Electroweak Physics at the LHC – Experimental Overview

42nd International Conference on High Energy Physics

Philip Sommer, on behalf of
the ATLAS, CMS and LHCb Collaborations

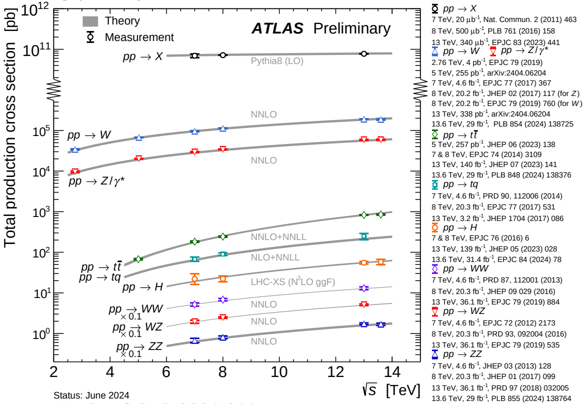
Technische Universität Dresden

24.07.2024

The Electroweak Theory

- Rich variety of electroweak interaction derived from symmetry principles

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$$
$$\rightarrow W^+, W^-, Z, \gamma$$



ATL-PHYS-PUB-2024-011

- Mass of electroweak gauge bosons and interaction strength predicted precisely from g, g', v, λ

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W}$$

- Four input parameters, e.g. $\alpha_{\mathrm{QED}}, G_F, m_Z$ and m_H

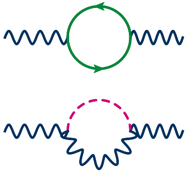
- At the LHC, we test the electroweak theory
  - precision measurements of single W/Z bosons
  - at high energy in multi-bosons production

Recent cross-section measurements:

- Special low-pileup datasets at 5 and 13 TeV (CMS-PAS-SMP-20-004 and arXiv:2404.06204)
- First measurements at 13.6 TeV (CMS-PAS-SMP-22-017 and PLB 854 (2024) 138725)

Experimental Test at the LHC

The Precision Frontier



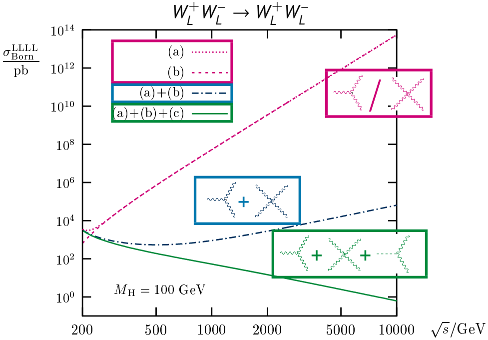
- Radiative corrections modify propagators and decay vertices

$$m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - 4\frac{\pi\alpha}{\sqrt{2}G_F m_Z^2}\frac{1}{1-\Delta r}}\right)$$

$$\sin^2\theta_W \longrightarrow \kappa_f \sin^2\theta_W = \sin^2\theta_{\text{eff}}^f$$

- Sensitivity to a wide range of physics through quantum loops

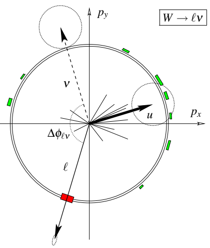
The Energy Frontier



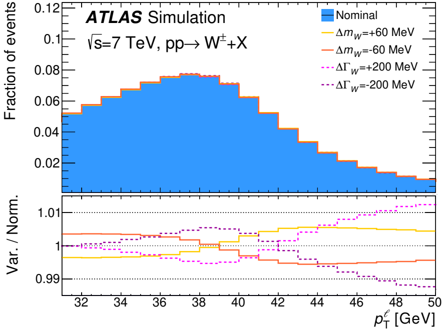
from Nucl. Phys. B525 (1998) 27-50

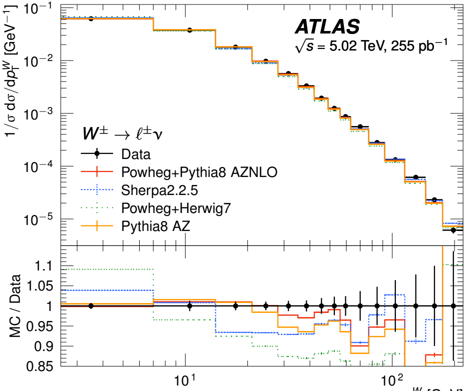
- Tests of the electroweak theory through delicate gauge cancellations at high energy
- Deviations can lead to potentially large effects

Measurement of the W Boson Mass and Width



arXiv:0901.0512





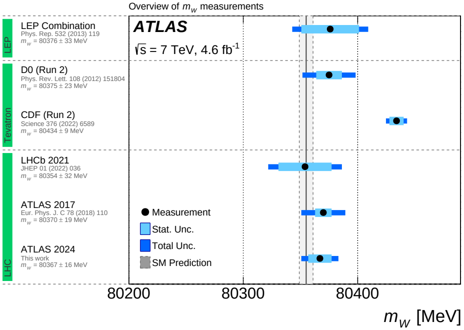
arXiv:2404.06204

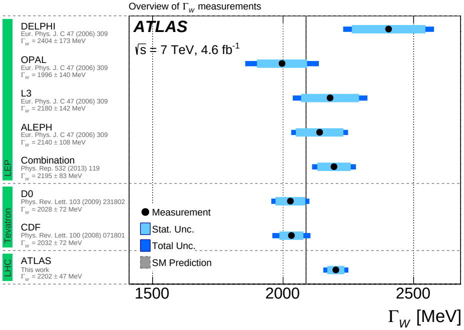
- Improved measurement of m_W and first measurement of Γ_W at LHC
- Measured from p_T^ℓ and m_T^W distributions in $W \to \ell\nu$ decays

- Rigorous checks of $p_T(W)$ modelling in dedicated measurements
- Progress in global PDF fits and theoretical calculations

$\Rightarrow$ Revisit 2011 data (favourable experimental environment for measurement of m_W)

Measurement of the W Boson Mass and Width



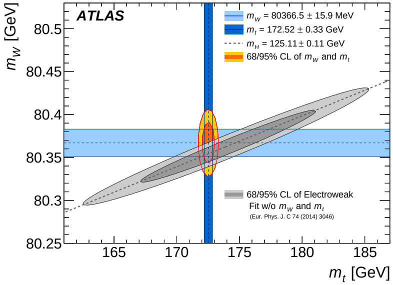


- Separate measurement of mass and width

$$m_W = 80366.5 \pm 15.9 \text{ MeV}$$

$$\Gamma_W = 2202 \pm 47 \text{ MeV}$$

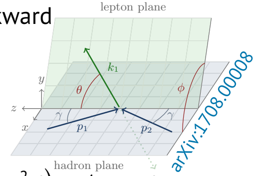
- ... as well as simultaneous extraction
- Most precise single-experiment measurements of Γ_W



More details in arXiv:2403.15085 (LHCb JHEP 01 (2022) 036)

Measurement of the Effective Weak Mixing Angle

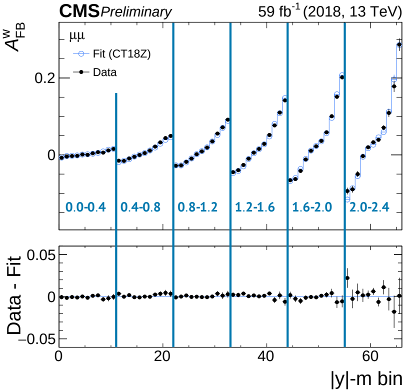
- Measurement of $pp \to \ell^+\ell^-$ forward-backward asymmetry at $\sqrt{s} = 13$ TeV

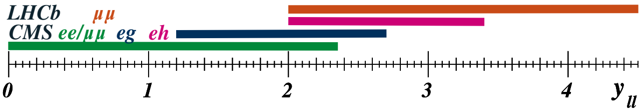


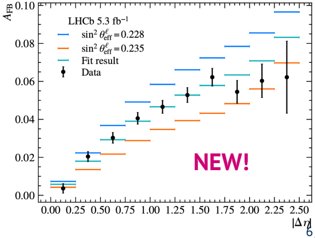
- Used to determine $\sin^2\theta^{\ell}_{\text{eff}}$

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta + \frac{1}{2}A_0\left(1 - 3\cos^2\theta\right) + A_4\cos\theta$$

- Ambiguity in quark direction resolved through rapidity-dependent measurement
- Reconstruction of electrons in CMS extended to $|\eta| < 4.36$
- High quality muon reconstruction in LHCb in $2.0 < |\eta| < 4.5$



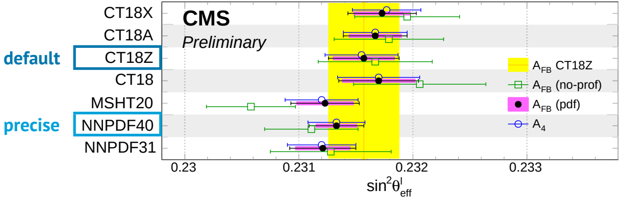




Measurement of the Effective Weak Mixing Angle

- PDF uncertainties profiled in fit of $\sin^2\theta^\ell_{\text{eff}}$

→ reduced differences between global PDF fits and reduced uncertainties



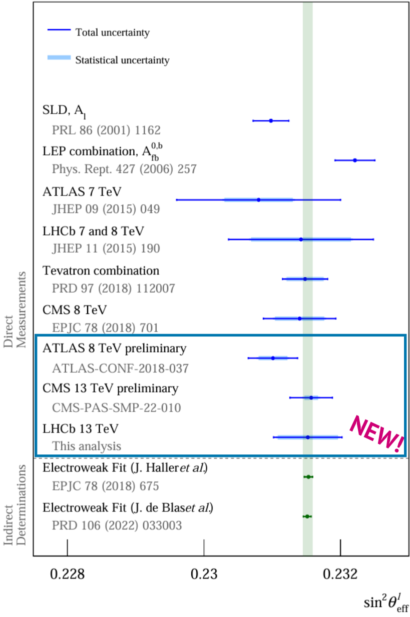
- New, precise measurements from hadron colliders

CMS: $\sin^2\theta^\ell_{\text{eff}} = 0.23157 \pm 0.00010\,(\text{stat}) \pm 0.00015\,(\text{syst}) \pm 0.00009\,(\text{theo}) \pm 0.00027(\text{PDF})$

LHCb: $\sin^2\theta^\ell_{\text{eff}} = 0.23152 \pm 0.00044\,(\text{stat}) \pm 0.00005\,(\text{syst}) \pm 0.00022\,(\text{theo/PDF})$

More details in CMS-PAS-SMP-22-010 (LHCb in preparation)

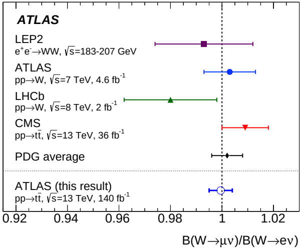
(ATLAS: ATLAS-CONF-2018-037)



W Boson Decay Branching Fractions

- Branching fraction measurements rely on W boson pairs

→ At the LHC, most prevalent in decays of top-quark pairs

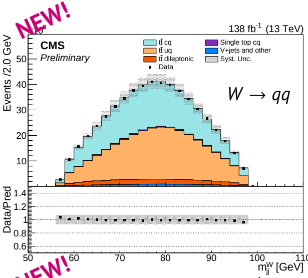


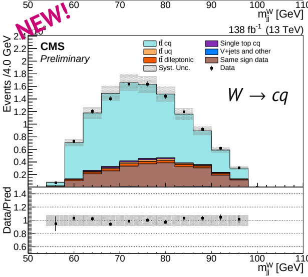
- Test of lepton flavour universality

$$R_W^{\mu/e} = \frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)}$$

- Measurement of $W \to cs$ branching ratio

$$R_W^c = \frac{\mathcal{B}(W \to cq)}{\mathcal{B}(W \to cq)\mathcal{B}(W \to ud)}$$



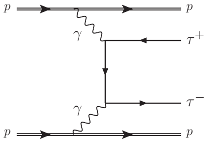


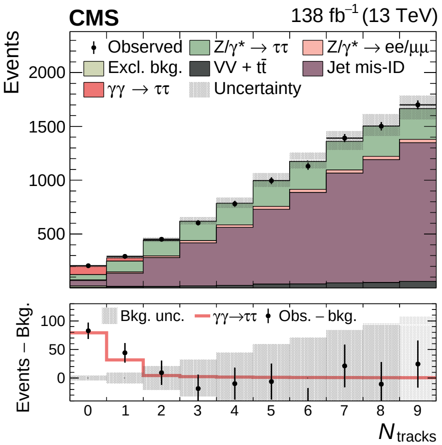
- Most precise measurement of e/μ ratio for on-shell W decays
- Most precise measurement of R^c for on-shell W decays
  - Used to determine $|V_{cs}| = 0.959 \pm 0.021$ (ATLAS measurement from W/Z ratio: $|V_{cs}| = 0.969^{+0.018}_{-0.030}$ (EPJC 77 (2017) 367))

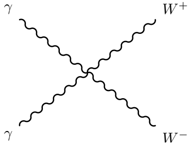
More details in arXiv:2403.02133 and CMS-PAS-SMP-24-009

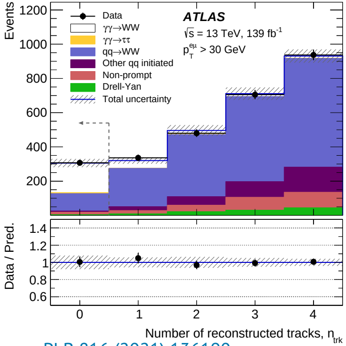
(CMS $e/\mu/\tau$/had PRD 105 (2022) 072008
ATLAS μ/τ NPHYS 17 (2021) 813)

Production of τ-Leptons from Photons







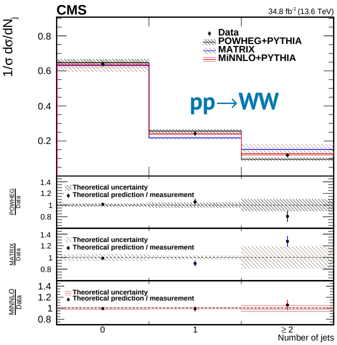


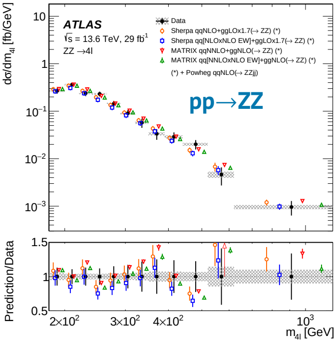
PLB 816 (2021) 136190

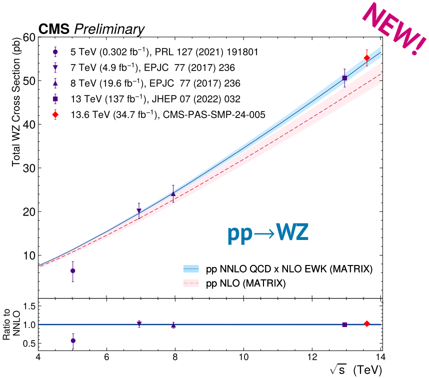
- Measurement of $\gamma\gamma \to \tau\tau$ production, for the first time in pp collisions
- Basis to constrain anomalous magnetic and electric dipole moments
- Energy of pp collisions allows production of particles at electroweak mass scale

More details in arXiv:2406.03975 (dramatically improving on constraints in UPCs by ATLAS and CMS)

Diboson Production at $\sqrt{s} = 13.6$ TeV





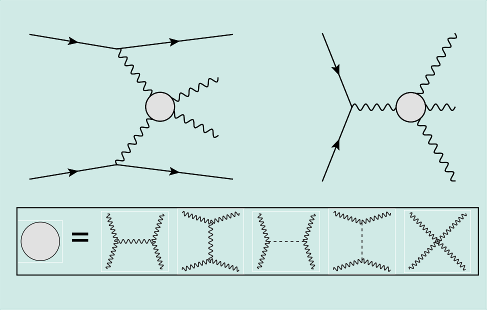


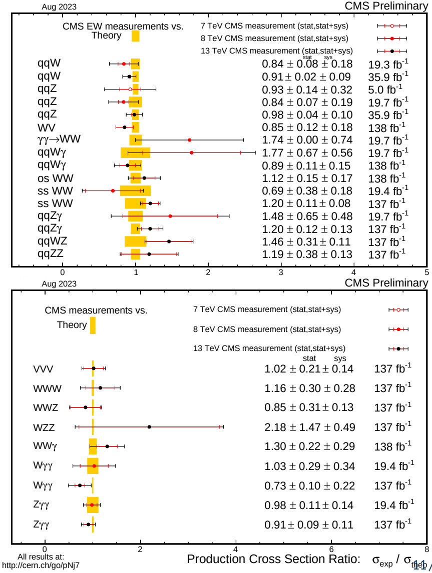
- First measurements of diboson processes in run-3 data taken in 2022
  - Jet-inclusive measurements of *WW* production now standard
  - Diboson measurements routinely achieve precision of better than 5%
  - *WW*, *ZZ*, *WZ* have been measured at $\sqrt{s} = 13.6$ TeV

More details in arXiv:2406.05101, PLB 855 (2024) 138764 and CMS-PAS-SMP-24-005

Quartic Electroweak Couplings

- Quartic electroweak coupling experimentally accessible in vector-boson scattering and triboson production



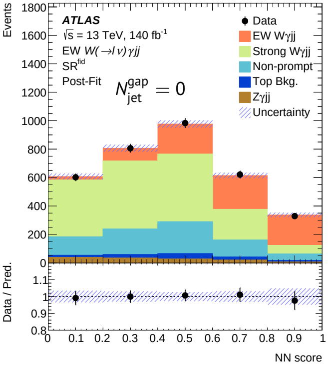


Summary Plots Webpage

- Some of the rarest processes experimentally accessible at LHC
- Vector-boson scattering observed in all major channels
  - exploiting characteristic signature
  - in agreement with theoretical predictions
- Triboson production experimentally more difficult

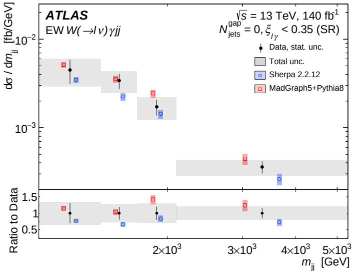
Electroweak $W\gamma jj$ and $WZ\gamma$ Production

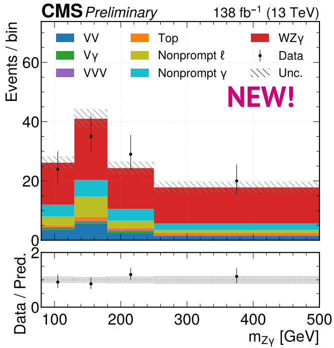
- Recent example from ATLAS: $W\gamma jj$ production
- Observation with $> 6\sigma$ exploiting characteristic signature in a neural net
- Differential measurement reducing model assumptions



More details in arXiv:2403.02809

(Observation in CMS in PRD 108 (2023) 032017)





- Recent example from CMS: $WZ\gamma$ production
- Observed with 5.4σ from fit to $m_{Z\gamma}$
- Measured slightly higher than theory prediction at NLO, $\mu = 1.47^{+0.33}_{-0.29}$

More details in CMS-PAS-SMP-22-018

(Observation in ATLAS in PRL 132 (2024) 021802)

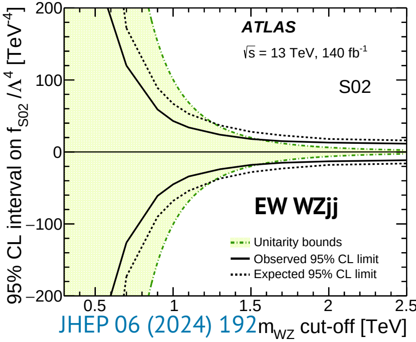
Anomalous Quartic Gauge Couplings

- Deviations from the SM are quantified in an Effective Field Theory approach

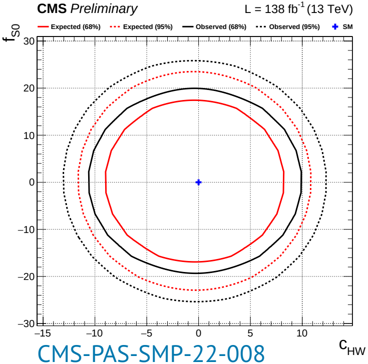
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \dots$$

- Considering operators only affecting QGC (at dim-8)
- Constrain operators sensitive to electroweak symmetry breaking

Electroweak WZjj production, *JHEP 06 (2024) 192*



JHEP 06 (2024) 192



CMS-PAS-SMP-22-008

- Study of interplay of dim-8 (QGC) and dim-6 (TGC)

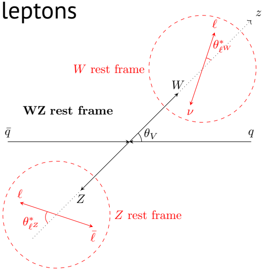
Electroweak $W^\pm W^\pm jj$ production with $W \to \tau\nu$, *CMS-PAS-SMP-22-008*

Diboson Polarisation

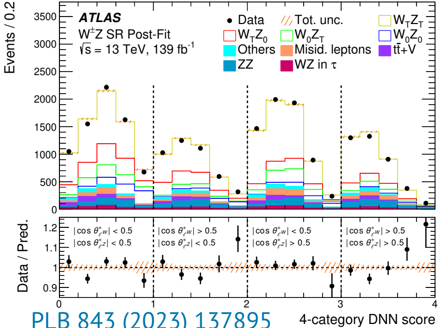
- Longitudinal polarisation generated by electroweak symmetry breaking

$\rightarrow$ asymptotically behave like Goldstone bosons of electroweak symmetry

- Measured from decay angles of the decay leptons
- Individually in *WZ* events:
  - ATLAS: PLB 843 (2023) 137895
  - CMS: JHEP 07 (2022) 032

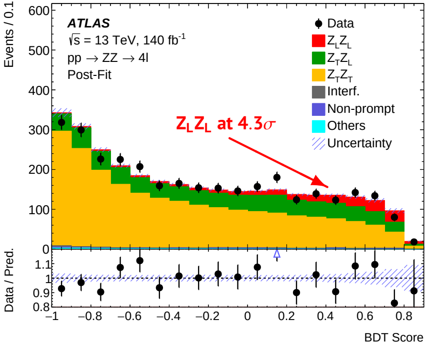


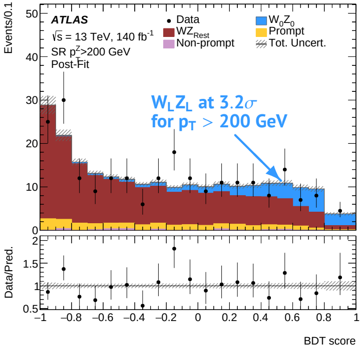
- Recent observation of joint polarisation
- Theoretical decomposition in individual components (LL, TL, LT, TT)
- Main challenge: incorporating higher-order corrections

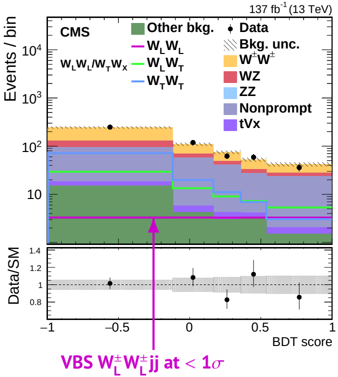


PLB 843 (2023) 137895

Polarisation Results







- Experiments gain sensitivity to V_LV_L production, starting to study energy dependence of cross section

Evidence for Z_LZ_L production in JHEP 12 (2023) 107
Study of energy dependence of W_LZ_L prod. in arXiv:2402.16365

- Ultimate test of electroweak symmetry breaking is the study of V_LV_L scattering at the HL-LHC

Analysis of $W_L^\pm W_X^\pm jj$ and $W_L^\pm W_L^\pm jj$ in PLB 812 (2020) 136018

⇒ Active field on both theoretical and experimental side

Summary

- Numerous results of precision electroweak physics released in the last 12 months!
- The LHC is competing with previous machines in electroweak precision
- Facilitated by large datasets, detailed understanding of the detectors, dedicated reconstruction techniques and state-of-the-art theory predictions

- New measurements of key electroweak parameters m_W and $\sin^2\theta^\ell_{\text{eff}}$
- High-precision measurements of lepton couplings

- The LHC tests the electroweak theory at highest energies in multiboson measurements
- They join precision probes in improving our understanding of electroweak symmetry breaking

Backup