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

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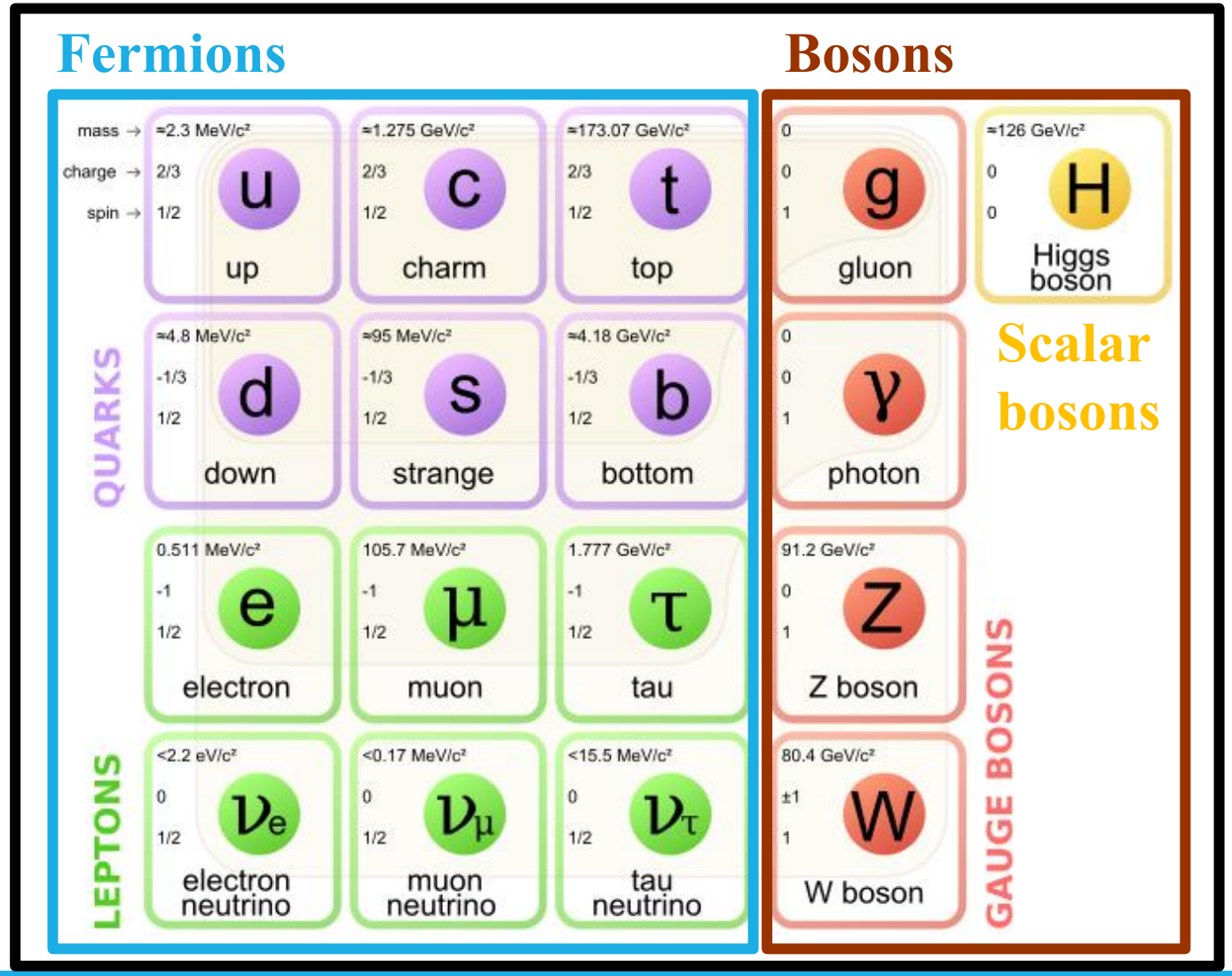
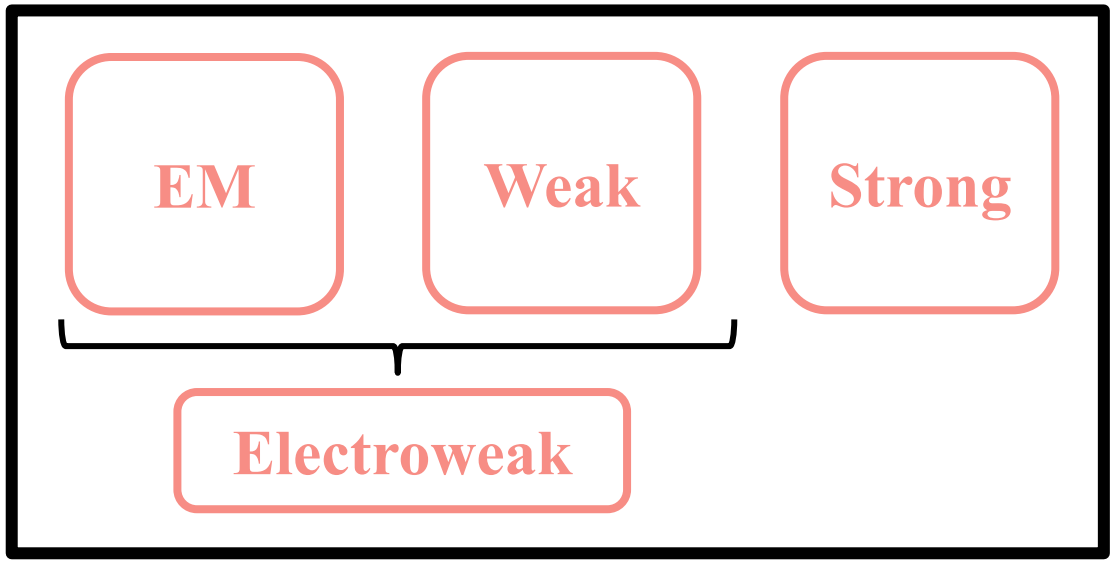
Standard Model (SM)

Particles

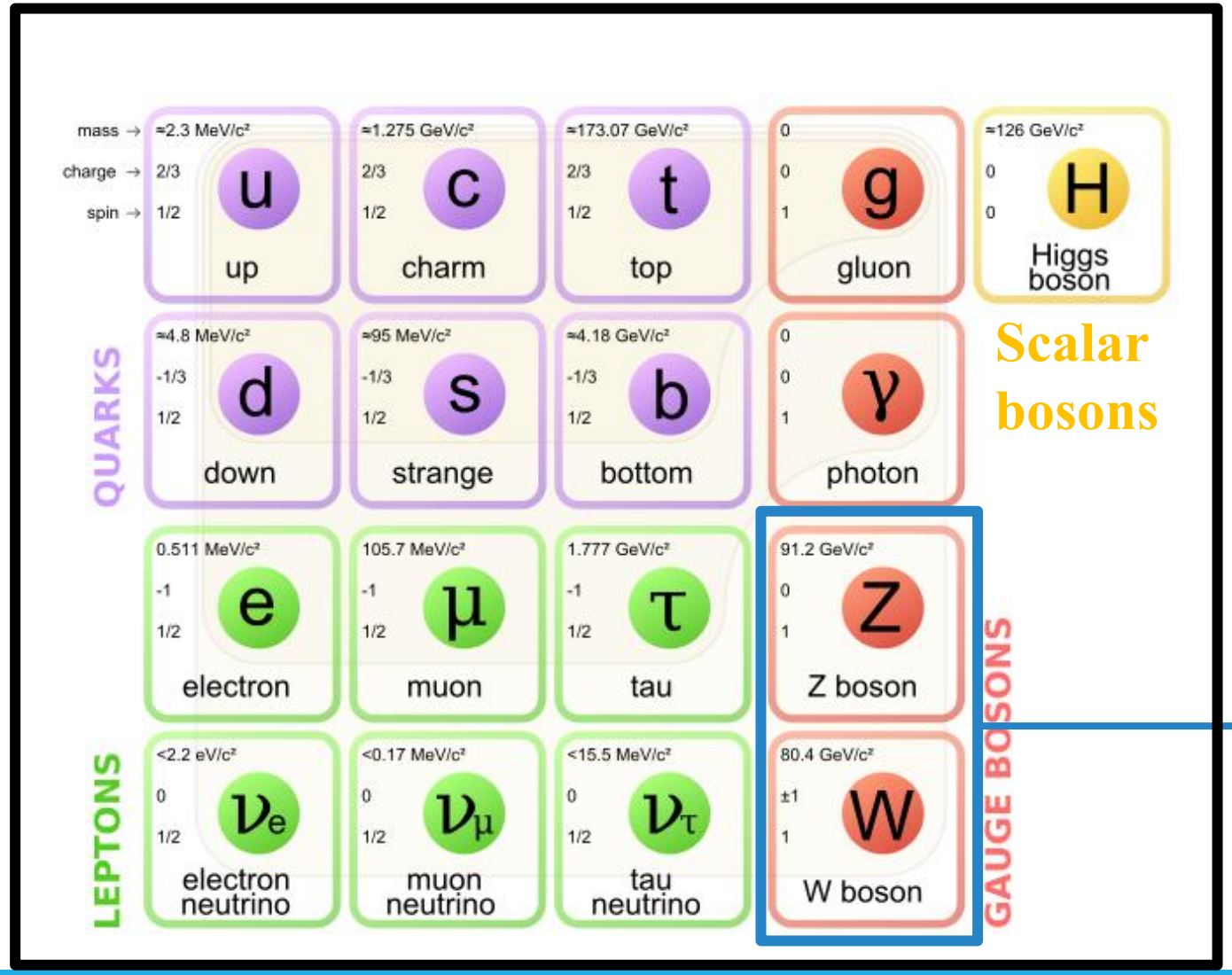


Interactions

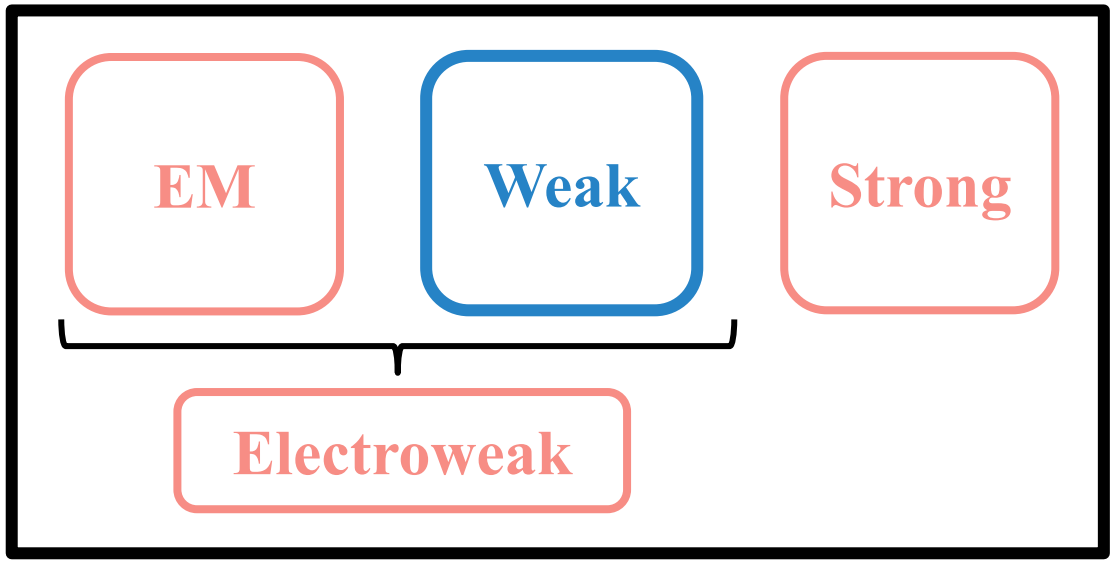


Standard Model (SM)

Particles



Interactions



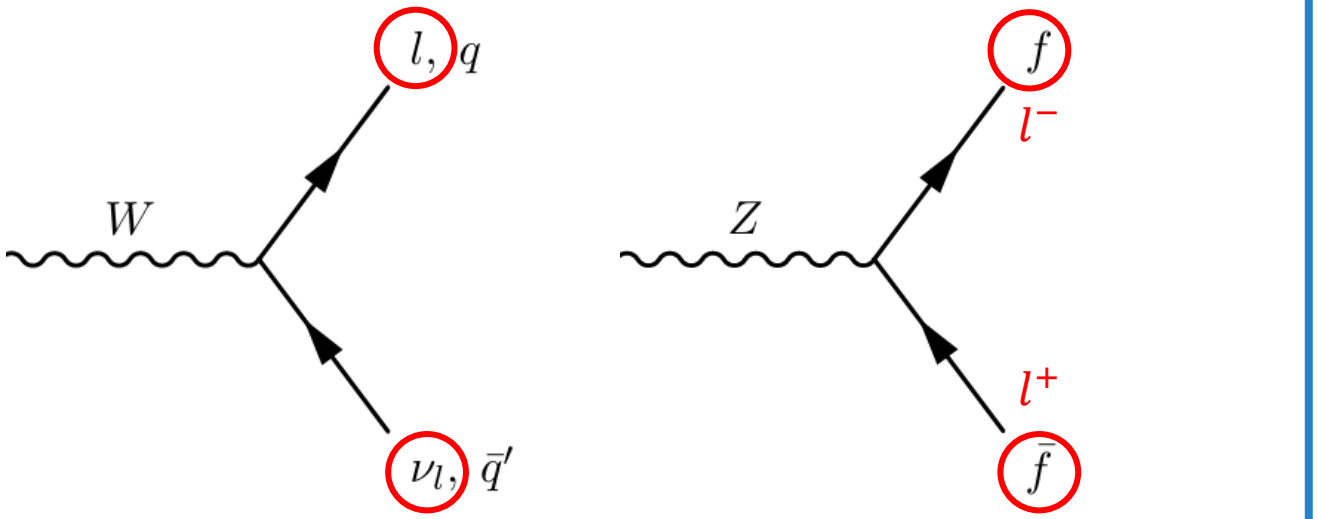
- Weak intermediate bosons
- Massive Gauge bosons

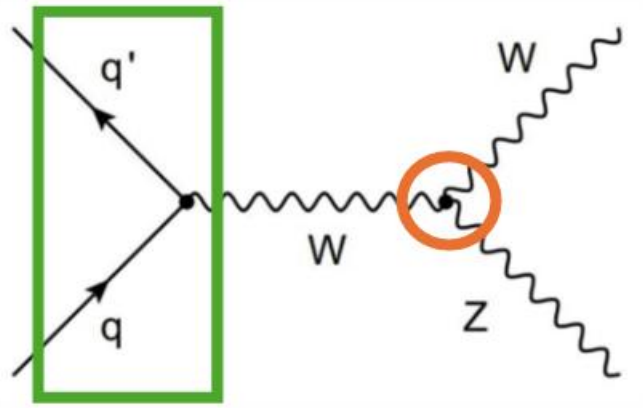
WZ production

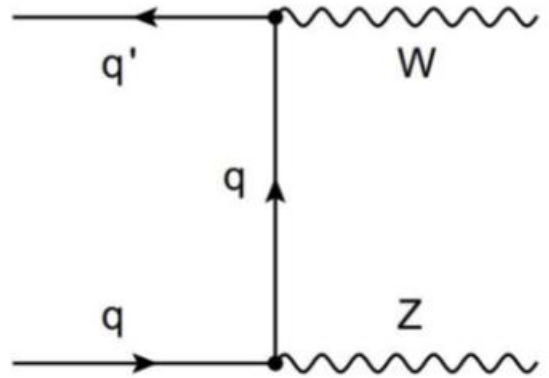
WZ is a process of interest for SMP and BSMP

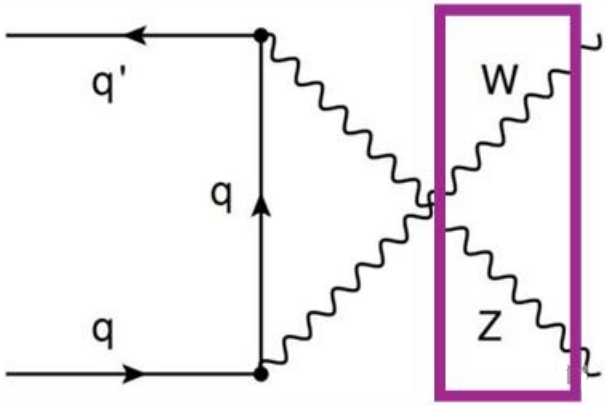
- Sensitive to charge asymmetries
- Direct access to Trilinear Gauge Couplings and anomalies
- **Boson polarization (final state leptons)**

Multileptonic final state

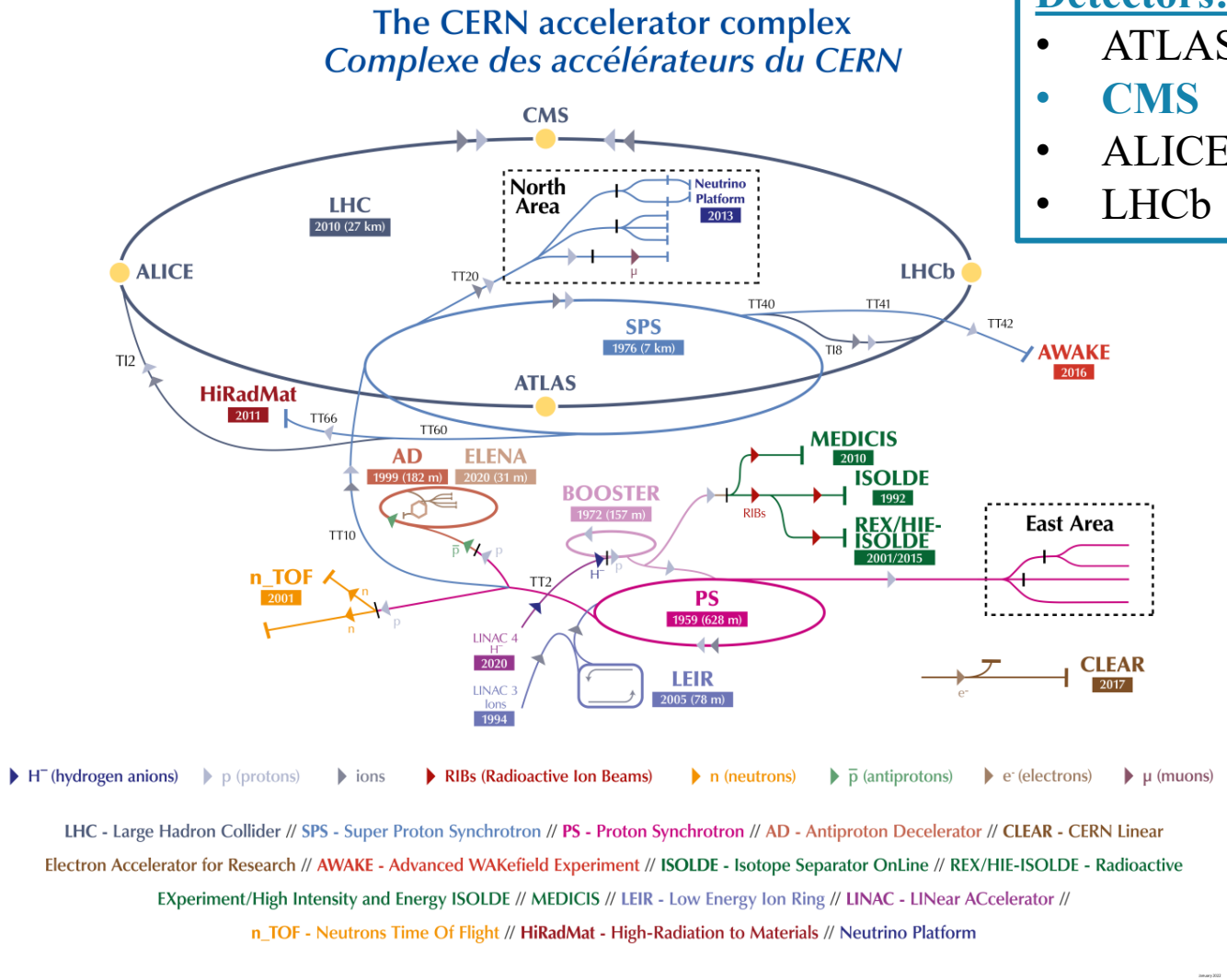








Large Hadron Collider (LHC)

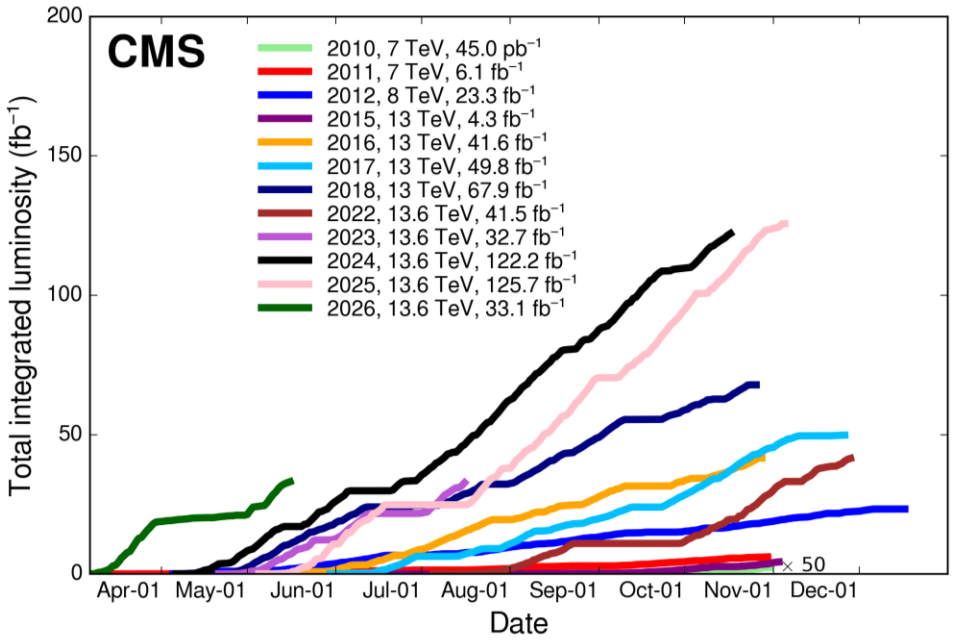


Detectors:

- ATLAS
- **CMS**
- ALICE
- LHCb

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

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



Compact Muon Solenoid (CMS)

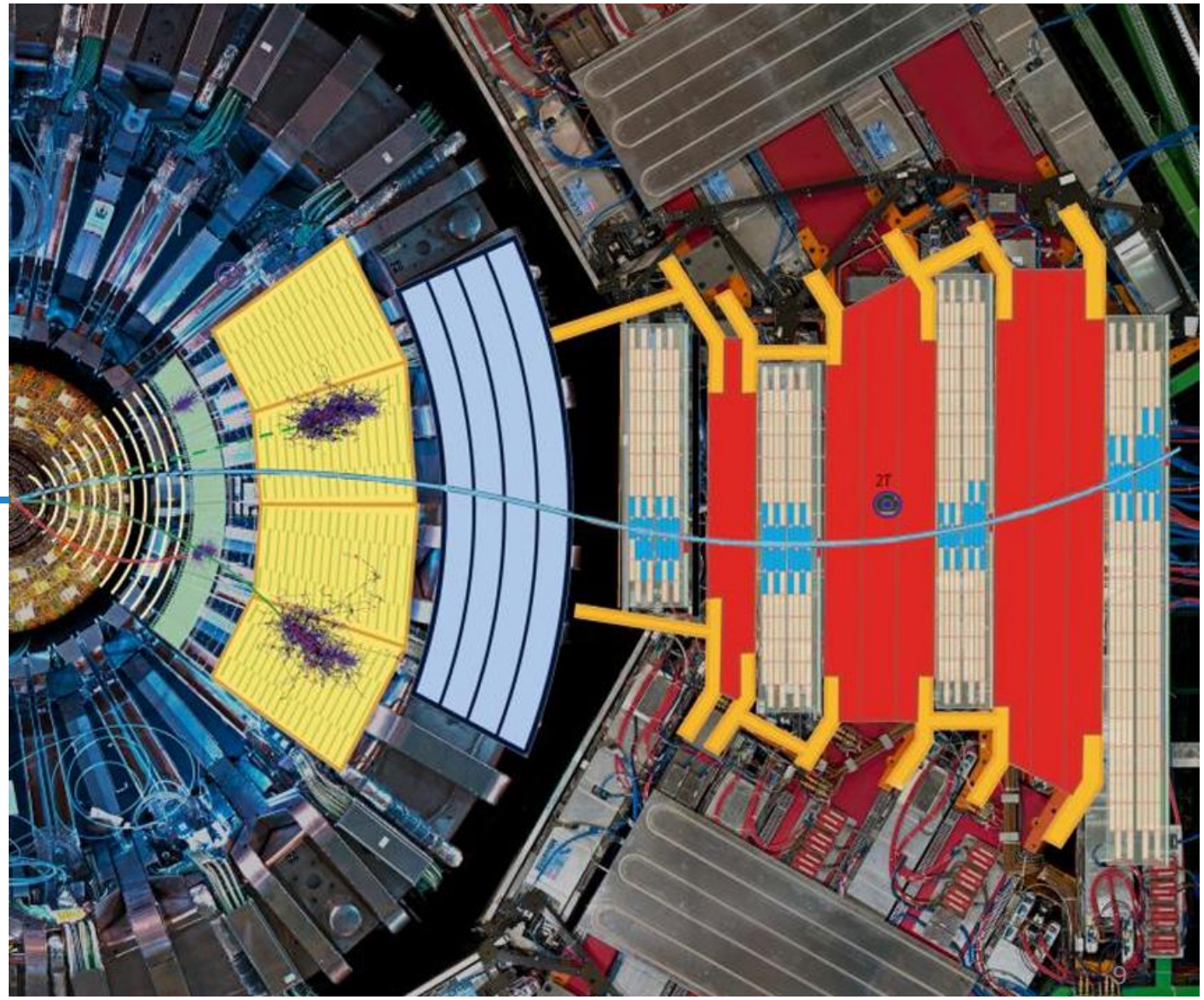
Tracker

Electromagnetic Calorimeter (ECAL)

Hadronic Calorimeter (HCAL)

Soleoid

Muon chambers



Trigger system:

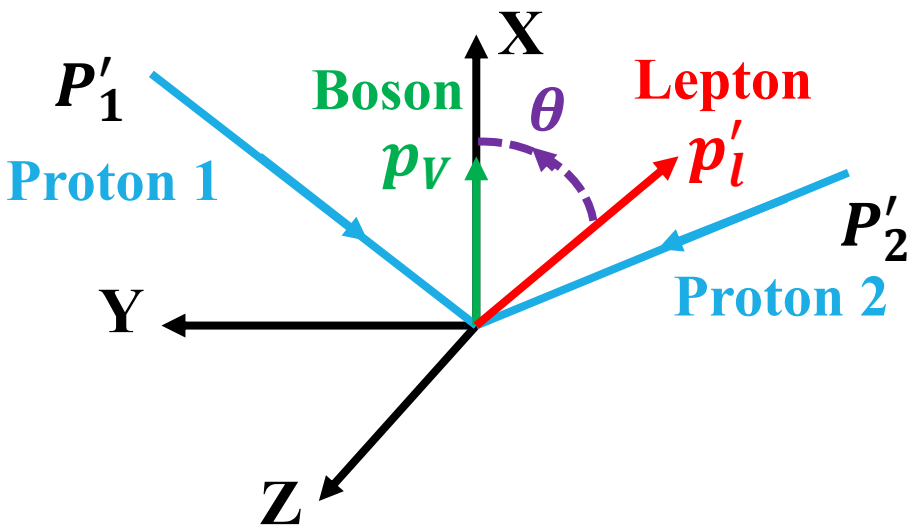
Initial data (40 MHz)

Level 1 trigger (10 kHz)

High level trigger (1 kHz)

Polarization

- Studied in terms of the polarization angle → θ between **W (Z) boson** and **l(-)**



- Single polarization → Measure W and Z polarization independently
- Double polarization → Measure W and Z polarization at the same time

Previous measurements of WZ polarization

CMS

- Full Run 2 data JHEP07 (2022) 032 (SMP-20-014) → WZ inclusive and differential cross section, single polarization, charge asymmetry and EFT interpretation

ATLAS

- Full Run 2 data (Phys. Lett. B 843 (2023) 137895) → WZ differential cross section, single and double polarization

Single polarization

- Following relation hold for θ:

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

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

- Where f_L, f_R, f_0 are the polarization fractions
  - f_L (left), f_R (right) → Transversal polarizations
  - f_0 → Longitudinal polarization

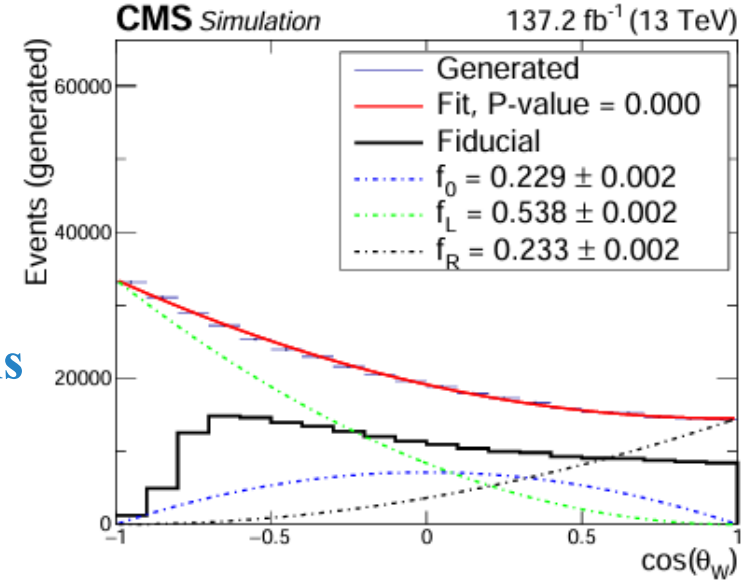
$$f_L + f_R + f_0 = 1$$

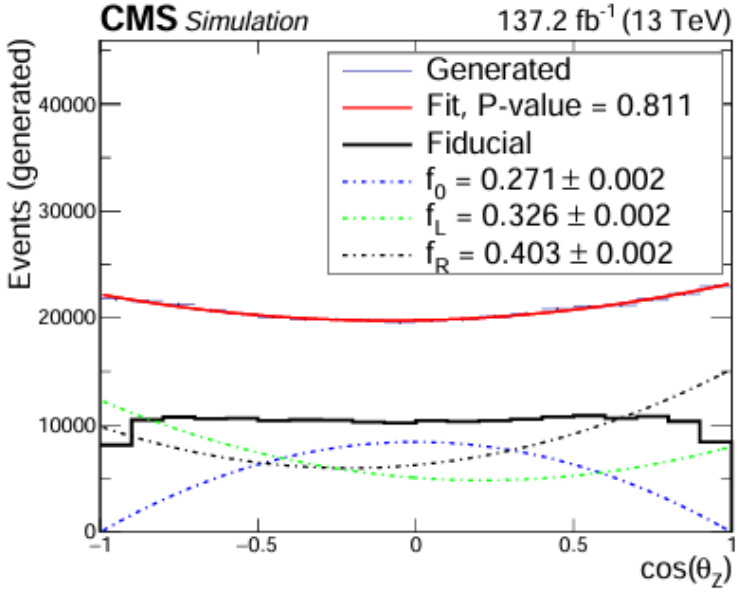
Due to Z coupling to fermions of different chiralities

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

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

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 …

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

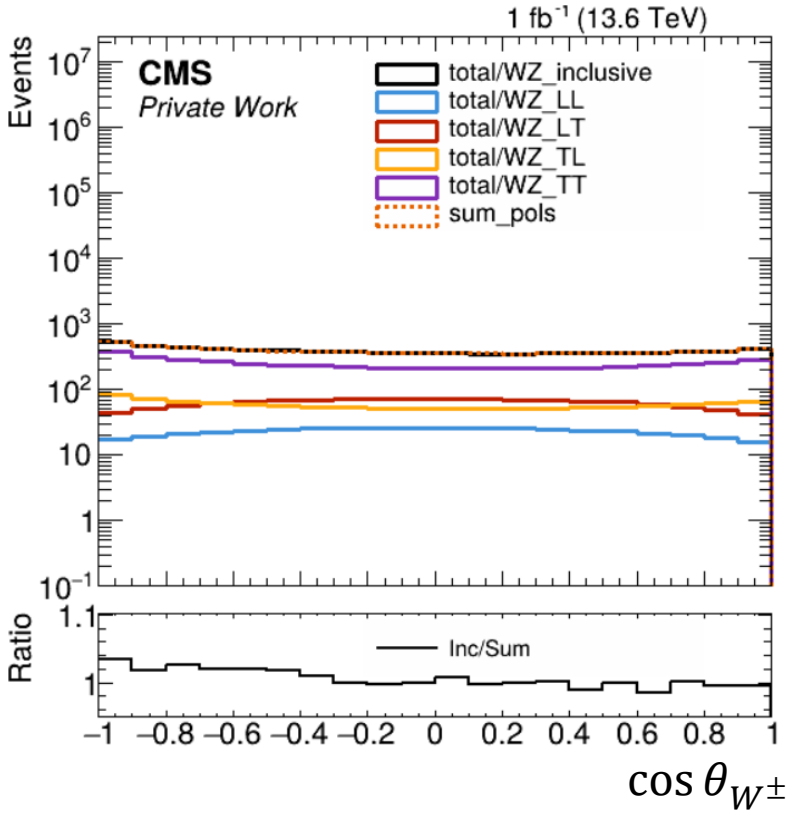
- Where the polarization fractions are $f_{ij}, i \in \{0, L, R\}, j \in \{0, L, R\}$, verifying

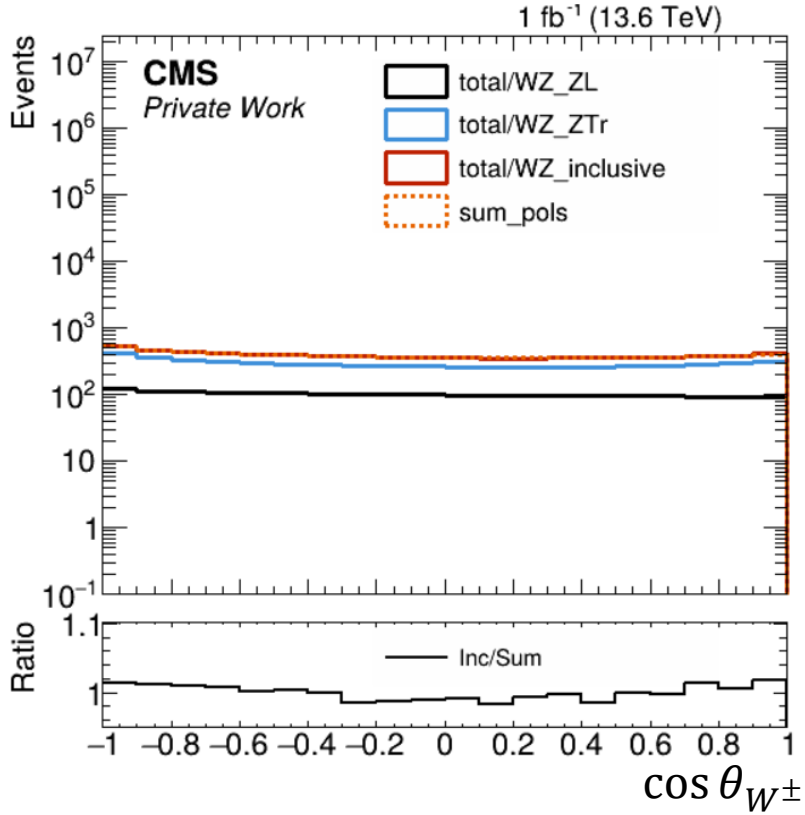
$$\sum_{i,j} f_{ij} = 1$$

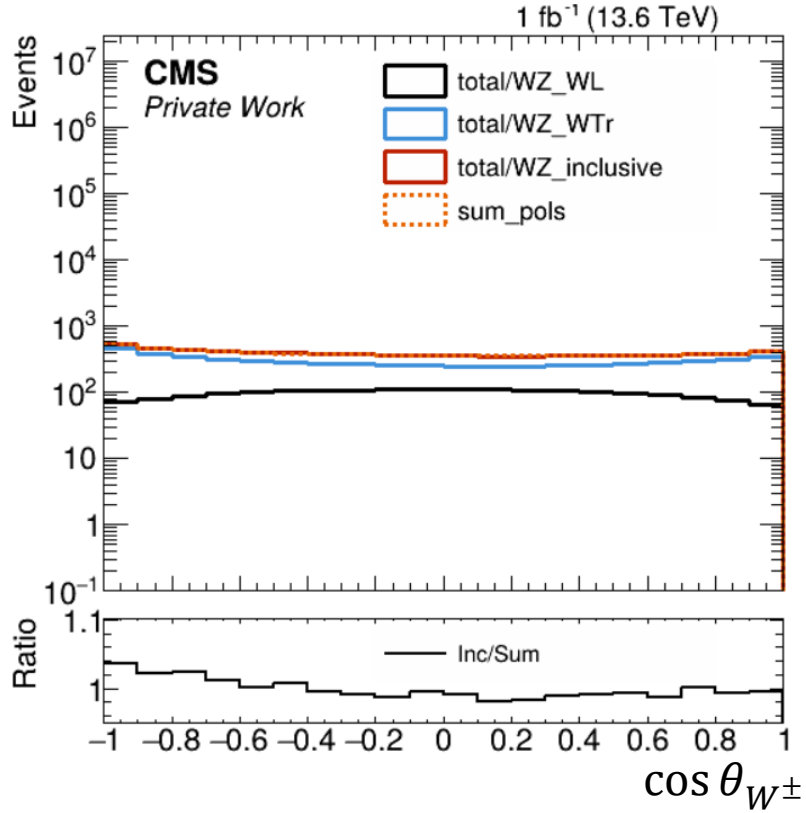
- To simplify, we consider 4 polarization modes → 00, 0T, T0, TT
  Grouping L and R into a single category T

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_LZ, $W_{Tr}Z$, WZ_L, WZ_{Tr}
  - Double: W_LZ_L, W_LZ_T, W_TZ_L, Z_TZ_T







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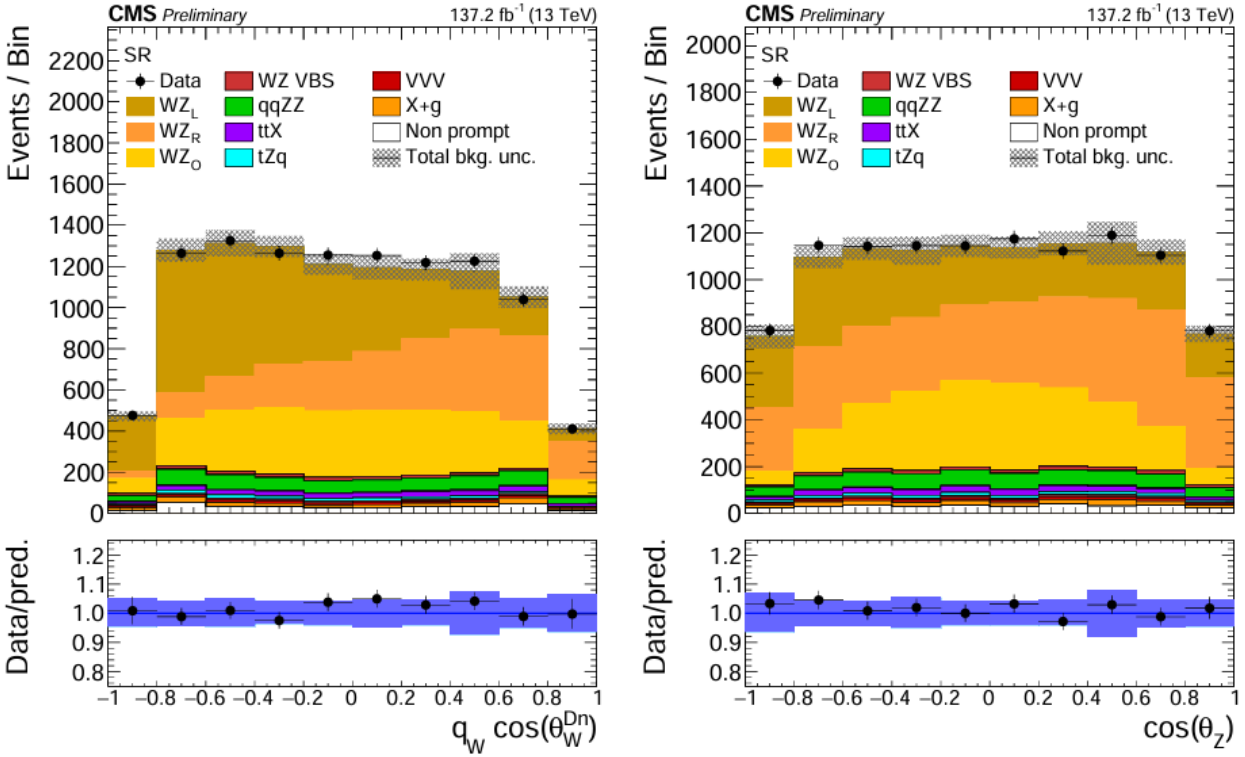
  - Double: W_LZ_L, W_LZ_T, W_TZ_L, Z_TZ_T
- Plot the distributions comparing data and MC simulations

Plots from Run 2 analysis



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  - Single: W_LZ, $W_{Tr}Z$, WZ_L, WZ_{Tr}
  - Double: W_LZ_L, W_LZ_T, W_TZ_L, Z_TZ_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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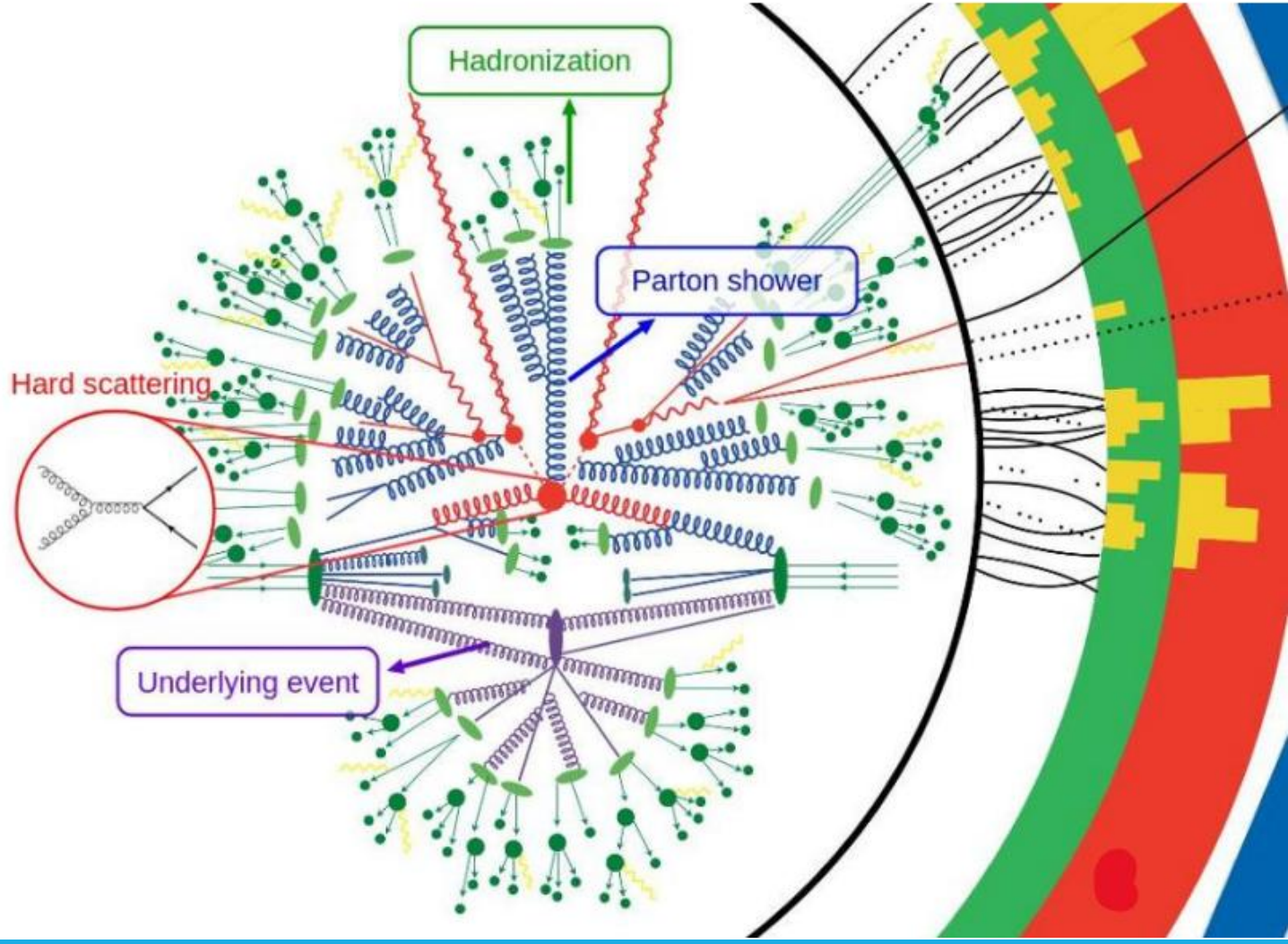
Backup

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, μμe, μμμ

Region	N_ℓ	$p_T\{\ell^1_Z, \ell^2_Z, \ell_W\}$ (GeV)	N_{OSSF}	$\lvert m(\ell^1_Z, \ell^2_Z) - m_Z \rvert$ (GeV)	p_T^{miss} (GeV)	$N_{b\ tag}$	$\min(m(\ell, \ell'))$ (GeV)	$m(\ell^1_Z, \ell^2_Z, \ell_W)$ (GeV)
SR	=3	>{25, 15, 25}	≥1	<15	>35	=0	>4	>100
ZZ CR	=4	>{25, 15, 25, 15}	≥1	<15	-	=0	>4	>100
$t\bar{t}Z$ CR	=3	>{25, 15, 25}	≥1	<15	>35	>0	>4	>100
$X + \gamma$ CR	=3	>{25, 15, 25}	≥1	-	≤35	=0	>4	<100

Single polarization

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

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

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

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

Due to Z coupling to fermions of different chiralities

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

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

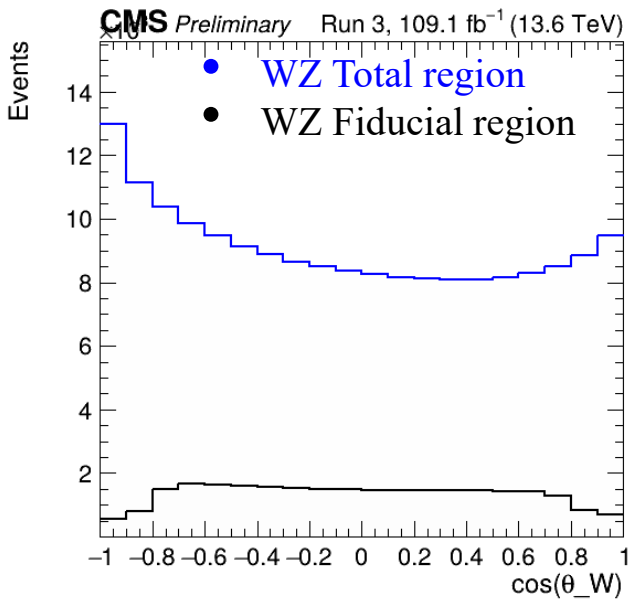
Region	Fiducial	Total
Lepton definition	Dressed (e, μ)	Dressed (e, μ, τ)
$N_\ell = 3$	✓	✓
$p_T\{\ell_Z^1, \ell_Z^2, \ell_W\} > \{25, 15, 25\}$ GeV	✓	—
$\lvert\eta\rvert\{\ell_Z^1, \ell_Z^2, \ell_W\} < \{2.5, 2.5, 2.5\}$	✓	—
$N_{OSSF} = 1$	✓	✓
$60 < m(\ell_Z^1, \ell_Z^2) < 120$ GeV	✓	✓
$\min(m(\ell, \ell')) > 4$ GeV	✓	✓
$m(\ell_Z^1, \ell_Z^2, \ell_W) > 100$ GeV	✓	—

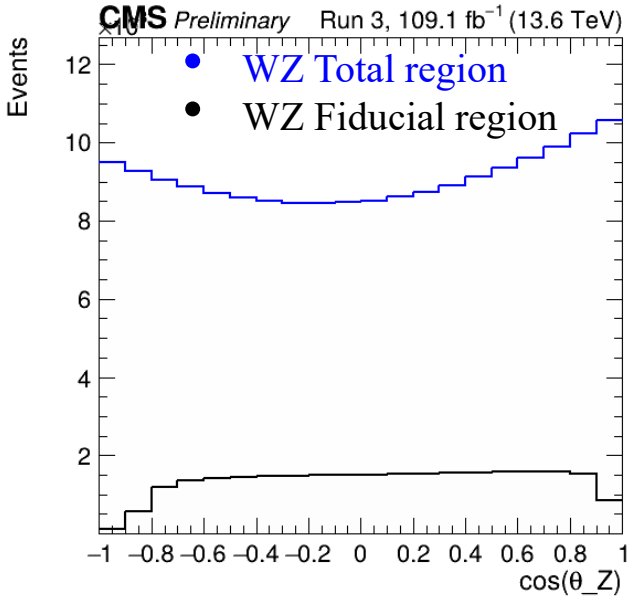
A really important fact is that these quadratic expressions for $\cos(\theta)$ distributions are only valid in the **Total** region. Once we impose fiducial (phase-space) requirements we lose the parabolic behaviour

Single polarization:

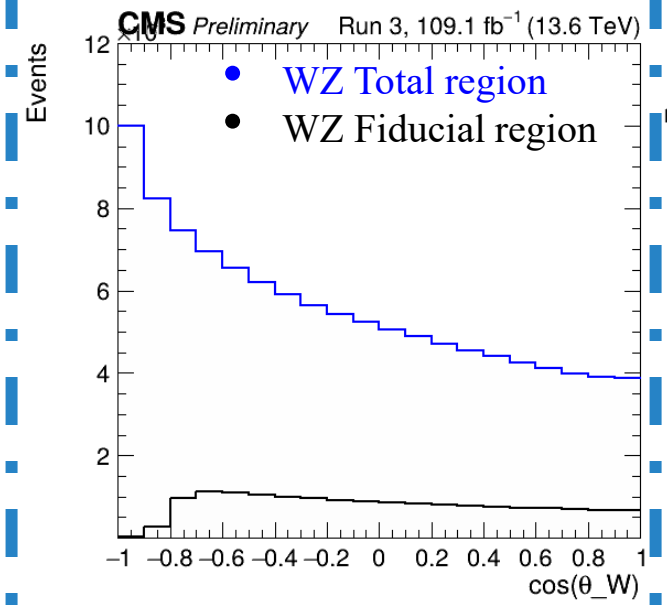
We consider 3 channels: 1 inclusive and 2 obtained by splitting the dataset considering the charge of the W boson

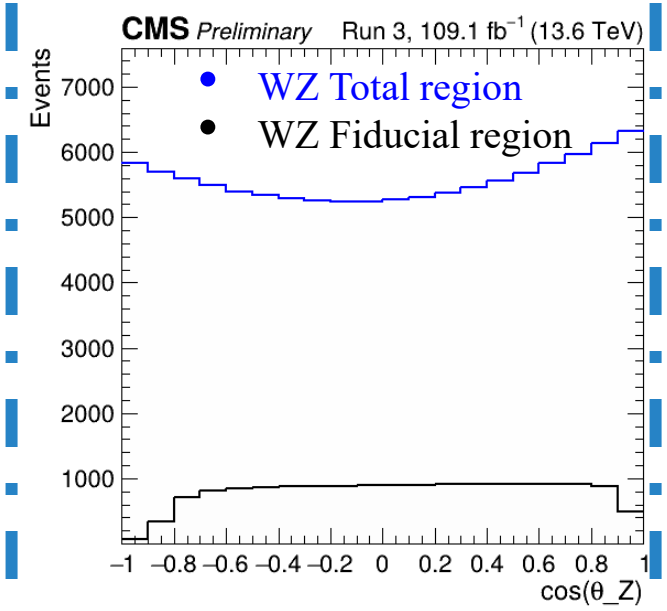
Inclusive channel





+ channel





- channel