Electroweak measurements (CMS)

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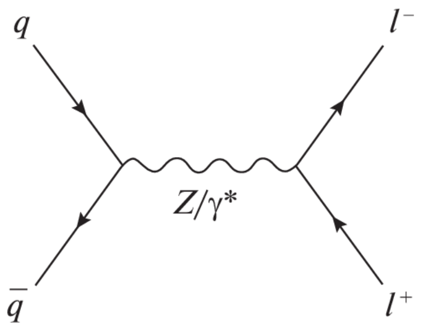
On behalf of the CMS Collaboration

International Conference on New Frontiers in Physics 2024, Kolymbari | 28 Aug 24

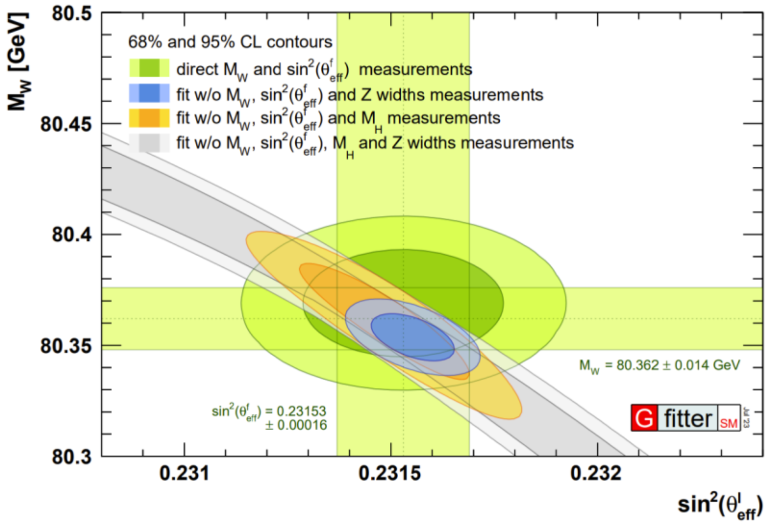
SCUOLA NORMALE SUPERIORE INFN erc CMS

Introduction



Why study Electroweak Physics at hadron colliders?

- **Large W, Z, γ production** in pp collisions
- Very **clean experimental signature** with e, μ ID eff. uncertainty <1% and momentum scale uncert. ~ 0.1%



DOI: 10.22323/1.449.0304

What can we study?

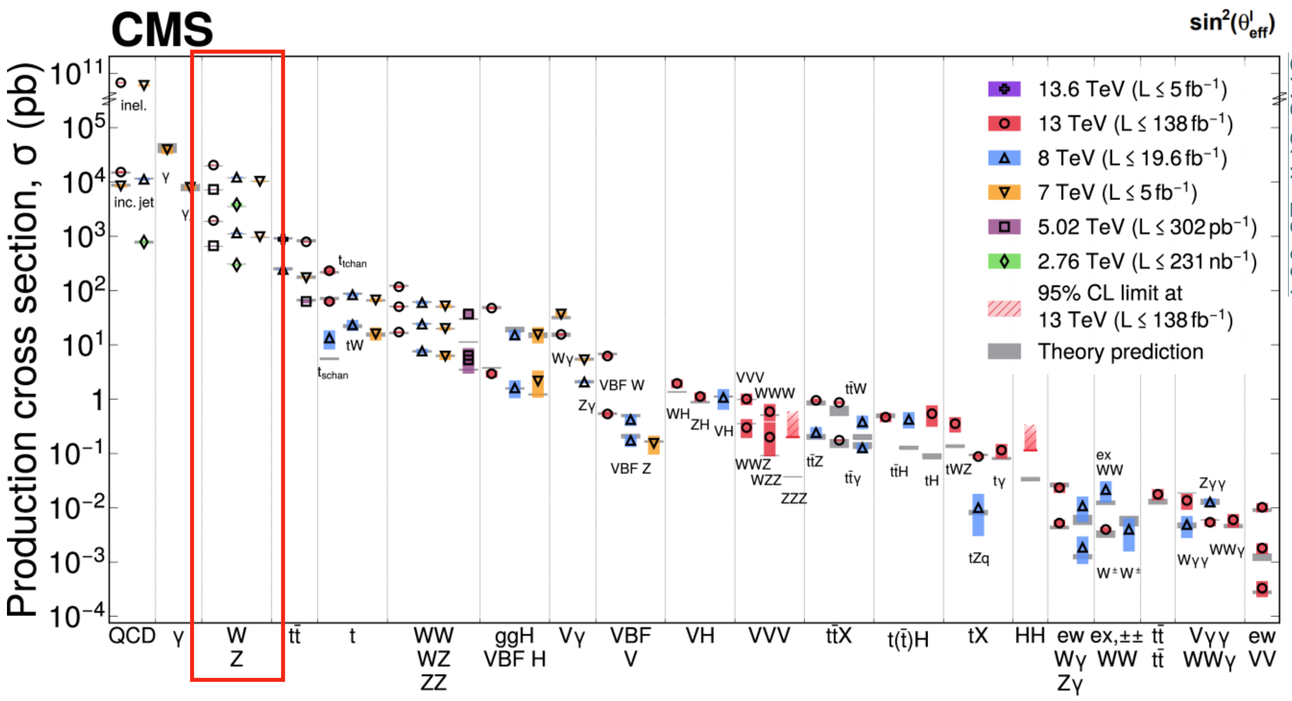
- **Precision Frontier**

Precise theoretical predictions of EW parameters: α_{QED}, G_F, m_Z and m_H → **NP from deviations** in precision measurements

- **Energy frontier**

At high energy, deviations from gauge cancellations could lead to possibly large effects → test in **multi-bosons production**: anomalous couplings, EFT, Higgs properties, ALP etc.

- Test QCD predictions + **probe PDFs**
- **Background** for other **searches**: Higgs, BSM

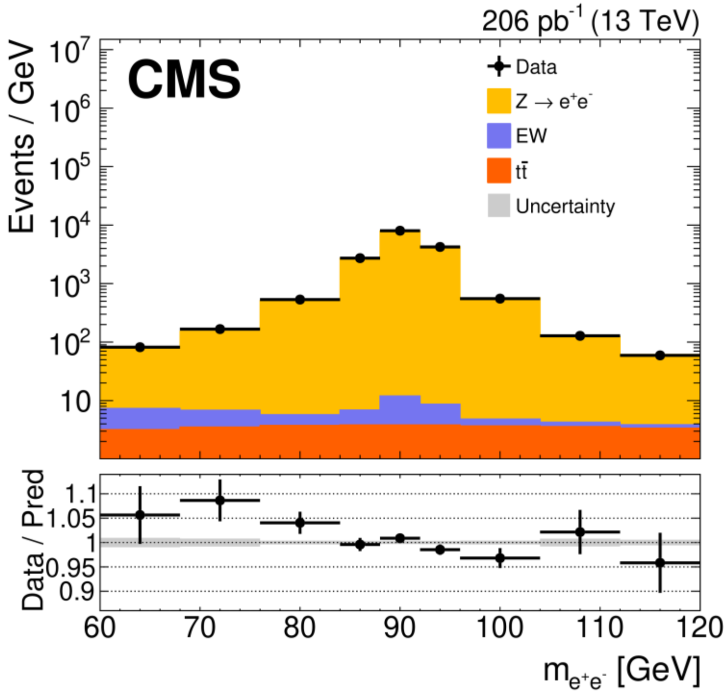


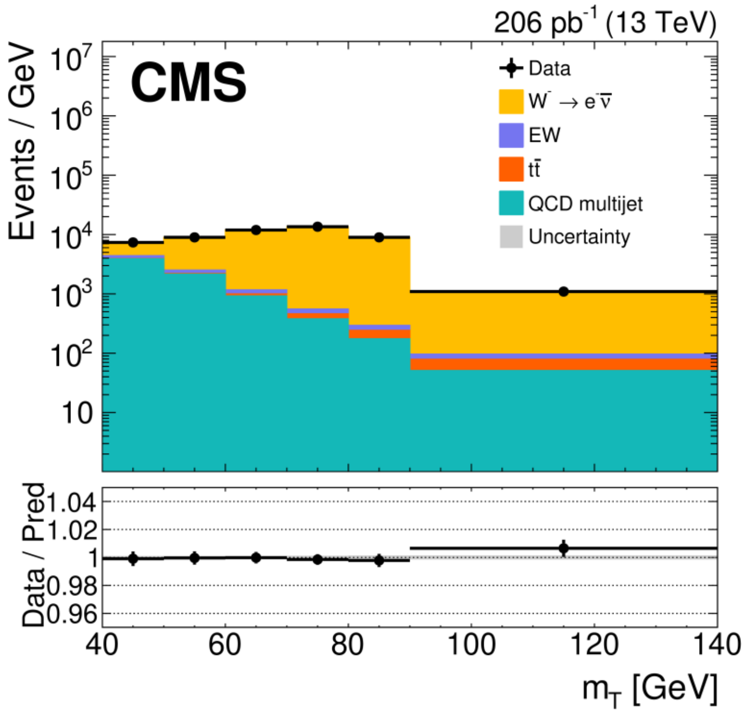
CMS-SMP-23-004

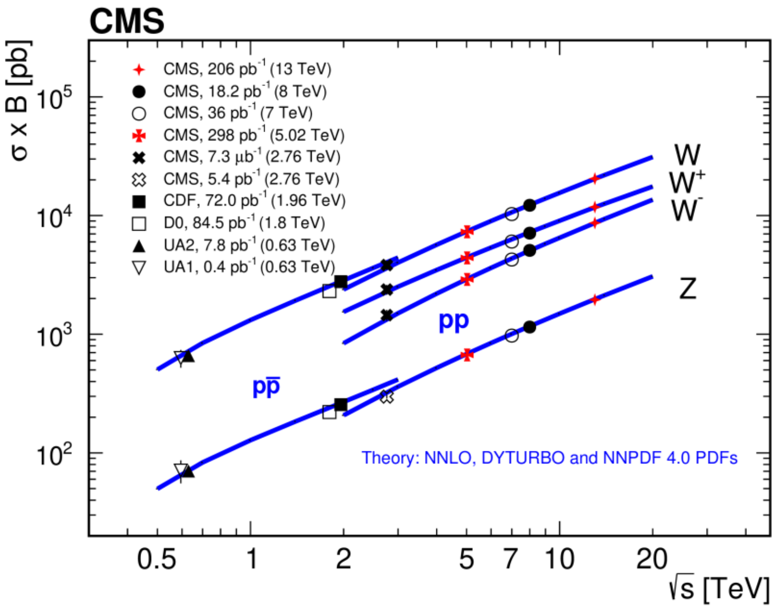
W and Z cross-sections at 5.02 TeV and 13 TeV

SMP-20-004

- **Electron** and **muon** decay modes considered
- Used dedicated **low luminosity runs**
- Cross-section and cross-section ratios from fitting **m_{ll} and m_T distributions** from Z and W

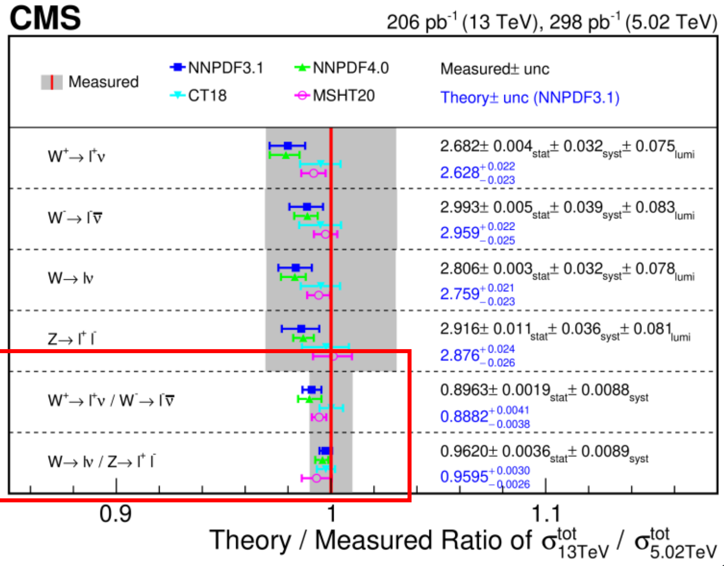






- Good **agreement with NNLO predictions**
- **Errors** dominated by systematics, particularly from **luminosity** at 1.9% (2.3%) for 5.02 TeV (13 TeV)

Luminosity & other systematics cancel in the ratio → improved consistency with theory

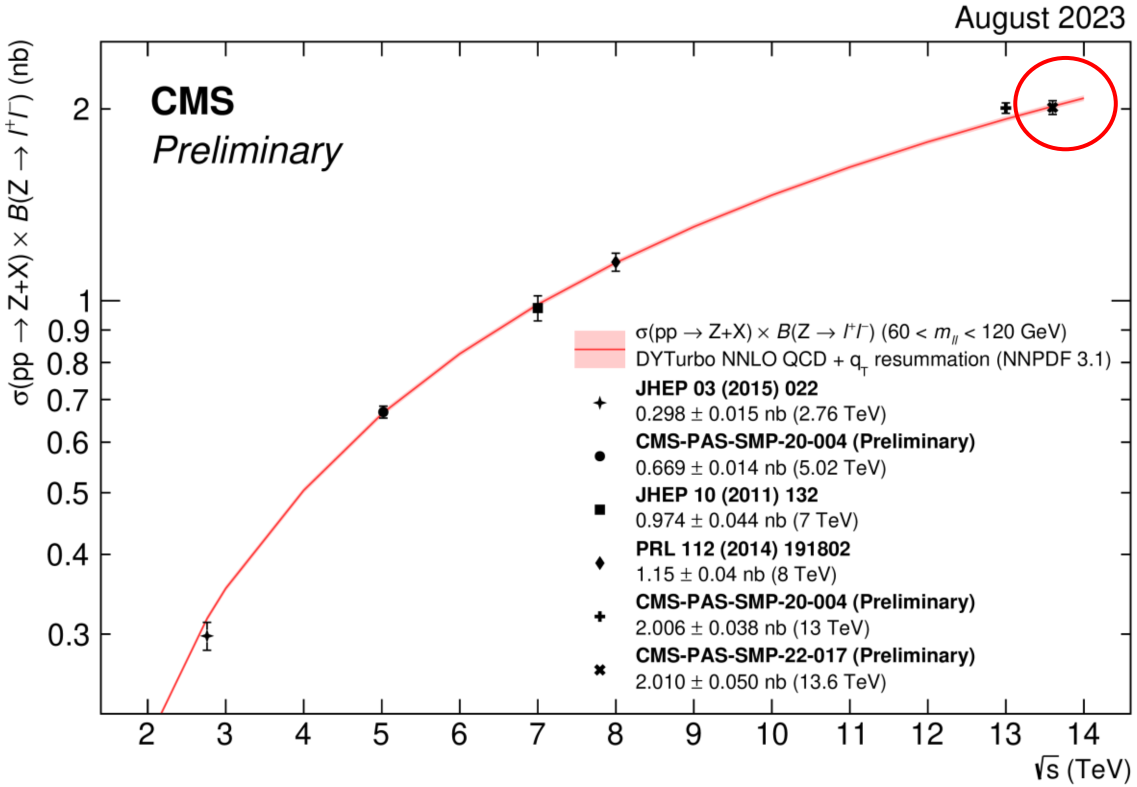


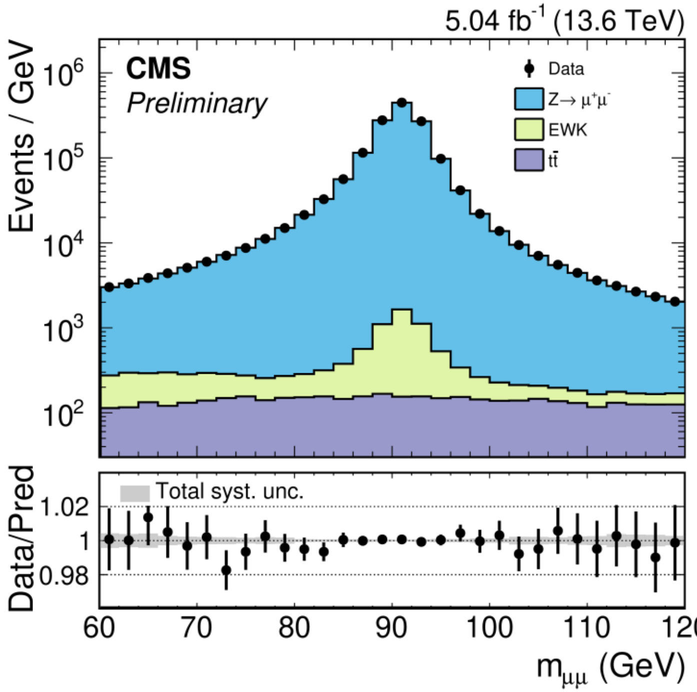
Z cross-section at 13.6 TeV

SMP-22-017

- **Muon** decay modes considered
- In **agreement with theory** calculations
- Statistical uncertainty is negligible

Source	Uncertainty (%)
Muon efficiencies	0.83
PDF, QCD scale and parton shower	0.53
Finite size of MC samples (bin-by-bin)	0.35
$t\bar{t}$ background	0.16
EWK background	0.12
Pileup	0.08
Muon momentum correction	0.08
Combined syst. uncertainty	0.92
Luminosity	2.3
Stat. uncertainty	0.06



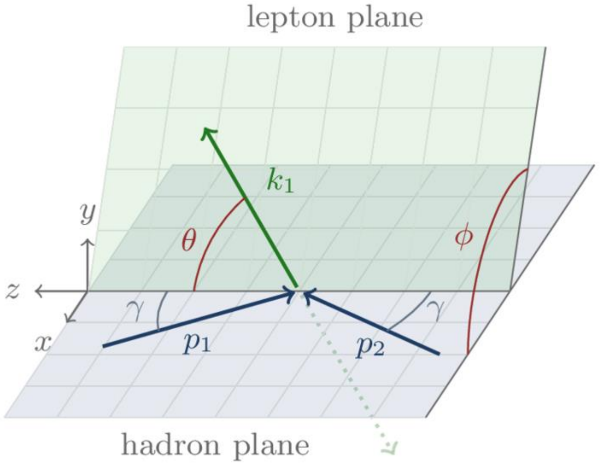


Drell-Yan forward-backward asymmetry and $\sin^2\theta^{\ell}_{\mathrm{eff}}$ at 13 TeV

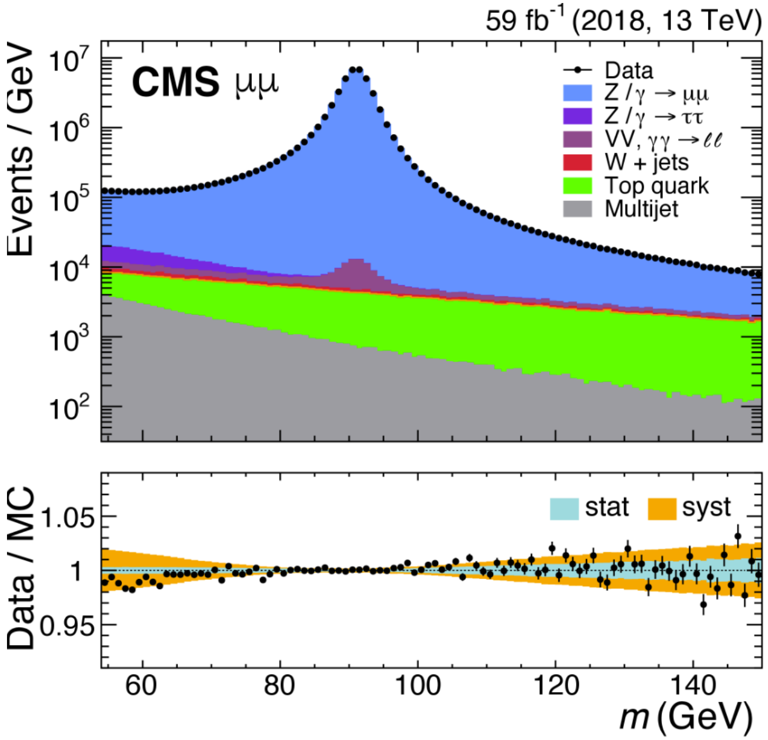
SMP-22-010

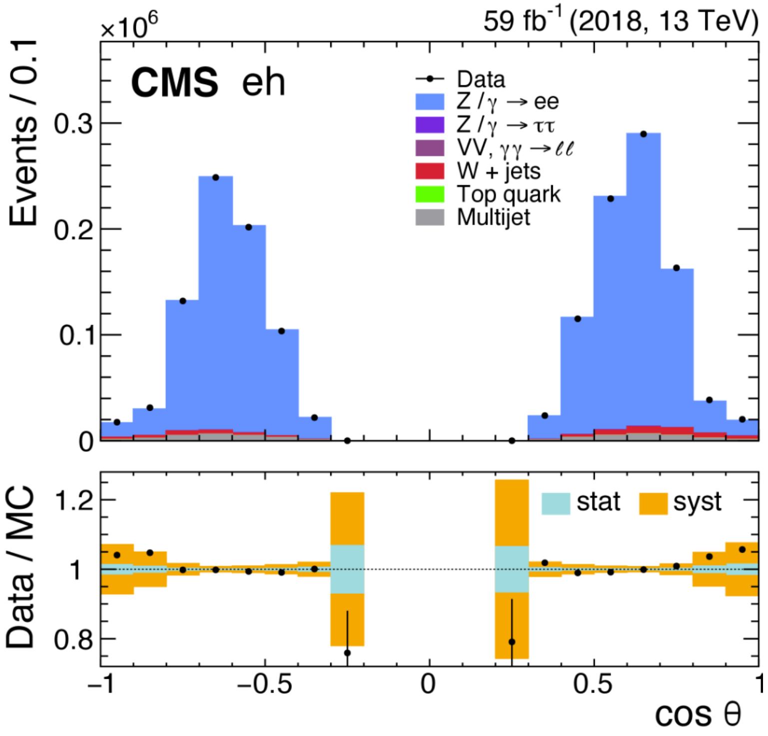
- **Precisely known** in SM $\sin^2\theta^{\ell}_{\mathrm{eff}} = k_f\left(1 - \frac{m_W^2}{m_Z^2}\right)$
- Access from final state **leptons angular distribution** in the Collins-Soper frame

$$\frac{d\sigma}{d(\cos\theta_{CS})} \propto 1 + \cos^2\theta_{CS} + A_4\cos\theta_{CS}$$ where $A_{\mathrm{FB}} = \frac{3}{8}A_4$ depends on $\sin^2\theta^{\ell}_{\mathrm{eff}}$



$$A_{FB} = \frac{N(\cos\theta_{CS} > 0) - N(\cos\theta_{CS} < 0)}{N(\cos\theta_{CS} > 0) + N(\cos\theta_{CS} < 0)}$$



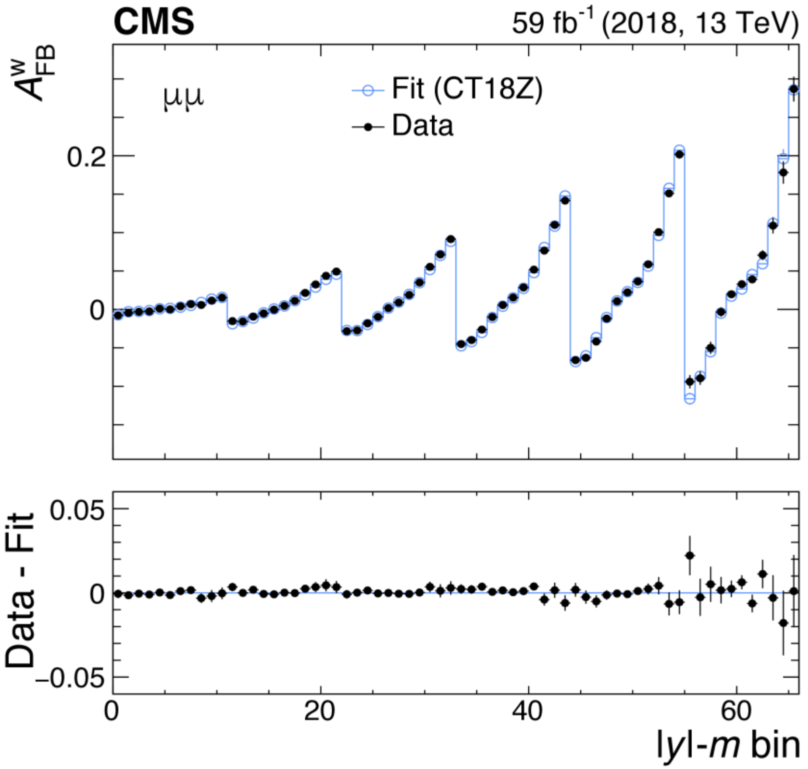


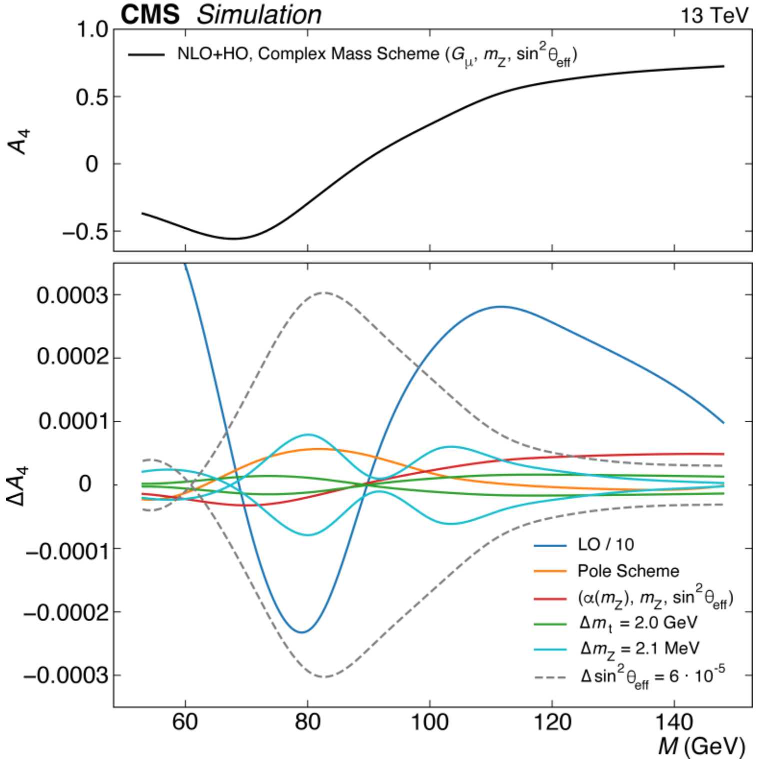
- Full Run 2 dataset
- Electrons divided according to |η| into:
  - central (e) → silicon tracker
  - forward ECAL (g)
  - forward HCAL (h)
- **Good data/MC agreement** across the phase space

Drell-Yan forward-backward asymmetry and $\sin^2\theta^{\ell}_{eff}$ at 13 TeV

SMP-22-010

- Extract $\sin^2\theta^{\ell}_{eff}$ from **template fits of A_{FB}** depending on mass and rapidity (y)
- Measuring lepton angles → dependence on rapidity y_{ll} → valence quarks are important
  → **A_{FB} measurement is sensitive to the PDF**





- Using the latest POWHEG-Z_ew version for the nominal configuration

Variations when changing input options

- **Maximum sensitivity** of A_{FB} to $\sin^2\theta^{\ell}_{eff}$ **near the Z peak**

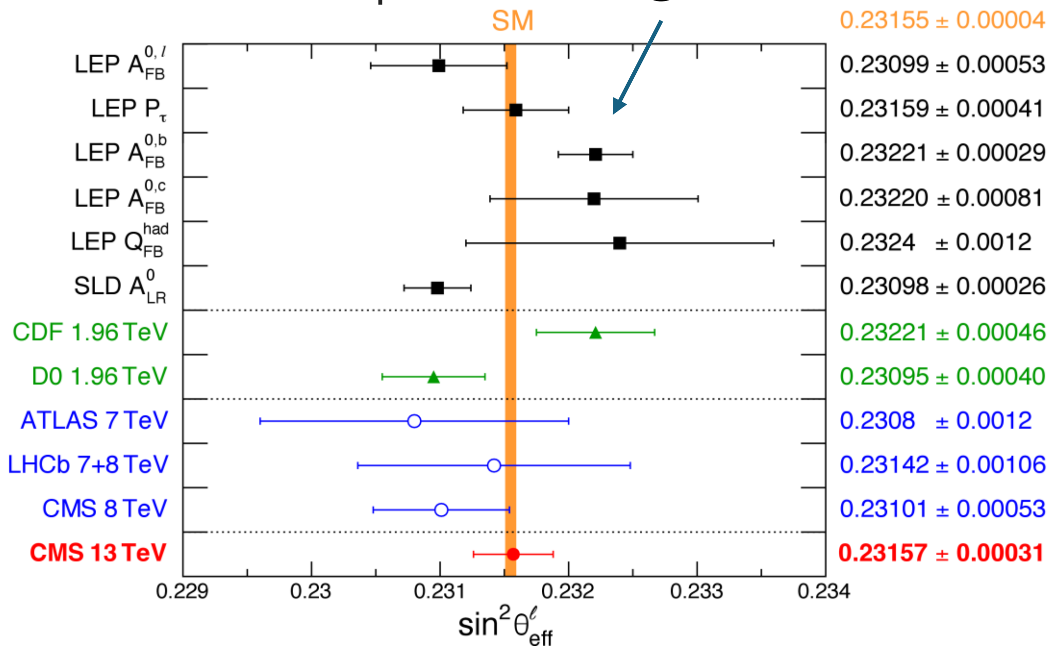
Drell-Yan forward-backward asymmetry and $\sin^2\theta^{\ell}_{\text{eff}}$ at 13 TeV

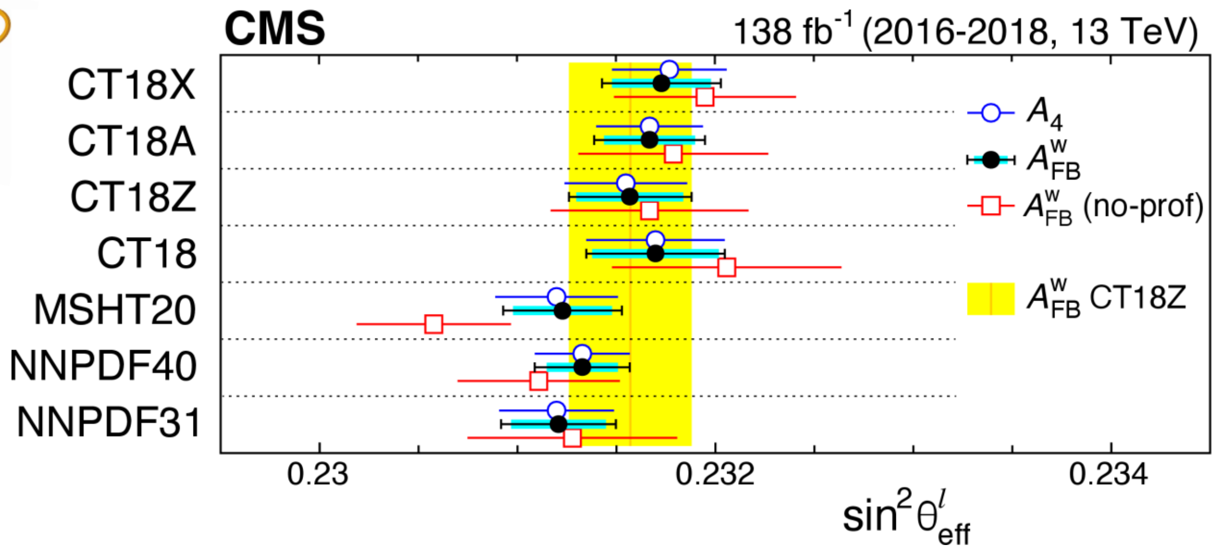
SMP-22-010

Best hadron collider measurement!

$\sin^2\theta^{\ell}_{\text{eff}}$ = 23157 ± 10 (stat.) ± 15 (syst.) ±9 (theo.) ± 27 (PDF) × 10^{-5}

Discrepancy between lepton and b-quark results @ LEP



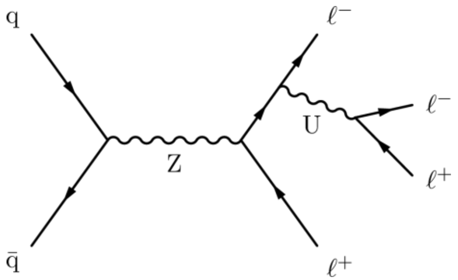


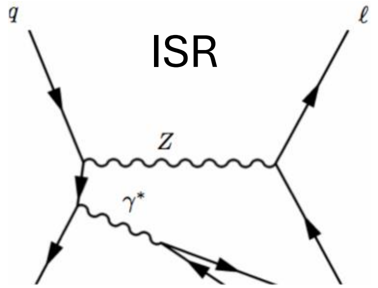
- **CT18Z** uncertainty covers best other central values → chosen as default

	χ^2_{min}	bins	$p(\%)$	$\sin^2\theta^{\ell}_{\text{eff}}$	stat	exp	th	PDF	MC	bg	eff	calib	other
$\mu\mu$	241	264	83	$23\,146 \pm 38$	17	17	7	30	13	3	2	5	4
ee	257	264	60	$23\,176 \pm 41$	22	18	7	30	14	4	5	3	7
eg	119	144	93	$23\,257 \pm 61$	30	40	5	44	23	11	12	19	9
eh	105	144	99	$23\,119 \pm 48$	18	33	9	37	14	10	16	18	6
$\ell\ell$	731	816	98	$23\,157 \pm 31$	10	15	9	27	8	4	6	6	3

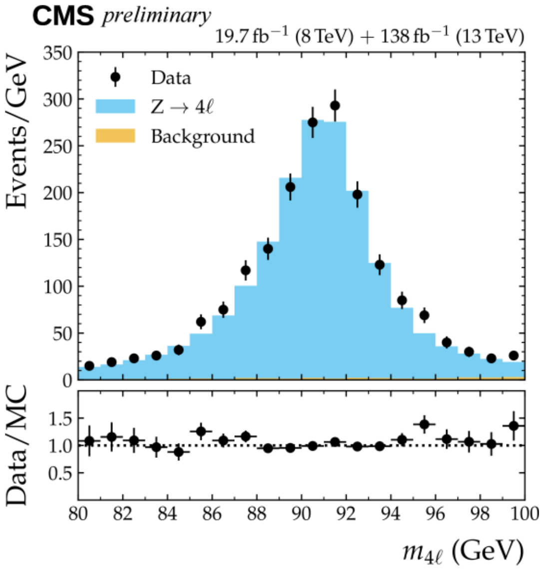
Z →4ℓ decays at 8 and 13 TeV

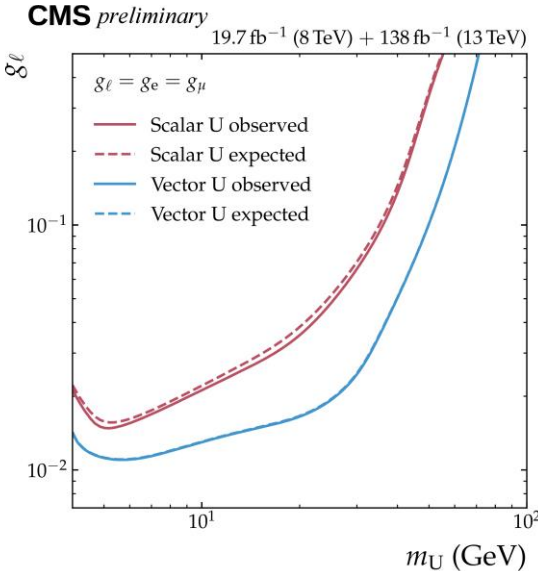
SMP-19-007





- Decays to e and μ considered
- B(Z→4ℓ) = 4.67 ± 0.11(stat) ± 0.10(sys)×10^{-6} → precision ~3%, **better than previous results** by CMS and ATLAS
- Measured **branching fractions & differential decay rates** consistent with SM
- **CP violation probed** through a triple-product asymmetry, consistent with SM
- Improved limits on **NP as a scalar or vector boson** mediating Z →4ℓ

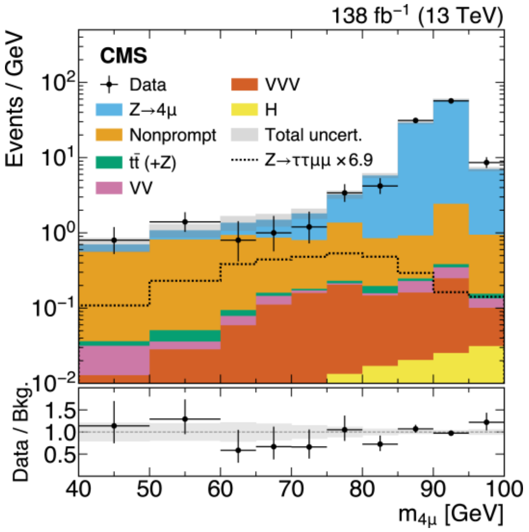




Search for Z→ ττμμ at 8 and 13 TeV

SMP-22-016

- **1st search** for Z→ττμμ @ the LHC
- **No excess over SM** background observed
- 1st time an **upper limit** at 95% CL was placed on the the **ratio of the Z→ττμμ to Z→4μ** branching fractions equivalent to 6.9 times the SM expectation of 0.90 ± 0.02
- The 1st constraints placed on **all flavor-conserving 4-lepton Wilson coefficients** involving 2μ and 2τ



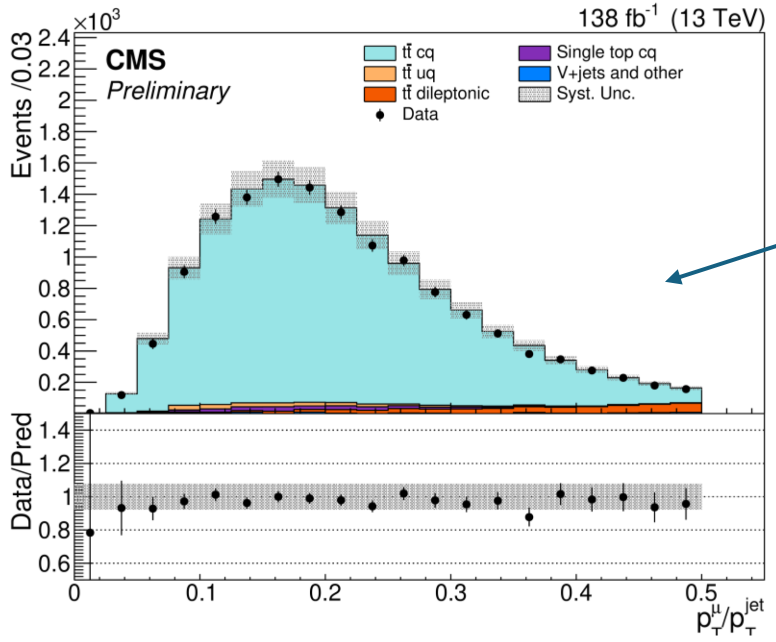
95% CL allowed region for $\mathcal{C}/\Lambda^2$ [10^3 / TeV^2]

$\mathcal{C}$	Only linear terms	Linear and quadratic terms
$\mathcal{C}^{2233}_{LL}$	[−2.7, 15.2]	[−3.8, 3.1]
$\mathcal{C}^{2332}_{LL}$	[−2.74, 0.01]	[−21.62, 0.01] ∪ [0.05, 20.82]
$\mathcal{C}^{2233}_{LR}$	[−3.0, 18.5]	[−4.3, 3.5]
$\mathcal{C}^{3322}_{LR}$	[−3.0, 17.2]	[−4.2, 3.4]
$\mathcal{C}^{2332}_{LR}$	—	[−17.4, 17.4]
$\mathcal{C}^{2233}_{RR}$	[−3.6, 20.0]	[−4.4, 3.6]

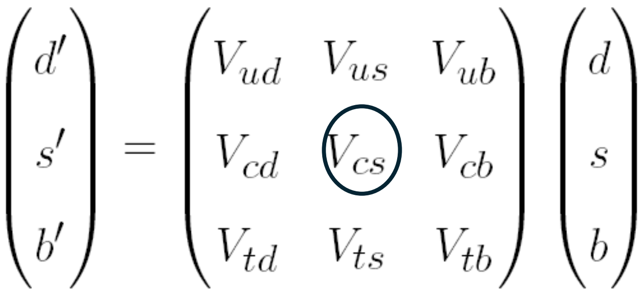
Measurement of the W→cq/W→$q\bar{q}'$ branching fraction ratio at 13 TeV

SMP-24-009

- **High-purity** sample of W bosons from $t\bar{t}$ cross section
- Select events with 1 **e or μ** and minimum 4 **jets** (2 b-tagged)
- **Charm jets tagged** using the presence of a μ inside the jet



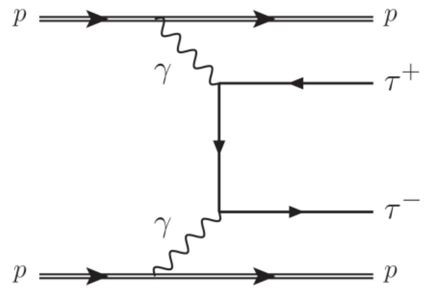
μ inside the c-tagged jets



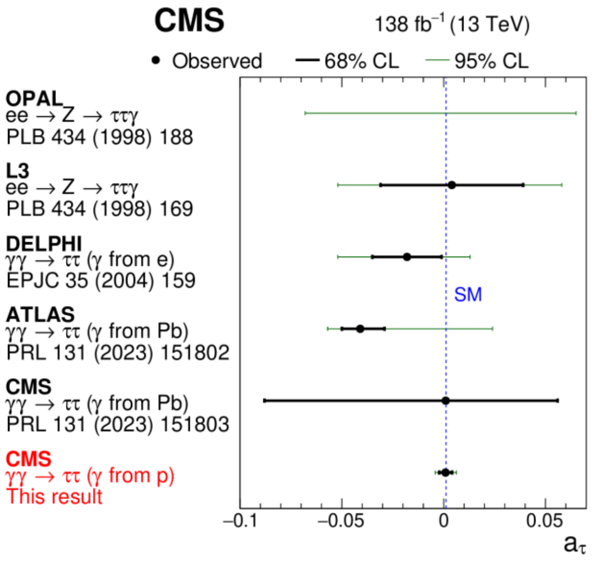
- The result $R_c^W = \mathcal{B}(W \to cq)/\mathcal{B}(W \to q\bar{q}')$ = 0.489 ±0.020 is consistent with SM and provides an **increase in precision by factor x2** to the world average
- The sum of squared elements in the **second row of the CKM matrix** determined at 0.970 ± 0.041
- Measured the **CKM matrix element** |Vcs|= 0.959 ± 0.021

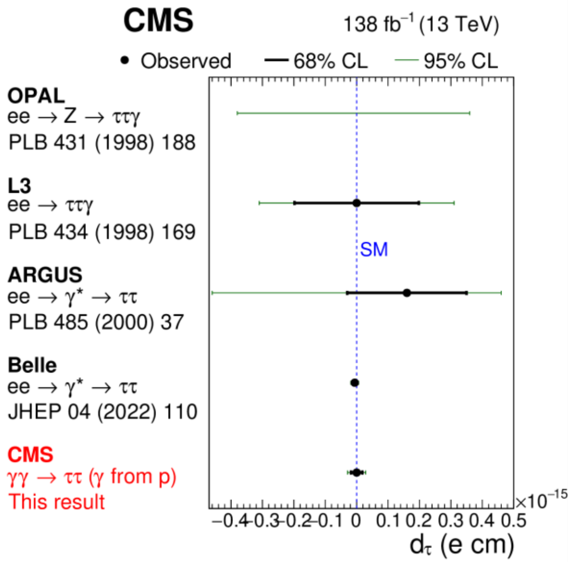
Observation of γγ→ττ, limits on the anomalous EM moments of the τ

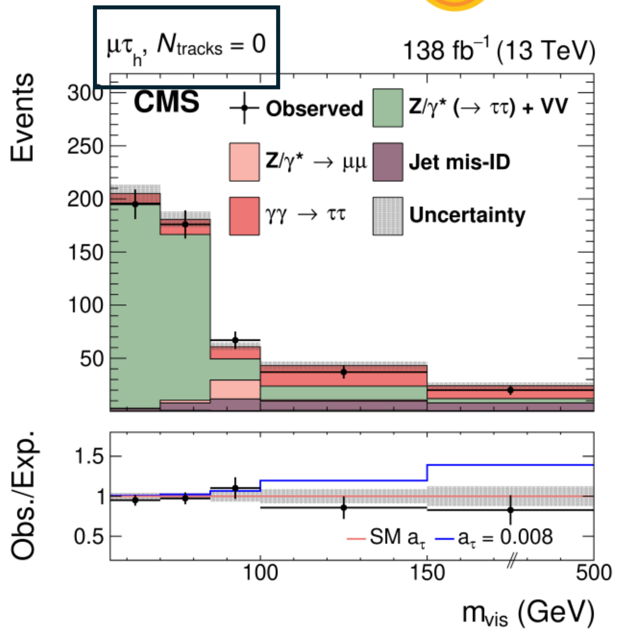
SMP-23-005

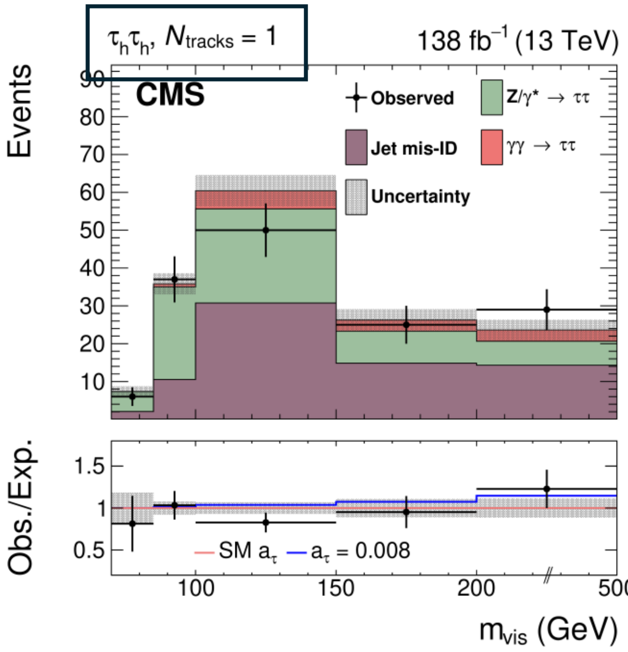


- τ leptons reconstructed in **leptonic and hadronic** decay modes
- **Require** events with **taus back-to-back** in the azimuthal direction and a minimum number of **charged hadrons** associated with their production vertex
- **First** observation **at pp collider** → significance of 5.3 standard deviations!







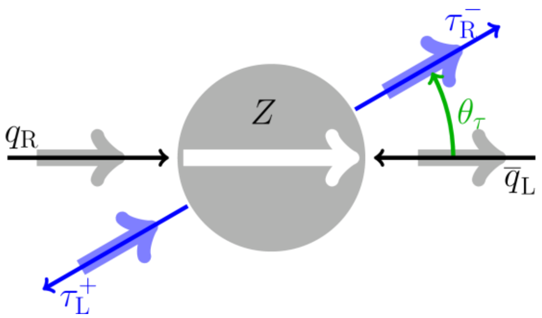


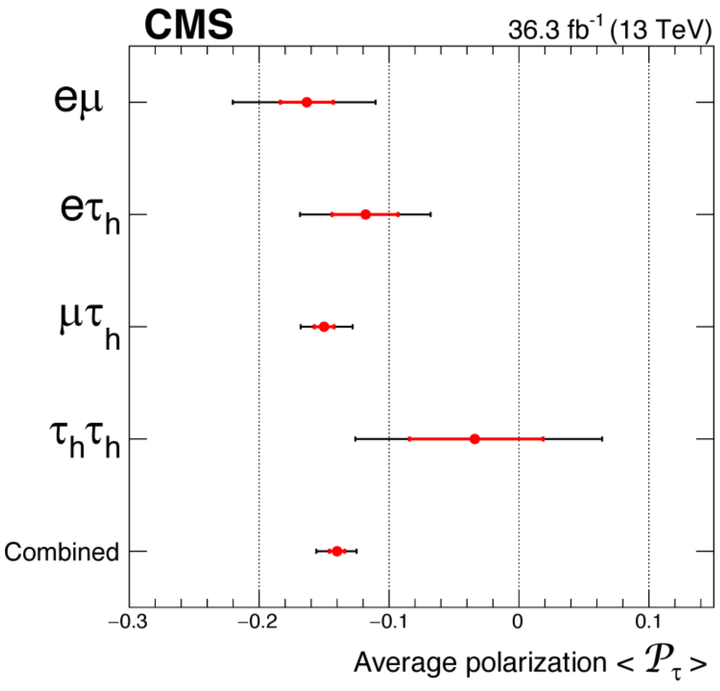
- **Constraints set on NP** contributions to the **anomalous magnetic moment** $a_\tau = 0.0009^{+0.0032}_{-0.0031}$ and **electric dipole moment** $|d_\tau| < 2.9 \times 10^{-17}\ e$cm (95% CL) of the τ → consistent with SM
- **Most stringent limit** on the **τ magnetic moment** to date → nearly **an order of magnitude better** than previous best constraints

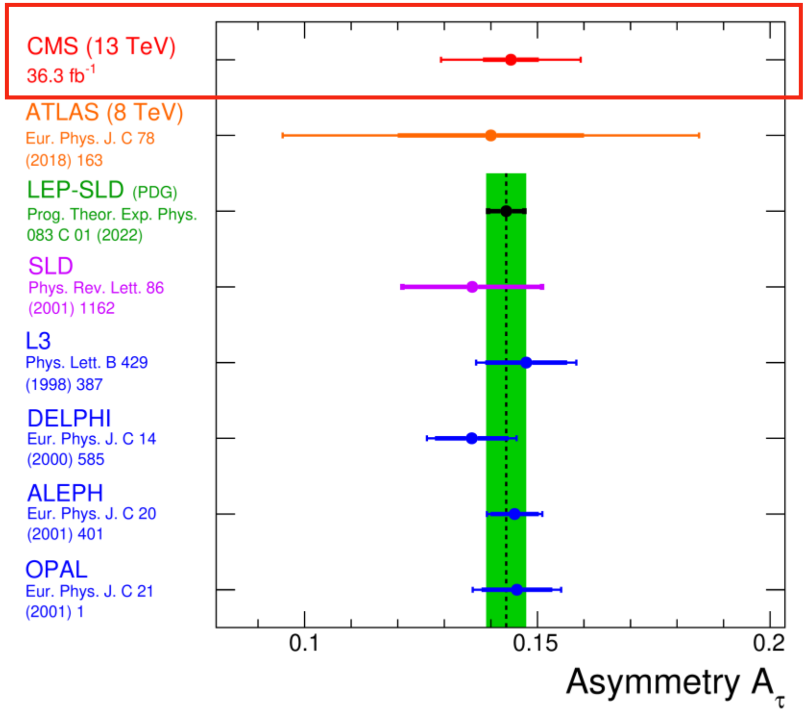
Measurement of the τ lepton polarization in Z boson decays at 13 TeV

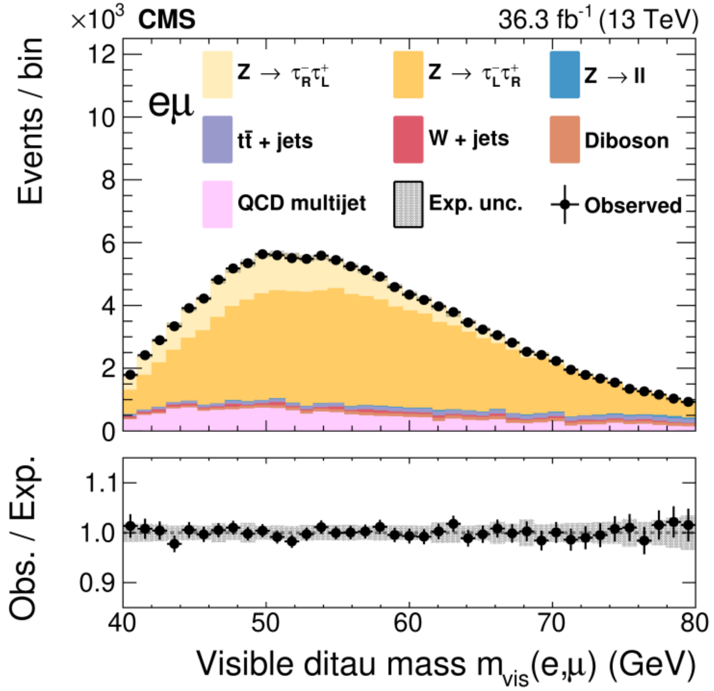
SMP-18-010

- τ^- polarization $\mathcal{P}_\tau = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$= -0.144 ± 0.015 → in **good agreement** with **existing results**
- **Most precise** measurement **at hadron colliders** → reaches precision similar to the SLD experiment
- The polarization constrains the **effective couplings** of τ^- leptons to the Z boson and determines $\mathbf{\sin^2\theta^{\ell}_{eff}}$ = 0.2319 ± 0.0019 → **precision of 0.8%** and independent of the Z production





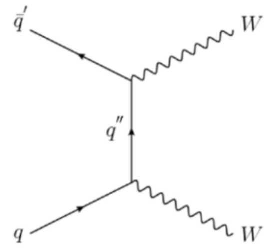


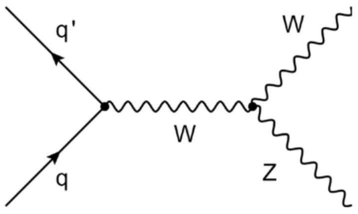


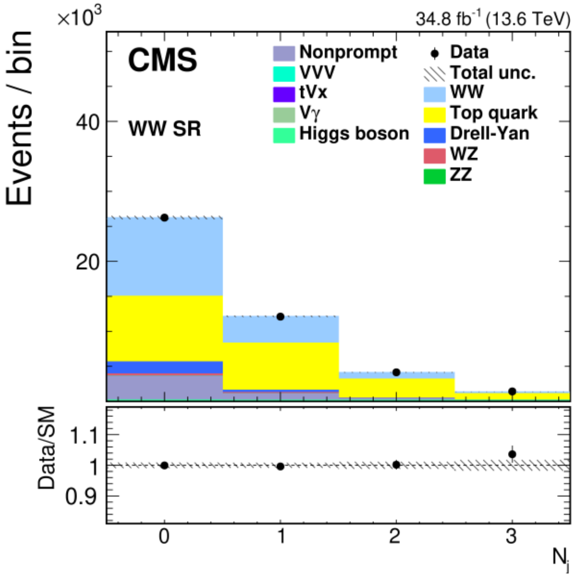
Multiboson production: diboson

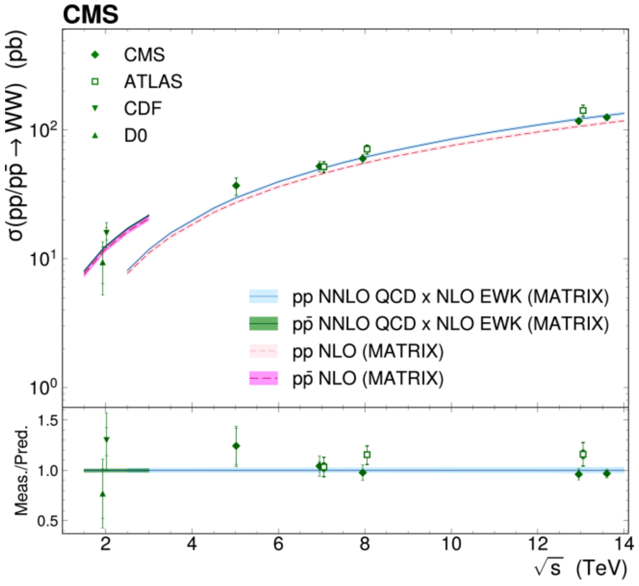
W+W− production at 13.6 TeV — SMP-24-001

- W decays to e/μ
- WW Signal region + 6 Control regions
- 1st time in pp collisions when WW events with **at least two reconstructed jets** are studied
- σ_{WW} = 125.7 ± 5.6 pb **compatible with predictions** (QCD NNLO and EW NLO from MATRIX)



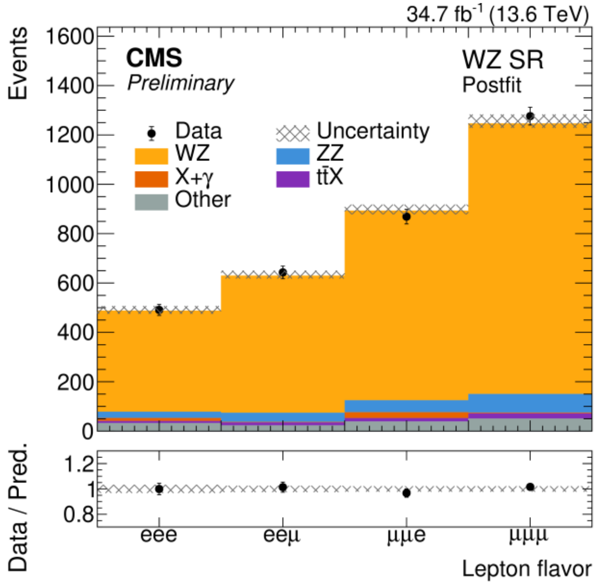


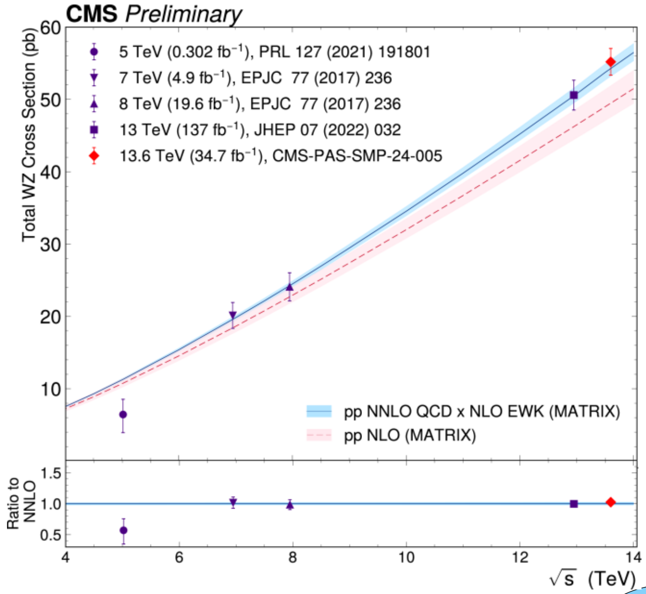




WZ production at 13.6 TeV — SMP-24-005

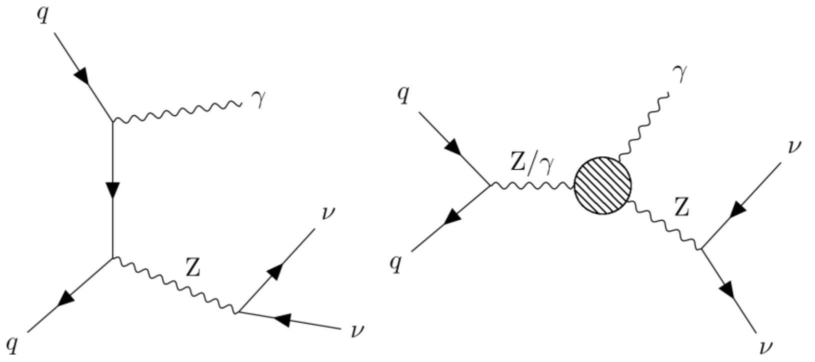
- Three lepton final state
- One of the **cleanest diboson channels** at the LHC
- σ_{WZ} = 55.2 ± 1.2(stat) ± 1.2(syst) ± 0.8(lumi) ± 0.1(theo) pb → good **agreement with predictions** (QCD NNLO and EW NLO from MATRIX)





Multiboson production: diboson

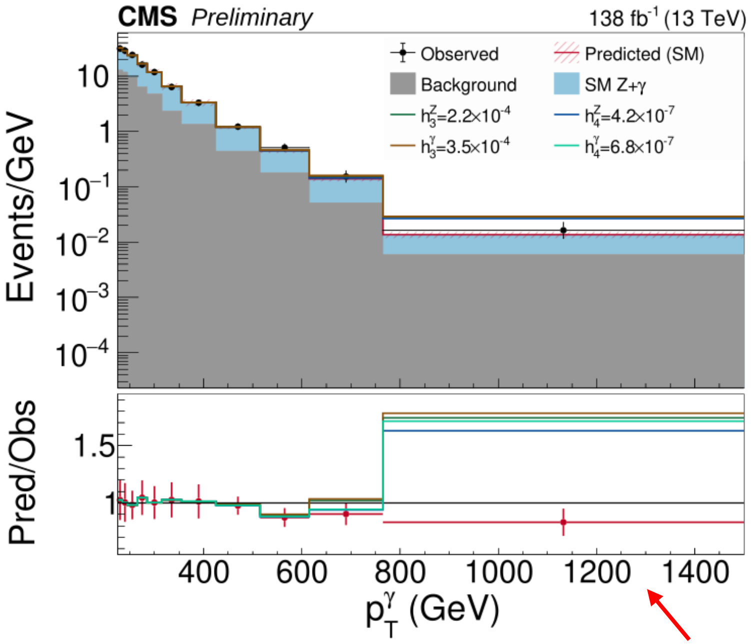
Z(→ $\nu\bar{\nu}$)γ production at 13 TeV SMP-22-009

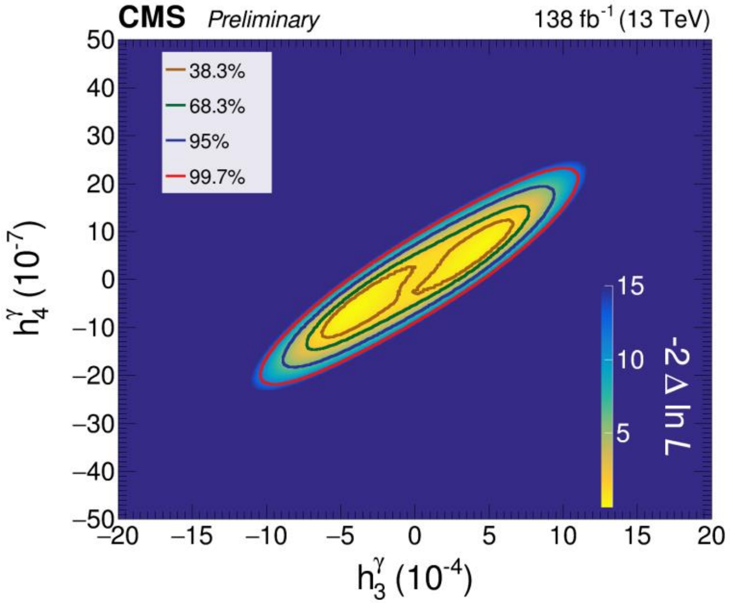


- Most stringent limits on the **anomalous Neutral Triple Gauge Coupling** from CMS
- Select events with **high-pT** and **missing transverse energy**
- **BDT algorithm** to identify high-pT photons

Source	Typical variation	Correlated between years
Experimental		
Luminosity	1.3–2.5%	Partially
Pile-up	0.4% – 2.2%	✓
Lepton ID SFs	< 0.01%	✓
Photon ID SFs	3.5% – 4.7%	✓
Photon energy scale and resolution	0.2% – 1.1 %	✓
Photon pixel veto SFs	0.1% – 0.9%	✓
Jet energy scale and resolution	0.2 – 2.8%	Partially
L1 ECAL prefiring	0.1% - 1.9%	✓
Jet→ γ fake ratio	2%-20%	✓
e → γ fake ratio	13%-45%	✓
Theoretical		
NLO electroweak corrections	2.7%	✓
PDF and α_S	1.5%–1.7%	✓
Renormalization/factorization scale	6%–7.2%	✓

Systematic uncertainties and their impact on the prediction for the signal





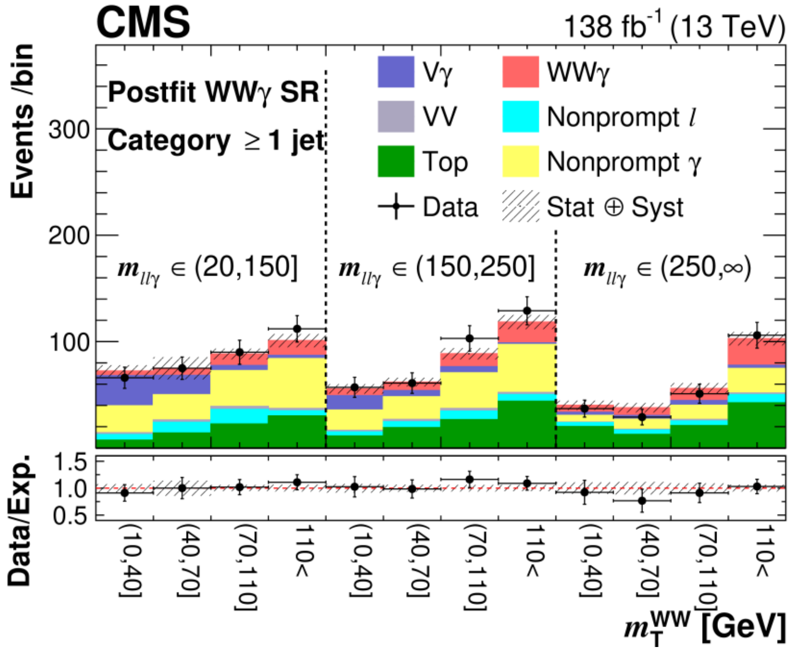
Reached p_T^γ > 1TeV !

Multiboson production: triboson

Observation of WWγ production at 13 TeV — SMP-22-006

- 1st observation of WWγ in pp collisions with 5.6 σ (5.1 σ) obs. (exp.)
- **Fully leptonic** final state
- **Cross section** for WWγ = 6.0 ± 0.8 (stat) ± 0.7 (syst) ± 0.6 (modeling) fb, **in agreement** with the NLO QCD prediction
- **search for Hγ production** and constrain **Higgs couplings to light quarks**

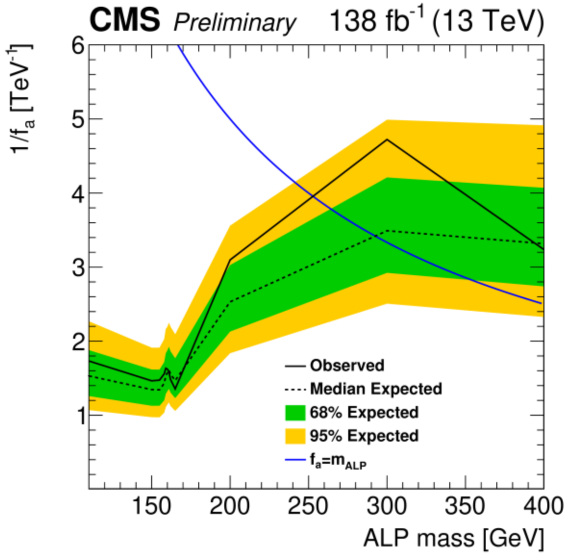
Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL	$\bar{\kappa}_q$ limits obs. (exp.) at 95% CL
$u\bar{u} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	85 (67)	$\|\kappa_u\| \leq 16000$ (13000)	$\|\bar{\kappa}_u\| \leq 7.5$ (6.1)
$d\bar{d} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\|\kappa_d\| \leq 17000$ (14000)	$\|\bar{\kappa}_d\| \leq 16.6$ (14.7)
$s\bar{s} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	68 (49)	$\|\kappa_s\| \leq 1700$ (1300)	$\|\bar{\kappa}_s\| \leq 32.8$ (25.2)
$c\bar{c} \to H+\gamma \to e\mu\nu_e\nu_\mu\gamma$	87 (67)	$\|\kappa_c\| \leq 200$ (110)	$\|\bar{\kappa}_c\| \leq 45.4$ (25.0)

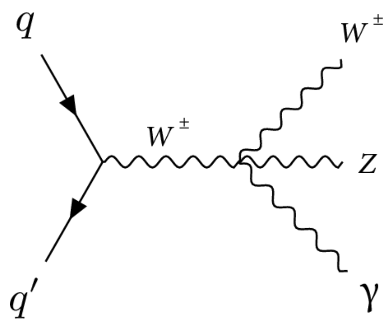


WZγ production at 13 TeV — SMP-22-018

- Limits on **anomalous Quartic Gauge Coupling** (aQGC)
- Limits on photophobic **axion-like particle models**
- **Fully leptonic** final states → $\sigma^{WZ\gamma}_{\text{fiducial}}$ = 5.48 ± 1.11 fb
- **Good agreement** with the NLO QCD prediction

Operators	Observed limits [TeV $^{-4}$]	Expected limits [TeV $^{-4}$]	Unitarity bound [TeV]
$F_{T,0}/\Lambda^4$	[-2.60, 2.60]	[-2.52, 2.52]	1.32
$F_{T,1}/\Lambda^4$	[-3.28, 3.24]	[-3.18, 3.14]	1.48
$F_{T,2}/\Lambda^4$	[-7.15, 7.05]	[-6.95, 6.85]	1.35
$F_{T,5}/\Lambda^4$	[-2.54, 2.56]	[-2.46, 2.50]	1.55
$F_{T,6}/\Lambda^4$	[-3.18, 3.22]	[-3.08, 3.14]	1.61
$F_{T,7}/\Lambda^4$	[-6.85, 7.05]	[-6.65, 6.85]	1.71

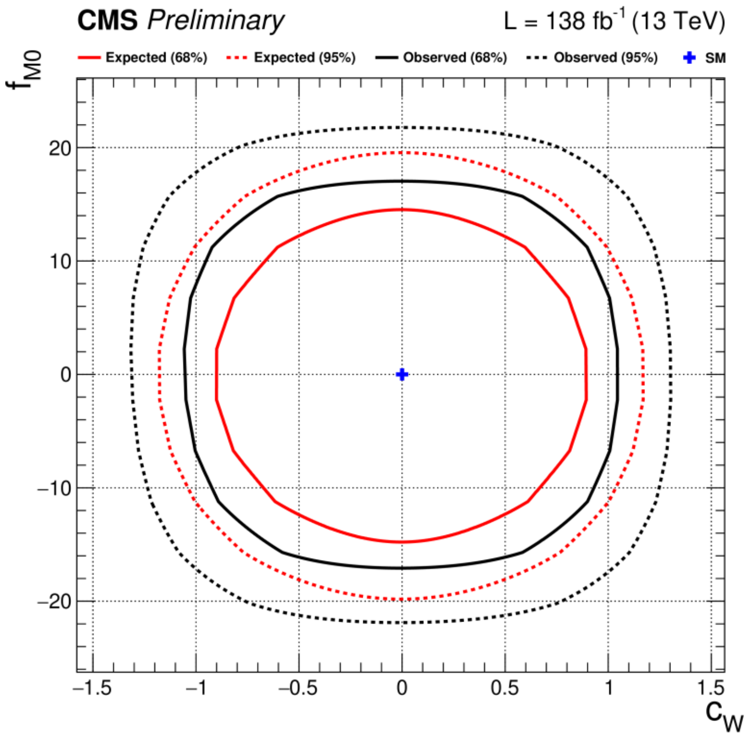


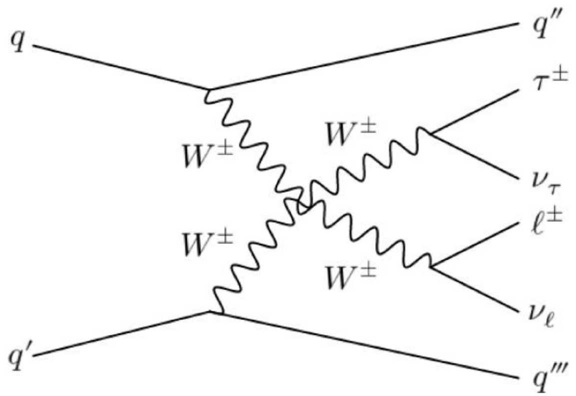


W±W± scattering with one hadronic τ at 13 TeV

SMP-22-008

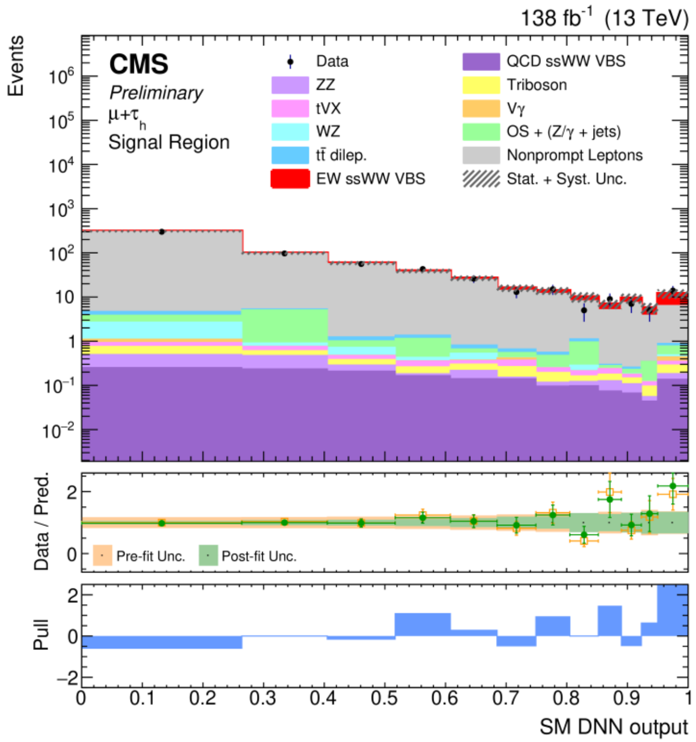
- **Quartic electroweak coupling** experimentally accessible in vector-boson scattering (VBS) and triboson production
- **1st study** of a **VBS process with a hadronic τ** in the decay channel
- **Deep neural network** algorithms used to **discriminate signal** from the main backgrounds (fakes from jets)





- **No deviation from SM** expectations
- **EFT analysis**

→ 1st dim-6 investigation with a VBS process
→ 1st study of EFT operators with different dim



Summary

CMS has a large and varied Electroweak Physics programme

Precision frontier

- **Tests of the Standard Model** @ 8, 13 and 13.6 TeV
- New measurements of **key EW parameters**: $\sin^2\theta^{\ell}_{\text{eff}}$ and Drell-Yan forward backward asymmetry, τ polarization
- Recent results reach/surpass the **precision of LEP**

Energy frontier

- **Tests of the EW theory** at highest energies in **multiboson measurements**

→1st observation of γγ→ττ at a hadron collider
→1st observation of WWγ in pp collisions
→1st study of a vector boson scattering process with a hadronic τ

Looking at the future

- Many results limited by **systematics**
- Need **more precise PDFs** → reached N3LO

More exciting EW measurements are under preparation @ CMS, stay tuned !

cms-results

C. Alexe acknowledges financial support from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement N. 10100120)