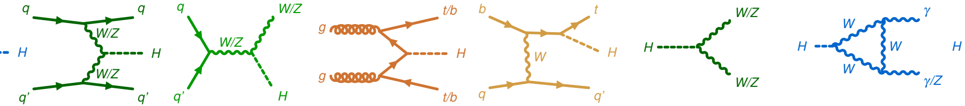


Measurements of Higgs boson production and decay rates with the ATLAS experiment

Lena Herrmann
on behalf of the ATLAS Collaboration

35th Rencontres de Blois

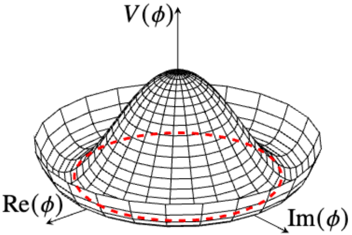
22.10.2024

UNIVERSITÄT BONN

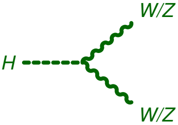
ATLAS EXPERIMENT

Why?

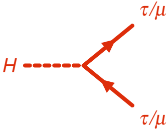
- challenge the SM to get a fundamental understanding of the universe
- particle couplings to Higgs boson are central to the theory



→ **Gauge Couplings** to vector bosons provide information of spontaneous symmetry-breaking
→ **Yukawa Couplings** further probe the Higgs sector
→ couplings to heavy particles like top quark **sensitive to BSM**

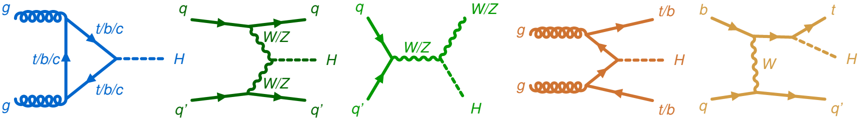


$$g_V = \frac{2m_V^2}{\text{vev}}$$

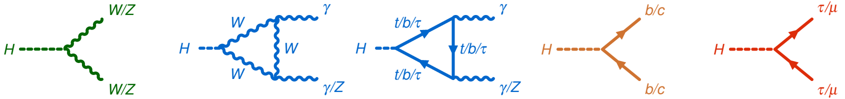


$$g_{Hf\bar{f}} = \frac{m_f}{\text{vev}}$$

Higgs Production & Decay



@13 TeV: 87% 7% 4% 1% < 1%



@125 GeV: 22%(WW)/3%ZZ 0.2%($\gamma\gamma$).2%(Zγ) 58%(bb).9% (cc) 6%($\tau\tau$).02%($\mu\mu$)

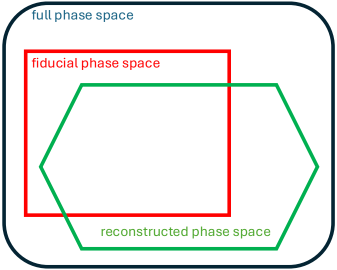
$\rightarrow$ ambitious program measuring all accessible production and decay channels
$\rightarrow$ latest results show evidence for rare decays ($Z\gamma$, ..)

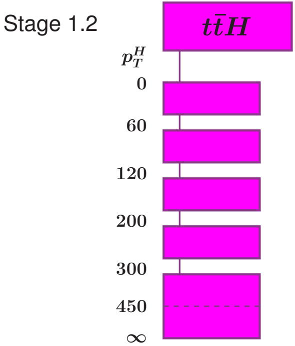
Key ingredients to challenge the SM:
$\rightarrow$ advanced analysis strategies
$\rightarrow$ more statistics (Run 2: 140 fb^{-1}, Run 3 targets $\sim$ 300 fb^{-1})

Measurement Strategies

→ **Fiducial Cross-Sections**

- fiducial: *having trust* (in the detector)
- select phase-space accessible to detector/ reliably reconstructable
- theory and experiment comparable with minimal extrapolations





→ **Simplified Template Cross-Sections (STXS)**

- phase-space regions split according to production mode/ kinematics
- reduction of theoretical uncertainties
- regions promising for BSM (high p_T^H)
- facilitation of combination

EFT Interpretation

- anomalous interactions may affect interaction vertices and are introduced in an EFT Lagrangian via higher dimensional operators $\mathcal{O}_i$

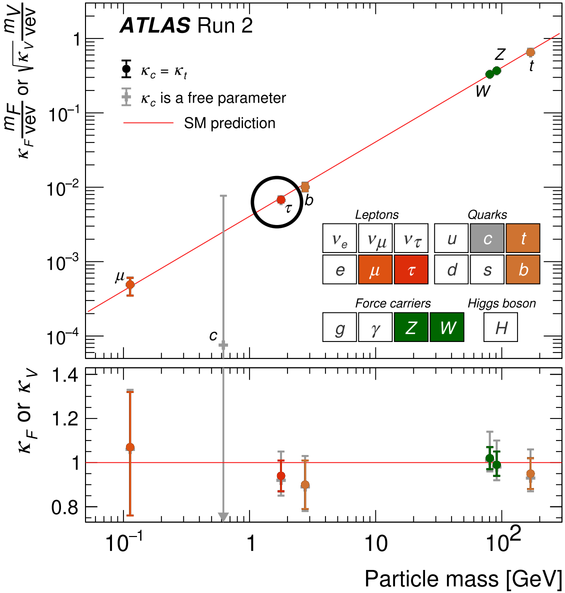
$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_d \sum_i \frac{c_i^d}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)}, \text{for d} > 4$$

- Wilson-coefficients $c_i^{(d)}$ specify strength of anomalous interaction
- Λ : scale of new physics
- only dimension 6 operators considered (dimension 5 and 7 violate lepton and baryon number conservation, higher dimensions suppressed)
- derive constraints on Wilson coefficients by comparing measured cross-section to the prediction of SMEFT
- differential cross-section depends on linear (suppressed by Λ^{-2}) and quadratic term (suppressed by Λ^{-4})(interference between SM and EFT amplitude/ pure EFT contribution)

$$\sigma \propto |\mathcal{M}_{\text{EFT}}|^2 = |\mathcal{M}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}_{\text{i}}|^2$$

Tau Coupling

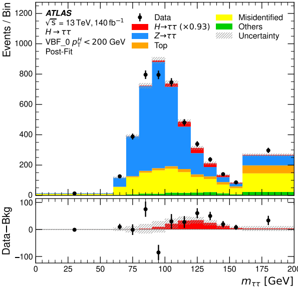
arXiv:2207.00092

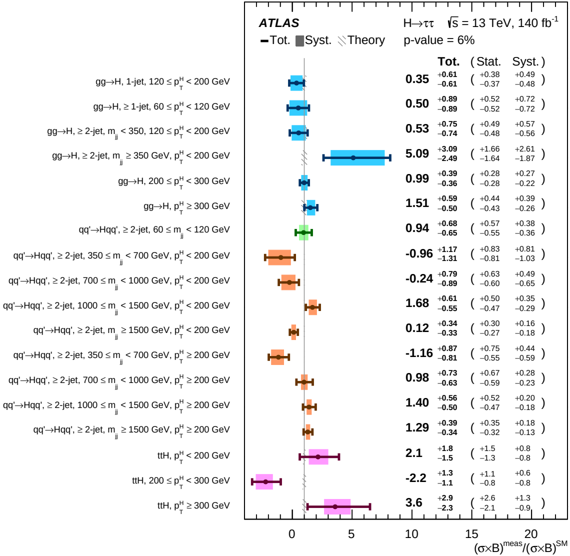


$H \to \tau\tau$: **STXS Results** (Run 2) (arxiv:2407.16320)

- di-tau channel promising branching ratio of 6.3%
- dominant background: $Z \to \tau\tau$
- 6 bins in ggF, 1 V(had)H, 8 VBF & 3 $t\bar{t}H$
- improved MVA strategies in VBF and $t\bar{t}H$

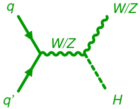
relative precision ($\mu = 1$): **35% - 300%**



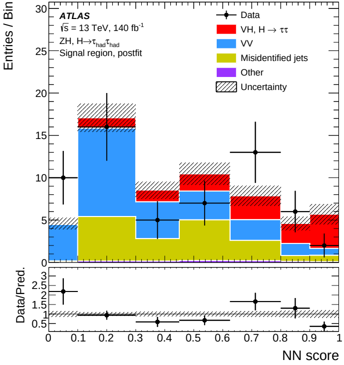


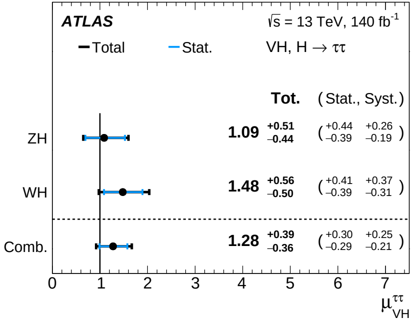
$V(lep)H \to \tau\tau$ (Run 2) (arxiv:2312.02394)

- four channels differentiated by leptonic decay of W or Z, and $\tau_{\text{lep}}\tau_{\text{had}}$ or $\tau_{\text{had}}\tau_{\text{had}}$ channel of Higgs decay
- μ measured by fit to NN score distribution, 6 classifiers trained (three for WH($\tau_{\text{lep}}\tau_{\text{had}}$))

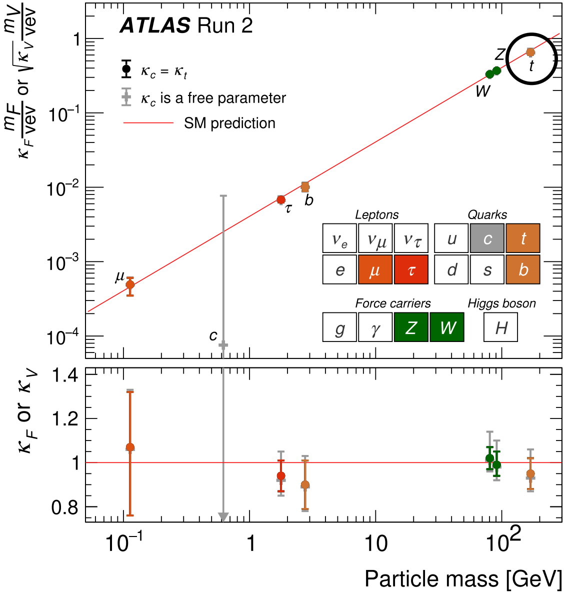


$\mu = 1.28 \pm 0.3(stat) \pm 0.2(syst)$, **evidence** of the process with a significance of 4.2σ





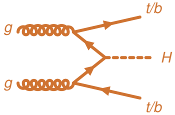
Top Coupling



arXiv:2207.00092

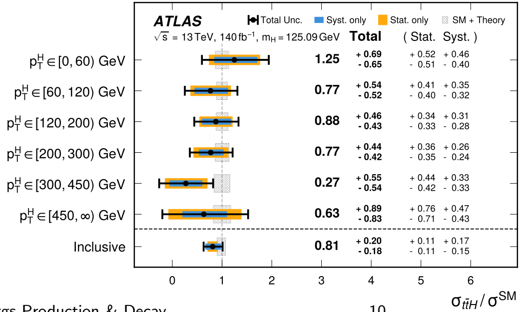
$t\bar{t}H(b\bar{b})$ (Run 2) (arxiv:2407.109004)

- heavy top interesting for BSM searches
- $t\bar{t}H$ channel enables top-Yukawa measurement
- high branching ratio of $b\bar{b}$ but large background from $t\bar{t}$ + jets
- advanced b-jet identification (DL1r: multiclass DNN differentiating b,c,l)
- multiclass NN differentiates signal from 5 background categories
- single lepton channel limited by systematics, dilepton by statistics

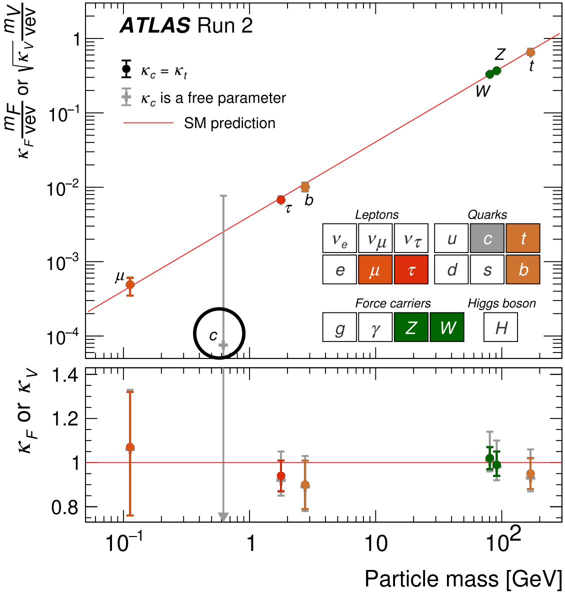


evidence with 4.6σ

- STXS cross-section measurement in 6 p_T^H bins, compatibility with SM prediction: **p-value of 89%**



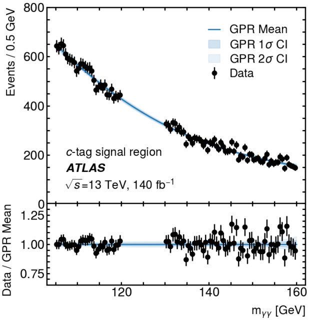
Charm Coupling

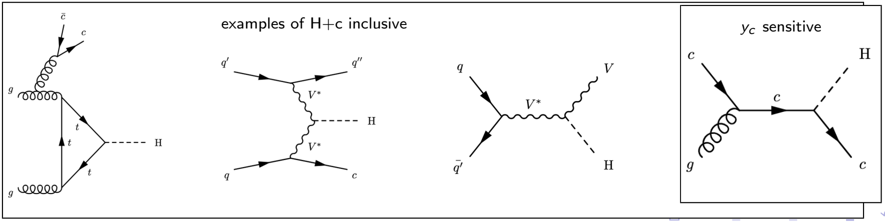


arXiv:2207.00092

$H(\rightarrow \gamma\gamma) + c$ (Run 2) (arxiv:2407.15550)

- charm coupling challenging due to **low branching ratio** and **large hadronic background**
- measure inclusive H+c: g+c $\rightarrow H + c$ (y_c sensitive) contributes with $\sim 1\%$
- non-resonant $pp \rightarrow \gamma + n$ parton background: data-driven estimation, interpolate contribution from sideband to SR using Gaussian process regression (GPR)
- resonant Higgs boson background modelled from simulation





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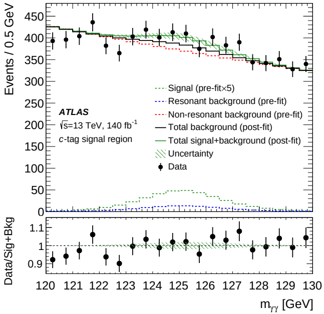
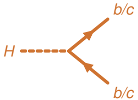


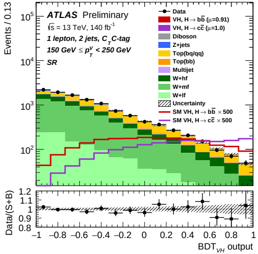
→ binned likelihood fit to $m_{\gamma\gamma}$
→ dominant uncertainties from GPR (statistical) & theory
→ 1.7σ **observed significance** of inclusive H+c process

$V(\rightarrow \textit{leptons})H(\rightarrow c\bar{c}/b\bar{b})$ (Run 2) (ATLAS-CONF-2024-010)

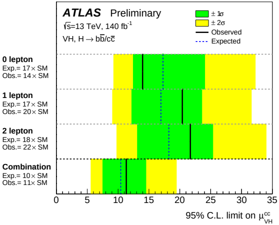
$\rightarrow$ study **c-Yukawa coupling in Higgs decay**



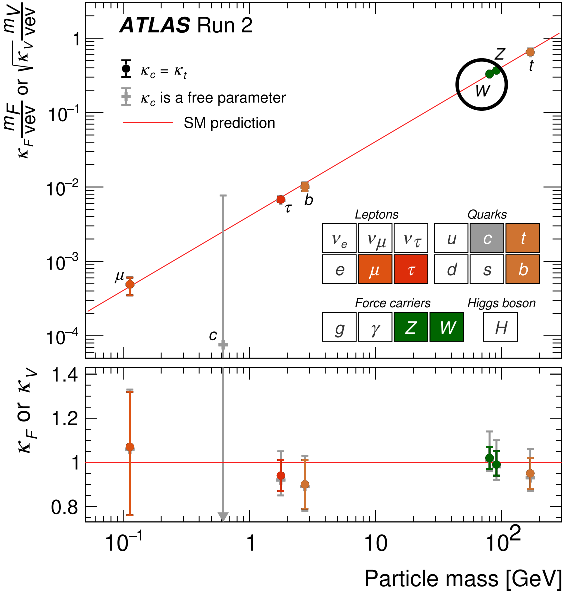
- V($\rightarrow$ leptons)H provides clean signature suppressing multi-jet background
- **reliable jet flavor tagging** crucial
  $\rightarrow$ dedicated flavor tagging regions based on the DL1r output
- 0-/1-/2-lepton channels differentiated
- methodology validated in VZ($\rightarrow c\bar{c}/b\bar{b}$)
- likelihood-fit to BDT-observable
- dominant backgrounds: $t\bar{t}$ and V+jets
- VH($\rightarrow c\bar{c}$) similarly affected by statistical and systematic uncertainties



$H \rightarrow c\bar{c}$ observed upper limit at $11.3 \times$ SM @95% CL



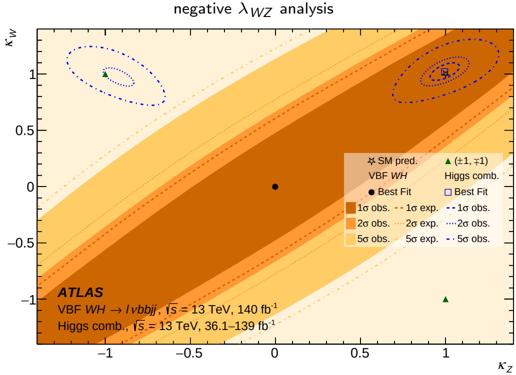
Gauge Coupling

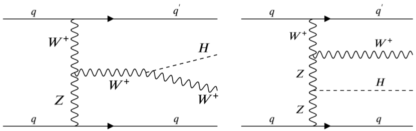


Relative Sign of Higgs Boson Couplings to W and Z in VBF WH Production (Run 2) (arxiv:2402.00426)

- channel: $WH \to l\nu bb$
- same-sign (SM-like) vs. opposite sign of $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$ corresponds to destructive vs. constructive interference of VBF WH production with H coupling to either W or Z
- combined Higgs measurements yield $|\lambda_{WZ}|$ consistent with 1 (κ_W expected to be positive due to interference with t)

opposite sign coupling excluded with significance $> 5\sigma$

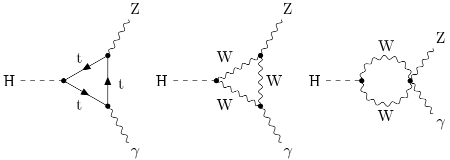


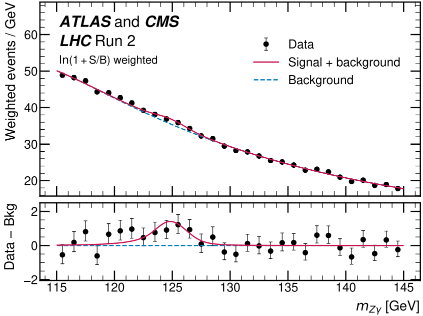


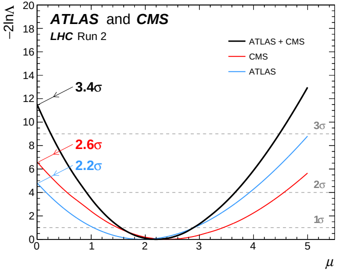
$H \to Z(\to ll)\gamma$ (Run 2)

(Phys. Rev. Lett. 132, 021803)

- rare decay, ATLAS + CMS analysis
- decay via loops
  $\to$ sensitive to BSM scenarios
- dominant background: Drell-Yan in association with γ
- ATLAS/CMS: 6/8 categories (i.e. VBF via BDTs, exploit kinematic properties..)







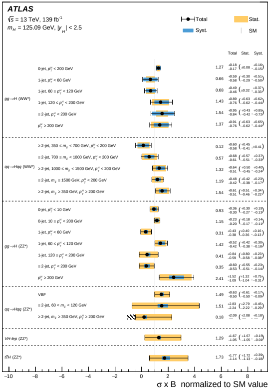
Evidence with 3.4σ significance from ATLAS + CMS combination

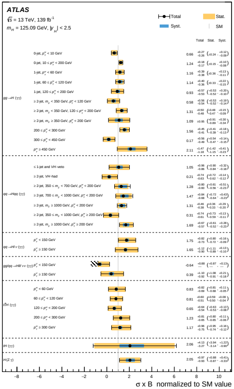
Interpretation : arxiv:2402.05742

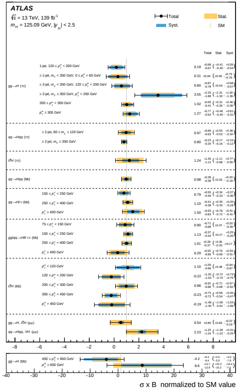
→ STXS measurements of various Higgs production modes and decays

Decay Channles

Production Modes



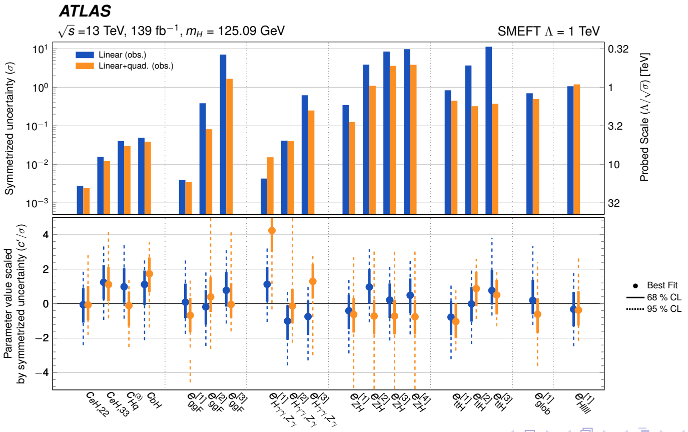




Compatibility with SM prediction: p-value 99.4%

Interpretation : arxiv:2402.05742

- SMEFT interpretation based on combined STXS results
- constrain d=6 wilson coefficients that impact Higgs coupling to SM particles
- data not sufficient to simultaneously constrain all 50 coefficients (see Appendix)
- choose **rotated basis** by principal component analysis



Conclusion

→ ATLAS is progressing well in characterizing Higgs production & decay rates

→ increasing level of detail: STSX cross-sections

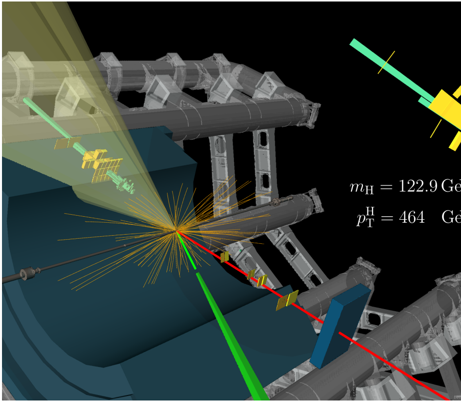
→ increasingly model-independent interpretation (SMEFT)

→ overall **good agreement with SM** at present level of precision

→ expected **increase in statistics** by a factor two in Run 3 and an order of magnitude in the HL-LHC era

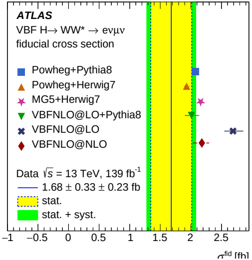
→ highly **complex analysis strategies** are continuously refined to profit from the full physics potential

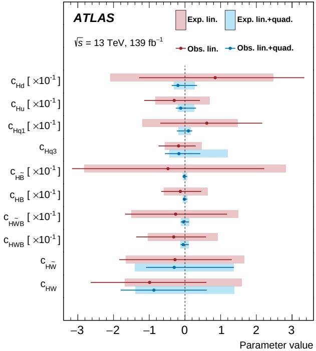
arxiv:1811.08856, $H \to \tau_{\text{lep}}\tau_{\text{lep}}$



Additional Material

VBF $H \to WW^* \to e\nu\mu\nu$ (arxiv:2304.03053)

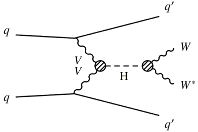




- fiducial cross-section measurement (integrated & differential)

$$\sigma_{\text{fid}} = 1.68 \pm 0.4\text{fb}$$

- statistical uncertainties dominate differential measurement
- constraints on anomalous interactions via interpreation in EFT formalism
- set limits on dimension six CP-even and CP-odd operators
- stringent constraints obtained when quadratic terms included

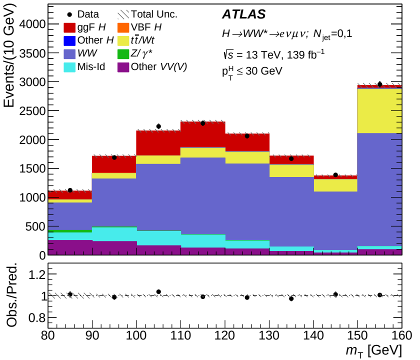


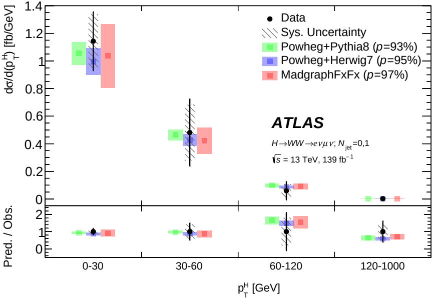
ggF $H \to WW^* \to e\nu\mu\nu$ (Run 2)

- channel profits from large branching fraction (22%)
- mixed decay to reduce Drell-Yann background
- single- and double-differential cross-sections measured in **bins of transverse mass**
  $$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - |\vec{p}_T^{\,ll} + \vec{p}_T^{\,miss}|}$$
- fiducial measurement: jet-criteria (sensitive to production kinematics) & leptonic kinematic observables
- leading uncertainties: jet/muon reconstruction, theoretical modelling of WW/ Vγ

measurement consistent with SM

Eur. Phys. J. C 83 (2023) 774





Considered operators and Wilson coefficient: arxiv:2402.05742

Wilson coefficient	Operator
c_H	$(H^\dagger H)^3$
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_G	$f^{abc} G_\mu^{a\nu} G_\nu^{b\rho} G_\rho^{c\mu}$
c_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$c^{(1)}_{Hl,11}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_1 \gamma^\mu l_1)$
$c^{(1)}_{Hl,22}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_2 \gamma^\mu l_2)$
$c^{(1)}_{Hl,33}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_3 \gamma^\mu l_3)$
$c^{(3)}_{Hl,11}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_1 \tau^I \gamma^\mu l_1)$
$c^{(3)}_{Hl,22}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_2 \tau^I \gamma^\mu l_2)$
$c^{(3)}_{Hl,33}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_3 \tau^I \gamma^\mu l_3)$
$c_{He,11}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_1 \gamma^\mu e_1)$
$c_{He,22}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_2 \gamma^\mu e_2)$
$c_{He,33}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_3 \gamma^\mu e_3)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q} \gamma^\mu q)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q} \tau^I \gamma^\mu q)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
$c^{(1)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q} \gamma^\mu Q)$
$c^{(3)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q} \tau^I \gamma^\mu Q)$
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t} \gamma^\mu t)$
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b} \gamma^\mu b)$

Wilson coefficient	Operator
$c^{(1,1)}_{Qq}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$
$c^{(1,8)}_{Qq}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$
$c^{(3,1)}_{Qq}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$
$c^{(3,8)}_{Qq}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$
$c^{(3,1)}_{qq}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$
$c^{(1)}_{tu}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$
$c^{(8)}_{tu}$	$(\bar{t}T^a\gamma_\mu t)(\bar{u}T^a\gamma^\mu u)$
$c^{(1)}_{td}$	$(\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d)$
$c^{(8)}_{td}$	$(\bar{t}T^a\gamma_\mu t)(\bar{d}T^a\gamma^\mu d)$
$c^{(1)}_{Qu}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
$c^{(8)}_{Qu}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$
$c^{(1)}_{Qd}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
$c^{(8)}_{Qd}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$
$c^{(1)}_{tq}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$
$c^{(8)}_{tq}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$
$c_{eH,22}$	$(H^\dagger H)(\bar{l}_2 e_2 H)$
$c_{eH,33}$	$(H^\dagger H)(\bar{l}_3 e_3 H)$
c_{uH}	$(H^\dagger H)(\bar{q} Y_u^\dagger u \widetilde{H})$
c_{tH}	$(H^\dagger H)(\bar{Q} \widetilde{H} t)$
c_{bH}	$(H^\dagger H)(\bar{Q} H b)$
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\, G^A_{\mu\nu}$
c_{tW}	$(\bar{Q}\sigma^{\mu\nu} t)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
c_{tB}	$(\bar{Q}\sigma^{\mu\nu} t)\widetilde{H}\, B_{\mu\nu}$
$c_{ll,1221}$	$(\bar{l}_1\gamma_\mu l_2)(\bar{l}_2\gamma^\mu l_1)$