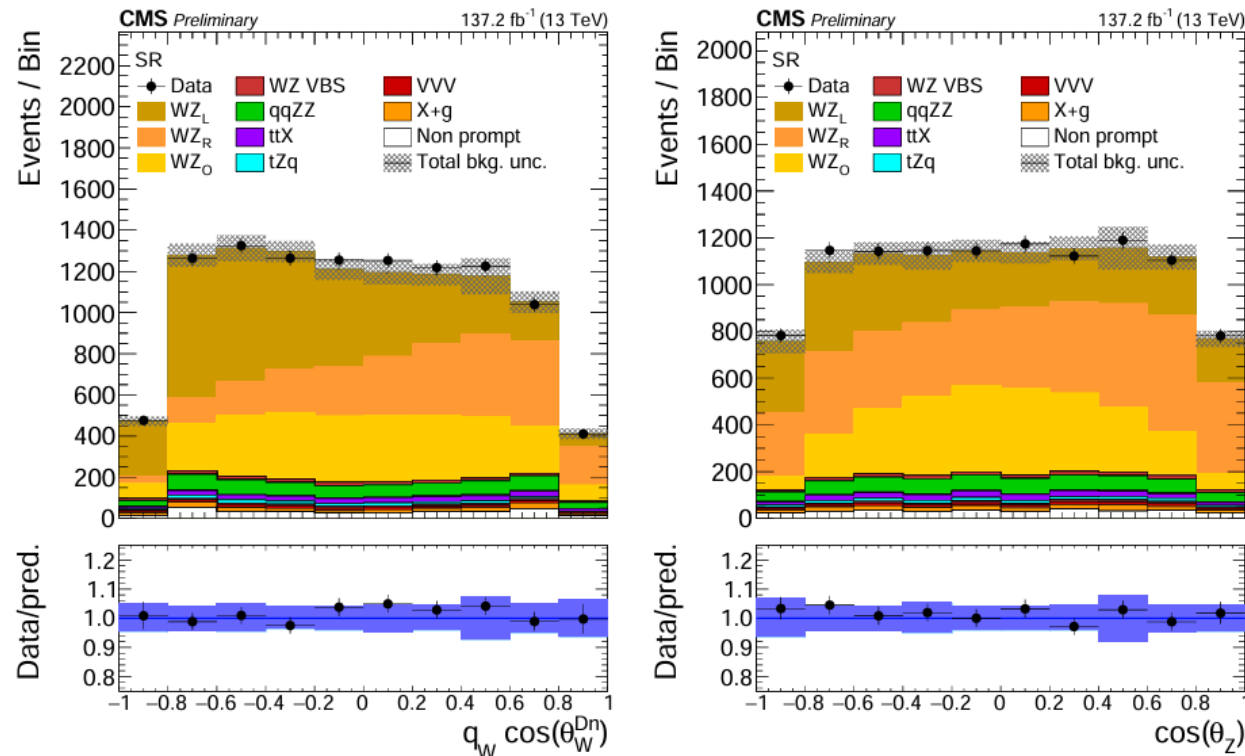
- Estimation of polarization fractions according to the SM → Compare with Run 2 results
- Generation of dedicated polarized MC samples → Simulate different polarization modes:
  - Single:  $W_L Z$ ,  $W_T Z$ ,  $W Z_L$ ,  $W Z_T$
  - Double:  $W_L Z_L$ ,  $W_L Z_T$ ,  $W_T Z_L$ ,  $Z_T Z_T$



# What comes next?

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  - Double:  $W_L Z_L$ ,  $W_L Z_T$ ,  $W_T Z_L$ ,  $Z_T Z_T$
- Plot the distributions comparing data and MC simulations

Plots from  
Run 2 analysis



# What comes next?

- Estimation of polarization fractions according to the SM → Compare with Run 2 results
- Generation of dedicated polarized MC samples → Simulate different polarization modes:
  - Single:  $W_L Z$ ,  $W_T Z$ ,  $W Z_L$ ,  $W Z_T$
  - Double:  $W_L Z_L$ ,  $W_L Z_T$ ,  $W_T Z_L$ ,  $Z_T Z_T$
- Plot the distributions at detector level comparing data and MC
- Perform a likelihood fit of the polarized MC samples to data → Obtain measurement of the polarization fractions

## Results from Run 2 analysis

Category	Observable	Result
W	$f_0$	$0.322^{+0.080}_{-0.077}$
	$f_{LR}$	$0.183^{+0.032}_{-0.032}$
Z	$f_0$	$0.245^{+0.024}_{-0.024}$
	$f_{LR}$	$-0.038^{+0.078}_{-0.078}$

$$f_{LR} = f_L - f_R$$

# Thank you!

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# Backup

# Event simulation

## Three stages:

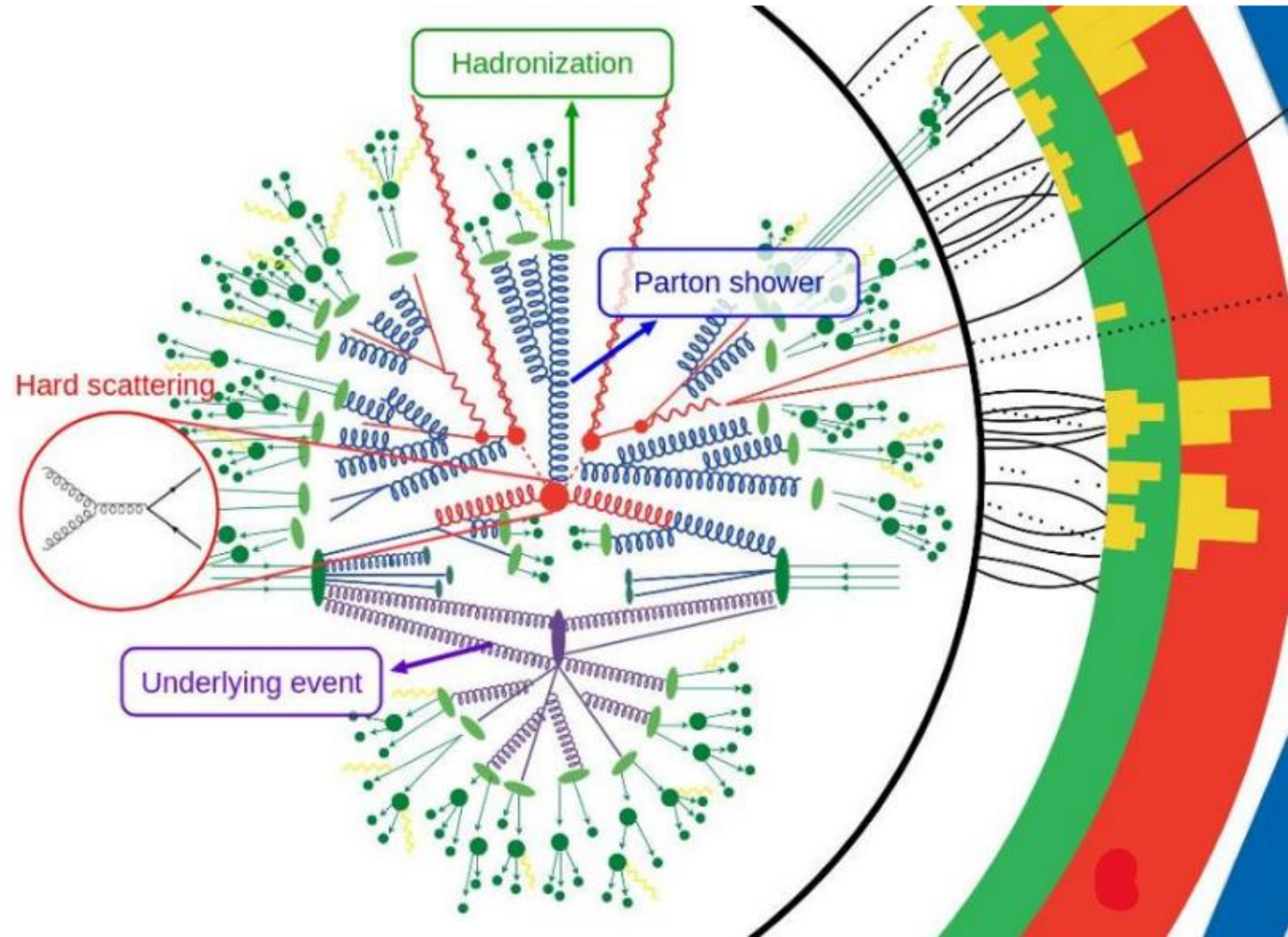
### 1. **Generation:**

Matrix element of QFT and hard scattering

### 2. **Simulation:**

Hadronization and detector simulation

### 3. **Reconstruction:** Same way as data



# Event selection

- **Baseline selection**
  - Strategy inherited from previous WZ analysis → [SMP-20-014](#) and [SMP-24-005](#)
  - Based on W/Z tagging algorithm → Selects the OSSF pair whose mass is nearer  $m_Z$
- **We define**
  - One signal region (**SR**)
  - Three control regions (CRs) based on the main backgrounds → **ZZ**, **ttX** and **Conversion**
  - Four channels (one per flavour bin): eee, eeμ, μμε, μμμ

Region	$N_\ell$	$p_T\{\ell_Z^1, \ell_Z^2, \ell_W\}$ (GeV)	$N_{\text{OSSF}}$	$ m(\ell_Z^1, \ell_Z^2) - m_Z $ (GeV)	$p_T^{\text{miss}}$ (GeV)	$N_{\text{b tag}}$	$\min(m(\ell, \ell'))$ (GeV)	$m(\ell_Z^1, \ell_Z^2, \ell_W)$ (GeV)
SR	=3	>{25, 15, 25}	≥1	<15	>35	=0	>4	>100
ZZ CR	=4	>{25, 15, 25, 15}	≥1	<15	-	=0	>4	>100
ttZ CR	=3	>{25, 15, 25}	≥1	<15	>35	>0	>4	>100
X + γ CR	=3	>{25, 15, 25}	≥1	-	≤35	=0	>4	<100

# Single polarization

- Studied in terms of the polarization angle  $\rightarrow \theta$  between **W (Z) boson** and  **$l^{(\pm)}$**
- For single polarization  $\rightarrow$  At LO in EW the following relation hold for  $\theta$

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

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

- Where  $f_L, f_R, f_0$  are the polarization fractions  $\rightarrow f_L + f_R + f_0 = 1$

Due to Z coupling to fermions of different chiralities

$$c = \frac{c_L^2 - c_R^2}{c_L^2 + c_R^2}$$

- $c_L = -\frac{1}{2} + \sin^2 \theta_{eff}$
- $c_R = \sin^2 \theta_{eff}$

Region	Fiducial	Total
Lepton definition	Dressed (e, $\mu$ )	Dressed (e, $\mu$ , $\tau$ )
$N_\ell = 3$	✓	✓
$p_T \{l_Z^1, l_Z^2, l_W\} > \{25, 15, 25\} \text{ GeV}$	✓	—
$ \eta  \{l_Z^1, l_Z^2, l_W\} < \{2.5, 2.5, 2.5\}$	✓	—
$N_{OSF} = 1$	✓	✓
$60 < m(l_Z^1, l_Z^2) < 120 \text{ GeV}$	✓	✓
$\min(m(l, l')) > 4 \text{ GeV}$	✓	✓
$m(l_Z^1, l_Z^2, l_W) > 100 \text{ GeV}$	✓	—

A really important fact is that these quadratic expressions for  $\cos(\theta)$  distributions are only valid in the **Total** region. Once we impose fiducial (phase-space) requirements we lose the parabolic behaviour

# Single polarization:

We consider 3 channels: 1 inclusive and 2 obtained by splitting the dataset considering the charge of the W boson

