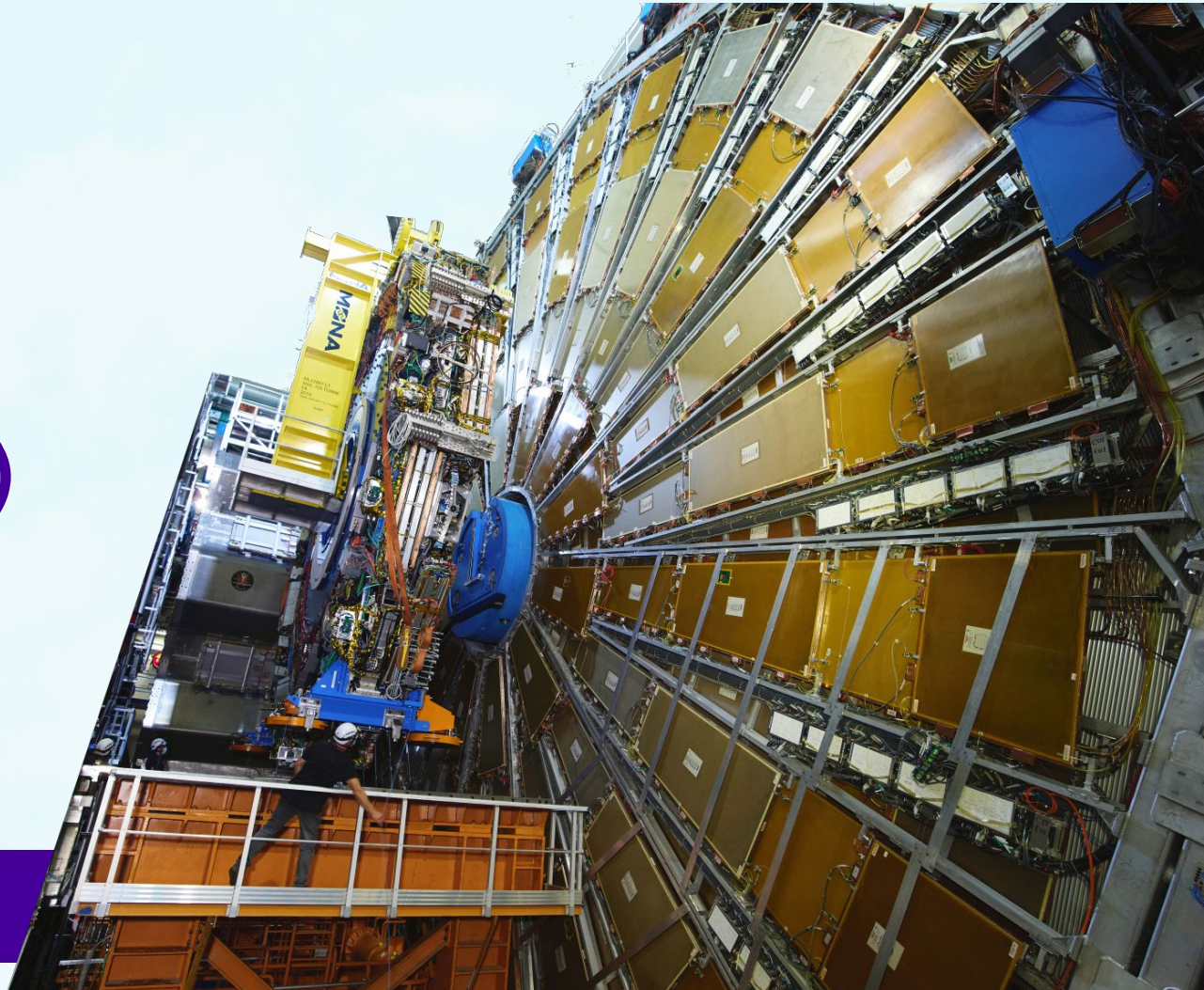
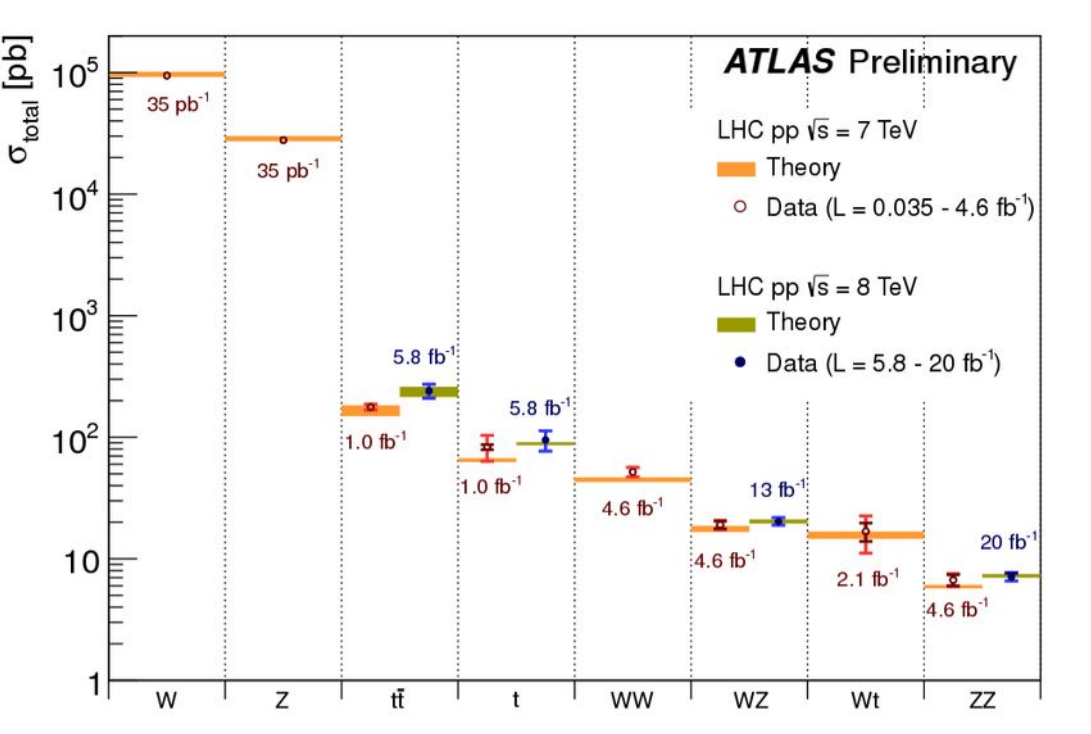
University of Sheffield

Precision EW measurements (beyond Higgs)



3rd November 2026

Electroweak Physics at the LHC….

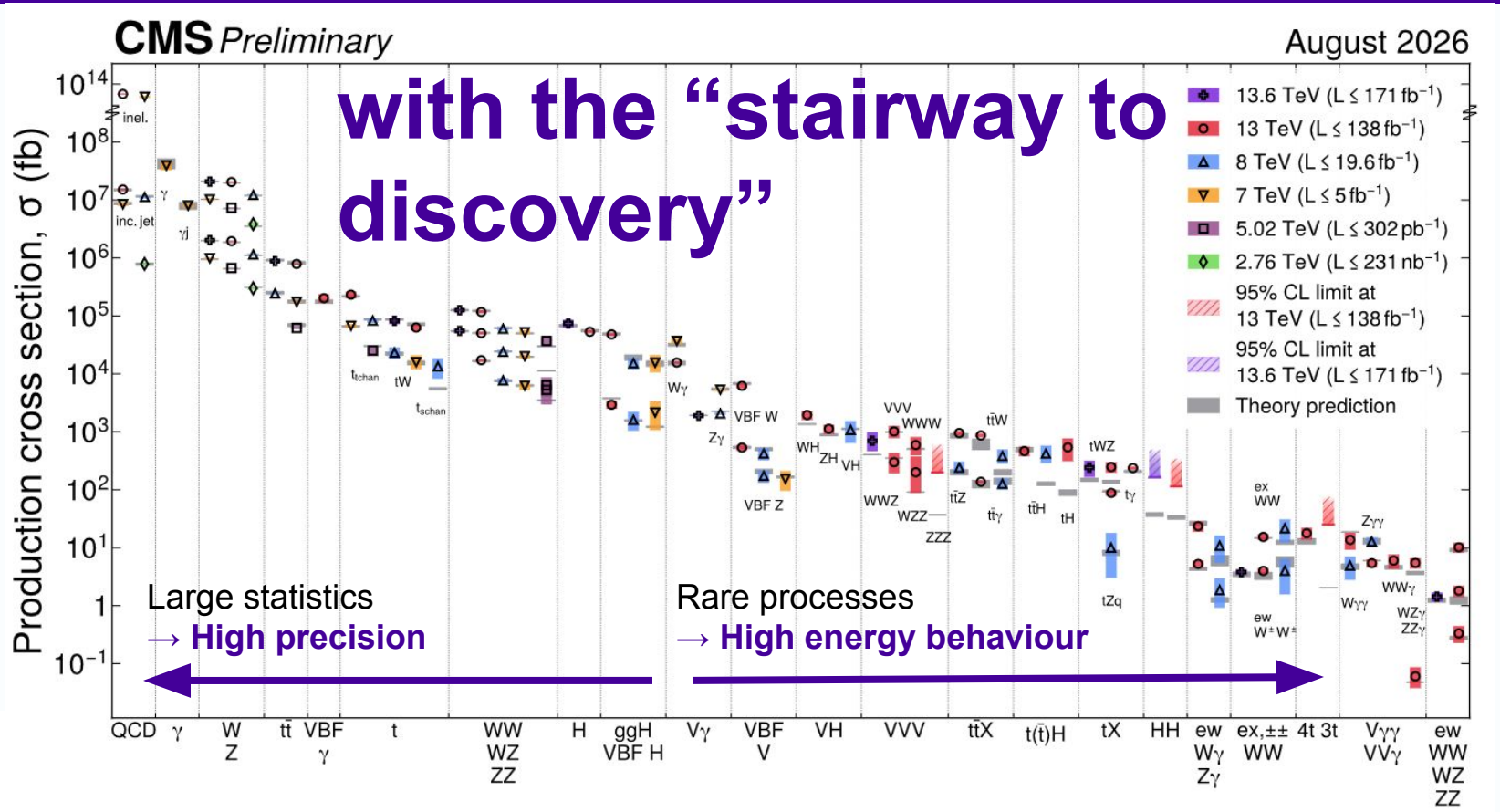


has come a long way from first "rediscoveries" in Run-1 to ….

2012….

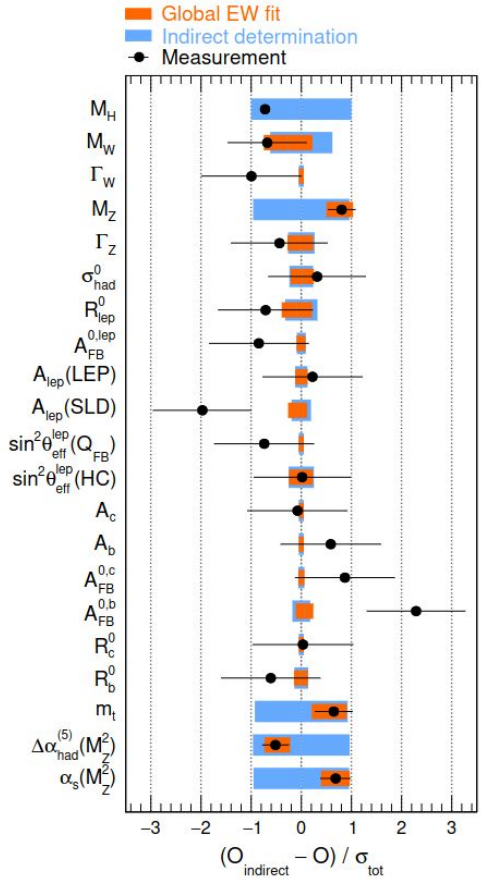
University of Sheffield

…Stress-testing the Standard Model



High precision electroweak tests

The global electroweak fit



https://arxiv.org/abs/2607.09861, Gfitter group

Consistency test of Standard Model using **precision measurements of the electroweak sector** and the **relationship of its fundamental parameters** through quantum corrections

After Higgs discovery: SM electroweak fit is fully constrained

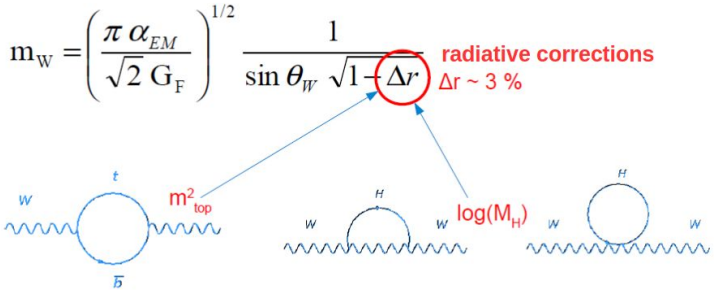
Improved fit probability after latest LHC results (m_W and $\sin^2\theta$) and updates to hadronic cross-section at the Z pole (through changes to LEP luminosity)
(p-value increase from 0.23 to 0.68)

Most interested input variables (from the LHC perspective): **$\sin^2\theta$**
as $A_{FB}^{0,b}$ and Aℓ(SLD) still have largest deviations

m_W and Γ_W
as the fit yields more precise predictions than the experimental measurements

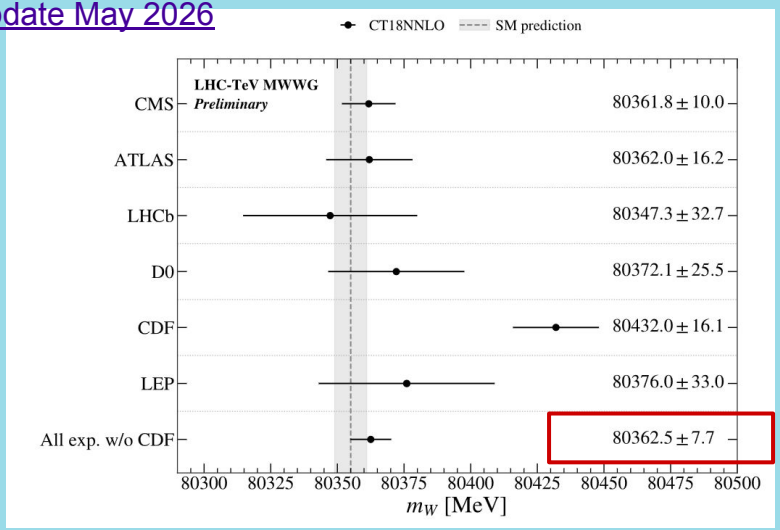
$$m_W = \left(\frac{\pi\,\alpha_{EM}}{\sqrt{2}\,G_F}\right)^{1/2} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

radiative corrections
$\Delta r \sim 3\,\%$



Improving the W Mass precision

Update May 2026



LHC-Tevatron W-boson mass Combination starts to approach the precision of the electroweak fit (m_W^{fit} = 80355.8 ± **6.1** MeV)

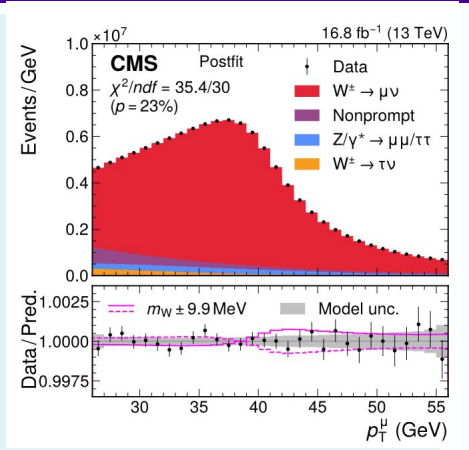
Measurements at low pile up still pending

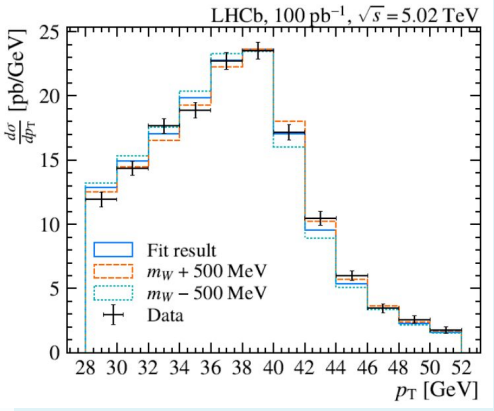
CMS hadronic W mass extraction (500 MeV)
LHCb measurement of W helicity (additional constrain in fits)

Most precise LHC result by CMS (**9.9 MeV** total)

m_W = 80 360.2 ± 2.4 (stat) ± 9.6 (syst) MeV

Dominated by muon momentum calibration and the *PDFs* (profiling of theory uncertainty)

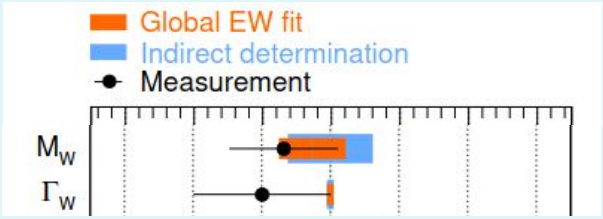




Latest LHCb results proof of principle for improved methodology in low luminosity sample

m_W = 80369 ± 130 (exp) ± *33 (theo)* MeV

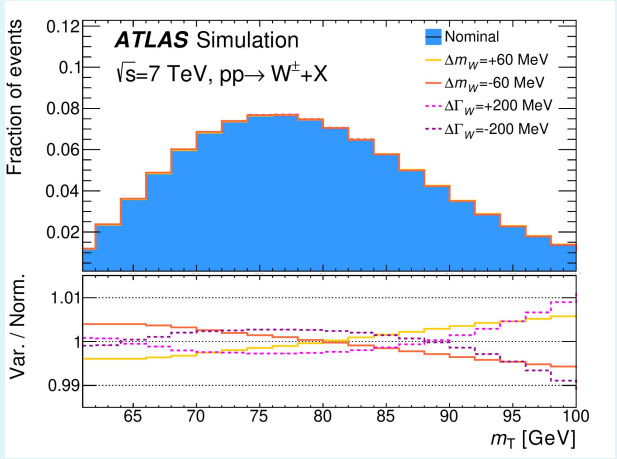
First determination of Γ_W at the LHC



Γ_W less well measured than m_W

→ important to determine too

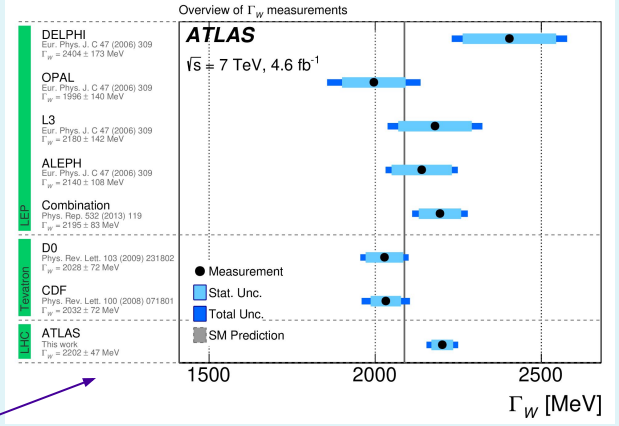
Recent determination by ATLAS through fit to m_T distribution, **fixing m_W** to SM prediction

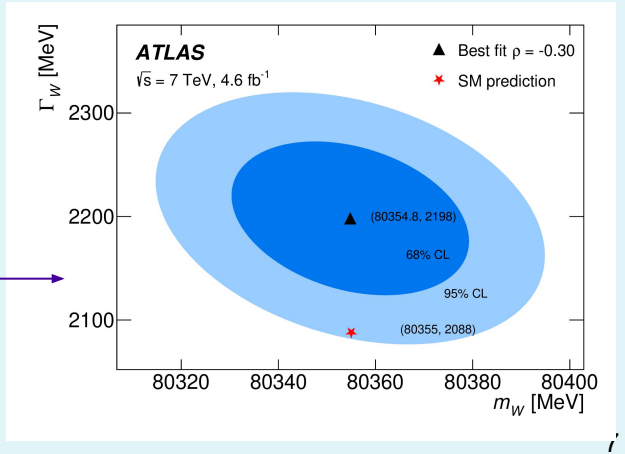


Γ_W = 2202 ± 32 ± 34 MeV
= 2202 ± 47 MeV

Combined determination:

m_W = 80354.8 ± 16.1 MeV
Γ_W = 2198 ± 49 MeV





The weak mixing angle $\sin^2\theta$

Hadron collider measurements are starting to reach precision comparable to the results at LEP and SLD
(~3σ tension with uncertainties 29 and 26 × 10^{-5})

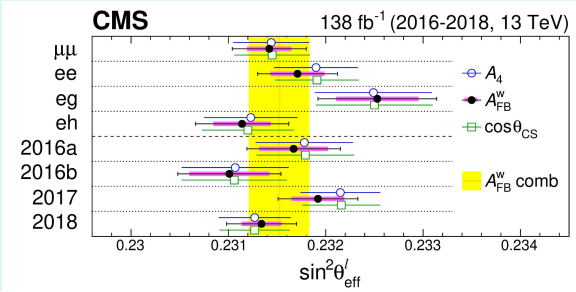
CMS achieves 31 × 10^{-5} dominated by PDF uncertainties
(extracted from angular-weighted asymmetry, A^{w}_{FB}, compatible with $\sin^2\theta$ through angular coefficient A4 using full Run 2 data set, using electrons up to |η|=4.36)

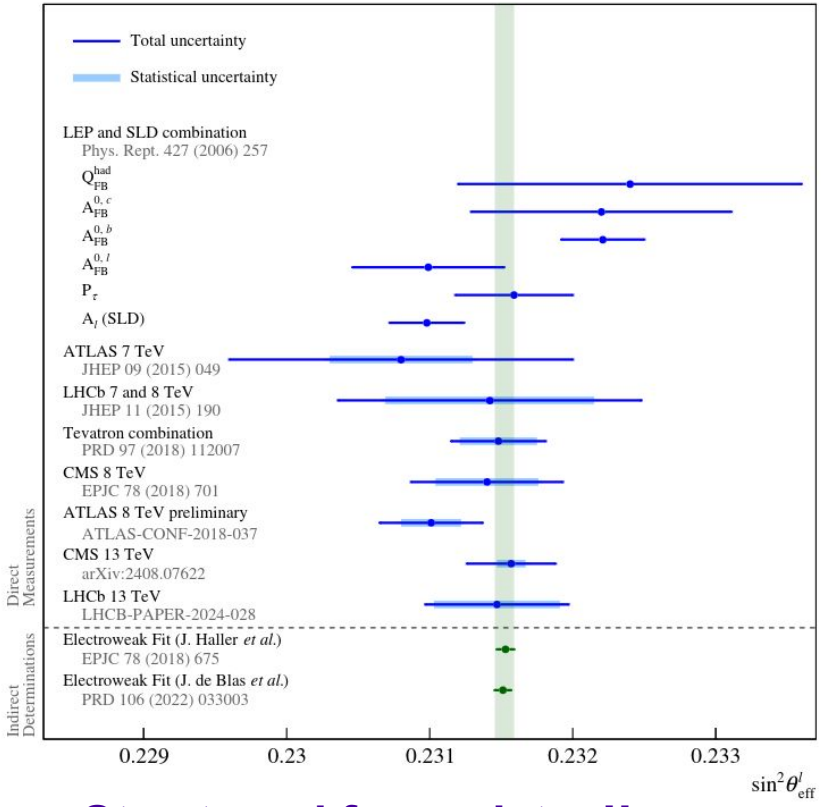
LHCb achieves 50 × 10^{-5} dominated by statistics
(subleading effects through fit model 23 × 10^{-5}, unique sensitivity due to forward acceptance)

Improvements expected through statistics (LHCb) as well as further PDF info (could achieve 24× 10^{-5})

Method to extract $A_{FB}^{0,b}$ at hadron colliders known

HL-LHC with increased forward reach





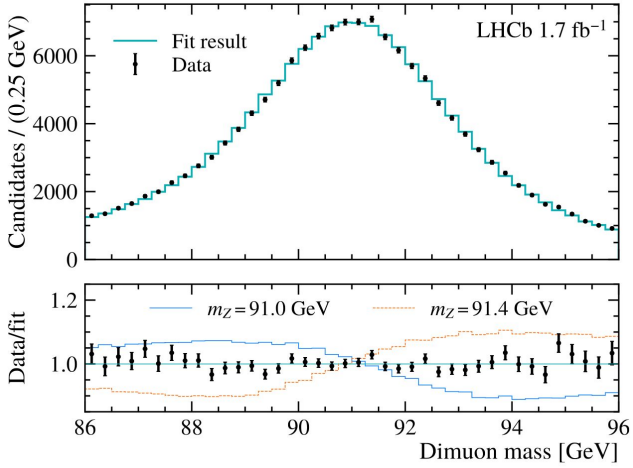
Stay tuned for updates!!

Z mass Surprise: Reaching LEP precision?

Never seemed to be in the card as Z is usually used to determine lepton calibrations and efficiencies - but now it's within reach: Precision measurements of m_Z

First dedicated measurement published by LHCb using dedicated precision calibration procedure for muons – using a curvature bias correction and a large samples of Y's and J/ψ

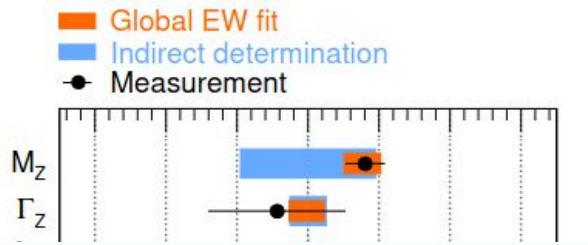
m_Z = 91185.7 ± **8.3 ± 3.9 MeV** - compared with the LEP combination of M_Z = 91187.6 **± 2.1 MeV**
→ measurement still dominated by statistics using 2016 dataset only



CMS' W mass measurement validated using Z mass determination: Within 2.2 MeV of PDG combination with **uncertainty of 4.8 MeV**

For m_Z EWK fit and measurements achieve similar uncertainties → however:

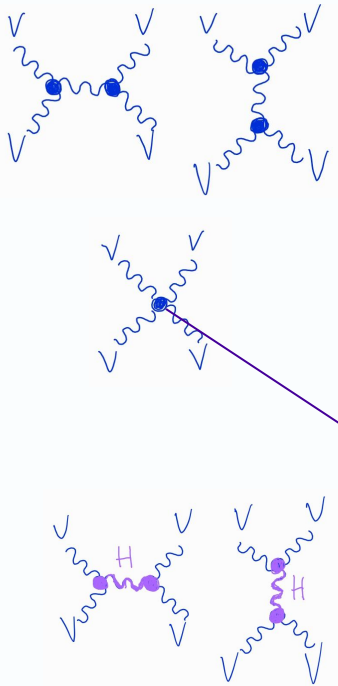
Γ_Z must be better measured to achieve precision of theory



Electroweak measurements at the Energy Frontier

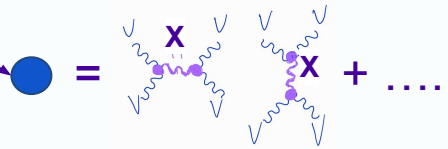
Completion of the electroweak SM

Gauge structure of SM



Electroweak symmetry Breaking → Talk by P. Francavilla

- LHC is the first collider that let's us *fully* explore the weak sector of the SM
- Non-Abelian structure of electroweak interactions allows for large cancellation and preservation of unitarity in key processes of the SM
- Delicate cancellations especially sensitive to potential new physics effects → explored in global fits → Talk by H. Mildner

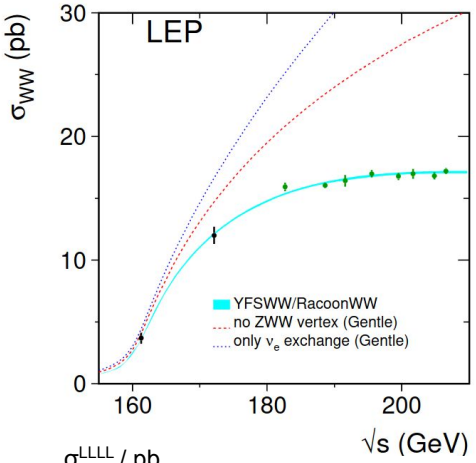


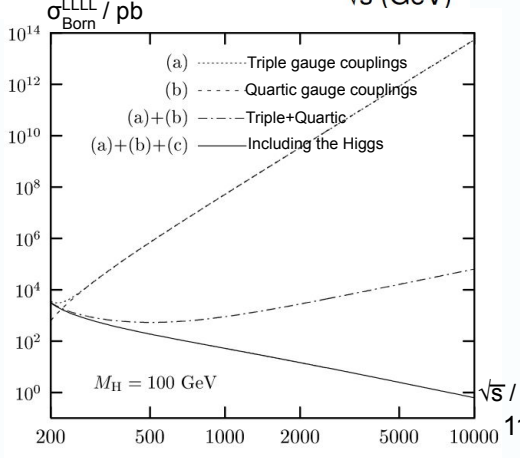
$$\mathcal{L}^{(\mathrm{dim})} = \frac{1}{\Lambda}\sum_k C_k^{(\mathrm{dim})} Q_k^{(\mathrm{dim})}$$

Number of Operator | Wilson Coefficient | Operator

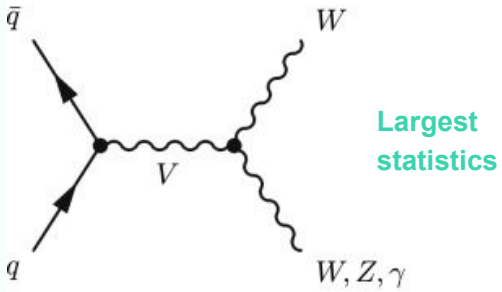
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- SM up to dim-4
- dim-5: neutrino masses but lepton-flavour violating
- dim-6: most studied at LHC
- dim-8: studied for VBS processes



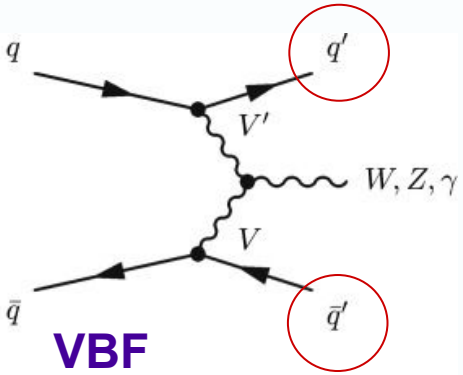


Morphology of electroweak interactions

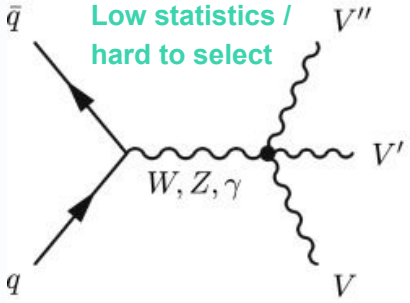


Largest statistics

Diboson



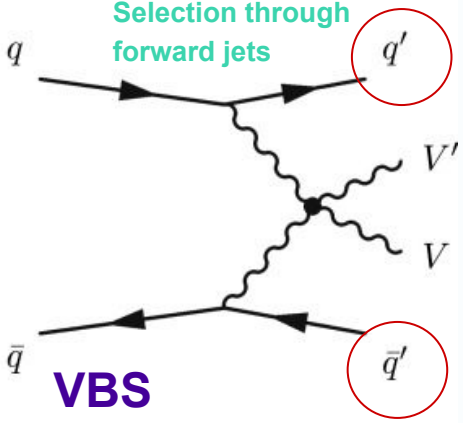
VBF
(vector boson fusion)



Low statistics / hard to select

Triboson

Selection through forward jets



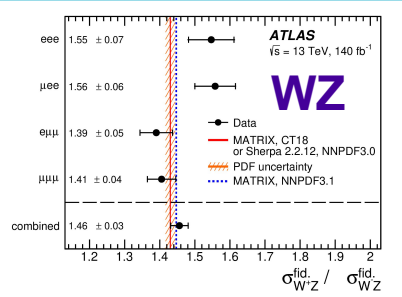
VBS
(vector boson scattering)

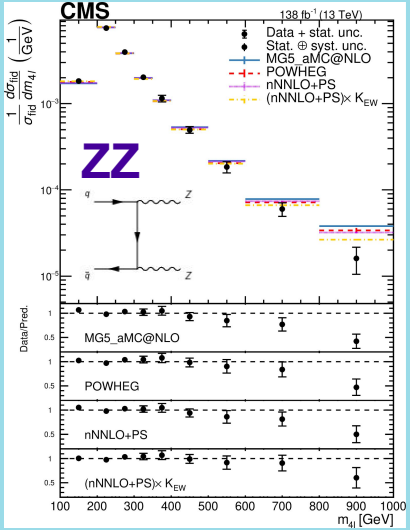
Triple and quartic vertices studied in various production modes – with different experimental and theoretical challenges

Global fits are consistency tests for vertex types

Vertex Type	Allowed Standard Model Combinations
Triple (VVV)	WWγ, WWZ
Quartic (VVVV)	WWWW, WWZZ, WWZγ, WWγγ

Diboson: Large statistics in Run 2

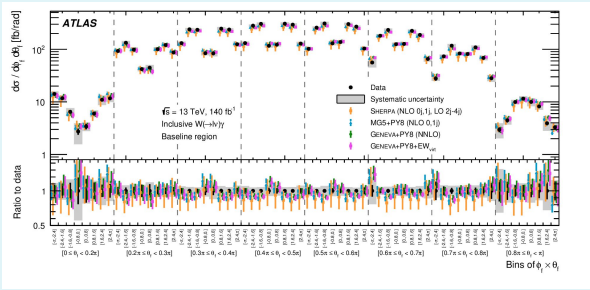


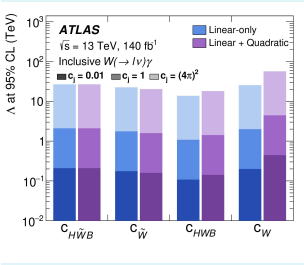


Need for NNLO and electroweak corrections are very apparent for diboson final states

ATLAS WZ and Wγ production sensitive to u/d quark differences, but experimental uncertainties dominate

nNNLO+PS predictions improve agreement in CMS ZZ production in the ≧1-jet regions - electroweak corrections O(-10%) needed for m4ℓ





Large statistics allow for dedicated measurements – the ATLAS Wγ measurement targets

- CP-violating effects
- Polarisation-sensitive observables
- phase space with radiation amplitude zero (sensitive to QCD and BSM effects).

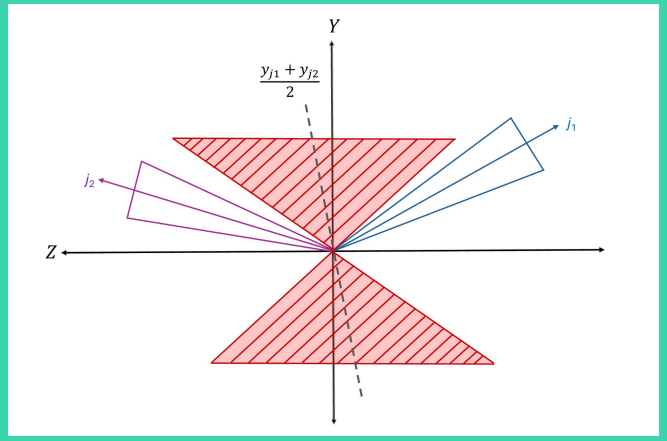
Use of unfolded ML-classifier improves sensitivity

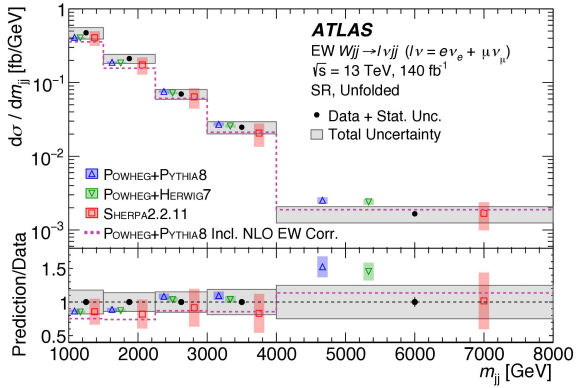
Sensitive to **new physics scales up to 80 TeV** depending on the reference coupling $c' = -\frac{c}{M_{Z'}^2}$
~ epoch of leptogenesis

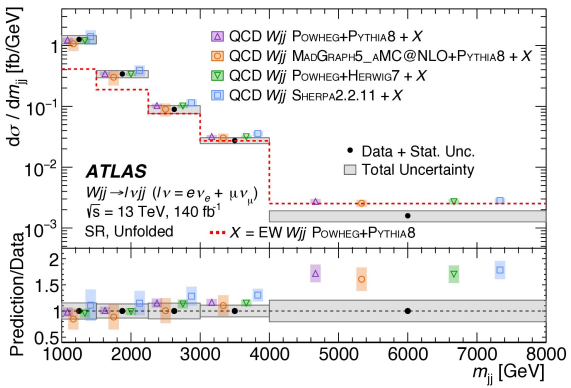
Vector Boson Fusion

Vector boson fusion (and scattering) processes characterized by **forward jets** (the proton remnants that radiated off the bosons)

Tagging jets help to select events and suppress backgrounds.





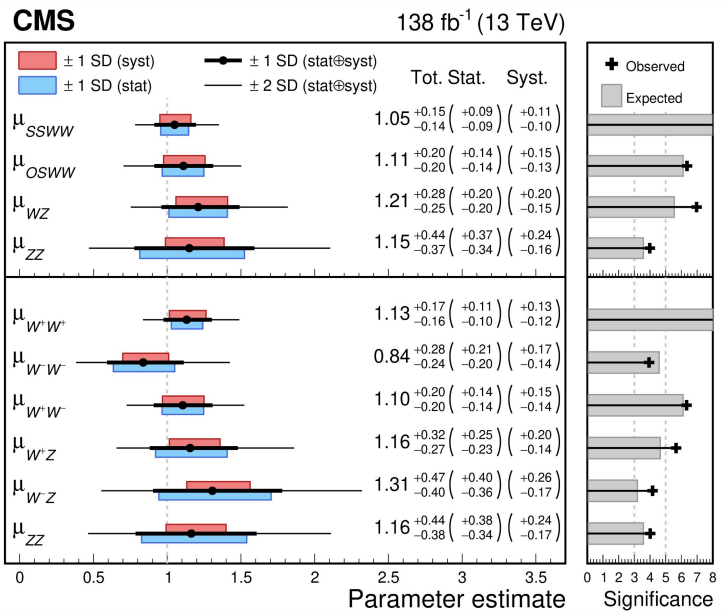


New measurement of W VBF explore electroweak and QCD MC modelling. Good overall agreement between predictions and measurement → *improved modelling*.

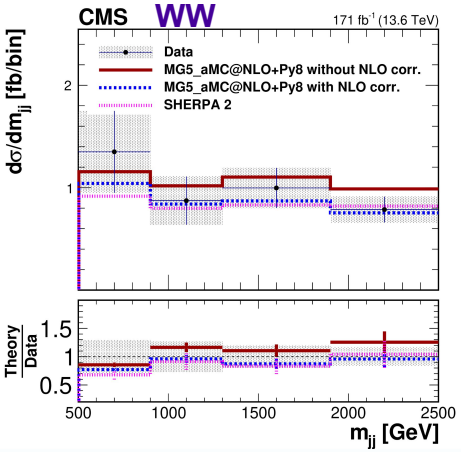
Sensitive to CP-even and CP-odd operators using the angular difference between the tagging jets

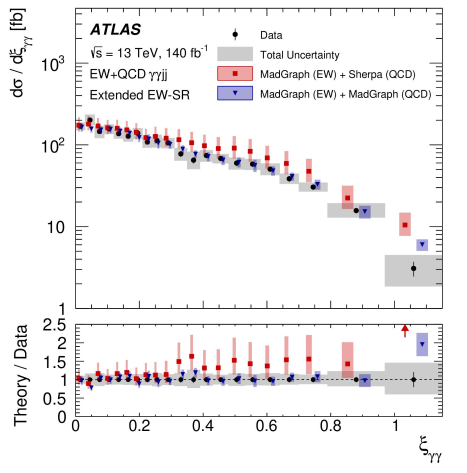
Limits on anomalous couplings among most stringent

Vector Boson Scattering



VV scattering processes firmly established with large number of new results (Overview from CMS leptonic combination analysis Run-2)



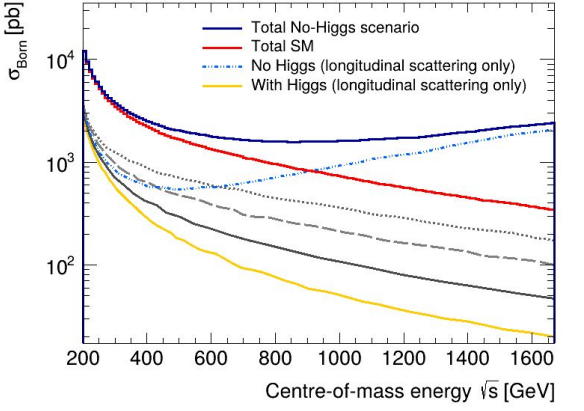


First measurements at Run-3 with 171 fb^{-1} by CMS show good agreement with theory – need for NLO not (yet) obvious.

ATLAS observed electroweak production of photons, γγjj, with reasonable agreement in EW and QCD+EW phase space. Outside EW-SR more noticeable differences in ξγγ distributions.

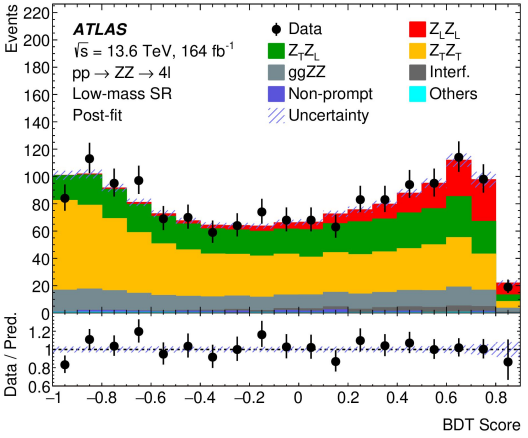
Issues with colour flow modelling are a thing of the past.

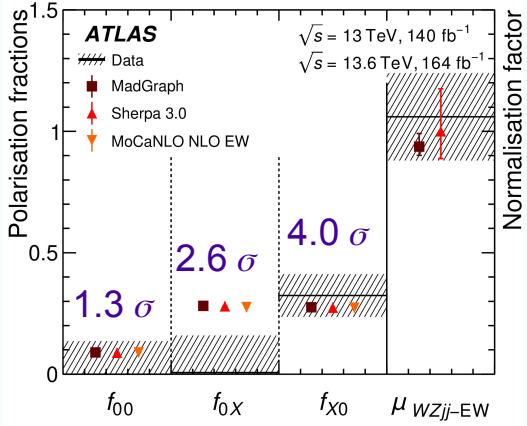
The next frontier: Polarisation



SM without the Higgs or an equivalent mechanism is excluded – VBS cross-sections would be factor 2-3 bigger.

Unitarity violation occurs only in the longitudinal Boson scattering: Measurements test whether Higgs is **fully responsible for unitarizing the electroweak sector**, or if there is new physics.





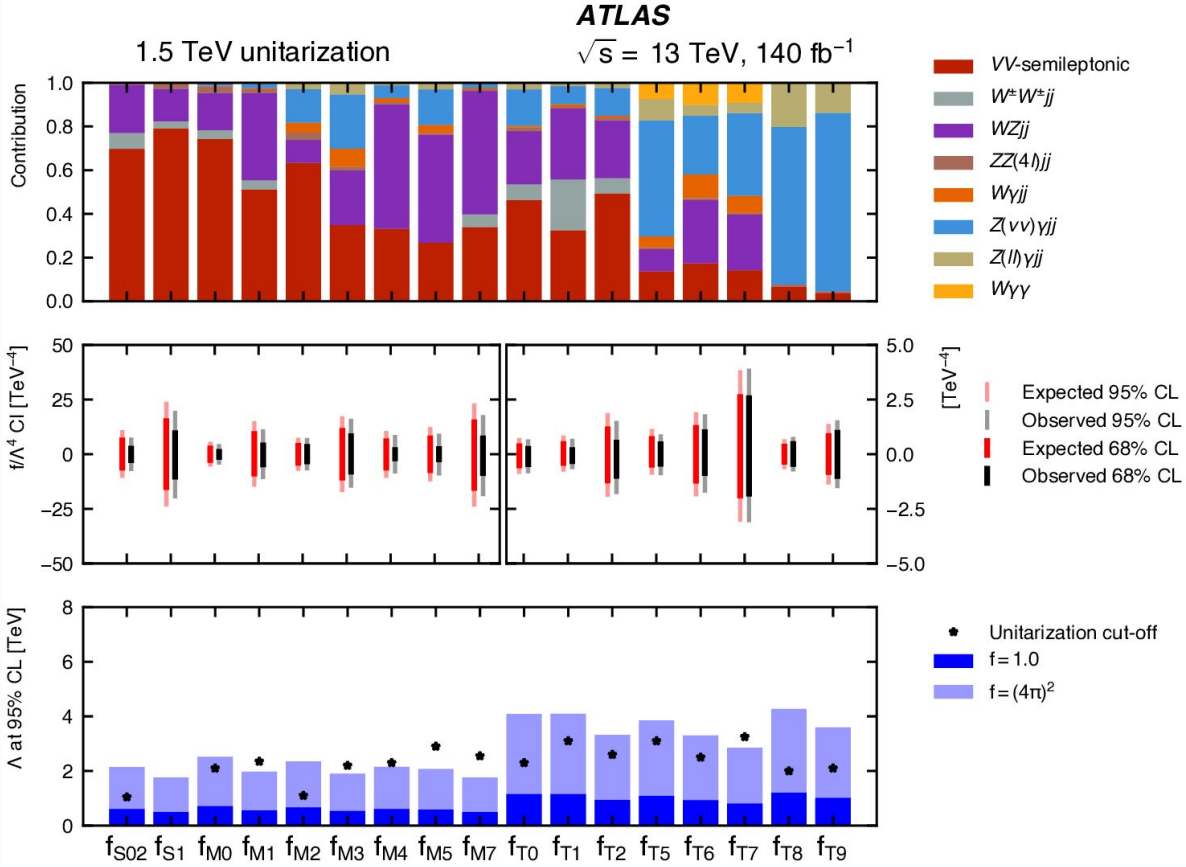
Extraction of Boson polarisation relies heavily on machine learning algorithms

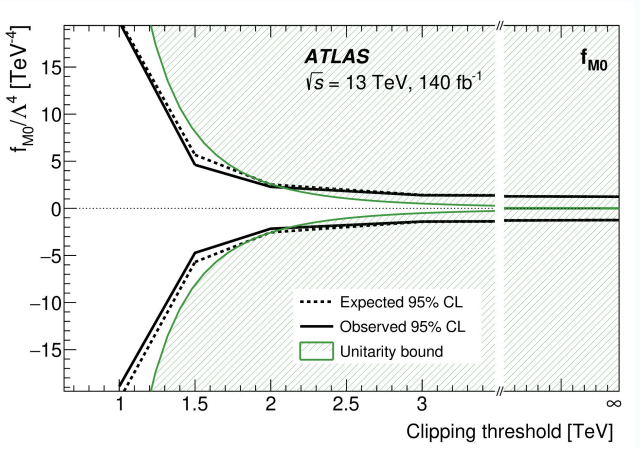
First observation of the production of two simultaneously longitudinally polarized bosons by ATLAS with 6.5σ (exp. 5.6σ) in ZZ events.

ATLAS finds evidence for a longitudinal Z Boson in WZ events with 4.0σ (exp. 2.9σ)

Significance for W±W± scattering with at least one longitudinally polarized boson is 3.3σ (exp. 4.0σ) at ATLAS

VBS Constraints on Dimension-8 EFT Operators





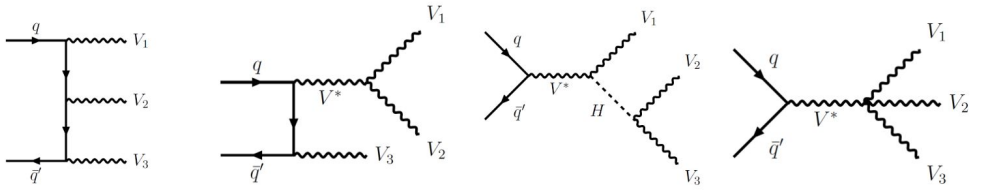
Combination of ATLAS VBS measurements to constrain Wilson coefficients for dimension 8 operators

Stringent limits on new physics

Triboson Production

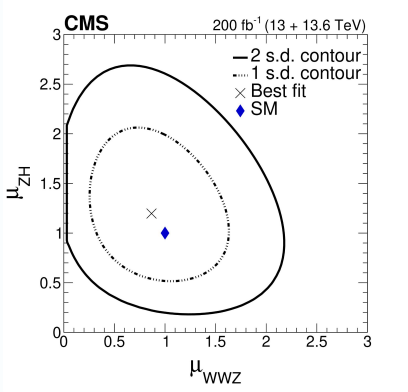
Process	ATLAS	CMS
WWW	8.0σ (exp. 5.4σ)	3.3σ (exp. 3.1σ)
VVV/VVZ	6.4σ (exp. 4.7σ) (VVZ) NEW	5.7σ (exp. 5.9σ) (VVV)
WZγ	6.3σ (exp. 5.0σ)	5.4σ (exp. 3.8σ) NEW
WWγ	5.9σ (exp. 6.0σ) NEW	5.6σ (exp. 5.1σ)
Wγγ/Zγγ	5.6σ (exp. 5.6σ) (Wγγ)	3.1 (exp. 4.5σ) (Wγγ) 4.8 (exp. 5.8σ) (Zγγ)
WWZ	4.4σ (exp. 3.6σ) NEW	13 TeV: 3.4σ (exp. 4.1σ) 13.6 TeV: 3.8σ (exp. 2.5σ) NEW
ZZγ	4.4σ (exp. 4.4σ) NEW	3.7σ (exp. 3.1σ) NEW
WZZ, ZZZ	n/a	1.6σ (exp 0.7σ) (WZZ) 0.0σ (exp 0.9σ) (ZZZ) cutoff date: Nov 2023

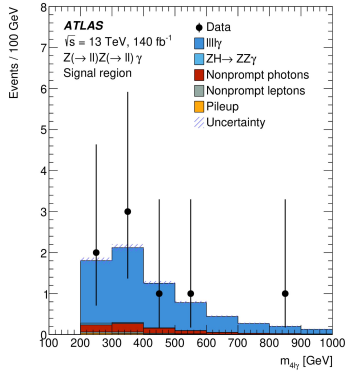
Half of these observations/evidences only occurred in the past three years !



Small statistics and difficult backgrounds with large modelling uncertainties → large k-factors

Generally at smaller energies compared to VBS processes → extracted standalone BSM limits weaker





Summary

- Vast number of (new) results on
  - Electroweak precision parameters
  - Boson self-couplings at the energy frontier
- LHC has really exceeded expectations
  - Encroaching LEP precision and on a path to surpass it
  - Evidence and Observation of longitudinal boson scattering already with a fifth of HL-LHC data
- Expect more to come!

Backup