Electroweak Physics

current status and prospects from the **experiment** side

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The Standard Model is our Core Theory

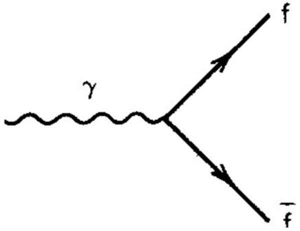
- What does that mean?

- **The Standard model** is *not a self contained theory*, because it **needs experimental inputs** to be quantitatively predictive: particle masses, strength couplings, mixing angles (depending on the choice).
    - there are **relations** that can be exploited to **verify the consistency of the theory** (see later).

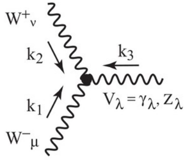
- Therefore, we need to make more and more precise measurements:
    - to **improve** our **predictions;**
    - to **test** the SM over key **observables**, such as cross sections and asymmetries… don’t need to stress that the devil (hopefully?) is in the details;
        - is there new physics? Are we really able to predict/interpret all experimental results? Is our picture complete or do we miss some pieces?

Experimental inputs to our theory

The **mixing angle** and the **interaction strengths** relations



$$\boxed{-ieQ_f\gamma^\mu}$$

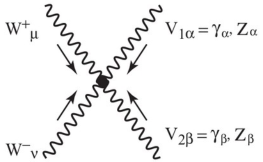


(a)

$ig_V[g_{\mu\nu}(k_1-k_2)_\lambda+g_{\nu\lambda}(k_2-k_3)_\mu+g_{\lambda\mu}(k_3-k_1)_\nu]$

$g_V=e$ for $V=\gamma$

$g_V=e\cot\theta_W$ for $V=Z$

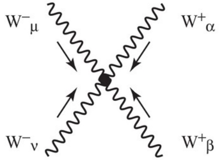


(b)

$-ig_{V_1}g_{V_2}[2g_{\alpha\beta}g_{\mu\nu}-g_{\alpha\mu}g_{\beta\nu}-g_{\alpha\nu}g_{\beta\mu}]$

$g_V=e$ for $V=\gamma$

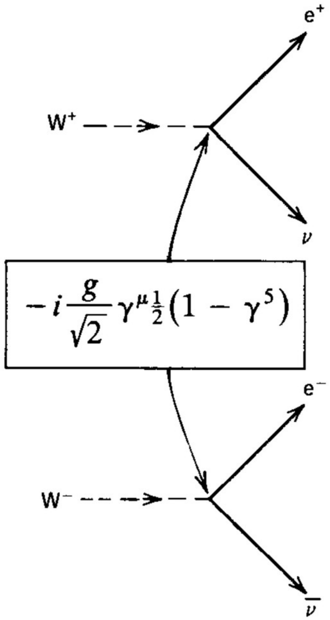
$g_V=e\cot\theta_W$ for $V=Z$



(c)

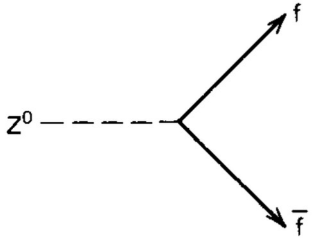
$ig_W^2[2g_{\alpha\beta}g_{\mu\nu}-g_{\alpha\mu}g_{\beta\nu}-g_{\alpha\nu}g_{\beta\mu}]$

$g_W=\frac{e}{\sin\theta_W}$



$$\boxed{-i\frac{g}{\sqrt{2}}\gamma^\mu\tfrac{1}{2}(1-\gamma^5)}$$

Reminder: g is the strength of the couplings between the isotriplet of vector field W_μ^i and the weak isospin current, while g'/2 is the strength between the single vector field B_μ and the hypercharge current.



$$\boxed{-i\frac{g}{\cos\theta_W}\gamma^\mu\tfrac{1}{2}(c_V^f-c_A^f\gamma^5).}$$

$$c_V^f=T_f^3-2\sin^2\theta_W Q_f$$
$$c_A^f=T_f^3,$$

Since $\boxed{e=g\sin\theta_W=g'\cos\theta_W}$ **once 2 parameters are fixed the others are determined.**

The couplings with the Higgs field depends on g, m_W, and the masses of the particle that interact with it.
→ the masses of the fermions cannot be determined in the theory.

Experimental inputs to our theory

- **The masses of the EW gauge bosons are not independent** to each other, but there are relations to each other which comes from the theory:

$$\frac{m_W}{m_Z}=\cos\theta_W \rightarrow \sin^2\theta_W=1-\frac{m_W^2}{m_Z^2} \qquad \frac{c_V^f}{c_A^f}=1-2\frac{Q_f}{T_f^3}\sin^2\theta_W \qquad \frac{G_F}{\sqrt{2}}=\frac{g^2}{8m_W^2}=\frac{\pi\alpha_{QED}}{2m_W^2\sin^2\theta_w}$$

- **From the *EWSB*** we also have the relations:

$$\frac{G_F}{\sqrt{2}}=\frac{1}{2v^2} \qquad m_Z=\frac{1}{2}v\sqrt{g^2+g'^2} \qquad m_W=\frac{1}{2}vg \qquad m_H^2=2v^2\lambda$$

- Therefore, excluding the fermion masses (and the CKM matrix), **the theory depends on 4 inputs**. The natural choice would be {g,g',v,λ}, but the one that *minimizes the parametric uncertainty* is **{α_{QED}, G_F, m_Z, m_H}**. The above relations (with radiative corrections) can be used as predictions to test the theory.

Menú of the day

We will

- go through the **most recent measurement at LHC of the predictions** of the Electroweak part of the Standard Model.
- go through the **most recent measurement at LHC of key-process cross sections:**
    - hold the key to test the couplings;
    - pave the road for the complete understanding of the EWSB;
    - constraints on anomalous couplings/Effective Field Theories (EFT) operators.

Studies of EW predictions

W mass measurement

arXiv:2403.15085

Reanalysis of ATLAS data used for the 2017 m_W measurement.

Use the decay in the electron and muon channels and exploit the **sensitivity of p_T^{ℓ} and m_T to the m_W and Γ_W variations.**

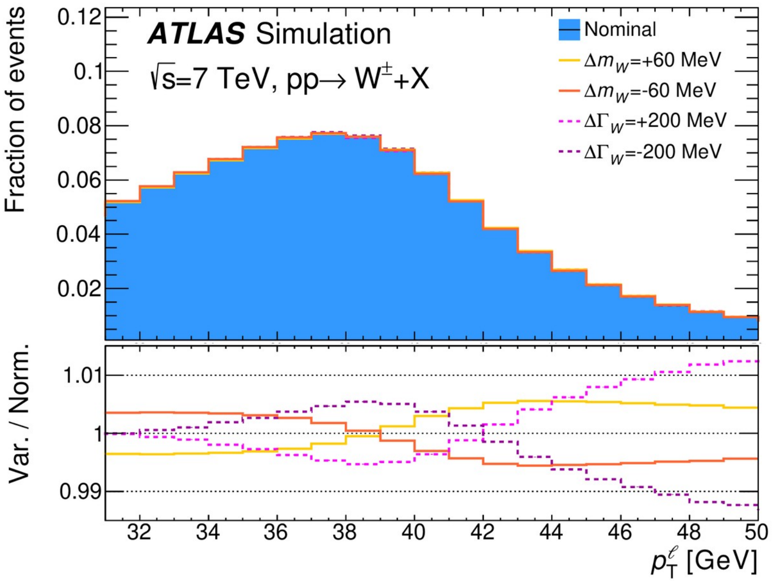
→ signal MC templates for a range of m_W-Γ_W values, reweighted to the Breit-Wigner parameterisation of the W mass.

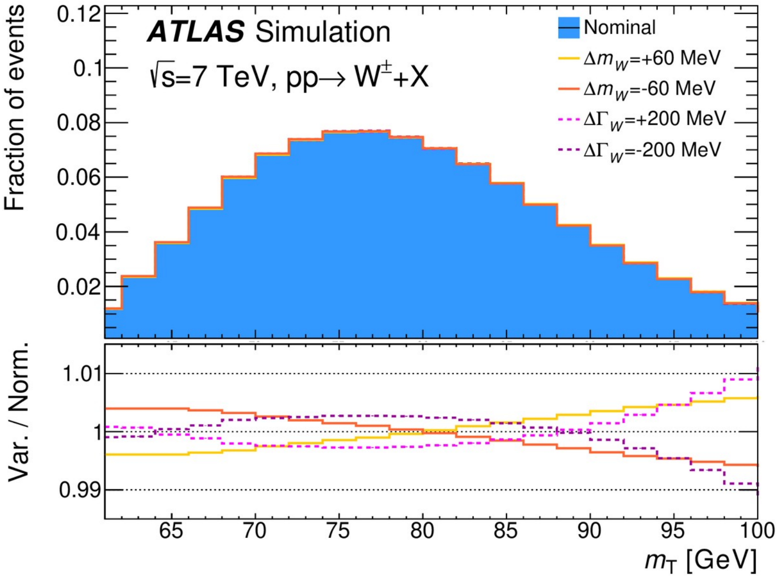
W mass can be compute precisely.

It is a prediction of the SM

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

$$\Delta r\propto-\frac{3\alpha}{16\pi s^4}\frac{m_t^2}{m_Z^2}+\frac{11\alpha}{24\pi s^2}\ln\left(\frac{m_H}{m_Z}\right)+\ldots$$





W mass measurement

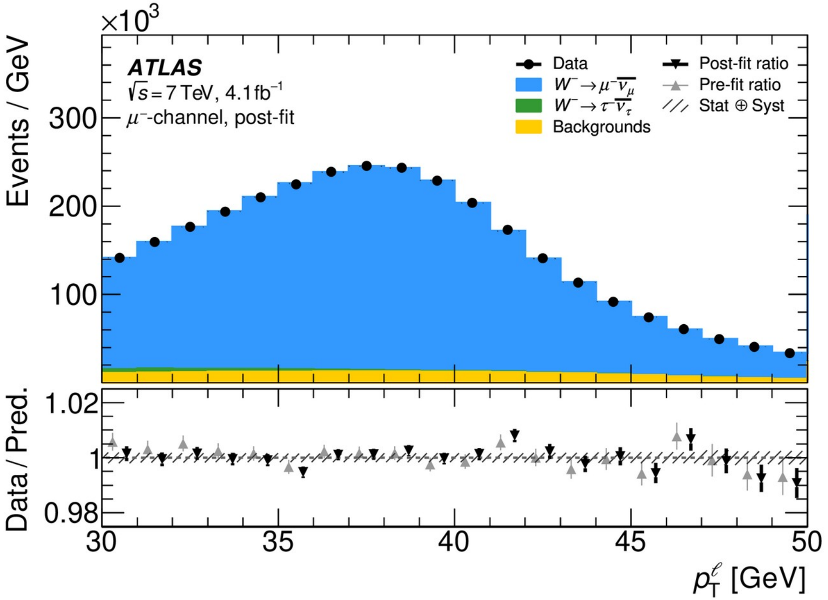
arXiv:2403.15085

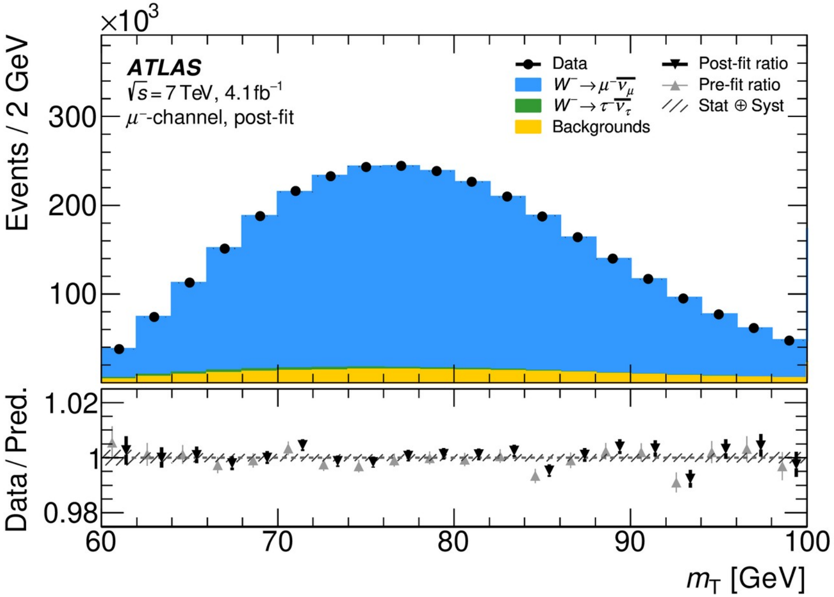
Background is composed by

I) **Z, W → τν, di-bosons, top processes**: estimated using *simulations*, account for 6.4% (μ channel) and 3.1% (e channel) of the total search region.

II) **multijet events**: estimated from *data*, accounts for 1.2% of the signal region.

Multi m_W and Γ_W measurements done **fitting separately p_T^ℓ and m_T distributions** for each leptonic category (flavour, charge, 3 pseudorapidity bins).





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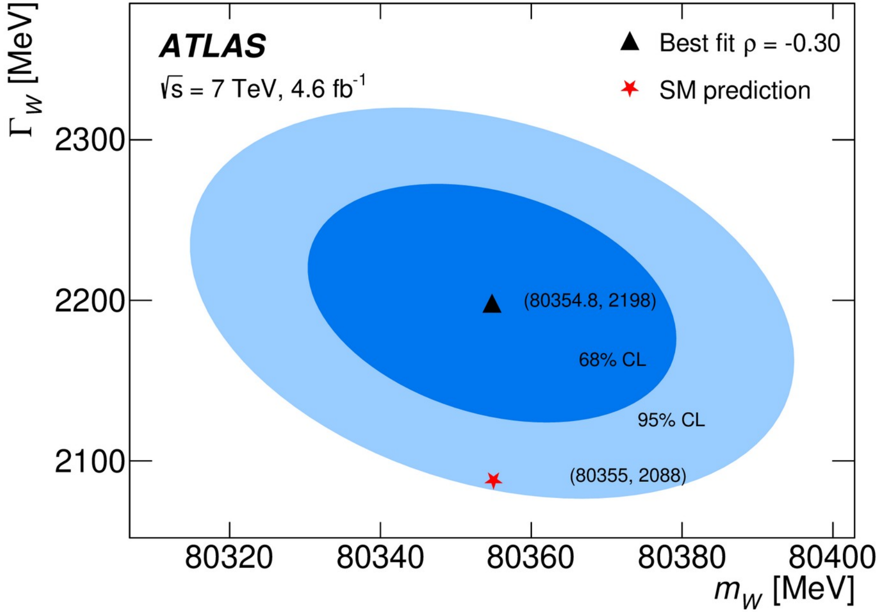
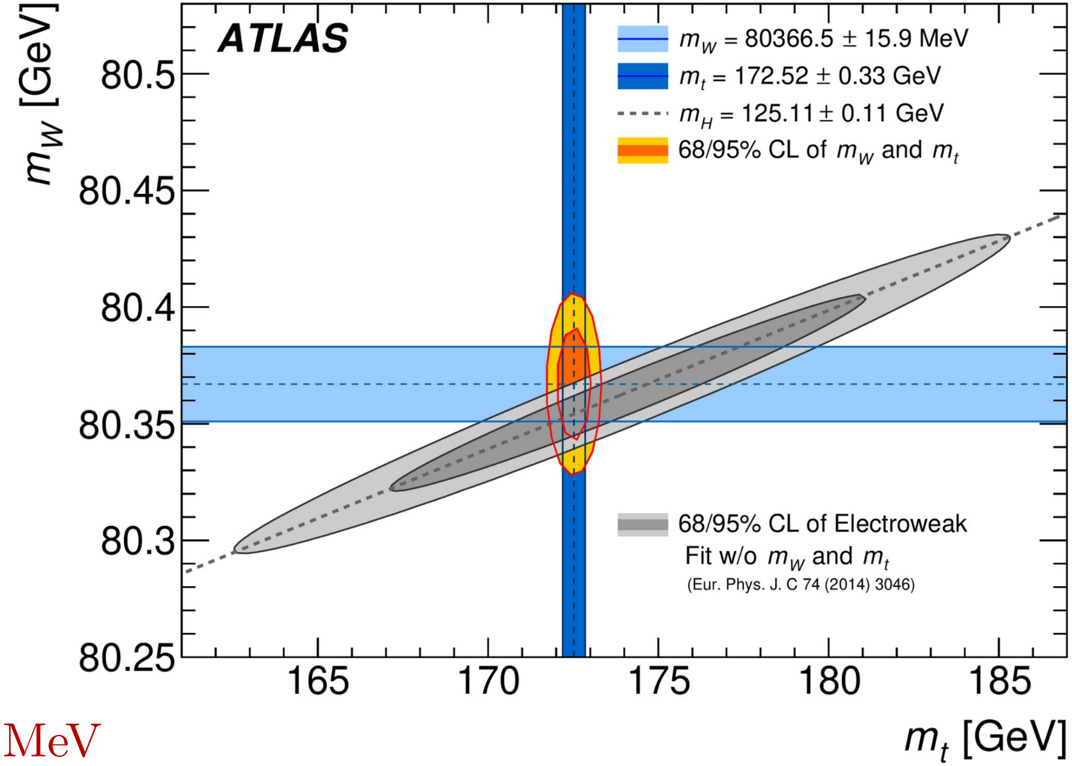




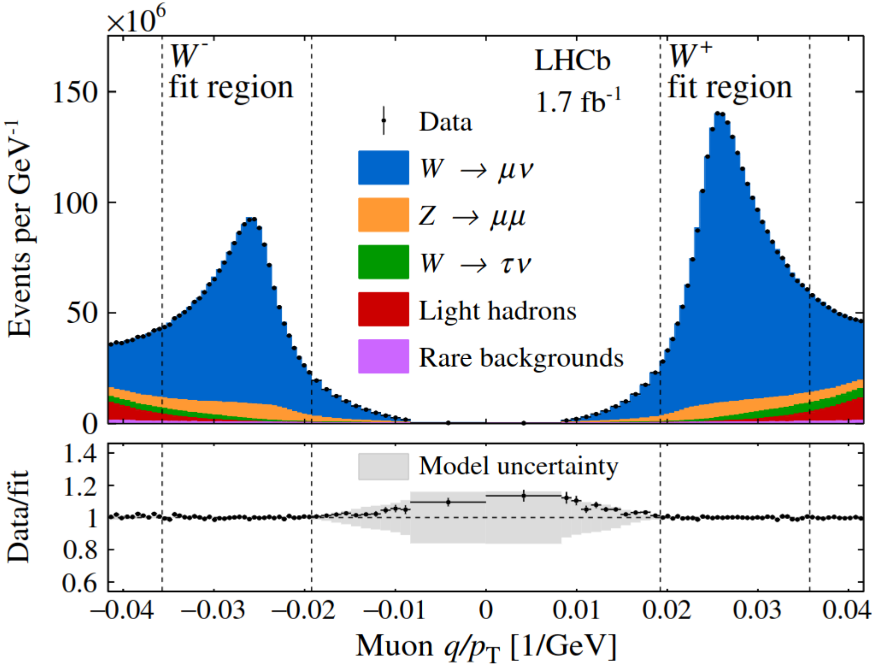
$$m_W = 80366.5 \pm 9.8(\mathrm{stat.}) \pm 12.5(\mathrm{syst.})\ \mathrm{MeV}$$

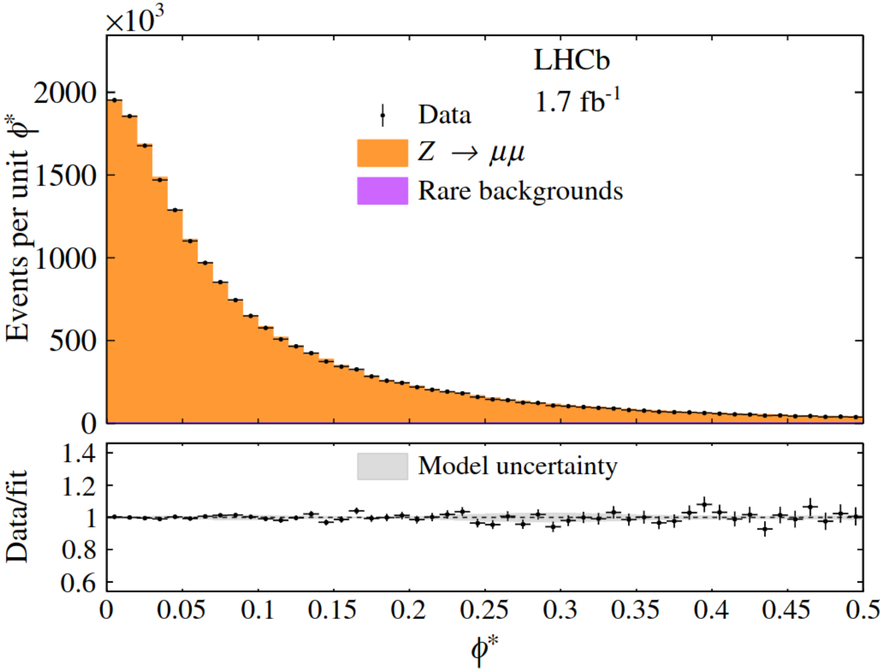
$$\Gamma_W = 2202 \pm 32(\mathrm{stat.}) \pm 34(\mathrm{syst.})\ \mathrm{MeV}$$

W mass measurement

JHEP 01 (2022) 036

The LHCb coll. measured the m$_W$ through a **simultaneous fit of the q/p$_T$ distribution of the muons from Ws, and the ϕ^* distribution of the Z boson**, which is used as a proxy, properly tuned, of the p$_T$ of the W.

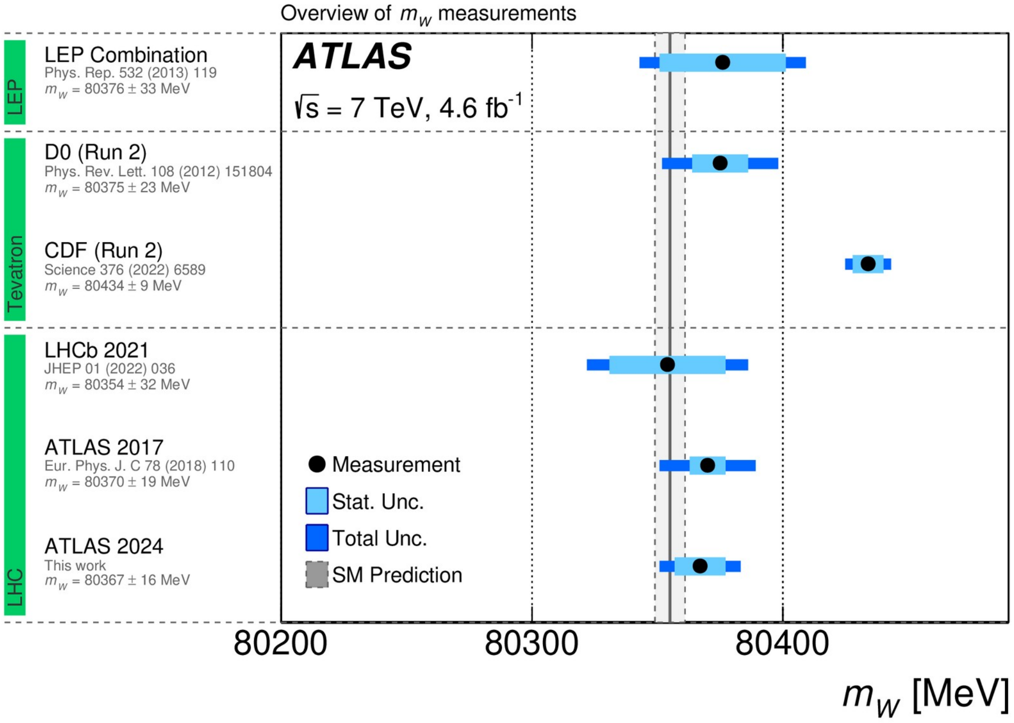


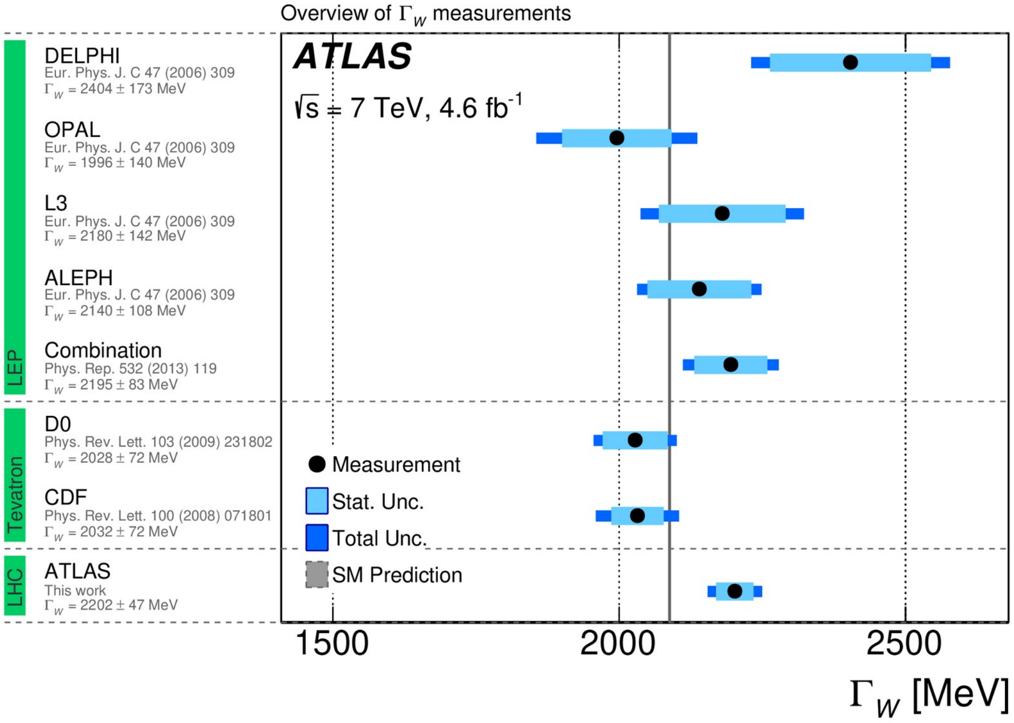


$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

W mass measurement

arXiv:2403.15085





Measurement of $\sin^2\theta_W$

CMS-SMP-2022-010

Measurement done by CMS using **di-muon and di-electron events**, collected at 13 TeV (137 fb^{-1}), as a function of **dilepton's mass and rapidity**.

$\sin^2\theta_{eff}^{\ell}$ Relates to $\sin^2\theta_W$ through $\frac{\tilde{c}_V^f}{\tilde{c}_A^f}=1-4|Q_f|\sin^2\theta_{eff}^f$

Having had absorbed in the V-A couplings the radiative corrections.

Or equivalently, $\sin^2\theta_{eff}^{\ell}=k(m_Z)\sin^2\theta_W$

Angular (weighted) **Forward-Backward asymmetry is sensitive to $\sin^2\theta_{eff}$**

We can write the cross section as

$$\frac{16\pi}{3\sigma}\frac{d\sigma}{d\cos\theta\, d\phi}=1+\cos^2\theta+\sum_{i=0}^{7}A_i f_i(\theta,\phi)$$

The only term that survive at the integration && subtraction of the F-B cross sections is A_4 (which multiply cos θ)

$$A_{FB}=\frac{\sigma_F-\sigma_B}{\sigma_F-\sigma_B}=\frac{3}{8}A_4$$

The function f_i are combination of sin&cos of θ and ϕ. To obtain the FB asymmetry we integrate x section over the solid angle separating cos(θ)>0 (F) and cos(θ)<0 (B).

The σ_F,σ_B are measured in the Collin-Sopper (CS) r.f.

$$\cos\theta_{CS}=\frac{2(P_1^+P_2^- - P_1^-P_2^+)}{\sqrt{m_{\ell\ell}^2(m_{\ell\ell}^2+p_{T,\ell\ell}^2)}}\frac{y_{\ell\ell}}{|y_{\ell\ell}|}$$

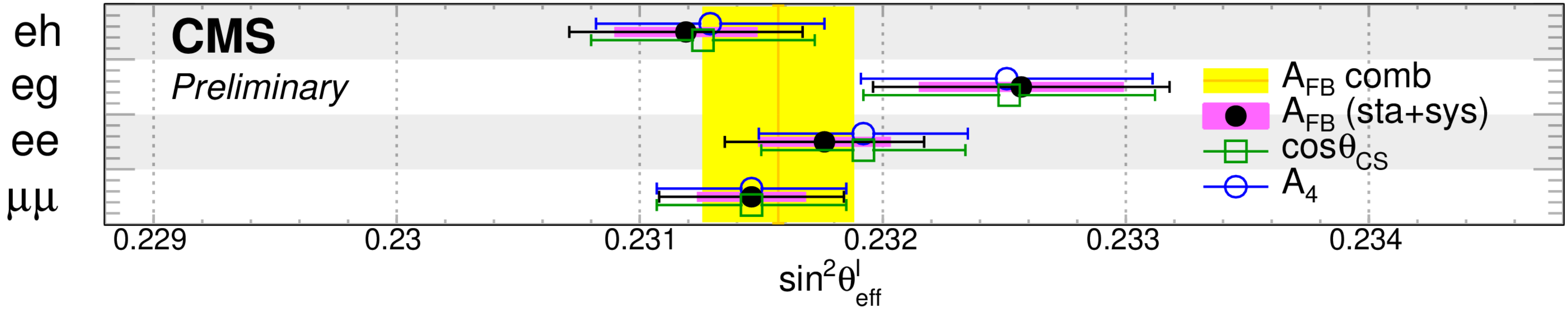
$$P_i^{\pm}=(E_i\pm p_{z,i})/\sqrt{2}$$

$\sin^2\theta_{eff}$ is obtained fitting A^W_{FB}, A_4 or $\cos\theta_{CS}$, floating $\sin^2\theta_{eff}$

Measurement of sin$^2\theta_W$

CMS-SMP-2022-010

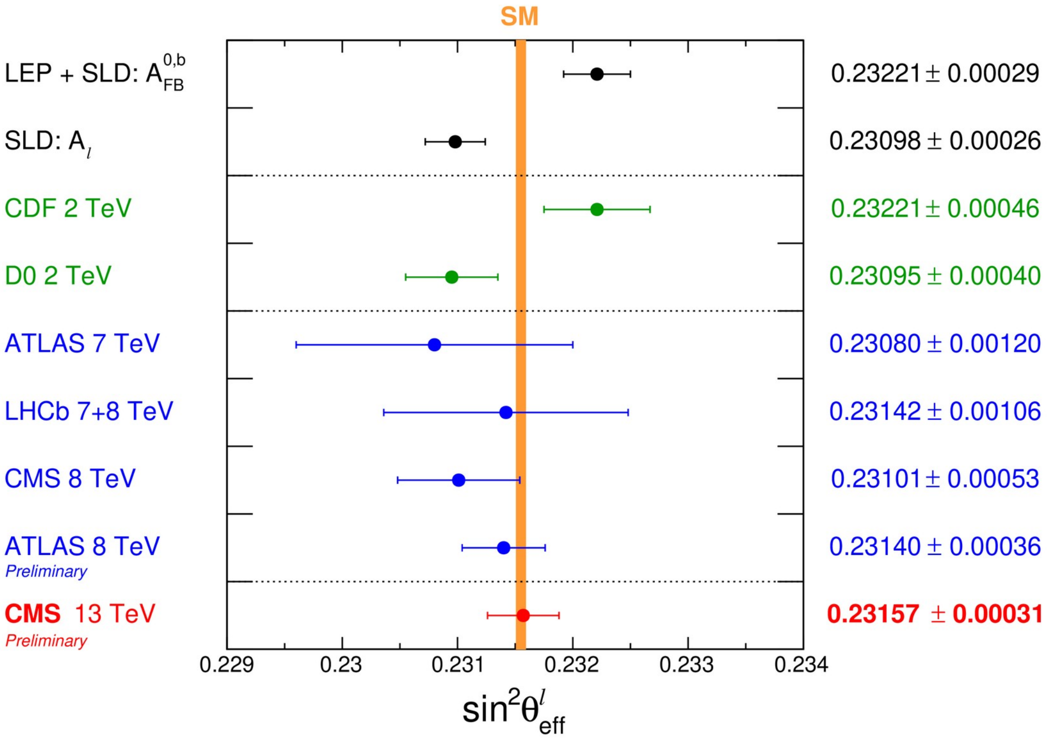
Measurement done dividing the dilepton events in **different categories**: dimuon (μμ), central dielectron (ee), central-forwar ECAL dielectron (eg) and central-forward HCAL dielectron (eh).



The yellow band is the combination of the black-pink points

Measurement of $\sin^2\theta_W$

CMS-SMP-2022-010

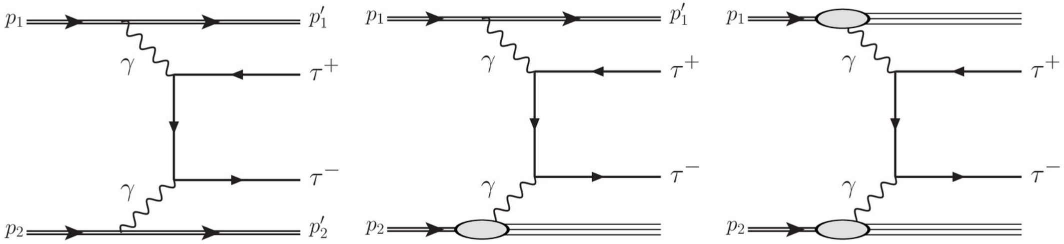


This is the most precise measurement at hadron colliders!!

(the quoted value refers to CT18Z PDF and A_{FB} based measurement)

$pp \rightarrow p^{(*)}\gamma\gamma\, p^{(*)} \rightarrow p^{(*)}\tau\tau p^{(*)}$ CMS-SMP-2023-005

First observation of this process in p-p collisions (both ATLAS and CMS observed in nuclei collisions for $m_{\tau\tau} \lesssim 20$ GeV).



The process is a **purely QED** and depend on the $\gamma\tau\tau$ vertex, which is a **function of g_τ**

$$\Gamma^\mu = \gamma^\mu F_1\left(q^2\right) + \frac{\sigma^{\mu\nu}q_\nu}{2m}\left[iF_2\left(q^2\right) + F_3\left(q^2\right)\gamma_5\right]$$

$$\hookrightarrow \quad F_3(0) = -\tfrac{2m}{e}d_\ell$$

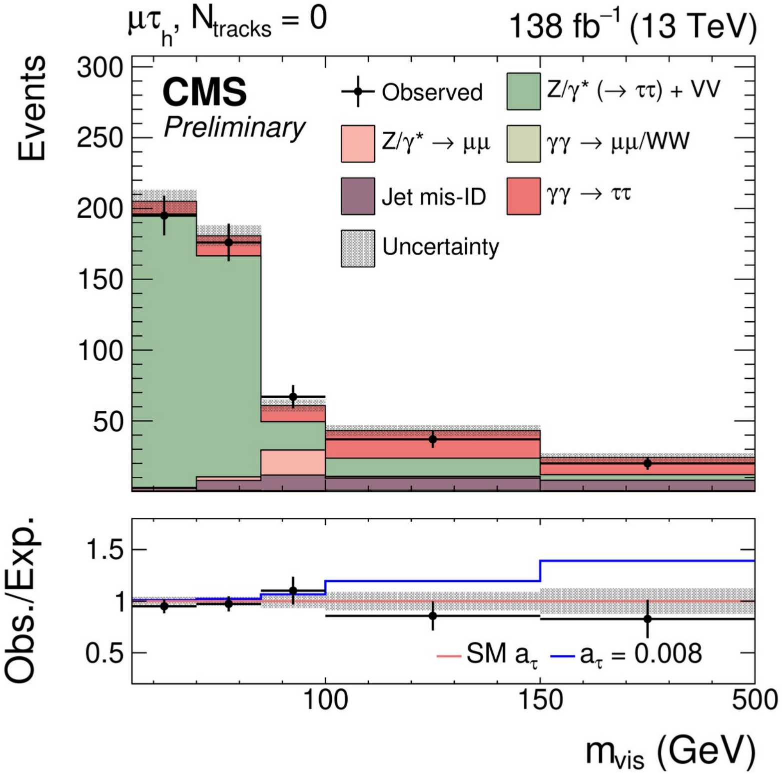
$$\hookrightarrow \quad F_2(0) = a_\ell \equiv (g_\ell - 2)/2$$

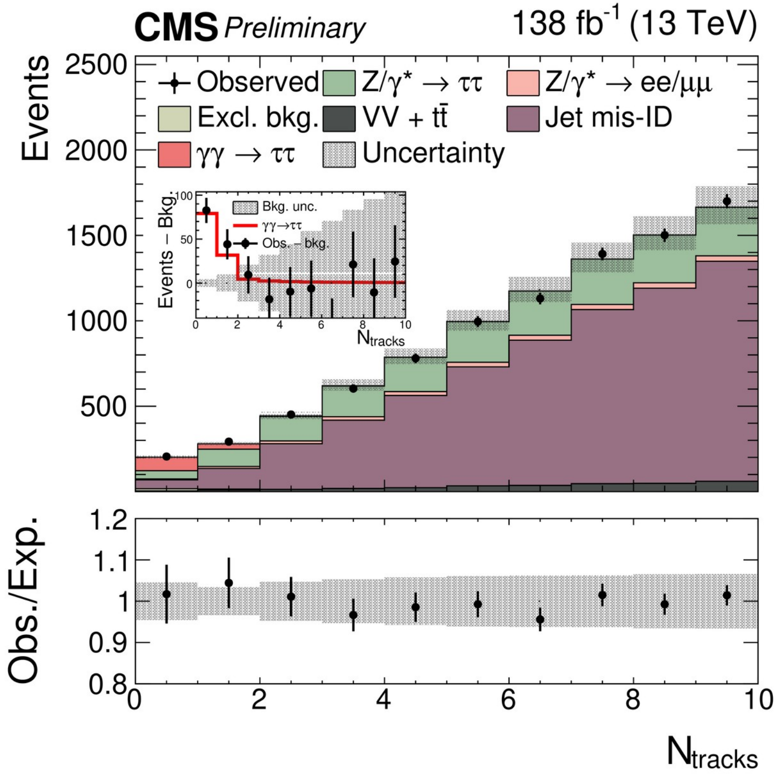
The anomalous electromagnetic moment **a_τ** is expected to be **0.00117721(5)** while the anomalous electric dipole **d_τ** is **$-7.3 \cdot 10^{-38}$ ecm**

→ **set limits on deviations from what predicted by the SM**

$pp \to p^{(*)}\gamma\gamma\, p^{(*)} \to p^{(*)}\tau\tau p^{(*)}$ CMS-SMP-2023-005

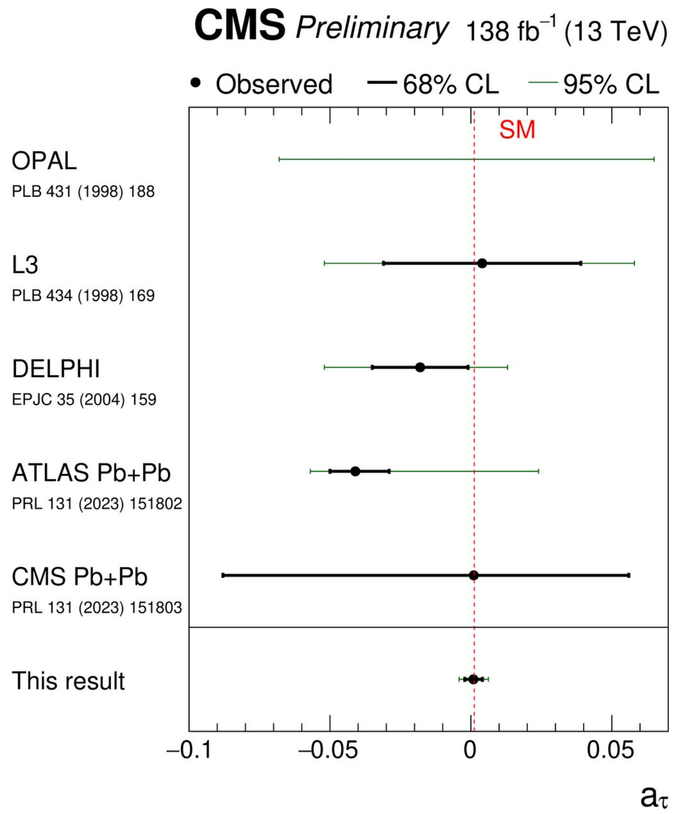
Select events with **few tracks close to the ττ (esperimental) vertex** in four τ-decay categories events: eμ, $e\tau_h$, $\mu\tau_h$ (the most sensitive) and $\tau_h\tau_h$.



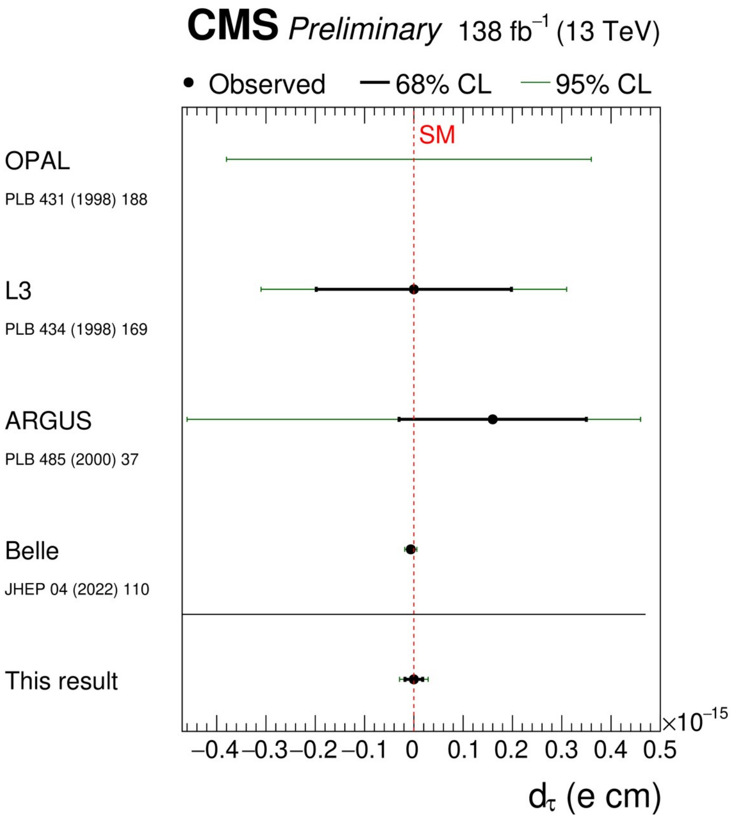


Observed (expected) significance 5.3σ (6.5σ)

$pp \rightarrow p^{(*)}\gamma\gamma\, p^{(*)} \rightarrow p^{(*)}\tau\tau p^{(*)}$ CMS-SMP-2023-005



$$a_{\tau} = 0.0009^{+0.0032}_{-0.0031}$$



$$\left(-0.17 < d_{\tau} < 1.7\right) \cdot 10^{-17}\, e\, cm$$

$pp \rightarrow p^{(*)}\gamma\gamma\, p^{(*)} \rightarrow p^{(*)}\tau\tau p^{(*)}$ CMS-SMP-2023-005

We can **set limits** on possible anomalies

Parametrize δa_τ and δd_τ using **SMEFT dim-6 operators:**

$$\mathcal{L}_{\text{BSM}} = \frac{C_{\tau B}}{\Lambda^2} \bar{L}_L \sigma^{\mu\nu} \tau_R H B_{\mu\nu} + \frac{C_{\tau W}}{\Lambda^2} \bar{L}_L \sigma^{\mu\nu} \tau_R \sigma^i H W^i_{\mu\nu} + \text{h.c.}$$

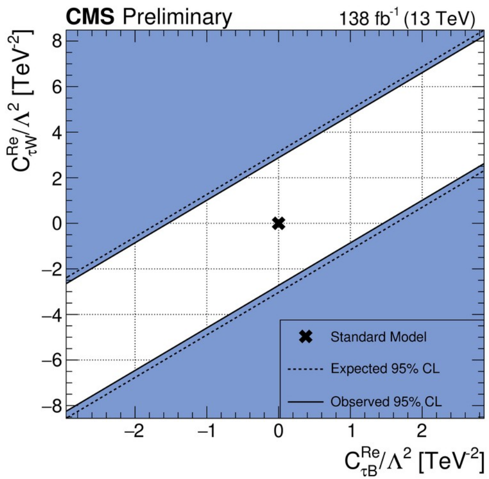
That translates in a **modification of the $\gamma\tau\tau$ vertex:**

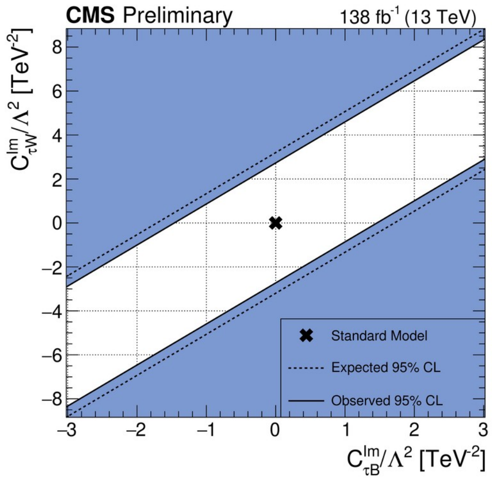
$$V_{\tau\tau\gamma} = ie\gamma^\mu - \frac{v\sqrt{2}}{\Lambda^2} \left[\text{Re}\left[C_{\tau\gamma}\right] + \text{Im}\left[C_{\tau\gamma}\right] i\gamma_5 \right] \sigma^{\mu\nu} q_\nu$$

Which induces **variations of a_τ and d_τ**:

$$\delta a_\tau = \frac{2m_\tau}{e} \frac{\sqrt{2}v}{\Lambda^2} \text{Re}\left[C_{\tau\gamma}\right] \qquad \delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2} \text{Im}\left[C_{\tau\gamma}\right]$$

with $C_{\tau\gamma} = \left(cos\theta_W C_{\tau B} - \sin\theta_W C_{\tau W} \right)$



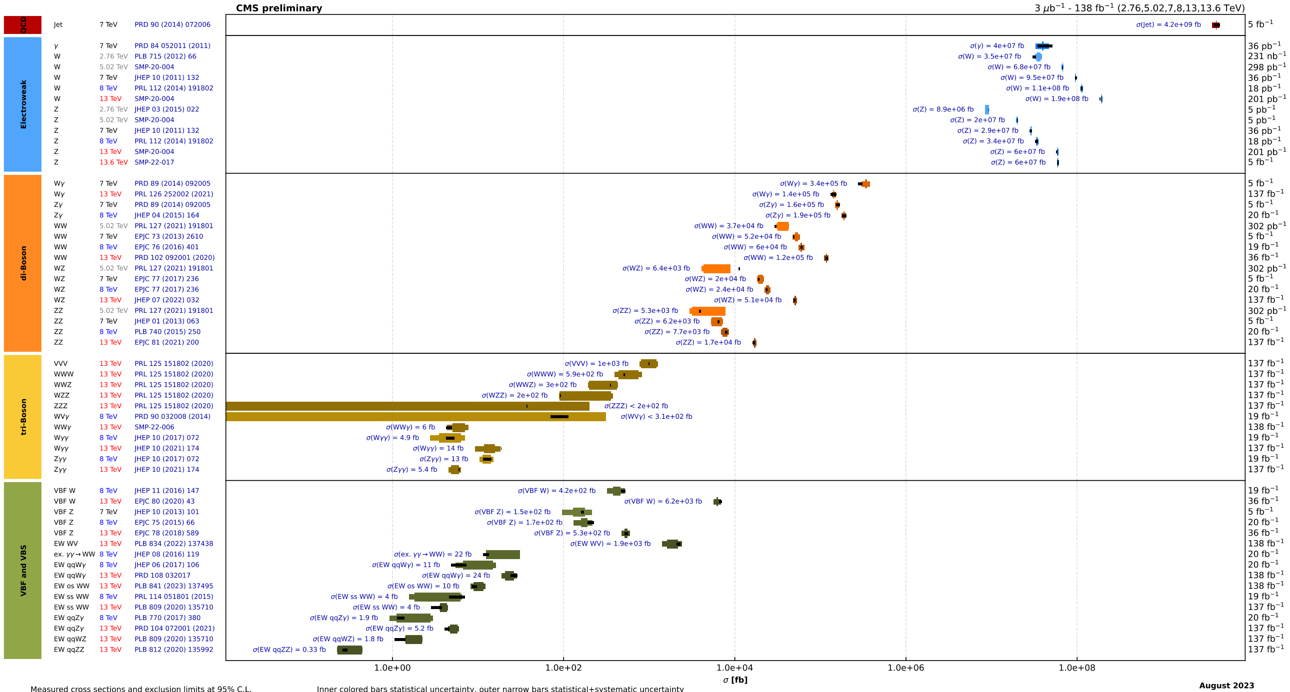


Studies of EW key processes

Stairway to Heaven

- Standard Model cross sections successfully tested over **11 orders of magnitude.**
- We **discovered** the **Higgs boson.**
- ***Still*** we have to understand **in detail the Electroweak Symmetry Breaking Mechanism** (EWSB), make **precision measurements** and observe **rare processes.**

Overview of CMS cross section results



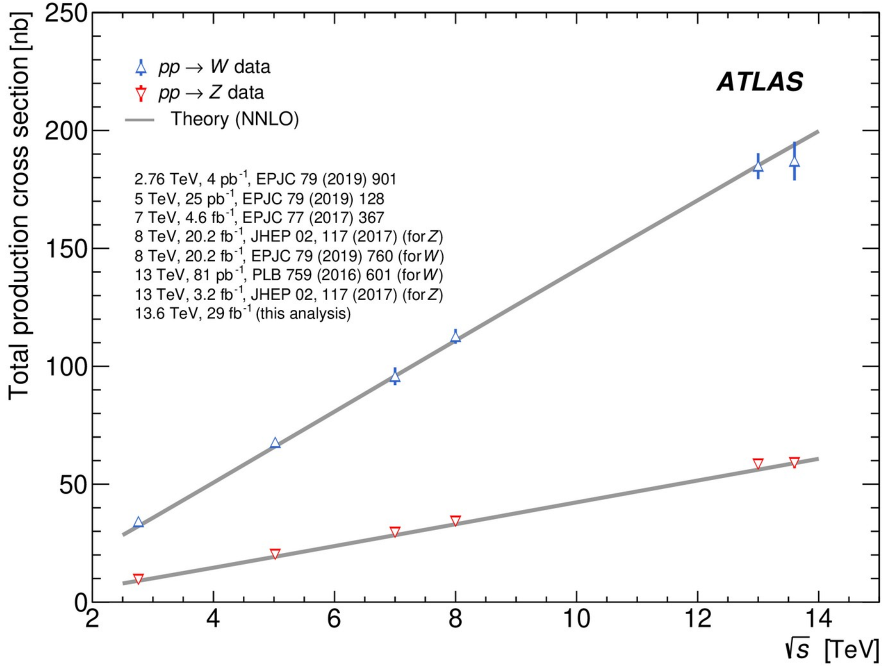
Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots

Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light to Dark colored bars: 2.76, 5.02, 7, 8, 13, 13.6 TeV, Black bars: theory prediction

It is a **long journey**, but **several milestones have been posed and we are on the road to study the most intimate part of the Standard Model!!**

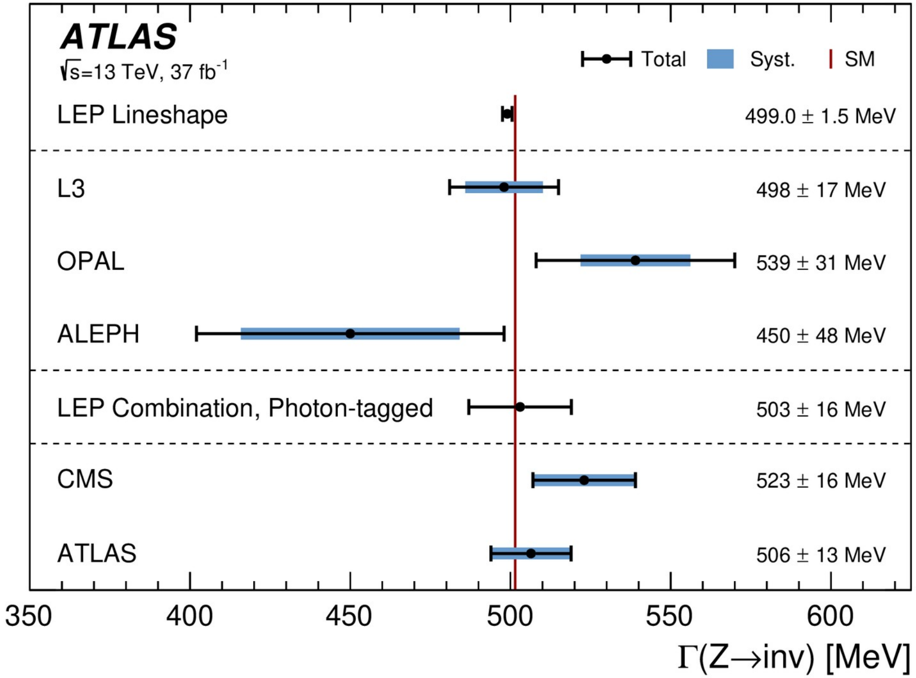
W and Z

arXiv:2403.12902



The measurements are in **agreement** with SM **predictions** calculated at NNLO in α_s, NNLL accuracy and NLO electroweak accuracy.

arXiv:2312.02789

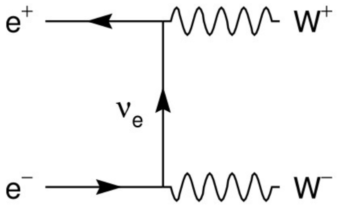


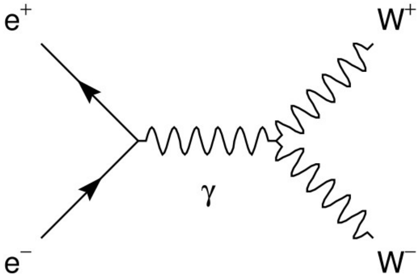
Result in **agreement** with the most precise **measurement** from LEP and the SM **prediction** based on 3 neutrino generations.

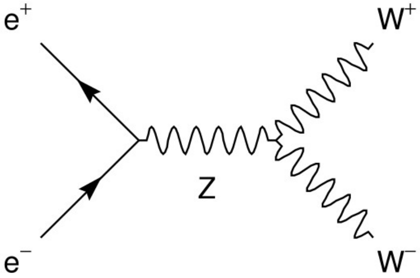
Multiboson production is important

- **Test of the non-Abelian gauge structure of the Electroweak theory** of the Standard Model
- **Test of standard model couplings**
  - In vector boson scattering processes, the unitarity is preserved via Higgs contributions, if not the **cross section rise as a function of the invariant mass of the $V_L V_L$ system**
  - **Test the couplings** between the Higgs and gauge bosons
- Search for **new physics**
  - Through **resonances,** if the new particle mass is accessible w/ LHC energies
  - Through **deviations,** if the energy scale of new physics is higher than those reachable at the LHC

Test of the non-Abelian structure of the SM

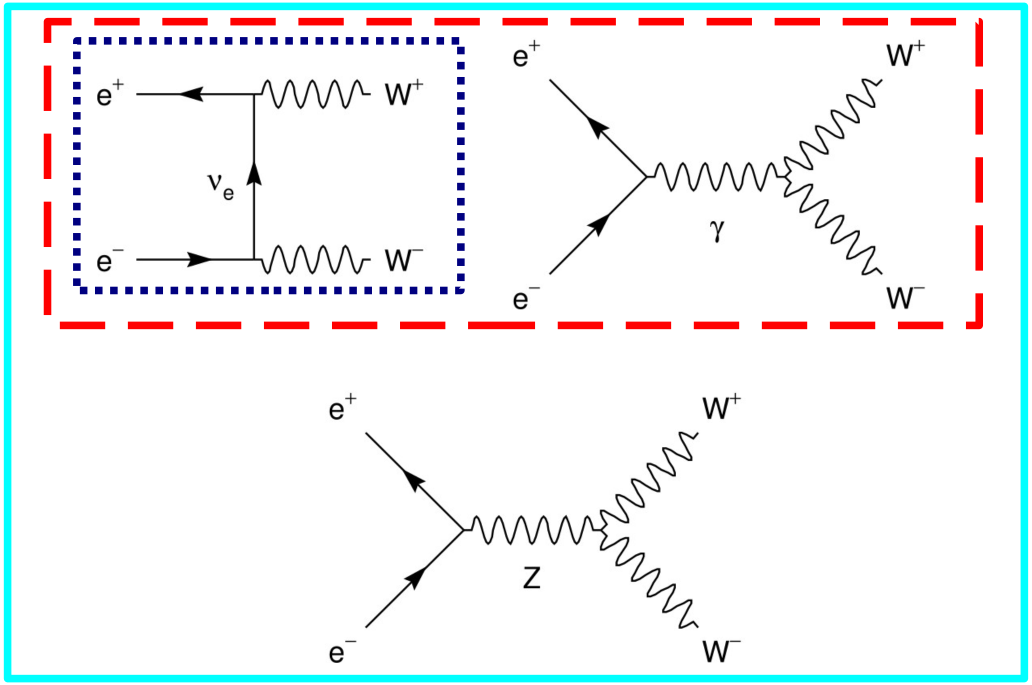


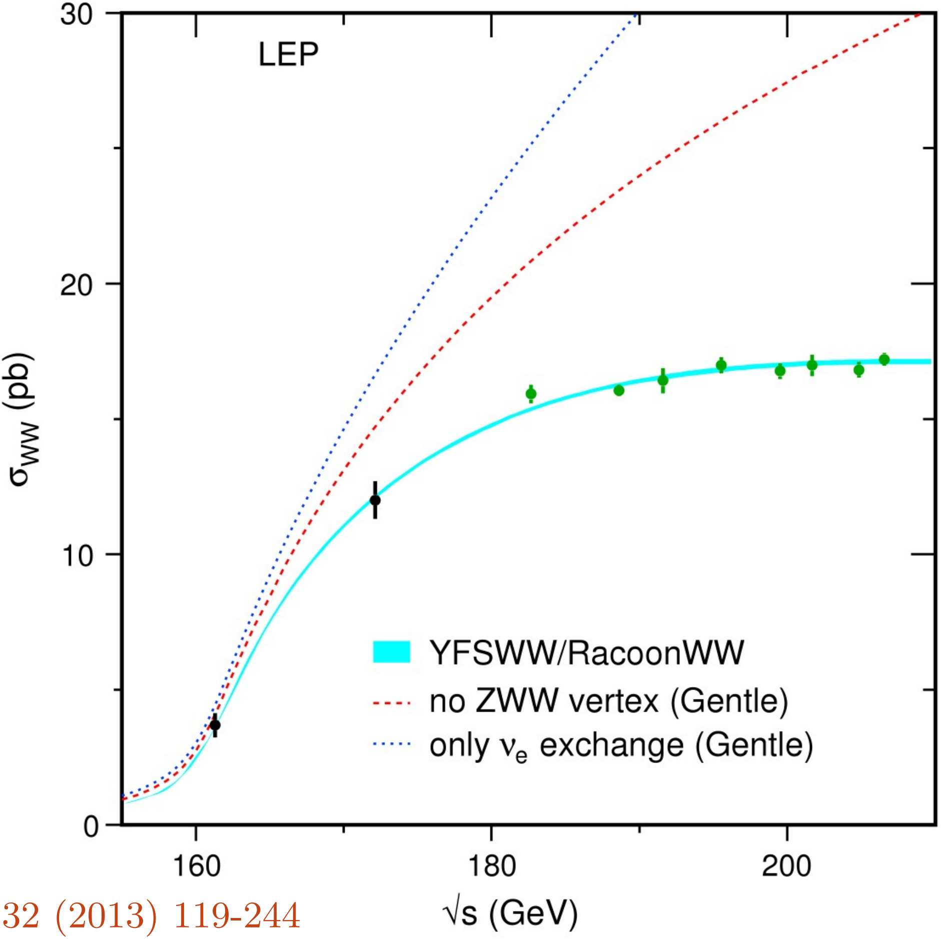




Physics Reports 532 (2013) 119-244

Test of the non-Abelian structure of the SM





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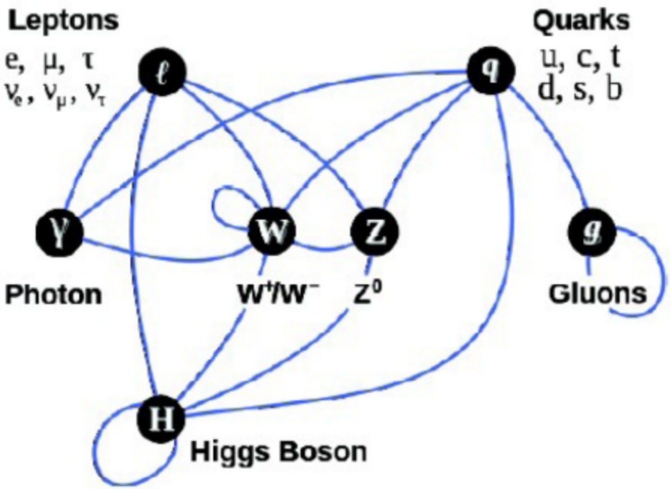
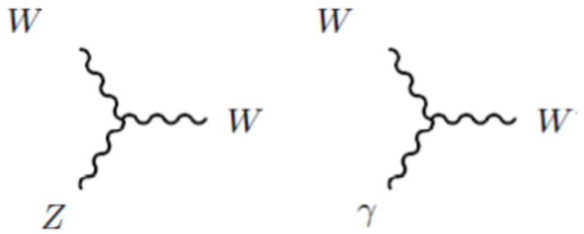
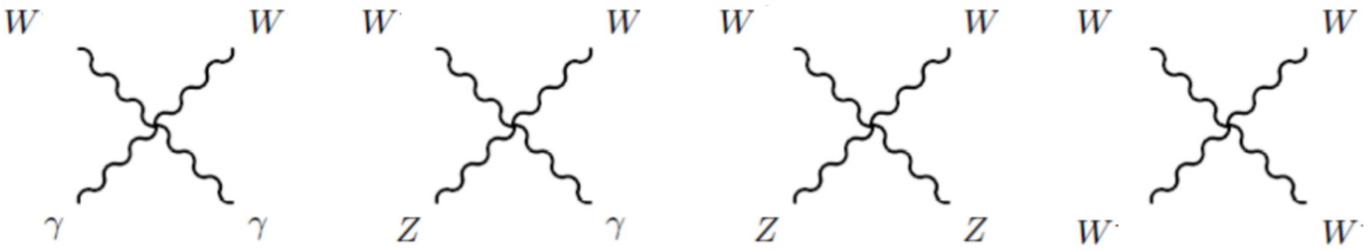


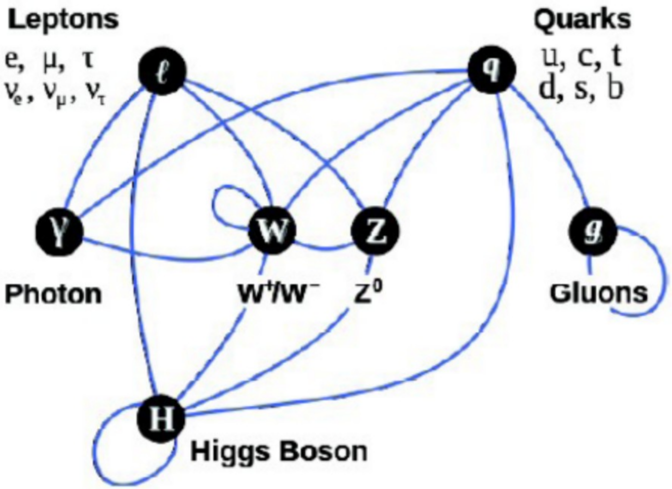
- **Triple gauge couplings (TGC)**



- **Quartic gauge couplings (QGC)**



Test of the non-Abelian structure of the SM



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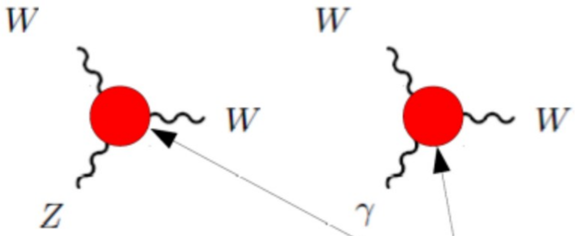
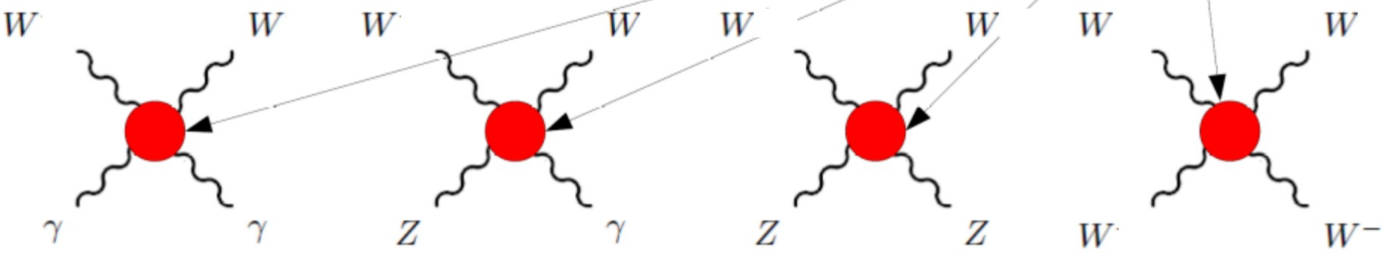
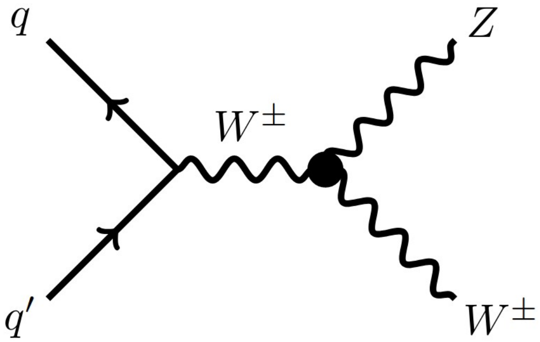


Anomalous couplings
+ what forbidden in SM

- **Quartic gauge couplings (QGC)**



Parametrization of new physics: Anomalous Gauge Couplings



Traditional parametrization for diboson production (assuming CP conservation, Lorentz invariance, $U_{QED}(1)$ gauge invariance)

$$\mathcal{L}_{WWZ} = -ig\cos\theta_W \Big[g_1^Z (W^+_{\mu\nu} W^{-\mu} Z^\nu - W^-_{\mu\nu} W^{+\mu} Z^\nu) + \kappa^Z W^+_\mu W^-_\nu Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2} W^+_{\rho\mu} W^{-\mu}_{\ \nu} Z^{\nu\rho} \Big]$$

$$\mathcal{L}_{WW\gamma} = -ie \Big[(W^+_{\mu\nu} W^{-\mu} A^\nu - W^-_{\mu\nu} W^{+\mu} A^\nu) + \kappa^\gamma W^+_\mu W^-_\nu F^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W^+_{\rho\mu} W^{-\mu}_{\ \nu} F^{\nu\rho} \Big]$$

with

$$g_1^Z = 1 + \delta g_1^Z, \;\; \kappa^{Z,\gamma} = 1 + \delta\kappa^{Z,\gamma}$$

and from SU(2) invariance

$$\delta g_1^Z = \delta\kappa^Z + \frac{s_W^2}{c_W^2}\delta\kappa^\gamma$$

$$\lambda^\gamma = \lambda^Z$$

Annals Phys. 335 (2013) 21-32

Parametrization of new physics: SM Effective Field Theory (SMEFT)

We can add to the SM lagrangian a series of dimension > 4 operators with a "new physics" cutoff Λ:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{d,k} \frac{C_k^d}{\Lambda^{d-4}} \mathcal{O}_k^d$$

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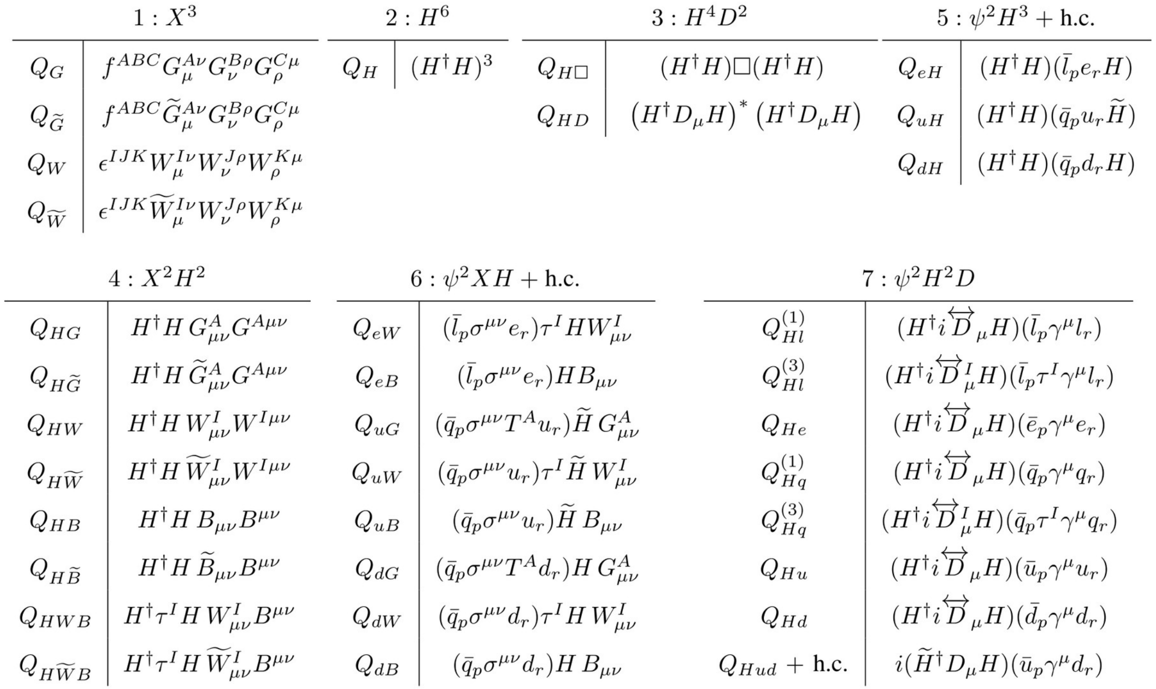
For example, for d = 6, we can have operators like



$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde H\, G_{\mu\nu}^A$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde H\, W_{\mu\nu}^I$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar q_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

JHEP10(2010)085

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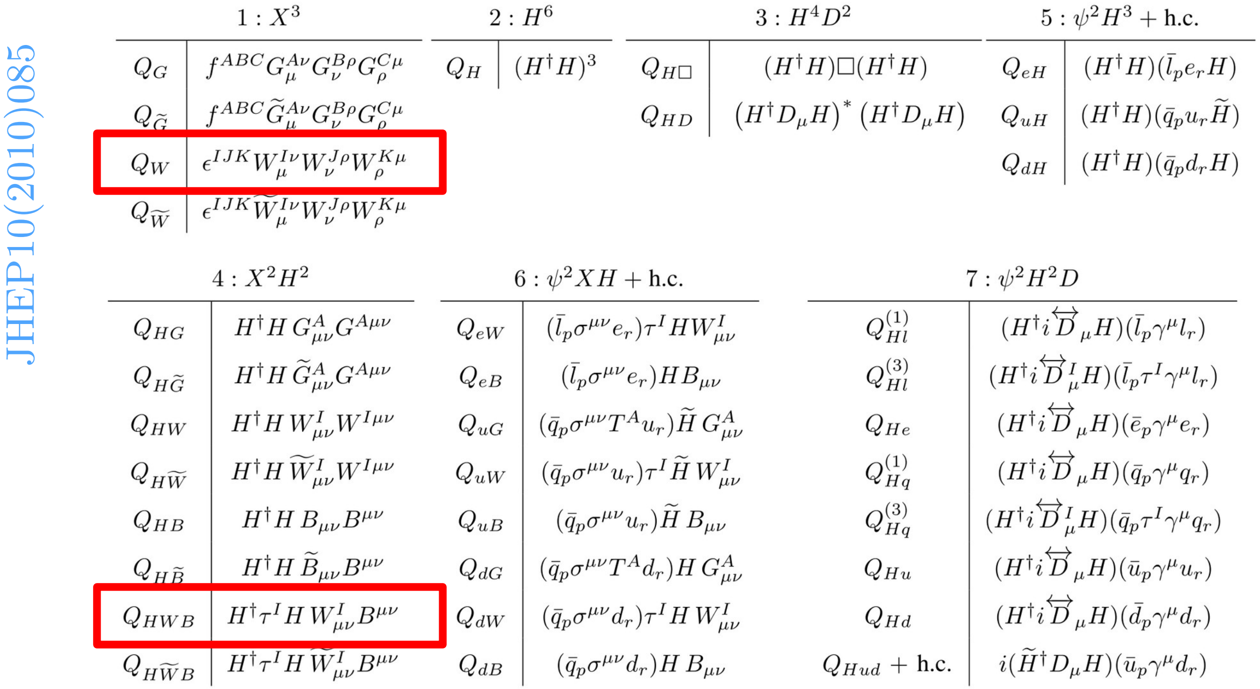
For example, for d = 6, we can have operators like



$1:X^3$		$2:H^6$		$3:H^4D^2$		$5:\psi^2H^3 + \mathrm{h.c.}$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4:X^2H^2$		$6:\psi^2XH + \mathrm{h.c.}$		$7:\psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar l_p\tau^I\gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
Q_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$Q_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

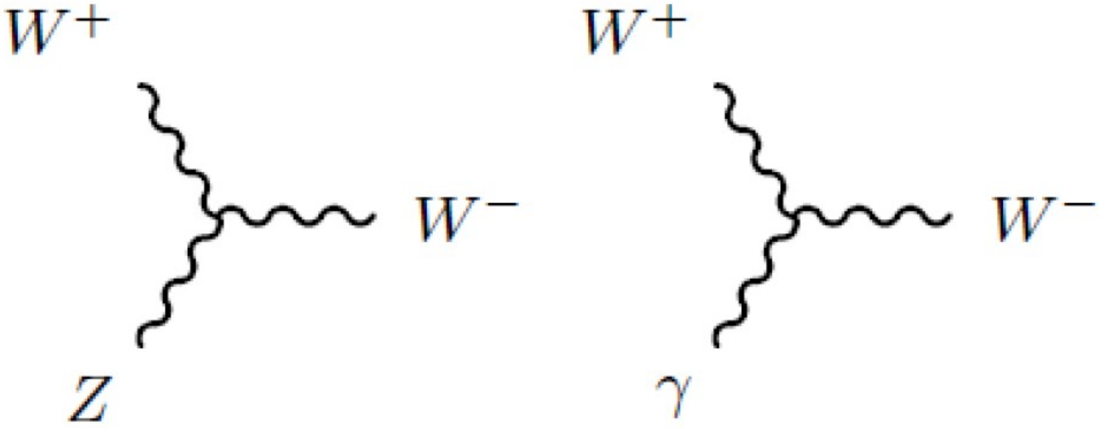
JHEP10(2010)085

In case we truncate the series to **d = 6**, then we have a simple relation with the aTGC view

$$\delta\kappa^\lambda = -\frac{v^2}{\Lambda^2}\frac{c_W}{s_W}C_{HWB}, \quad \lambda^Z = \frac{v}{\Lambda^2}3M_W C_W$$

The EFT is more general and in present days is the preferred framework for the interpretation of the experimental results

TGC, where to find them



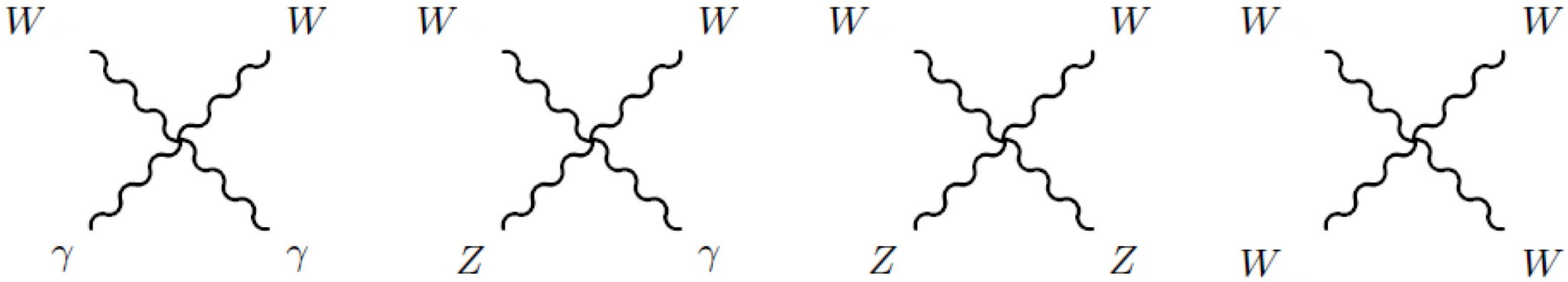
Can be probed in:

single boson production, especially in the VBF channel,

diboson production, inclusive and VBS,

triboson production.

QGC, where to find them



Now things become nastier, because QGC are *one order higher in EW* with respect to TGC, therefore processes mediated by a QGC can also mediated by one or more TGC.

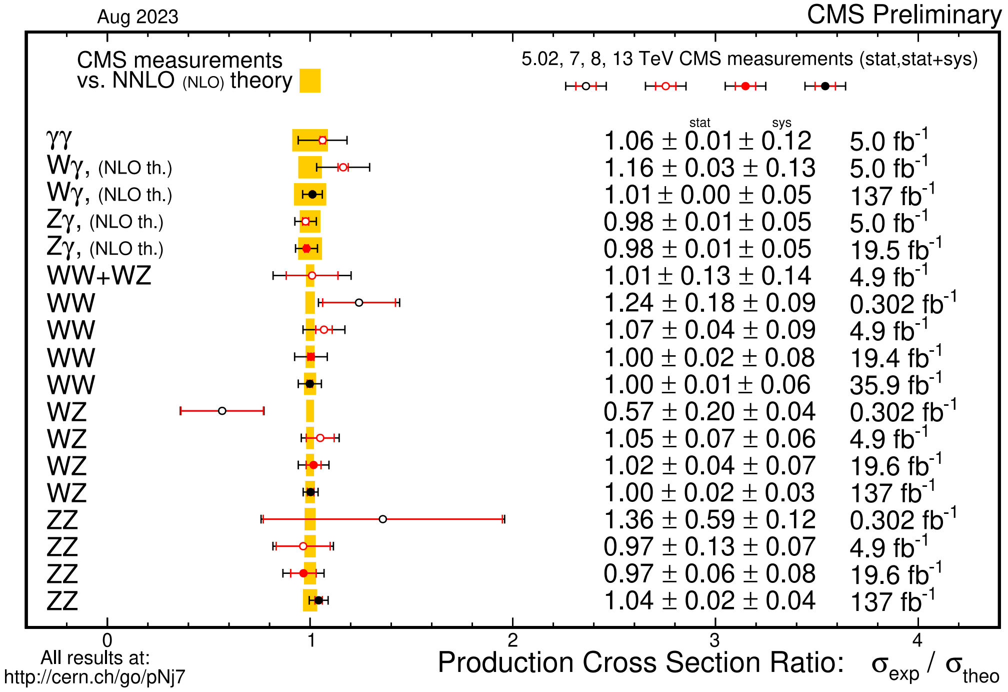
Processes particularly sensitive to them are:

diboson production via VBS and central exclusive production;

triboson production

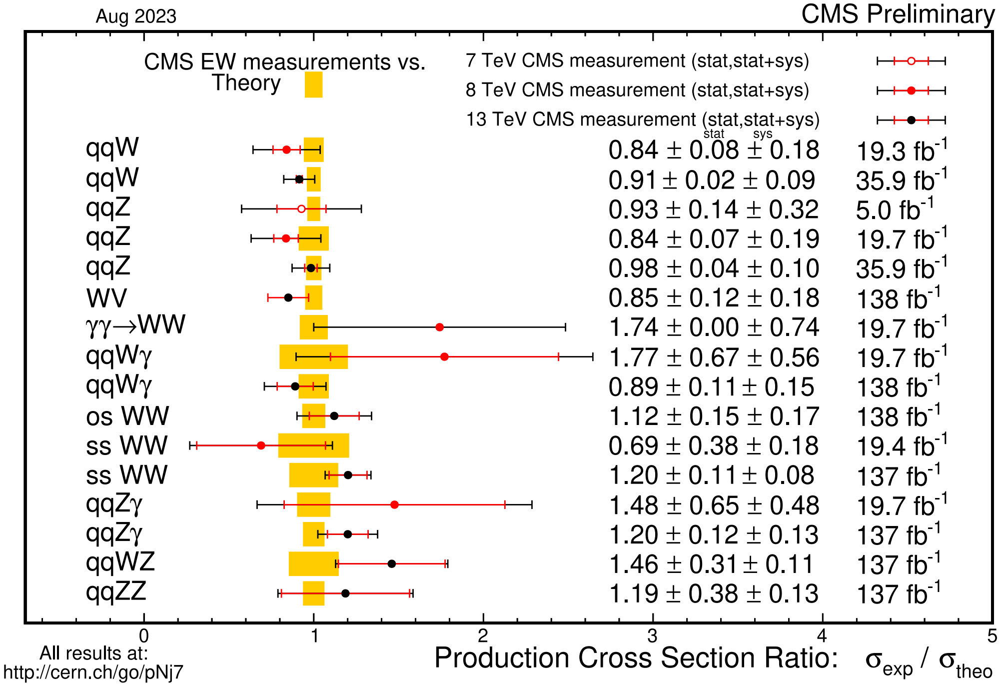
An overview on diboson measurements

di-boson



Inclusive production

VBS



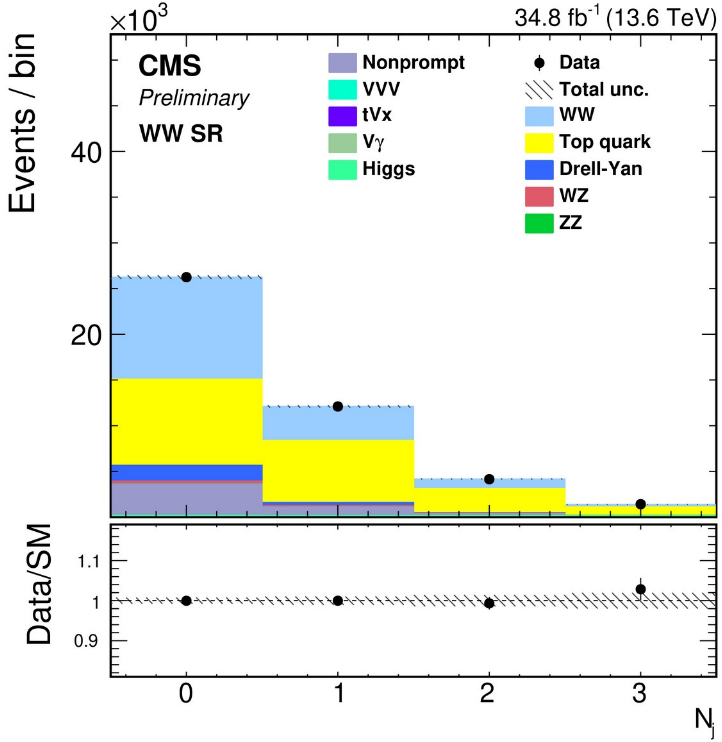
VBS production

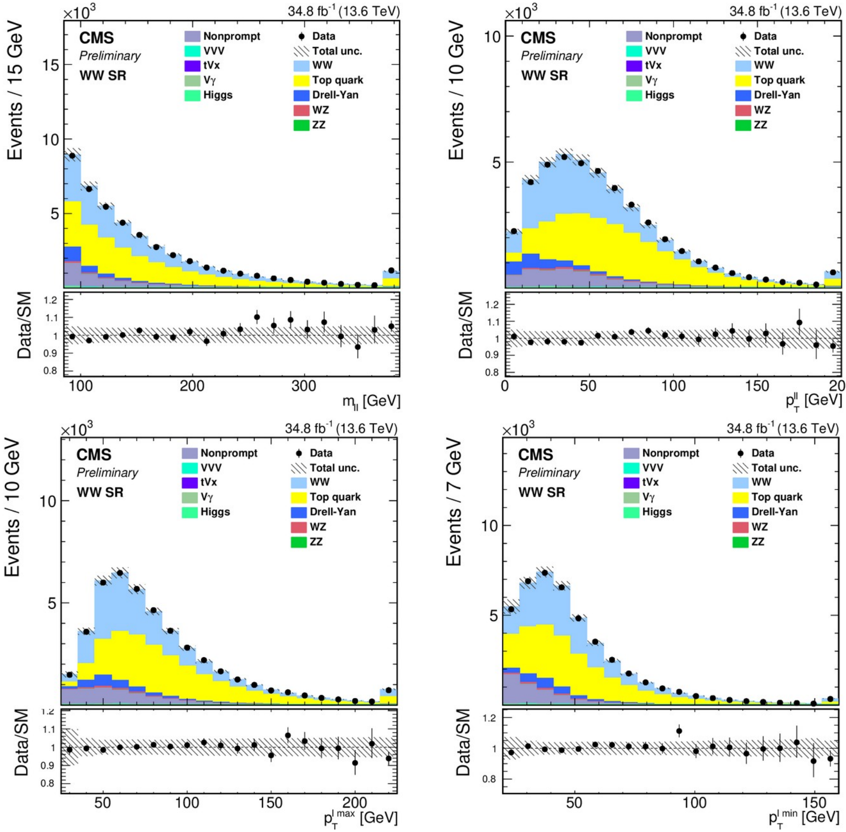
Similarly for ATLAS, see ATL-PHYS-PUB-2023-039 fig. 9

$pp \rightarrow W^+W^- \rightarrow \mu\nu_\mu e\nu_e$ CMS-SMP-2024-001

First measurement of opposite-sign WW production at $\sqrt{s} = 13.6$ TeV ($\mathscr{L}$=34.8 fb^{-1})

Max likelihood fit on different event categories defined by flavour and charge of the leptons, number of jets, and b-tagging





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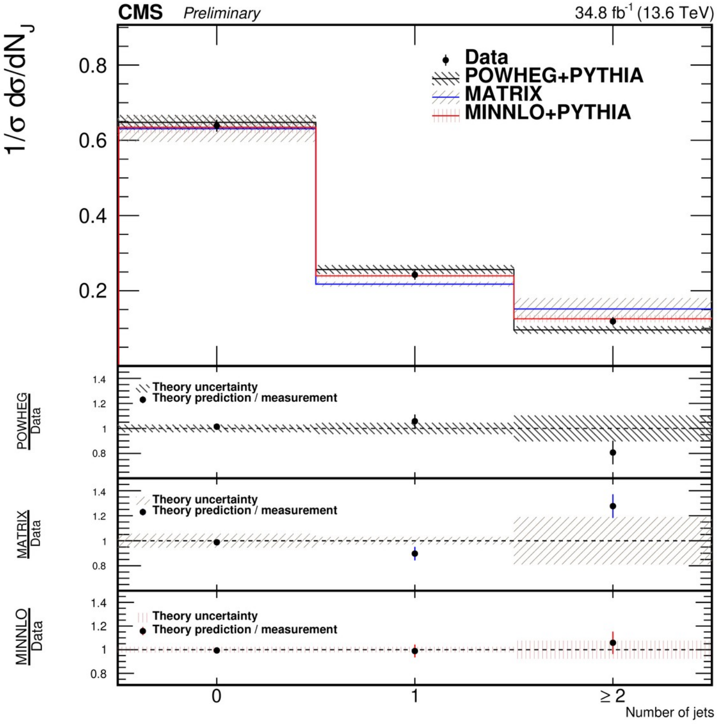
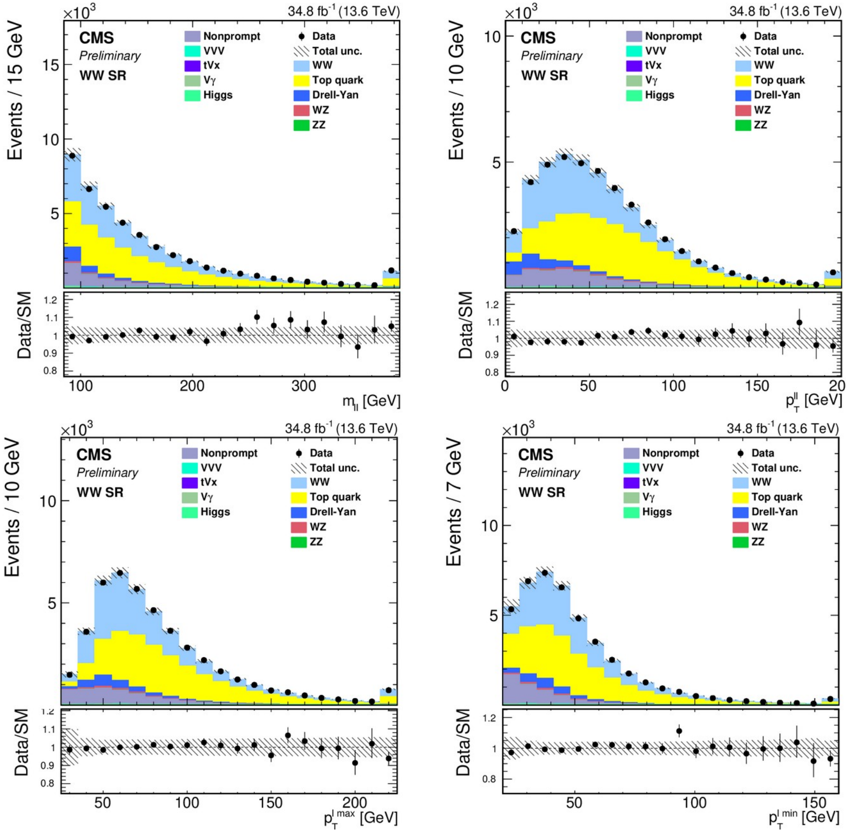
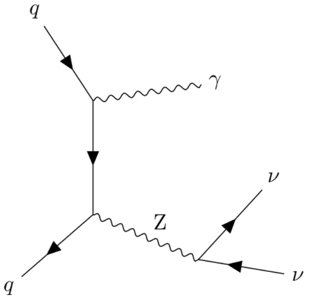
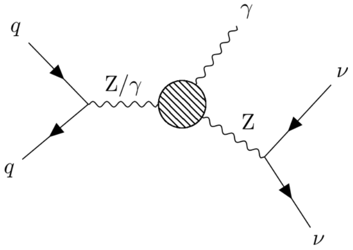




$pp \to Z\gamma \to \nu\nu\gamma$

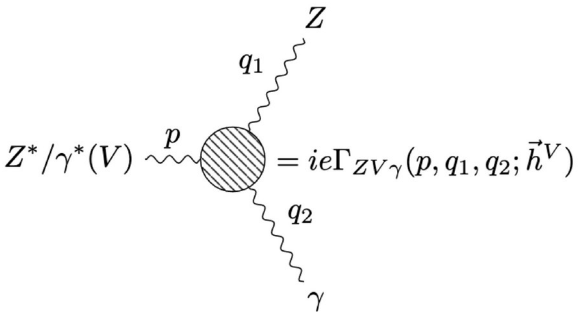
CMS-SMP-2022-009





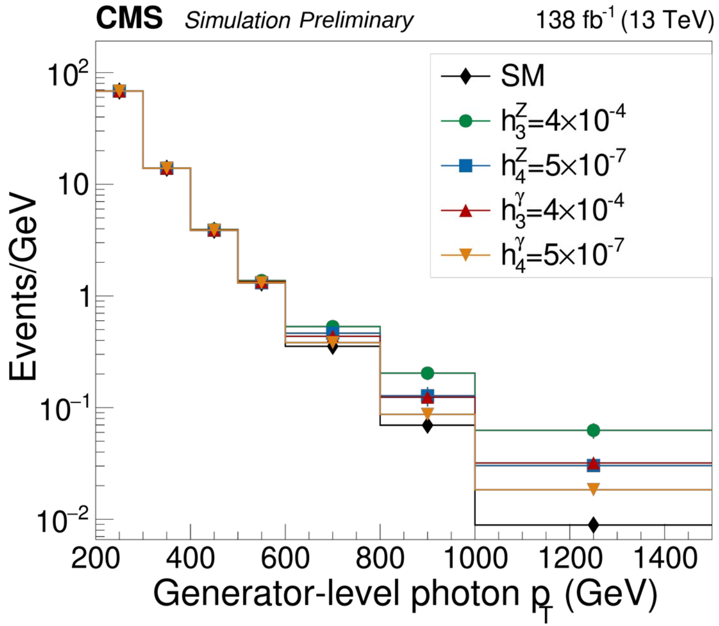
Very powerful process to study anomalous TGC, in fact, this analysis provides the **most stringent CMS limits** to date. Parametrize the anomalies as

$$\Gamma^{\alpha\beta\mu}_{ZZ\gamma} = \frac{p^2 - q_1^2}{m_Z^2}\left[h_1^Z(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^Z}{m_Z^2}p^\alpha\left[(p\cdot q_2)g^{\mu\beta} - q_2^\mu p^\beta\right] + h_3^Z\epsilon^{\mu\alpha\beta\rho}q_{2\rho} + \frac{h_4^Z}{m_Z^2}p^\alpha\epsilon^{\mu\beta\rho\sigma}p_\rho q_{2\sigma}\right],$$



$\Gamma^{\alpha\beta\mu}_{Z\gamma\gamma}$ is given by the replacement

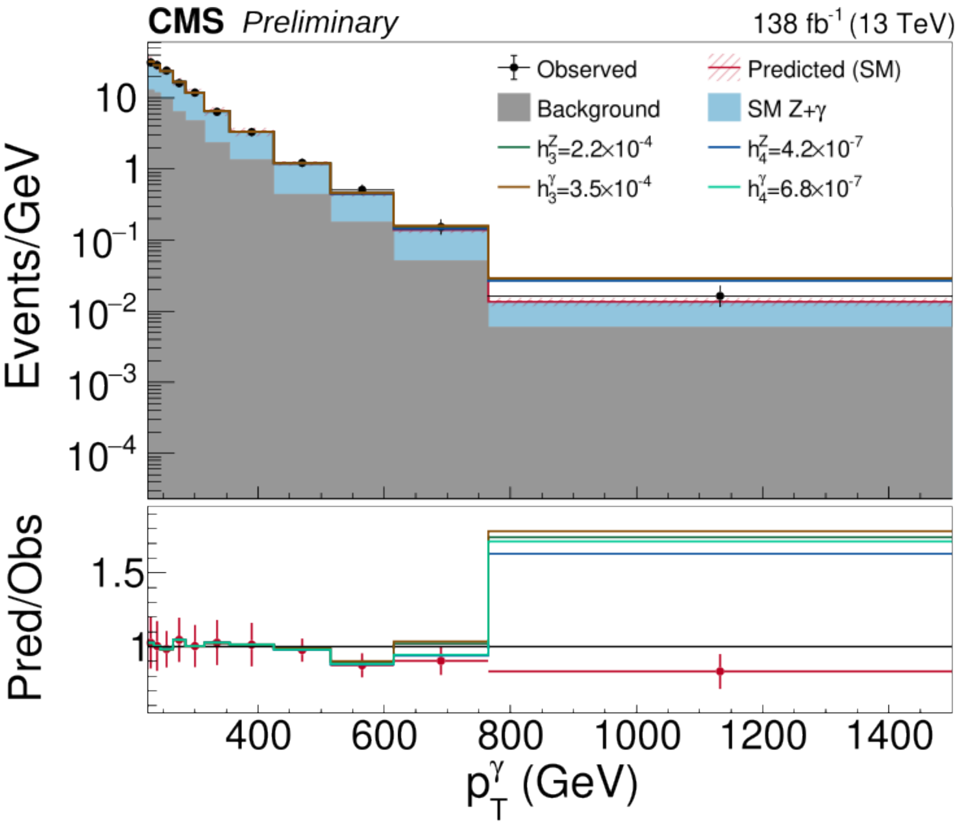
$$\frac{p^2 - q_1^2}{m_Z^2} \to \frac{p^2}{m_Z^2} \text{ and } h_i^Z \to h_i^\gamma$$

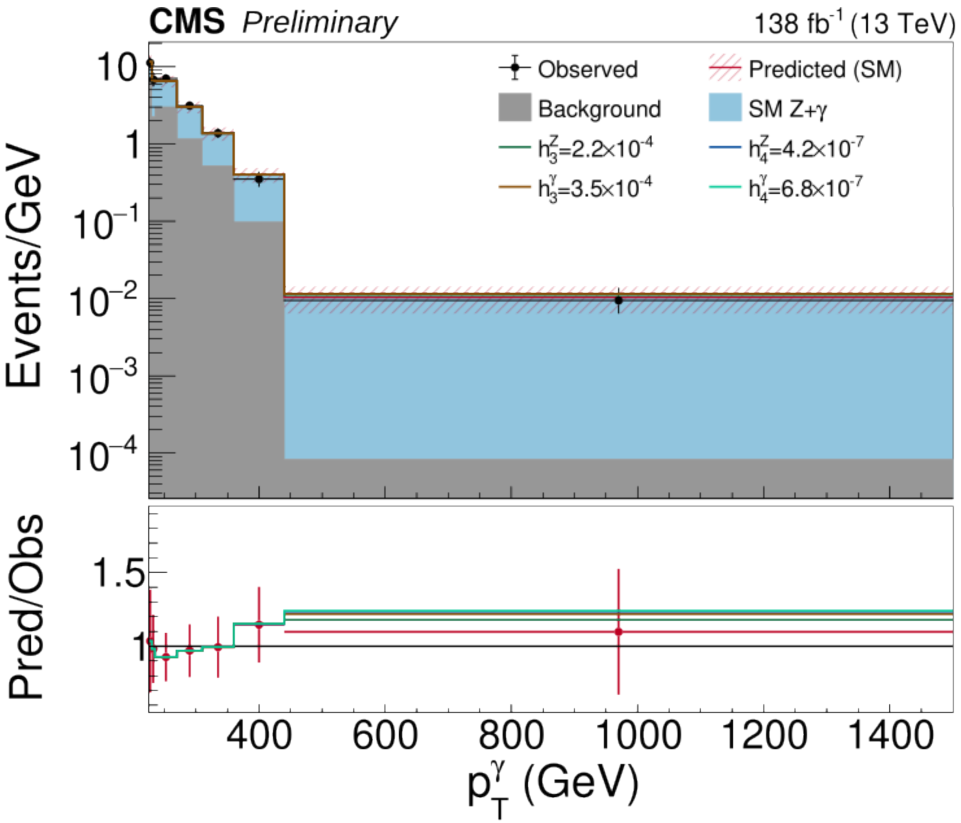


Analysis put **limits on CP-conserving operators h_3^V and h_4^V**.

$pp \to Z\gamma \to \nu\nu\gamma$

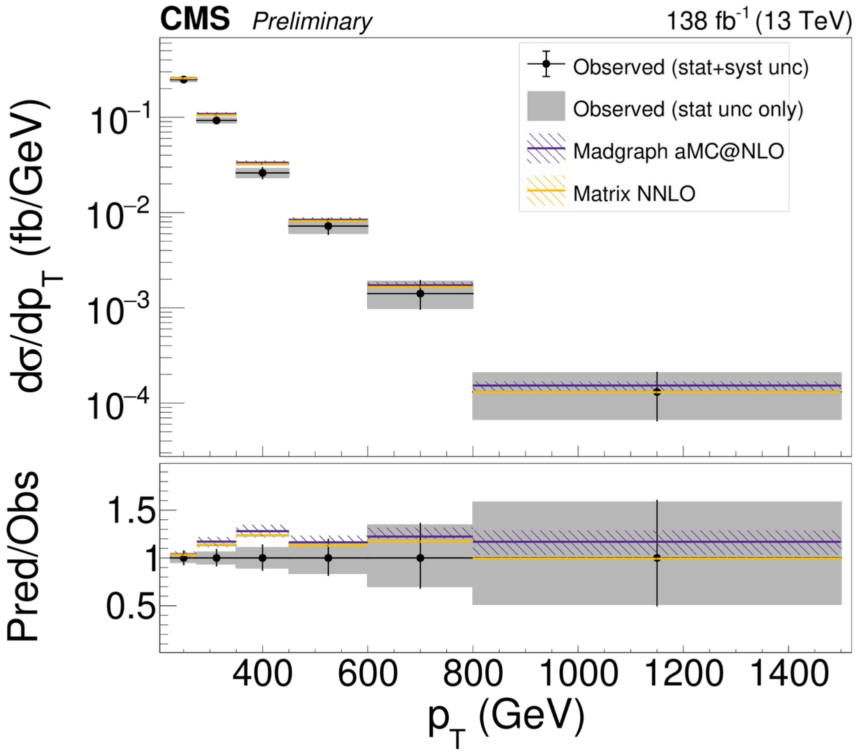
CMS-SMP-2022-009



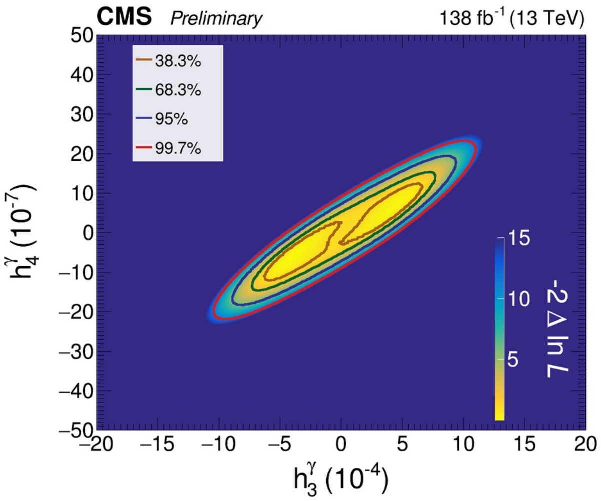


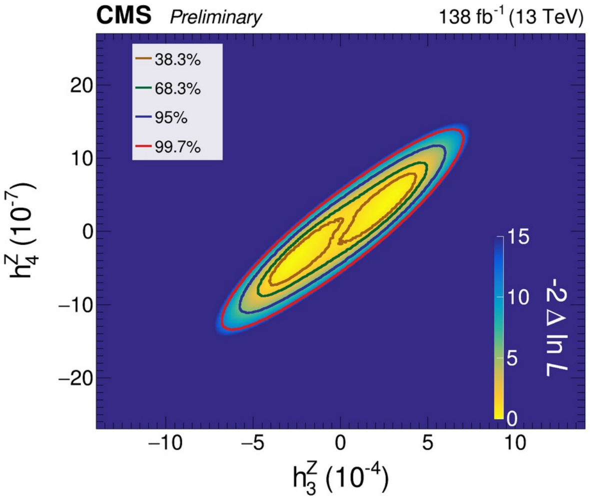
$pp \rightarrow Z\gamma \rightarrow \nu\nu\gamma$

CMS-SMP-2022-009



$$\sigma(Z\,\gamma) = 26.1^{+1.6}_{-1.5}\, fb$$

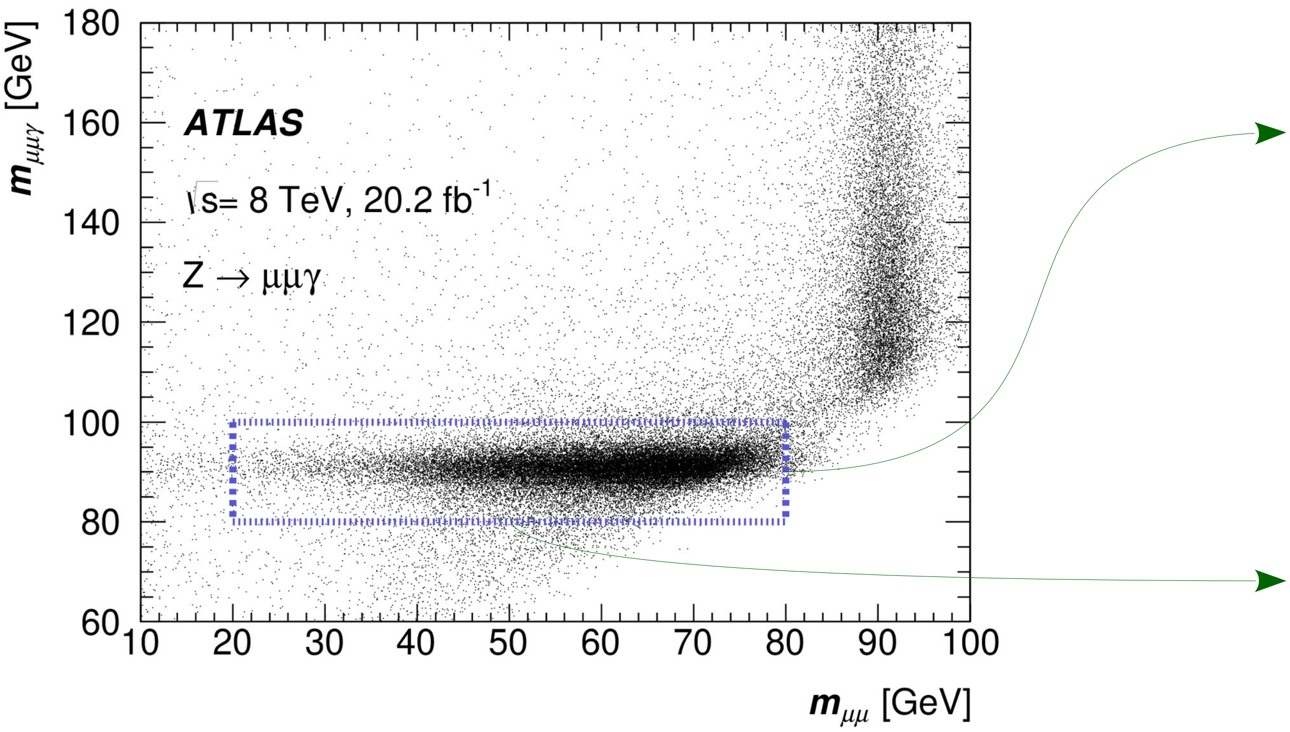


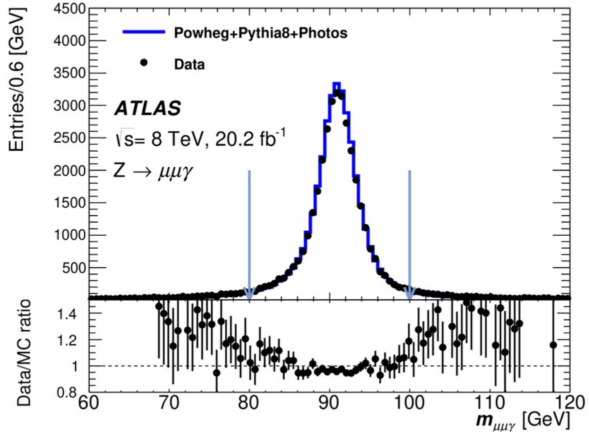


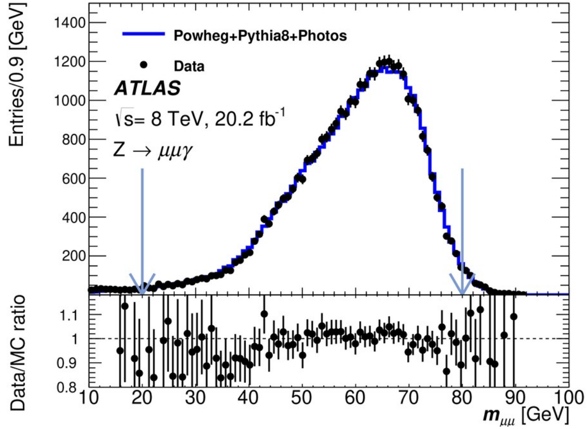
$Z \to \ell\ell\gamma$

ATLAS-STDM-2017-05
EPJ C 84 (2024) 195

Very related to Zγ diboson measurement. **This analysis targets the production of the photon(s) through Final State Radiation (FSR)**



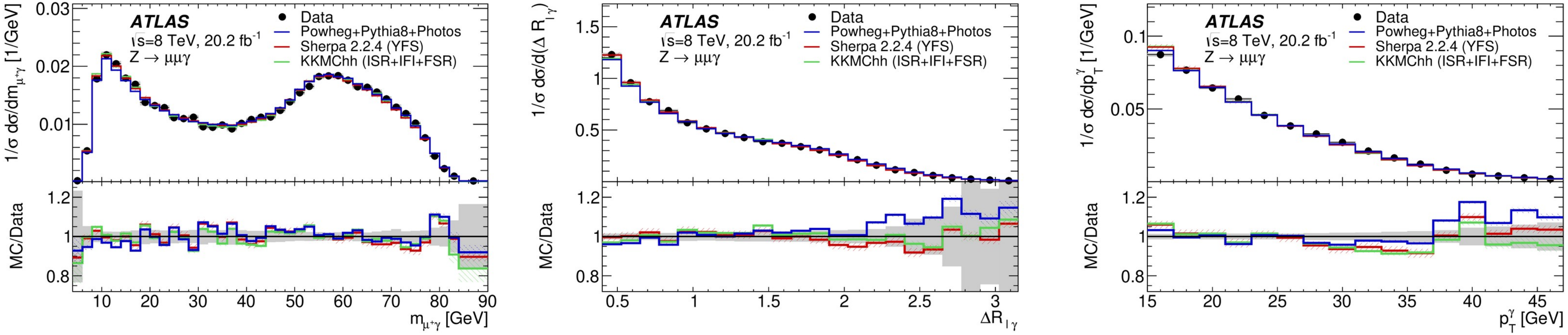




$Z \to \ell\ell\gamma$

ATLAS-STDM-2017-05
EPJ C 84 (2024) 195

The measurement results are presented as unfolded normalised differential cross-sections for the **3 observables**: the *invariant mass of the positively charged lepton and the photon*, the *angular distance between the photon and the closer of the two leptons*, and the *transverse momentum of the photon*.

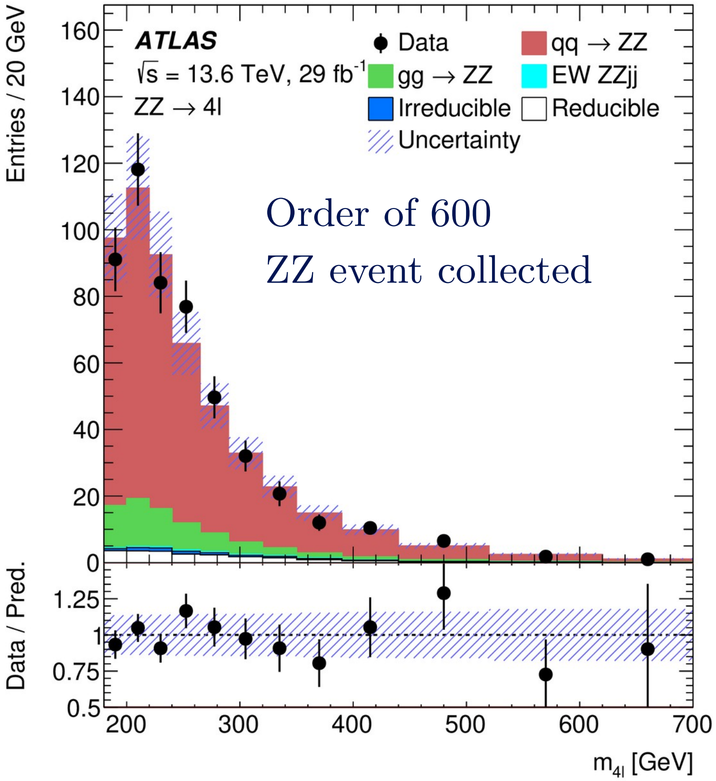


In the analysis' paper is also reported the **first observation of $Z \to \ell\ell\gamma\gamma$**, with the corresponding differential cross sections.

pp → ZZ → 4 (ℓ=e,μ)

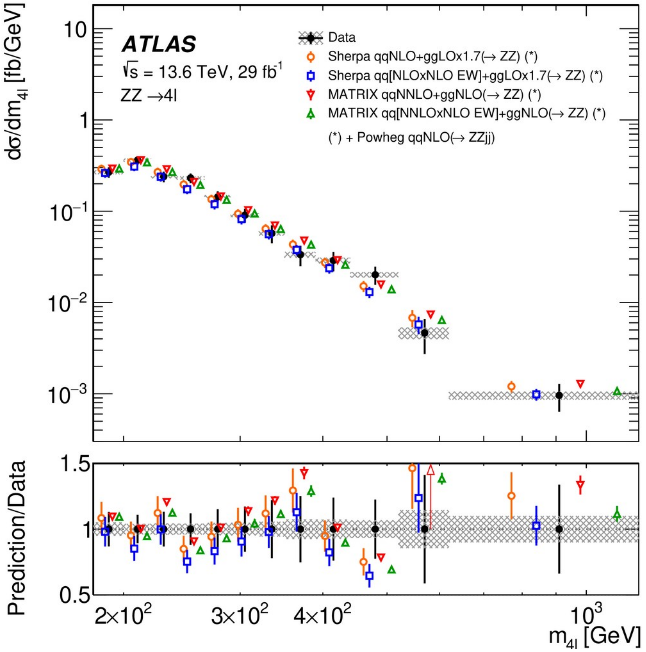
arXiv:2311.09715

First di-boson measurement at LHC at √s = **13.6 TeV** ($\mathscr{L}$=29 fb^{-1})



Order of 600 ZZ event collected

Extract measurement of fiducial (+ total) and **differential cross sections**

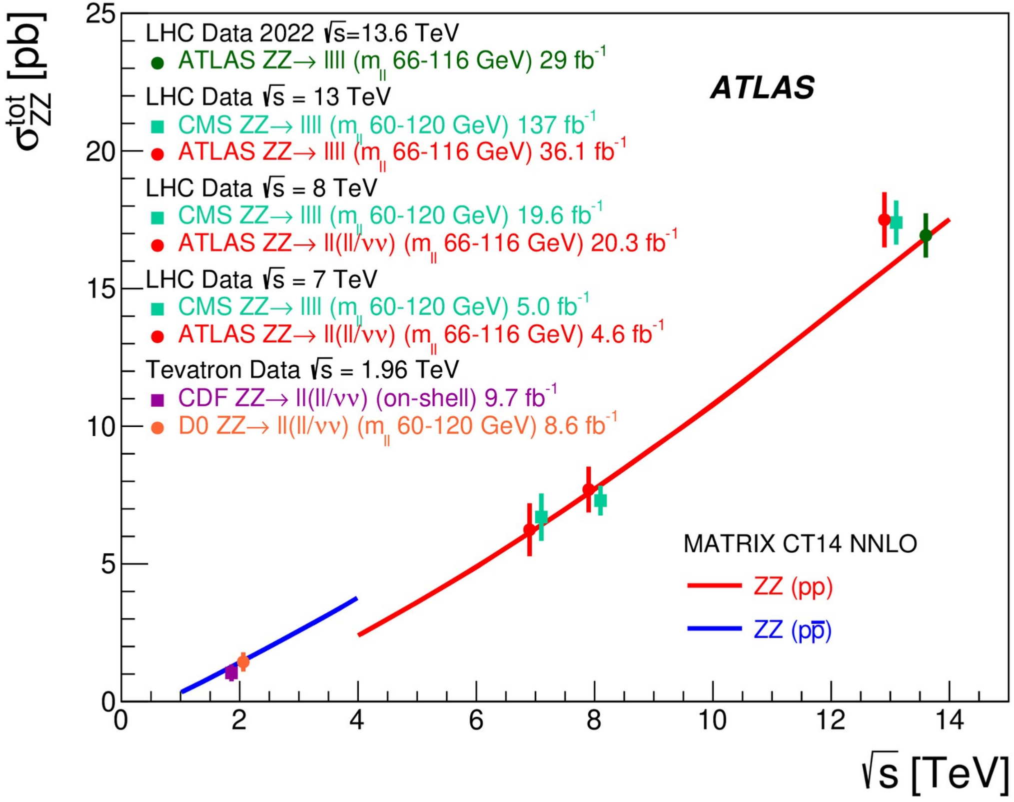


Comparison with several predictions, **All in good agreement**

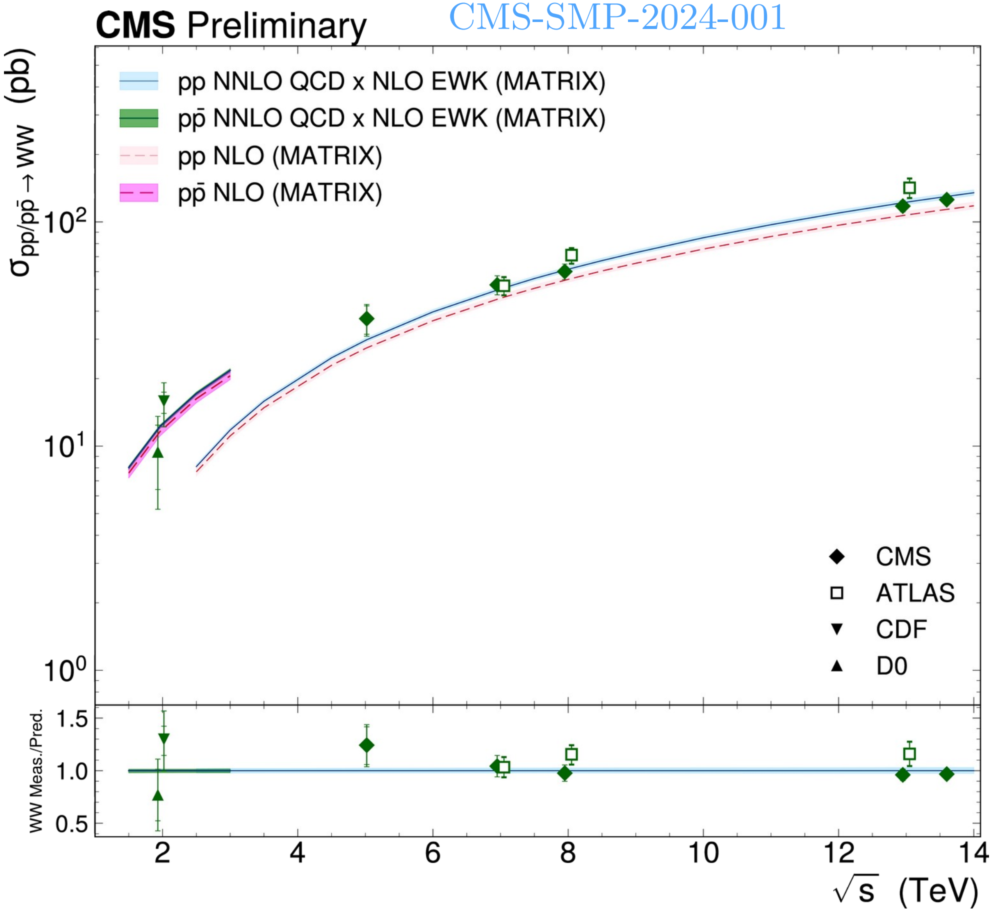
	Measurement	MC prediction	MATRIX prediction
Fiducial	$36.7 \pm 1.6(\text{stat}) \pm 1.5(\text{syst}) \pm 0.8(\text{lumi})$ fb	$36.8\ ^{+4.3}_{-3.5}$ fb	36.5 ± 0.7 fb
Total	$16.8 \pm 0.7(\text{stat}) \pm 0.7(\text{syst}) \pm 0.4(\text{lumi})$ pb	$17.0\ ^{+1.9}_{-1.4}$ pb	16.7 ± 0.5 pb

pp → VV cross sections summary

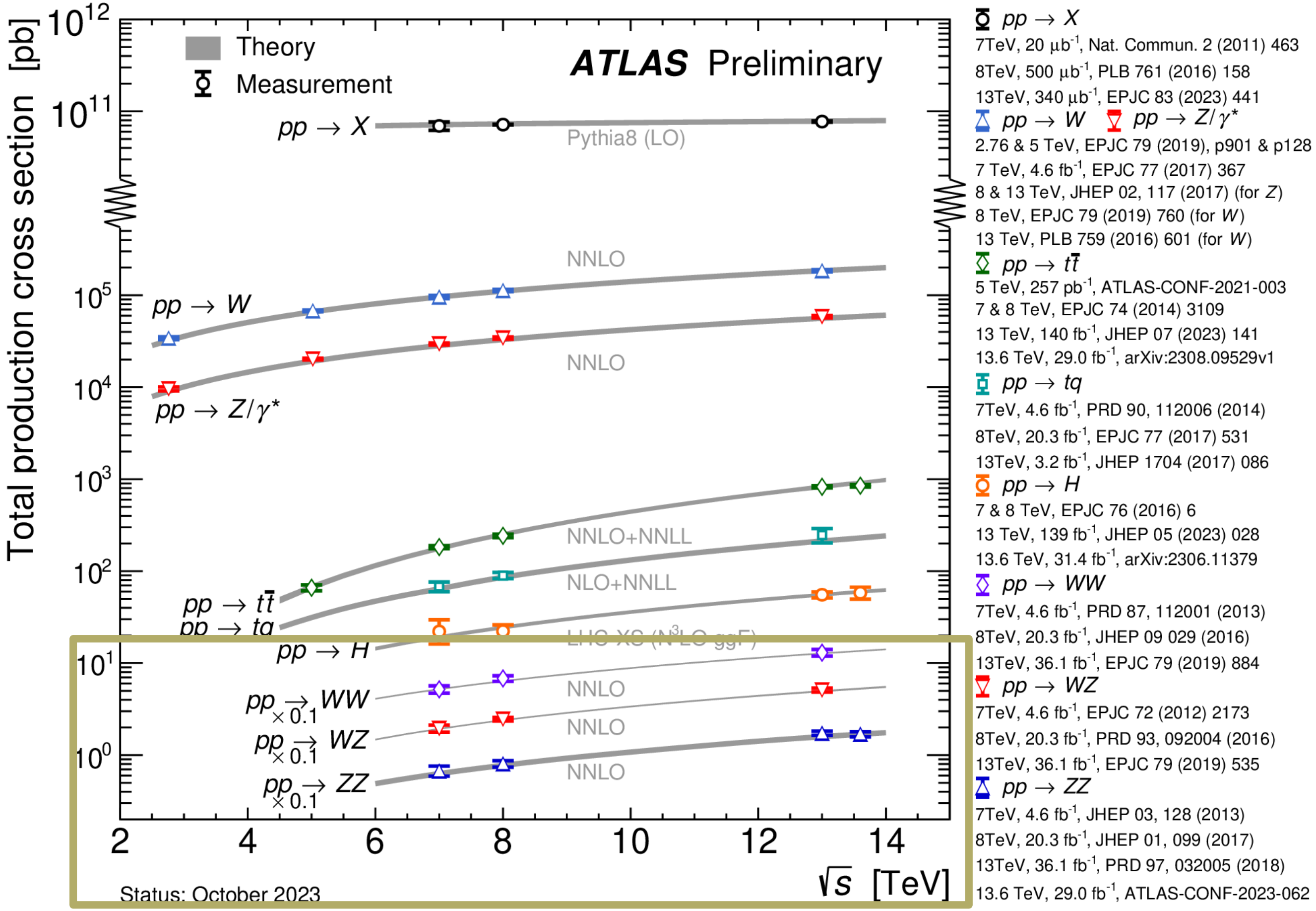
arXiv:2311.09715



CMS-SMP-2024-001



pp → VV cross sections summary



ATL-PHYS-PUB-2023-039

VBS, an introduction

The **longitudinally polarized vector bosons (V_L) are coupled to the Higgs** and they are the ones **sensitive to the EWSB**.

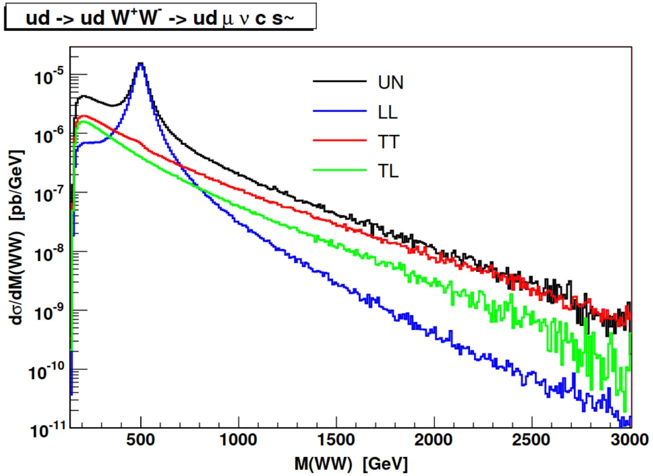
The behavior of the **V_LV_L cross section** only can give information on the **scale at which the symmetry breaks**.

If the cancellation of the **Higgs diagrams is not complete**, then we expect a **g_{HVV} coupling smaller than the SM**.

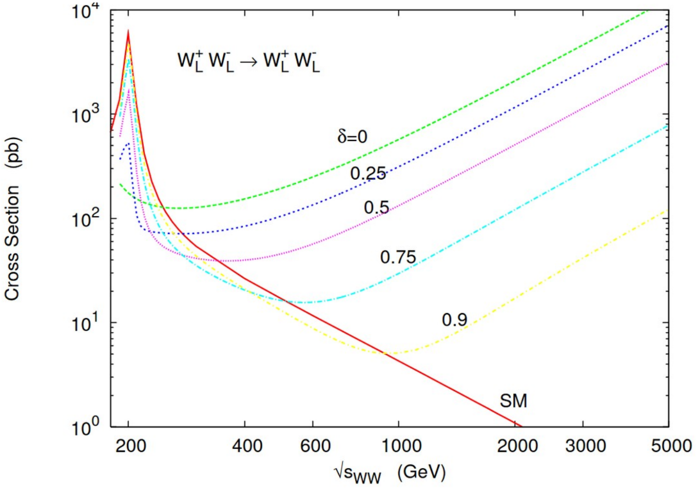
The **V_LV_L will keep growing with √s**, up to the the new resonance, or more generally to the **new physics scale Λ**.

Suppose the Higgs-WW coupling is √δ **of the SM value**, then the amplitudes become

$$
\begin{aligned}
i\mathcal{M}^{\text{gauge}} &= -i\frac{g^2}{4m_W^2}\,u + \mathcal{O}((E/m_W)^0)\\
i\mathcal{M}^{\text{higgs}} &= i\frac{g^2}{4m_W^2}\,u\,\delta + \mathcal{O}((E/m_W)^0)\\
i\mathcal{M}^{\text{all}} &= -i\frac{g^2}{4m_W^2}u(1-\delta) + \mathcal{O}((E/m_W)^0)
\end{aligned}
$$

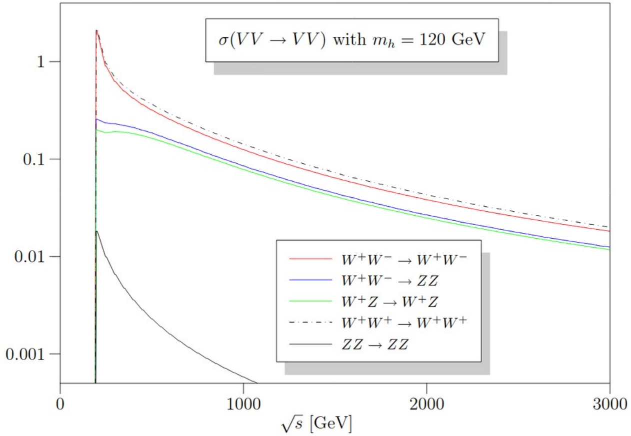


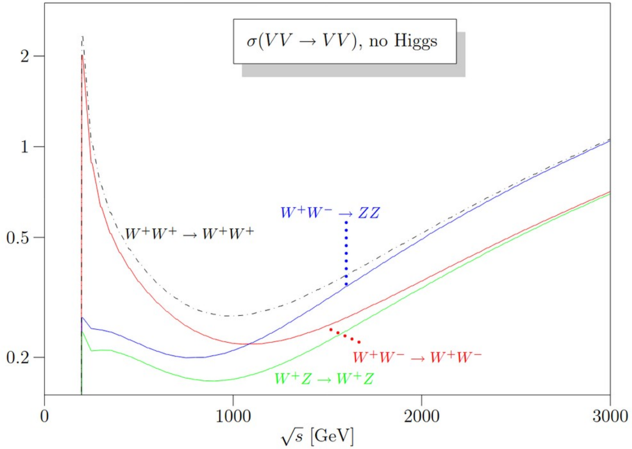
JHEP 03 (2006) 093

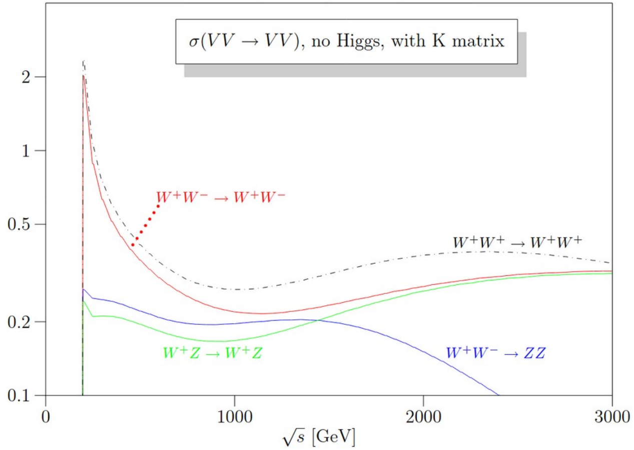


Phys. Rev. D 78 051701

VBS, an introduction







JHEP11(2008)010

Experimentally we should design search regions, and/or develop new techniques, to **enhance $\mathrm{V_LV_L}$ scattering** with respect to $\mathrm{V_TV_T}$ and $\mathrm{V_LV_T}$ and **measure the cross sections at the highest $\mathrm{m_{VV}}$ as possible**.

Contextually, we shall *measure precisely the HVV couplings*.

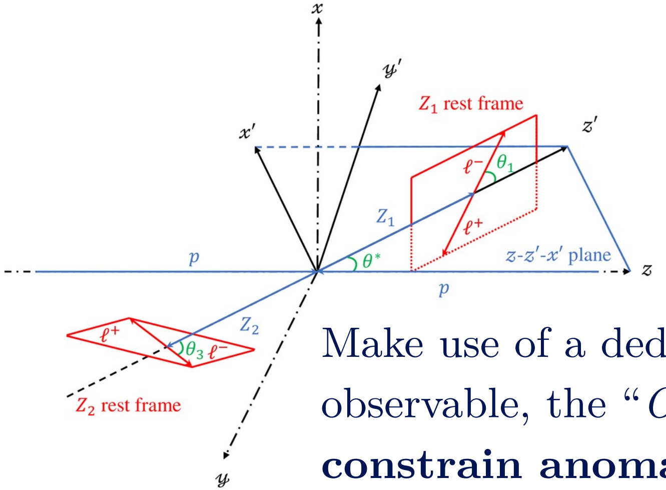
$pp \to Z_LZ_L \to 4\ (\ell = e,\mu)$

ATLAS-STDM-2021-05
JHEP 12 (2023) 107

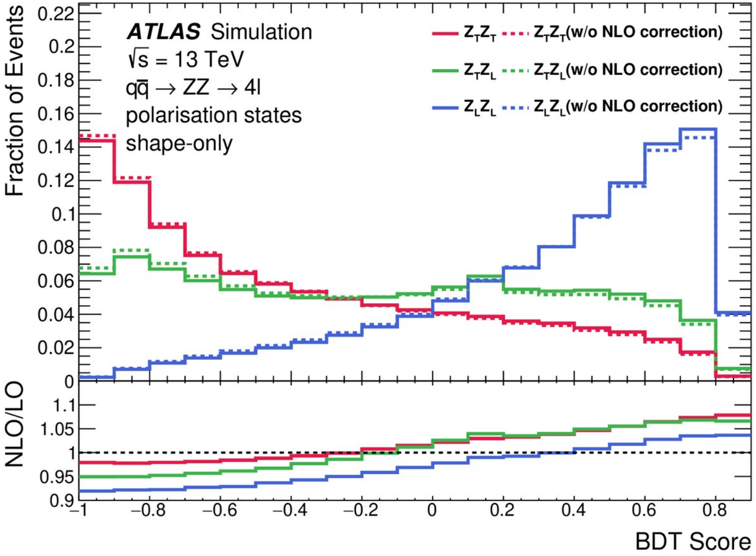
Using the full Run 2 data ($\mathscr{L}$=140 fb^{-1}) it was possible to get **evidence** (4.3σ) **of the production of longitudinally polarized vector bosons** and study the CP properties of the ZZ events

MC templates generated at LO, but employed a three-steps re-weighting method to **incorporate QCD and EW corrections** calculated at fixed order with MoCaNLO

Use a BDT to **separate Z_LZ_L wrt Z_TZ_X**, trained over *lepton and boson angular variables*, then via profile binned maximum-likelihood of the BDT shape extract Z_LZ_L

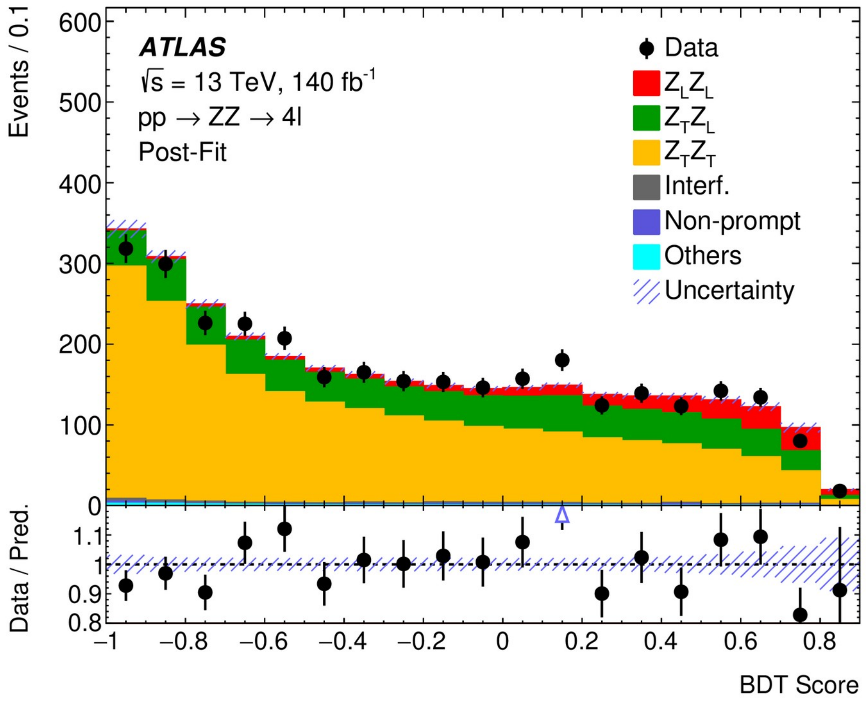


Make use of a dedicated CP-odd angular observable, the "*Optimal Observable*", to **constrain anomalous neutral triple gauge couplings**



pp → $Z_L Z_L$ → 4 (ℓ=e,μ)

ATLAS-STDM-2021-05
JHEP 12 (2023) 107



		Pre-fit	Post-fit
ZZ	$Z_L Z_L$	189.3 ± 8.7	220 ± 54
	$Z_T Z_L$	710 ± 29	711 ± 29
	$Z_T Z_T$	2170 ± 120	2147 ± 60
	Interference	33.7 ± 2.8	33.4 ± 2.7
Non-prompt		18.7 ± 7.1	18.5 ± 7.0
Others		20.0 ± 3.7	19.9 ± 3.7
Total		3140 ± 150	3149 ± 57
Data		3149	3149

$$\sigma^{\mathrm{obs.}}_{Z_L Z_L} = 2.45 \pm 0.56(\mathrm{stat.}) \pm 0.21(\mathrm{syst.})\,\mathrm{fb} = 2.45 \pm 0.60\,\mathrm{fb}$$

$$\sigma^{\mathrm{pred.}}_{Z_L Z_L} = 2.10 \pm 0.09\,\mathrm{fb}$$ (NLO QCD and EW)

$pp \rightarrow Z_L W_L \rightarrow 3\ell\nu$ $(\ell = e,\mu)$

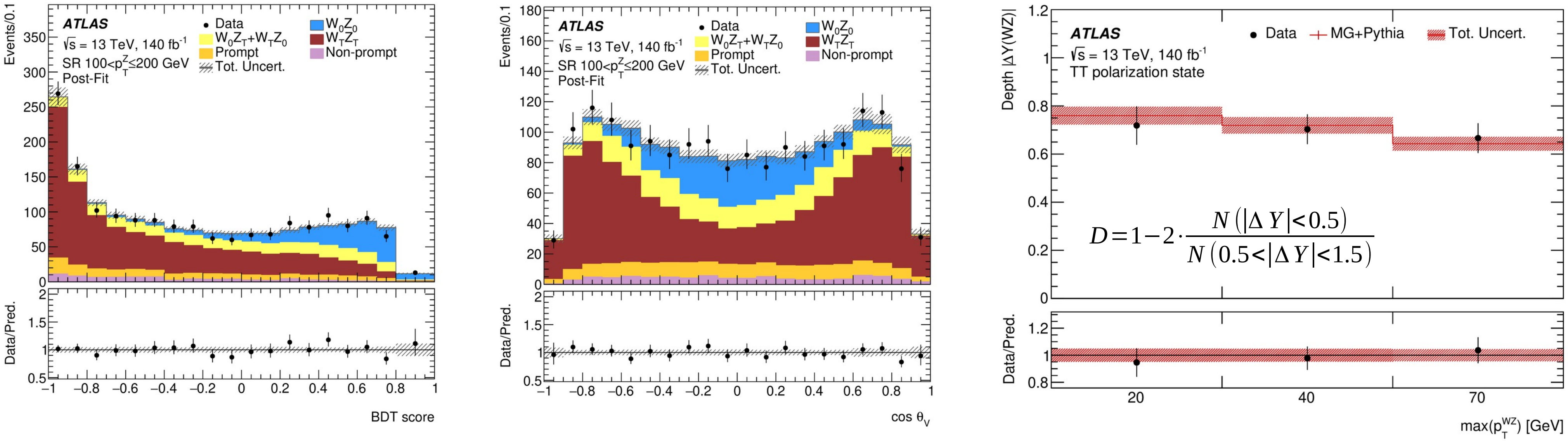
arXiv:2402.16365

Study the **two vector boson with longitudinal polarization** in two p_T^Z regions:

100-200 GeV → observation at 5.3σ and >200 GeV → measurement at 1.6σ.

For both regions $p_T^{WZ} > 70$ GeV.

Additionally, study of the *Radiation Amplitude Zero (RAZ) effect* in three p_T^{WZ} bins < 20, 40 or 70 GeV.



$$D = 1 - 2 \cdot \frac{N(|\Delta Y| < 0.5)}{N(0.5 < |\Delta Y| < 1.5)}$$

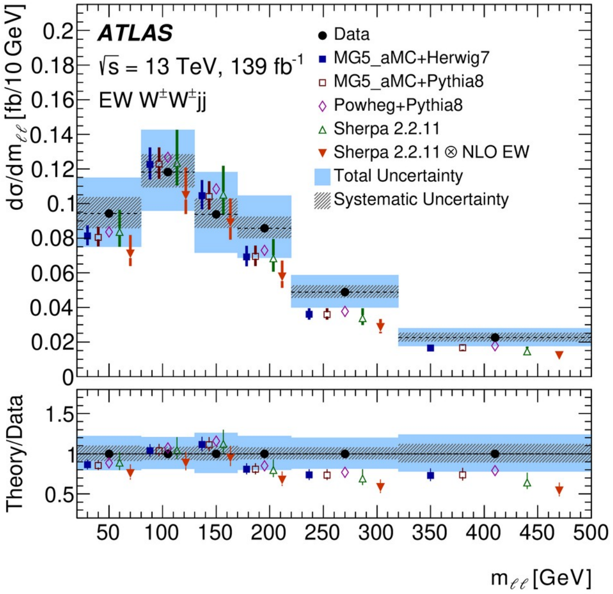
Most recent results on VBS

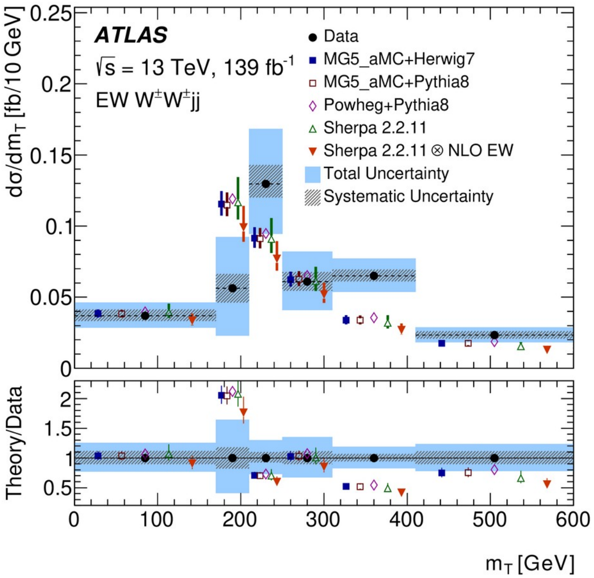
$pp \to W^{\pm}W^{\pm}jj$

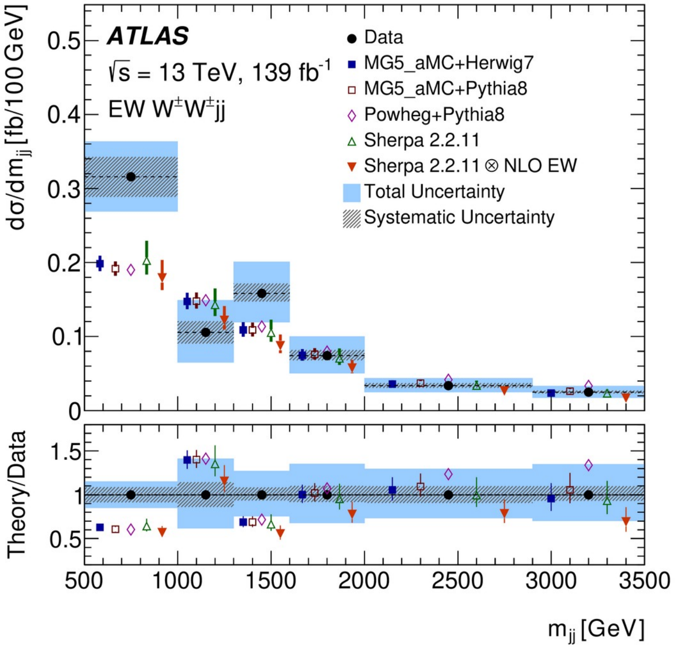
ATLAS-STDM-2018-32
JHEP 12 (2023) 107

Full Run 2 data ($\mathscr{L}$=139 fb^{-1}) analysis in **fully leptonic channel** (e,μ). Measured the EW and inclusive WWjj cross sections: $\boldsymbol{\sigma_{EW} = 2.92 \pm 0.22\ (\text{stat.}) \pm 0.19\ (\text{syst.})\ \text{fb}}$.

Measured the *differential cross section* for both EW and inclusive processes. Some discrepancies found with respect to the MC predictions.





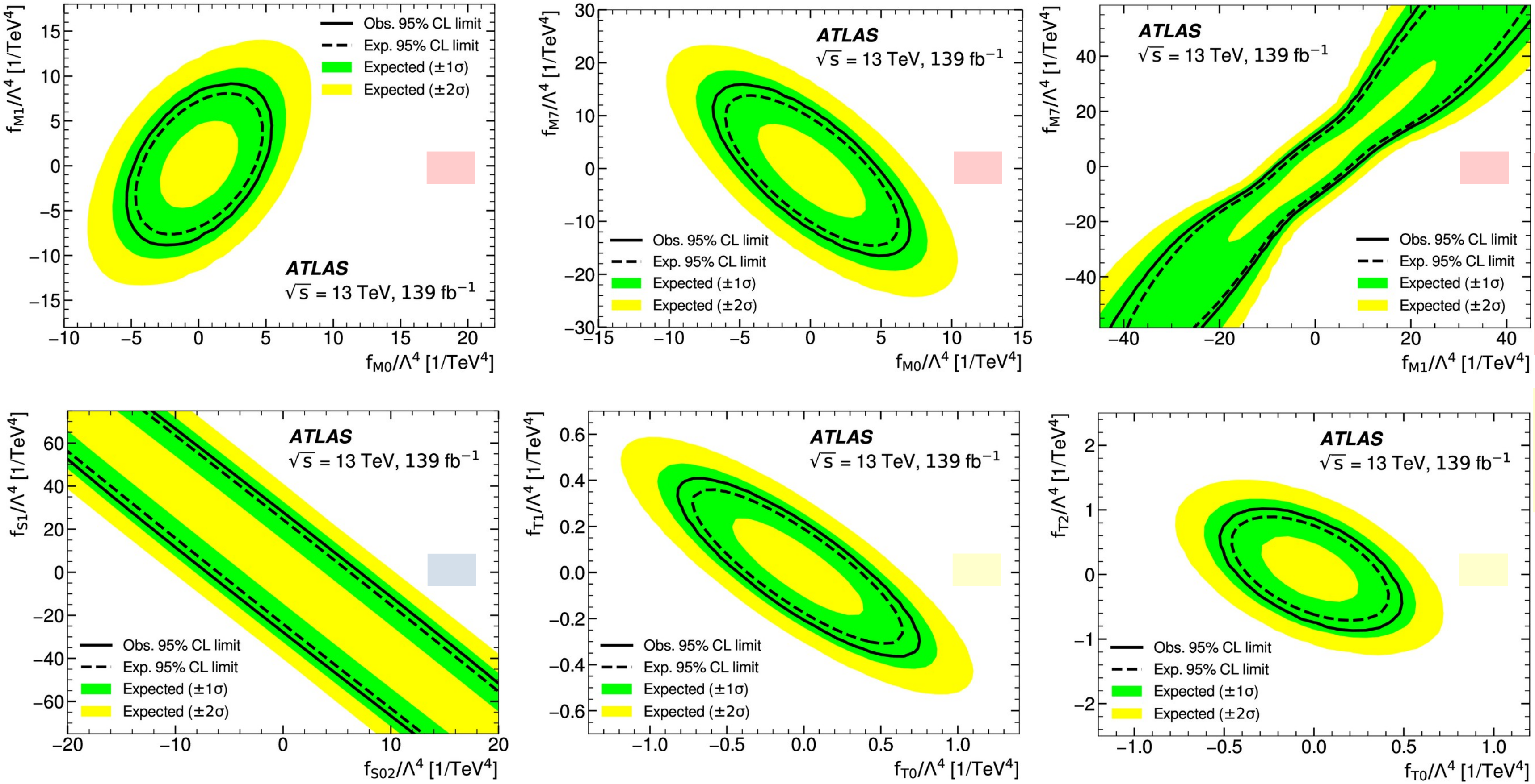


CMS corresponding measurement Phys. Lett. B 809 (2020) 135710

$pp \rightarrow W^{\pm}W^{\pm}jj$

ATLAS-STDM-2018-32
JHEP 12 (2023) 107

Constrain anomalous quartic gauge couplings via dim-8 EFT operators



$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$
$$\mathcal{L}_{M,6} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\nu} D^\mu\Phi\right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi\right]$$

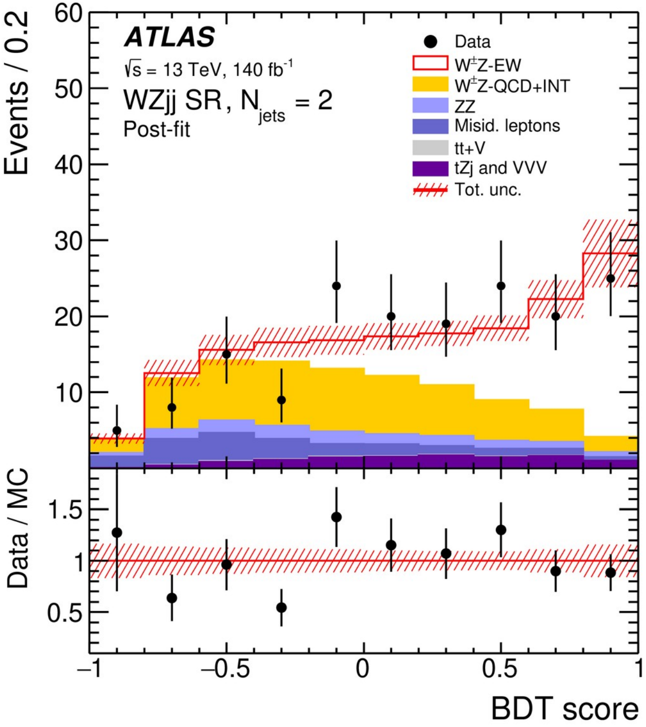
$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

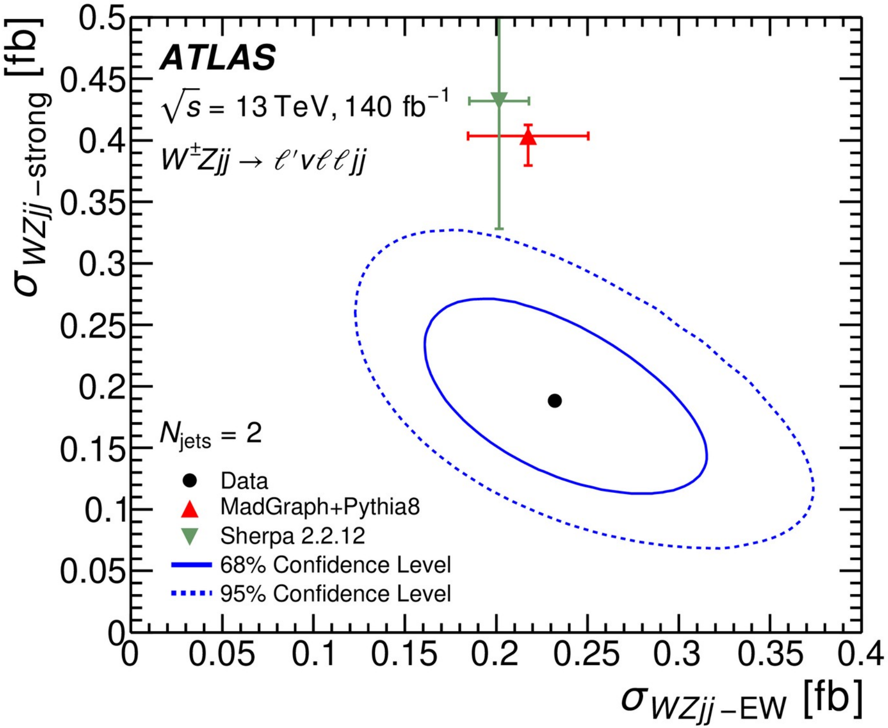
$$\mathcal{L}_{S,0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D^\mu\Phi)^\dagger D^\nu\Phi\right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu\Phi)^\dagger D^\mu\Phi\right] \times \left[(D_\nu\Phi)^\dagger D^\nu\Phi\right]$$

$pp \to W^{\pm}Zjj$

arXiv:2403.15296

Measure differential cross sections for the *inclusive* WZjj and **EW** WZjj productions and **extract the EW component by means of a BDT**

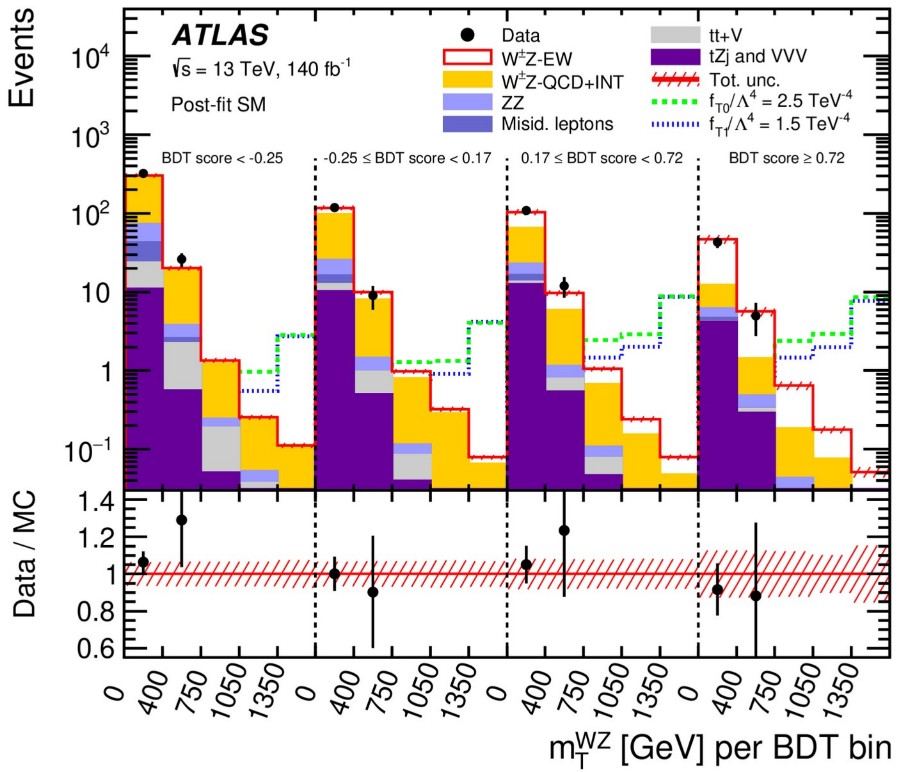


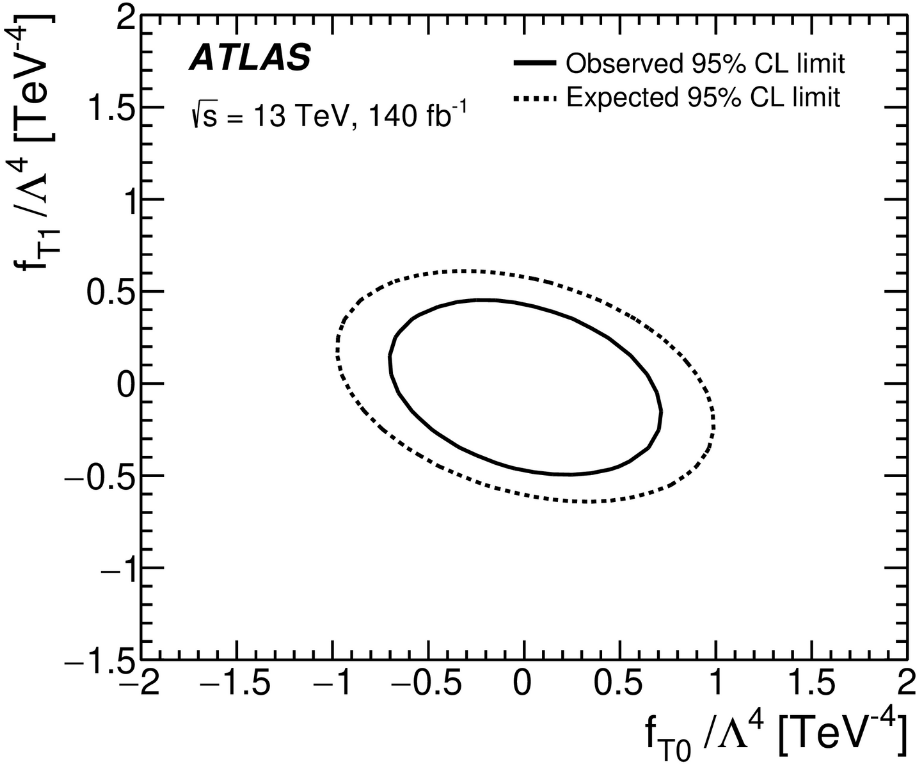


CMS corresponding measurement Phys. Lett. B 809 (2020) 135710

$pp \rightarrow W^{\pm}Zjj$

arXiv:2403.15296



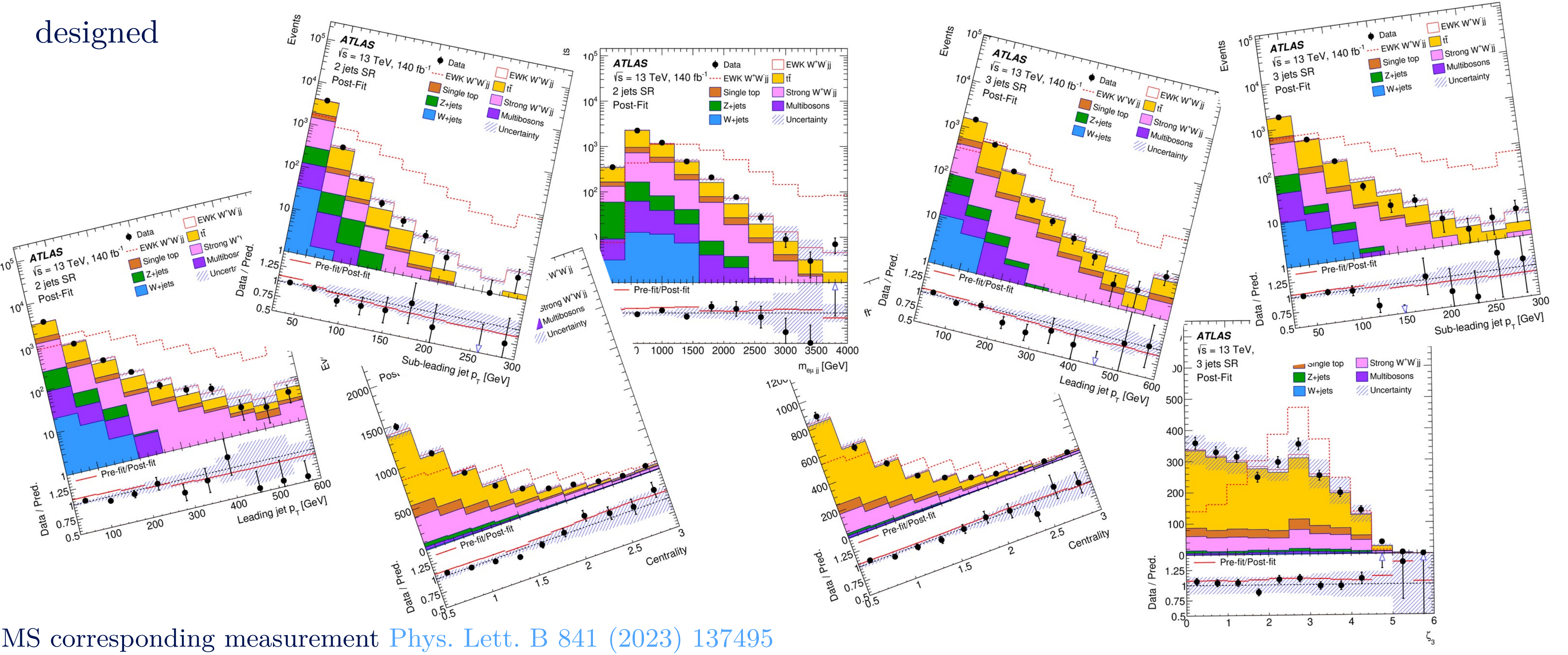


$pp \to W^+W^-jj$

arXiv:2403.04869

Observed in the different-flavour dilepton channel, measuring a fiducial cross section of **2.7±0.5 fb.**

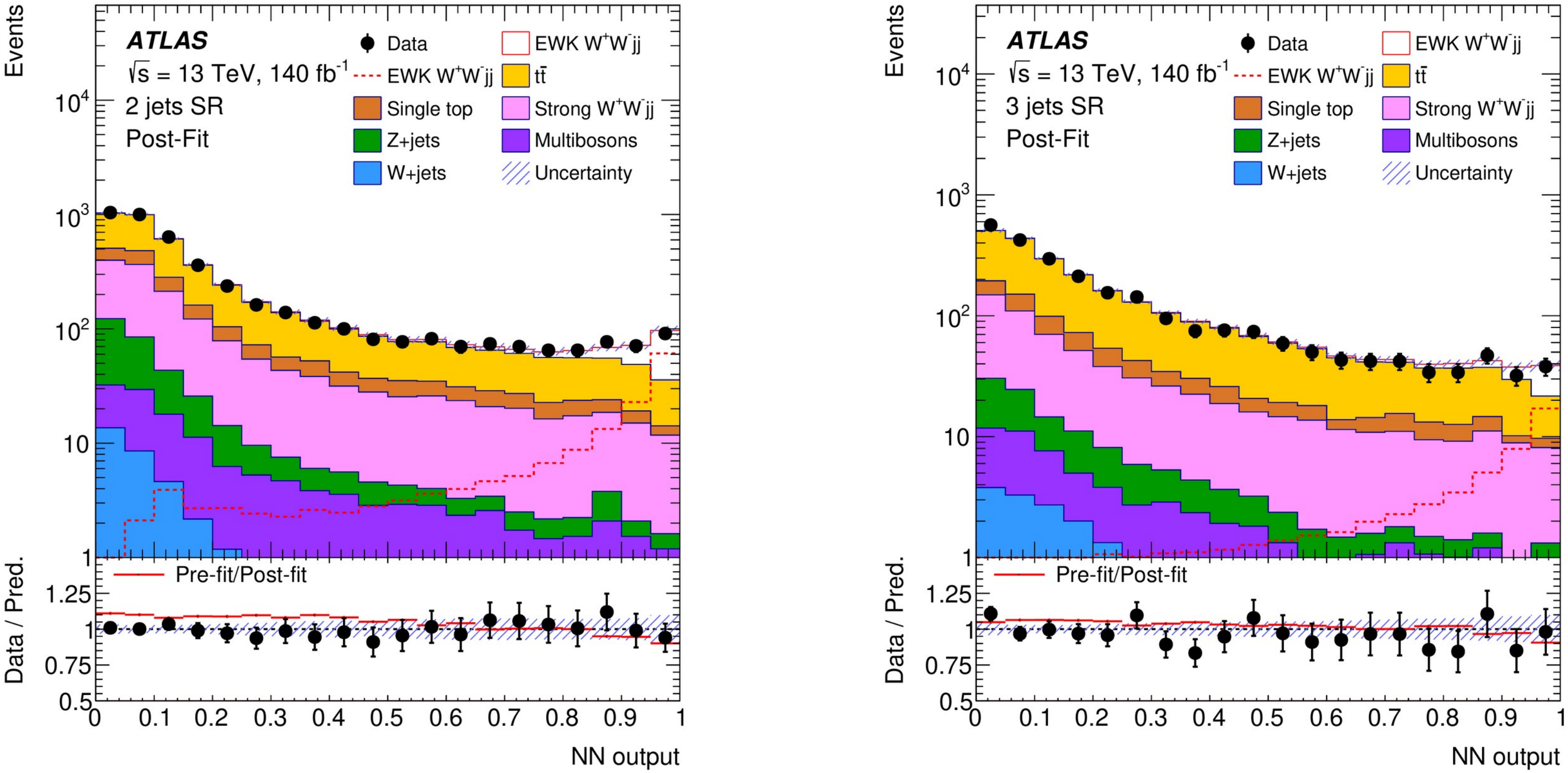
To disentangle the signal from the large top quark production background a neural network has been designed



CMS corresponding measurement Phys. Lett. B 841 (2023) 137495

$pp \rightarrow W^+W^-jj$

arXiv:2403.04869

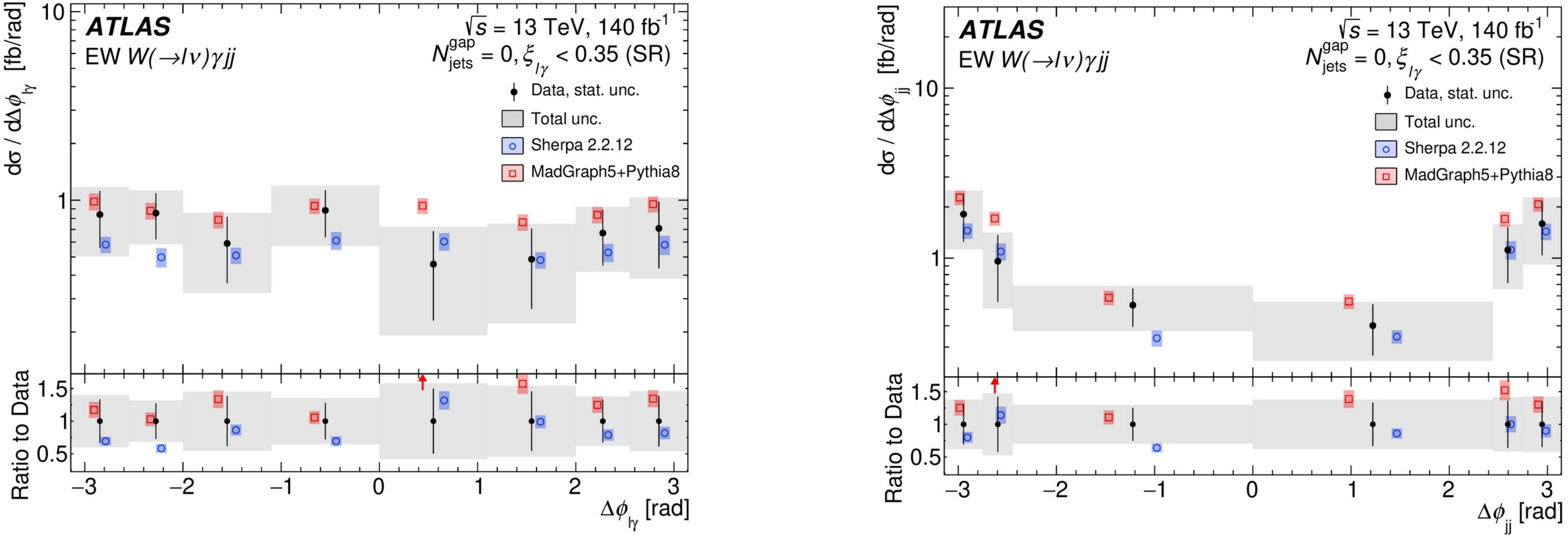


The **largest uncertainties** are the from the data (~12%) and simulation (~8%) **sample size**, followed by theoretical uncertainties on the top background and signal (~6% each)

pp → Wγjj

arXiv:2403.02809

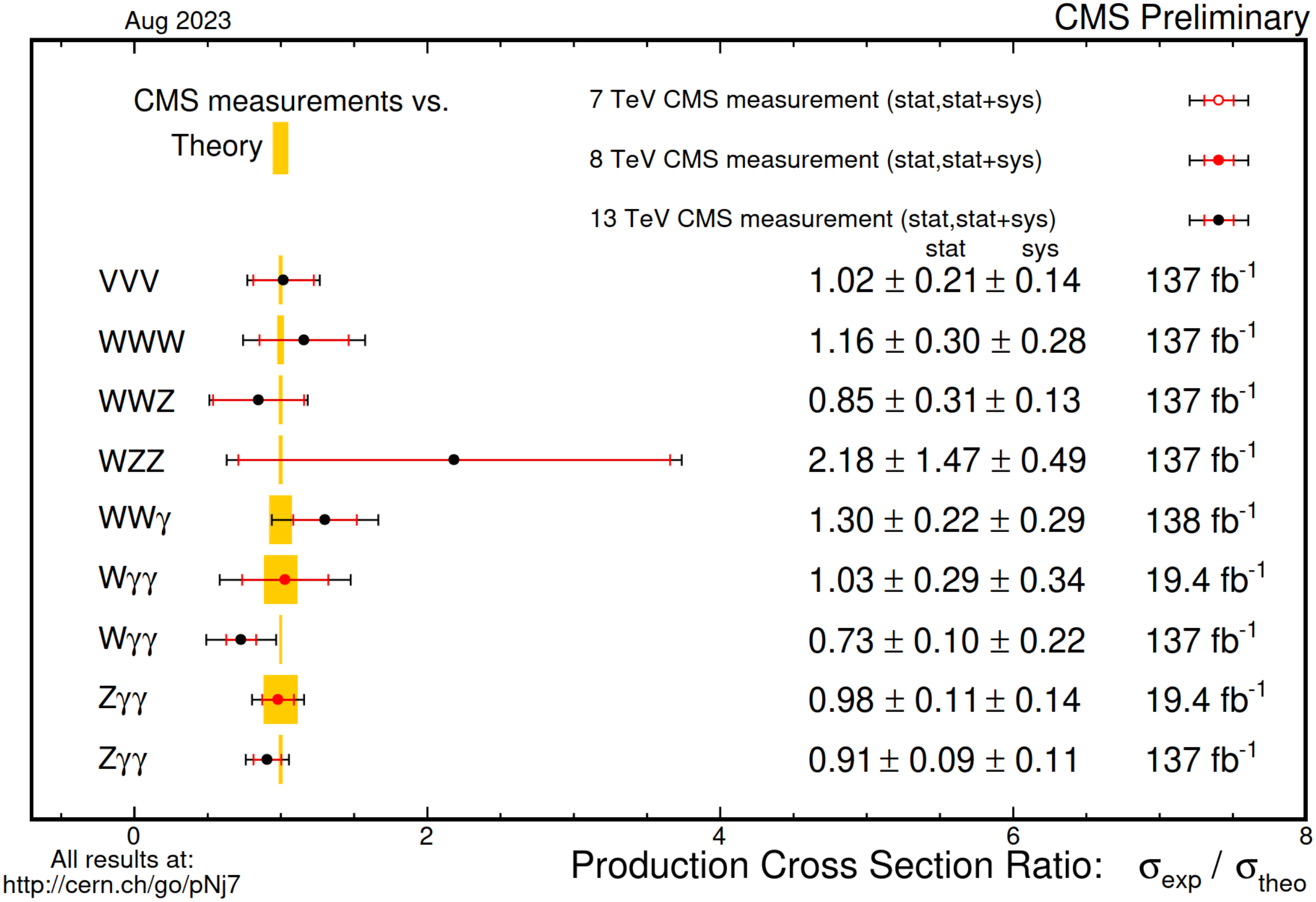
Use a BDT to extract the **EW signal from the inclusive Wγjj production** and measure the differential cross section of key **observables**, especially new ones **sensitive to CP violation**



Use $m_{W\gamma}$ as observable to put limits on dim-8 operators: f_{T0}/Λ^4 up to f_{T7}/Λ^4 and f_{M0}/Λ^4 up to f_{M7}/Λ^4

CMS corresponding measurement Phys. Lett. B 811 (2020) 135988

Triboson production

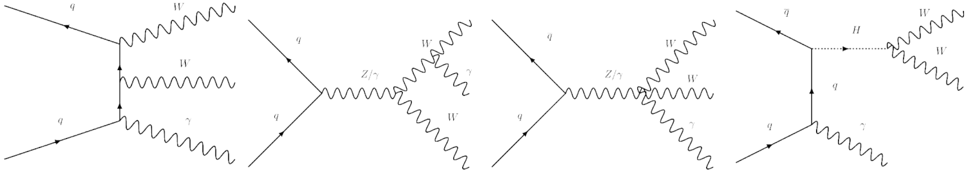


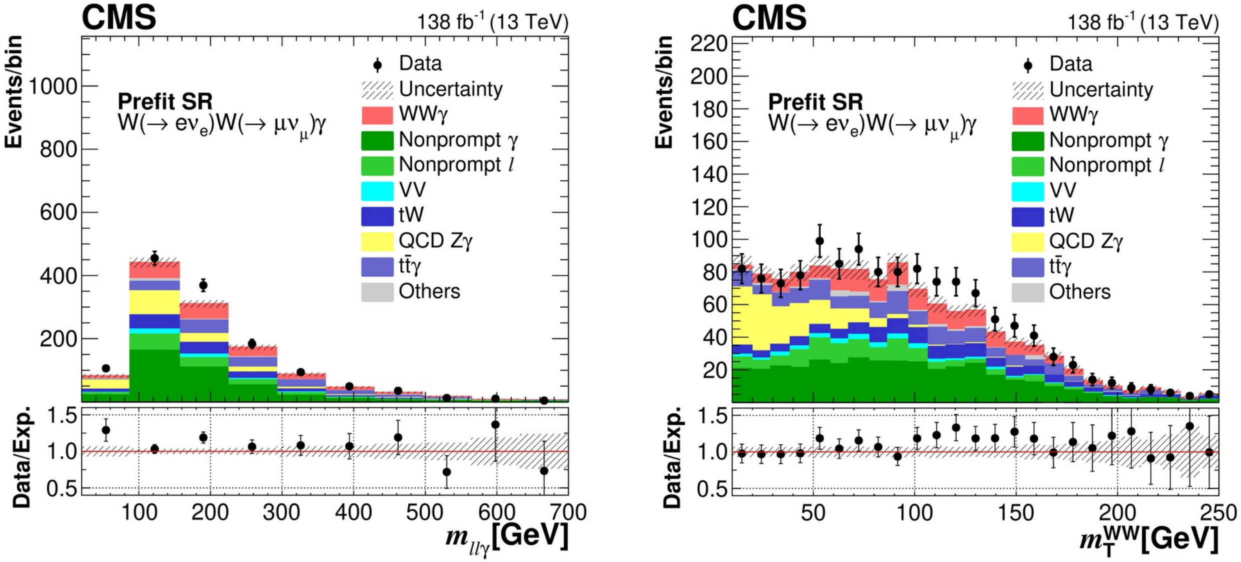
$pp \rightarrow W^+W^-\gamma \rightarrow e^\pm\mu^\mp\upsilon\upsilon\gamma$

CMS-SMP-2022-006
PRL 132 (2024) 121901

First observation of the WWγ production

- Search for it in **opposite-sign and different flavor** WW lepton decay

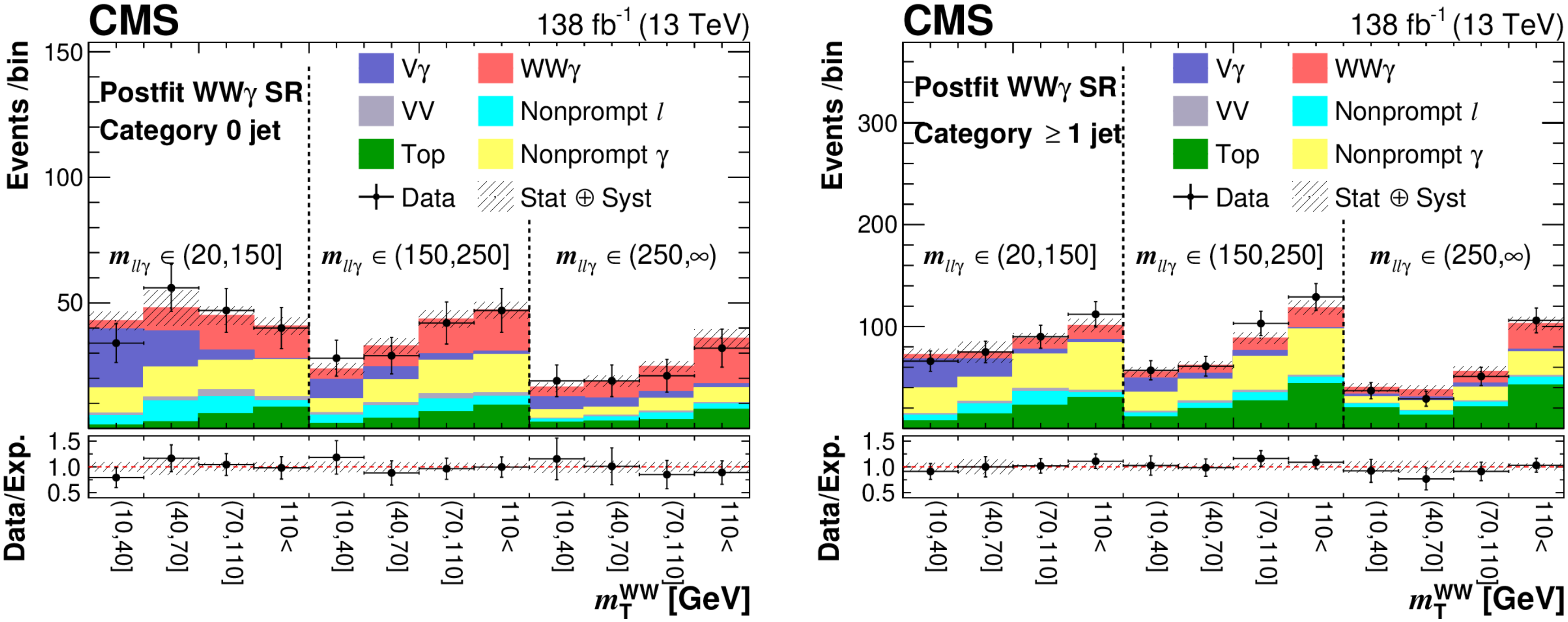




Bin in $\mathbf{m_{ll\gamma} - m_T}$ **and (0,1) jet category** to increase the significance

$pp \rightarrow W^{+}W^{-}\gamma \rightarrow e^{\pm}\mu^{\mp}\upsilon\upsilon\gamma$

CMS-SMP-2022-006
PRL 132 (2024) 121901



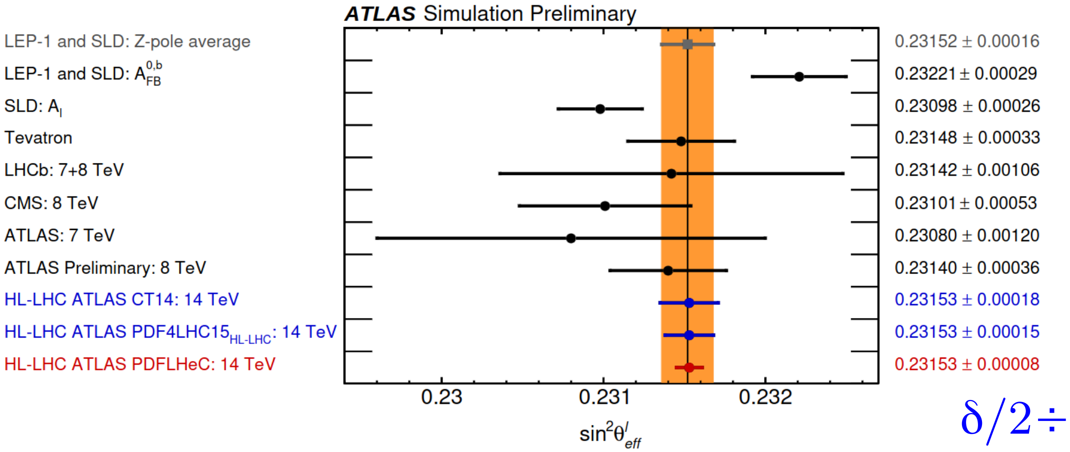
$$\sigma_{WW\gamma} = 6.0 \pm 0.8\ (\text{stat}) \pm 0.7\ (\text{syst}) \pm 0.6\ (\text{modeling})\ \text{fb}$$

With an observed (expected) significance of **5.6** (4.7) **σ**

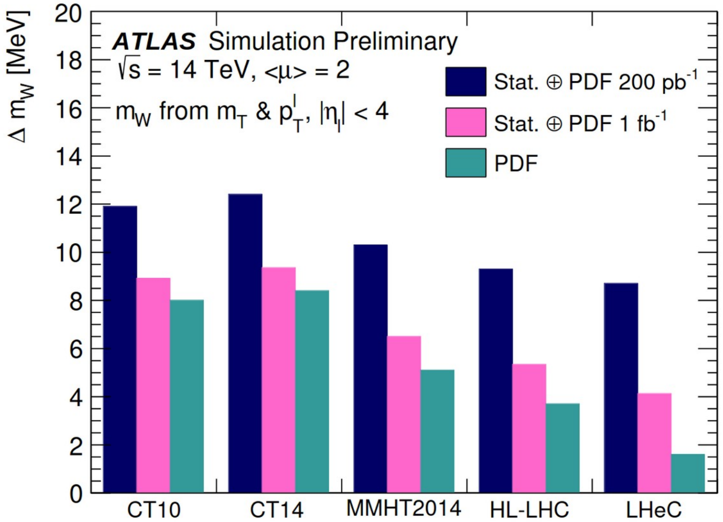
Prospects for HL-LHC and FA

ATLAS and CMS in Phase-2

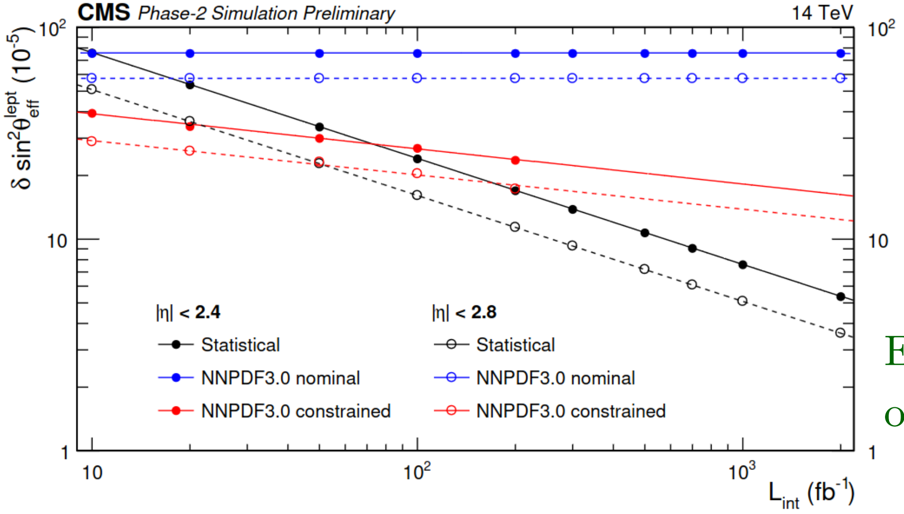
CMS-PAS-FTR-22-001



δ/2÷3!



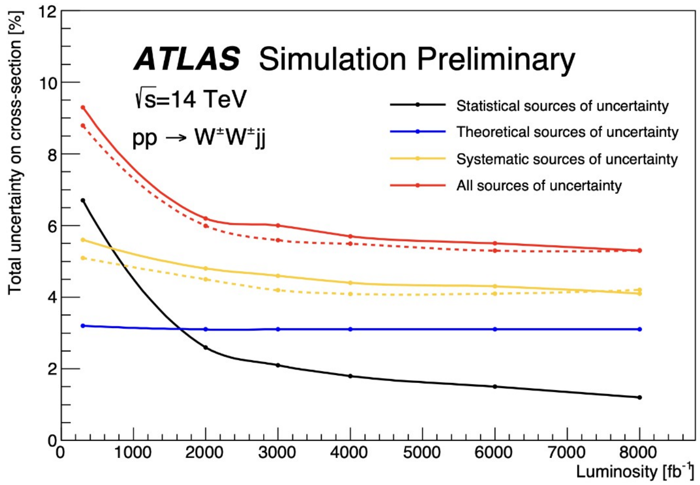
This measurement would require a dedicated dataset collected at low instantaneous luminosity.
→ Can reach < 10 MeV precision

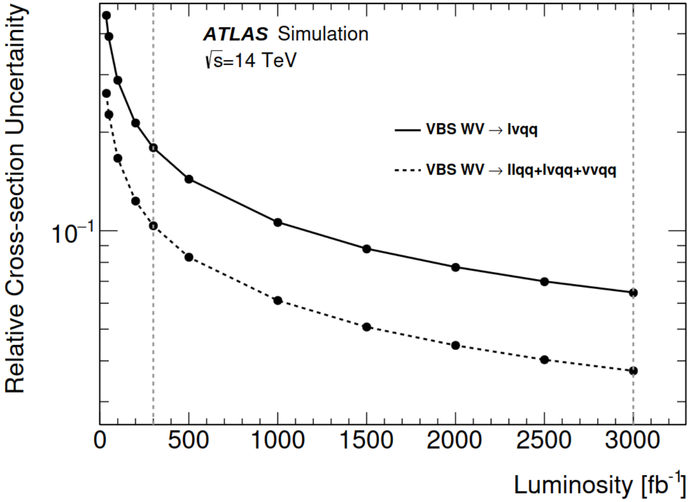


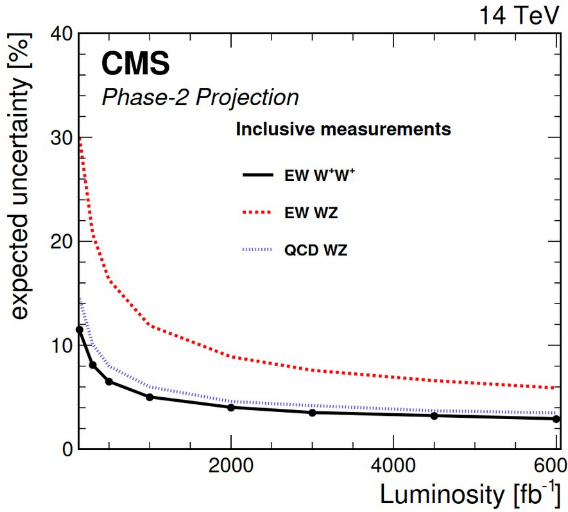
Extending the **eta coverage** there is a gain of the order of **30%** in each type of uncertainty (can access larger x).

ATLAS and CMS in Phase-2

CMS-PAS-FTR-22-001



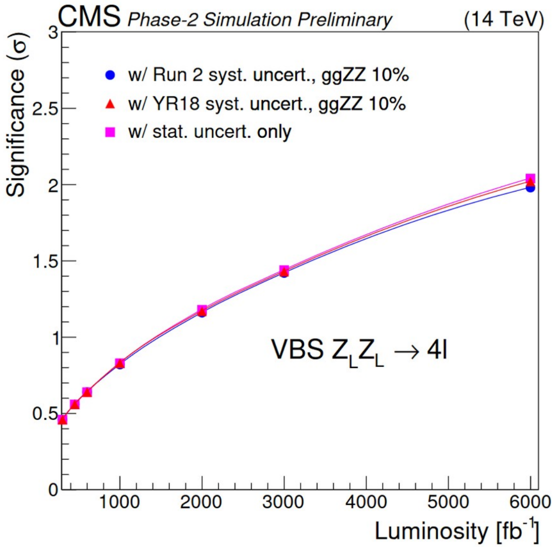


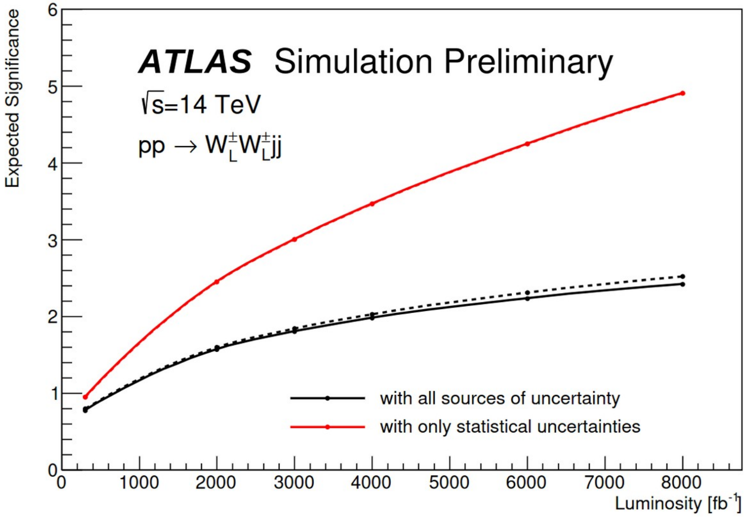


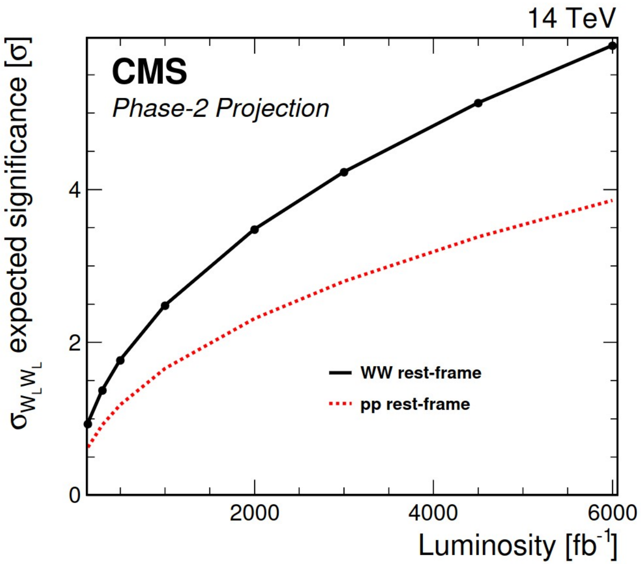
ATLAS and CMS have performed projections of analysis sensitivities for measuring the cross sections of leptonic and semi-leptonic decays of several VBS diboson processes: WW, WZ, and ZZ. In general, the uncertainties on the cross sections are expected to ranges from **3 to 10%** (for ZZ $\to 4\ell$), by the **end of the HL-LHC data taking**.

ATLAS and CMS in Phase-2

CMS-PAS-FTR-22-001



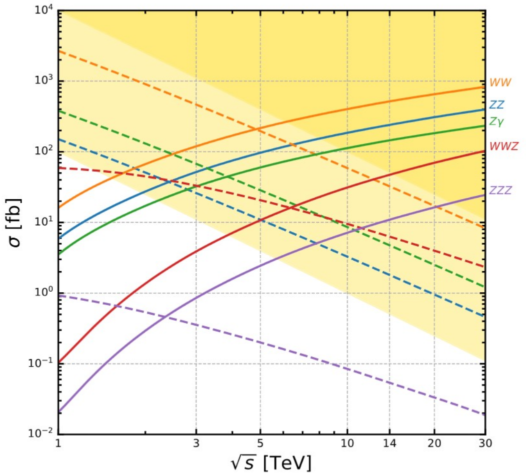


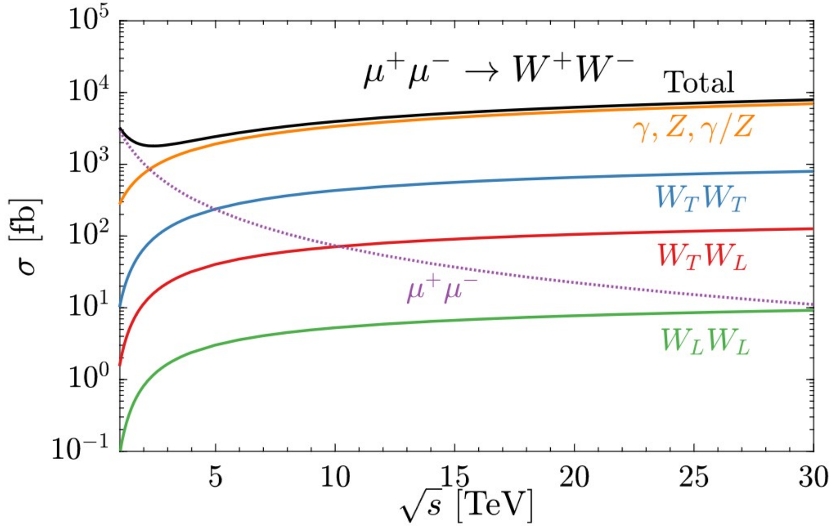


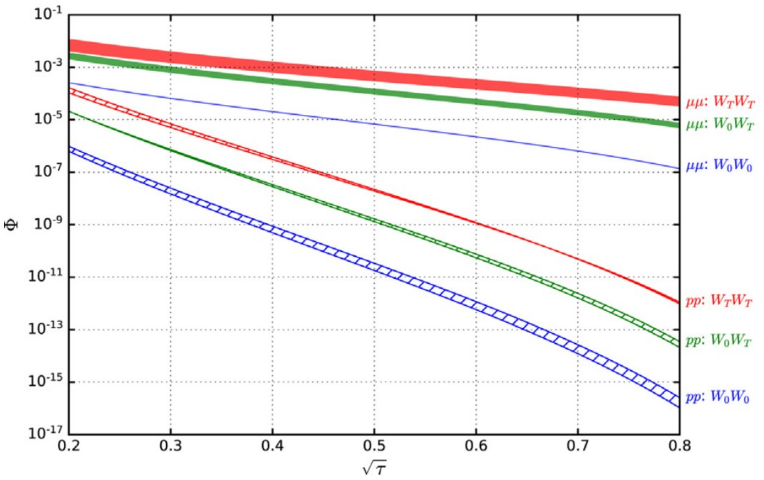
Reaching an evidence of V_LV_L at HL-LHC *will be very though*, however, history of particle physics thought us that *projections were pessimistic*, as they did not consider **improvements in techniques, better description of the detector, etc**. Also, combination between ATLAS and CMS should be considered.

Perspective at future accelerators

Rev.Phys. 8 (2022) 100071







$\mu^+\mu^-$ and **e^+e^-** colliders have similar physics for VBS production, and are **superior** in term of parton luminosity (Φ) with respect to **pp**.

For VBS Z_LZ_L to reach the same significance level (~2σ) as HL-LHC with **4 ab^{-1}** of collected data, a μμ collider requires **√s = 6 TeV**; **5σ** discovery can instead be reached with **3 ab^{-1}** of data and **√s = 14 TeV** [PRD.104.093003].

Conclusions

- **Many** **new interesting results** from **LHC** in the last 2-3 months
  - More are yet to come!
- **Run 2 data exploited at maximum**, but still there are analyses that can be performed
  - **More precise measurements** and **very rare processes** to be found
- **Run 3 data analyses are underway**, but **important benchmarks have been presented**
- **HL-LHC and FA represent an unique opportunity to dig deeper in the EW sector of our core theory**

Standard ~~Model~~ Theory Rules

Backup

Instructions to directly access the analysis page

CMS

- For publications

  http://cms-results.web.cern.ch/cms-results/public-results/publications/AAA-BB-CCC/index.html

- For PAS

  http://cms-results.web.cern.ch/cms-results/public-results/publications/AAA-BB-CCC/index.html

W mass measurement

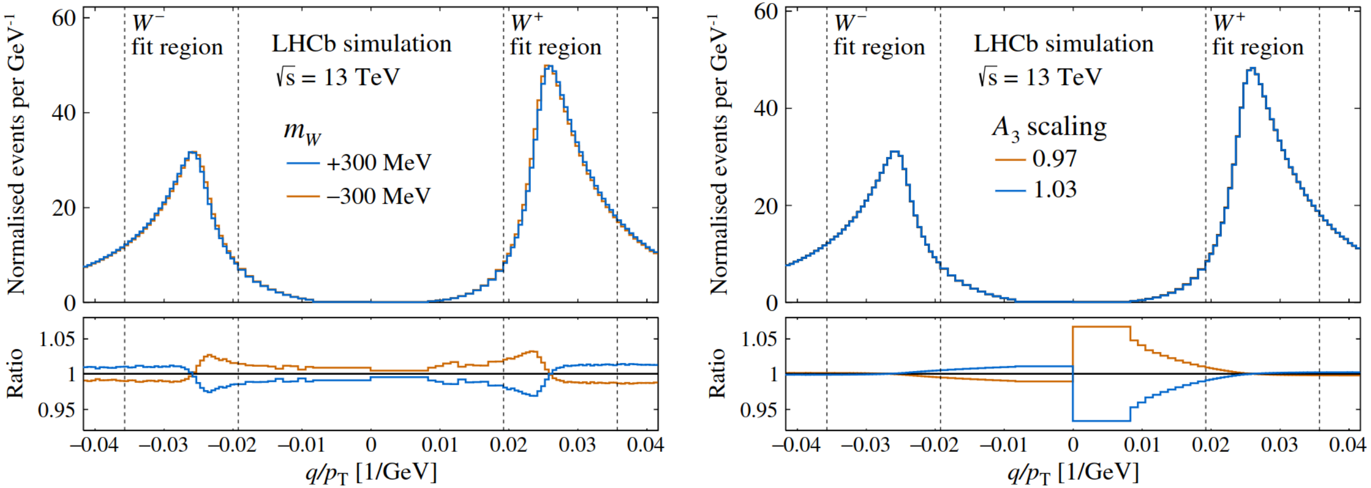
JHEP 01 (2022) 036

Analyzed the W → μν events taken in 2016 ($\sqrt{s} = 13$ TeV, $\mathscr{L}$=1.7 fb^{-1})

Use the **curvature of the muon track (q/p_T)**, which is sensitive to m_W

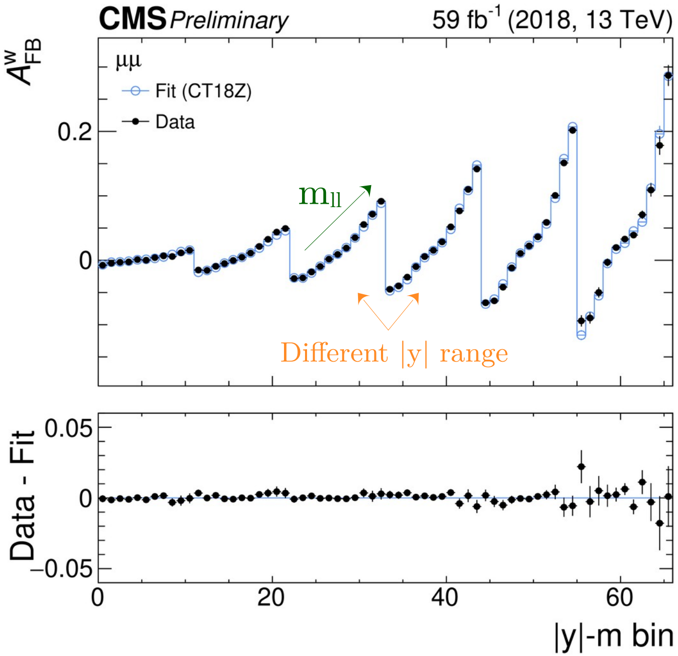
$$\frac{d\sigma}{dp_T^W dy dM d\cos\vartheta d\varphi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{dp_T^W dy dM}$$
$$\{(1+\cos^2\vartheta) + A_0\frac{1}{2}(1-3\cos^2\vartheta) + A_1\sin 2\vartheta\cos\varphi$$
$$+ A_2\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\sin\vartheta\cos\varphi + A_4\cos\vartheta$$
$$+ A_5\sin^2\vartheta\sin 2\varphi + A_6\sin 2\vartheta\sin\varphi + A_7\sin\vartheta\sin\varphi\}$$

Coefficients A_5-A_7 are small, as they are second-order in α_s, while **A_3 particularly influence q/p_T**



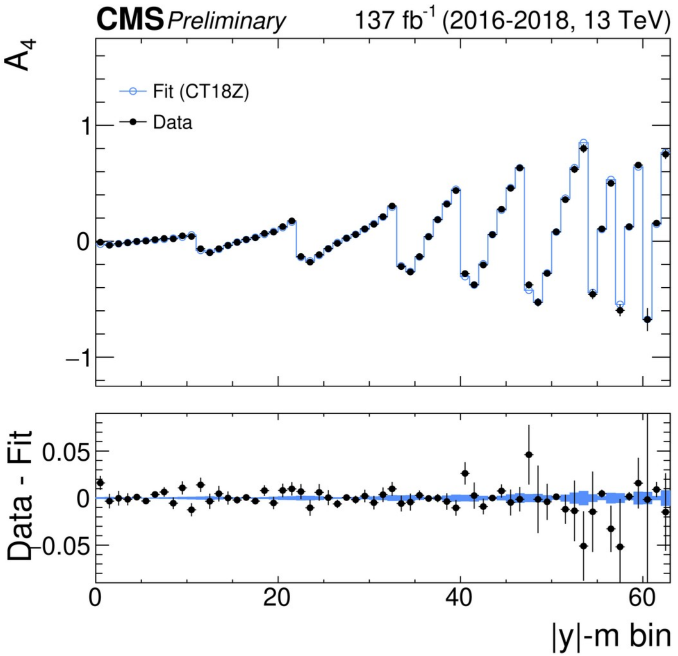
Measurement of $\sin^2\theta_W$

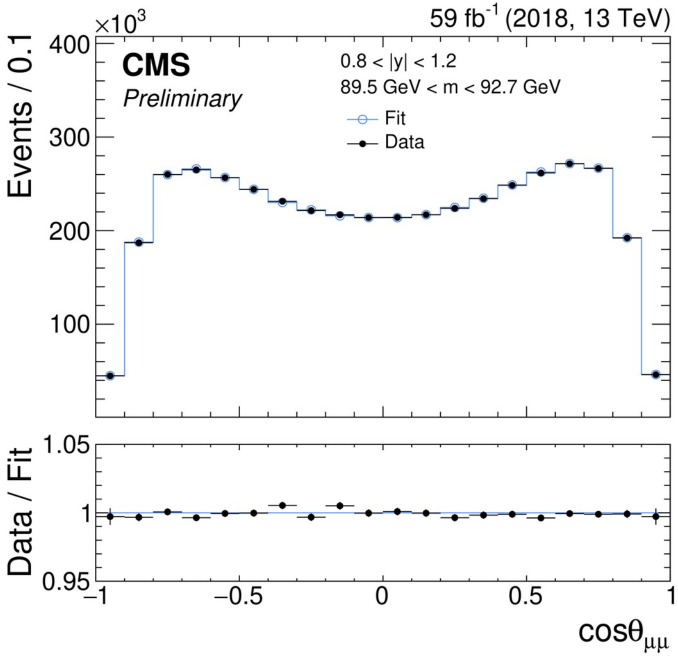
CMS-SMP-2022-010



m_{ll}

Different |y| range



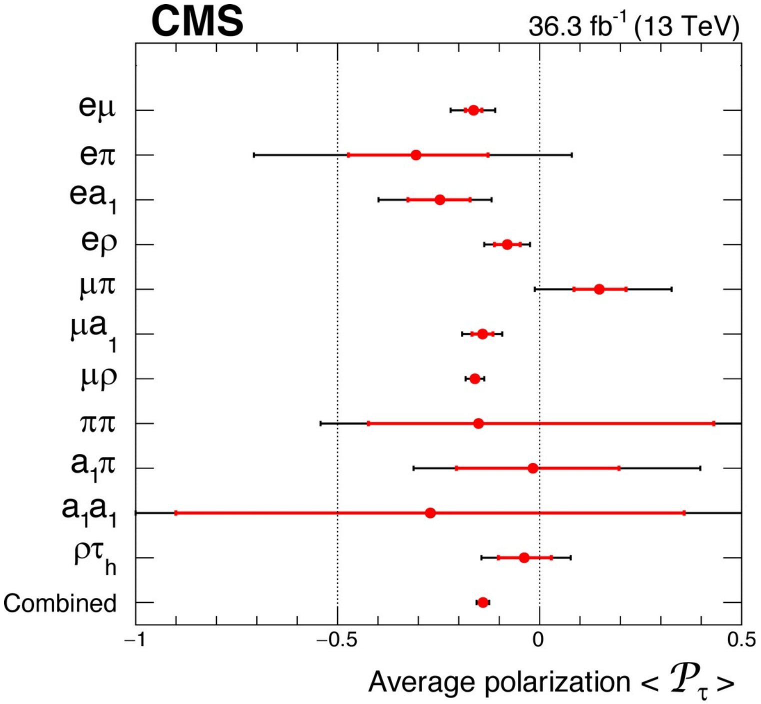


τ polarization in Z → $\tau\tau$

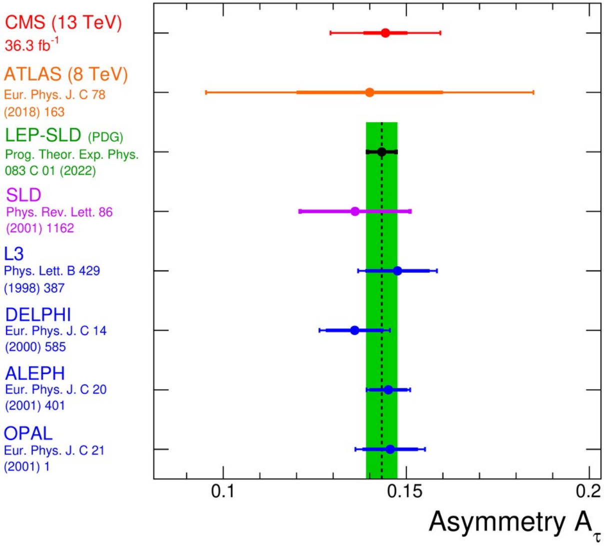
CMS-SMP-2018-010
JHEP 01 (2024) 101

Measured the **τ polarization** in pp → Z → $\tau\tau$ events @ 13 TeV

- Events classified in **11 categories**



The polarization (= -A_τ) depends on the ratio of the vector and axial-vector couplings and is used to **determine the weak mixing angle** independently of the production process of the Z resonance

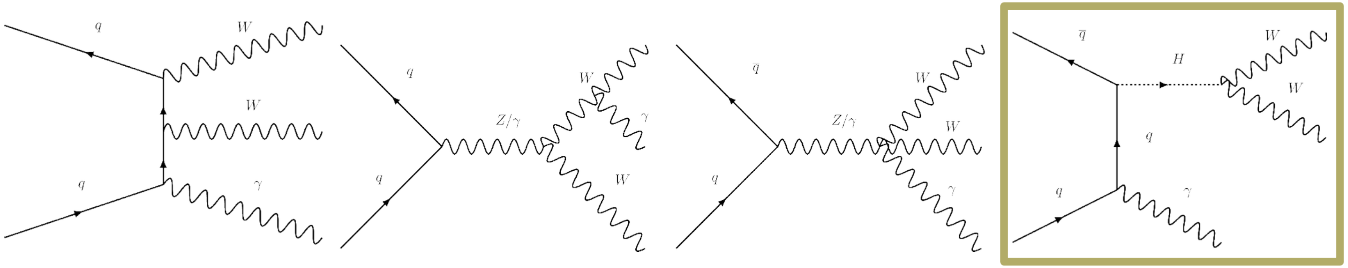


$$\boxed{\sin^2\theta_W^{eff} = 0.2319 \pm 0.0019}$$

$pp \rightarrow W^{+}W^{-}\gamma \rightarrow e^{\pm}\mu^{\mp}\upsilon\upsilon\gamma$

CMS-SMP-2022-006
PRL 132 (2024) 121901

It can be used to **explore H couplings to light quarks** (u,d,s,c)

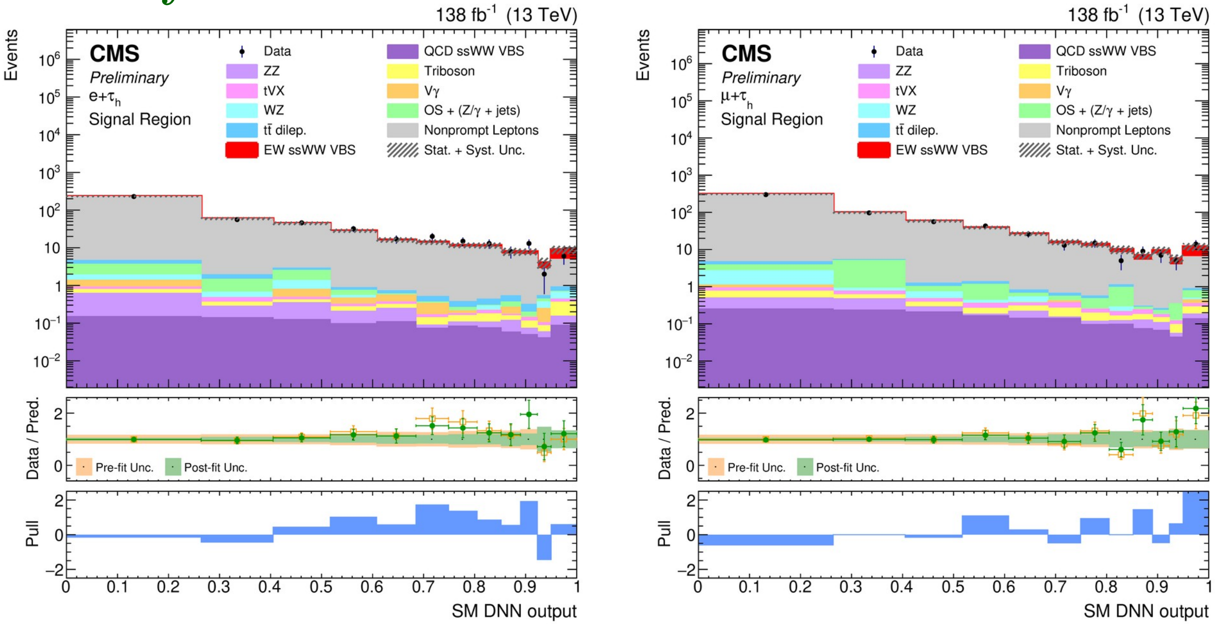


Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL	$\overline{\kappa}_q$ limits obs. (exp.) at 95% CL
$u\overline{u} \rightarrow H + \gamma \rightarrow e\mu\nu_e\nu_\mu\gamma$	85 (67)	$\lvert\kappa_u\rvert \leq$ 16000 (13000)	$\lvert\overline{\kappa}_u\rvert \leq$ 7.5 (6.1)
$d\overline{d}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

$pp \rightarrow W^{\pm}W^{\pm}jj \rightarrow \tau\upsilon\ell\upsilon jj$ SMP-22-008

Search for **$W^{\pm}W^{\pm}$ scattering** in final state with a **τ** and either a **μ** or an **e** (plus MET)

- **First study of VBS with taus**



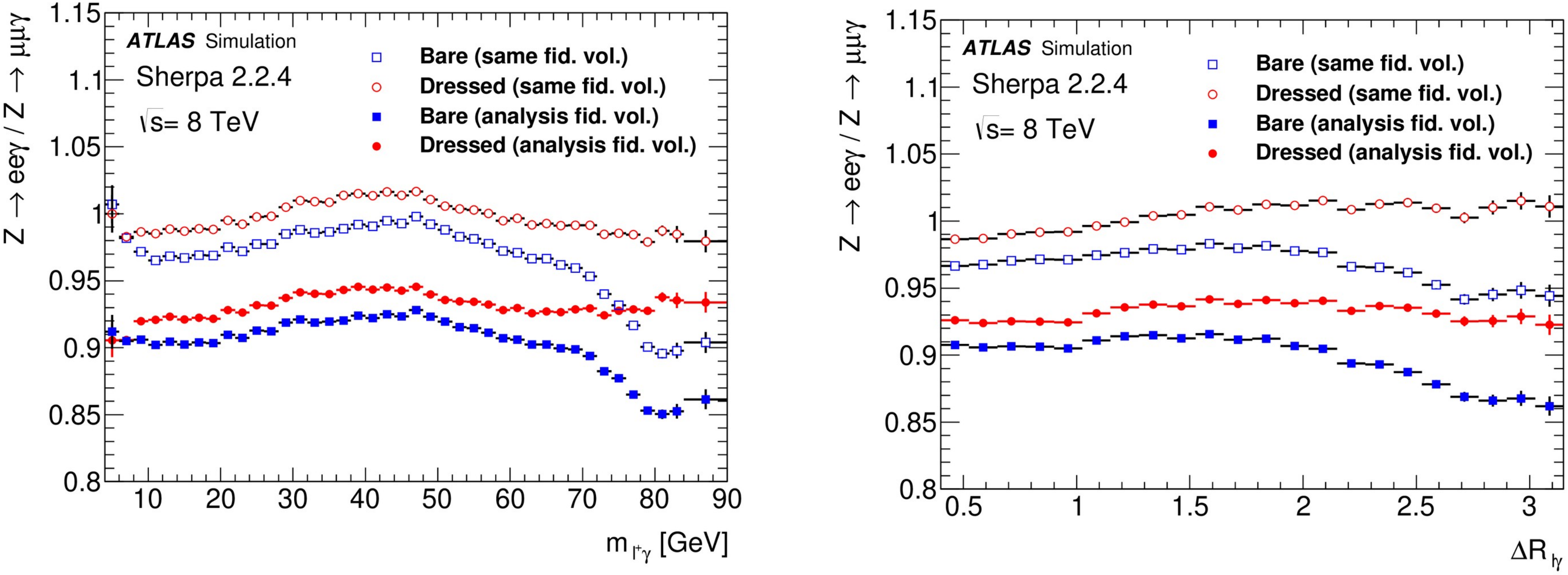
Statistical uncertainty dominates, but total systematic uncertainty is of the same order

Measured the **EW signal strength**: $\boxed{\mu_{W^{\pm}W^{\pm}} = 1.44^{+0.63}_{-0.56}}$

with an observed (expected) significance of **2.7** (1.9) **σ**

$Z \to \ell\ell\gamma$

The predictions for the kinematic observables describing the final state differ significantly in some regions of phase space between bare electrons and bare muons.
Dressed lepton definition minimises the differences between electrons and muons.



pp → ZZ + jets

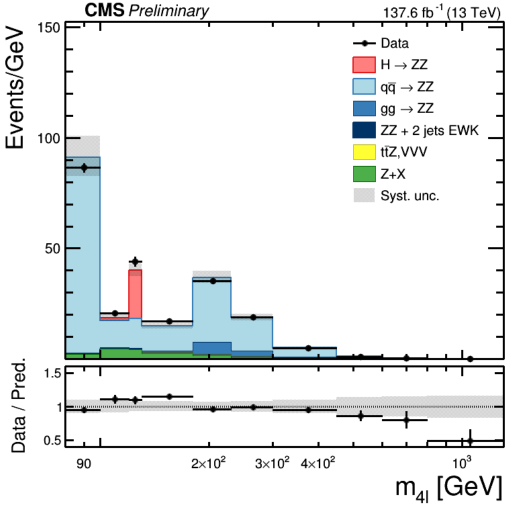
CMS-SMP-2022-001

Measurements in the **fully leptonic (μ,e) decay channels** with the full Run 2 data

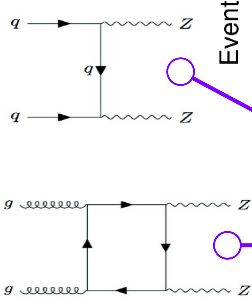
Z pair associated to jets are **among the rarest processes observed at LHC** (σ~1 fb!)

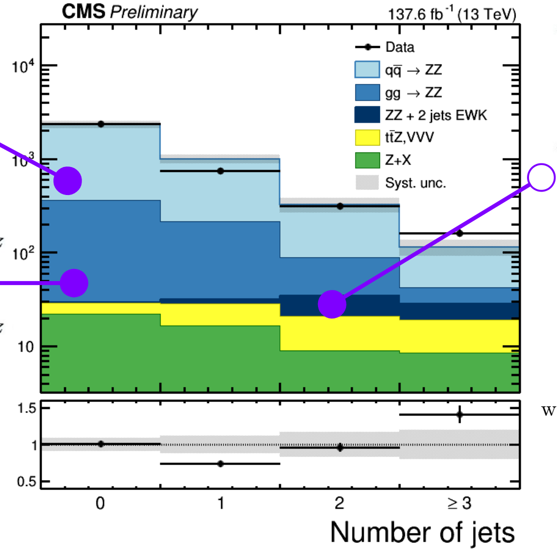
Measurements of the **full 4 leptons spectrum**

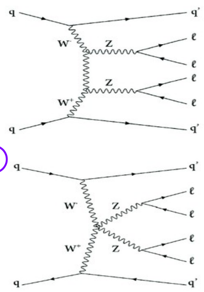
→ **includes H and Z** decays in 4 leptons



Very important for keeping under control the irreducible **background of vector boson scattering and triboson productions**



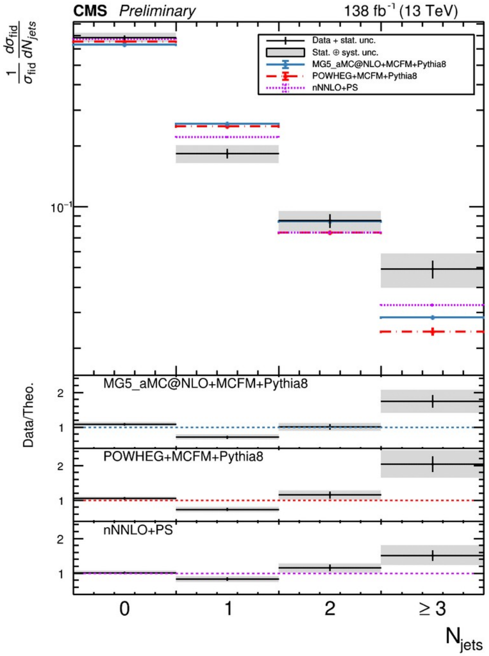




+

non-VBS diagrams, with (α_{EW}^{6}) at tree level, **including tribsons**

Extracted **differential distribution** of **several observables**



pp → ZZ → 4 (ℓ=e,μ) ATLAS-STDM-2022-17

	Fiducial phase space	**Total lepton phase space**
Muon selection	Bare, $p_\mathrm{T} > 5$ GeV, $\lvert\eta\rvert < 2.5$	Born
Electron selection	Dressed, $p_\mathrm{T} > 7$ GeV, $\lvert\eta\rvert < 2.47$	Born
Four-lepton signature	≥ 2 SFOC pairs	≥ 2 SFOC pairs
Lepton kinematics	$p_\mathrm{T} > 27/10$ GeV	
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.05$	
Low-mass $\ell^+\ell^-$ veto	$m_{ij} > 5$ GeV	$m_{ij} > 5$ GeV
Z mass window	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV
ZZ on-shell	$m_{4l} > 180\ GeV$	

pp → ZZ → 4 (ℓ=e,μ)

ATLAS-STDM-2022-17

Process	$q\bar{q} \to ZZ$	$gg \to ZZ$	EW $qq \to ZZ + 2j$	$t\bar{t}Z$	VVV	Reducible	Total	Data
Yield	515 ± 50	74 ± 44	4.7 ± 1.0	5.5 ± 0.8	2.1 ± 0.2	25.4 ± 8.1	626 ± 88	625

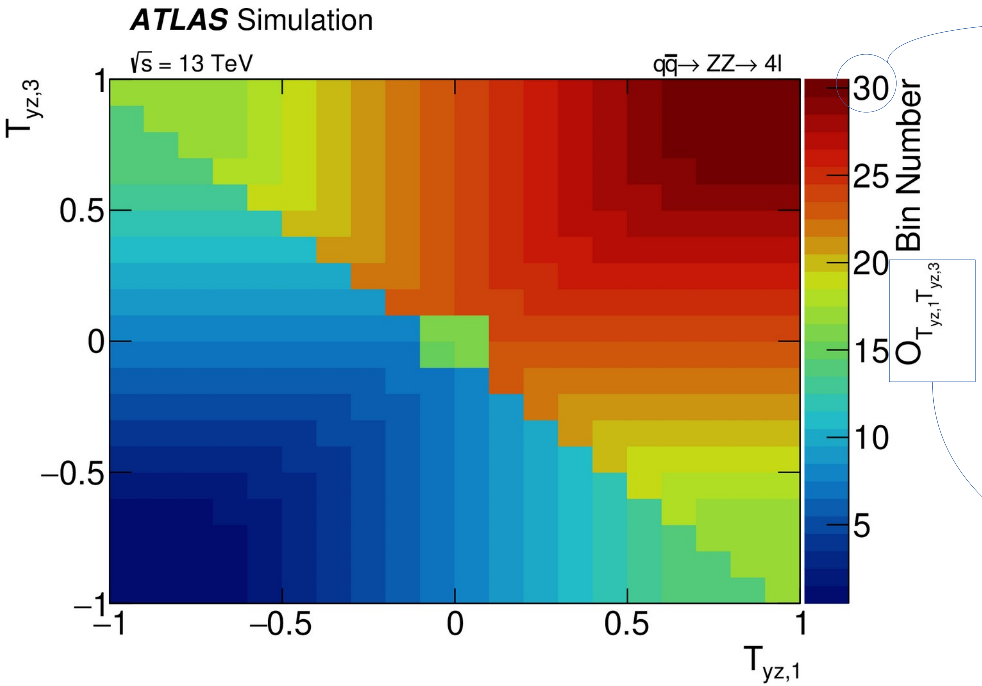
Source	Relative uncertainty(%)
Data statistical uncertainty	4.2
MC statistical uncertainty	0.3
Luminosity	2.2
Lepton momentum	0.2
Lepton efficiency	3.7
Background	1.6
Theoretical uncertainty	1.0
Total	6.3

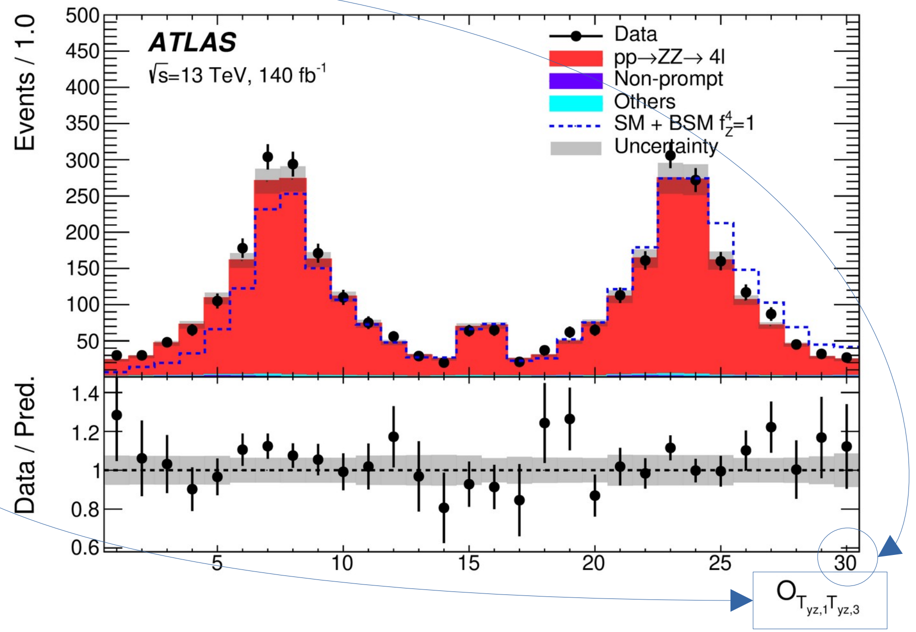
$pp \rightarrow Z_L Z_L \rightarrow 4\ (\ell=e,\mu)$

ATLAS-STDM-2021-05
JHEP 12 (2023) 107

Optimal Observable ($OO_{T_{xy,1}T_{xy,3}}$) built up using angles defined in the previous slide, where

$$T_{yz,1(3)} = \sin\phi_{1(3)} \cos\theta_{1(3)}$$





$pp \to Z_L Z_L \to 4\ (\ell = e,\mu)$

ATLAS-STDM-2021-05
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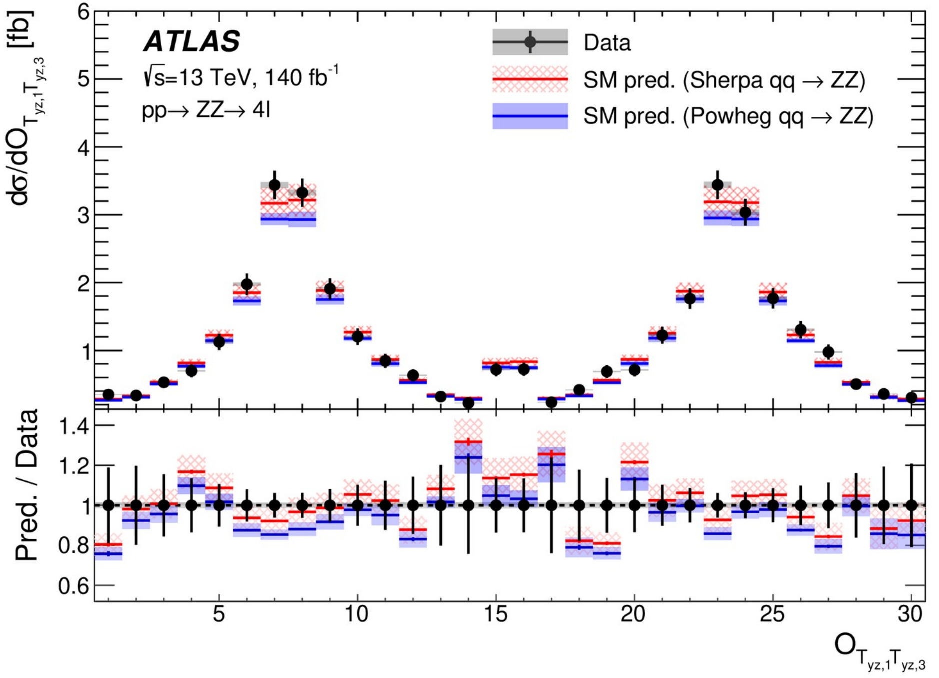
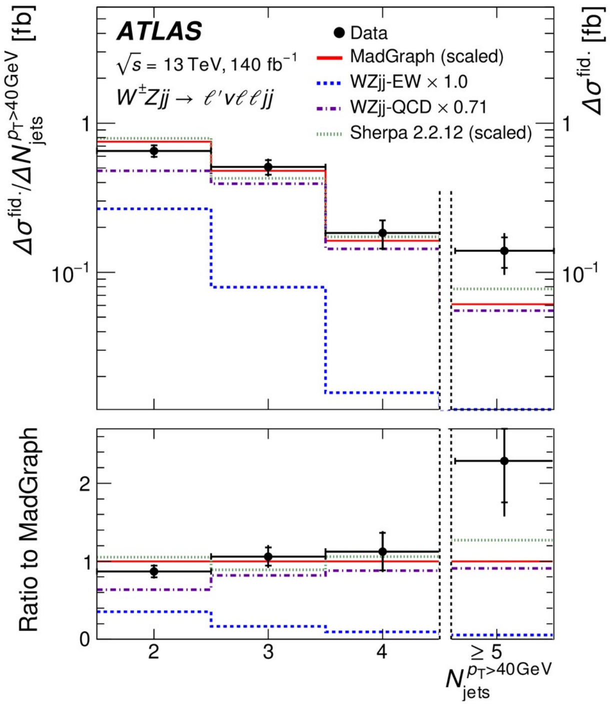
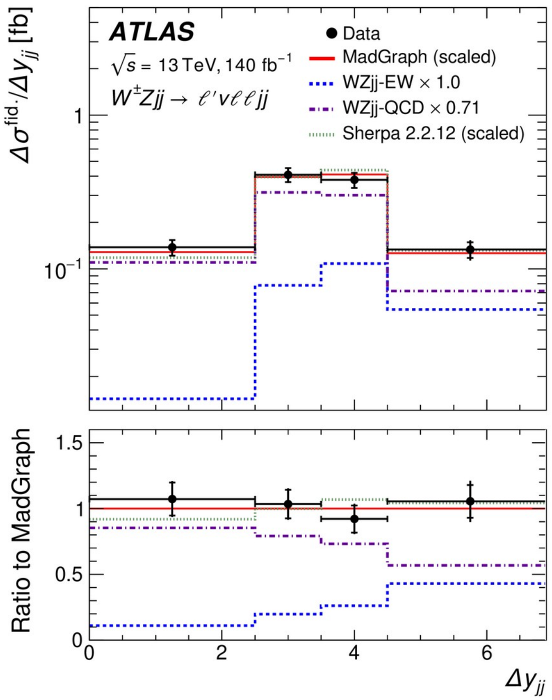
aNTGC parameter	Interference only		Full	
	Expected	Observed	Expected	Observed
f_Z^4	$[-0.16, 0.16]$	$[-0.12, 0.20]$	$[-0.013, 0.012]$	$[-0.012, 0.012]$
f_γ^4	$[-0.30, 0.30]$	$[-0.34, 0.28]$	$[-0.015, 0.015]$	$[-0.015, 0.015]$

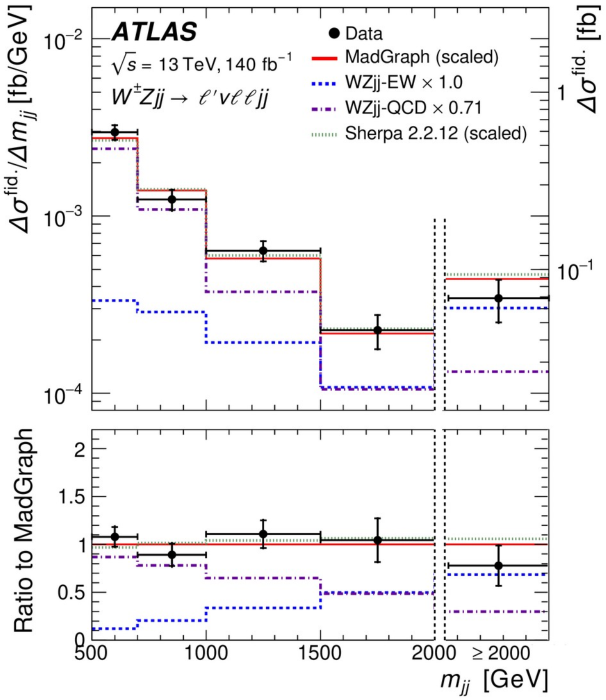


$pp \to W^{\pm}Zjj$

arXiv:2403.15296

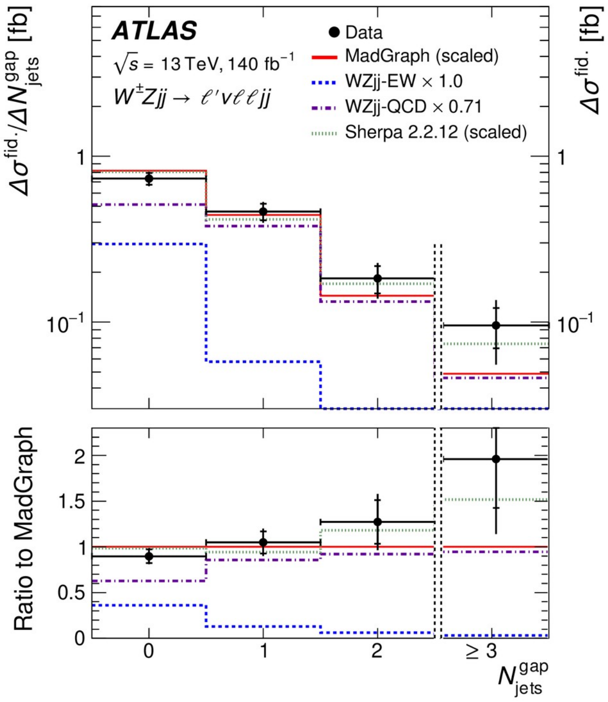


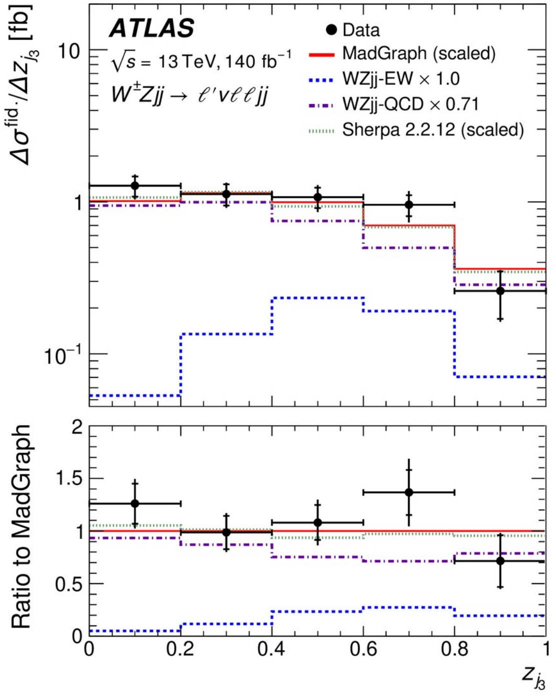




pp → $W^{\pm}Zjj$

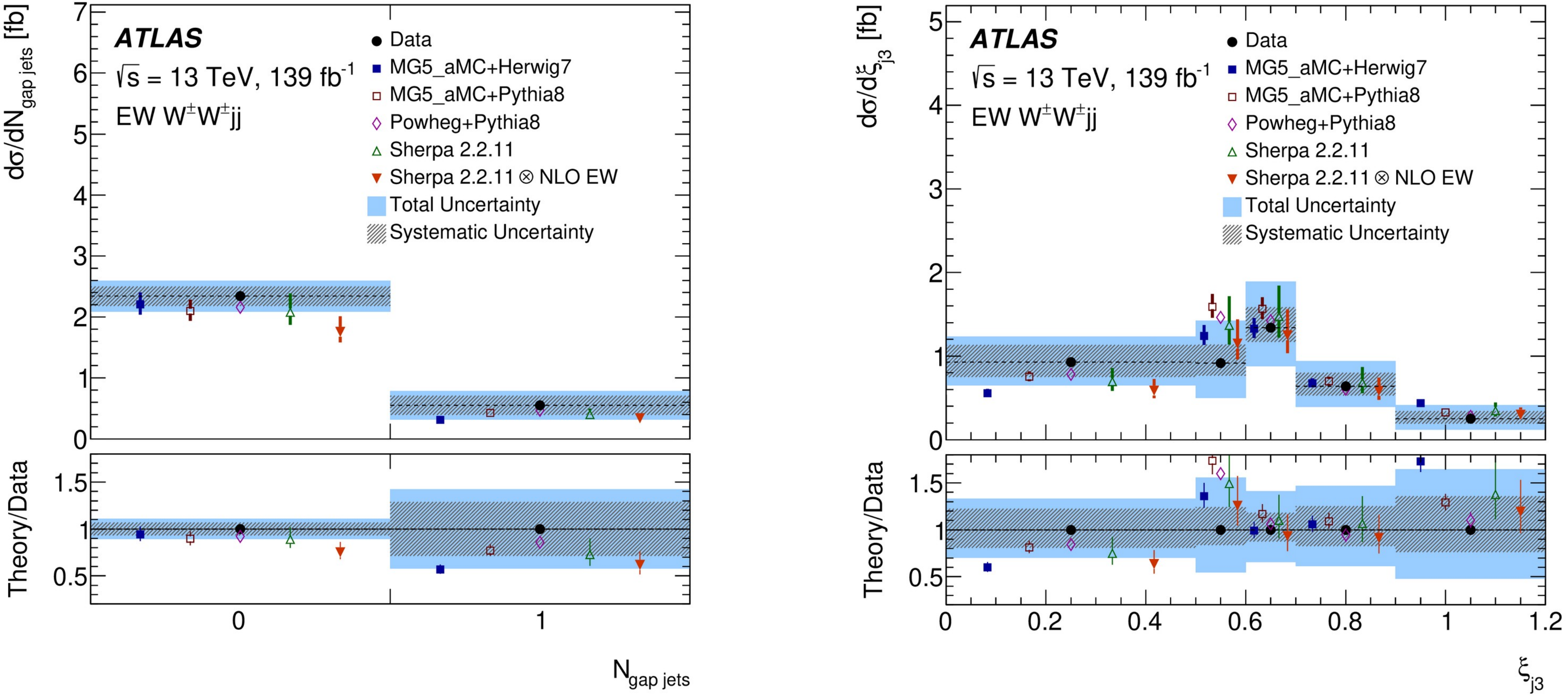
arXiv:2403.15296





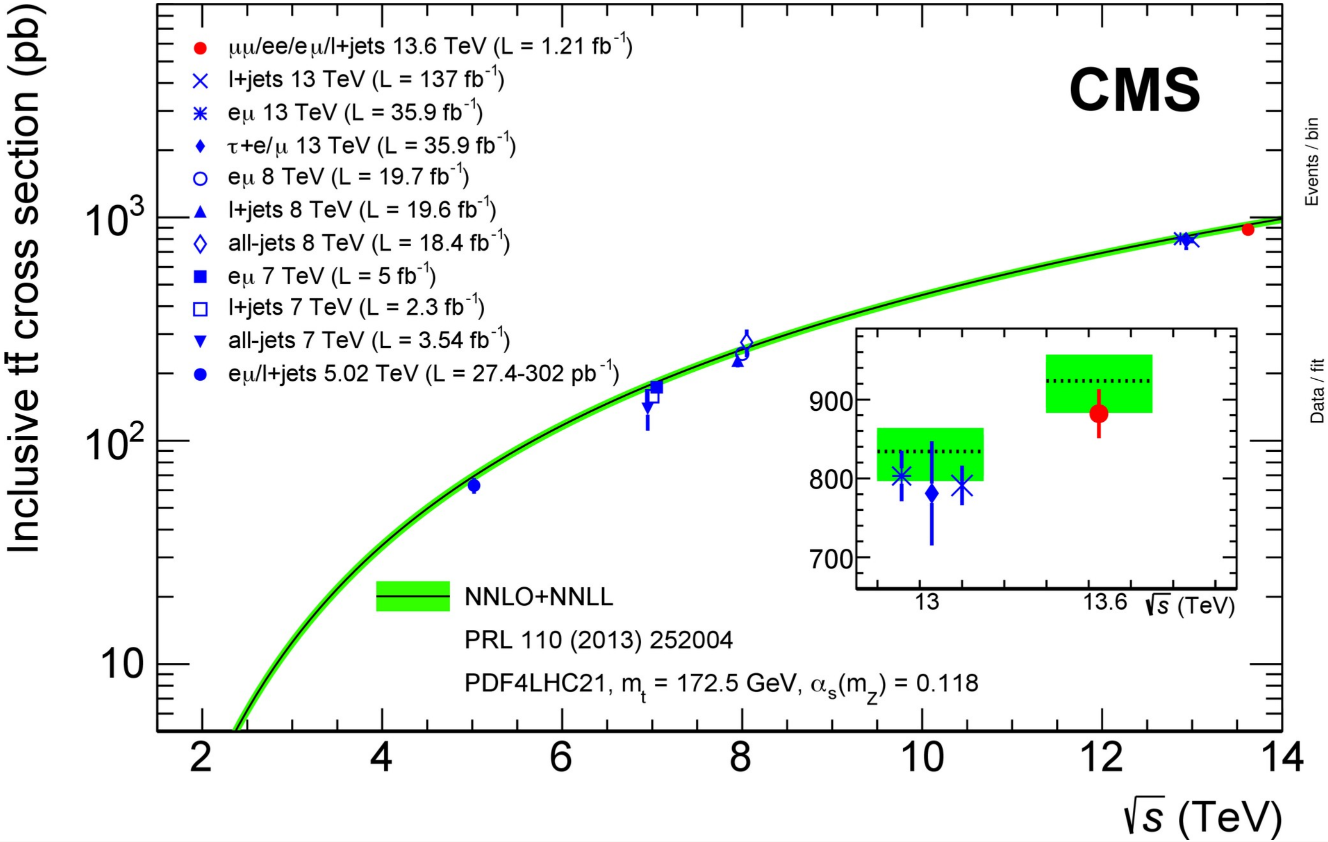
$pp \to W^{\pm}W^{\pm}jj$

ATLAS-STDM-2018-32
JHEP 12 (2023) 107

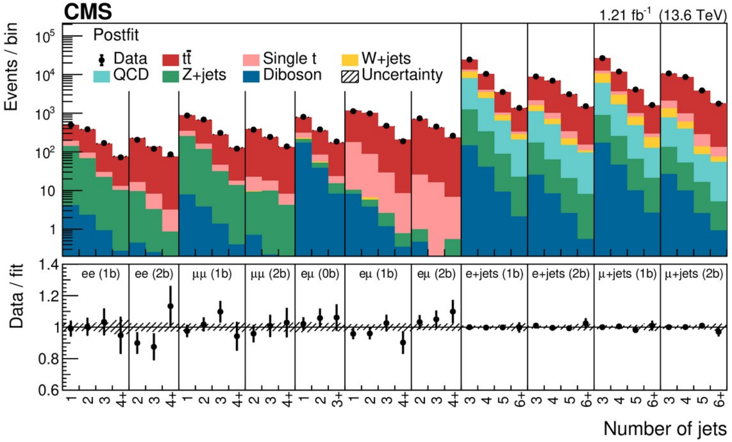


Top quark results in Run 3 TOP-22-012

First measurement of the top quark pair production cross section in proton-proton collisions **at 13.6 TeV**, with 1.21 fb^{-1} of data from 2022



Measured in **dilepton and lepton + jets channels**

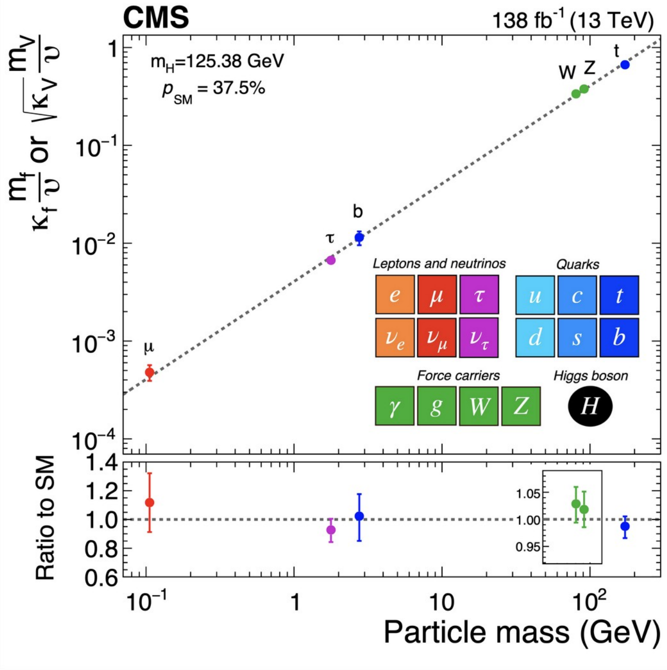


$$\sigma(t\bar{t}) = 881 \pm 23\ (\text{stat+syst}) \pm 20\ (\text{lumi})\ \text{pb}$$

Higgs Couplings

HIG-22-008

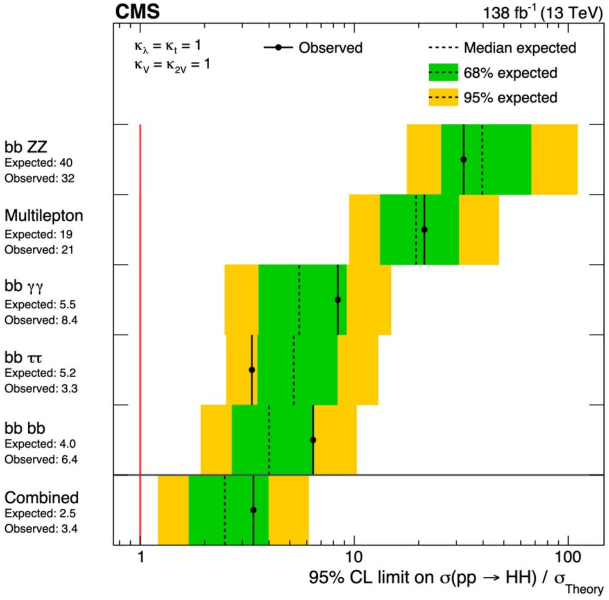
Higgs



Nature 607 (2022) 60-68

Still missing somes, but we are **under way**.

k_e < 240 (HIG-21-015) k_c < 47 (HIG-21-12) @ 95 C.L.



Recently studied **Higgs anomalous couplings** from its production and decay in the WW channel (eμ final state). Used several categories: ggFusion, EWK VBS, and HV associated production

Coupling	Observed	Expected
$c_{H\Box}$	$-0.76^{+1.43}_{-3.43}$	$0.0^{+1.37}_{-1.84}$
c_{HD}	$-0.12^{+0.93}_{-0.32}$	$0.0^{+0.43}_{-0.30}$
c_{HW}	$0.08^{+0.43}_{-0.87}$	$0.0^{+0.37}_{-0.48}$
c_{HWB}	$0.17^{+0.88}_{-1.79}$	$0.0^{+0.77}_{-0.96}$
c_{HB}	$0.03^{+0.13}_{-0.26}$	$0.0^{+0.11}_{-0.14}$
$c_{H\tilde{W}}$	$-0.26^{+0.67}_{-0.50}$	$0.0^{+0.48}_{-0.52}$
$c_{H\tilde{W}B}$	$-0.54^{+1.37}_{-1.03}$	$0.0^{+0.99}_{-1.07}$
$c_{H\tilde{B}}$	$-0.08^{+0.20}_{-0.15}$	$0.0^{+0.15}_{-0.16}$

W mass measurement

	ATLAS m_W 2017	ATLAS m_W 2023	Effect on central value	Effect on uncertainty
Statistical interpretation	χ^2 fit with stat-only uncertainties, systematics added aposteriori	Profile max. likelihood (ML) fit - for the first time in context of m_W measurements; O(1000) NPs reduced to ~200 NPs with PCA	-16.3 MeV	↓
Baseline PDF	CT10	CT18	+4.6 MeV	↑
Electroweak theory unc.	Evaluated at truth level	Evaluated at detector level		↑
Multijet background	2023: Systematic shape variations using PCA, new transfer function from CR to SR		+1.9 MeV	↓
Detector calibration	Unchanged			
EW and top background	Unchanged			

Good compatibility

W mass measurement

JHEP 01 (2022) 036

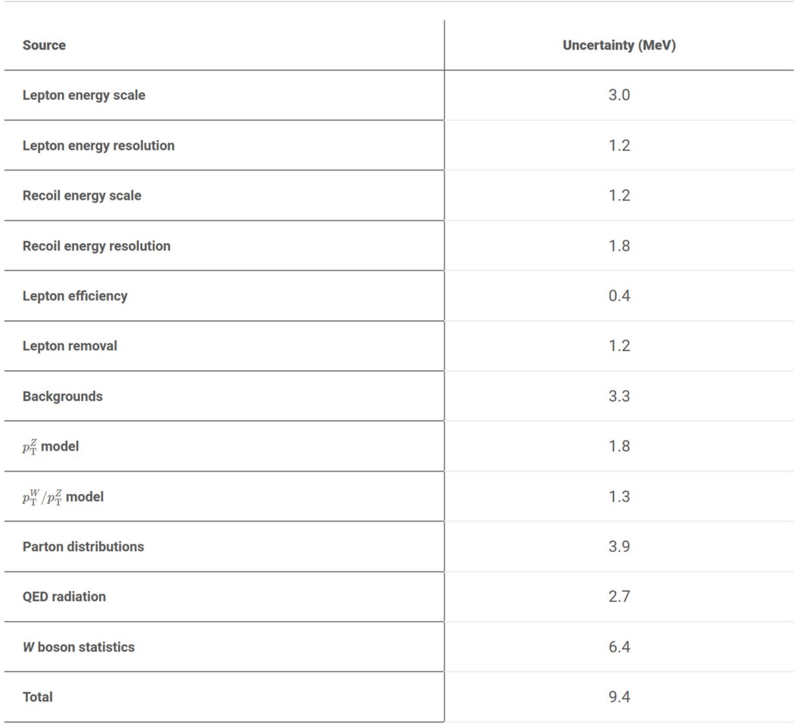
Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

W mass measurement

CDF W mass measurement

Science 376 (2022) 6589, 170-176

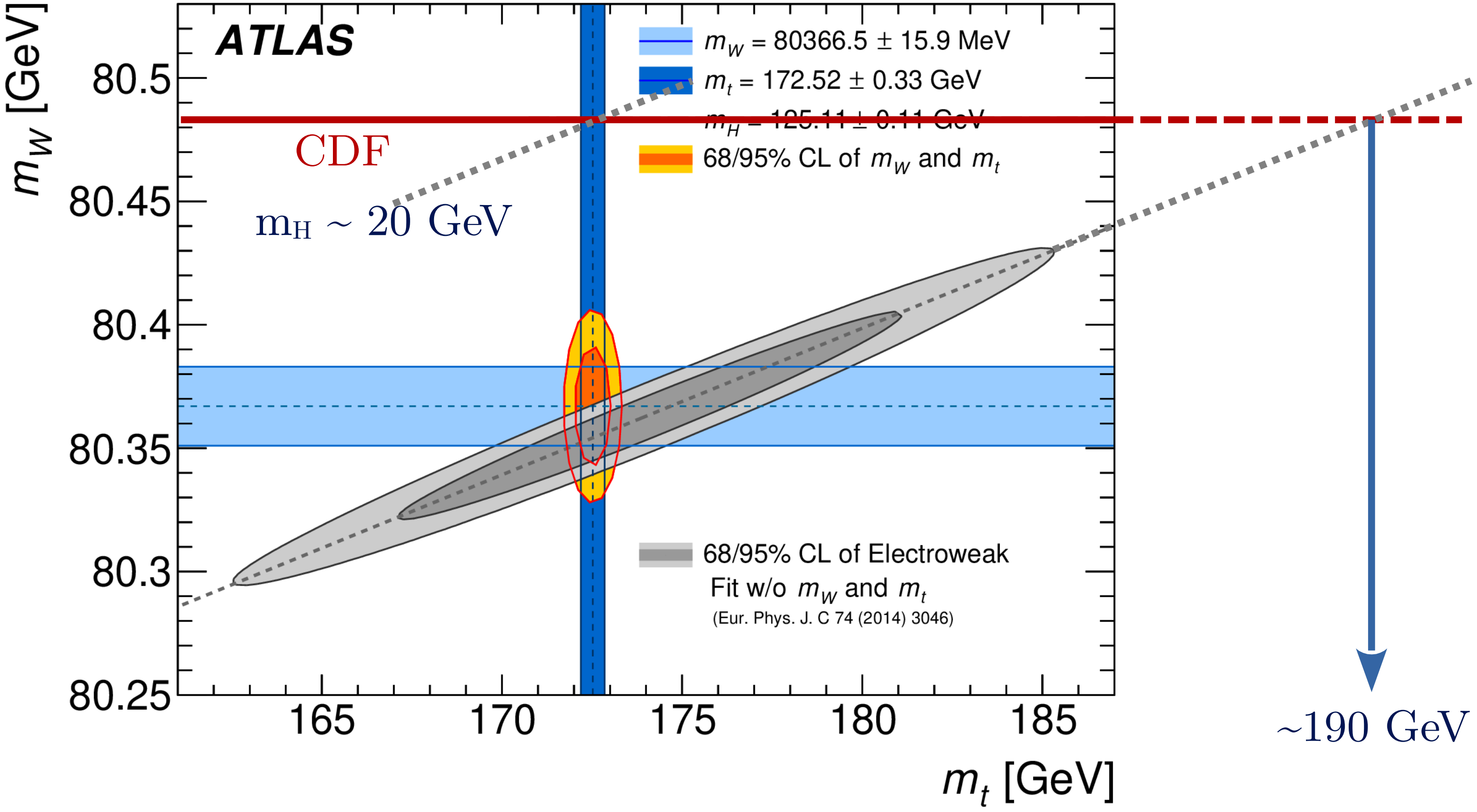
- Full Run II Tevatron data
- Most precise m_W measurement to date (even than combinations)
- Significant systematics reduction using cosmic data:
  - Tracking detector alignment & drift model
  - Uniformity of the EM calo response and resolution model
- Custom detector response simulation (not full simulation unlike LHC experiments)
- Six m_W values from template fits to m_T, p_T^{ℓ}, p_T^{ν} distributions in e and μ channels
  - Technique similar to 2017 ATLAS first measurement



Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

$$m_W = 80'435.5 \pm 6.4(stat) \pm 6.9(syst)\,MeV = 80'435.5 \pm 9.4\,MeV$$

W mass compatibility check



CDF

$m_H \sim 20$ GeV

~190 GeV

Few key points in SMEFT

The effective field theory reveals high energy physics through precise measurements at low energies. **Its validity is for E << Λ**.

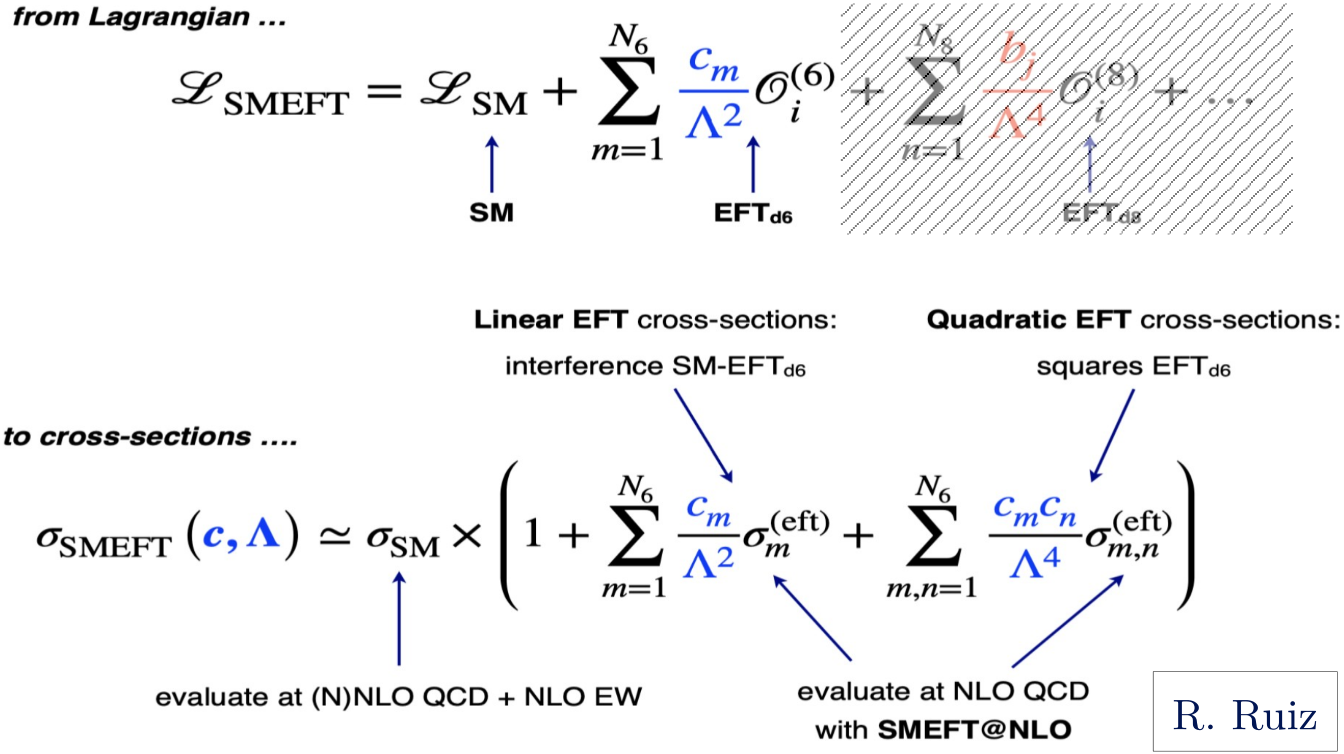
from Lagrangian ...

$$\mathscr{L}_{\text{SMEFT}} = \underset{\substack{\uparrow \\ \textbf{SM}}}{\mathscr{L}_{\text{SM}}} + \sum_{m=1}^{N_6} \underset{\substack{\uparrow \\ \textbf{EFT}_{\textbf{d6}}}}{\frac{c_m}{\Lambda^2}\mathcal{O}_i^{(6)}} + \sum_{n=1}^{N_8} \underset{\substack{\uparrow \\ \textbf{EFT}_{\textbf{d8}}}}{\frac{b_j}{\Lambda^4}\mathcal{O}_i^{(8)}} + \dots$$

Few key points in SMEFT

The effective field theory reveals high energy physics through precise measurements at low energies. **Its validity is for E << Λ.**

It allows us to **compute precise** **<u>cross sections</u>** starting from the **<u>lagrangian</u>**



from Lagrangian ...

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_{m=1}^{N_6} \frac{c_m}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_{n=1}^{N_8} \frac{b_j}{\Lambda^4} \mathcal{O}_i^{(8)} + \cdots$$

Linear EFT cross-sections: interference SM-EFT$_{d6}$

Quadratic EFT cross-sections: squares EFT$_{d6}$

to cross-sections ....

$$\sigma_{\mathrm{SMEFT}}\left(c, \Lambda\right) \simeq \sigma_{\mathrm{SM}} \times \left(1 + \sum_{m=1}^{N_6} \frac{c_m}{\Lambda^2} \sigma_m^{(\mathrm{eft})} + \sum_{m,n=1}^{N_6} \frac{c_m c_n}{\Lambda^4} \sigma_{m,n}^{(\mathrm{eft})}\right)$$

evaluate at (N)NLO QCD + NLO EW

evaluate at NLO QCD with **SMEFT@NLO**

R. Ruiz

The **quadratic dim 6 cross section** contains both **pure** (i.e., m=n) and **mixed** contributions.

When considering **dim 6 quadratic** term **one should include the dim 8 linear term**, unless the measurement is **proven to be insensitive** to the addition of the dim 6 quadratic term.