Electroweak physics: experimental status

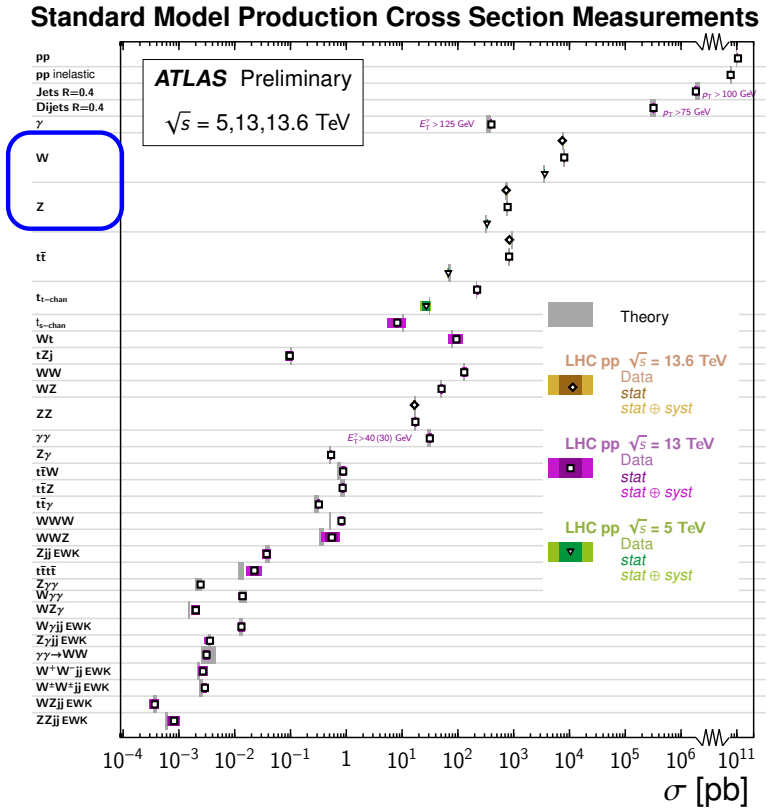
Julien Maurer, on behalf of ATLAS, CMS, LHCb collaborations

IFIN-HH Bucharest

Corfu Workshop on Future Accelerators, May 2025

Overview of hadron collider measurements

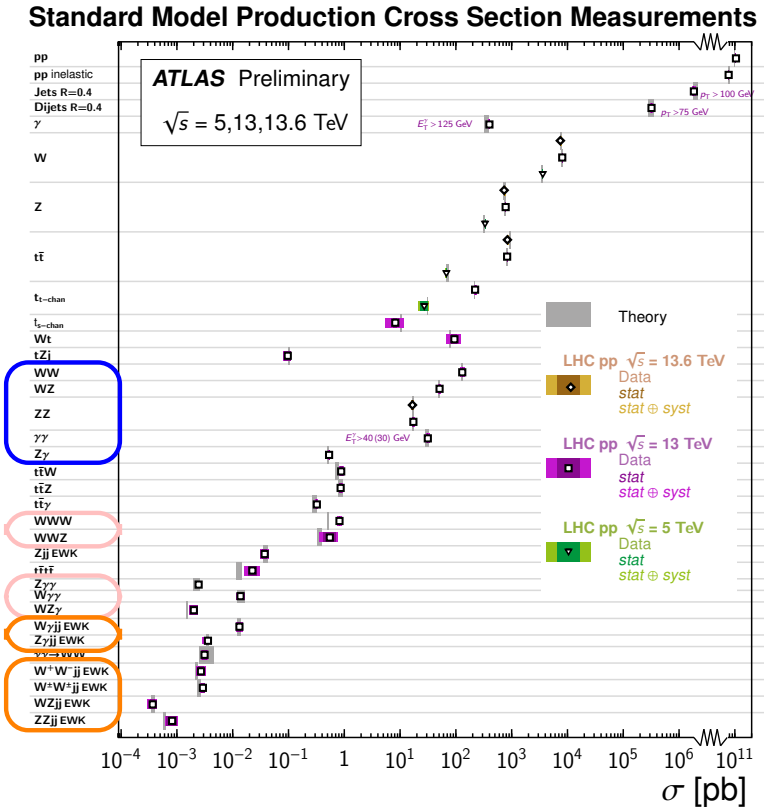
- Drell-Yan processes: differential cross-sections, charge asymmetry, angular coefficients, A_{FB}...
  - strong tests of pQCD and PDFs
  - cf Maren's presentation on Wednesday
- Multiboson production
  - triple and quartic $SU(2)$ gauge couplings
  - Higgs mechanism
- Lepton flavour universality
  - W and Z decay branching fractions
  - radiative emission of lepton pairs
- Effective weak mixing angle $\sin^2\theta^{\ell}_{\text{eff}}$
- W and Z masses
- Exclusive $\gamma\gamma \to \ell\ell/VV$ (not covered here)



(adapted from ATL-PHYS-PUB-2024-011)

Overview of hadron collider measurements

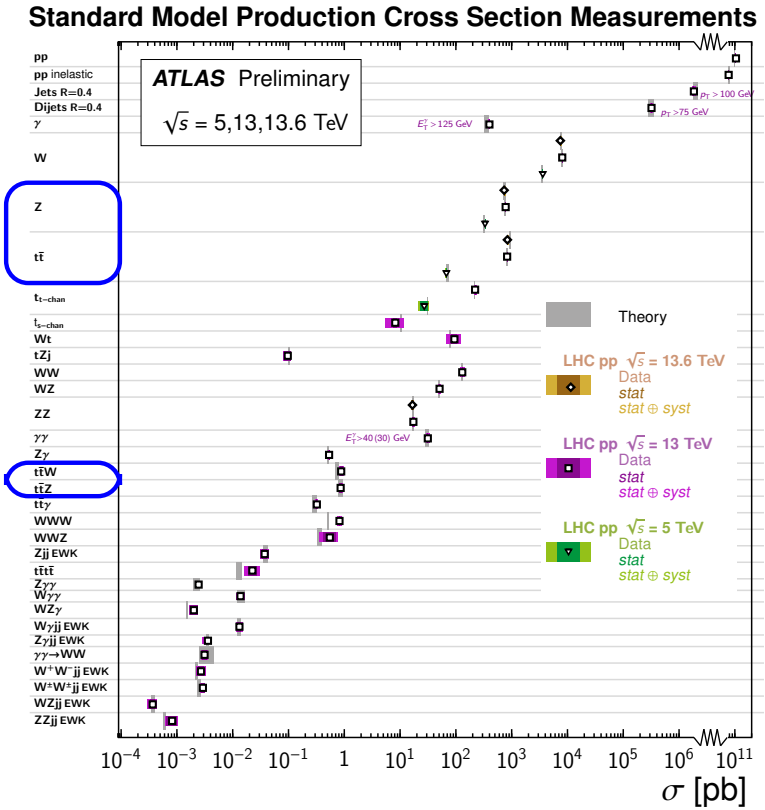
- Drell-Yan processes: differential cross-sections, charge asymmetry, angular coefficients, A_{FB}...
  - strong tests of pQCD and PDFs
  - cf Maren's presentation on Wednesday
- Multiboson production
  - triple and quartic $SU(2)$ gauge couplings
  - Higgs mechanism
- Lepton flavour universality
  - W and Z decay branching fractions
  - radiative emission of lepton pairs
- Effective weak mixing angle $\sin^2\theta^{\ell}_{\text{eff}}$
- W and Z masses
- Exclusive $\gamma\gamma \to \ell\ell/VV$ (not covered here)



(adapted from ATL-PHYS-PUB-2024-011)

Overview of hadron collider measurements

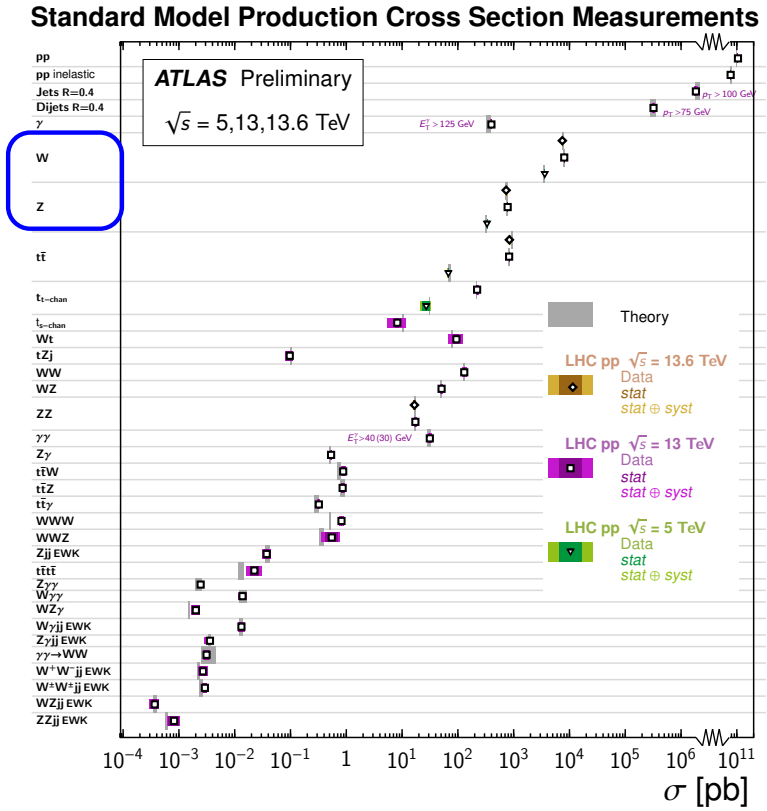
- Drell-Yan processes: differential cross-sections, charge asymmetry, angular coefficients, A_{FB}...
  - strong tests of pQCD and PDFs
  - cf Maren's presentation on Wednesday
- Multiboson production
  - triple and quartic $SU(2)$ gauge couplings
  - Higgs mechanism
- Lepton flavour universality
  - W and Z decay branching fractions
  - radiative emission of lepton pairs
- Effective weak mixing angle $\sin^2\theta^{\ell}_{\text{eff}}$
- W and Z masses
- Exclusive $\gamma\gamma \to \ell\ell/VV$ (not covered here)



(adapted from ATL-PHYS-PUB-2024-011)

Overview of hadron collider measurements

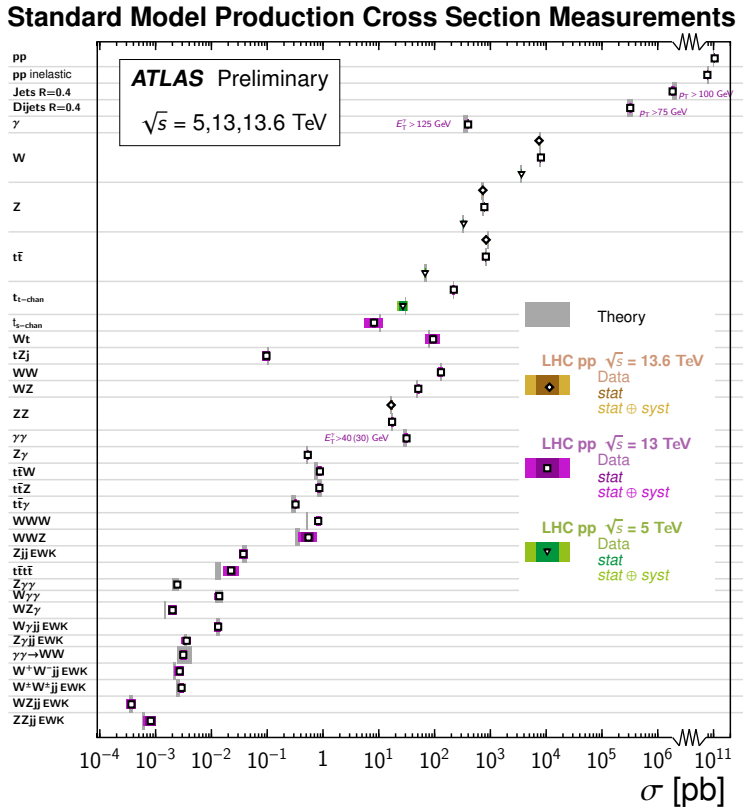
- Drell-Yan processes: differential cross-sections, charge asymmetry, angular coefficients, A_{FB}...
  - strong tests of pQCD and PDFs
  - cf Maren's presentation on Wednesday
- Multiboson production
  - triple and quartic $SU(2)$ gauge couplings
  - Higgs mechanism
- Lepton flavour universality
  - W and Z decay branching fractions
  - radiative emission of lepton pairs
- Effective weak mixing angle $\sin^2\theta^{\ell}_{\text{eff}}$
- W and Z masses
- Exclusive $\gamma\gamma \to \ell\ell/VV$ (not covered here)



(adapted from ATL-PHYS-PUB-2024-011)

Overview of hadron collider measurements

- Drell-Yan processes: differential cross-sections, charge asymmetry, angular coefficients, A_{FB}...
  - strong tests of pQCD and PDFs
  - cf Maren's presentation on Wednesday
- Multiboson production
  - triple and quartic $SU(2)$ gauge couplings
  - Higgs mechanism
- Lepton flavour universality
  - W and Z decay branching fractions
  - radiative emission of lepton pairs
- Effective weak mixing angle $\sin^2\theta^{\ell}_{\text{eff}}$
- W and Z masses
- Exclusive $\gamma\gamma \to \ell\ell/VV$ (not covered here)

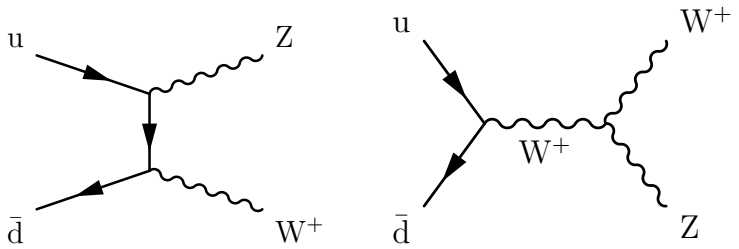


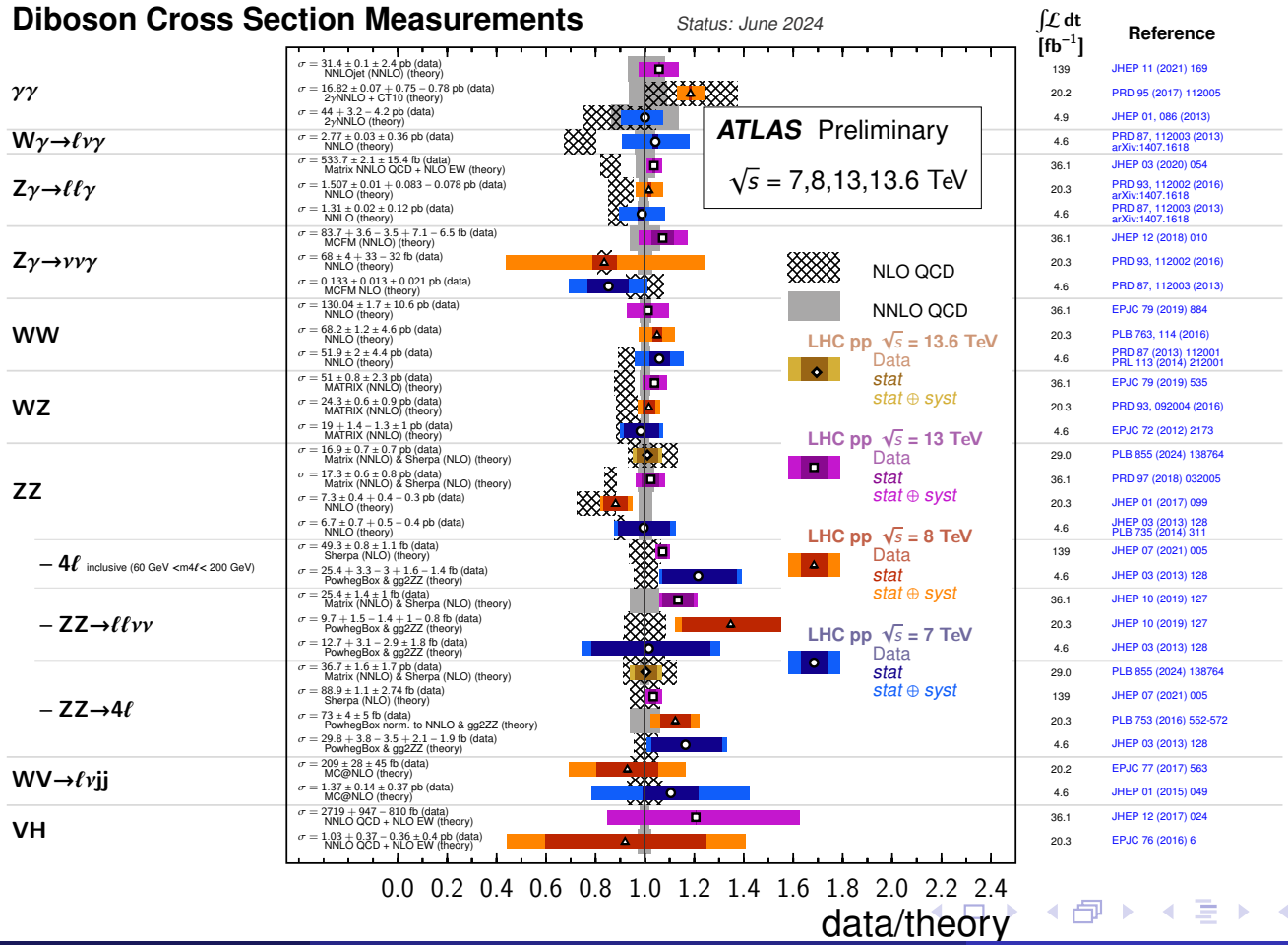
(adapted from ATL-PHYS-PUB-2024-011)

Will mostly show highlights of newest experimental results.

Inclusive diboson processes

[ATL-PHYS-PUB-2024-011]





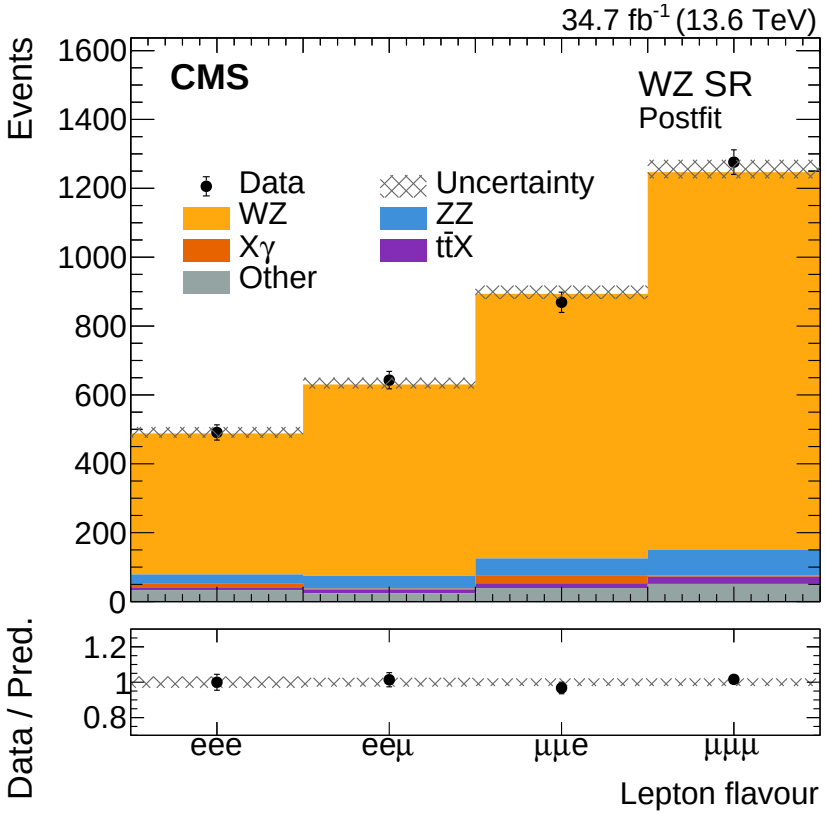
$\sigma(pp \to WZ)$ at 13.6 TeV

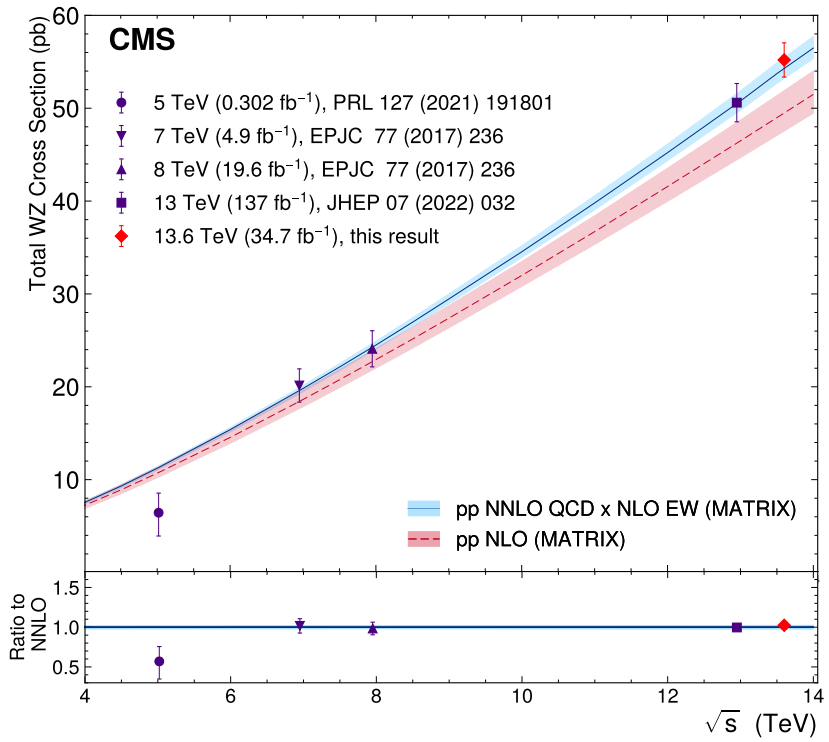
[arXiv:2412.02477]

Amongst the most precisely measured cross-sections.

$$\sigma_{\text{fid}} = 297.6 \pm 6.4(\text{stat}) \pm 6.4(\text{syst}) \pm 4.2(\text{lumi}) \pm 0.5(\text{th})\ \text{fb}$$

with fiducial cuts ($\to 17\%$ of $\mathcal{A}$) to miminise $\Delta\sigma(\text{th})$
syst $= e/\mu$ reco (1.6%) $\oplus$ bkg (1%) $\oplus$ ...

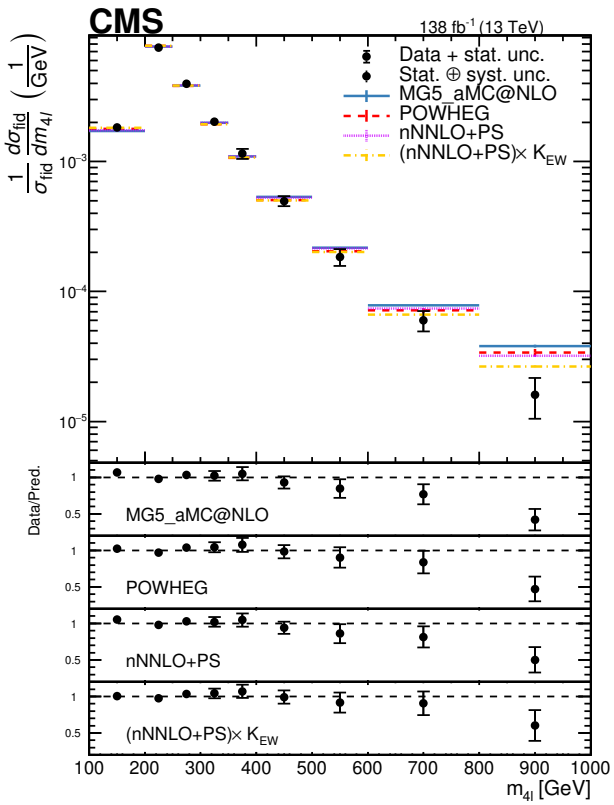


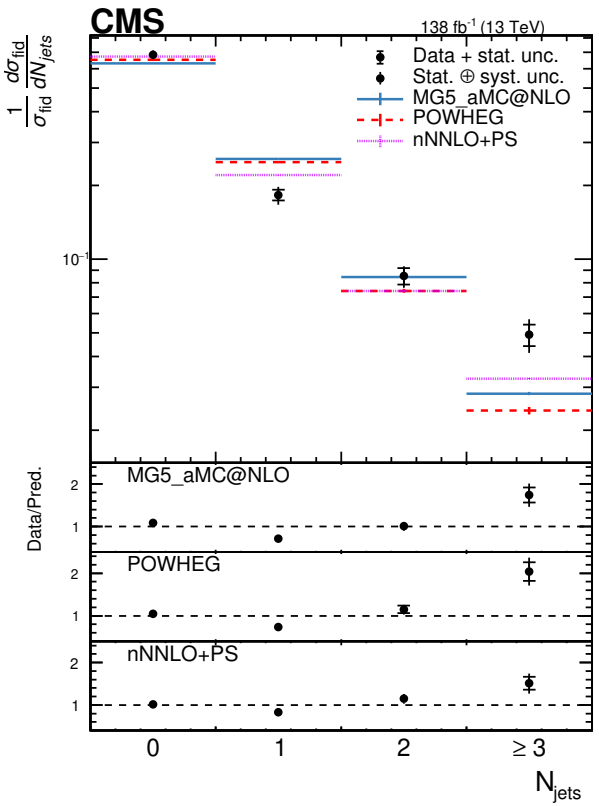


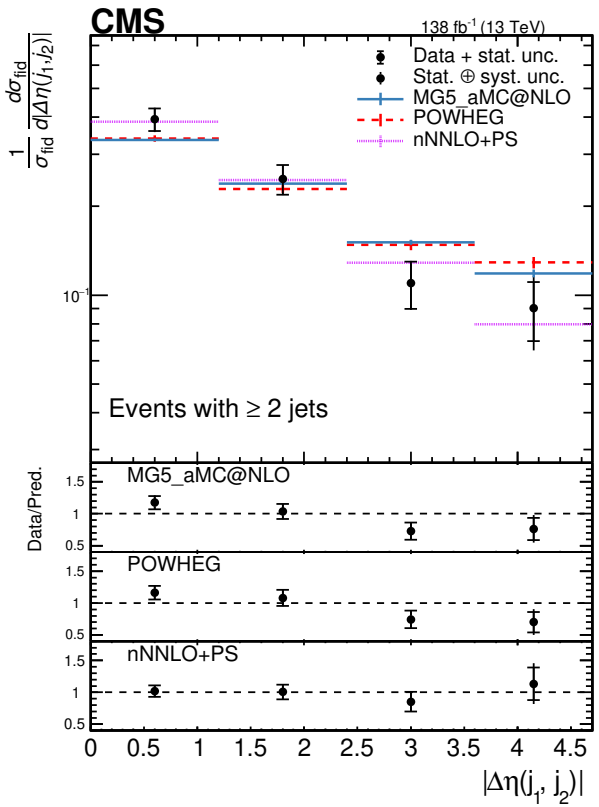
wrt 13 TeV measurement: $80\%\Delta\sigma(\text{syst, lumi})$, $\frac{1}{4}\Delta\sigma(\text{theory})$

$\mathrm{d}\sigma(pp \to ZZ + \text{jets})$ [JHEP 10 (2024) 209]

Extension of EPJC (2021) 200 focussed on jet variables:

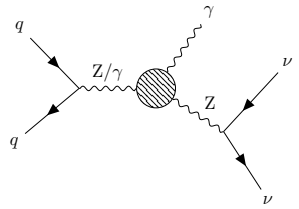


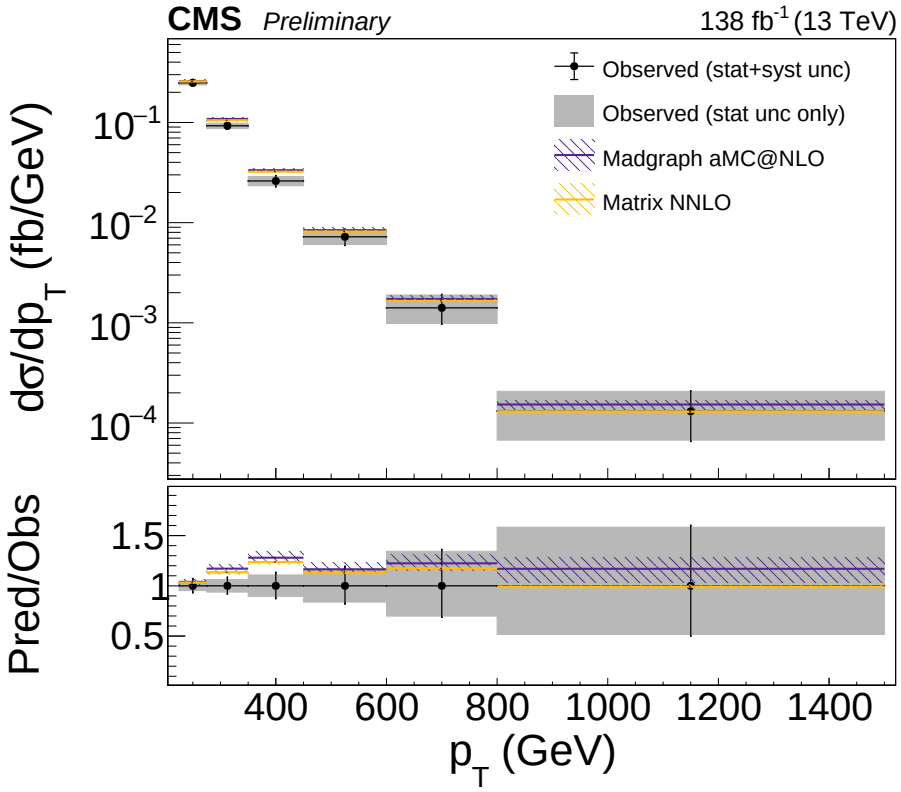




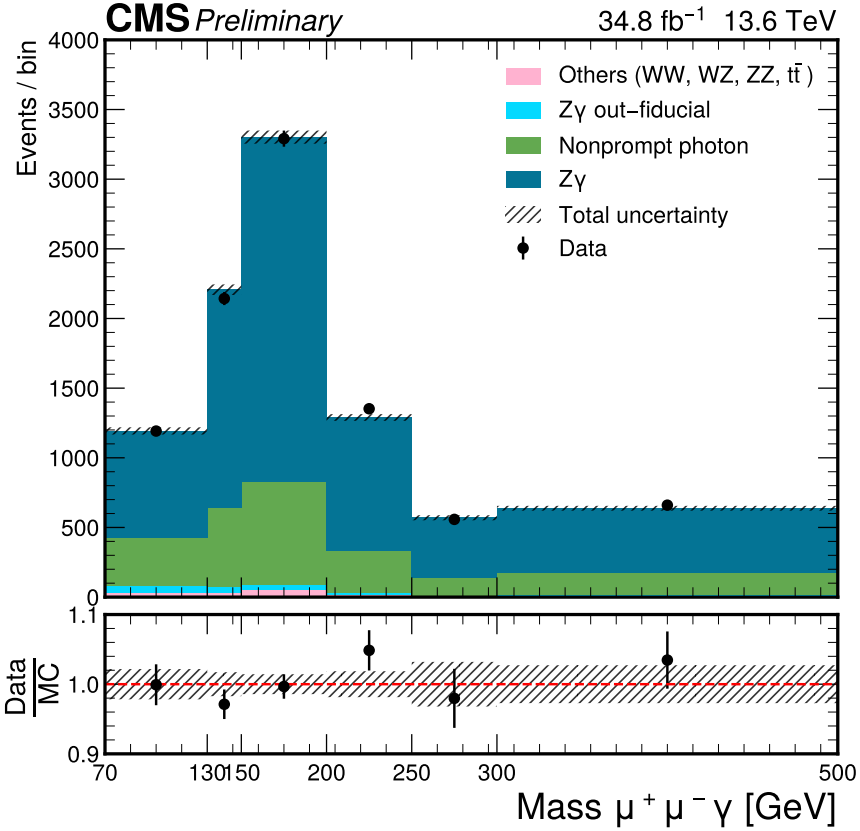
Effect of NLO EW differential corrections visible for $m_{4\ell}$, other distributions not corrected.

No $\gamma\gamma Z$ or γZZ couplings at tree level in the SM. Studied using $Z \to \nu\nu$ (i.e. $\gamma + E_T^{miss}$) or $Z \to \ell\ell$, very clean processes:





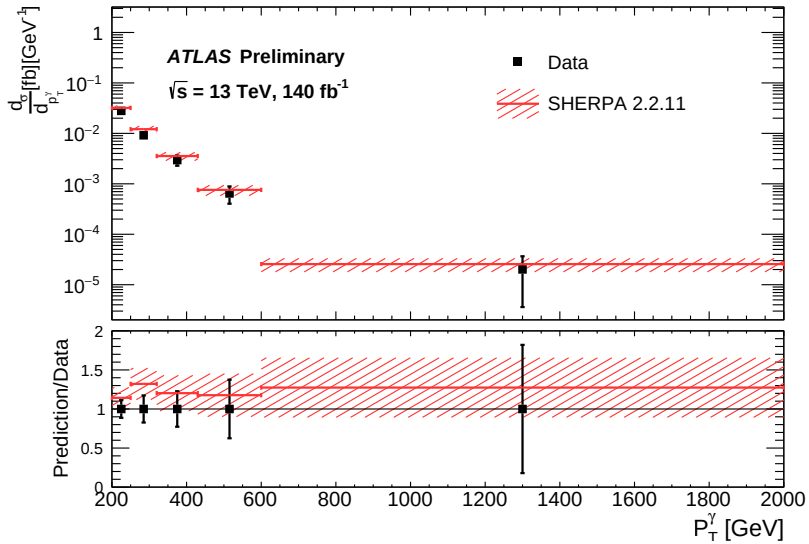
beam-halo tagger suppresses muons in endcaps; remaining bkg mostly $W \to e\nu$ and $W\gamma$

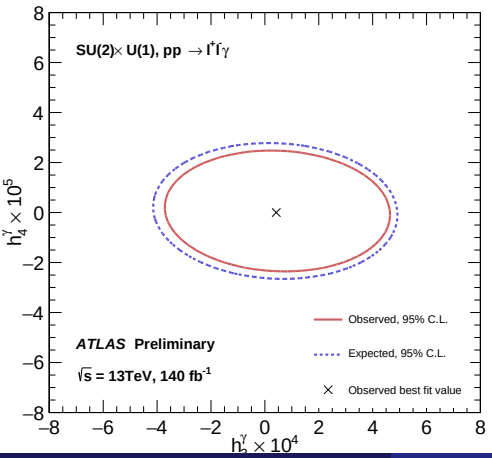


non-prompt γ predicted from data

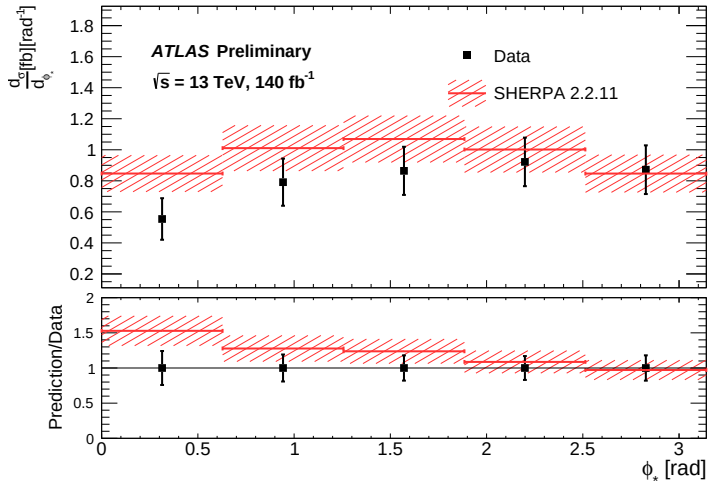
Extension of JHEP 07 (2023) 072 with high-p_{T} + jet veto SR to target aTGC.

First LHC results with new formulation of nTGC form factors accounting for $SU(2) \times U(1)$ gauge symmetry instead of $U(1)_{\mathrm{EM}}$ [PRD 107 (2023) 035005]

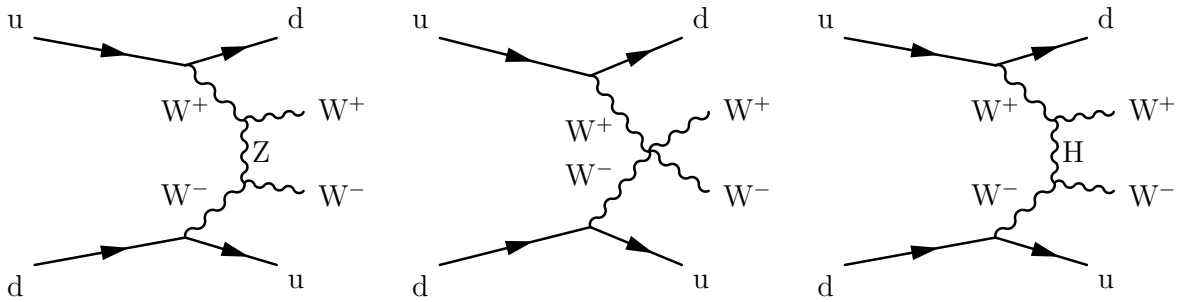


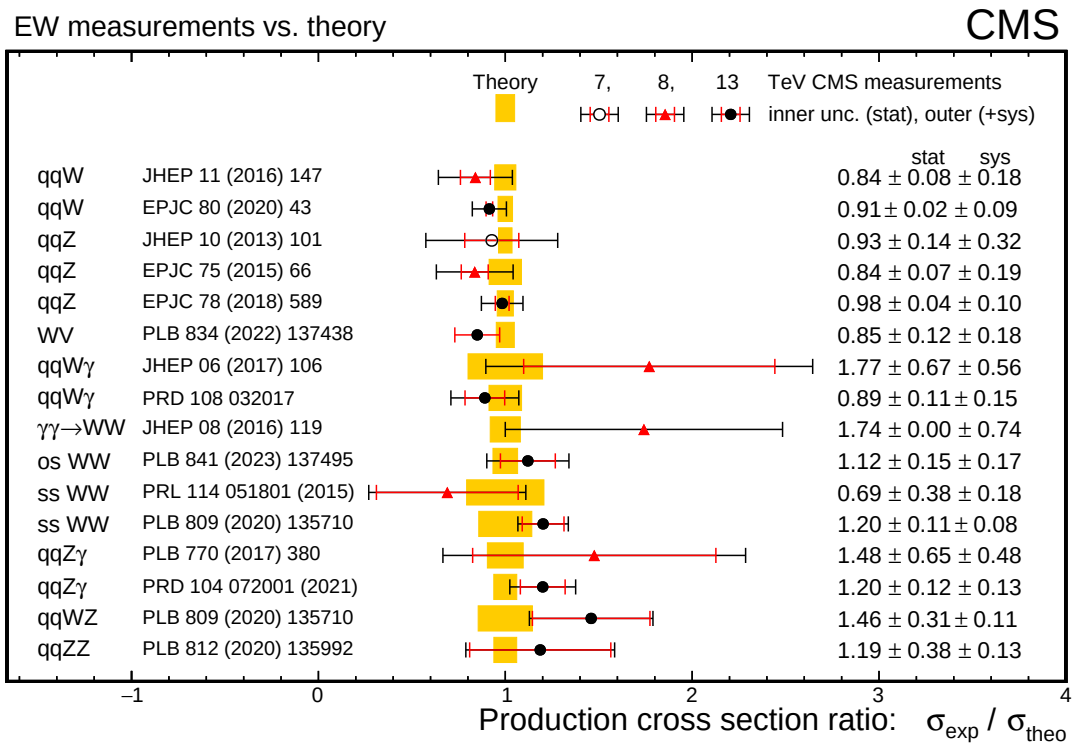


Also extraction of cross-section vs ϕ^* (angle between scattering and Z decay planes) to bring forth SM-BSM interferences



Vector boson scattering





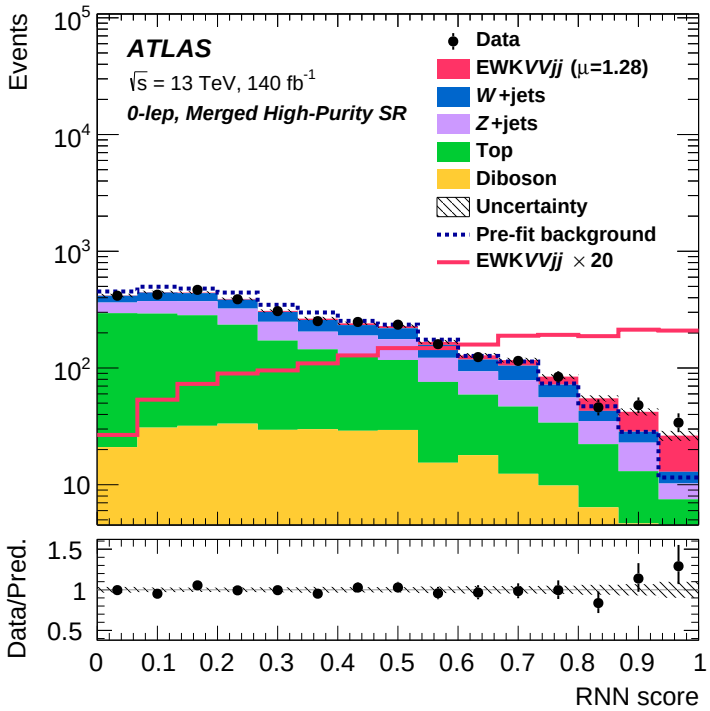
⇒ constraints on dimension-8 operators (aQGC) in SM effective field theory

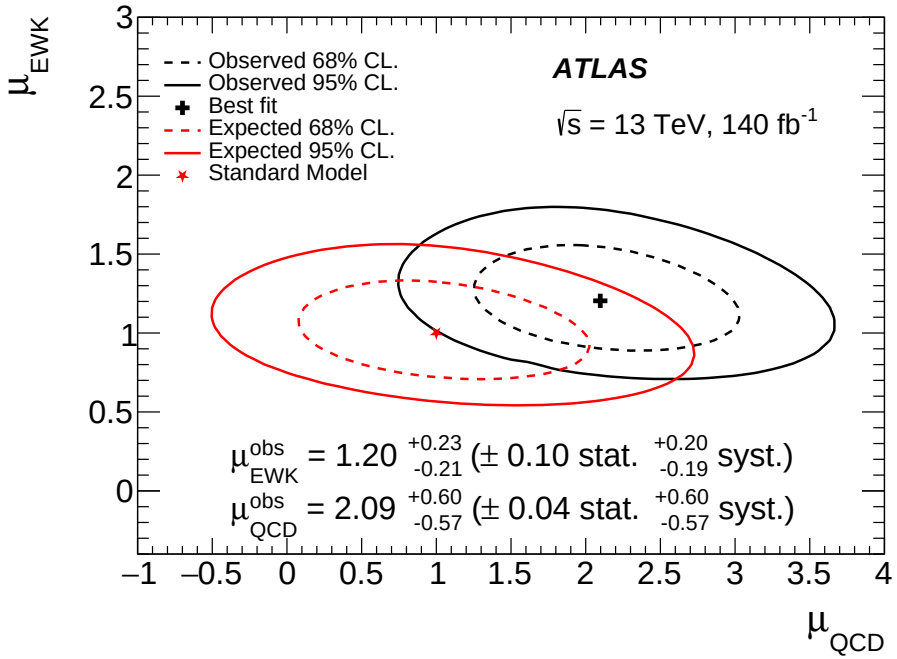
VBS at high energy

[arXiv:2503.17461]

BSM effects enhanced at higher energies $\Leftrightarrow$ easier to reconstruct $W/Z \to qq$
$\Rightarrow$ study semileptonic VBS topologies with $V \to j(j)$ either resolved or tagged

Signal separation: RNN (+ DNN for merged SRs) to handle variable multiplicities

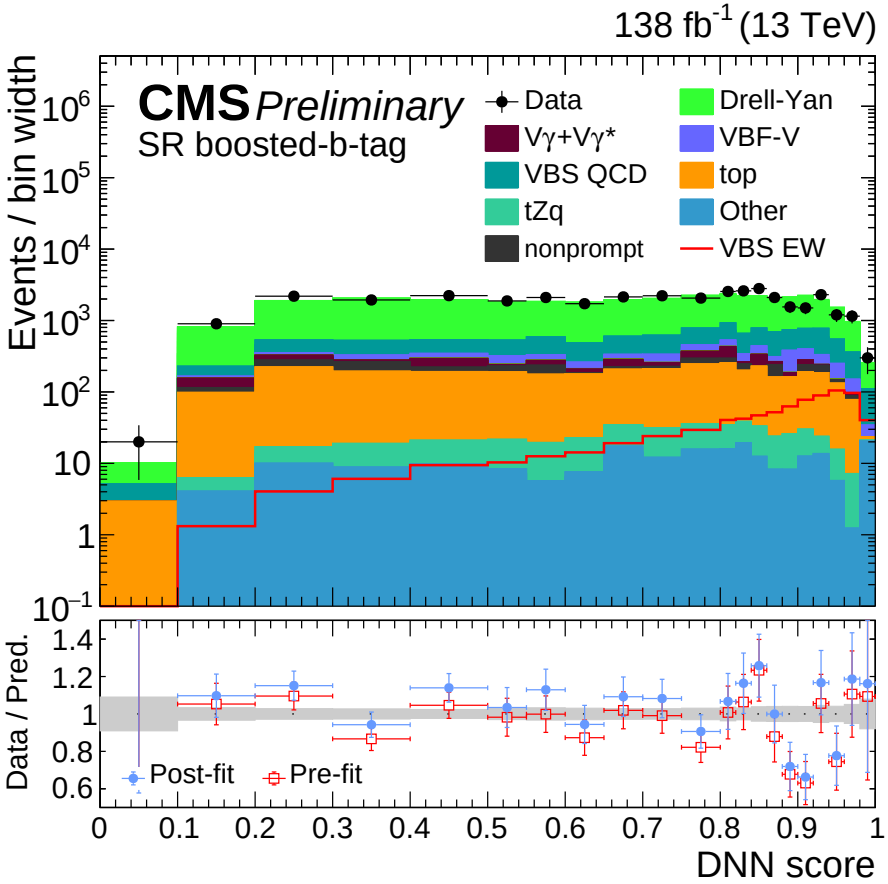


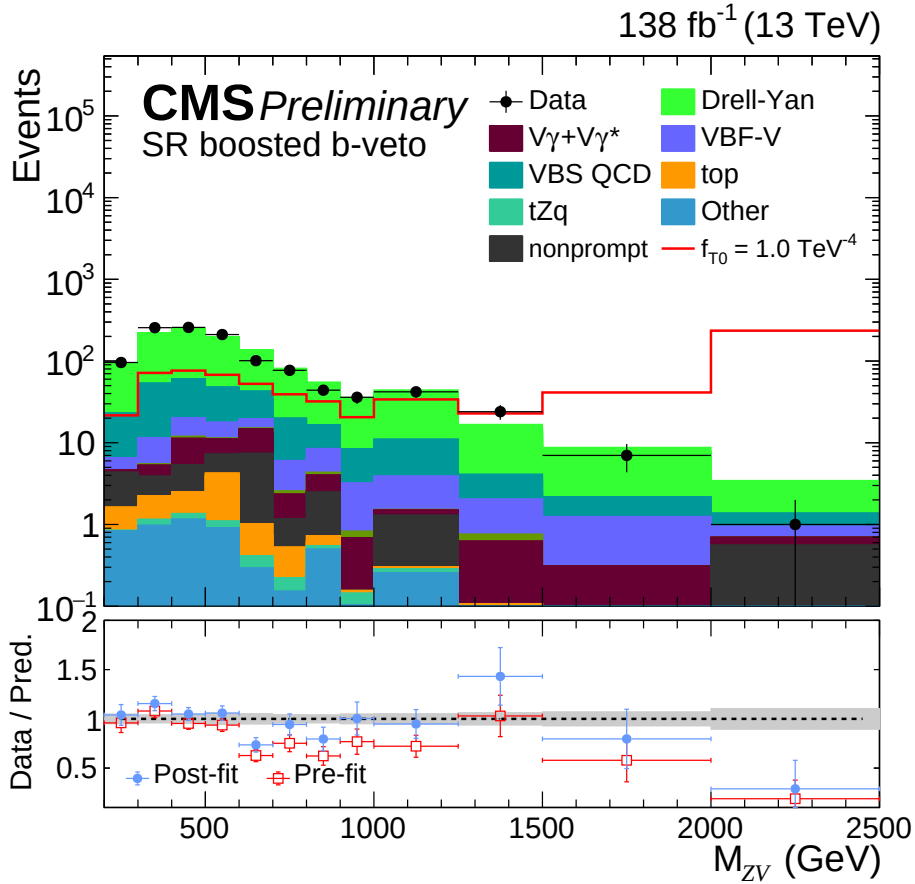


Combined sensitivity to VBS: 7.4σ

VBS $ZV \to \ell\ell qq$ [CMS-PAS-SMP-22-011]

Signal separation: DNN trained in each category with 13-14 inputs (out of 24 probed)





Sensitivity to VBS: 1.3σ (1.8 expected), complementing the earlier VBS $WV \to \ell\nu qq$ observation (4.4σ) [PLB 834 (2022) 137438]

Semileptonic VBS constraints on aQGC

ATLAS: SRs split into low/high m_{VV} or m_{T} regions (transition at 1-1.5 TeV)
CMS: binned m_{VV} distributions fits up to ≥ 2 TeV

95% CL on dim-8 SMEFT operators (only one $\neq 0$ at a time)—best to date!

	CMS (SMP-22-011)				ATLAS (arXiv:2503.17461)		
	WV (exp) (TeV^{-4})	ZV (exp) (TeV^{-4})	VV (obs) (TeV^{-4})	VV (exp) (TeV^{-4})	VV (obs) (TeV^{-4})	VV (exp) (TeV^{-4})	
f_{S0}/Λ^4	$[-4.7, 4.77]$	$[-13.9, 14.0]$	$[-2.86, 2.96]$	$[-4.68, 4.75]$	$[-3.96, 3.96]$	$[-3.22, 3.22]$	$(D_\mu\Phi)^\dagger D_\nu\Phi (D^\mu\Phi)^\dagger D^\nu\Phi$
f_{S1}/Λ^4	$[-6.56, 6.6]$	$[-13.9, 13.9]$	$[-3.97, 4.02]$	$[-6.45, 6.49]$	$[-8.06, 8.06]$	$[-6.84, 6.86]$	$(D_\mu\Phi)^\dagger D^\mu\Phi (D_\nu\Phi)^\dagger D^\nu\Phi$
f_{S2}/Λ^4	$[-6.81, 6.86]$	$[-13.9, 14.0]$	$[-4.04, 4.11]$	$[-6.68, 6.73]$	$[-3.96, 3.96]$	$[-3.22, 3.22]$	
f_{M0}/Λ^4	$[-0.844, 0.843]$	$[-1.74, 1.74]$	$[-0.539, 0.534]$	$[-0.828, 0.827]$	$[-1.26, 1.25]$	$[-1.13, 1.12]$	$\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu})(D_\lambda\Phi)^\dagger D^\lambda\Phi$
f_{M1}/Λ^4	$[-2.6, 2.63]$	$[-5.28, 5.29]$	$[-1.59, 1.62]$	$[-2.55, 2.58]$	$[-3.95, 3.95]$	$[-3.23, 3.24]$	$\mathrm{Tr}(W_{\mu\nu}W^{\nu\lambda})(D_\lambda\Phi)^\dagger D^\mu\Phi$
f_{M2}/Λ^4	$[-1.11, 1.11]$	$[-2.37, 2.37]$	$[-0.703, 0.703]$	$[-1.1, 1.1]$	$[-1.85, 1.85]$	$[-1.66, 1.67]$	$B_{\mu\nu}B^{\mu\nu}(D_\lambda\Phi)^\dagger D^\lambda\Phi$
f_{M3}/Λ^4	$[-4.2, 4.2]$	$[-7.47, 7.47]$	$[-2.55, 2.55]$	$[-4.08, 4.07]$	$[-5.68, 5.71]$	$[-5.29, 5.29]$	$B_{\mu\nu}B^{\nu\lambda}(D_\lambda\Phi)^\dagger D^\mu\Phi$
f_{M4}/Λ^4	$[-2.6, 2.59]$	$[-3.61, 3.61]$	$[-1.48, 1.48]$	$[-2.42, 2.41]$	$[-2.96, 2.97]$	$[-2.62, 2.62]$	$(D_\mu\Phi)^\dagger W_{\lambda\nu}D^\mu\Phi B^{\lambda\nu}$
f_{M5}/Λ^4	$[-3.77, 3.76]$	$[-5.21, 5.23]$	$[-2.14, 2.13]$	$[-3.5, 3.5]$	$[-4.41, 4.44]$	$[-3.81, 3.82]$	$(D_\mu\Phi)^\dagger W_{\lambda\nu}D^\nu\Phi B^{\lambda\mu}$
f_{M7}/Λ^4	$[-4.35, 4.32]$	$[-8.26, 8.24]$	$[-2.63, 2.58]$	$[-4.24, 4.2]$	$[-6.60, 6.43]$	$[-5.32, 5.20]$	$(D_\mu\Phi)^\dagger W_{\lambda\nu}W^{\lambda\mu}D^\nu\Phi$
f_{T0}/Λ^4	$[-0.14, 0.128]$	$[-0.33, 0.32]$	$[-0.0921, 0.0785]$	$[-0.138, 0.127]$	$[-0.25, 0.22]$	$[-0.20, 0.18]$	$\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu})\,\mathrm{Tr}(W_{\lambda\rho}W^{\lambda\rho})$
f_{T1}/Λ^4	$[-0.142, 0.149]$	$[-0.30, 0.31]$	$[-0.0863, 0.0943]$	$[-0.14, 0.147]$	$[-0.24, 0.24]$	$[-0.19, 0.19]$	$\mathrm{Tr}(W_{\mu\nu}W^{\lambda\rho})\,\mathrm{Tr}(W_{\lambda\rho}W^{\mu\nu})$
f_{T2}/Λ^4	$[-0.336, 0.335]$	$[-0.74, 0.76]$	$[-0.21, 0.214]$	$[-0.331, 0.332]$	$[-0.55, 0.55]$	$[-0.44, 0.44]$	$\mathrm{Tr}(W_{\mu\nu}W^{\nu\lambda})\,\mathrm{Tr}(W_{\lambda\rho}W^{\rho\mu})$
f_{T3}/Λ^4	$[-0.311, 0.31]$	$[-0.64, 0.66]$	$[-0.191, 0.194]$	$[-0.305, 0.305]$	$[-0.48, 0.48]$	$[-0.38, 0.38]$	$\mathrm{Tr}(W_{\mu\nu}W^{\nu\lambda}W^{\rho\mu})B_{\lambda\rho}$
f_{T4}/Λ^4	$[-1.58, 1.53]$	$[-1.84, 1.77]$	$[-0.895, 0.828]$	$[-1.4, 1.35]$	$[-1.51, 1.37]$	$[-1.46, 1.32]$	$\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu}W^{\lambda\rho})B_{\lambda\rho}$
f_{T5}/Λ^4	$[-0.391, 0.383]$	$[-0.76, 0.73]$	$[-0.265, 0.237]$	$[-0.382, 0.373]$	$[-0.64, 0.58]$	$[-0.57, 0.53]$	$\mathrm{Tr}(W_{\mu\nu}W^{\mu\nu})B_{\lambda\rho}B^{\lambda\rho}$
f_{T6}/Λ^4	$[-0.976, 0.954]$	$[-0.94, 0.92]$	$[-0.5, 0.478]$	$[-0.794, 0.775]$	$[-0.74, 0.71]$	$[-0.76, 0.72]$	$\mathrm{Tr}(W_{\mu\nu}W^{\lambda\rho})B_{\lambda\rho}B^{\mu\nu}$
f_{T7}/Λ^4	$[-1.39, 1.36]$	$[-2.26, 2.16]$	$[-0.85, 0.8]$	$[-1.34, 1.29]$	$[-1.94, 1.70]$	$[-1.78, 1.52]$	$\mathrm{Tr}(W_{\mu\nu}W^{\nu\lambda})B_{\lambda\rho}B^{\rho\mu}$
f_{T8}/Λ^4	–	$[-0.67, 0.67]$	$[-0.53, 0.53]$	$[-0.67, 0.67]$	$[-0.48, 0.48]$	$[-0.59, 0.59]$	$B_{\mu\nu}B^{\mu\nu}B_{\lambda\rho}B^{\lambda\rho}$
f_{T9}/Λ^4	–	$[-1.47, 1.45]$	$[-1.17, 1.16]$	$[-1.47, 1.45]$	$[-1.02, 1.03]$	$[-1.22, 1.22]$	$B_{\mu\nu}B^{\nu\lambda}B_{\lambda\rho}B^{\rho\mu}$

Non-unitarized limits $\Leftrightarrow$ sensitive to binning, no guarantee to remain within EFT validity range

Complementary set of limits with clipping / unitarization approaches also available.

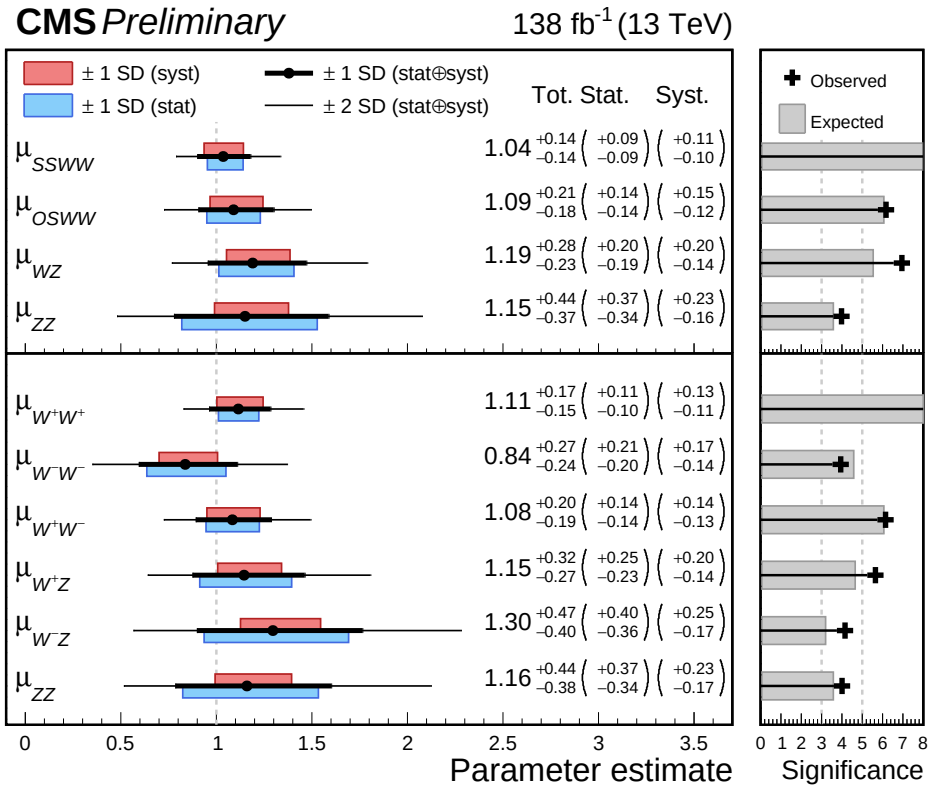
VBS combination

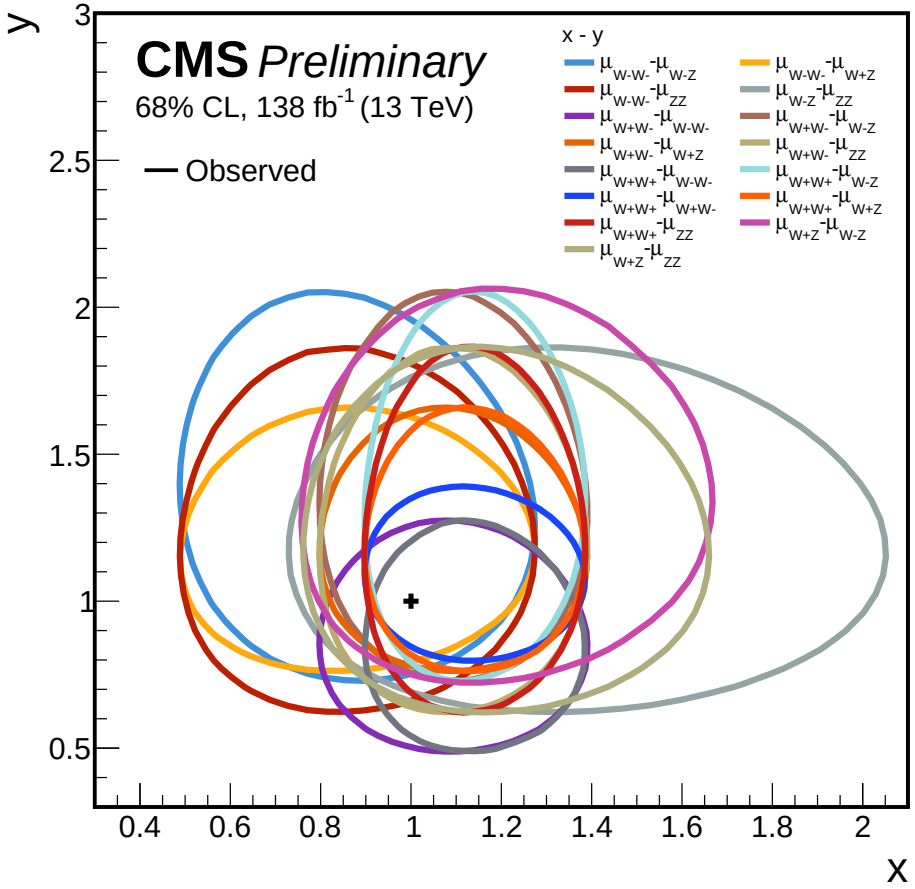
[CMS-PAS-SMP-24-013]

W vs Z unresolved in $V \to jj \Rightarrow$ statistical combination of 7 VBS measurements

$\Rightarrow$ 5 – 10% improved precision on signal strengths

$\Rightarrow$ evidence for all charge-distinct processes





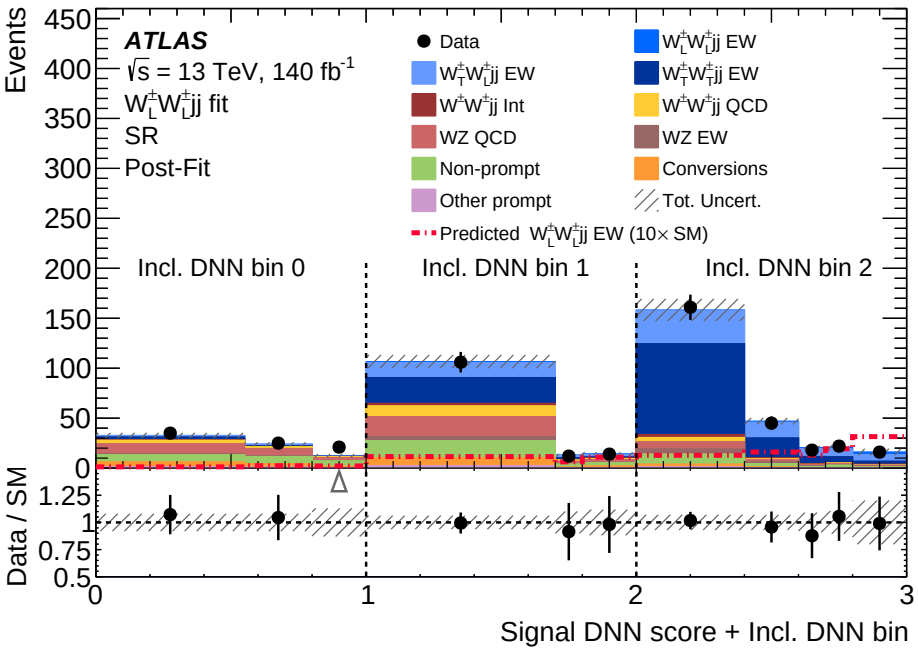
$W^{\pm}W^{\pm}$ polarization

[arXiv:2503.11317]

Higgs mechanism $\leftrightarrow$ longitudinal V polarization $\leftrightarrow$ unitarization of VBS

DNNs to separate WW from bkg, then $W_L W$ from $W_T W_T$ or $W_L W_L$ from $W_T W$

Polarized NLO EW corrections as function of m_{jj} applied.



Description	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)
$W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\pm}jj$	0.19 ± 0.05	0.16 ± 0.22 (tot.)
$W_{\mathrm{T}}^{\pm}W^{\pm}jj$	2.67 ± 0.66	3.40 ± 0.35 (tot.)
$W_{\mathrm{L}}^{\pm}W^{\pm}jj$	1.24 ± 0.31	0.84 ± 0.37 (tot.)
$W_{\mathrm{T}}^{\pm}W_{\mathrm{T}}^{\pm}jj$	1.62 ± 0.39	2.46 ± 0.37 (tot.)

$\Rightarrow$ evidence for $W_L^{\pm}W^{\pm}jj$ at 3.3σ, reinforcing previous measurements (PLB 812 (2020) 136018)

Also observed for (non-VBS) WZ (PLB 843 (2023) 137895), ZZ (JHEP 12 (2023) 107)

$W_L W_L$ projections for HL-LHC

[arXiv:2504.00672]

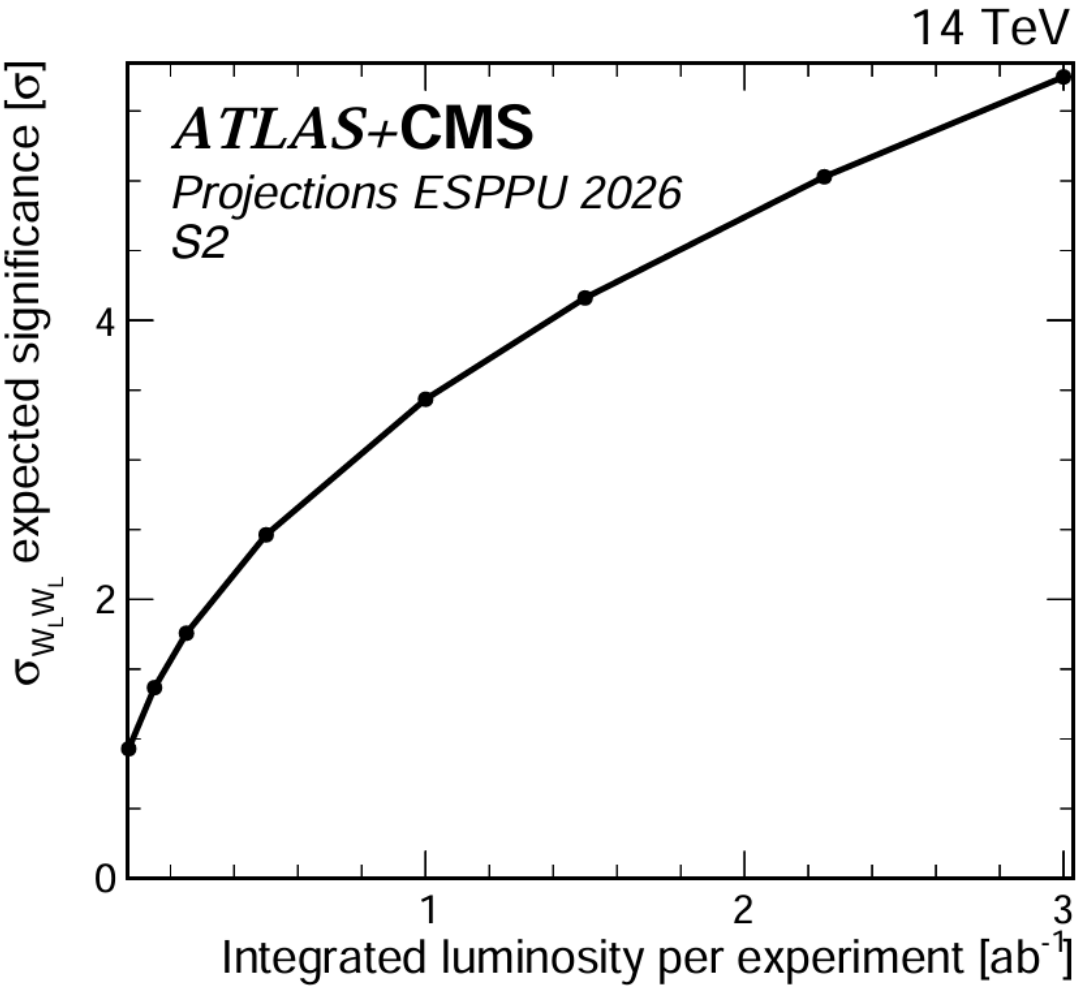
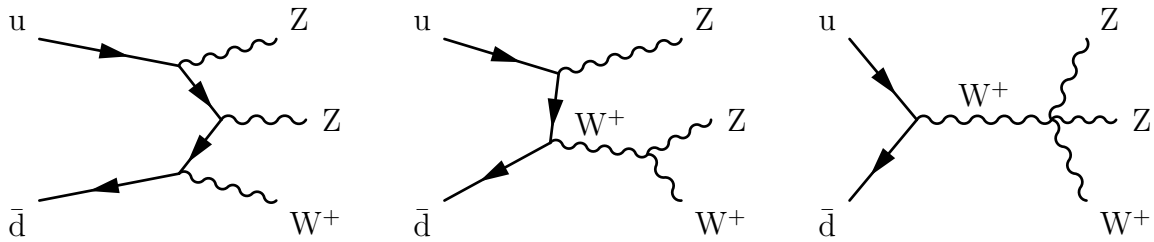


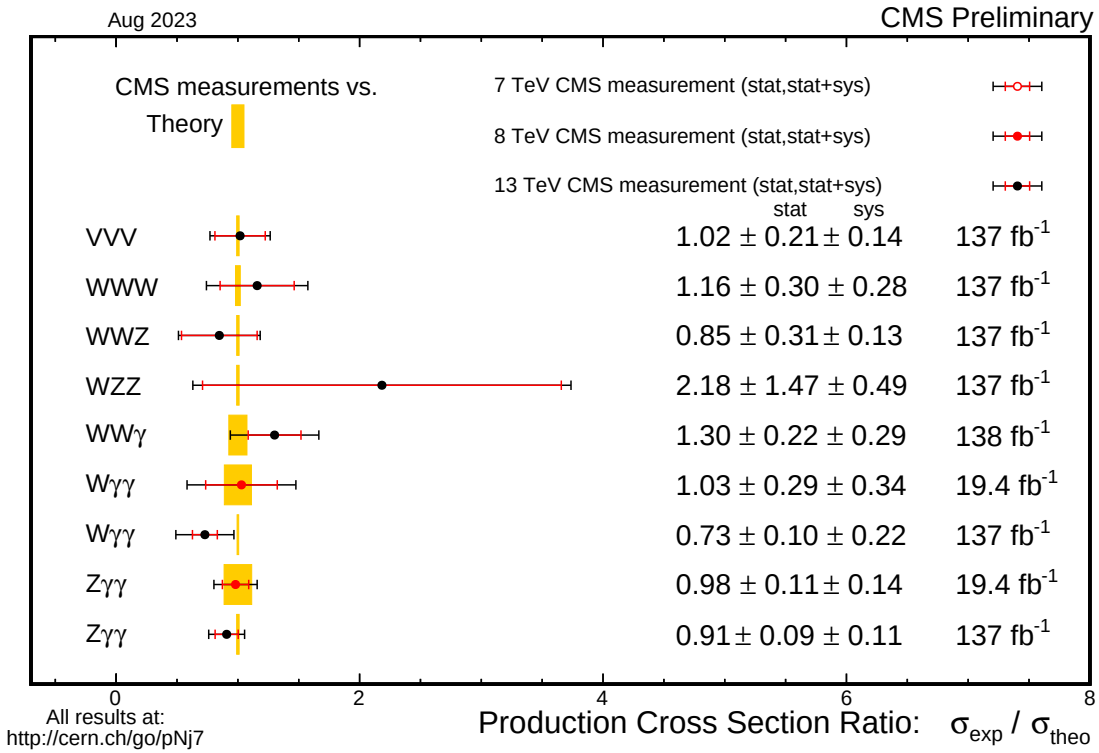
Figure 8: Expected significance of the longitudinally polarized WW scattering as a function of the luminosity in the *S2* scenario.

Triboson processes

[arXiv:2405.18661]



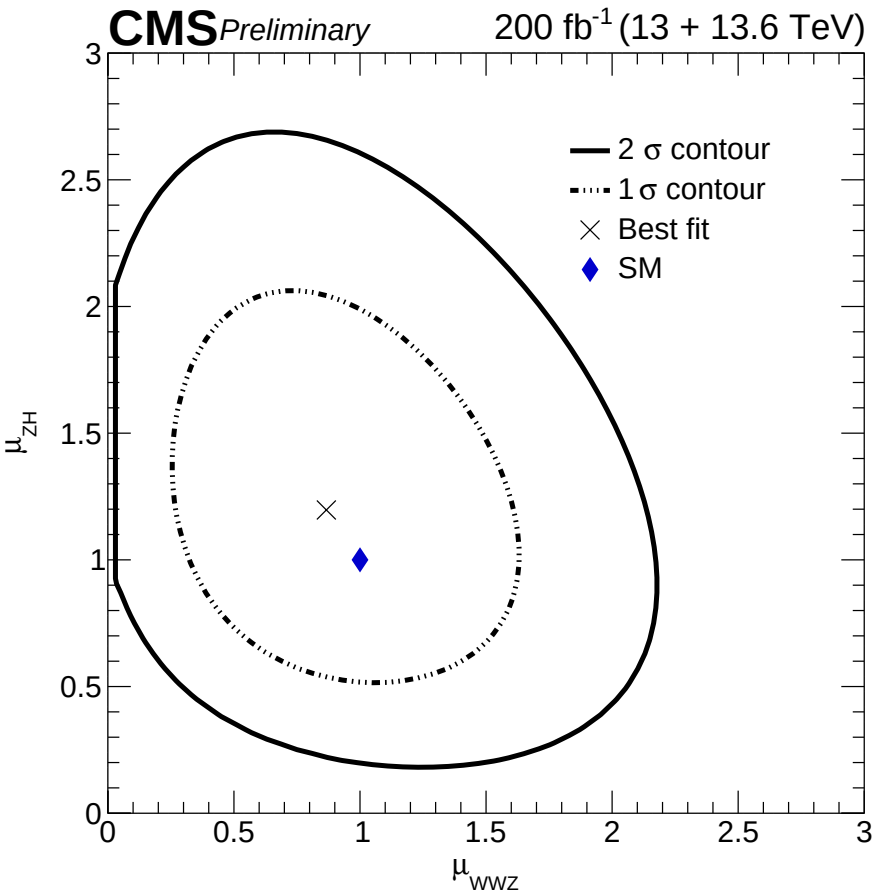
- Most processes accessible with LHC Run 2 + 3 statistics
- Same motivation: probe triple and quartic gauge couplings, and to Higgs / scalars



WWZ production

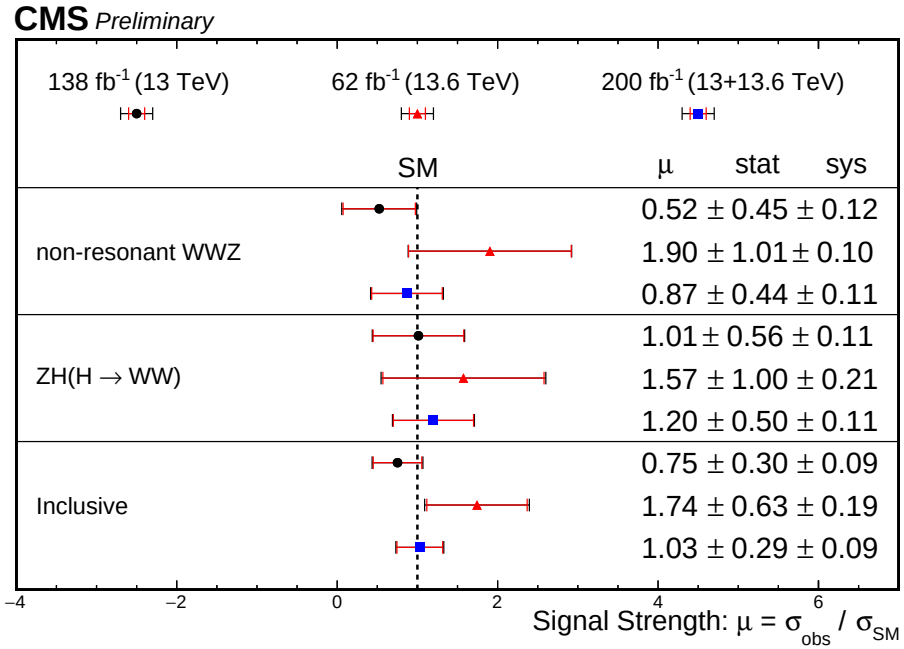
[CMS-PAS-SMP-24-015]

Era	Total	WWZ	ZH
Run 2	2.9 (4.4)	1.3 (3.1)	2.0 (2.6)
Run 3	3.8 (2.5)	2.5 (1.3)	2.5 (1.7)
Total	4.5 (5.0)	2.4 (3.3)	3.1 (3.1)



Measured in 4ℓ events, simultaneously to the $ZH(\rightarrow WW)$ process

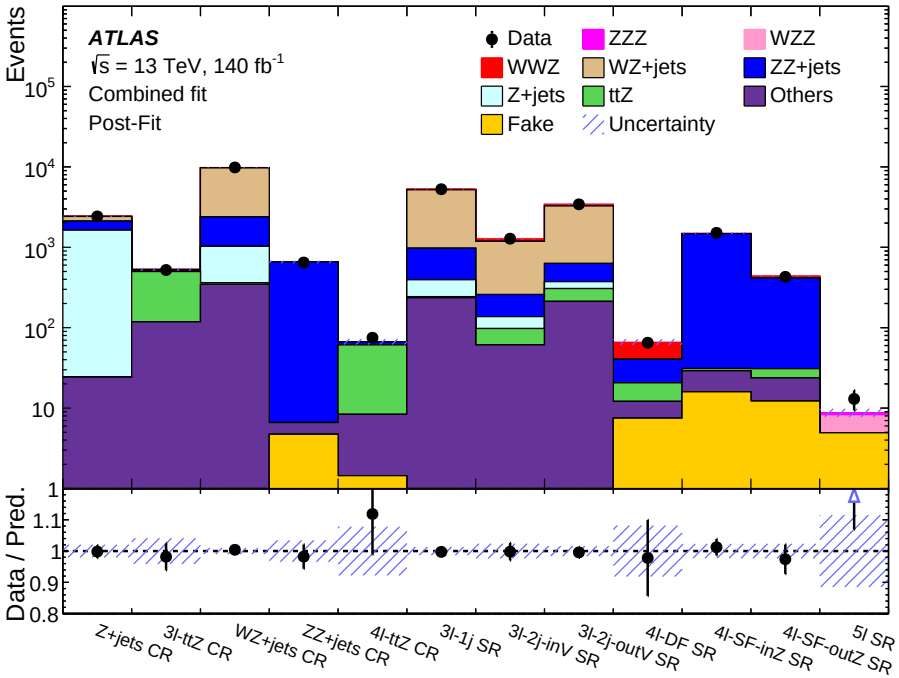
SRs binned in multiclass BDT discriminants separating WWZ / ZH / $ZZ + ttZ$

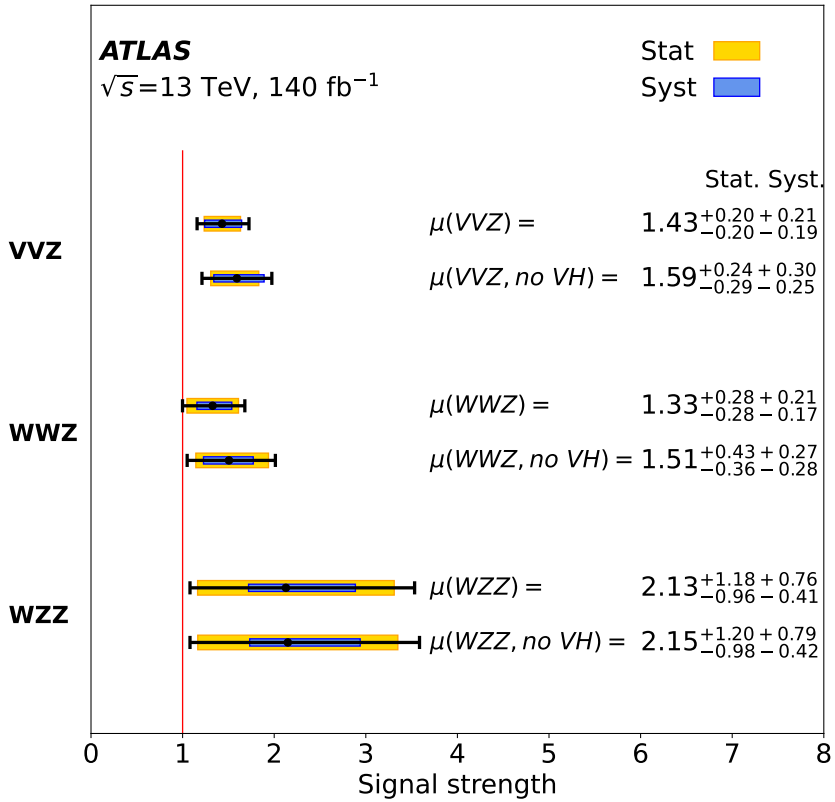


VVZ production

[arXiv:2412.15123]

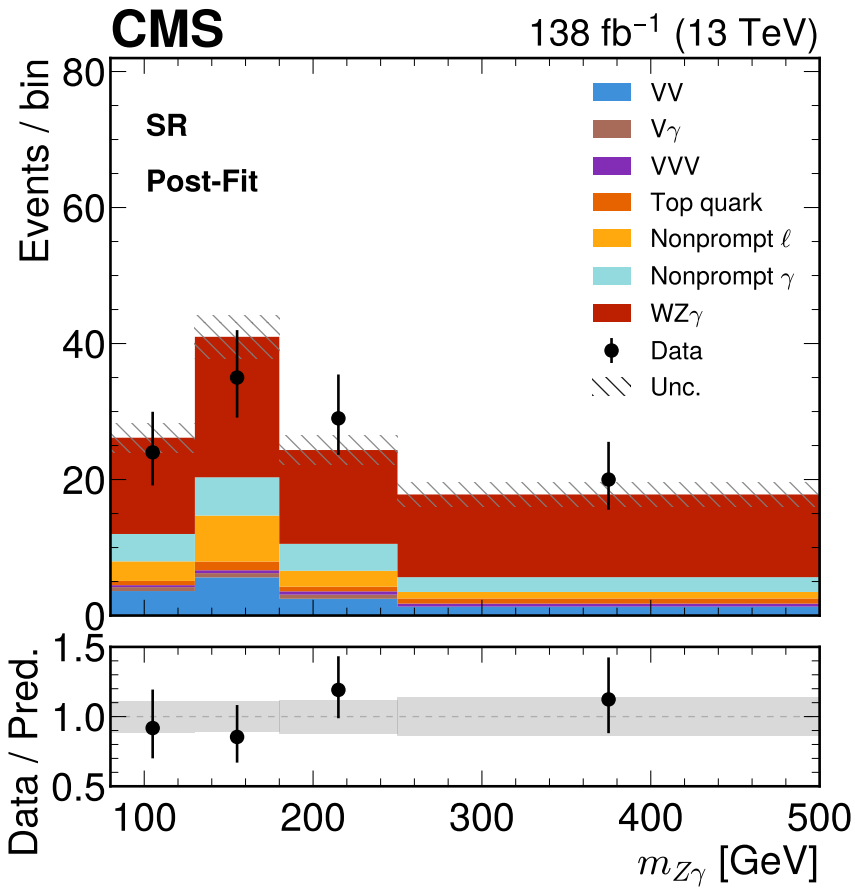
Simultaneous determination of *WWZ*, *WZZ* and *ZZZ* signal strengths using multilepton categories, with individually-trained BDTs as final discriminants ⇒ 58 SR bins.





\+ constraints on aQGC dim-8 operators f_{M2-5}, though less sensitivity than VBS

Recently observed in resonant $\ell\nu\ell\ell\gamma$ events, using simple cut-and-count (ATLAS) or binned $m_{3\ell\gamma}$ as final discriminant (CMS):



CMS (5.4σ obs.):

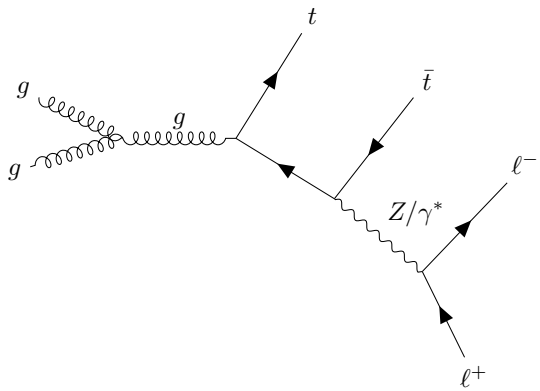
$$\mu = 1.47 \pm 0.25(\text{stat}) \pm 0.15(\text{syst}) \pm 0.11(\text{th})$$

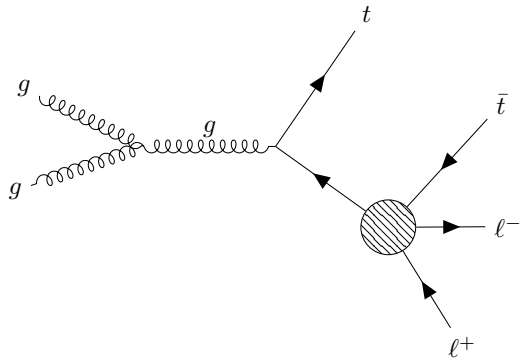
ATLAS (6.3σ obs.):

$$\mu = 1.34 \pm 0.20(\text{stat}) \pm 0.10(\text{syst}) \pm 0.07(\text{th})$$

+ constraints on aQGC dim-8 operators f_{T0-7}, though less sensitivity than VBS
+ limits on associate production $pp \to Wa$ of photophobic ALP

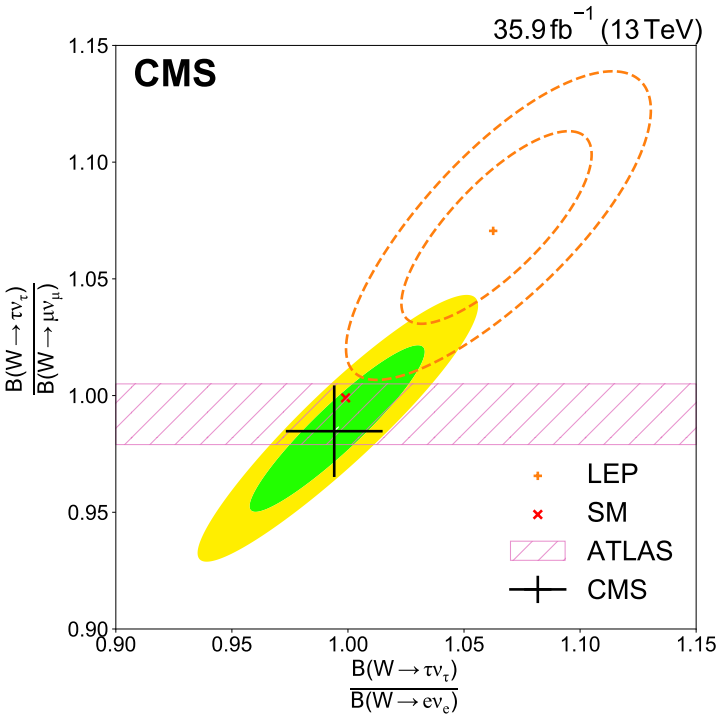
Electroweak couplings of fermions, flavour universality

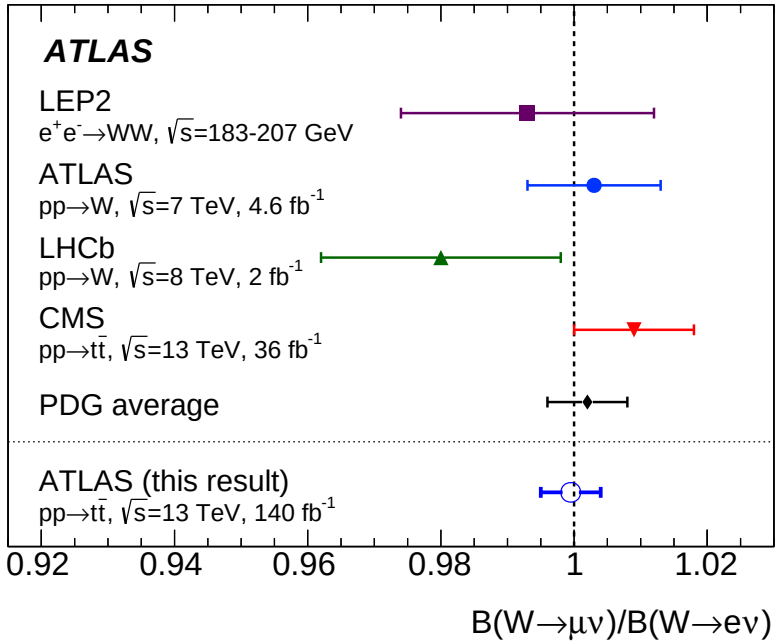




LFU in W decays [PRD 105 (2022) 072008; EPJC 84 (2024) 993]

$t\bar{t}$ events $\rightarrow$ high-purity unbiased Ws $\rightarrow$ precise decay rates to $e/\mu/\tau$/hadrons





For $\mathcal{B}(\tau)/\mathcal{B}(\ell)$ using only $\tau \rightarrow \ell\nu\bar{\nu}$ decays $\Rightarrow$ ℓ reco+trigger uncertainties cancel

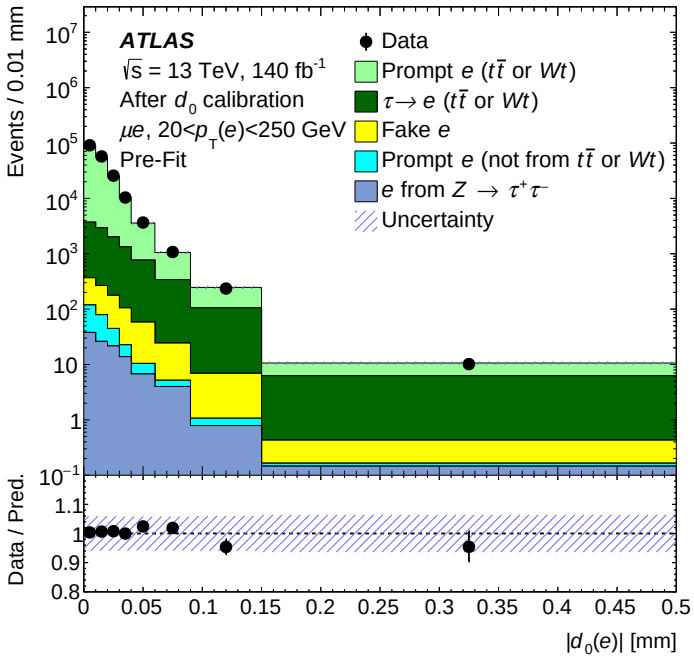
For $\mathcal{B}(\mu)/\mathcal{B}(e)$ using control measurement of LFU in Z decays (well constrained by LEP + SLAC) + careful transport from Z to $t\bar{t}$ environment (e.g. lepton isolation)

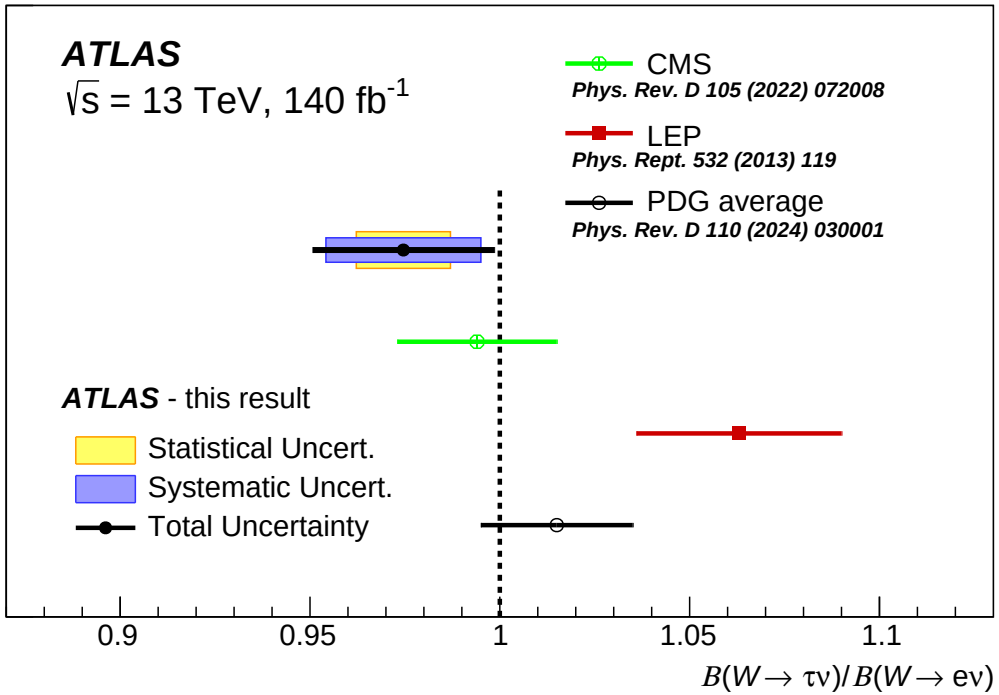
Also measured $|V_{cs}|$ and $\sum |V_{uj}|^2 + |V_{cj}|^2$ at 1% precision.

LFU in W decays

[arXiv:2412.11989]

CMS measurement of the $\mathcal{B}(W \to \tau\nu)/\mathcal{B}(W \to e\nu)$ in tension with LEP recently comforted by ATLAS, achieving a similar precision and compatibility with the SM:



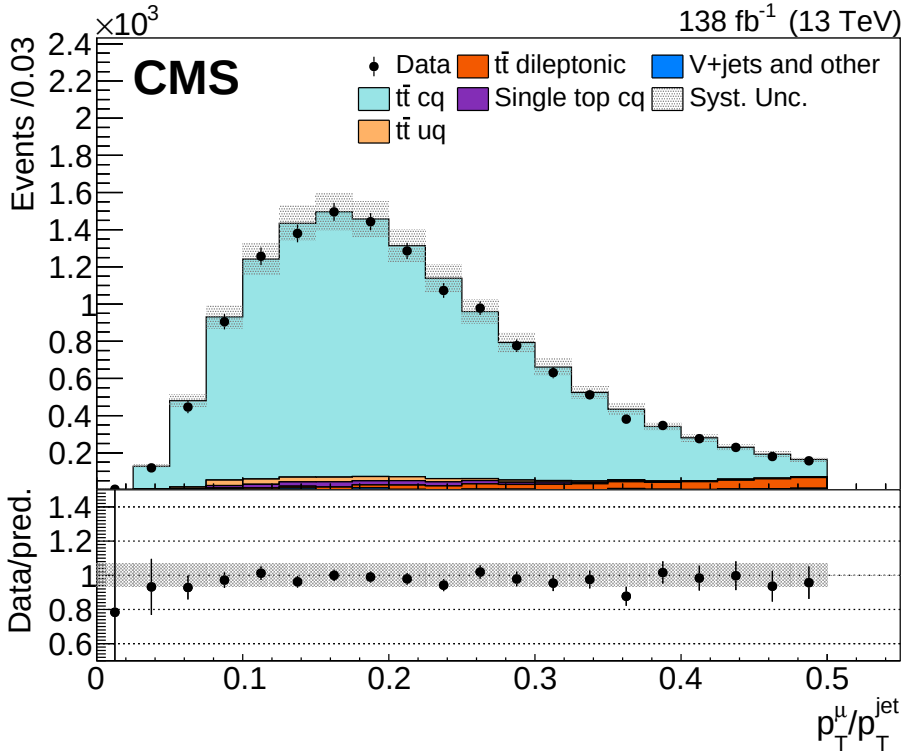


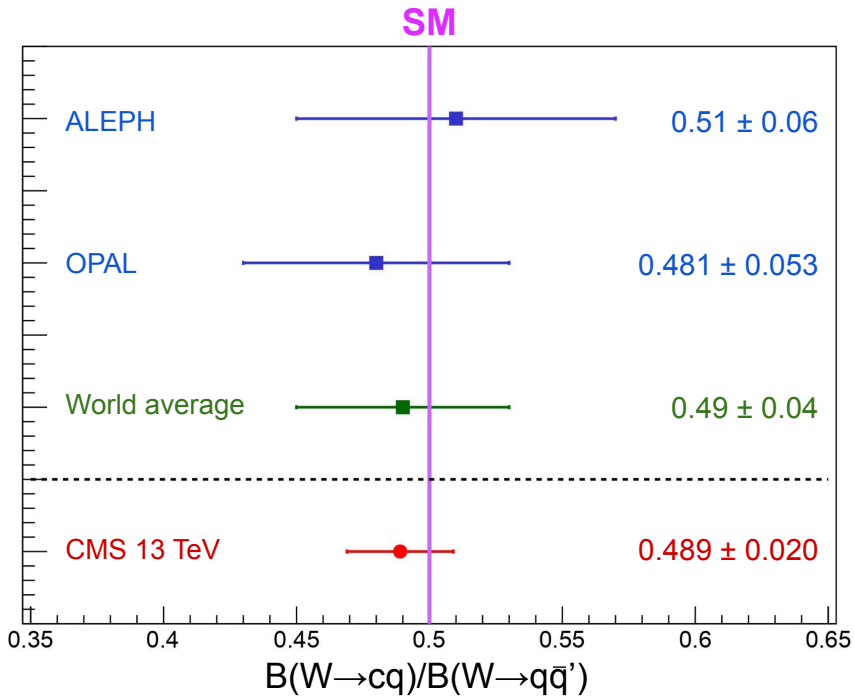
W to charm

[arXiv:2412.16296]

Again with $t\bar{t}$ events, identifying $W \to cq$ via non-prompt muons ($\approx 9\%$ of such jets);

MC corrections: latest charm fragmentation fractions & (semi)leptonic BRs for charm hadrons ($\approx 5\%$) + calibration with b-jets data ($\leq 15\%$)



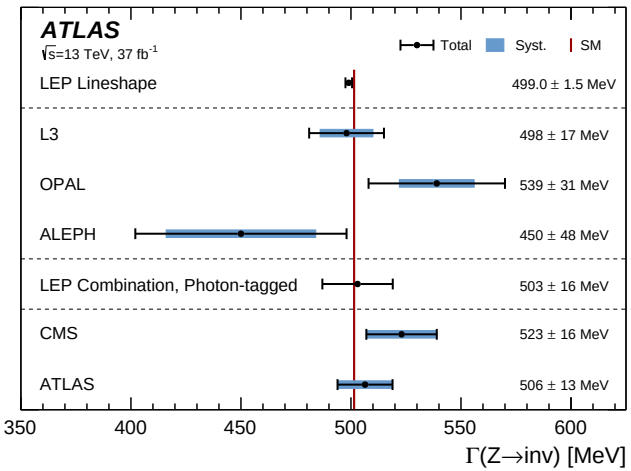


Reached 4% precision ($\approx$ tagging uncertainties): twice more precise than PDG average!

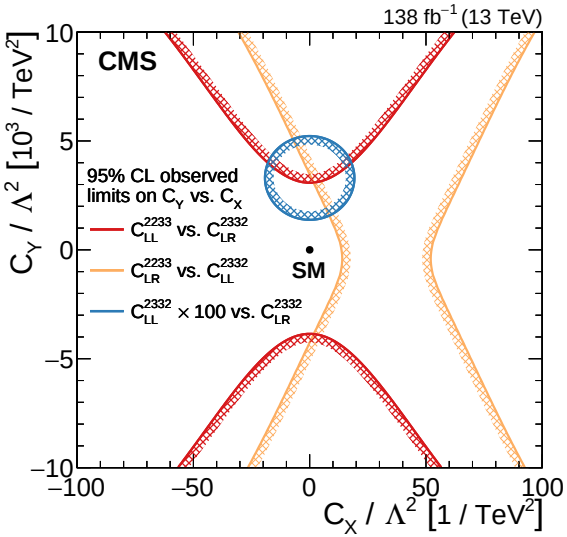
Side measurements: $|V_{cs}| = 0.959 \pm 0.021$ and $\sum |V_{ci}|^2 = 0.970 \pm 0.041$.

Z decay modes

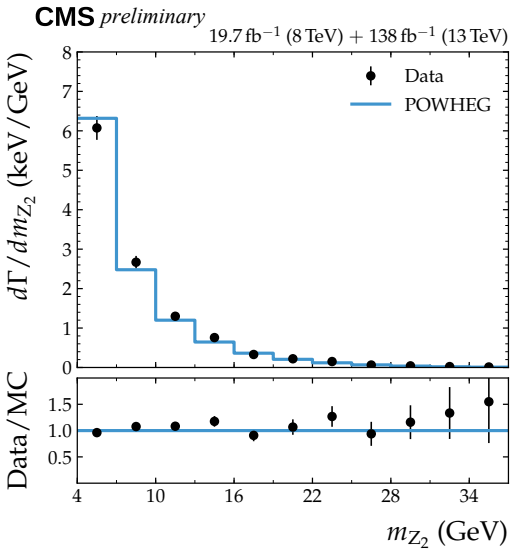
$Z \to$ invisible
[PLB 854 (2024) 138705; PLB (2023) 137563]



$Z \to \tau\tau\mu\mu$
[PRL 133 (2024) 161805]



$Z \to 4\ell$
[CMS-PAS-SMP-19-007]



Also numerous upper bounds on rare exclusive $Z \to$ hadrons (incl. radiative) decays [arXiv:2312.11211]

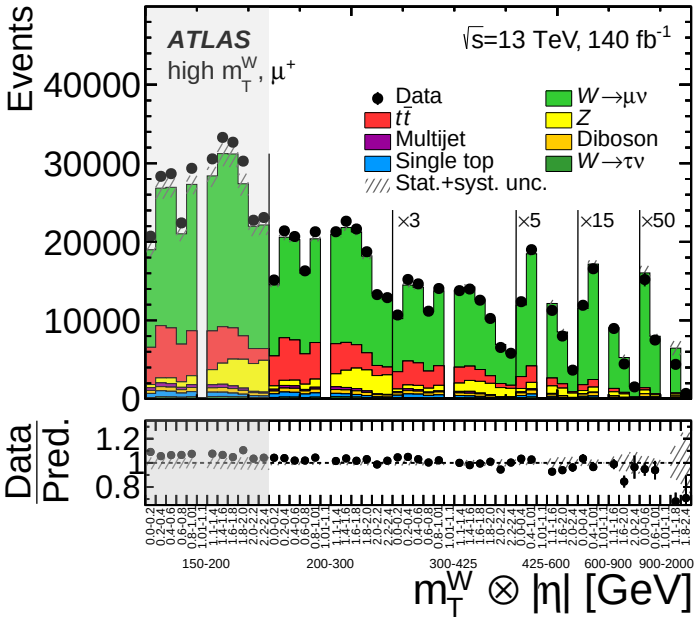
$pp \to \ell\nu$ at high m_{T}

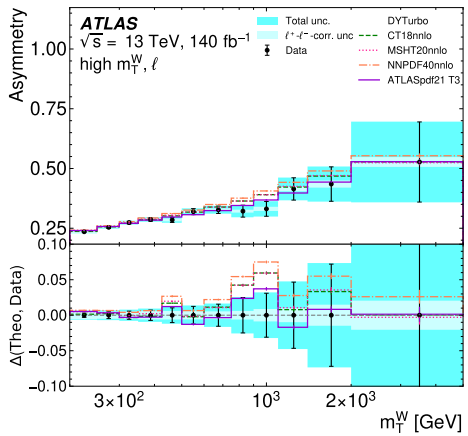
[arXiv:2502.21088]

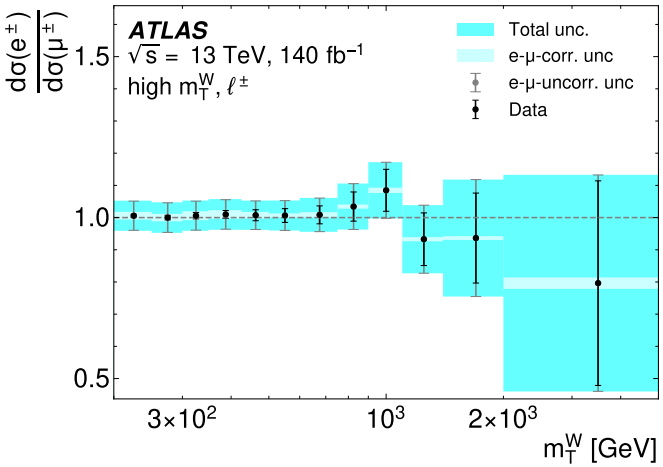
Measured $\sigma(m_{\mathrm{T}}, |\eta|, \text{flavour}, \text{charge})$
$\to$ constraints on PDFs (high-x), contact interactions, LFV...

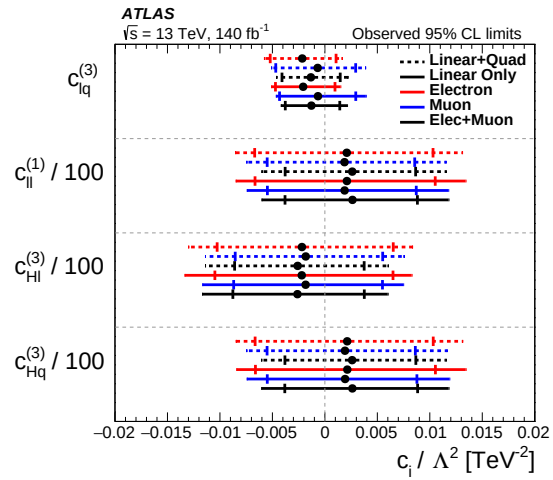
Region $150 < m_{\mathrm{T}} < 200$ GeV only used to stabilise unfolding as contains 60% resonant $\ell\nu$

SM NNLO QCD corrections from VRAP, NLO EW corrections from MCSANC $\leq 10\%$







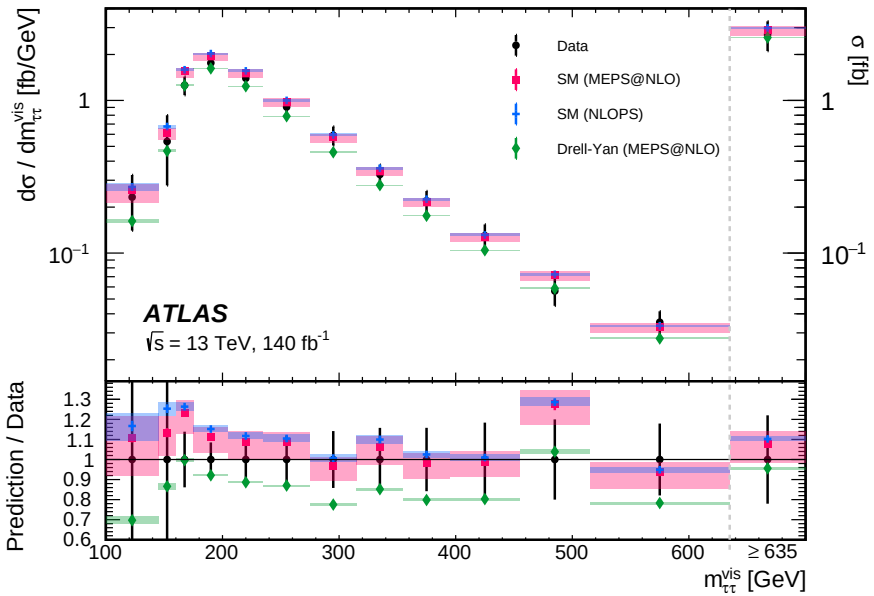


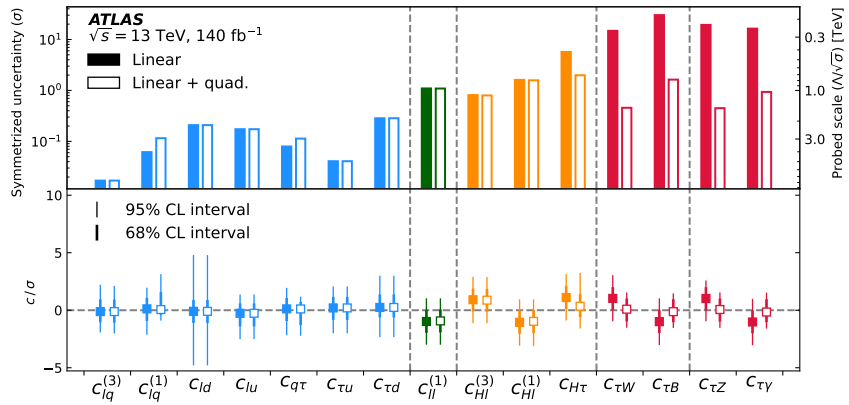
Only $c_{\ell q}^{(3)}$ enhances σ at high m_{T} $\Rightarrow$ best constrained!

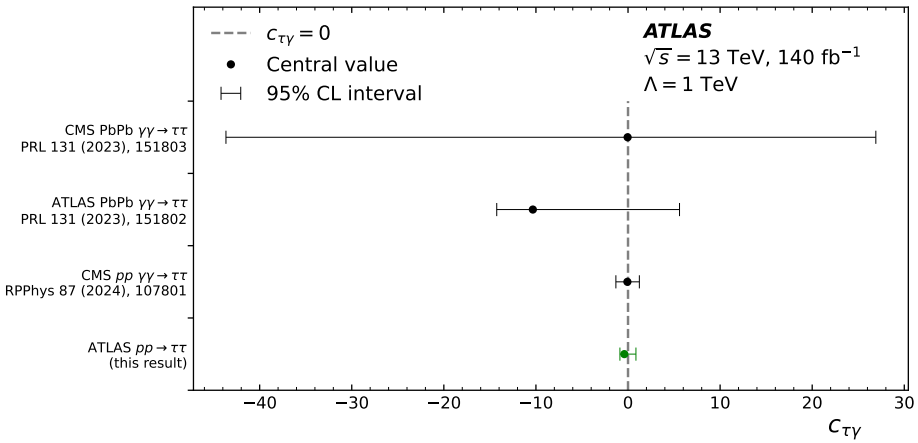
$pp \to \tau^+\tau^-$ at high $m_{\text{vis.}}$

[arXiv:2503.19836]

Similarly, neutral Drell-Yan process probed at high masses for $\tau^+\tau^-$ pairs to look for contact interactions:



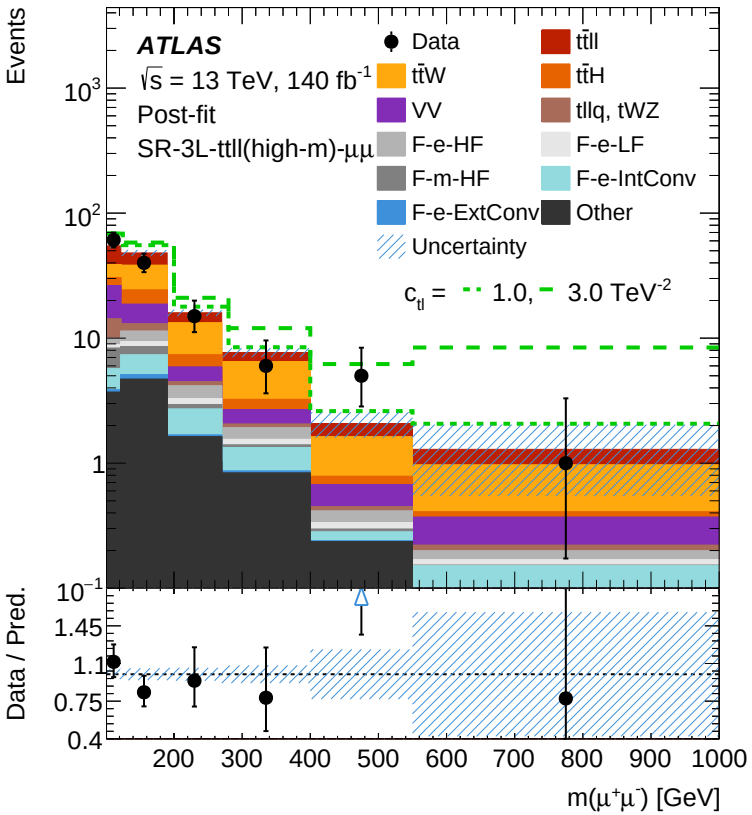


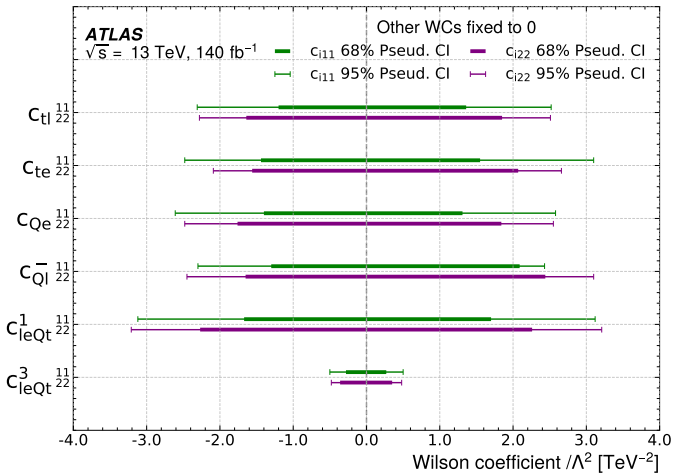


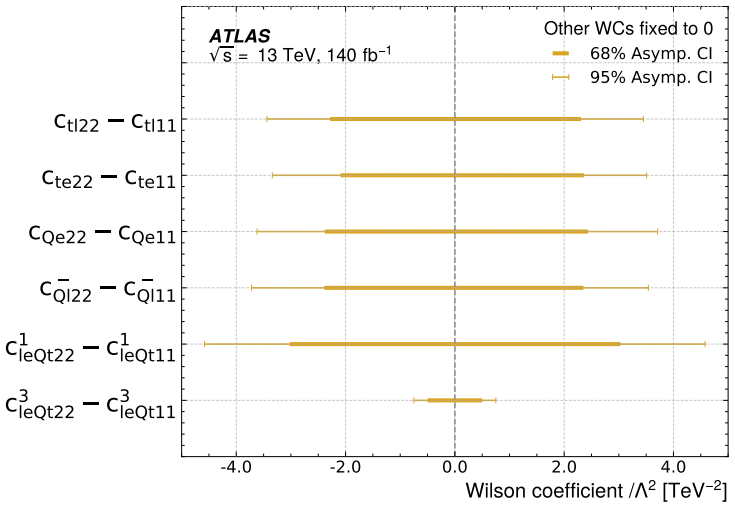
Measurements performed as function of the b-jet multiplicity (Z', leptoquarks).

$t\bar{t}\ell\ell$ at high $m_{\ell\ell}$

[arXiv:2504.05919]





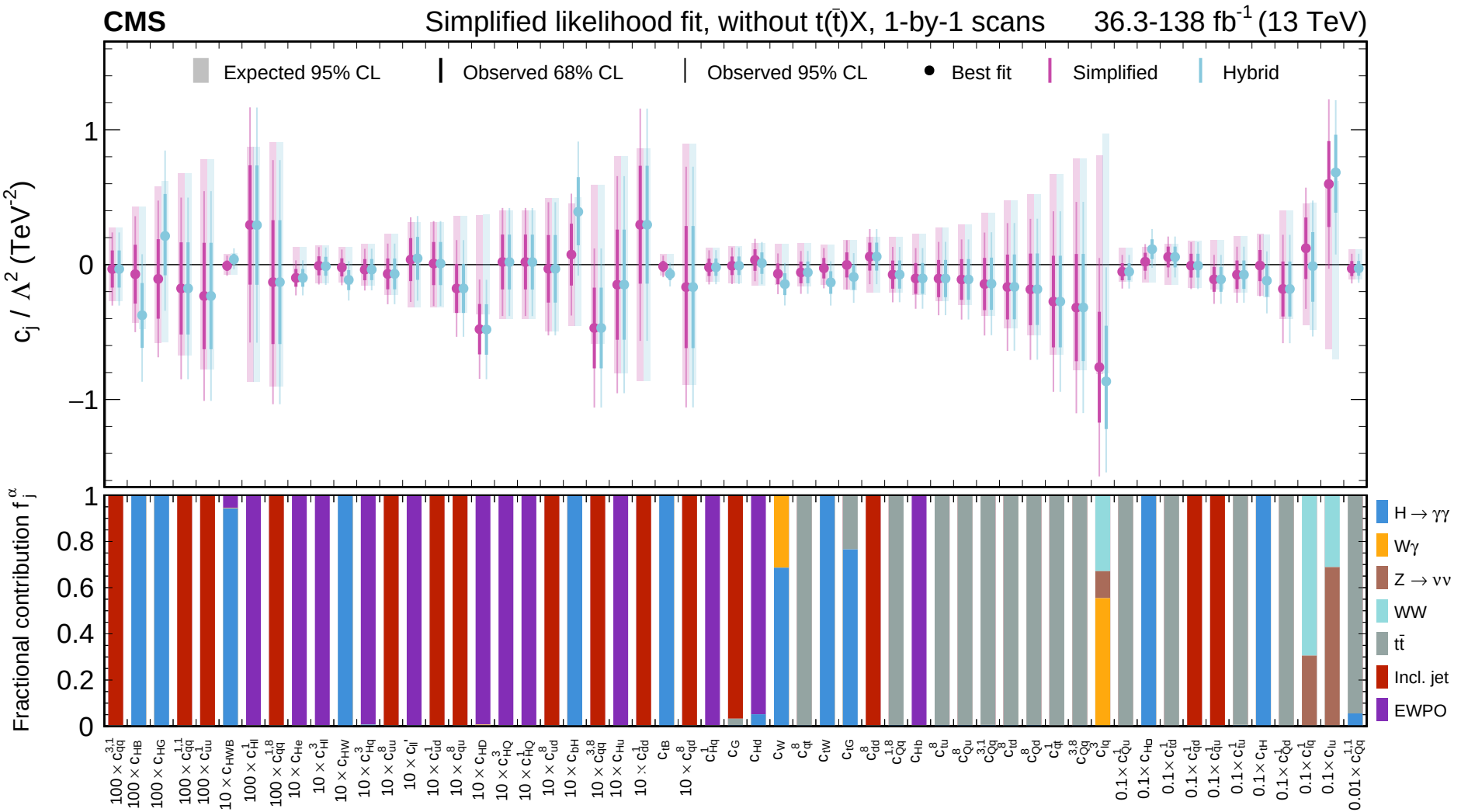


dim-6 operators constrained assuming LFU, or individually (e, μ); Δ also constrained to exploit uncertainty cancellations

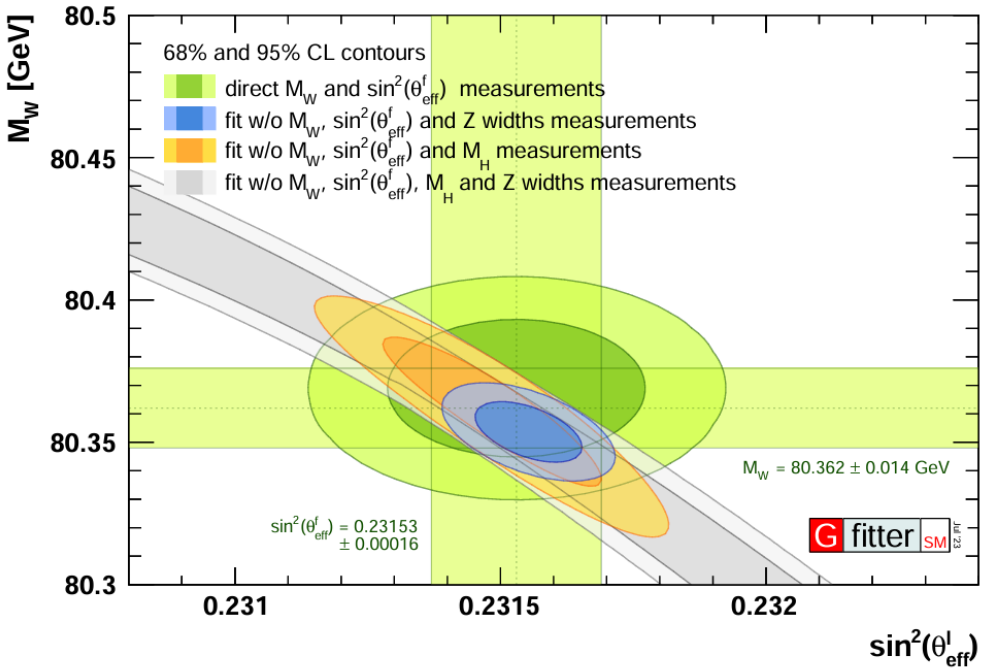
Greater sensitivity to contact interactions than resonant $t\bar{t}Z$ [JHEP 07 (2024) 163]; flavour-inclusive operators similarly constrained by CMS [JHEP 12 (2023) 068].

Role in global SMEFT picture

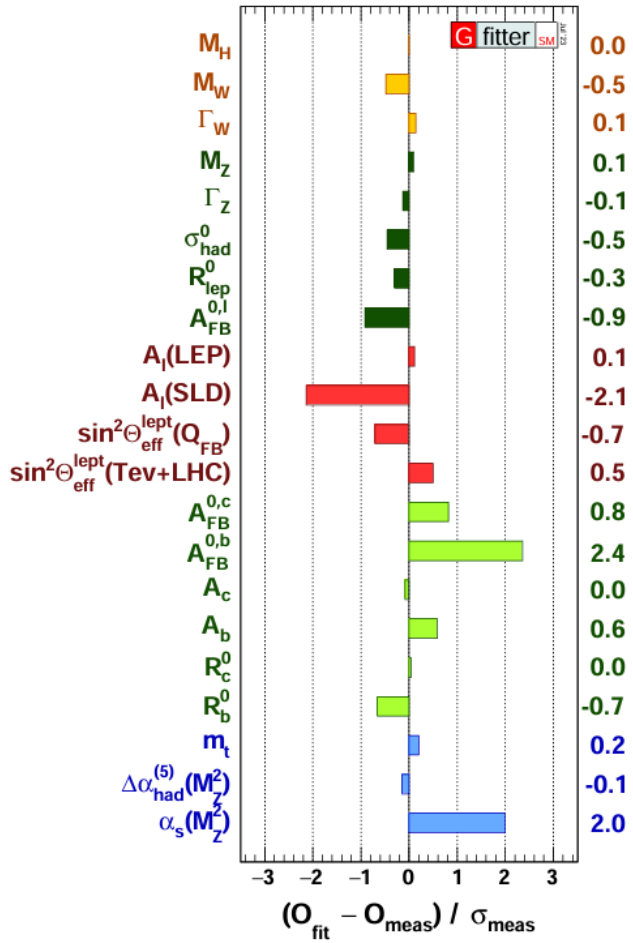
[CMS-SMP-24-003]



Precision measurements of EW observables



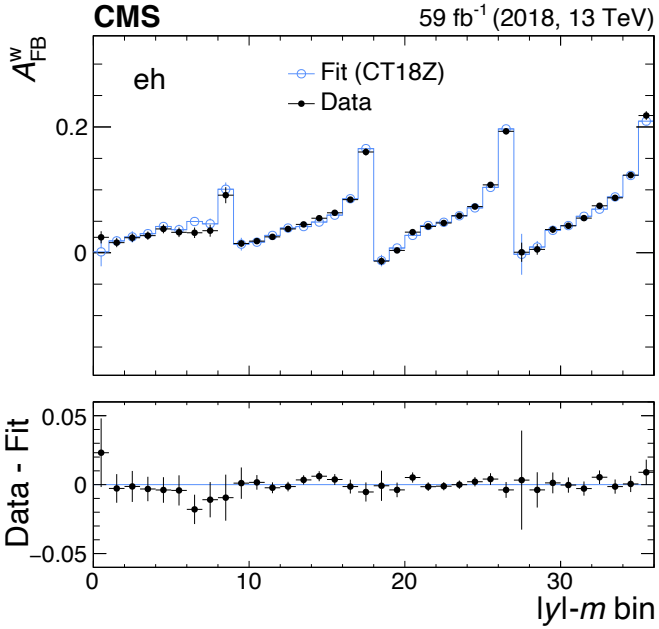
source: PoS EPS-HEP2023 (2024) 304

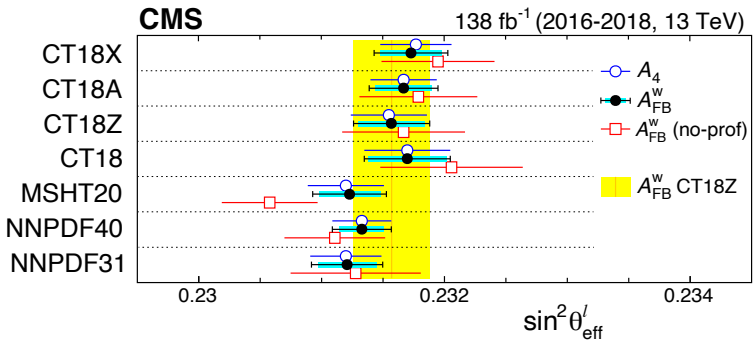


$\sin^2\theta^{\ell}_{\text{eff}}$ in $Z/\gamma^* \to \ell\ell$ [arXiv:2408.07622]

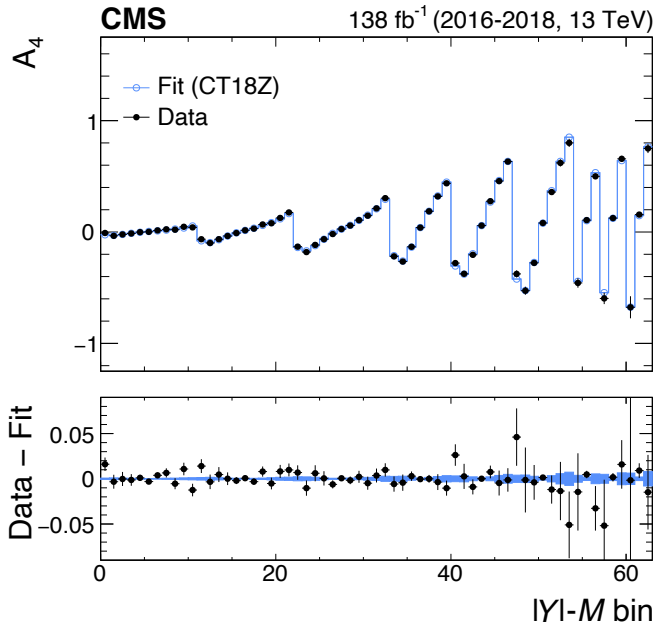
With ee ($|\eta| \leq 4.36$) and $\mu\mu$ ($|\eta| < 2.4$), $\sin^2\theta^{\ell}_{\text{eff}}$ extracted from MC templates fitted to:

the observed angular-weighted A^{w}_{FB}, aiming for reduced stat errors & cancellation of reco uncertainties:





or A_4 coefficients unfolded from $n_{\text{obs}}(m, |y|, \cos\theta_{CS})$, aiming for reduced PDF + theory uncertainties:



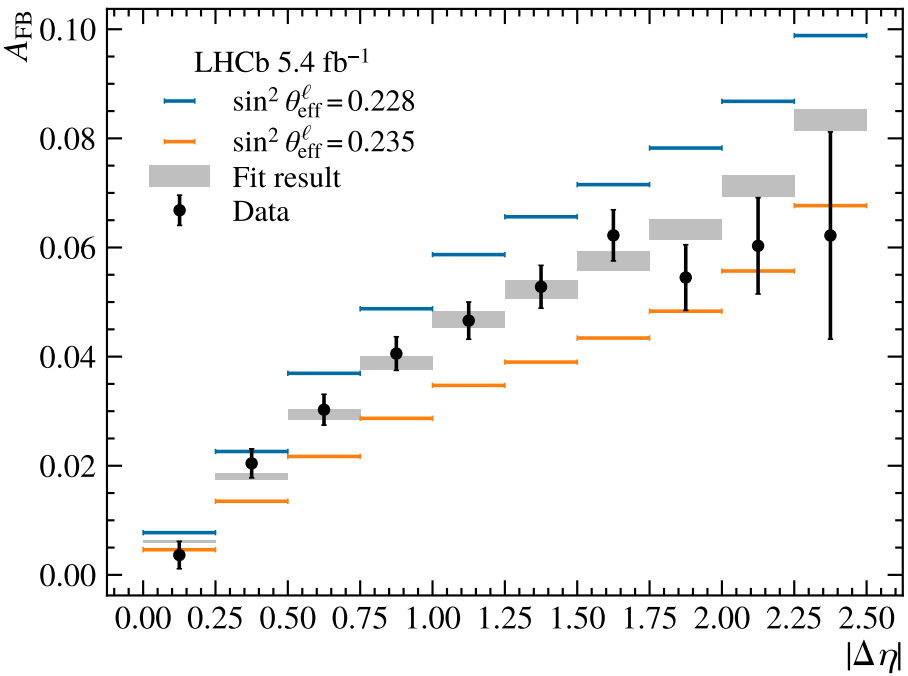
Uncertainties		
	total	31×10^{-5}
	stat	10×10^{-5}
	experimental	15×10^{-5}
	theory	9×10^{-5}
	PDF	27×10^{-5}

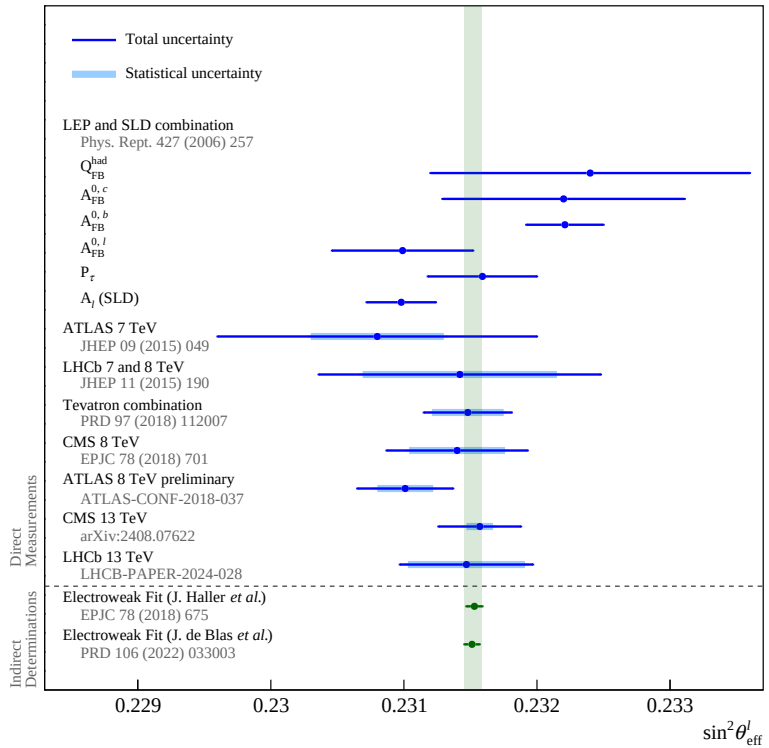
. . . and at high rapidity

[JHEP 13 (2024) 026]

With LHCb, access to $2 < \eta(\mu) < 4.5$ + benefits of high y (asymmetry ↑, PDF impact ↓)

Instead of A_{FB}^{w} approach, A_{FB} measured directly vs $\Delta\eta(\mu^-, \mu^+)$:





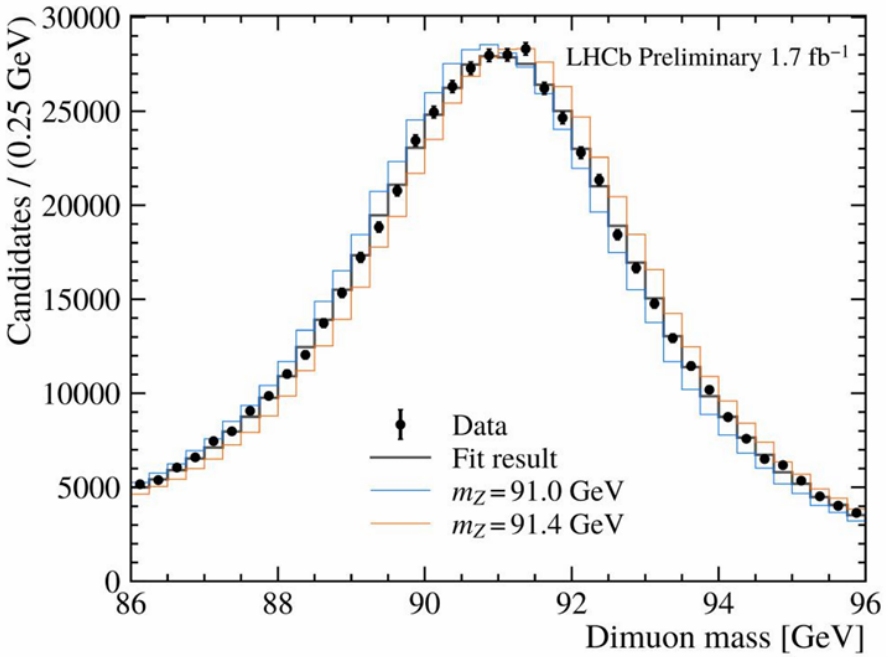
$$\Rightarrow \sin^2\theta^{\ell}_{\rm eff} = 0.23147 \pm 0.00044\,(\text{stat}) \pm 0.00023\,(\text{mostly PDF})$$

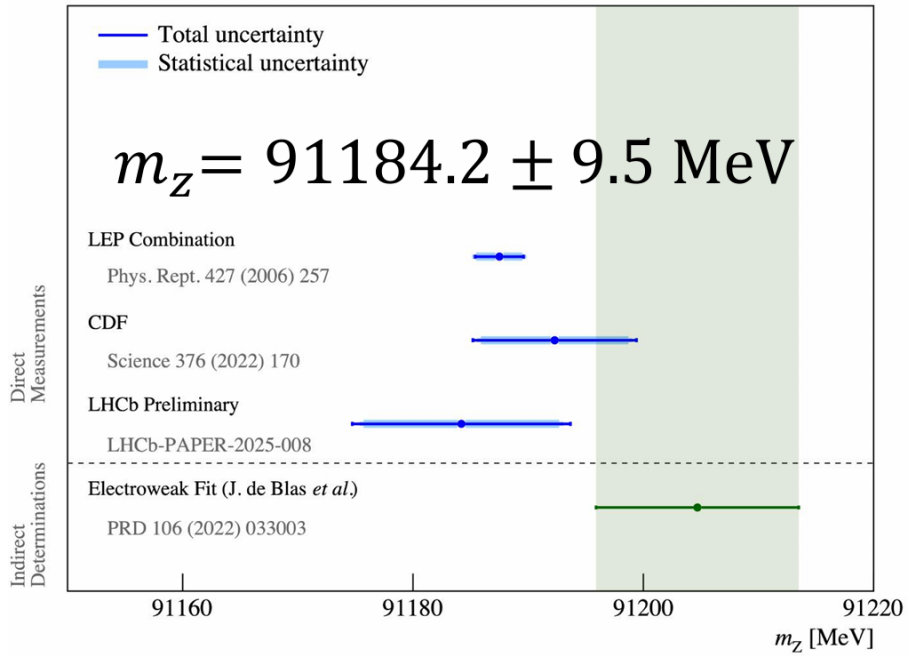
Prospects: $\mathcal{L}_{\rm inst} \times 5$ in Run 3 with new TDAQ [JINST 19 (2024) P05065], PDF uncertainty profiling [LHCb-PUB-2018-013], $Z \to e^+e^-$ (HL-LHC). . .

Z mass with LHCb [LHCB-PAPER-2025-008]

Exquisite p calibration needed $\leftrightarrow$ alignment, material (E_{loss}, scattering)...

For this measurement, calibration based on $\Upsilon(1S)$ completed by *pseudomass* method [JINST 19 P03010] for $Z \to \mu\mu$ events, preserving unbiasedness for m_Z





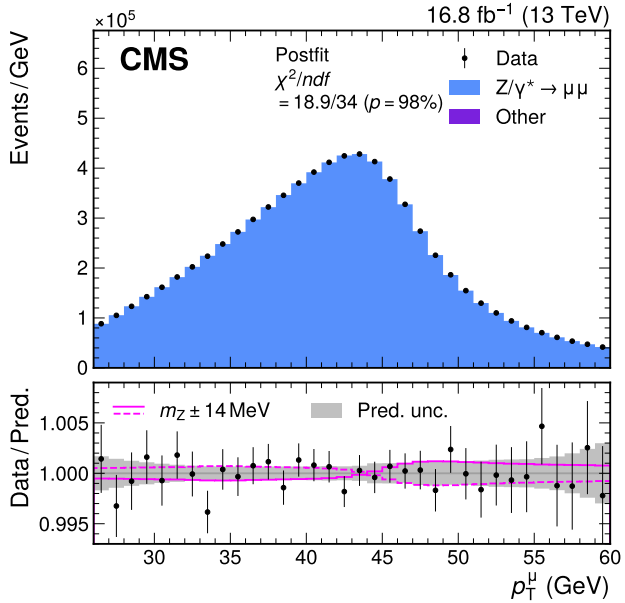
Uncertainties					
Δp	4.1 MeV	$\leftarrow$	material description	2.6 MeV
QED corrections	0.8 MeV		calibration samples	2.0 MeV
PDF	0.7 MeV		smearing fit	1.8 MeV
Reco	0.1 MeV		$\Upsilon(1S)$ mass	1.5 MeV
Stats	8.5 MeV		curvature biases	0.7 MeV
			QED corrections	0.6 MeV

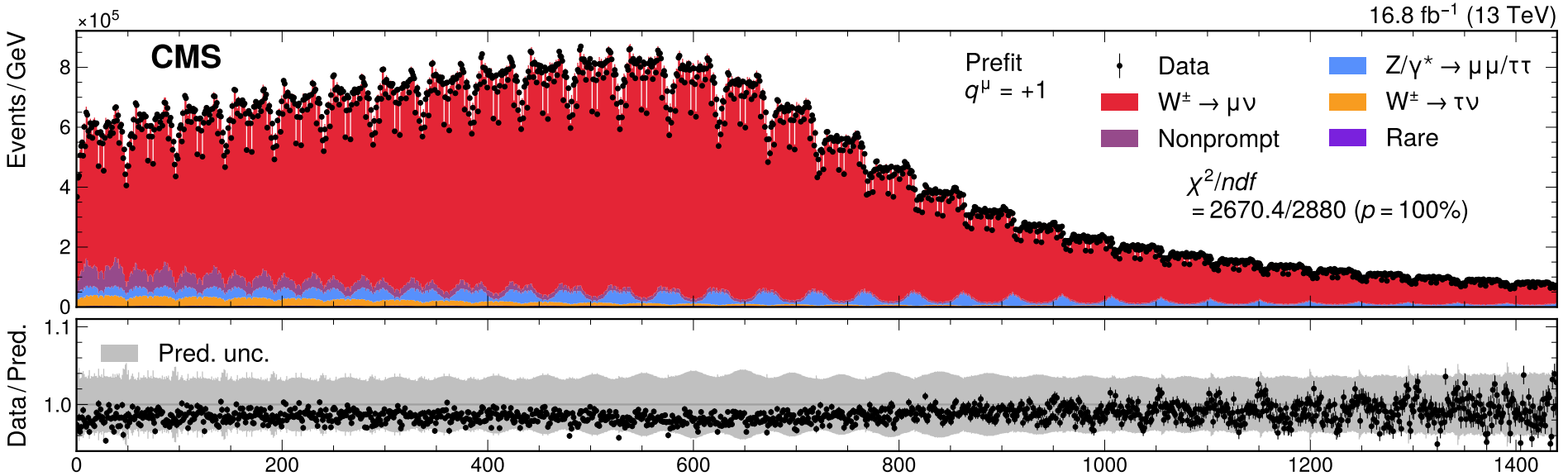
W mass with CMS 2016 data

[arXiv:2412.13872]

- High pileup data → focus on muons and p_{T}^{μ}
- Modelling at NNLO + N3LL accuracy including non-perturbative effects; TNP approach to correlate uncertainties in the resummed predictions
- $Z \to \mu\mu$ data reserved for independent validation
  - e.g. $\Delta m_Z(\mathrm{PDG}, m_{\mu\mu}) = 2.2$ MeV!
- Theoretical modelling (p_{T}^{V}, PDFs) is instead constrained in situ with big $(p_{\mathrm{T}}, \eta, q)$ PRL fit:

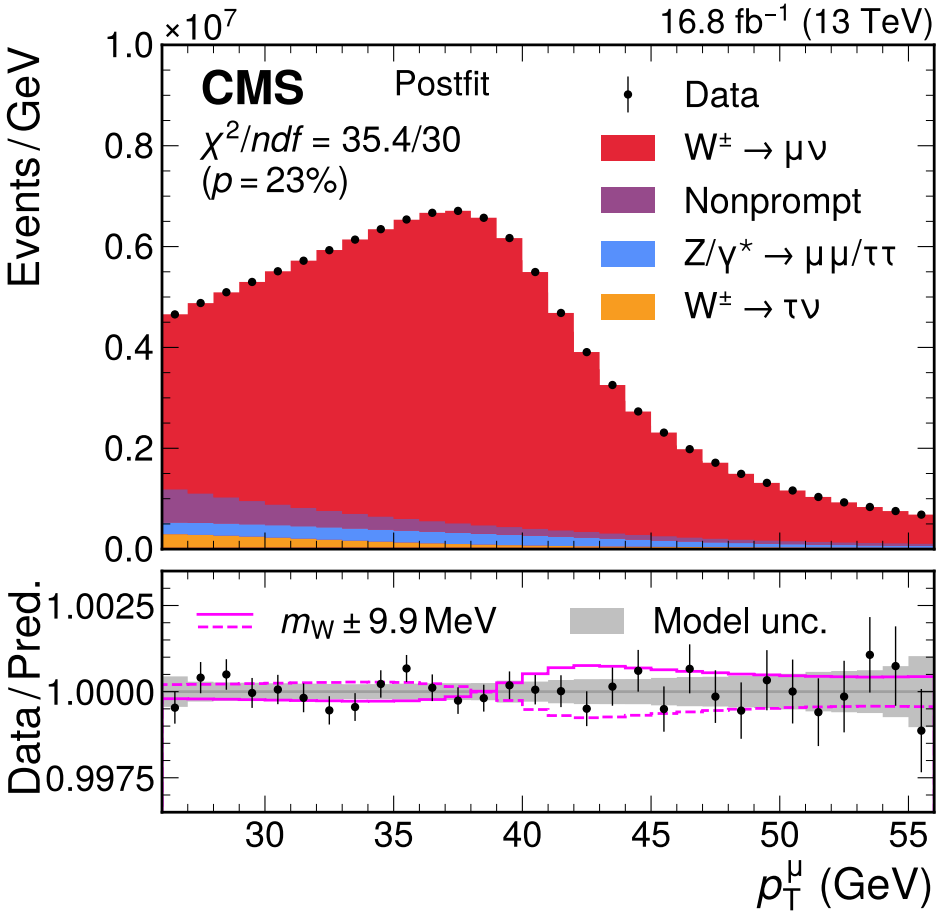
Extraction of m_Z from p_{T}^{μ}:



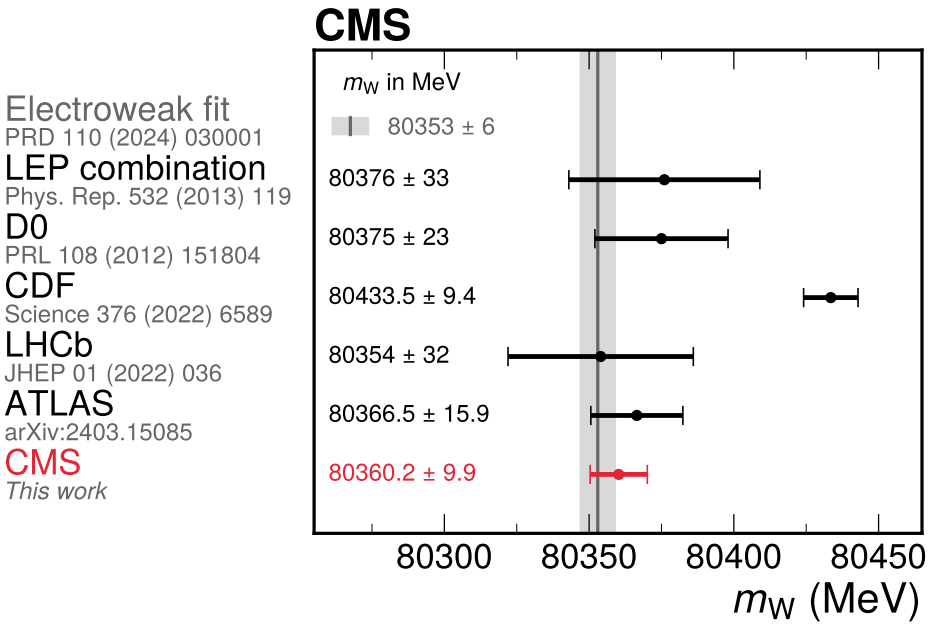


W mass

[arXiv:2412.13872]



Source of uncertainty	Impact (MeV) Nominal in m_Z	Nominal in m_W	Global in m_Z	Global in m_W
Muon momentum scale	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt-muon background	—	3.2	—	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9

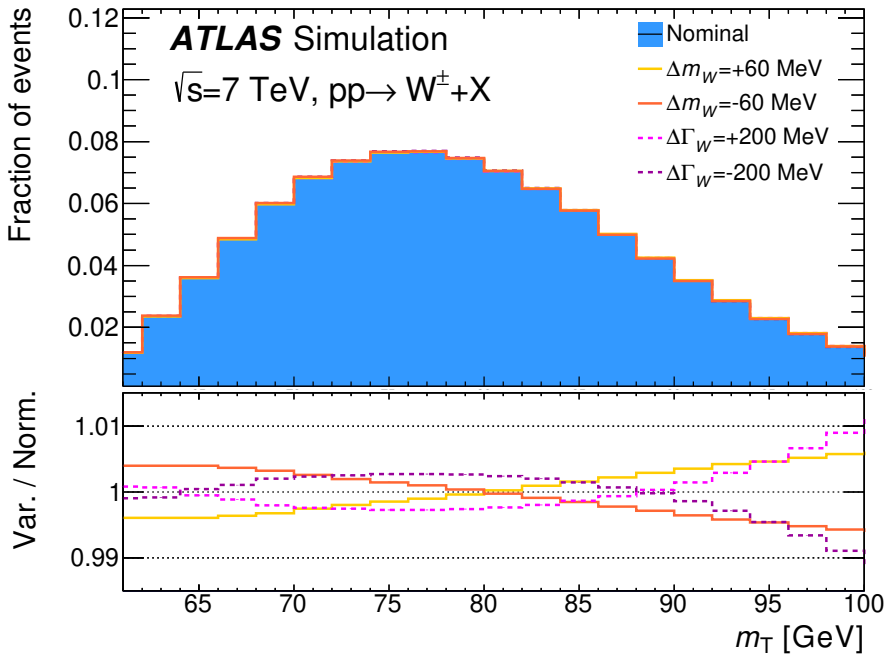


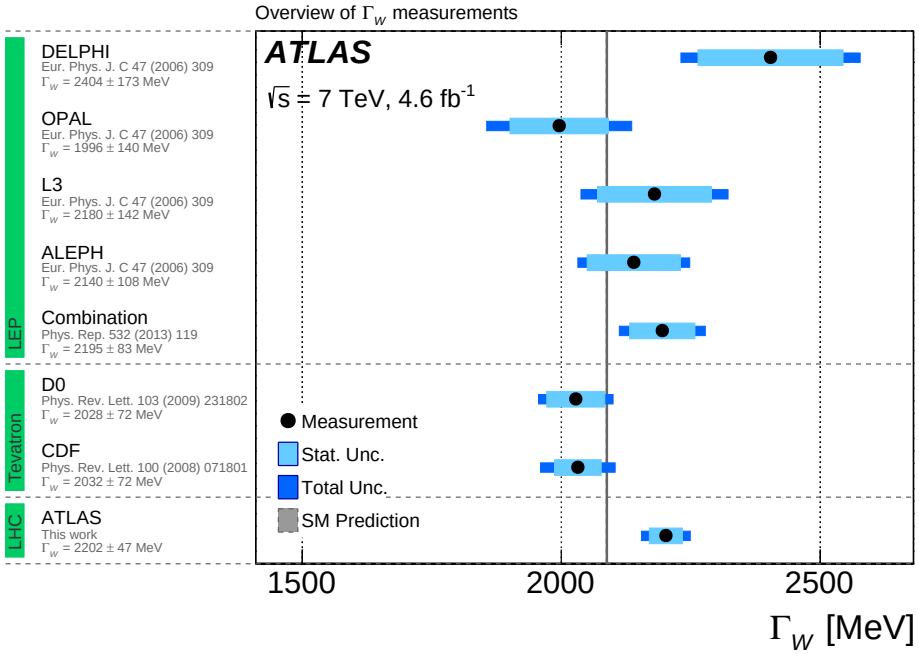
Alternative "helicity fit" also demonstrated: more freedom left to helicity amplitudes via NPs binned in (p_T^W, y^W); reduction of theory uncertainties, but loss of stat. power

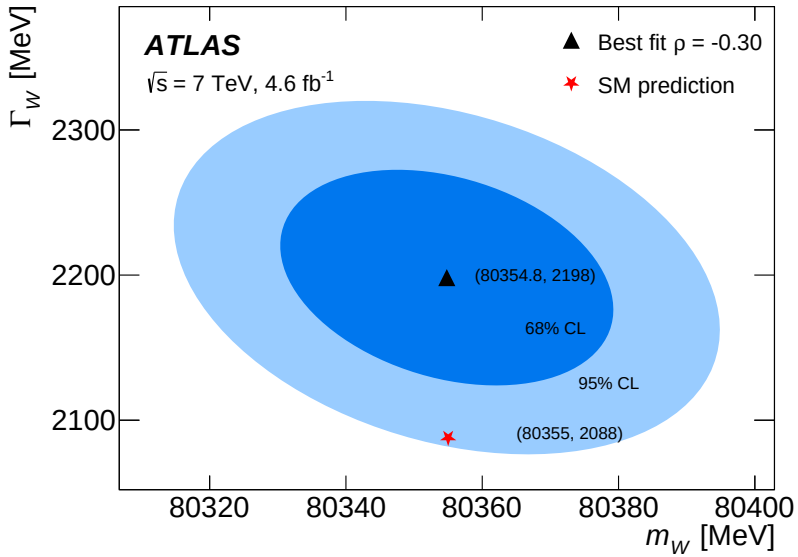
W width

[EPJC 84 (2024) 1309]

The strategy followed for the ATLAS m_W measurement, in particular the usage of the m_T distribution, allows to also either determine Γ_W for fixed m_W, or (m_W, Γ_W) simultaneously:







Conclusion

- Rich program of measurements at LHC testing the SM EW sector
- Many measurements (rare processes, tails...) are still limited by statistics
  - nice prospects for full Run 3 data set, and HL-LHC!
- For others, progress often goes hand in hand with theory
  - availability of higher-order corrections, PDFs, uncertainty schemes...
- EFT interpretations are widely used
  - several unitarisation / clipping approaches $\Rightarrow$ complicates comparisons
  - LHC EFT working group (`https://lpcc.web.cern.ch/lhc-eft-wg`)
- Machine learning techniques (in particular DNNs) have become widespread and often crucial to reach the best performances out of the available data
  - a natural consequence to their successful introduction for lower-level tasks, such as track classification, flavour tagging...
- Detector upgrades for HL-LHC may also contribute to substantial improvements
  - e.g. high-energy electrons in LHCb for $\sin^2\theta^{\ell}_{\text{eff}}$

Extra resources

Recent CERN seminars

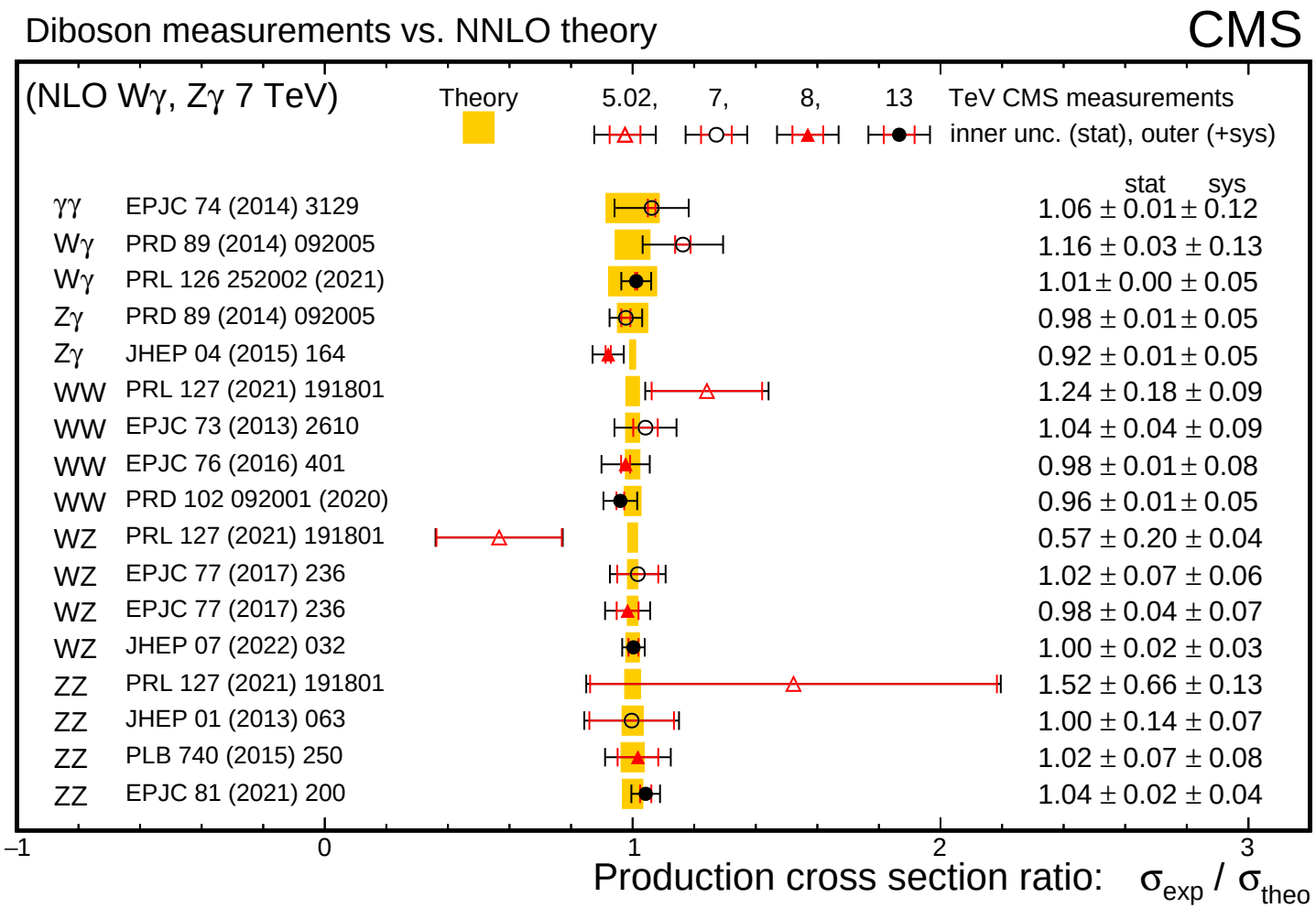
- ATLAS VBS (2025): `https://indico.cern.ch/event/1540006`
- LHCb m_Z (2025): `https://indico.cern.ch/event/1525997`
- CMS m_W (2024): `https://indico.cern.ch/event/1441575`
- LHCb $\sin^2\theta^{\ell}_{\text{eff}}$ (2024): `https://indico.cern.ch/event/1403080`
- CMS $g_\tau - 2$ (2024): `https://indico.cern.ch/event/1355799`

Reviews

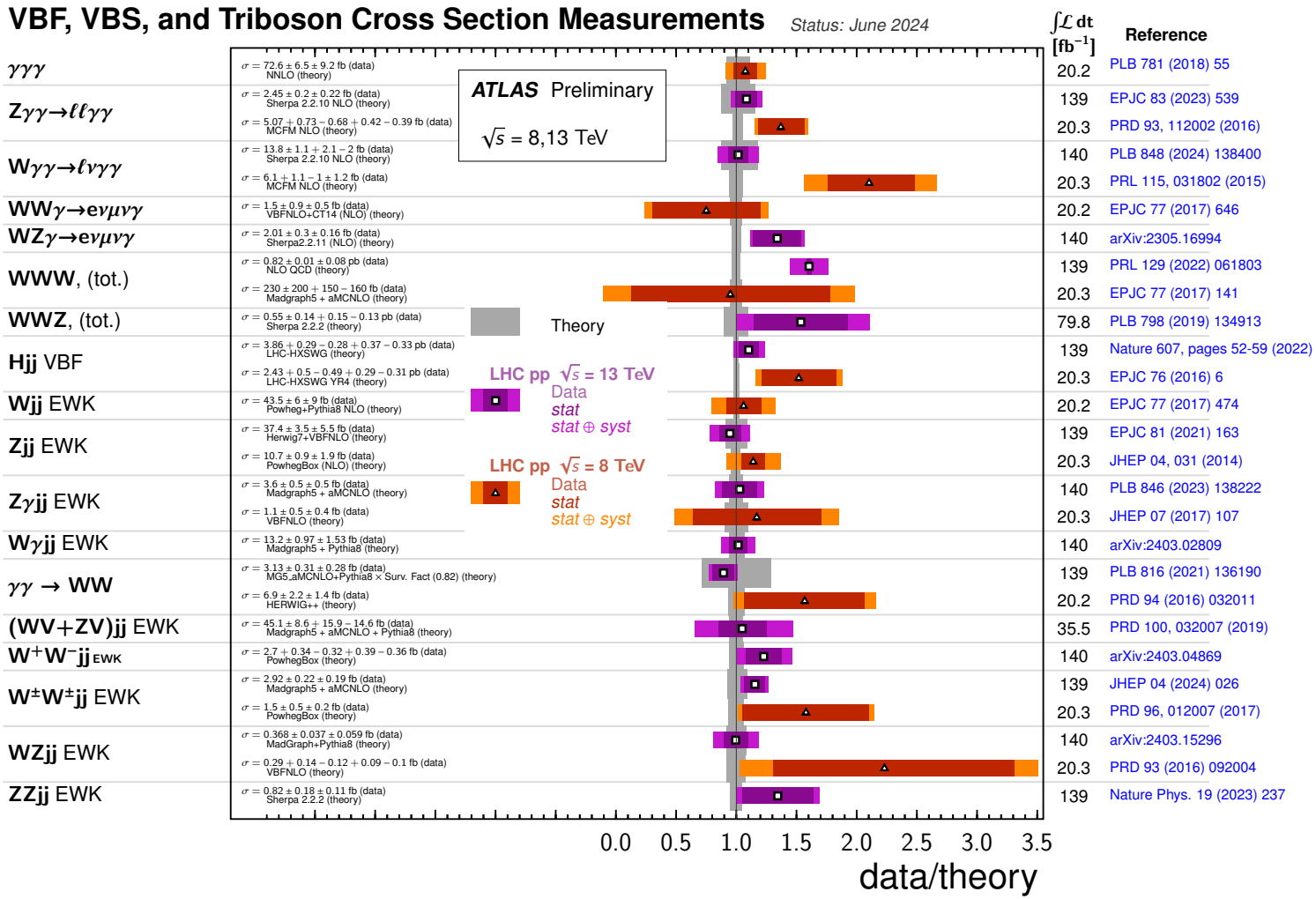
- "Stairway to discovery: a report on the CMS programme of cross section measurements from millibarns to femtobarns", Phys. Rep. 1115 (2025) 3, arXiv:2405.18661
- "Electroweak, QCD and flavour physics studies with ATLAS data from Run 2 of the LHC", Phys. Rep. 1116 (2025) 57, arXiv:2404.06829

Backup

CMS inclusive diboson measurements [arXiv:2405.18661]



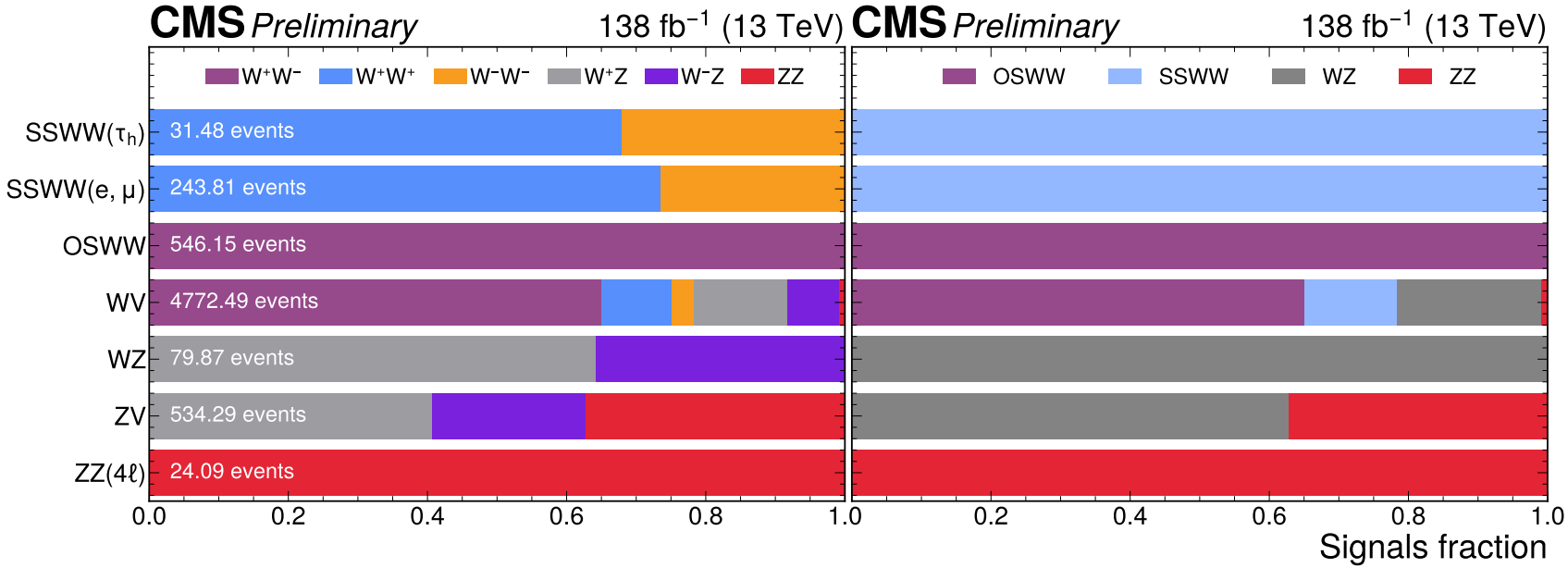
ATLAS VBS + triboson measurements [ATL-PHYS-PUB-2024-011]



CMS-SMP-24-005

Region	Fiducial	Total
Lepton definition	Dressed (e, μ)	Dressed (e, μ, τ)
$N_\ell = 3$	✓	✓
$p_T\{\ell^1_Z, \ell^2_Z, \ell_W\} > \{25, 15, 25\}$ GeV	✓	—
$\lvert\eta\rvert\{\ell^1_Z, \ell^2_Z, \ell_W\} < \{2.5, 2.5, 2.5\}$	✓	—
$N_{OSSF} = 1$	✓	✓
$\lvert m(\ell^1_Z, \ell^2_Z) - m_Z\rvert < 30$ GeV	✓	✓
$\min(m(\ell, \ell')) > 4$ GeV	✓	✓
$m(\ell^1_Z, \ell^2_Z, \ell_W) > 100$ GeV	✓	—

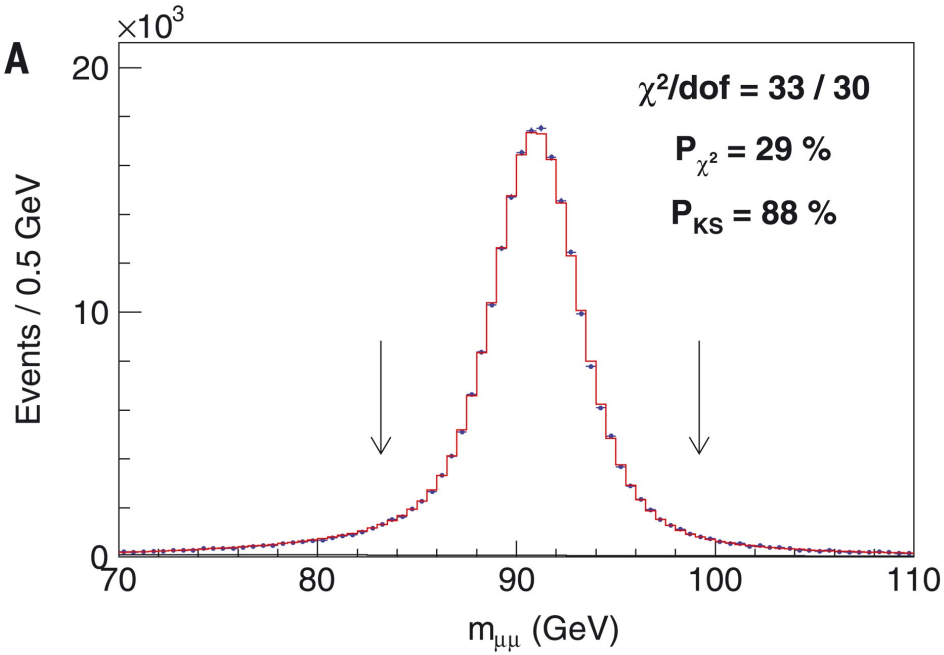
CMS-PAS-SMP-24-013



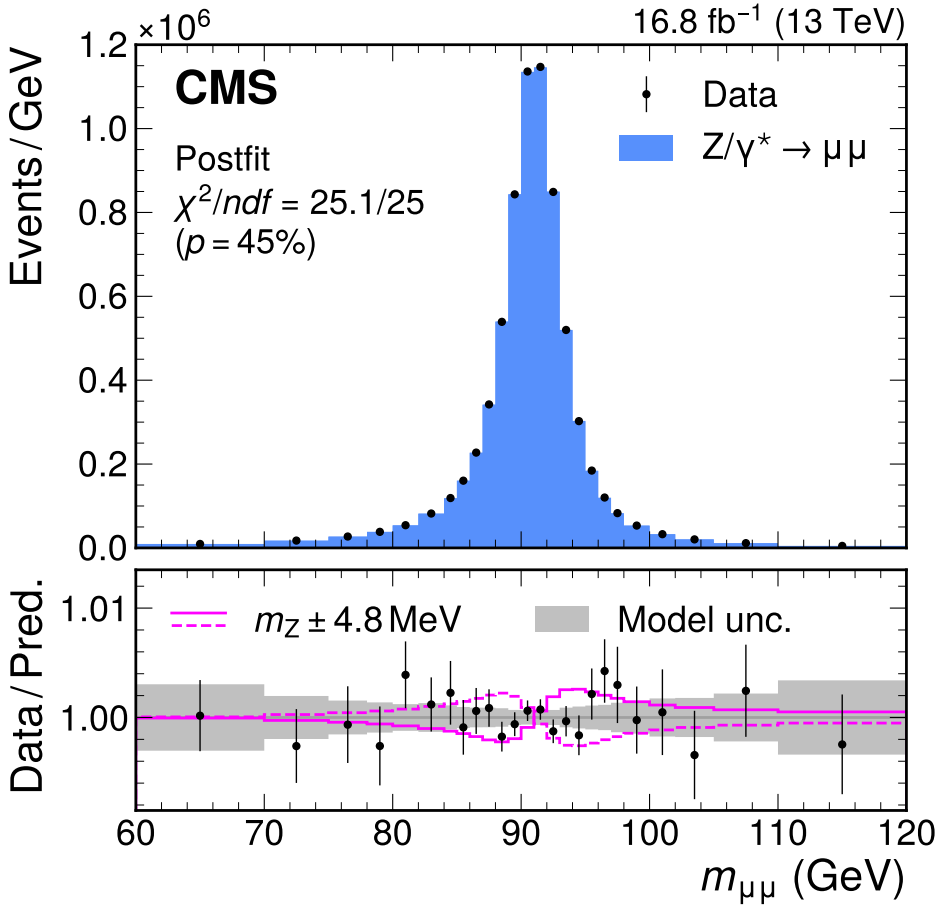
Z mass

[Science 376 (2022) 6589; arXiv:2412.13872]

From beam energy scans (e^+e^- colliders) or reconstructed leptons (hadron colliders)



CDF (2022): $m = 91192 \pm 7$ MeV ($\mu^+\mu^-$), $m = 91194 \pm 16$ MeV (e^+e^-), both limited by stats.

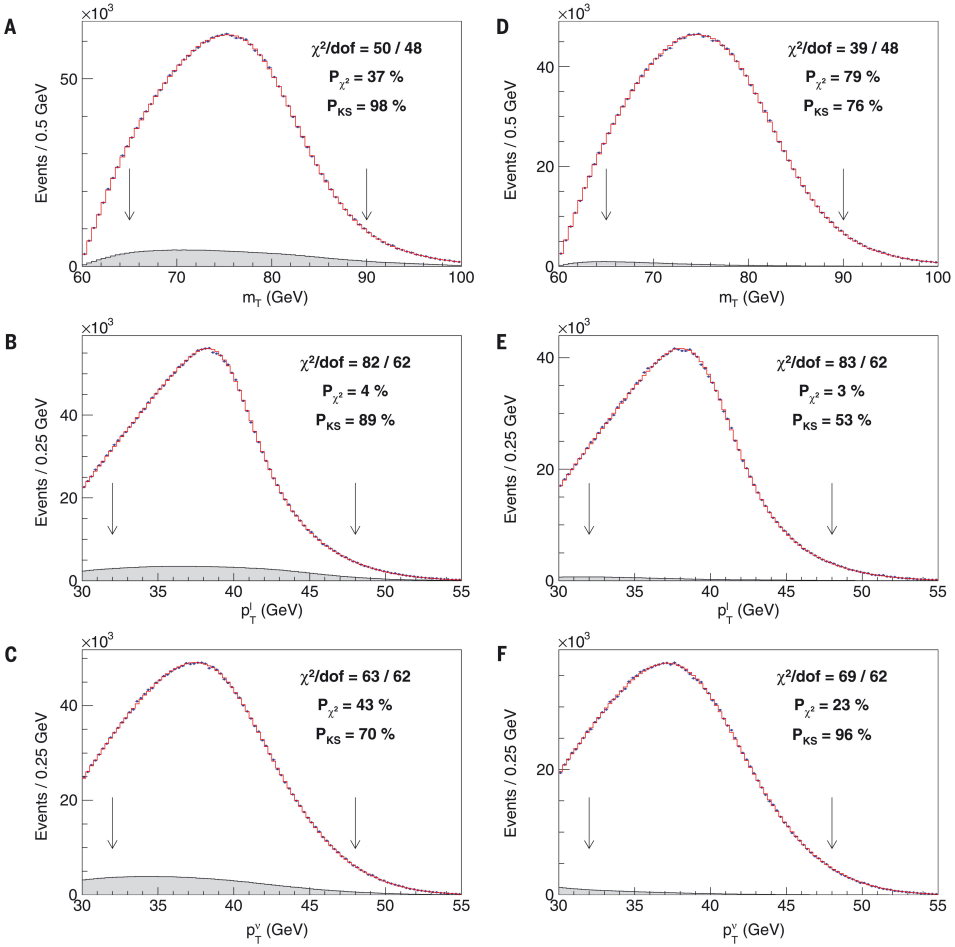


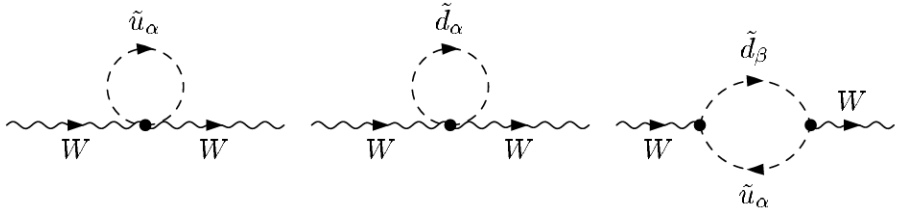
$m_Z^{\mu\mu} - m_Z^{\text{PDG}} = -2.2 \pm 4.8$ MeV, central value unbiased but not the uncertainties

W mass

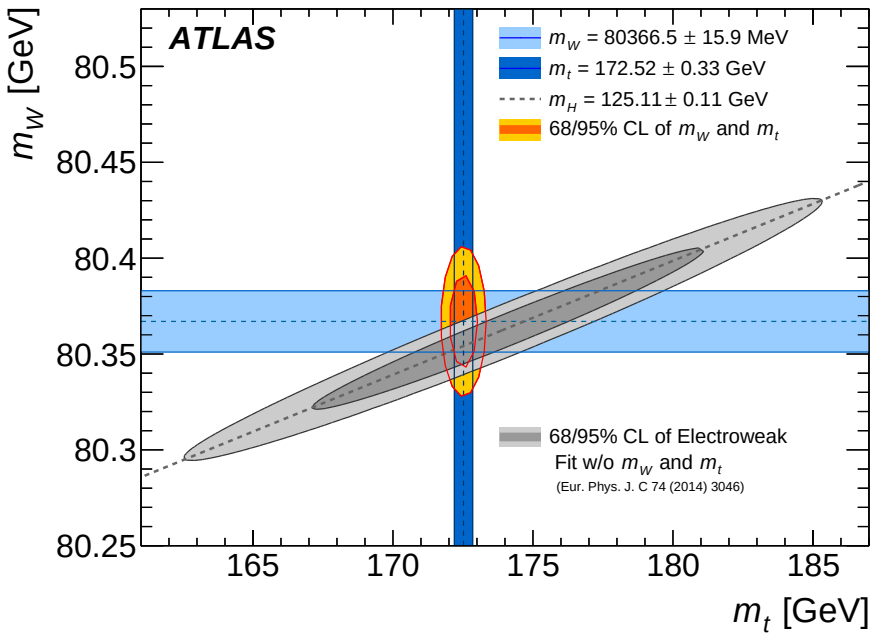
[Science 376(2022)6589; EPJC 84(2024)1309]

Distributions sensitive to m_W used in the 2021 CDF measurement:





2024 ATLAS measurement with 7 TeV data:



W mass uncertainties in recent measurements

CDF [Science 376 (2022) 6589]

Lepton scale	3.0 MeV
Lepton resolution	1.2 MeV
Recoil scale	1.2 MeV
Recoil resolution	1.8 MeV
Lepton efficiency	0.4 MeV
Lepton removal	1.2 MeV
Backgrounds	3.3 MeV
p_{T}^{Z} model	1.8 MeV
$p_{\mathrm{T}}^{W}/p_{\mathrm{T}}^{Z}$ model	1.3 MeV
PDF	3.9 MeV
QED radiation	2.7 MeV
Statistics	6.4 MeV
Total	**9.4 MeV**

CMS [arXiv:2412.13872]

Muon scale	4.8 MeV
Muon efficiency	3.0 MeV
Angular coeffs	3.3 MeV
Higher-order EW	2.0 MeV
p_{T}^{W} modeling	2.0 MeV
PDF	4.4 MeV
Background	1.7 MeV
Luminosity	0.1 MeV
MS stats	1.5 MeV
Statistics	2.4 MeV
Total	**9.9 MeV**

ATLAS [EPJC 84 (2024) 1309]

Electrons	6.0 MeV
Muons	5.4 MeV
Recoil	2.3 MeV
Angular coeffs	3.7 MeV
Higher-order EW	5.4 MeV
PDF	5.7 MeV
Background	2.0 MeV
Luminosity	1.3 MeV
Γ_W	0.1 MeV
Statistics	9.8 MeV
Total	**15.9 MeV**

LHCb [JHEP 01 (2022) 036]

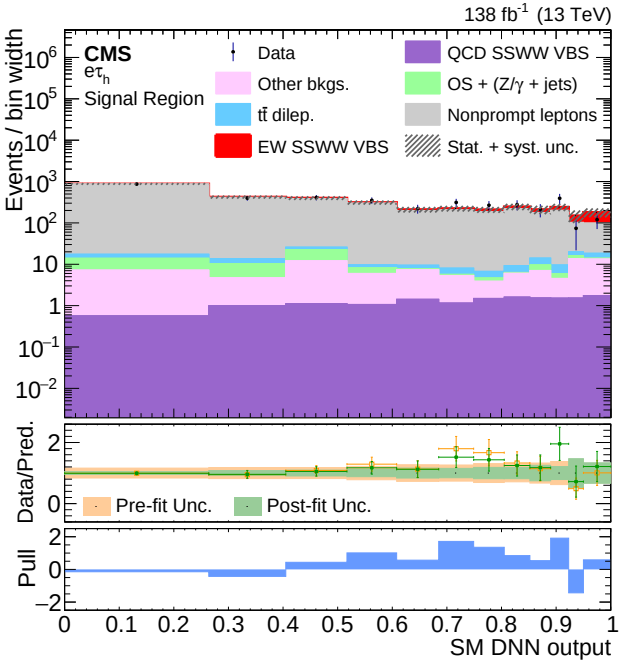
Momentum scale + reso	7 MeV
Muon efficiency	6 MeV
Muon isolation	4 MeV
Angular coeffs	10 MeV
QED FSR	7 MeV
EW corrections	5 MeV
p_{T}^{W} modeling	11 MeV
PDF	9 MeV
Background	2 MeV
Statistics	23 MeV
Total	**32 MeV**

$W^{\pm}W^{\pm}$ with taus

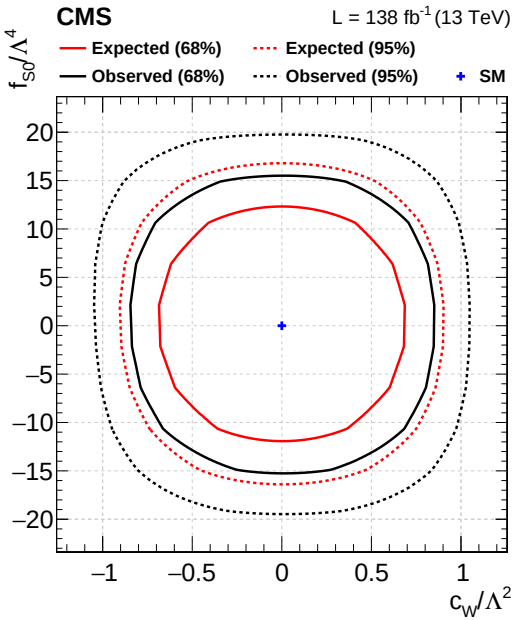
[arXiv:2410.04210]

Stronger BSM coupling to 3rd fermion generation? $\Rightarrow$ study VBS in τ final states

DNNs to isolate signal: 3 separate trainings for SM, a mixture of dim-6 SMEFT operators (contact interactions, aTGC), and a mixture of dim-8 operators (aQGC)



	Wilson coefficient	68% CL interval(s) Observed	Expected
dim-6	$c_{ll}^{(1)}/\Lambda^2$	$[-11.6, 0.045]$	$[-12.9, -8.03] \cup [-2.95, 1.91]$
	$c_{qq}^{(1)}/\Lambda^2$	$[-0.341, 0.416]$	$[-0.501, 0.576]$
	c_W/Λ^2	$[-0.513, 0.481]$	$[-0.681, 0.669]$
	c_{HW}/Λ^2	$[-5.48, 4.31]$	$[-7.00, 6.09]$
	c_{HWB}/Λ^2	$[-30.7, 89.2]$	$[-41.7, 69.6]$
	$c_{H\Box}/\Lambda^2$	$[-12.0, 14.0]$	$[-16.6, 18.1]$
	c_{HD}/Λ^2	$[-15.3, 31.5]$	$[-24.6, 34.7]$
	$c_{Hl}^{(1)}/\Lambda^2$	$[-38.2, 39.5]$	$[-28.8, 29.9]$
	$c_{Hl}^{(3)}/\Lambda^2$	$[-0.045, 8.58]$	$[-1.43, 2.23] \cup [5.88, 9.54]$
	$c_{Hq}^{(1)}/\Lambda^2$	$[-3.27, 3.44]$	$[-4.53, 4.42]$
	$c_{Hq}^{(3)}/\Lambda^2$	$[-1.88, 0.705]$	$[-2.39, 1.37]$
dim-8	f_{T0}/Λ^4	$[-0.774, 0.842]$	$[-1.02, 1.08]$
	f_{T1}/Λ^4	$[-0.319, 0.381]$	$[-0.426, 0.480]$
	f_{T2}/Λ^4	$[-0.851, 1.12]$	$[-1.15, 1.37]$
	f_{M0}/Λ^4	$[-8.07, 7.70]$	$[-9.89, 9.74]$
	f_{M1}/Λ^4	$[-9.54, 11.15]$	$[-12.5, 13.3]$
	f_{M7}/Λ^4	$[-17.6, 15.3]$	$[-20.3, 19.2]$
	f_{S0}/Λ^4	$[-9.60, 9.82]$	$[-11.6, 12.0]$
	f_{S1}/Λ^4	$[-40.9, 41.3]$	$[-37.4, 38.8]$
	f_{S2}/Λ^4	$[-40.9, 41.3]$	$[-37.4, 38.8]$



Constraints on individual operators, or pairs (including mixed dims 6 and 8)