Recent highlights in the Standard Model and Higgs Results from the LHC

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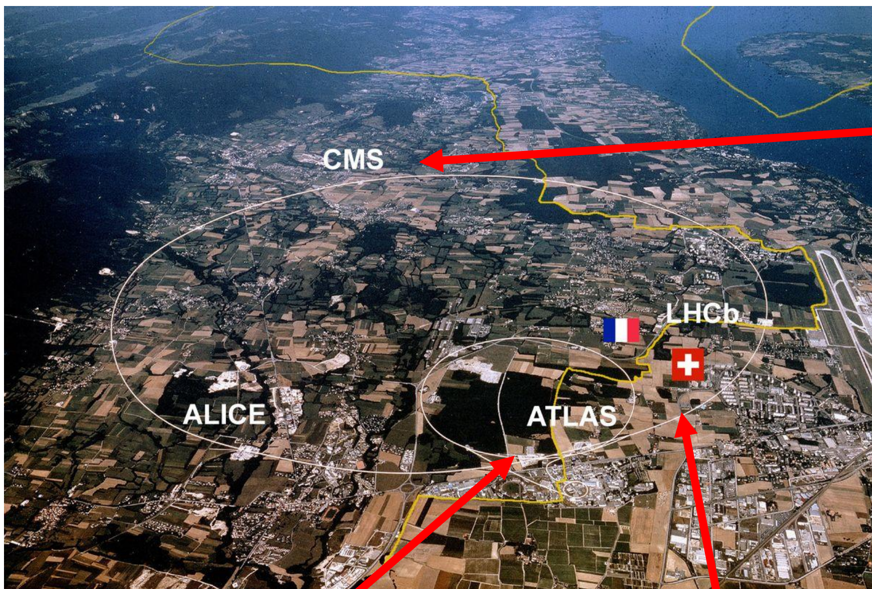
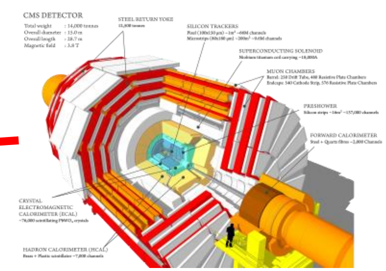
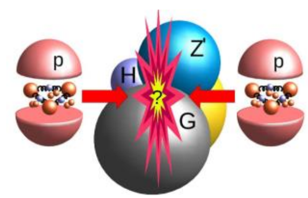
CIPANP 2025, Madison WI

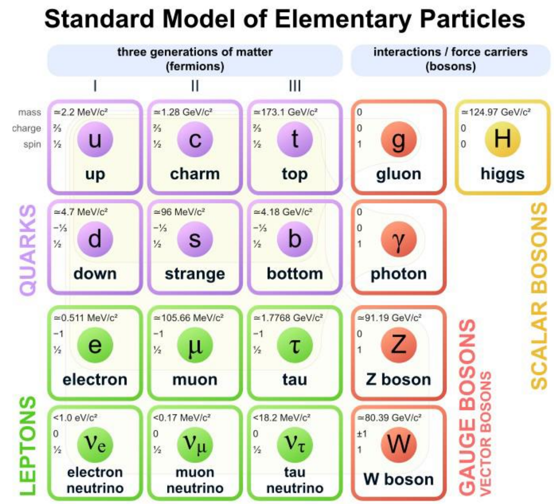
The Large Hadron Collider

- The Large Hadron Collider: the world's highest energy particle accelerator
  - protons are accelerated to 13—13.6 TeV
  - kinetic energy is transformed to matter at the collision

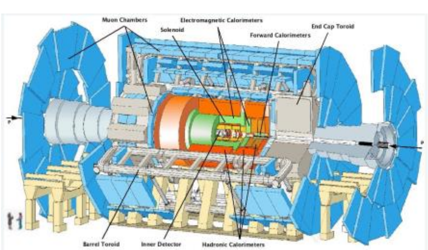


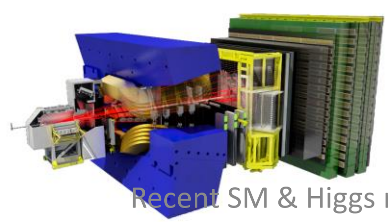






- The Standard Model: so far, the best theory to describe the most fundamental blocks of the universe
  - successfully explained most experimental results
  - precisely predicted a wide variety of phenomena, including the Higgs boson





Breakthrough physics

- The LHC experiments have a broad and ambitious physics program probing various aspects of the Standard Model
  - trying hard to find the cracks that would give us a hint of BSM physics
- We are doing Breakthrough Physics

The 2025 Breakthrough Prize in Fundamental Physics was awarded to four LHC collaborations for their "detailed measurements of Higgs boson properties confirming the symmetry-breaking mechanism of mass generation, the discovery of new strongly interacting particles, the study of rare processes and matter-antimatter asymmetry, and the exploration of nature at the shortest distances and most extreme conditions at CERN's Large Hadron Collider".

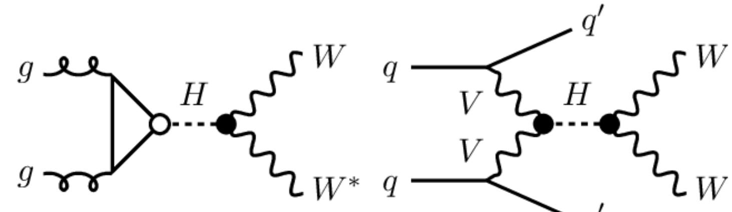
L.A., April 5, 2025

Recent Higgs and SM highlights

- There are so many great physics results – no time to cover them all
  - selection of topics: personal preference + most recent results were given a priority
- Topics (partially) covered in this talk
  - Higgs boson production cross-section
  - Higgs boson mass and width
  - di-Higgs production
  - jet cross-section and substructure
  - physics with same-sign WW pairs
  - Z mass
  - SMEFT interpretations
- Topics (unfortunately) not covered in this talk
  - top quark physics
  - VV and VVV production cross-section
  - heavy flavor jet substructure
  - W mass
  - …

ggF+VBF H→WW* (1)

- Measurement of gluon-gluon fusion and vector-boson fusion using H→WW*→lνlν decays
  - ATLAS Run 2, 140/fb
  - arXiv:2504.07686



ggF VBF

Improvements over earlier analysis: adding ee, μμ to eμ; DNN-based S/B discrimination; SMEFT interpretation

Signal regions:
Njets=0, Njset=1: eμ, Δϕ(ll,miss)>π/2
Njets≥2: ggF-enriched, VBF-enriched

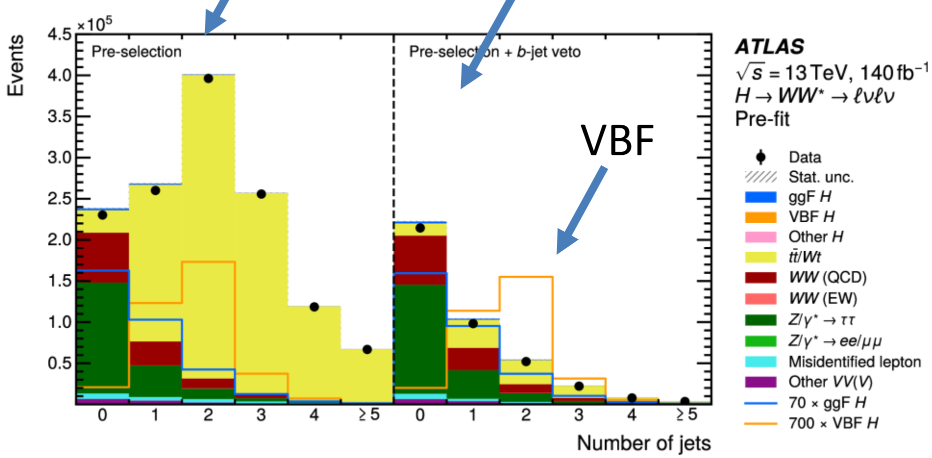
Results are presented as total cross-sections and in STXS categories

Standard Template cross-section categorization: split the production modes into exclusive kinematic fiducial regions relevant for theory interpretations
LHCHWG-INT-2025-001

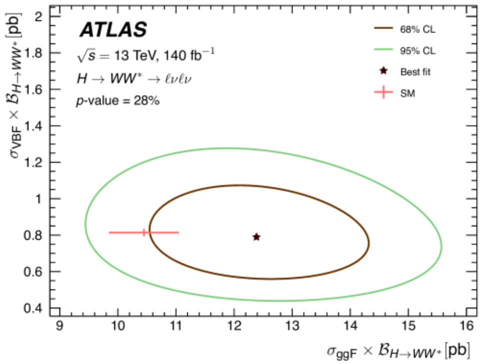
preselection: l^+l^-

b-veto: get rid of ttbar

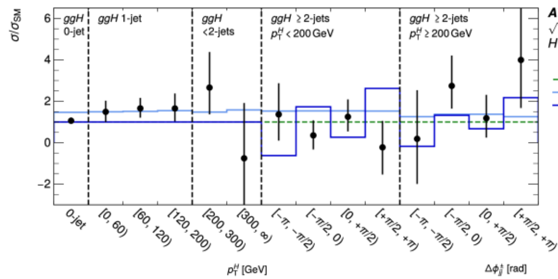
VBF



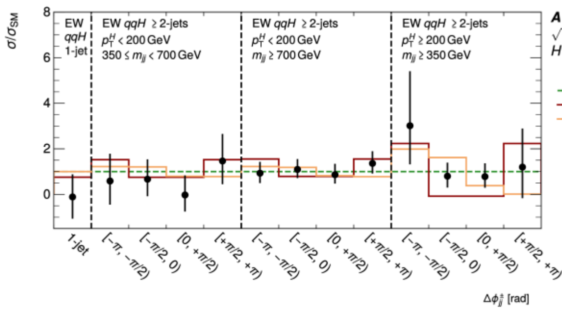
ggF+VBF H→WW* (2)



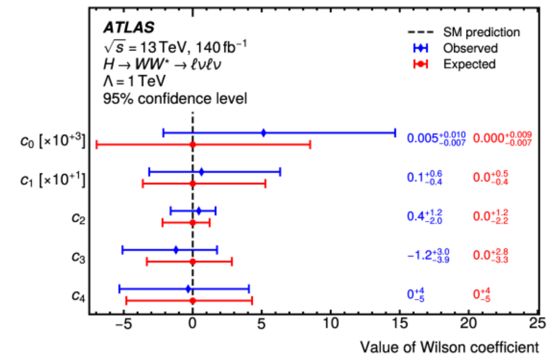
total cross-section



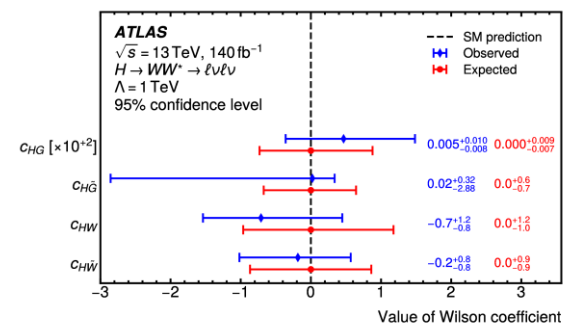
STXS, ggH



STXS, EW qqH



CP-conserving scenario, d=6 WCs in rotated basis



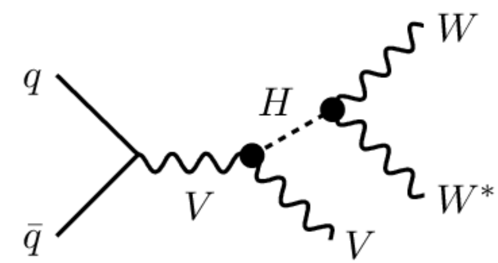
CP-violating scenario, d=6 WCs in Warsaw basis

- Results: total cross-section
  - $\sigma_{ggF}\times B(H \to WW^*)=12.4+1.3-1.2$ pb
  - $\sigma_{VBF}\times B(H \to WW^*)=0.79+0.18-0.16$ pb
  - overall improvement w.r.t the previous result using the same data (eνμν only): 11% overall, up to 36% in large p_T^H STXS categories
  - SMEFT interpretation compatible with SM prediction

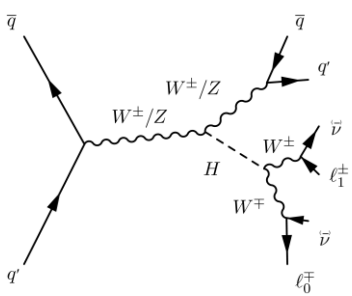
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,j} \frac{c_j^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_j^{(d)}$$

VH, H→WW* (1)

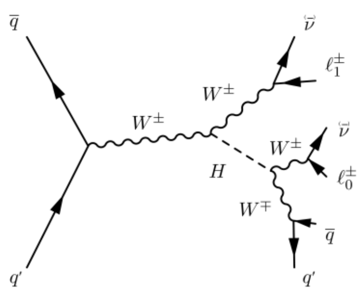
- Measurement of associated VH production using H→WW*→lνlν decays
  - ATLAS Run 2, 140/fb
  - [arXiv:2503.19420]



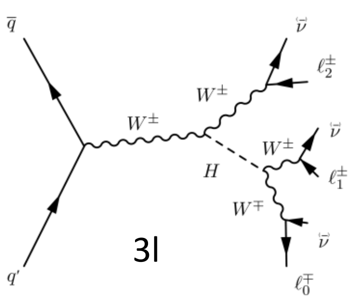
Previous ATLAS measurement was for 36.1/fb



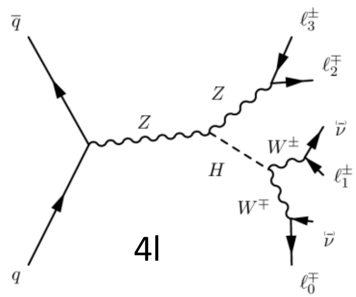
opposite-sign 2l



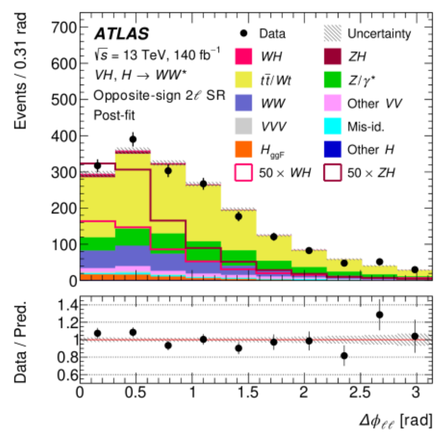
same-sign 2l



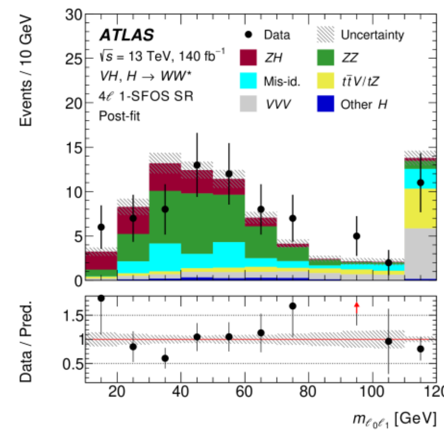
3l



4l



OS2l

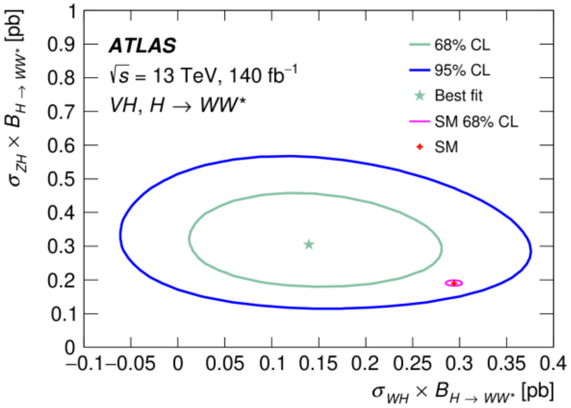


4l

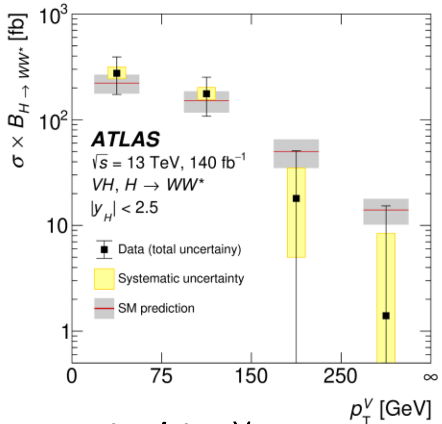
S/B separation: ANN (OS2l, 3l), RNN (SS2l), BDT (4l)

Dominant backgrounds: ttbar (OS2l) – attack with b-veto, dibosons (3l/4l)

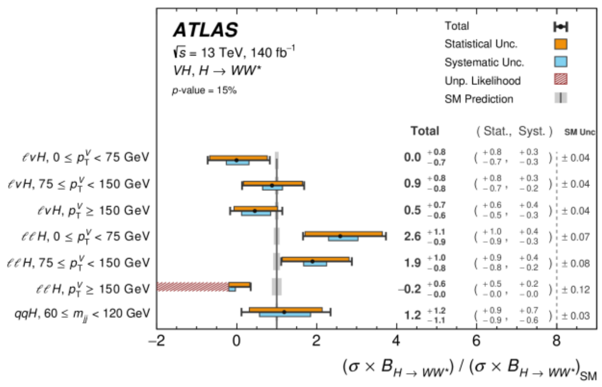
VH, H→WW* (2)



total cross-section



$d\sigma/dp_T^V$



STXS measurement

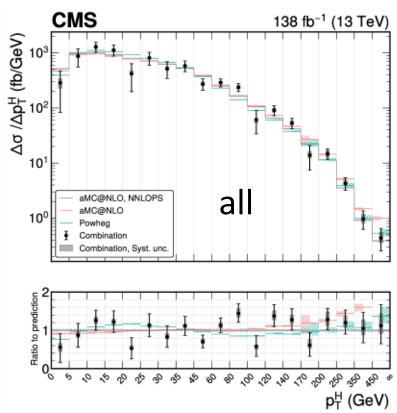
- Results: total cross-section
  - $\sigma_{VH} \times B(H \rightarrow WW^*) = 0.44 + 0.10 - 0.09(stat) + 0.06 - 0.05(syst)$ pb
  - $\mu_{VH} = 0.92 + 0.21 - 0.20(stat) + 0.13 - 0.12(syst)$
  - differential cross-sections in p_T^V and STXS categories

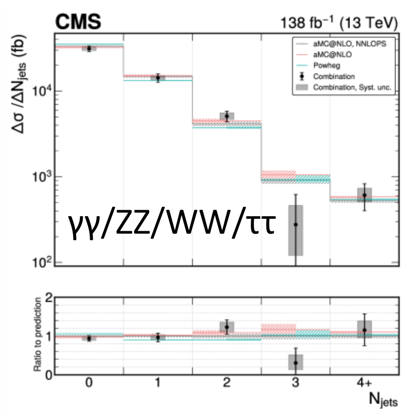
Differential Higgs XS combination (1)

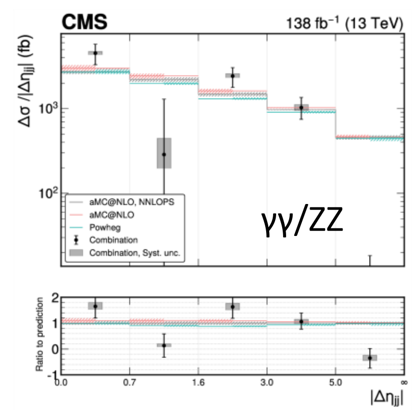
- Combination of differential Higgs XS in γγ / ZZ*→4l / WW*→eνμν / ττ / boosted ττ
  - CMS Run 2, 138/fb
  - arXiv:2504.13081

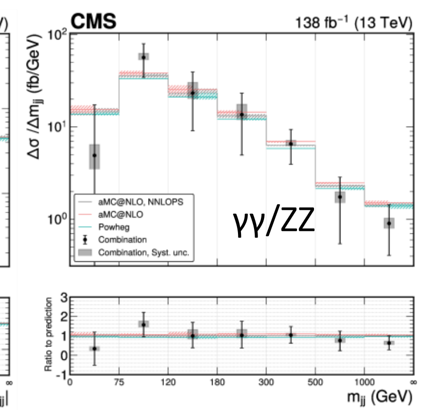
Observables: p_T^H, N_{jets}, p_T^{j1}, $|y_H|$, $|\Delta\eta_{jj}|$, m_{jj}, τ_C^j (the last three are new)

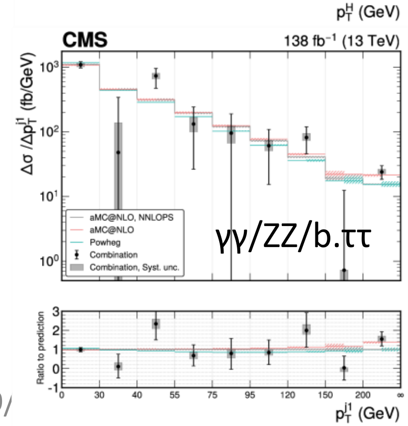
jet pT weighted by a function of its y: arXiv:1412.4792

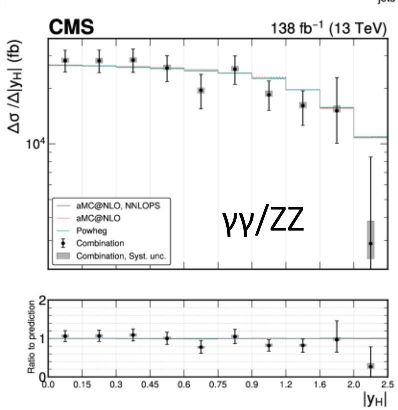


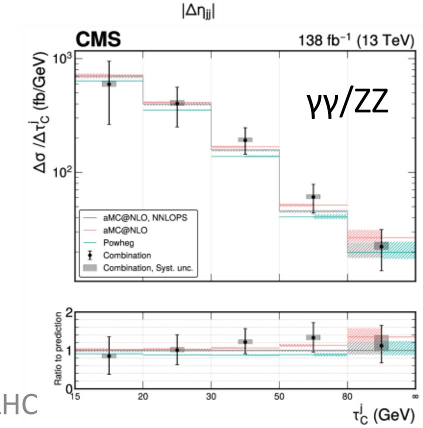




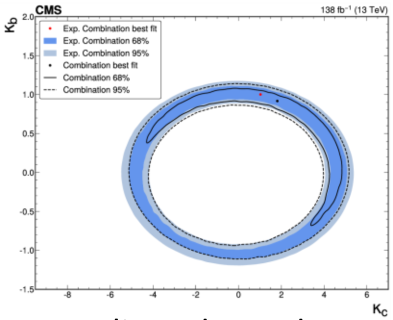




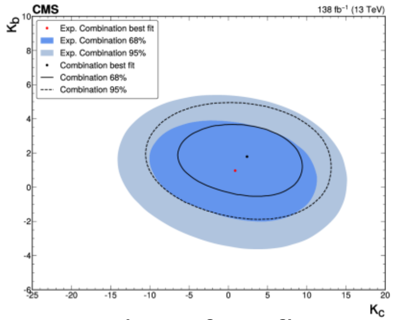




Differential Higgs XS combination (2)



couplings depend on Br

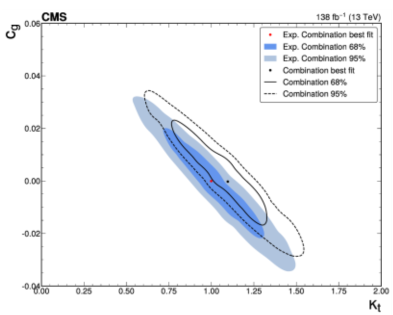


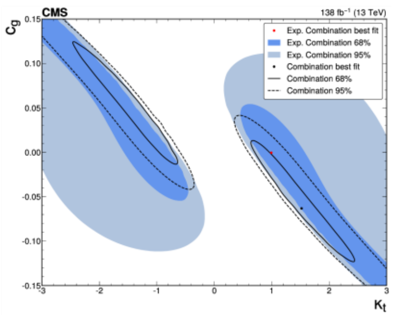
couplings free-float

Coupling modifiers: $\kappa_i = \frac{y_i}{y_i^{SM}}$

y_i is Higgs coupling to particle *i*

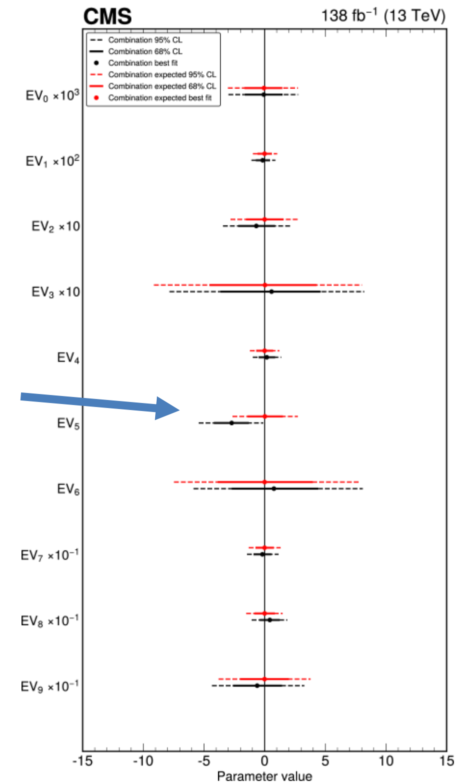
Model: κ_b-κ_c





Model: κ_b-κ_t-c_g (adding dim-6 operators to Lagrangian)

largest tension with SM: EV_5=2.71+1.33-1.39, dominated by WC $c_{Hq}^{(3)}$

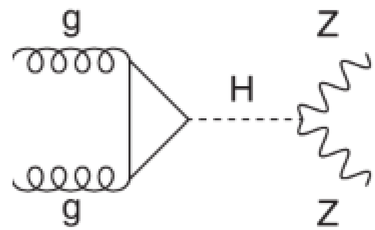


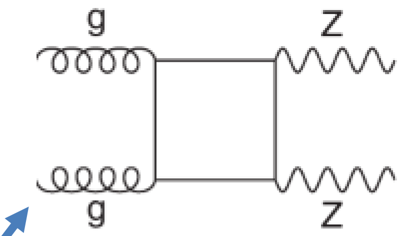
first 10 eigenvalues

- Results:
  - $d\sigma/dp_T^H$ improved by 23% compared to γγ alone
  - total XS (γγ+ZZ*→4l): σ=53.4+2.9-2.9(stat)+1.9-1.8(syst) pb
  - $d\sigma/dp_T^H$ κ-framework interpretation: κ_b-κ_c, κ_b-κ_t-c_g
  - $d\sigma/dp_T^H$ SMEFT interpretation: 2D constraints on pairs of Wilson coefficients

Higgs mass and width with H*→ZZ/H→ZZ* (1)

- Measurement of Higgs mass and width using on-shell H→ZZ*→4l and off-shell H*→ZZ→4l
  - CMS Run 2, 138/fb
  - [arXiv:2409.13663](https://arxiv.org/abs/2409.13663)





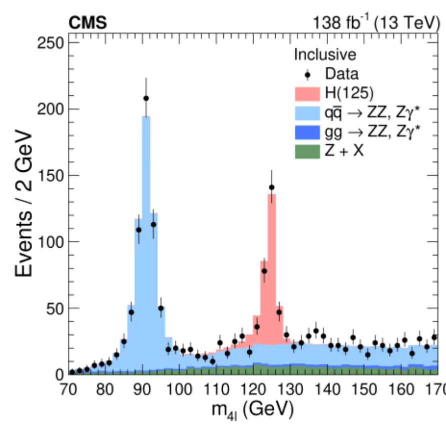
CMS: Γ_H=3.2+2.4-1.7 MeV
(*Nature Phys. 18 (2022) 1329*)

On-shell measurement: precision mass

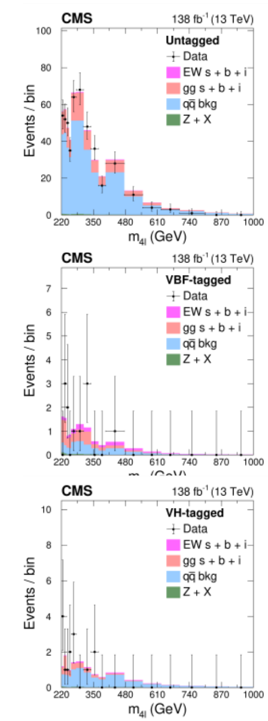
Higgs width ~4 MeV, can't measure it directly (need a muon collider)

Can do it by comparing on-shell and off-shell Higgs production (*Phys. Rev. D 88, 054024*):

$$\sigma^{\text{on-shell}} \propto \frac{g_p^2 g_d^2}{\Gamma_H} \propto \mu_p \Rightarrow \sigma^{\text{off-shell}} \propto g_p^2 g_d^2 \propto \mu_p \, \Gamma_H$$



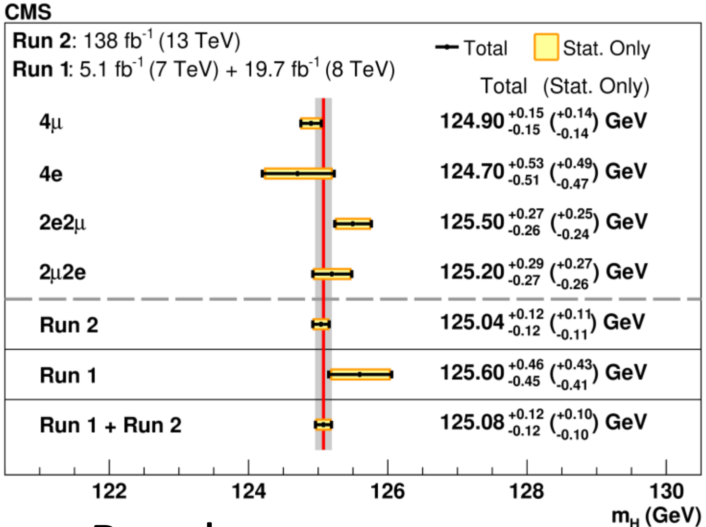
on-shell 4l channels: 4μ, 4e, 2e2μ, 2μ2e

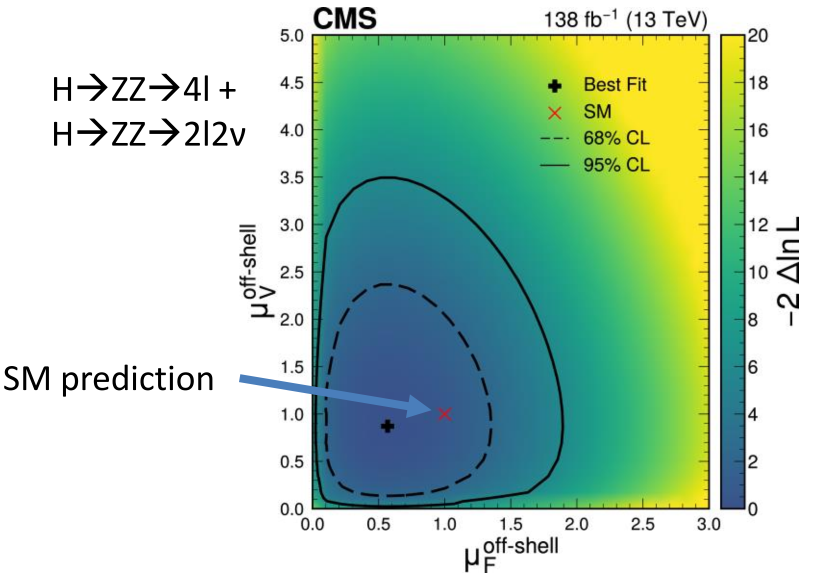


off-shell 4l channels

This analysis: first width measurement with full 4l + 2l2ν Run 2 data

Higgs mass and width with $H^* \to ZZ/H \to ZZ^*$ (2)

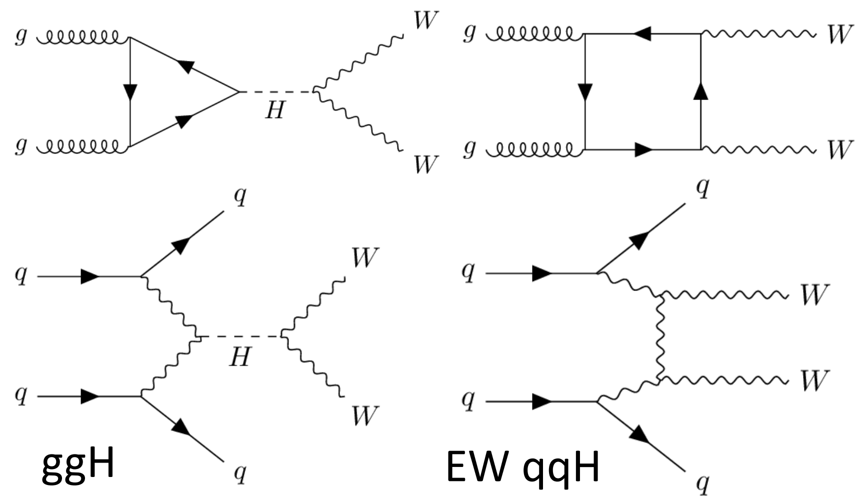




- Results:
  - mass from on-shell: m_H=125.04±0.11(stat)±0.05(syst) GeV
    - CL95 limit from on-shell production: Γ_H<330 MeV
  - observed(expected) width, $H \to ZZ^* \to 4l/H^* \to ZZ \to 4l$ combination: Γ_H=2.9+2.3-1.7 (4.1±4.0) MeV
    - CL95 limit: [0.3,7.9] (<11.5) MeV
  - observed(expected) width, $H \to ZZ^* \to 4l/H^* \to ZZ \to 4l/H^* \to ZZ \to 2l2\nu$ combination: Γ_H=3.0+2.0-1.5 (4.1±3.5) MeV
    - CL95 limit: [0.6,7.3] ([0.1,10.5]) MeV

Higgs width with H*→WW/H→WW* (1)

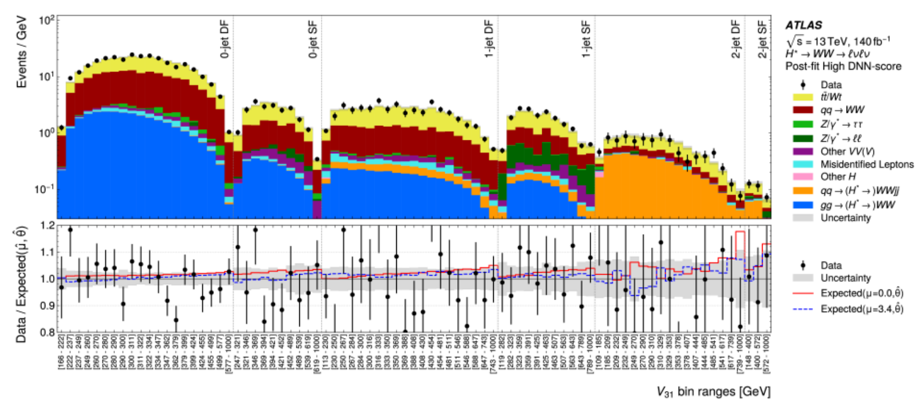
- Measurement of off-shell Higgs production using H*→WW→lvlv decays
  - ATLAS Run 2, 140/fb
  - [arXiv:2504.07710](https://arxiv.org/abs/2504.07710)



Larger statistics than H*→ZZ
May differ from H*→ZZ in presence of BSM

Can't reconstruct Higgs mass, need a proxy (V_{31})

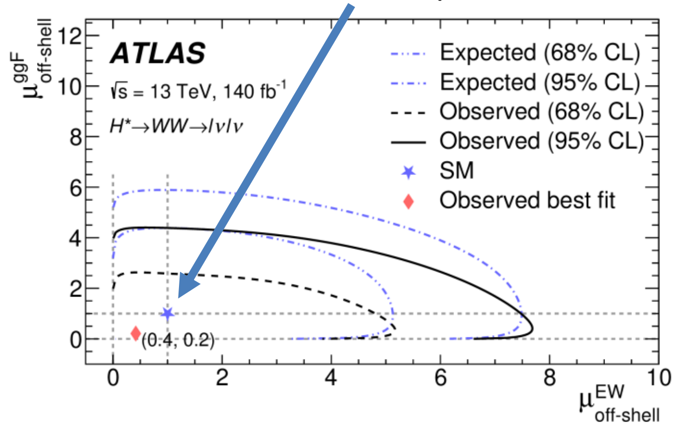
S/B separation: DNN fit to V_{31}

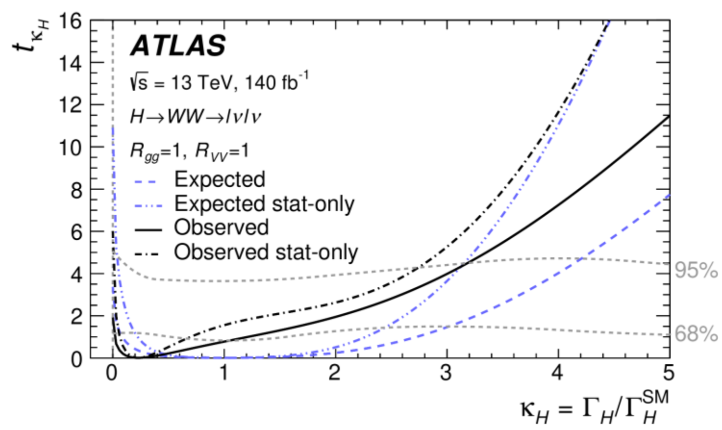


Destructive interference: presence of H* results in deficit of events compared to background-only, leads to a non-monotonic event yield vs $\mu_{\text{off-shell}}$: likelihood fit is non-trivial

Higgs width with H*→WW/H→WW* (2)

SM prediction

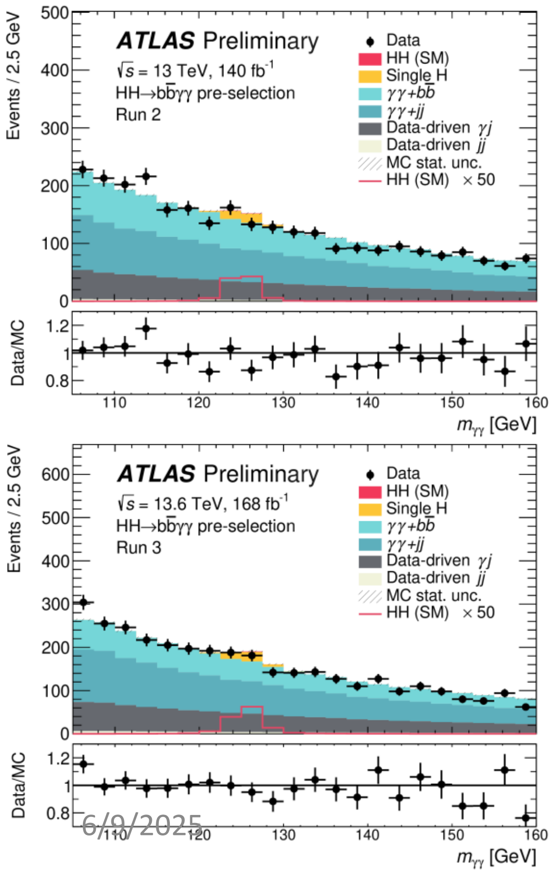


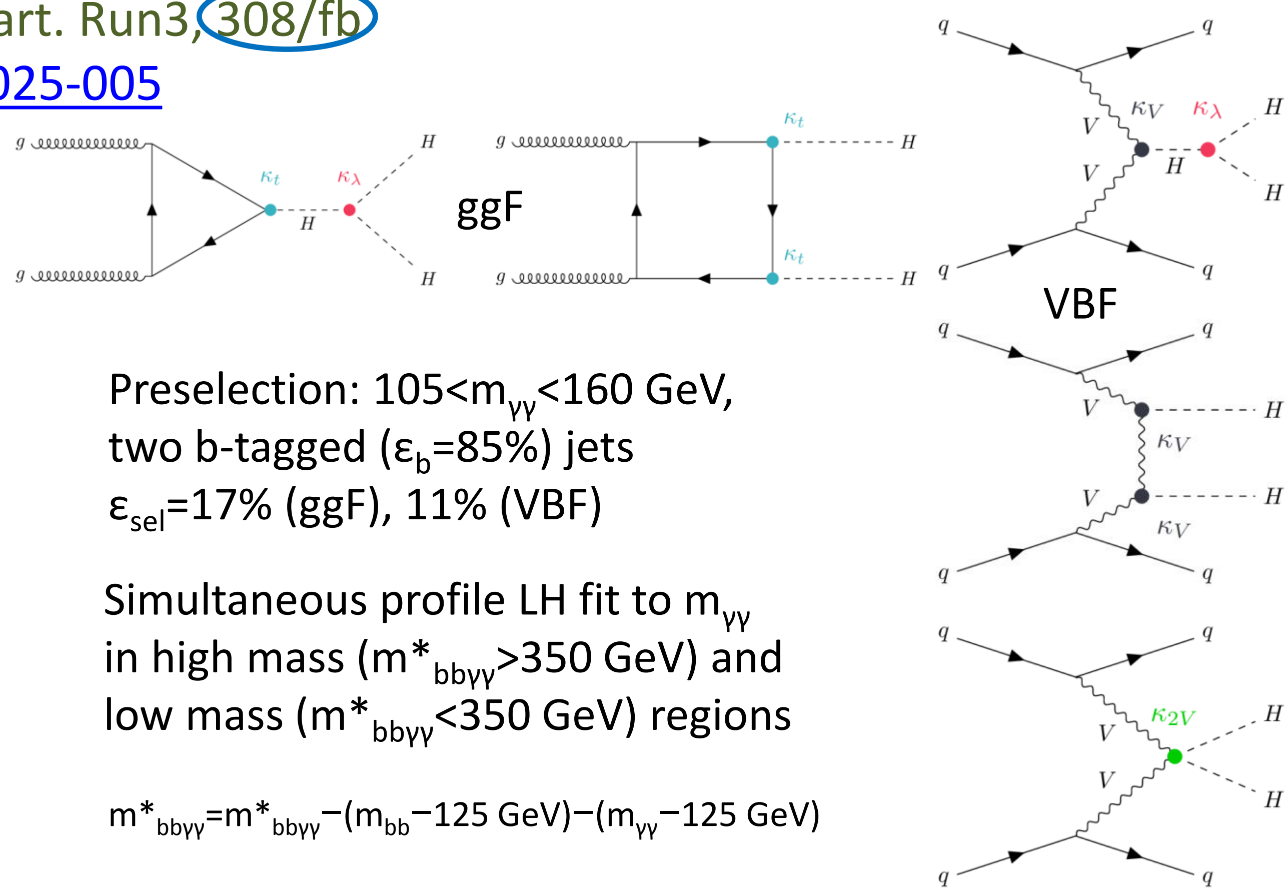


- Results: observed (expected)
  - $\mu_{\text{off-shell}}$=0.3+0.9-0.3 (1.0+2.3-1.0), CL95 upper limit: 3.4(4.4)
    - previous ATLAS result: 17.2(21.3)
  - combined with on-shell H→WW*, the result can be interpreted in terms of the Higgs width: $\Gamma_H/\Gamma_H^{SM}=\mu_{\text{off-shell}}/\mu_{\text{on-shell}}$
    - assuming Γ_H^{SM}=4.1 MeV, Γ_H=0.9+3.4-0.9 (4.1+8.3-3.8) MeV

HH→bbγγ (1)

- Study of Higgs pair production in the HH→bbγγ final state
  - ATLAS Run 2+Part. Run3, 308/fb
  - ATLAS-CONF-2025-005



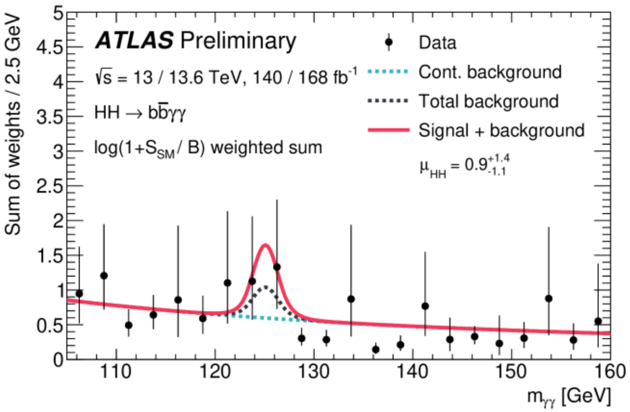


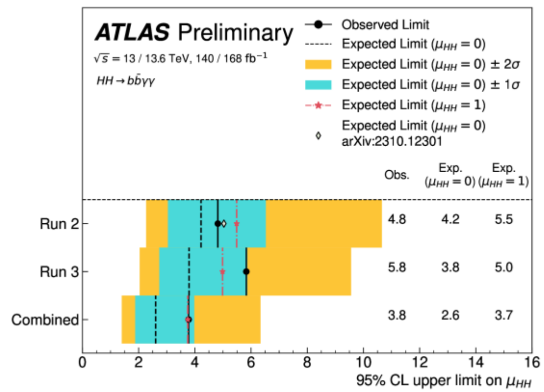
Preselection: $105<m_{\gamma\gamma}<160$ GeV, two b-tagged (ε_b=85%) jets
ε_{sel}=17% (ggF), 11% (VBF)

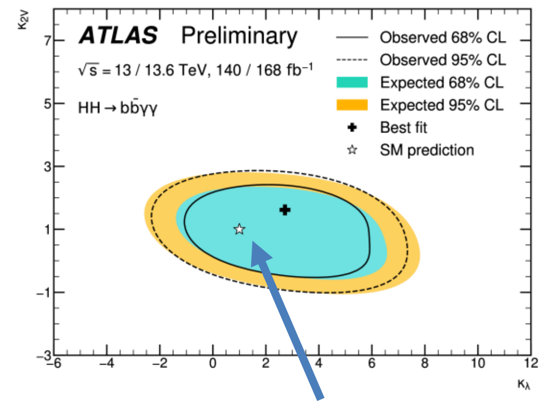
Simultaneous profile LH fit to $m_{\gamma\gamma}$ in high mass ($m^*_{bb\gamma\gamma}>350$ GeV) and low mass ($m^*_{bb\gamma\gamma}<350$ GeV) regions

$m^*_{bb\gamma\gamma}=m^*_{bb\gamma\gamma}-(m_{bb}-125\text{ GeV})-(m_{\gamma\gamma}-125\text{ GeV})$

HH→bbγγ (2)







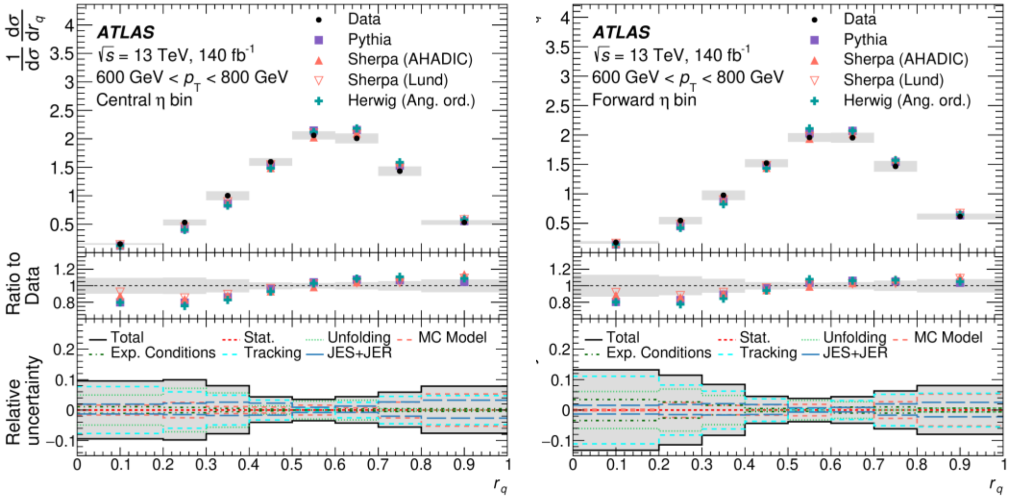
SM prediction

- Results: observed (expected)
  - μ_{HH}=0.9+1.4-1.1 (1+1.3-1.0)
  - CL95 limit: μ_{HH}<3.8
- ×2 improvement compared to 140/fb result

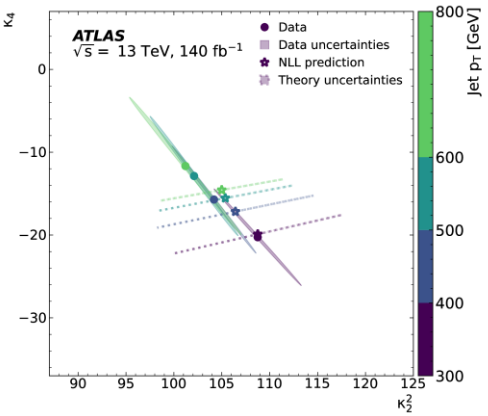
Constraints on coupling modifiers κ_λ, κ_{2V}

Jet track functions

- Measurement of track-based jet substructure with track functions
  - ATLAS Run 2, 140/fb
  - arXiv:2502.02062



Track functions describe energy fraction carried out by charged particles from a fragmenting parton, can be determined from distribution of $r_q = p_T(\text{charged})/p_T(\text{jet})$



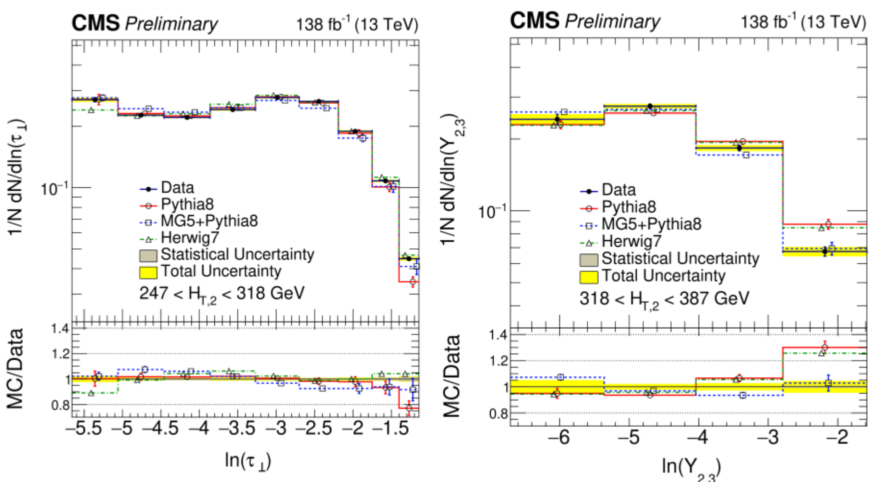
energy dependence of relationship between pairs of r_q cumulants is determined by non-trivial renormalization group flows

- Results:
  - measurement of the differential cross-section $1/\sigma\, d\sigma/dr_q$
  - measurement of r_q momenta and cumulants – in good agreement with theory

Event shape variables

- Measurement of event shape variables (ESV) inside jets
  - CMS Run 2, 138/fb
  - CMS-PAS-SMP-22-004

ESVs: ratios of hadron momenta or their combinations, sensitive to energy flow. Examples:



complement of transverse thrust

$$\tau_{\perp} \equiv 1 - T_{\perp}, \quad T_{\perp} \equiv \max_{\vec{n}_{\mathrm{T}}} \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \vec{n}_{\mathrm{T}}|}{\sum_i p_{\mathrm{T},i}}$$

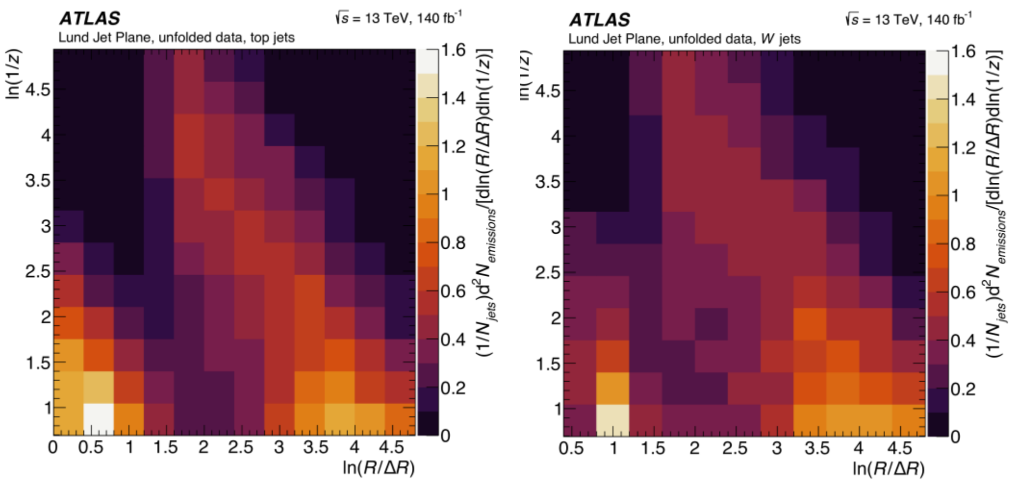
third-jet resolution parameter

$$Y_{23} = \frac{\max(p_{\mathrm{T},3}^2, [\min(p_{\mathrm{T},i}, p_{\mathrm{T},j})^2 (\Delta R_{i,j})^2 / R^2])}{p_{12}^2}$$

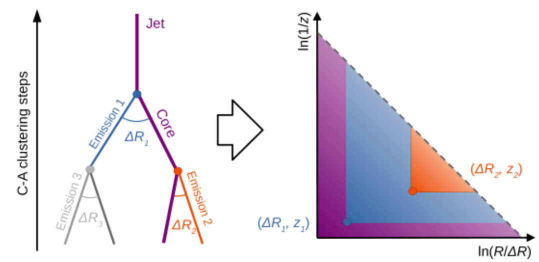
- Results:
  - measurement of the differential cross-section $1/\sigma \ d\sigma/dx$, for five ESVs
  - various levels of data/MC agreement, e.g. Pythia 8 and Herwig 7 have good agreement with data for $\tau_{\perp}$ but overestimate Y_{23}

Measurement of Lund jet plane (1)

- Measurement of Lund jet plane (LJP) in hadronic decays of top quarks and W bosons (R=1.0 jets with p_T>350 GeV)
  - ATLAS Run 2, 140/fb
  - [Eur. Phys. J. C 85 (2025) 416]



- LJP: representation of kinematics of radiation that makes a jet
- Originally designed to observe quark and gluon emissions inside the parton shower – can't be done experimentally
- Use charged particles to construct a LJP proxy



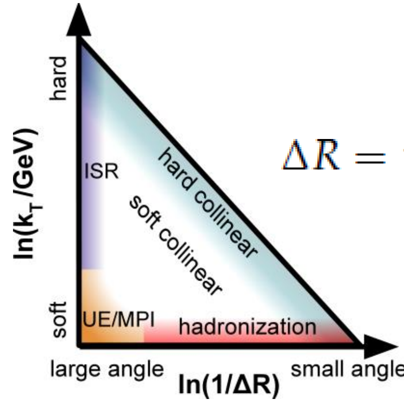
- Follow Cambridge-Aachen jet clustering algorithm in reverse
- For each pair of proto-jets, fill a point in LJP with

$$\Delta R^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2, \quad z = \frac{p_T^j}{p_T^i + p_T^j}$$

- Results: measurement of the LJP density $1/N_{jets}\, d^2N_{emissions}/d\ln(R/\Delta R)\, d\ln(1/z)$
- Compared to various MC generators, for tt, found p-value = 33% for Sherpa 2.2.10, and <5% for Powheg+Herwig / Powheg+Pythia

Measurement of Lund jet plane (2)

- Measurement of LJP in inclusive multijets (R=0.4 or 0.8 jets with p_T>700 GeV)
  - CMS Run 2, 138/fb
  - [JHEP 05 (2024) 116]()

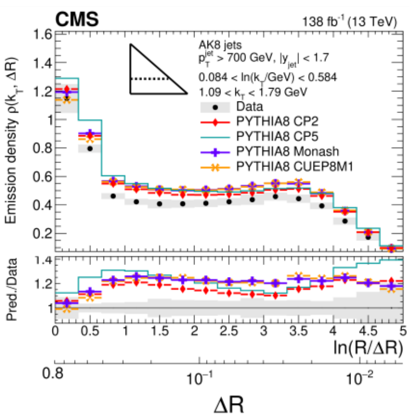


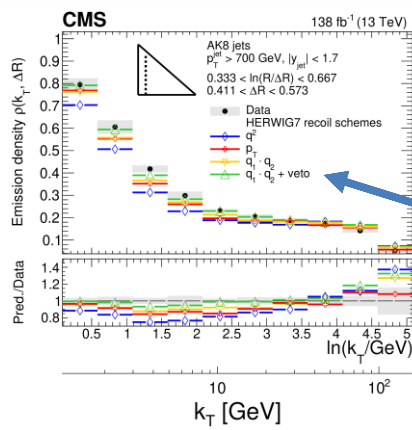
Slightly different variables:

$$\Delta R = \sqrt{(y^{j_1} - y^{j_2})^2 + (\phi^{j_1} - \phi^{j_2})^2}$$

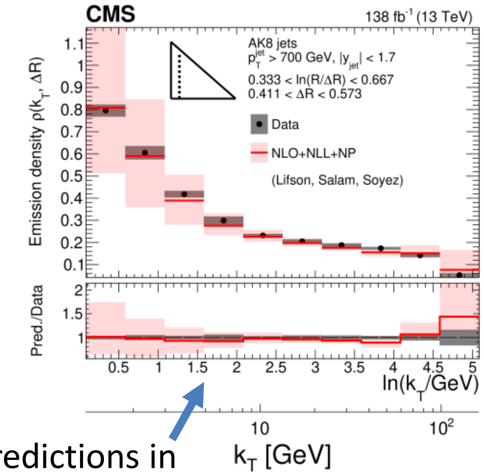
$$k_\mathrm{T} = p_\mathrm{T}^{j_2} \Delta R$$

Large R is better (mitigates clustering effects)





best

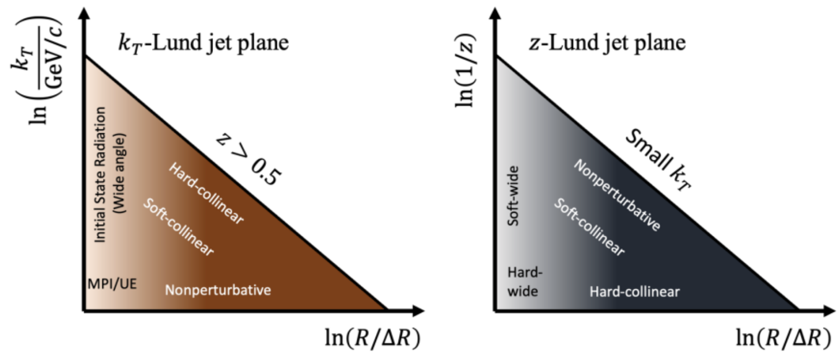


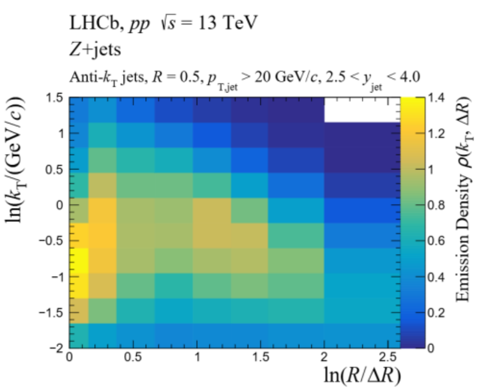
Parton-level pQCD predictions in agreement with unfolded data

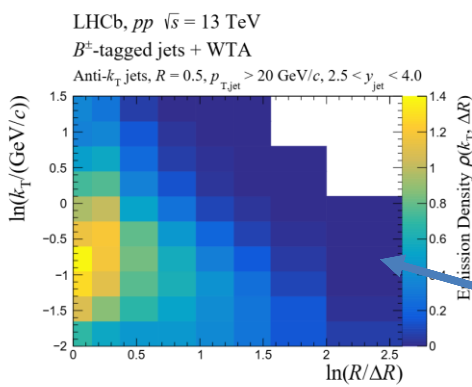
- Results: measurement of the LJP density $1/N_{jets}\ d^2N_{emissions}/d\ \ln(R/\Delta R)\ d\ k_T$
  - Compared to various MC generators, cluster-based showers (Herwig, Sherpa) do better than string fragmentation (Pythia)

Measurement of Lund jet plane (3)

- Measurement of LJP in light- and beauty-jets (R=0.5, p_T>20 GeV)
  - LHCb Run 2, 5.4/fb
  - [arXiv:2505.23530](https://arxiv.org/abs/2505.23530)





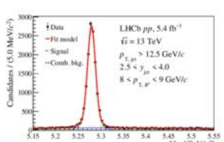


collinear radiation (small ΔR)

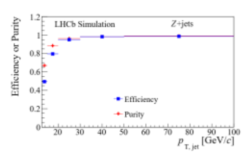
wide-angle radiation (large ΔR)

dead-cone effect: suppression of collinear radiation from heavy quarks (hard fragmentation vs parton shower)

light jets (Z+jets)



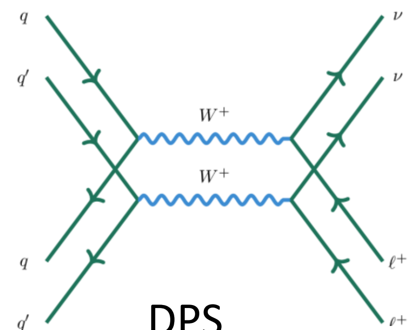
b-jets ($B^{\pm}$ tagged)



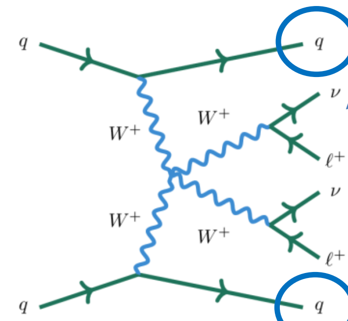
- Results: first comparison of light- vs beauty-enriched jets
  - direct observation of the dead-cone effect

Double parton scattering

- Measurement of double parton scattering in same-sign W pairs
  - ATLAS Run 2, 140/fb
  - [arXiv:2505.08313](https://arxiv.org/abs/2505.08313)



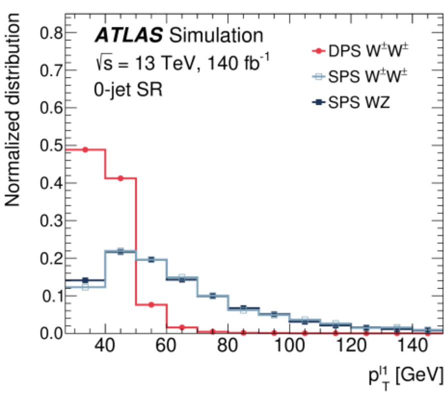
DPS

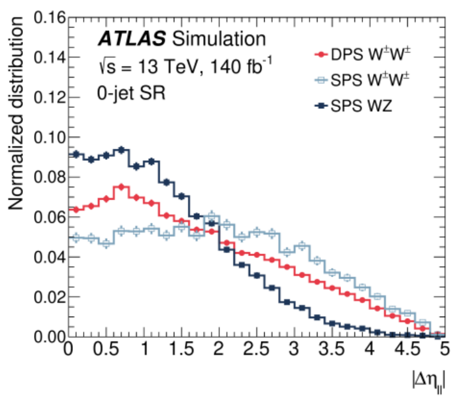


SPS

$$\sigma_{AB}^{DPS} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

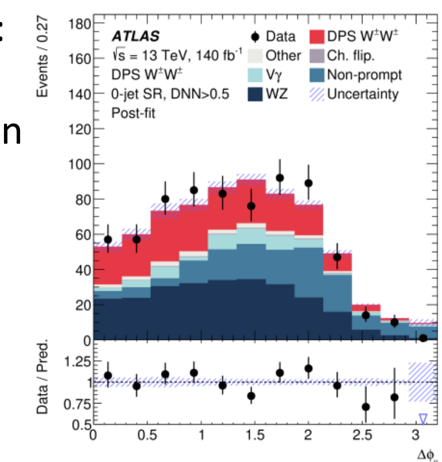
use to suppress





Signal regions: 0-jet, 1-jet

Dominant backgrounds:
WZ: use DNN
non-prompt: data-driven (fake factor)

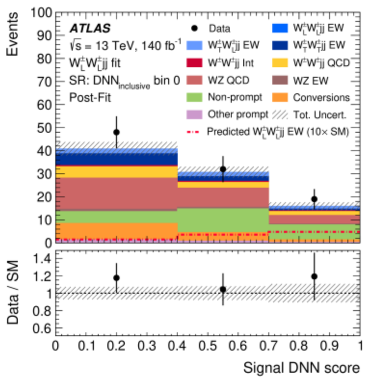


post-fit distributions in 0-jet, DNN score >0.5

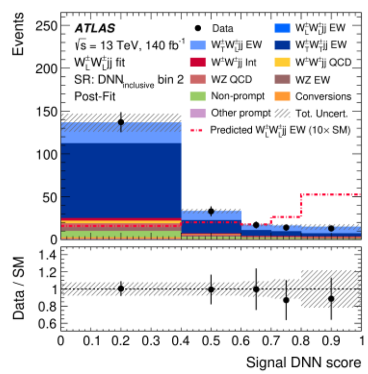
- Results:
  - fiducial DPS cross section $\sigma\times B(W^{\pm}W^{\pm})=4.59\pm0.64$ fb
    - excess of events over background: 8.8σ
  - DPS effective cross section $\sigma_{eff}=10.6\pm1.8$ mb

W polarization

- Evidence of longitudinally polarized W in same-sign W pairs
  - ATLAS Run 2, 140/fb
  - arXiv:2503.11317



inclusive DNN, bin 0

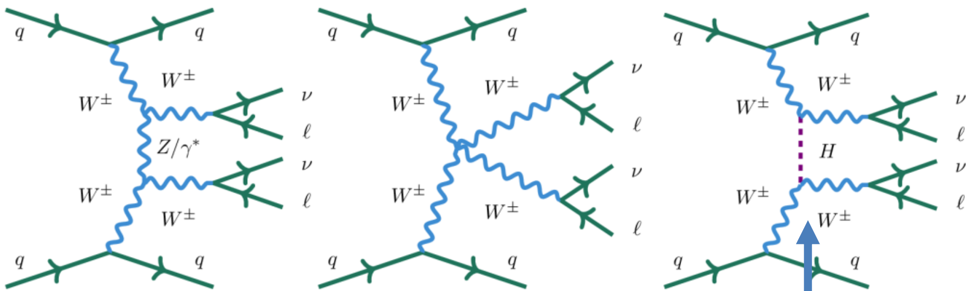


inclusive DNN, bin 2

Dominant background: WZ+jj

Inclusive DNN: separate VBS WW

Dedicated signal DNNs: detect the polarized signals



W_L to Higgs couplings prevent the divergence of tree-level VBS amplitudes at high energies

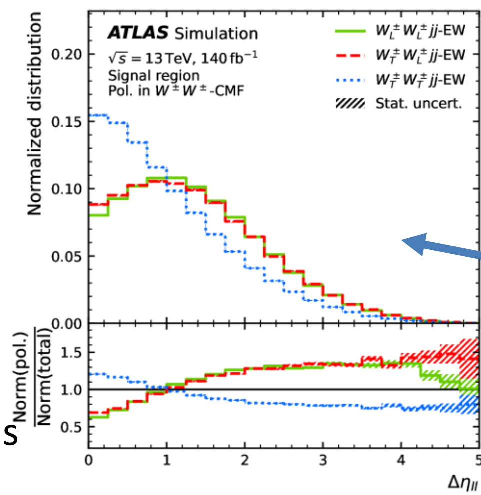
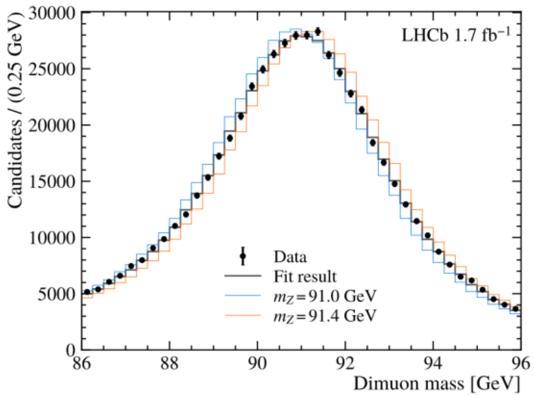


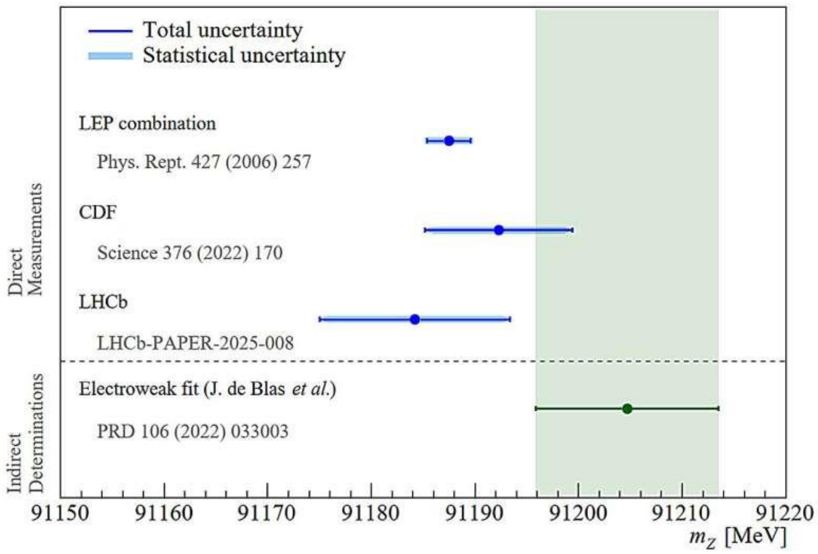
figure polarization from kinematics

- Results:
  - The first evidence (3.3σ) of VBS with longitudinally polarized, same-sign W pairs
  - An observed (expected) 95% C.L. limit on doubly polarized W production (10% of all cases) at 0.45 (0.70) fb

Z mass

- Measurement of the Z-boson mass with Z→μμ
  - LHCb Run 2, 1.7/fb
  - arXiv:2505.15582





Sample: 174k Z-bosons

main challenge: precise muon momentum measurement, ΔM/M ~ Δp/p
general purpose momentum calibration accuracy: 3×10^{-4}
improve it by dedicated Υ→μμ based calibration

- Results:
  - The first dedicated Z-boson mass measurement at the LHC
  - m_Z=91184.2±8.5(stat)±3.8(syst) MeV

Combined H/V/top/multijet SMEFT interpretation (1)

- Constraints on d=6 Wilson coefficients from H→γγ, tt→l+jets, t(t)X (ttH, ttll, ttlν, tllq, tHq, tttt), WW(lνlν), W(lν)γ, Z→νν, inclusive multijets
  - CMS Run 2, 36.3–138/fb
  - arXiv:2504.02958

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,j} \frac{c_j^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_j^{(d)}$$

Hybrid likelihood

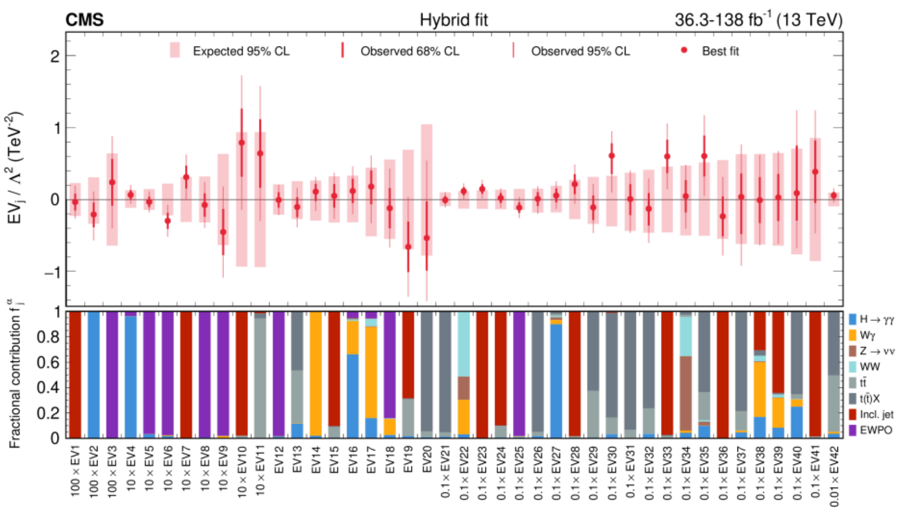
$$\mathcal{L}\left(\mathrm{data}\,;\,\vec{c},\vec{\nu}\right) = \mathcal{L}^{\mathrm{expt}}\left(\vec{c},\vec{\nu}\right)\mathcal{L}^{\mathrm{simpl}}\left(\vec{c}\right)$$

experimental measurements with available likelihood

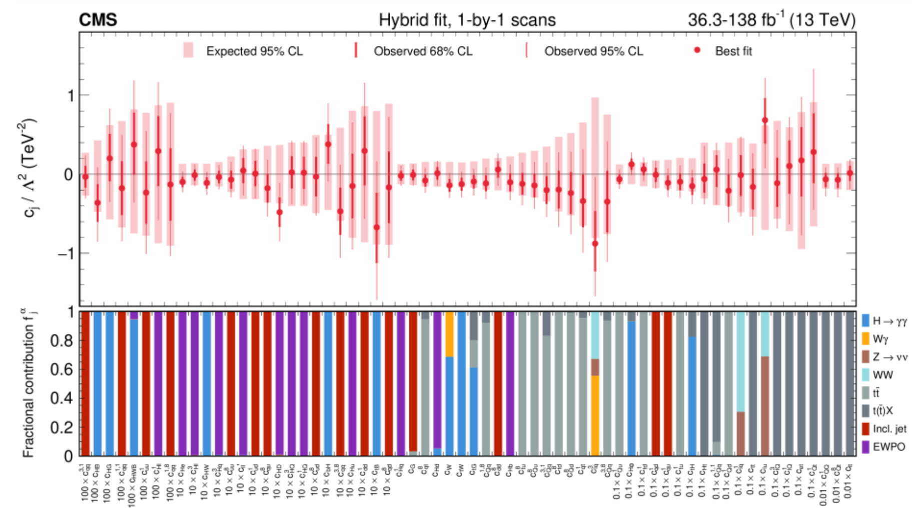
multivariate Gaussian for remaining measurements

$\mathrm{H} \to \gamma\gamma$	Differential cross sections	STXS bins [54]
$\mathrm{W}\gamma$	Fiducial differential cross sections	$p_{\mathrm{T}}^{\gamma} \times \lvert\phi_f\rvert$ [33]
$\mathrm{Z} \to \nu\nu$	Fiducial differential cross sections	$p_{\mathrm{T}}^{\mathrm{Z}}$
WW	Fiducial differential cross sections	$m_{\ell\ell}$
$\mathrm{t\bar{t}}$	Fiducial differential cross sections	$m_{\mathrm{t\bar{t}}}$
$\mathrm{t(\bar{t})X}$	Direct EFT	Yields in regions of interest
Inclusive jet	Fiducial differential cross sections	$p_{\mathrm{T}}^{\mathrm{jet}} \times \lvert y^{\mathrm{jet}}\rvert$
EWPO	Pseudo-observables	$\Gamma_{\mathrm{Z}}, \sigma^0_{\mathrm{had}}, R_\ell, R_{\mathrm{c}}, R_{\mathrm{b}}, A^{0,\ell}_{\mathrm{FB}}, A^{0,\mathrm{c}}_{\mathrm{FB}}, A^{0,\mathrm{b}}_{\mathrm{FB}}$ [36]

Combined H/V/top/multijet SMEFT interpretation (2)



constraints on linear combinations of WCs



constraints on individual WCs

- Results:
  - Out of considered 129 operators, constrain 64 individual WCs and 42 linear combinations of WCs
    - for the latter, the p-value for SM compatibility is 1.7%
    - when excluding inclusive multijets, the p-value is 26%

Summary

- Since the Higgs discovery in 2012, studying its properties with increasing precision remains focus of the physics programs of the LHC experiments
  - revealing the mechanics of the SM
  - looking for hints of deviations from the SM
- The experiments keep producing interesting physics results
  - most are on Run 2 (2015-18) data
  - results on Run 2 + early Run 3 (2022-24) data begin to arrive
- More to come!