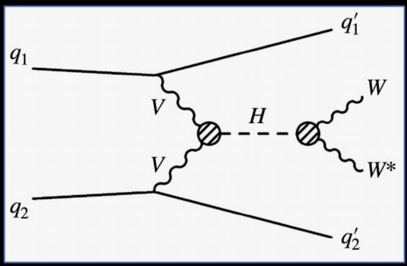
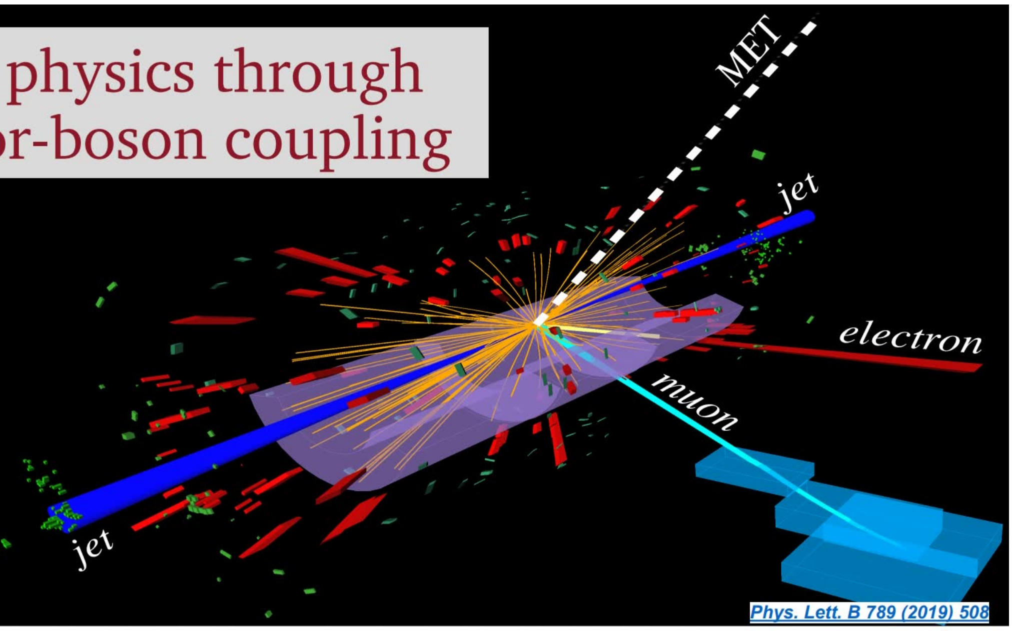
Probing new physics through Higgs-to-vector-boson coupling





$H \to WW^* \to e\nu\mu\nu$ candidate
and two jets with VBF topology
Run 305618, Ev. no. 2461194919
Aug. 05, 2016, 08:37:53 CEST

Phys. Lett. B 789 (2019) 508

陈嘉艺 (Jiayi Chen)
中国科学院高能物理研究所 *(IHEP)*,
Experimental Physics Division Seminar
Aug 11, 2026

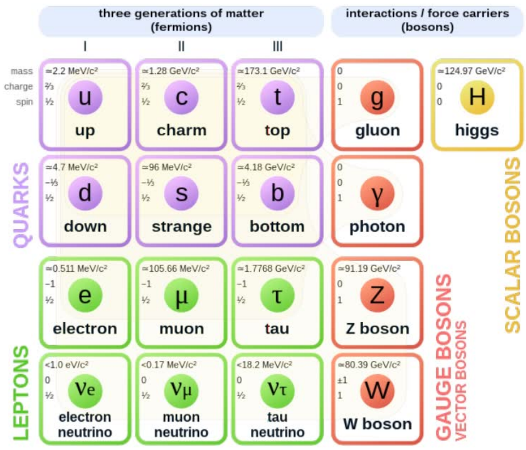
ATLAS EXPERIMENT

SFU SIMON FRASER UNIVERSITY

Introduction - Standard Model and the Higgs mechanism

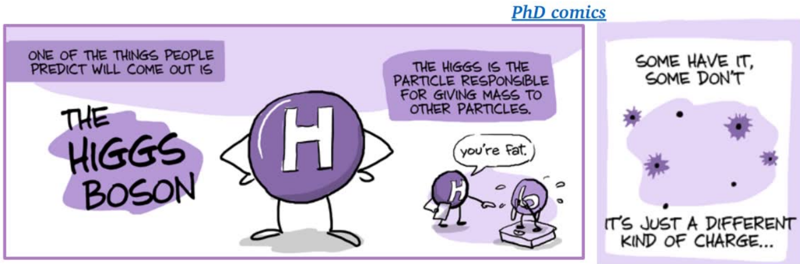
- The Standard Model (SM) is a successful model describing the past 50 years of experimental data
- **Higgs**, the last missing piece co-discovered by ATLAS and CMS collaborations in 2012
  - **fundamental particles acquire mass through interaction with the Higgs field**

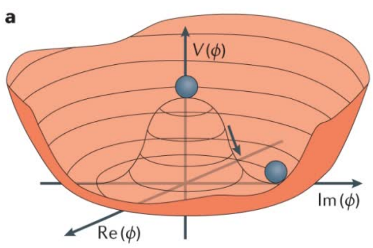
Standard Model of Elementary Particles



Wikipedia contributors.

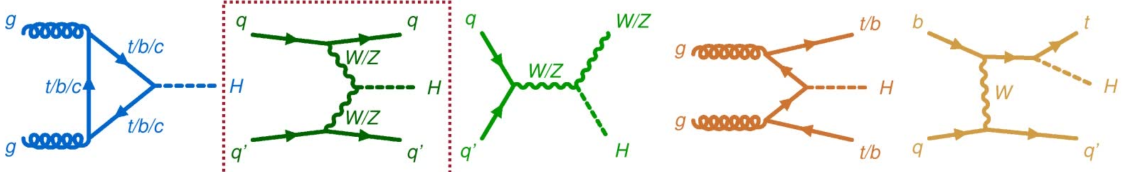
PhD comics





Nature Reviews Physics volume 3, pages608–624 (2021)

Introduction - Higgs boson production and decay modes



Dominant production modes (at *13 TeV* center-of-mass energy):

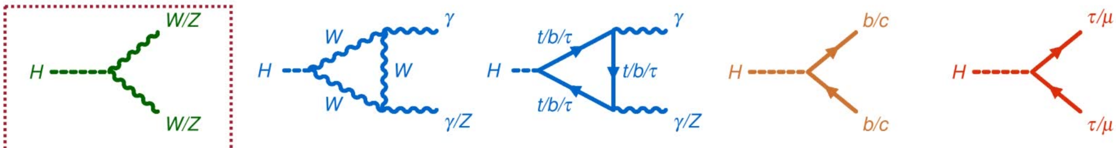
gluon-gluon fusion (ggF): 87%

vector boson fusion (VBF): 7%

in-association with weak boson (VH): 4%

in-association with t/b-quark pair ($t\bar{t}H/b\bar{b}H$): 1%

in-association with single top (tH): 0.05%



Decay channels branching ratio at $m_H = 125$ GeV:

$H \to WW$: 22%
$H \to ZZ$: 3%

$H \to \gamma\gamma$: 0.2%
$H \to Z\gamma$: 0.2%

$H \to bb$: 58%
$H \to cc$: 3%

$H \to \tau\tau$: 6%
$H \to \mu\mu$: 0.02%

[Nature 607 (2022)]

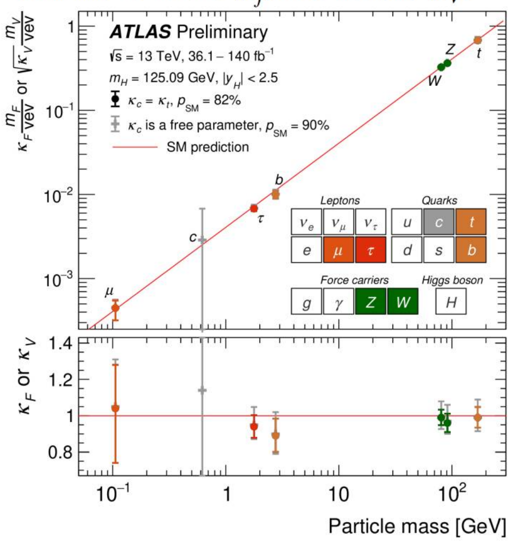
Different production modes probe different couplings.

This talk focuses on VBF because it provides unique sensitivity to anomalous *HVV* interactions.

Combined Higgs cross-section measurement in ATLAS (my slide 1week ago)

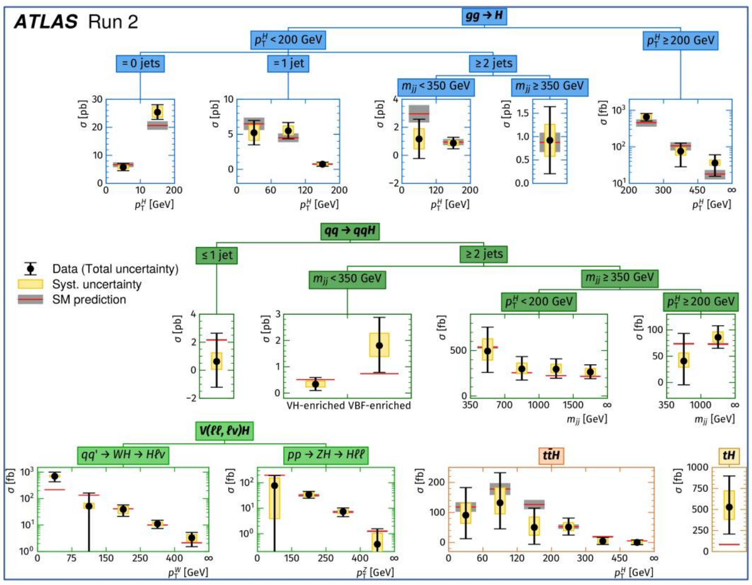
- Experimental data shows agreement with the SM prediction
- However, **agreement with SM within current uncertainties doesn't imply absence of BSM effects**

- Coupling modifiers for the Higgs coupling with the fermions (κ_f) and bosons (κ_V)



[ATLAS-CONF-2025-006]

- Differential cross-section (or STXS bins)



[Nature 607 (2022)]

Combined Higgs cross-section measurement in ATLAS [NEW!] [CERN-EP-2026-228]

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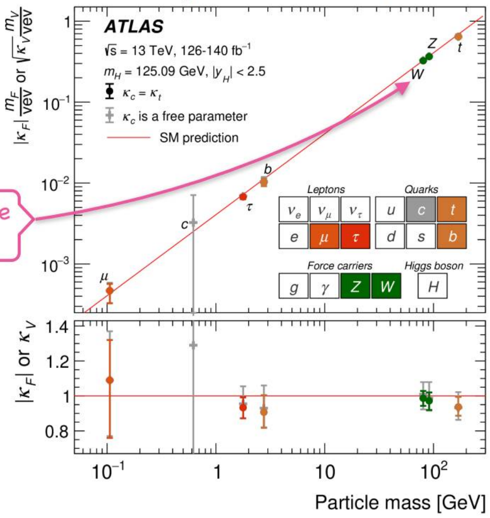
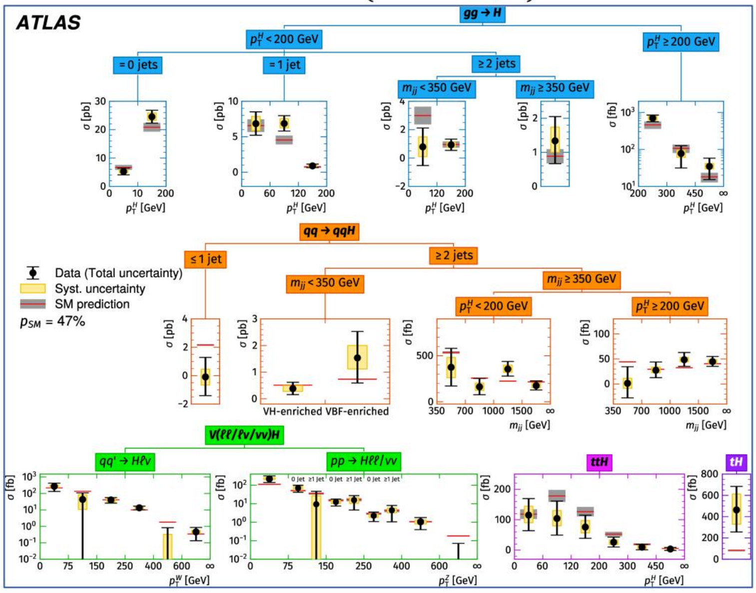


My favorite dot…

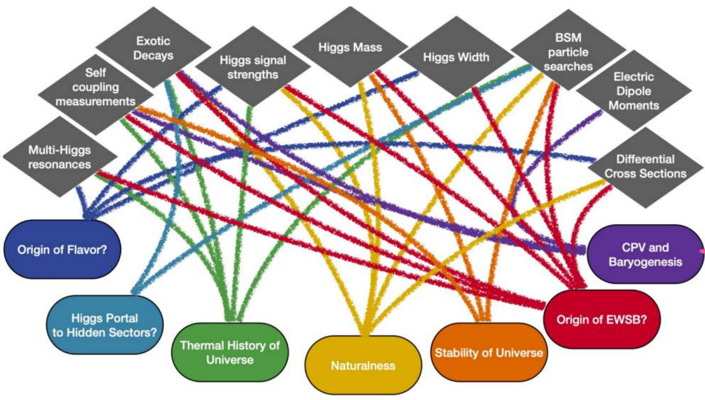
- Differential cross-section (or STXS bins)



Introduction - Standard Model and the Higgs mechanism

The next question:

is this particle exactly the SM Higgs or the first window onto new physics



Snowmass [arXiv:2209.07510]

Higgs sector remains largely unexplored…?

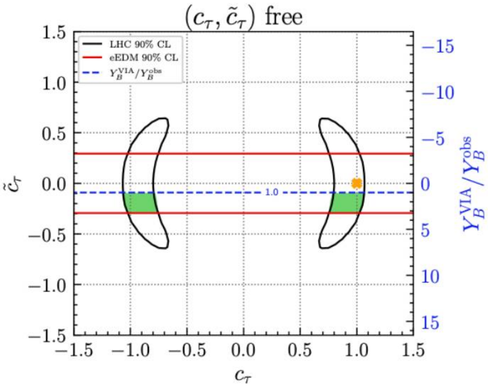
- Charge-parity (CP) violation is one of the Sakharov conditions required to generate the baryon asymmetry of the Universe…
- …but CP-violating component in the SM is too small (via CKM mixing matrix for the three generations of quarks).

Probing new physics with Higgs-to-fermion coupling

Higgs–fermion (Hff)	Higgs–gauge boson (HVV)
SM: $\mathcal{L} \supset -y_f\,\bar{f}fh$	SM: $\mathcal{L} \supset g\,m_V\,hV_\mu V^\mu$
BSM: $\bar{f}(a + ib\gamma_5)fh$	BSM: $hV_\mu V^\mu + hV_{\mu\nu}\tilde{V}^{\mu\nu}$

Hff probes whether there is a pseudoscalar admixture in an existing interaction

LHC sensitivity complements other theoretical and experimental sources



Eur. Phys. J. C 82 (2022) 604

Below blue line is requirement for observed baryon asymmetry

eEDM constraint

Current LHC sensitivity

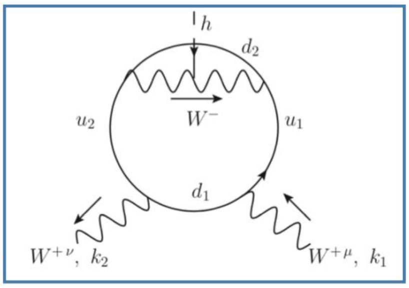
Free space from theoretical and other exp. source

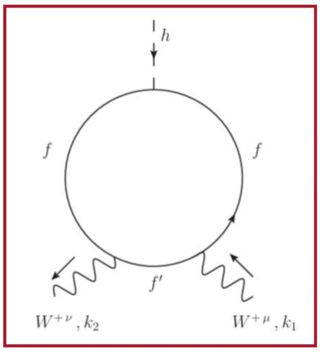
Probing new physics with Higgs-to-vector-boson coupling

Higgs–fermion (Hff)	Higgs–gauge boson (HVV)
SM: $\mathcal{L} \supset -y_f\,\bar{f}fh$	SM: $\mathcal{L} \supset g\,m_V\,hV_\mu V^\mu$
BSM: $\bar{f}(a + ib\gamma_5)fh$	BSM: $hV_\mu V^\mu + hV_{\mu\nu}\tilde{V}^{\mu\nu}$

Any CP odd effect at *HVV* is BSM:

- No tree-level CP-odd diagram - SM contribution at two-loop level—>**tiny**;
- HVV uniquely probe BSM model such as complex 2-Higgs doublet model (1-loop) - minimal extension of SM that introduces new CPV directly into the Higgs sector

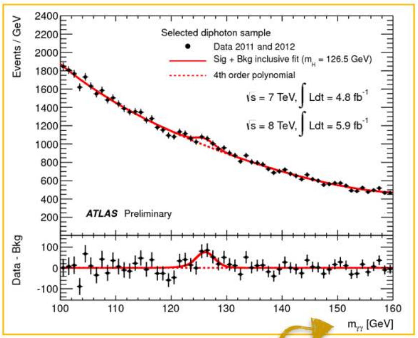




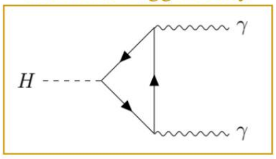
"Within reach at HL-LHC"

Huang, Morais, RS, JHEP 01 (2021) 168.

How to probe BSM effect from SM Higgs measurement?



Invariant mass of the photons from the Higgs decay



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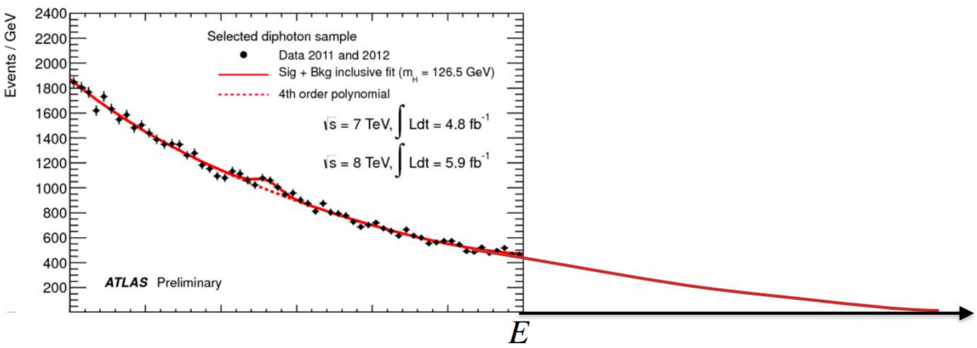
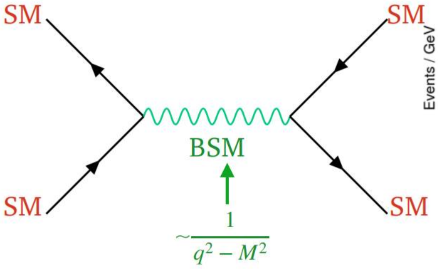
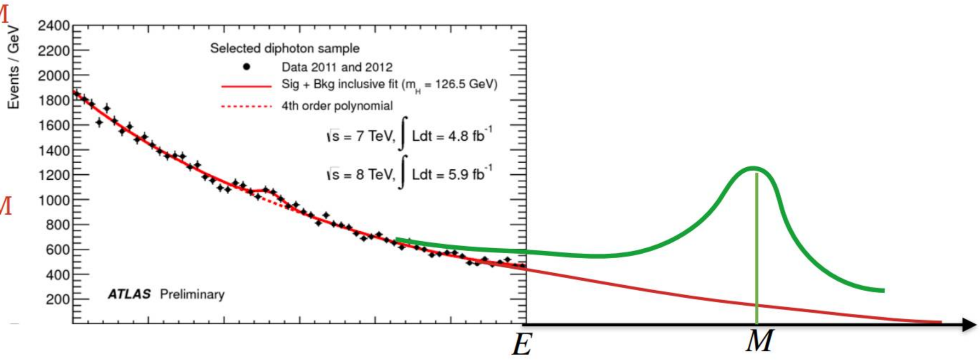


- The SM with no new resonance

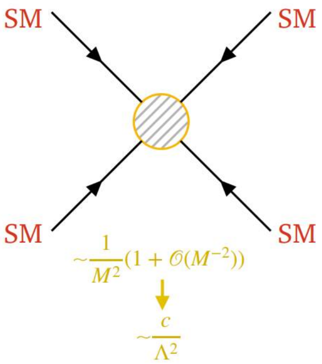
How to probe BSM effect from SM Higgs measurement?

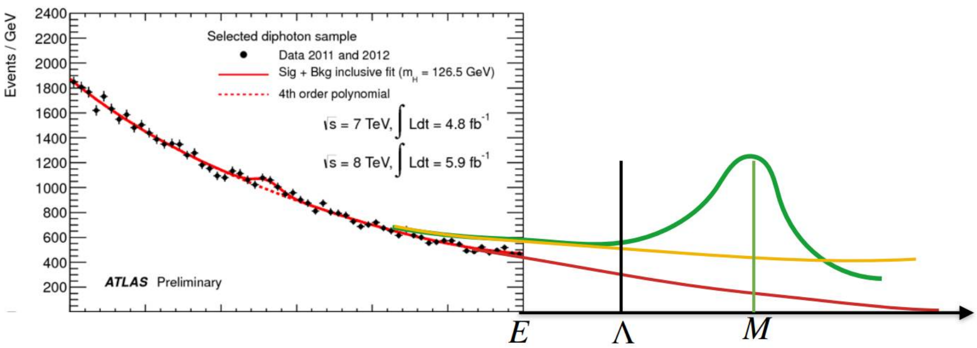




- The SM with no new resonance
- Complete beyond the Standard Model (BSM) theory with new resonance with mass M

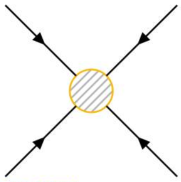
How to probe BSM effect from SM Higgs measurement?





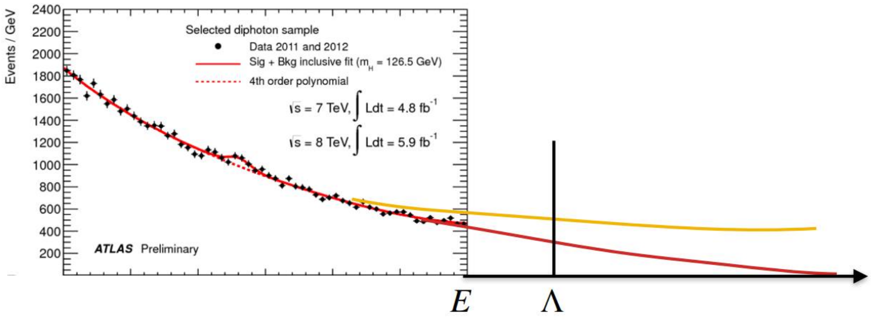
- The SM with no new resonance
- Complete BSM theory with new resonance with mass M
- The effective theory
  - “integrates out” the heavy new particle field —> **model-independent!**
  - equivalently describes the phenomena at energy below cut-off scale Λ
  - has no knowledge of the the resonance

EFT parametrization



SMEFT operators
(dimension-6)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)}$$



- Reparametrize cross-section as a **linear** and **quadratic** function of the Wilson coefficients:

$$|\mathcal{M}_{\text{SMEFT}}|^2 = \boxed{|\mathcal{M}_{\text{SM}}|^2} + \boxed{2\sum_{i} \frac{c_i}{\Lambda^2} Re(\mathcal{M}^*_{\text{SM}}\mathcal{M}_i)} + \boxed{\sum_{i,j} \frac{c_i c_j}{\Lambda^4} Re(\mathcal{M}^*_i\mathcal{M}_j)}$$

$$\sigma_{\text{SMEFT}} = \boxed{\sigma_{\text{SM}}} + \boxed{\sigma_{\text{int}}} + \boxed{\sigma_{\text{BSM}}}$$

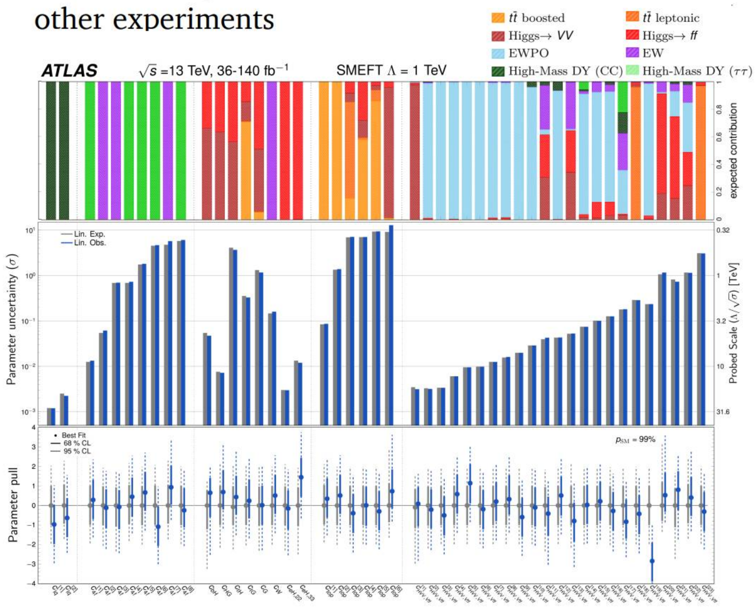
SM contribution

Interference between SM and EFT operators (linear)

Pure BSM from square of individual EFT operators or cross-terms of different operators (quadratic)

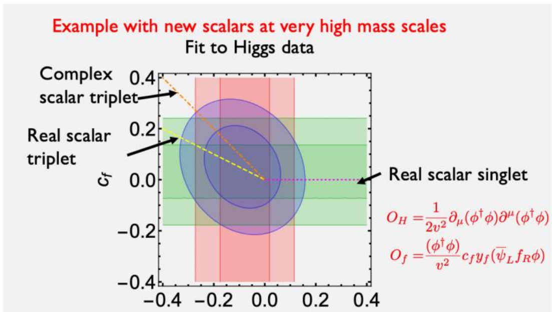
EFT beyond Higgs and LHC

- Combinability with other LHC measurements and other experiments



JHEP 07 (2026) 238

- Model independent, but can be translated to exclude specific model's parameter phase space

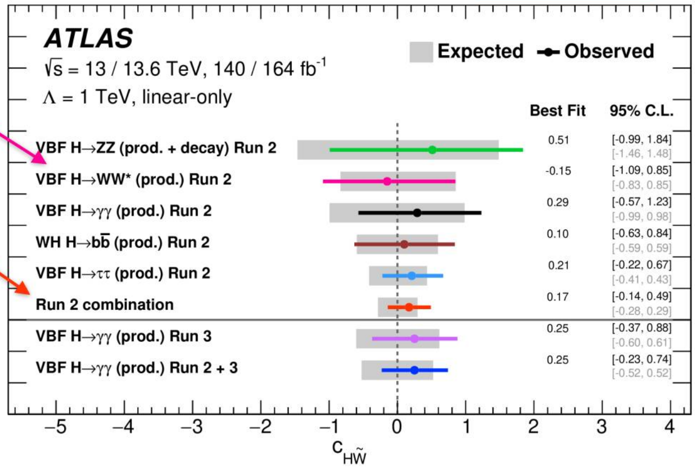


Slide credit: Sally Dawson; paper: https://arxiv.org/abs/1704.07851

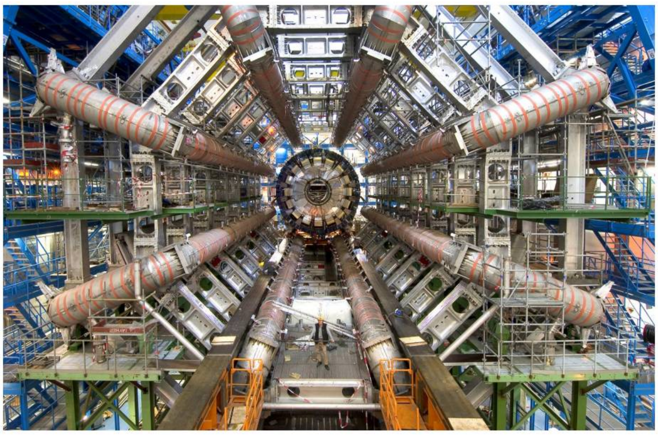
Talk: outline

- Apparatus: the ATLAS detector
- Highlight the HWW channel:
  - Eur. Phys. J. C 85 (2025) 1403
  - Latest ggF and VBF cross-section measurements and their EFT interpretations
- CP combination:
  - Phys. Rev. Lett. 137 (2026) 021801
  - Combine 5 different decay channels using the Run-2 ATLAS dataset - ***best constraint** on HVV CP-odd effective couplings **to-date***
- Reducing theoretical uncertainties in VBF analyses
  - *The Yellow Report 5 series:* *SciPost Phys. Comm. Rep. 13 (2025)*
- High-Luminosity LHC and the new inner tracker
  - JINST 21 P07026
  - Assembly and testing of the local support structure

arXiv:2603.20087



Apparatus

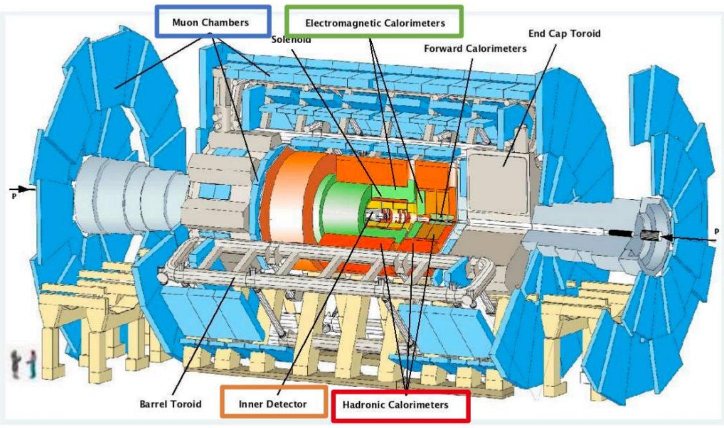


The Large Hadron Collider

- LHC is the world's largest (27-km long) and most powerful collider
- Proton-proton (*pp*) collision energy up to 14 TeV (few tens of km/h slower than speed of light)
- Results shown in this talk use the dataset collected during the second operational run (Run-2) from 2015-2018 with an *integrated luminosity* (L) of 140 fb^{-1}, at 13 TeV
  - 1 fb^{-1} $\sim$ 100 trillion *pp* interactions

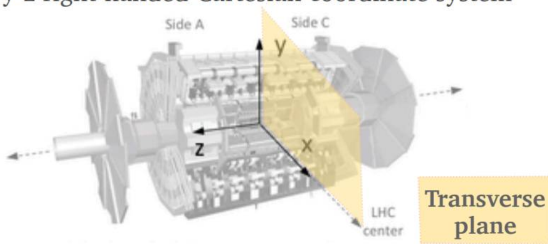
The ATLAS detector

- **A T**oroidal **L**HC **A**pparatu**S**: a general-purposed cylindrical-shaped multi-layer detector
- *pp* collision at the center and outgoing particles leave signatures (tracks or energy) in each sub-detector

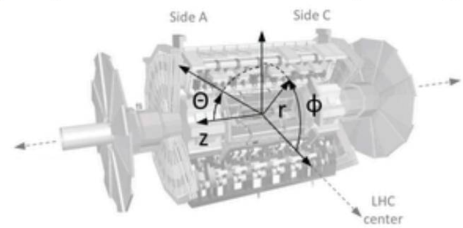


- From beamline going outward
  - Inner detector (ID) in a 2T magnetic field in z-direction
  - Electromagnetic calorimeter (ECAL)
  - Hadronic calorimeter (HCAL)
  - Muon Spectrometer (MS) with toroidal magnet at 3.5T

x-y-z right-handed Cartesian coordinate system



r-ϕ-z cylindrical coordinates and polar angel Θ

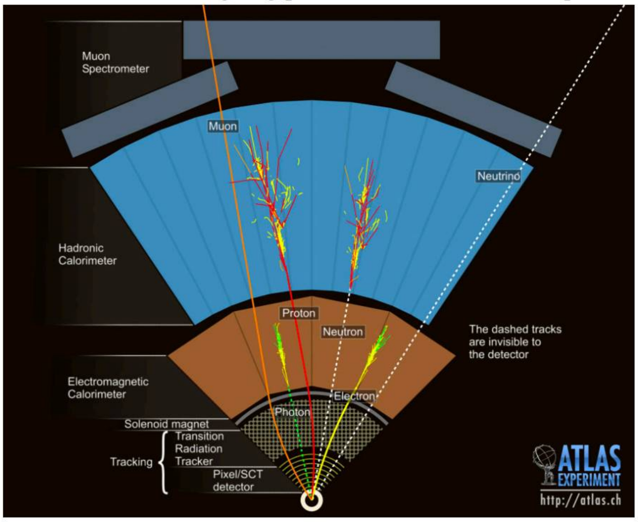


The ATLAS detector - object reconstruction

- Reconstruction“translates” detector signals into meaningful information about the outgoing particles

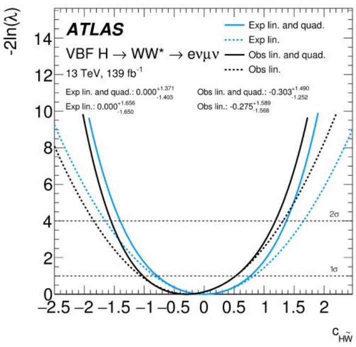
- Electrons:
  - track from ID + energy deposition in ECAL
- Muons:
  - tracks from ID + MS
- Jets (parton shower induced by a gluon/quark)
  - energy deposition in HCAL
  - Within the acceptance of ID, tracks of charged jet components included
- Missing transverse energy (MET)
  - Inferred from other reconstructed objects plus additional reconstructed tracks from the primary vertex

Visualization of outgoing particles in the transverse plane



The *HWW* channel

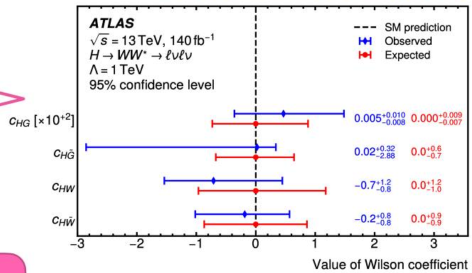
[Phys. Rev. D 108 (2023) 072003]



From PhD study to...

...postdoc study, over 50% improvement on the H-W CP-odd anomalous coupling!

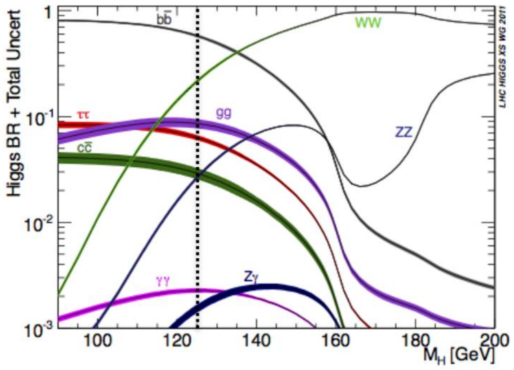
[Eur. Phys. J. C 85 (2025) 1403]



Meet the ATLAS non-resonant multi-lepton (NRML) group

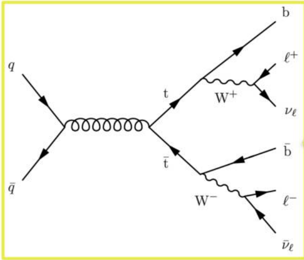
HWW channel in a nut-shell

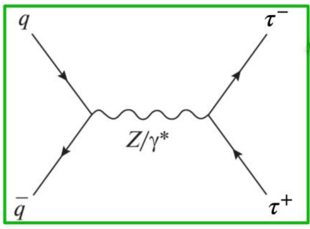
Large branching ratio

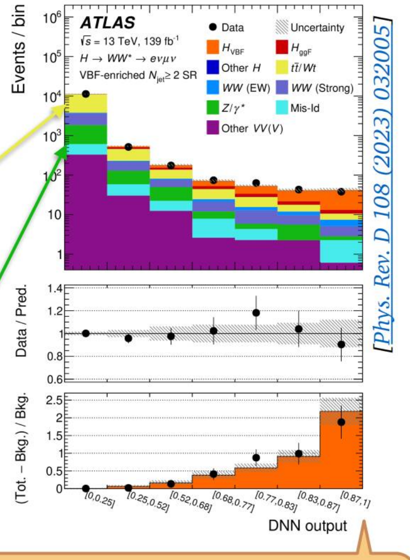


- Typically studied in the W leptonic decay channel

Challenging backgrounds







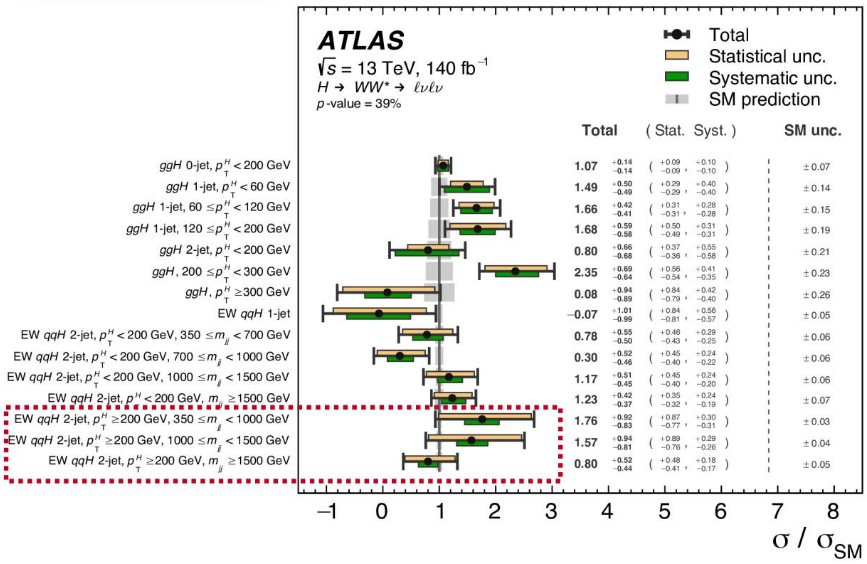
[Phys. Rev. D 108 (2023) 032005]

First observation ($> 7\sigma$) of Higgs signal in the VBF production and $H \to WW^* \to e\nu\mu\nu$ decay channel, using deep neutral network!

HWW channel in a nut-shell cont.

[Eur. Phys. J. C 85 (2025) 1403]

Sensitivity to BSM

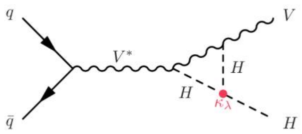


- One of the leading decay channel to **probe high Higgs transverse momentum** (p_T^H) EW qqH phase space
- High energy regime is more sensitive to BSM

HWW channel in a nut-shell cont.

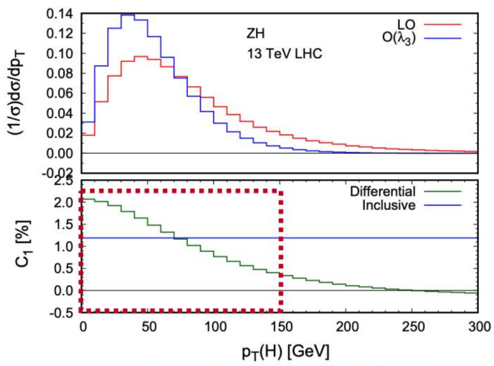
Sensitivity to Higgs self-coupling

NLO EW corrections on VH

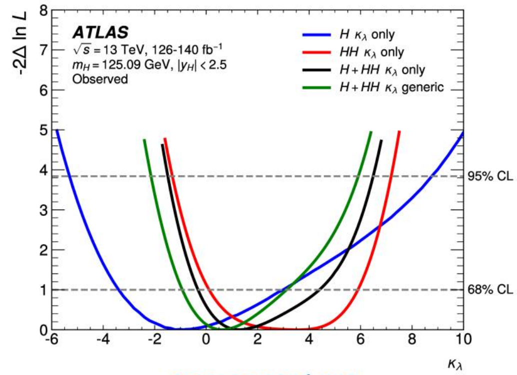


[Phys. Lett. B 843 (2023) 137745]

- Out of other production modes, ***VH*** at low Higgs transverse momentum (p_T^H) regime **has strong sensitivity to Higgs self-coupling through NLO EW correction**
- Out of other decay modes, ***HWW*** can measure low p_T^H most precisely
- **Nice preparation for future electron colliders, e.g. CEPC (can only probe single Higgs production)**



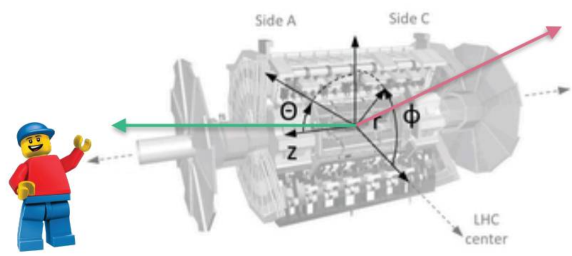
[Eur. Phys. J. C 77, 887 (2017)]

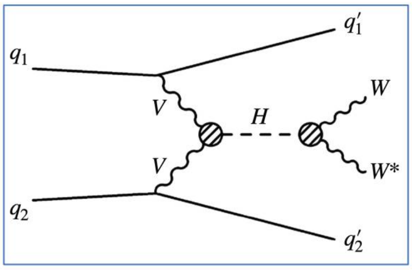


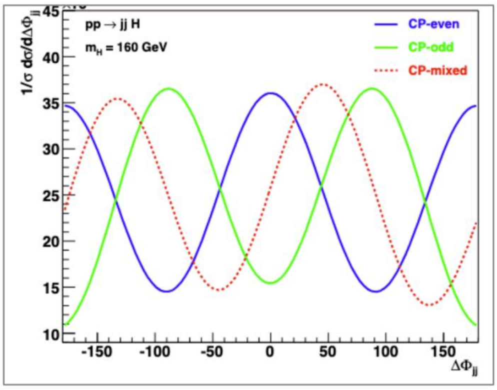
[CERN-EP-2026-228]

Signed $\Delta\phi_{jj}$ as the CP-sensitive observable

- The signed $\Delta\phi_{jj}$ provides distinct feature for CP-even vs CP-odd coupling
  - "signed": the azimuthal angle of the "away" jet minus the angle of the "toward" jet







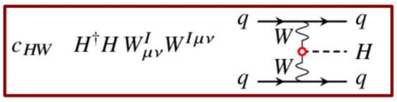
Pure CP-even and CP-odd symmetric about $\Delta\phi_{jj}^{\text{signed}}$ =0 with phase shift
CP-mixed asymmetric

[hep-ph/0703202]

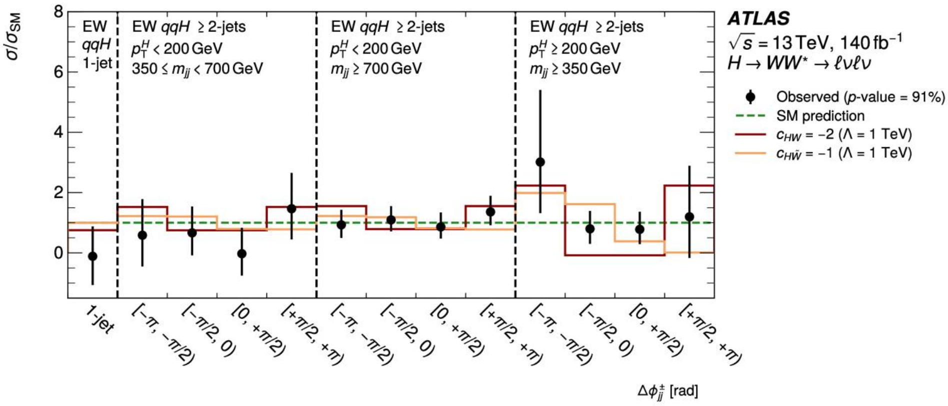
CPV strategy in the ggF+VBF $H \to WW^* \to l\nu l\nu$ channel

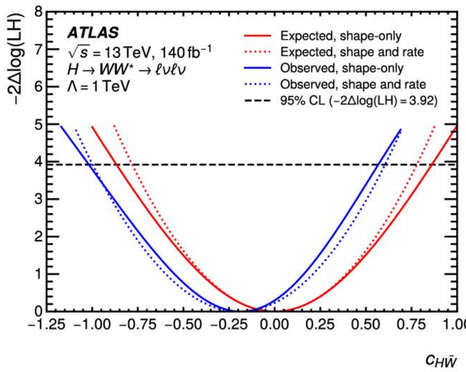
[Eur. Phys. J. C 85 (2025) 1403]

- Multi-dimensional differential measurement to constrain CP-odd HWW coupling ($c_{H\tilde{W}}$): p_T^H vs m_{jj} vs $\Delta\phi_{jj}^{\text{signed}}$
  - **This attempt will bridge towards global implementation in the STXS framework for both ATLAS and CMS in Run-3**



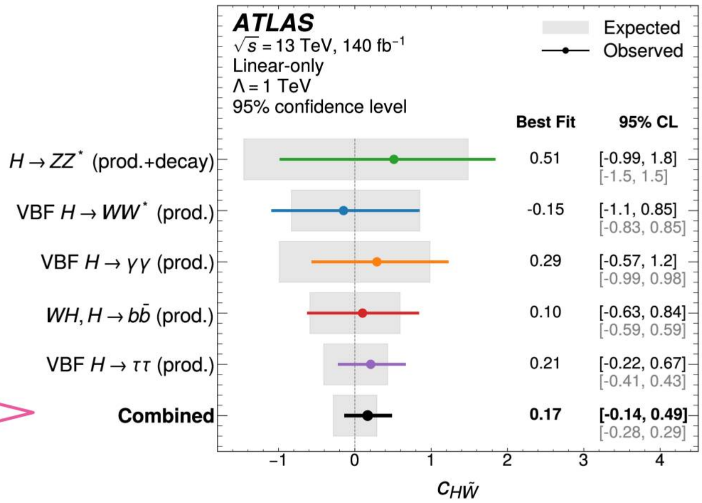
- **Improved the $c_{H\tilde{W}}$ limits by over 50%** compared to the 1-dimensional $\Delta\phi_{jj}^{\text{signed}}$ sensitivity (Phys. Rev. D 108 (2023) 072003)





CP combination

[Phys. Rev. Lett. 137 (2026) 021801]

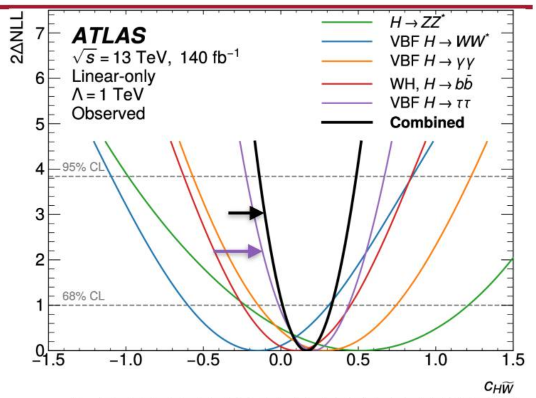


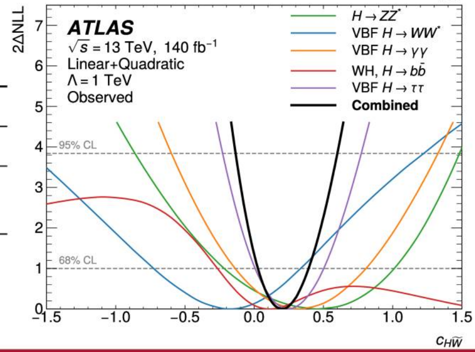
Lots of IHEP collaborators in this work :)

Combined results - single-parameter fit

[Phys. Rev. Lett. 137 (2026) 021801]

- WH $H \to b\bar{b}$ uses similar multi-dimensional differential measurement as HWW
- HZZ, $H \to \gamma\gamma$ and $H \to \tau\tau$ also use Matrix-Element optimal observable as the CP sensitive observable
- Result compatible with SM ($c = 0$)
- **Combined single-parameter fit provides a constraint on $c_{H\tilde{W}}$ which is improved by over 40%** compared to the most stringent single-channel constraint ($H \to \tau\tau$)
  - **Most stringent limit to-date**





Single-parameter fit				
Parameterization	68% CL (exp)	95% CL (exp)	68% CL (obs)	95% CL (obs)
$c_{H\tilde{W}}$ Linear-only	[-0.14, 0.15]	[-0.28, 0.29]	[0.01, 0.33]	[-0.14, 0.49]
$c_{H\tilde{W}}$ Linear + quadratic	[-0.15, 0.15]	[-0.30, 0.30]	[0.03, 0.39]	[-0.13, 0.60]

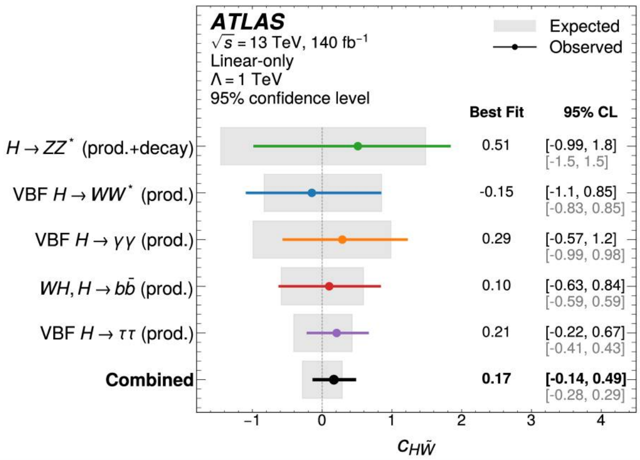
Combined results - quadratic effect

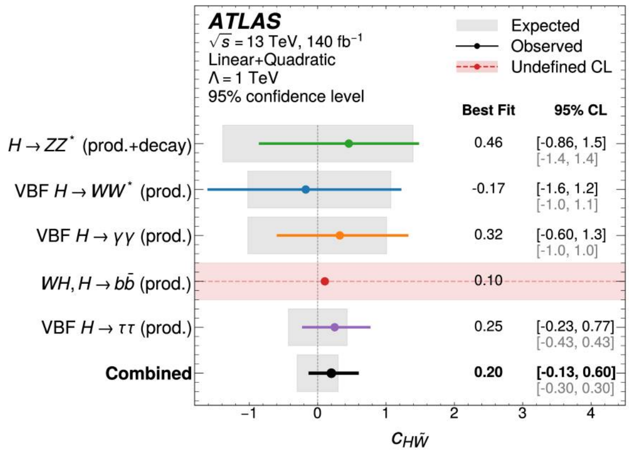
[Phys. Rev. Lett. 137 (2026) 021801]

- Lesson learnt in Run-2: **quadratic effect is non-negligible** and typically deteriorates limits on $c_{H\tilde{W}}$
- This is because quadratic effect is CP-even and reduces degree of asymmetry on the CP observable of each input channel

$$|\mathcal{M}_{\text{SMEFT}}|^2 = \boxed{|\mathcal{M}_{\text{SM}}|^2} + \boxed{2\sum_i \frac{c_i}{\Lambda^2} Re(\mathcal{M}^*_{\text{SM}}\mathcal{M}_i)} + \boxed{\sum_{i,j} \frac{c_i c_j}{\Lambda^4} Re(\mathcal{M}^*_i \mathcal{M}_j)}$$

  - Most noticeable in the WHbb channel



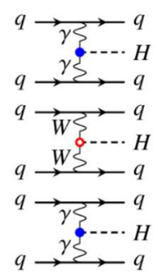


$H \to ZZ^*$ CP

[Eur. Phys. J. C 85 (2025) 1403]

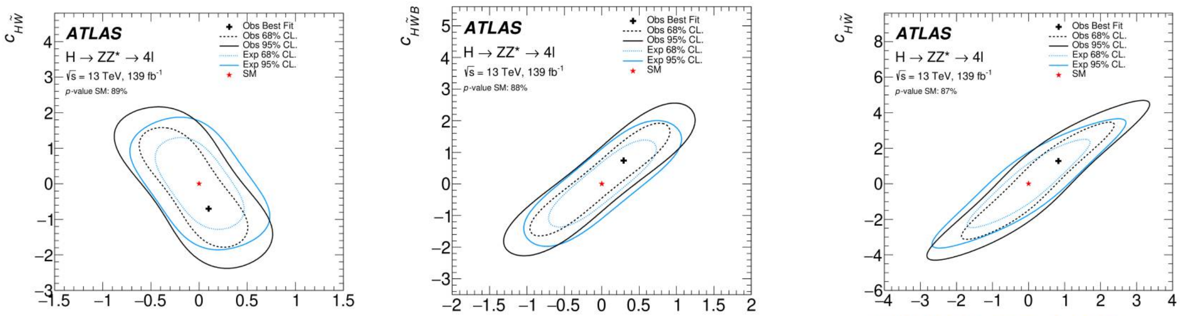
- HZZ channel has a unique opportunity to probe two additional *HVV* CP-odd couplings

Wilson coefficient	Operator	Effect or affected diagram
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}	$H^\dagger \tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	



Modification of SM vertices

Insertion of BSM vertices

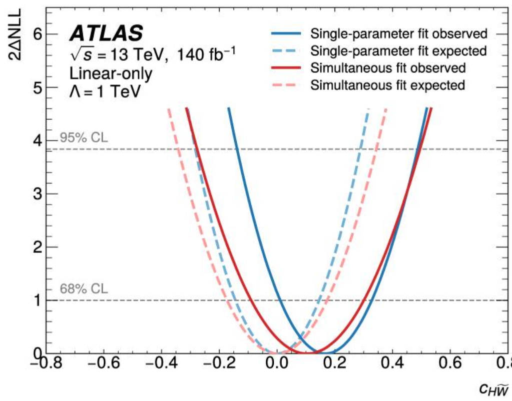


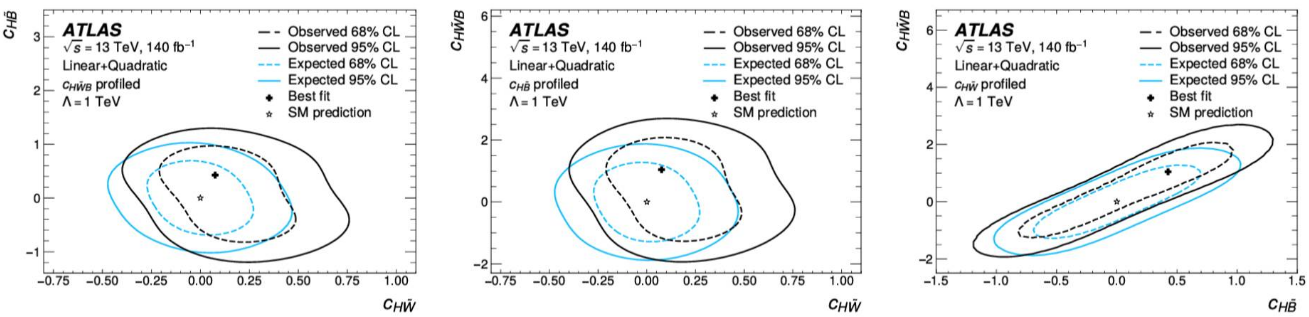
[JHEP 05 (2024) 105]

Combined results - simultaneous fit

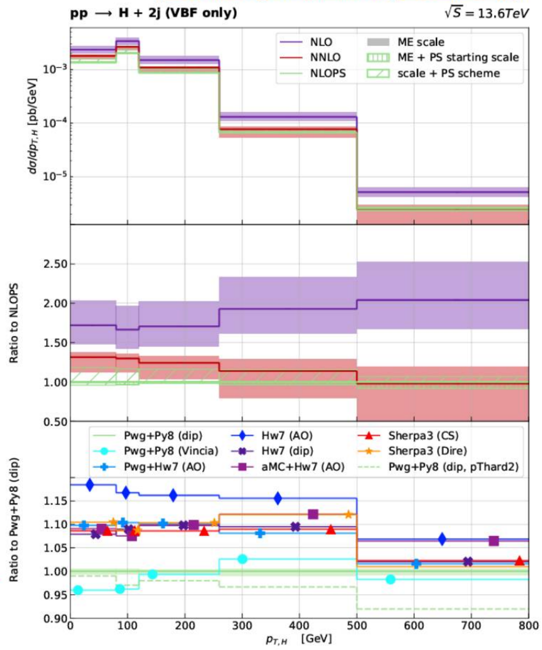
[Phys. Rev. Lett. 137 (2026) 021801]

- Result compatible with SM
- Constrain all three CP-odd couplings simultaneously
  - still most stringent $c_{H\tilde{W}}$ limit to-date
- Sensitivity to $c_{H\tilde{B}}$ and $c_{H\tilde{W}B}$ arise from *HZZ* channel
- **Combination helps to improve degeneracy**





[SciPost Phys. Comm. Rep. 13 (2025)]



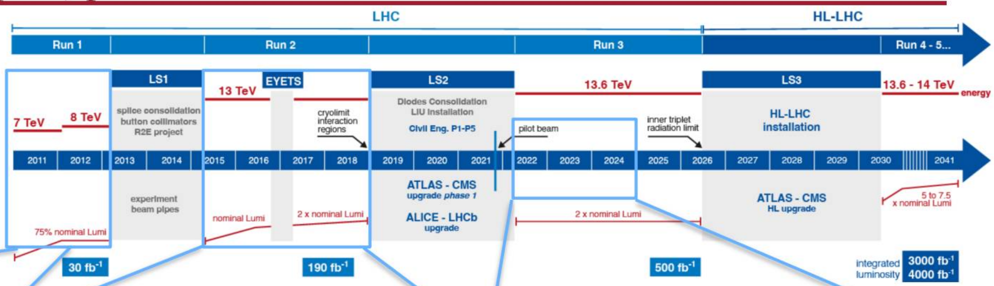
Reducing theoretical uncertainties in VBF analyses

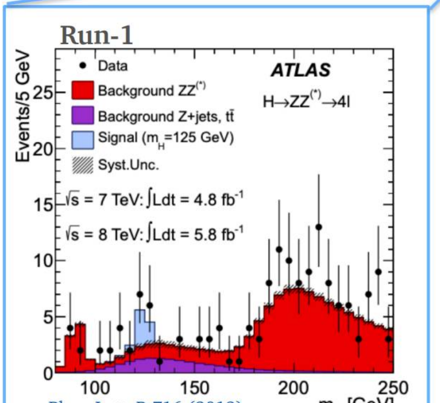
Have you ever seen a theory plot busier than experiment plot...? That's because an experimentalist made it...

Higgs measurements - past, present and future

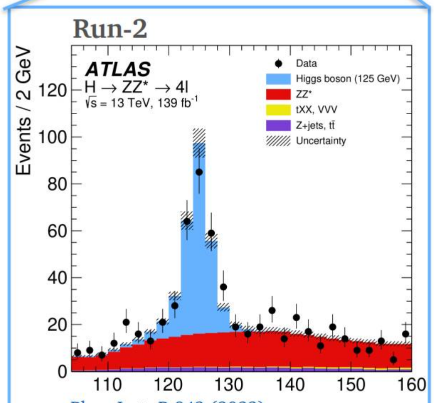
[High Lumi LHC Project]

- Run-3 delivered ~twice integrated luminosity compared to Run-2
- Another 10 folds of increment data statistics at HL-LHC phase

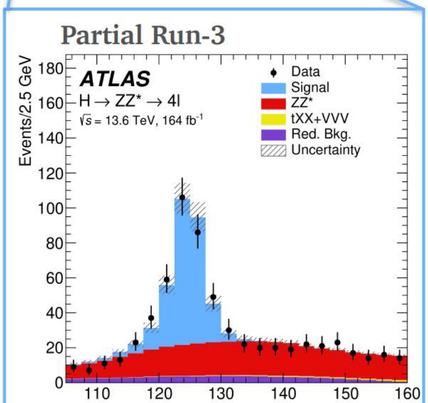




Phys. Lett. B 716 (2012)



Phys. Lett. B 843 (2023)



arXiv:2605.19016

Theoretical bottleneck for VBF

[*Eur. Phys. J. C 85 (2025) 1403*]

- **Theoretical uncertainty can no longer hide behind statistical uncertainty**
- VBF signal modeling uncertainty are now comparable to the statistical uncertainty of the HWW measurement
  - Also seen in other decay channels
- Particularly, large contribution from the *modeling of parton shower and matching*
  - **Different event generators** simulate VBF in slightly different ways because they make **different practical choices**, which affects how extra jets are added and how the hard scattering from matrix-element (parton-level) simulation is combined with the parton shower (process know as "matching")

Source	$\frac{\Delta(\sigma_{\mathrm{ggF}}\times\mathcal{B}_{H\to WW^*})}{\sigma_{\mathrm{ggF}}\times\mathcal{B}_{H\to WW^*}}$ [%]	$\frac{\Delta(\sigma_{\mathrm{VBF}}\times\mathcal{B}_{H\to WW^*})}{\sigma_{\mathrm{VBF}}\times\mathcal{B}_{H\to WW^*}}$ [%]
Total	**10**	**22**
Data statistical uncertainties	**5.2**	**14**
Total systematic uncertainties	**8.7**	**16**
Experimental uncertainties	**7.2**	**7.9**
MC statistical uncertainties	**2.2**	**4.5**
Experimental uncertainties (excl. MC stat.)	**7.0**	**6.8**
Electrons	1.9	1.3
Muons	4.1	0.7
Jet energy scale	1.6	5.6
Jet energy resolution	1.1	2.2
Flavour tagging	2.7	1.0
Missing transverse momentum	0.6	0.2
Pile-up	2.2	0.9
Luminosity	0.9	1.0
Misidentified leptons	2.5	0.9
Theory uncertainties	**5.0**	**15**
ggF H	2.2	4.3
VBF H	1.1	13
Other Higgs	0.5	0.2
Top quark	2.2	1.8
WW	2.8	2.2
Other VV	1.2	0.9
$Z/\gamma^* \to \tau\tau$	1.9	3.3
$Z/\gamma^* \to ee/\mu\mu$	0.5	1.2

Systematic comparison of theoretical modeling

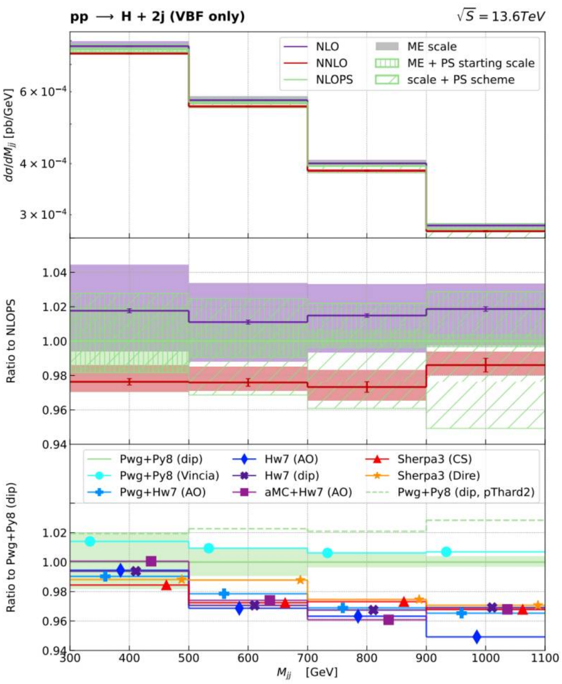
[*SciPost Phys. Comm. Rep. 13 (2025)*]

SciPost Physics Community Reports **Submission**

LHCHWG-2025-003, CERN-TH-2025-126, FERMILAB-PUB-25-0410-T, FR-PHENO-25-08, MCNET-25-16, TIF-UNIMI-2025-14, TTK-25-19

Higgs production via vector-boson fusion at the LHC

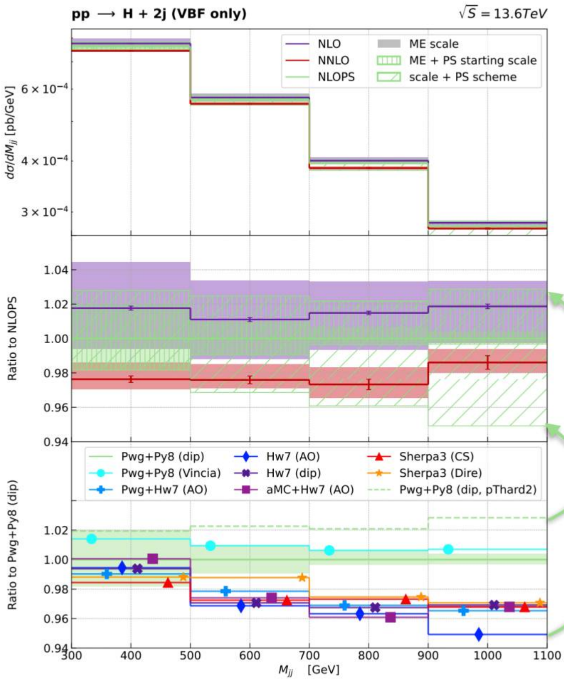
Gaetano Barone[1], Jiayi Chen[2], Stephane Cooperstein[3], Nikita Dolganov[2], Silvia Ferrario Ravasio[4], Yacine Haddad[5], Stefan Höche[6], Barbara Jäger[7], Alexander Karlberg[4], Alexander Mück[8], Mathieu Pellen[9], Christian T. Preuss[10], Daniel Reichelt[4], Simon Reinhardt[7], Marco Zaro[11]



- The study compare multiple simulation with QCD NLO matrix-element calculation + parton shower programs (NLOPS), within a common ATLAS/CMS kinematic phase space for VBF
- **We recommend how to estimate theoretical uncertainties related to parton shower** which sufficiently capture the difference between NLOPS and fixed-order QCD accuracy at NNLO in Run-3
- *Published results part of Yellow Report 5*

Systematic comparison of theoretical modeling

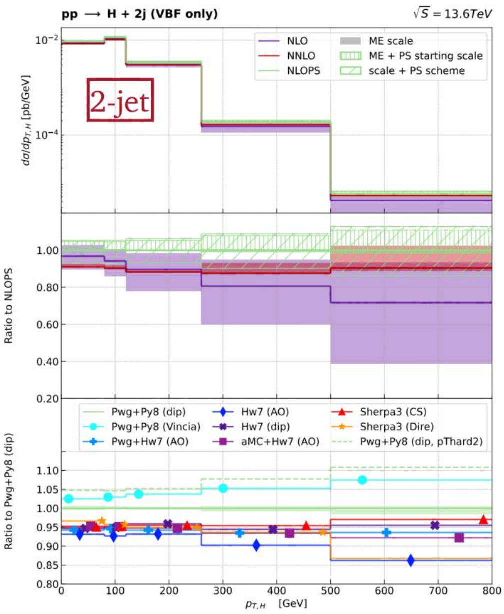
[SciPost Phys. Comm. Rep. 13 (2025)]

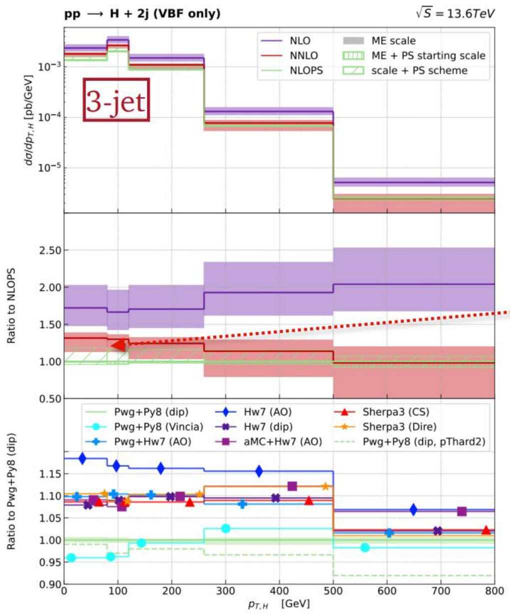


- NLOPS uncertainty is the sum of QCD scale variation and the envelop of 9 different NLOPS modeling
- Only at percent level, doesn't match the 10-15% observed impact from experiment?

Systematic comparison of theoretical modeling

[SciPost Phys. Comm. Rep. 13 (2025)]

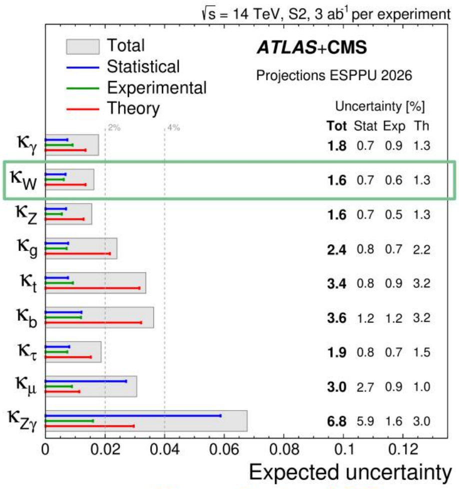




- **Modeling of the 3rd jet with NLOPS is problematic**
- Uncertainty reaches >15%
- More concerning: total uncertainty doesn't cover the difference between NLOPS and NNLO
- Experimental measurements need to reconsider event selection or machine learning using 3rd jet kinematics —> **likely to reduce uncertainty from 10% to few percent level**

Summary and outlook

- HWW decay channel has its unique physics reach
  - Topics NOT covered such as, Higgs width interpretation, quantum entanglement, etc.
- Effort for searching CP-odd interaction at the Higgs sector has marched
  - **New LHC Higgs CP working group initiated this year: joint ATLAS+CMS and theory effort**
    - ➡To make early and unanimous decisions on basis and strategy for future combination, as well as theory input on other *Hff/HVV* benchmark models
  - **ATLAS reported the most stringent limit on CP-odd effective *HWW* coupling** while simultaneously constraining other *HVV* CP-odd interactions under the SMEFT framework
- Projecting the ATLAS Run-2 measurement to HL-LHC (ATLAS+CMS), sensitivity improvements for Higgs coupling
  - W boson, from 9% to *percent level*
  - **We are now a the precision era for Higgs measurements - require high-precision theoretical modeling (down to few-percent level)**

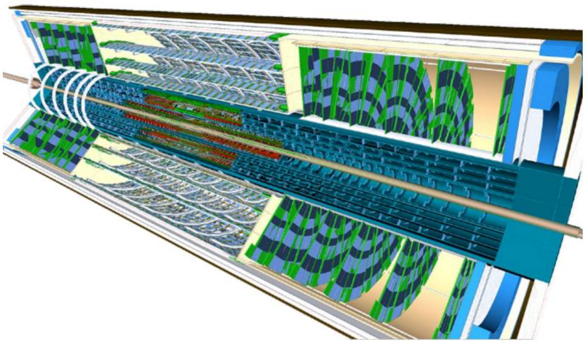


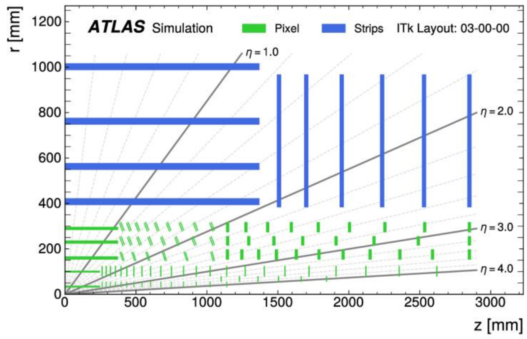
[Europe Strategy 2025]

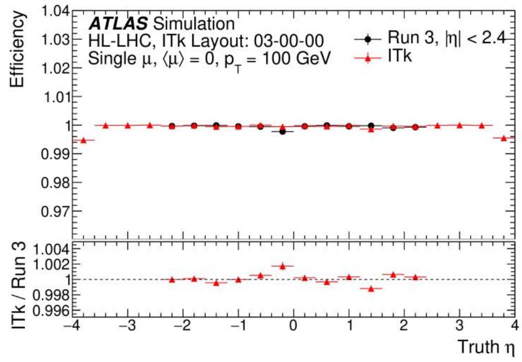
The new inner tracker

High-Luminosity LHC - ATLAS inner tracker upgrade

[JINST 20 (2025) P02018]



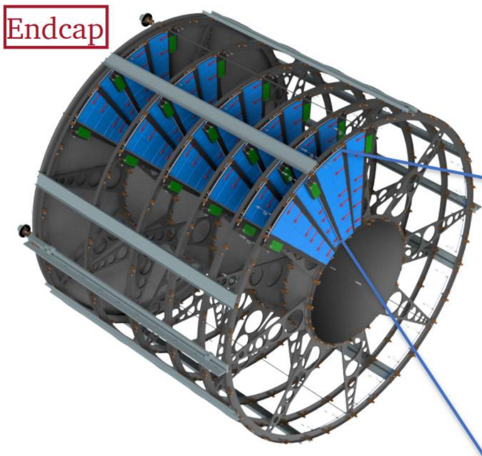




- New ATLAS Inner Tracker (ITk) replaces current inner detector
  - All silicon: inner pixel and outer strip detectors
  - Increase from 100M channels to 5000M
  - More front/back coverage to capture forward objects (typically larger pile-up)
- Vancouver effort: electrical unit (module) production and assembly of local support for the ITk Strip Endcap

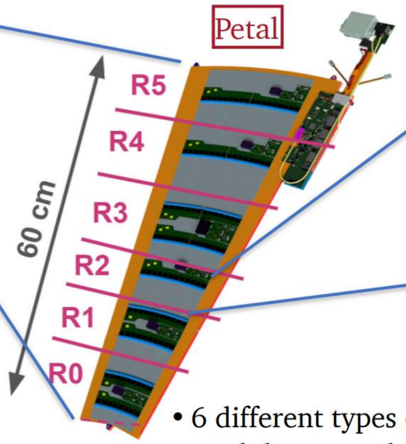
ITk Strip Endcap support structure - Petal

Endcap



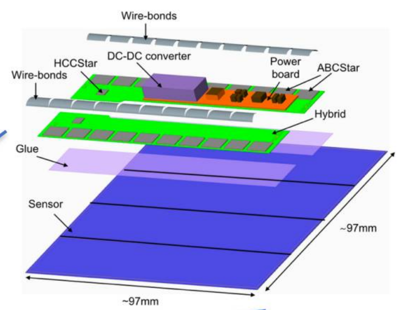
- 12 disks of petals

Petal



- 6 different types of modules on each side

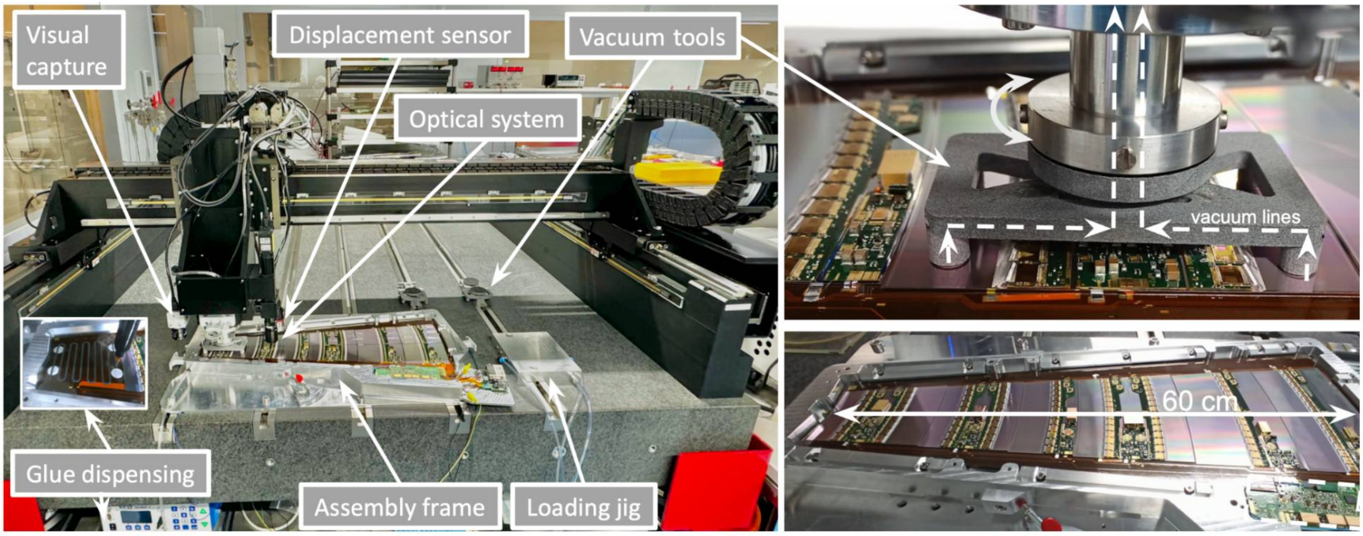
Module



- Silicon sensor strip pitch 70-80 μm

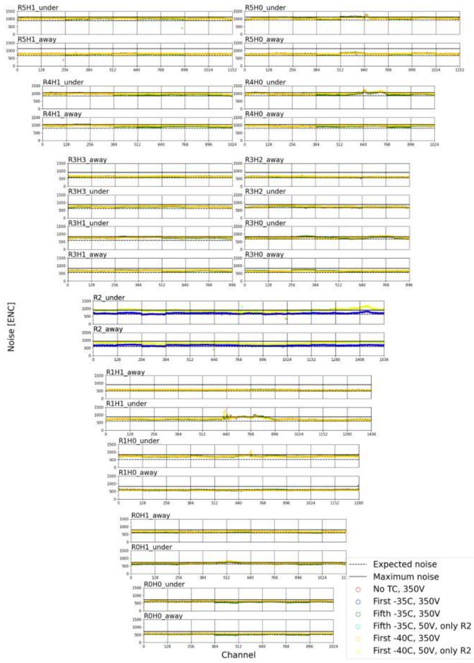
Bonus slide: petal assembly

Automated Petal assembly at Vancouver



Electrical testing for quality control

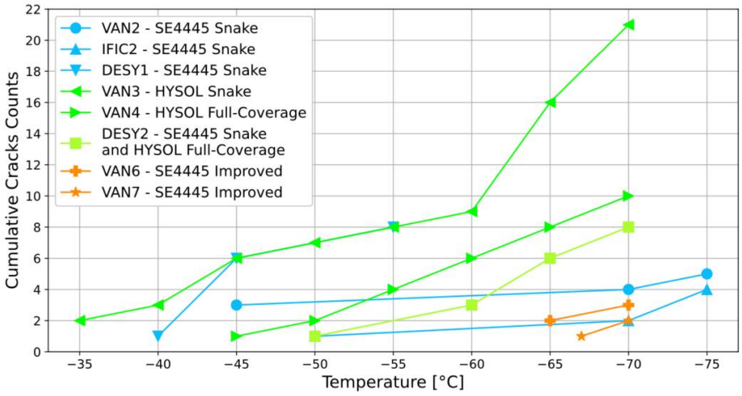
- Test petal electrically at near operation condition: -35C

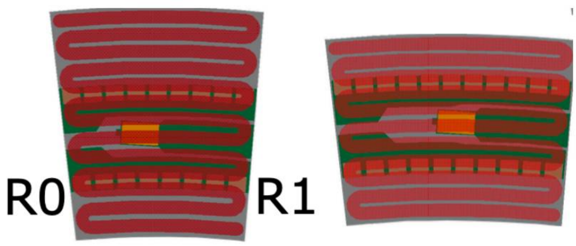


Cracking under pressure

[JINST 21 P07026]

- **The surprise:** silicon sensors designed for extreme radiation were being defeated by something much simpler—the cold.
- **The culprit:** a mismatch in the coefficients of thermal expansion (CTEs) between the copper-based PCBs and the silicon sensor, as well as glue dots and unsupported edges which concentrate the stress on the silicon sensor
- **The fix:** omit glue dots and improved glue pattern
- **The result:** No cracking down to **−45 °C**, safely below the detector's **−35 °C** operating temperature, with rare failures at **−55 °C**.





Backup

Single-Higgs combined measurement

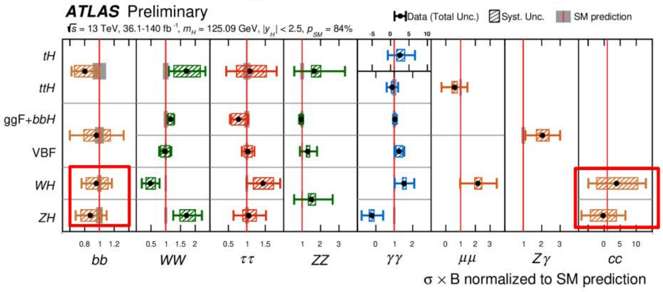
[ATLAS-CONF-2025-006]

- Latest combination reported 10% improvement in single Higgs signal strength compared to the "10th year anniversary" Nature paper:

$$\mu = 1.023^{+0.056}_{-0.053} = 1.023 \pm 0.028\ \text{(stat.)}\ ^{+0.026}_{-0.025}\ \text{(exp.)}\ ^{+0.039}_{-0.036}\ \text{(sig. theo.)}\ \pm 0.012\ \text{(bkg. theo.)}$$

Analysis	Prod. modes	$\mathcal{L}$ (fb^{-1})	STXS stage	Improvements relative to Ref.
$H \to ZZ^* \to 4\ell$	All	140	1.2	-
$H \to WW^* \to \ell\nu\ell\nu$	ggF,VBF	140	0	Reanalysis
$H \to WW^* \to \ell\nu\ell\nu$	VH	140	1.2	Full Run 2
$H \to \gamma\gamma$	All	140	1.2	-
$H \to Z\gamma$	All	140	0	-
$H \to \tau\tau$	All	140	1.2	Reanalysis
$H \to \tau\tau$	VH	140	0	New analysis
$H \to \mu\mu$	All	140	0	-
$H \to bb$	VBF	126	1.2	-
$H \to bb, cc$	VH	140	1.2	Reanalysis
$H \to$ multileptons	ttH	36.1	0	-
$H \to bb$	ttH	140	1.2	Reanalysis

29 simultaneous measured cross-section times branching ratios



- Measurement also split by 5 production cross-sections, or 7 branching ratios
  - *WH* (*ZH*) sensitivity improved by 30% (20%) thanks to updated *VH bb/cc* analysis
  - Uncertainties on $H \to WW^*$ and $H \to \tau\tau$ branching ratios reduced by 20% and 10% respectively, thanks to improved analysis strategies

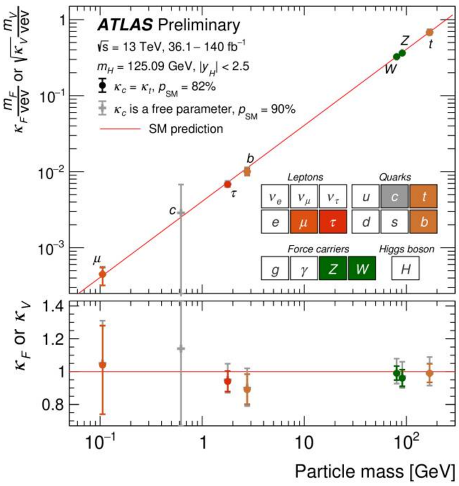
The κ-framework

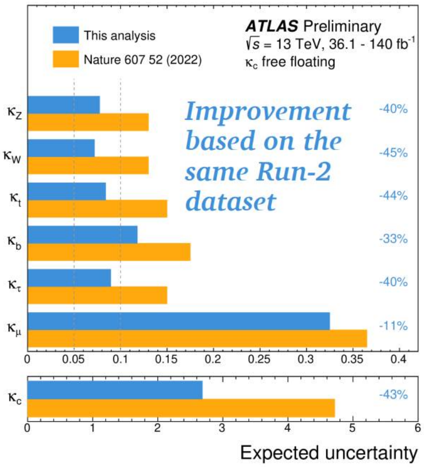
[ATLAS-CONF-2025-006]

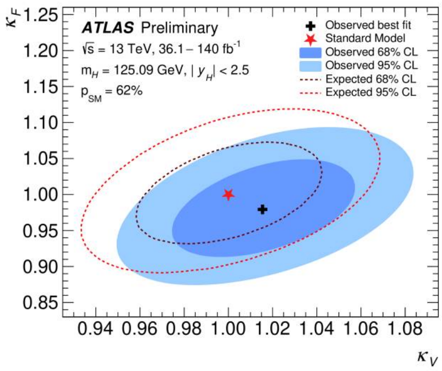
- The **κ-framework** introduces coupling modifiers for the Higgs coupling with the fermions (κ_f) and bosons (κ_V)

$$\sigma \cdot \mathcal{B}(i \to H \to f) = \kappa_i^2 \cdot \kappa_f^2 \cdot \sigma_i^{\mathrm{SM}} \cdot \frac{\Gamma_f^{\mathrm{SM}}}{\Gamma_H(\kappa_i^2, \kappa_f^2)}$$

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \quad \text{and} \quad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{\mathrm{SM}}}$$



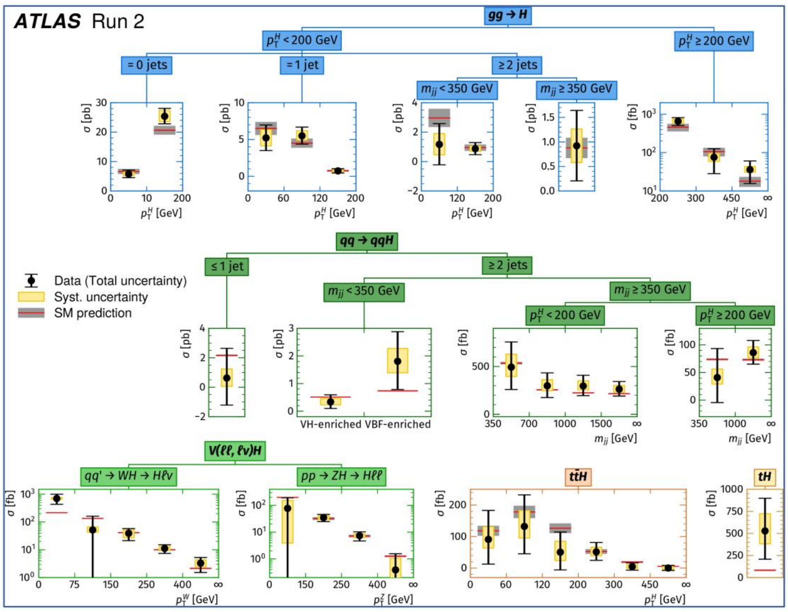


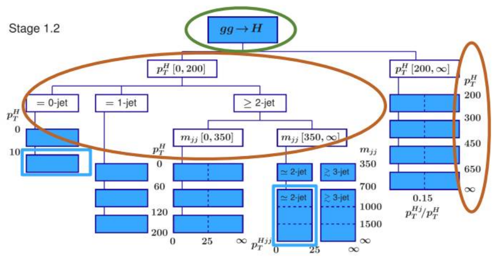


Simplified Template Cross Sections (STXS)

[Nature 607 (2022)]

- STXS *bin* defined by *production mode* and *kinematic selections*

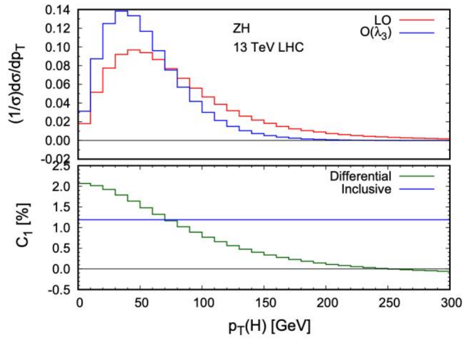




- The STXS binning minimize measurement dependency on theory predictions
- STXS also maximize BSM sensitivity
- Run2 measurements are designed around Stage1.2 of the STXS
- Run3 with planned Stage1.3 and HL-LHC with Stage2.0

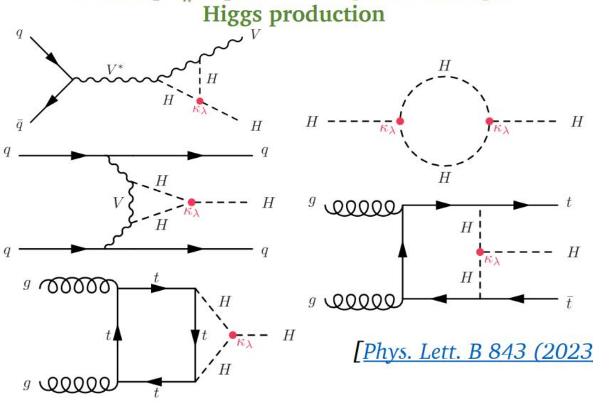
Single-Higgs helping to constrain Higgs self-coupling

- Higgs self-coupling (coupling modifier κ_λ) can be probed not only directly via di-Higgs production but also indirectly via **NLO EW corrections on single-Higgs**
- Low p_T^V of ZH STXS bins are particularly sensitive to κ_λ
  - Addition of *VH HWW* will provide more sensitivity (not in Nature paper)

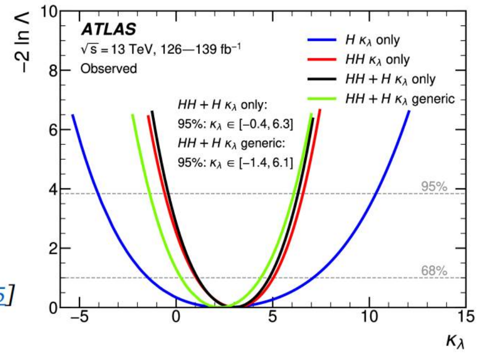


[Eur. Phys. J. C 77, 887 (2017)]

One-loop κ_λ dependent diagrams of single-Higgs production



[Phys. Lett. B 843 (2023) 137745]

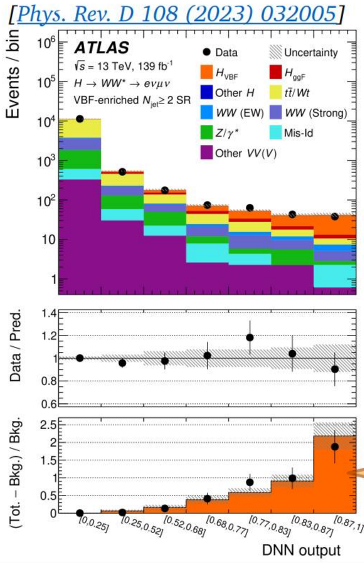


Signal extraction - Multi-variant technique

Signal optimization

- Machine learning techniques to further separate signal from bkg while modeling major bkgs in control regions

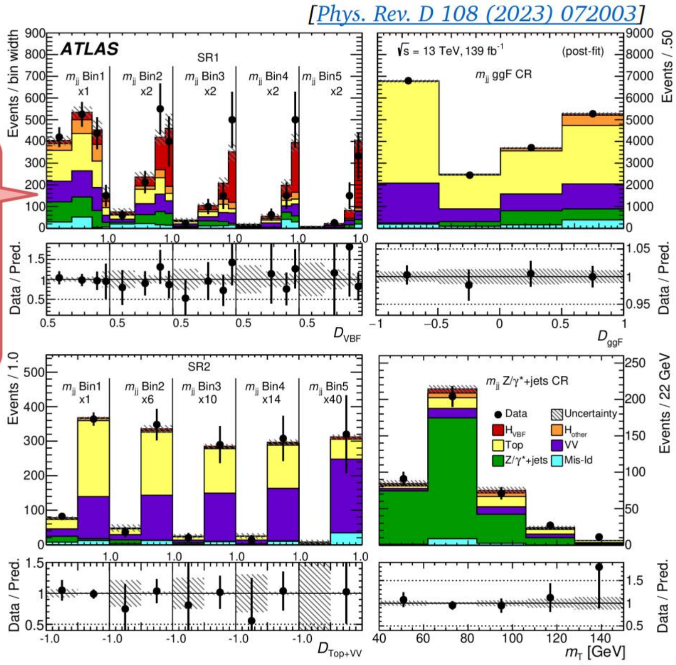
[Phys. Rev. D 108 (2023) 032005]



First observation of Higgs signal in the VBF production and $H \to WW^* \to l\nu l\nu$ decay channel!

First cross-section measurement differential in various production and decay kinematic variables with signal-background separation from boosted decision tree

[Phys. Rev. D 108 (2023) 072003]



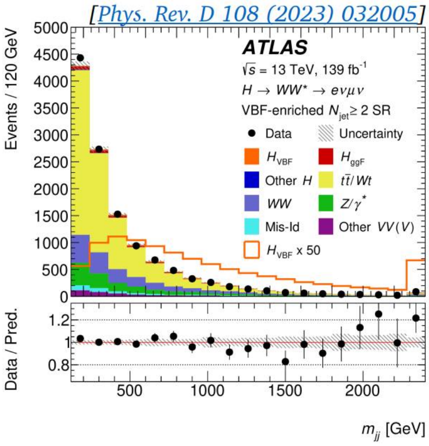
Signal extraction - kinematic selection

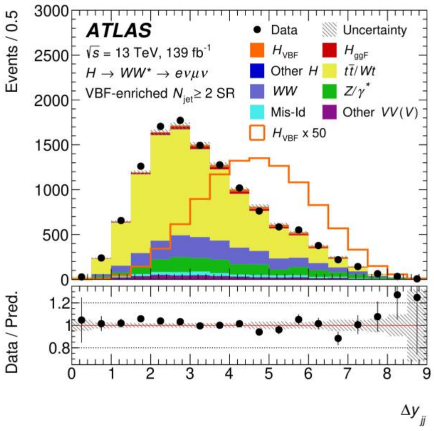
Signal optimization

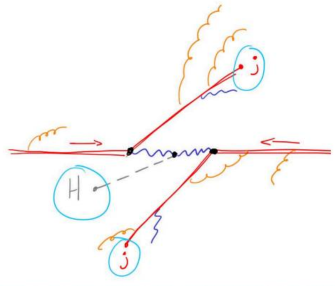
- Kinematic selection to select **signal** and reject backgrounds

- Production kinematics example:
  - Jets separated by a large rapidity gap (Δy_{jj}) and large invariant mass (m_{jj}) with no significant hadronic activity in the central region
  - Typically also apply a veto on events with central jet (central jet veto) between the two VBF jets

[Phys. Rev. D 108 (2023) 032005]







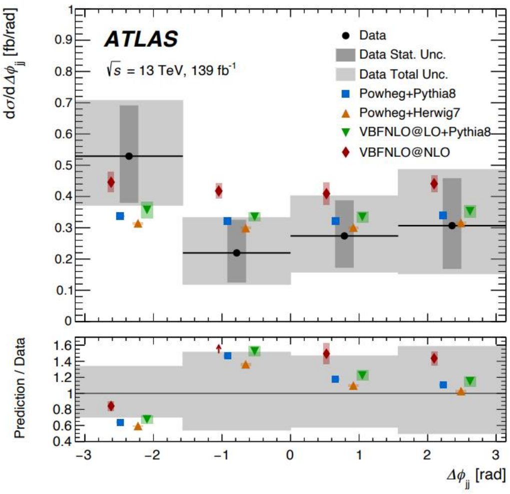
Bookmark

- Coming back to central jet veto in theory advancement

Constrain HVV CP-odd effect with signed $\Delta\phi_{jj}$ in the VBF HWW channel

- Measurement of signed $\Delta\phi_{jj}$ is shows compatibility with SM predictions

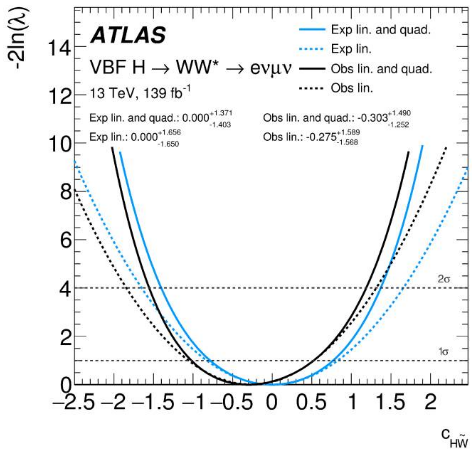
[Phys. Rev. D 108 (2023) 072003]



- Constrain single Wilson coefficient:

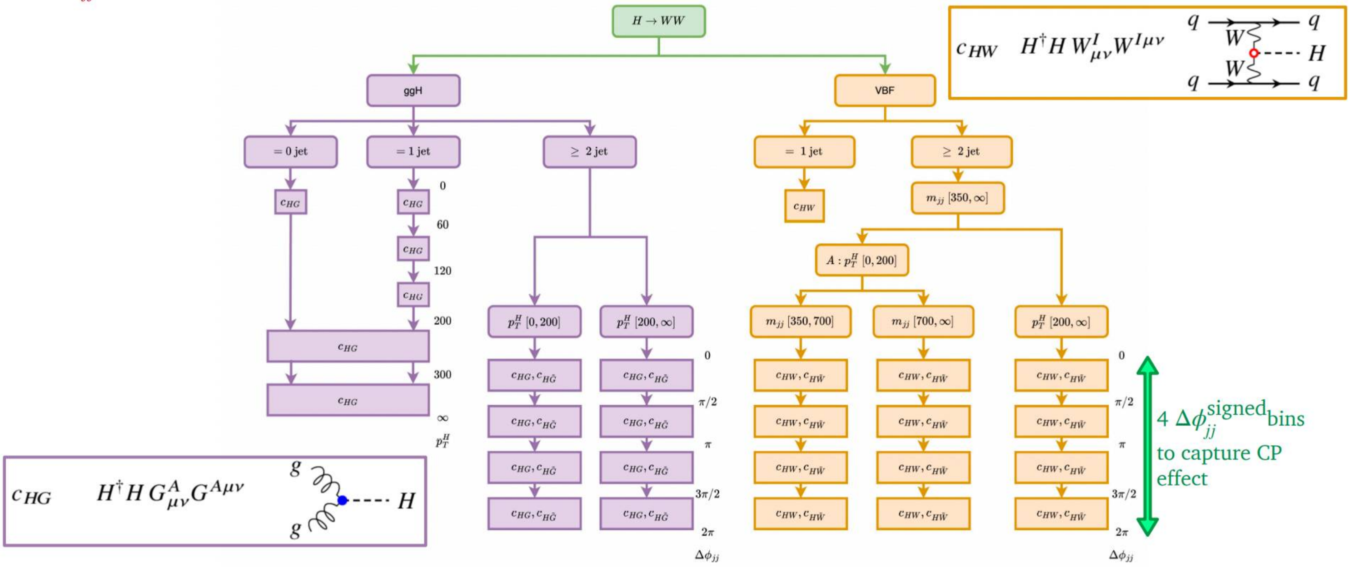
Obs lin. and quad.: $-0.303^{+1.490}_{-1.252}$

Obs lin.: $-0.275^{+1.589}_{-1.568}$



ggF+VBF $H \to WW^* \to l\nu l\nu$ - CP-sensitive STXS

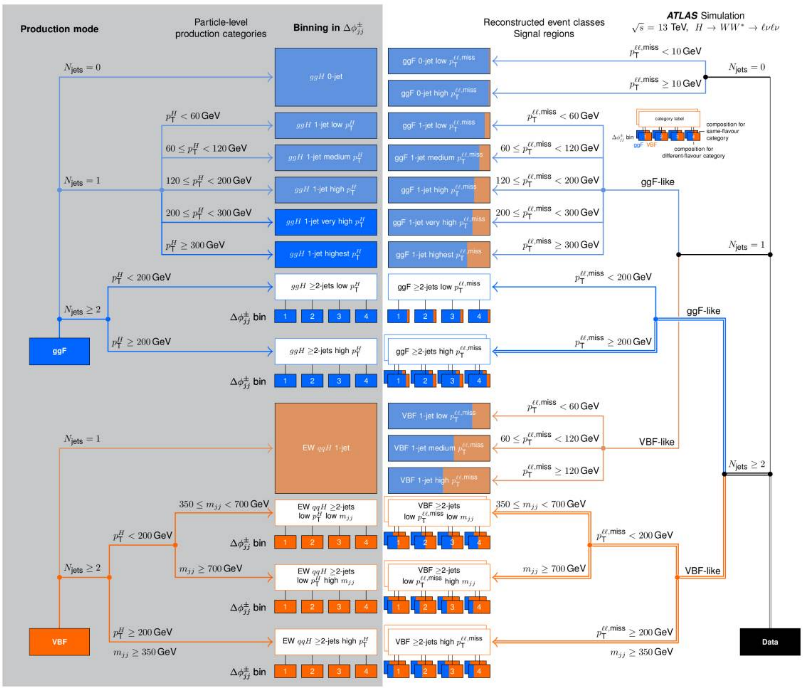
- An alternative STXS scheme is developed to probe the Higgs CP property: p_T^H vs m_{jj} vs $\Delta\phi_{jj}^{\text{signed}}$
- Simultaneous constraint on CP even/odd and ggF/VBF CP couplings
- *N.b. $\Delta\phi_{jj}^{signed}$ added to updated STXS scheme - to be used in Run-3 analysis*



ggF contamination in the CP analysis

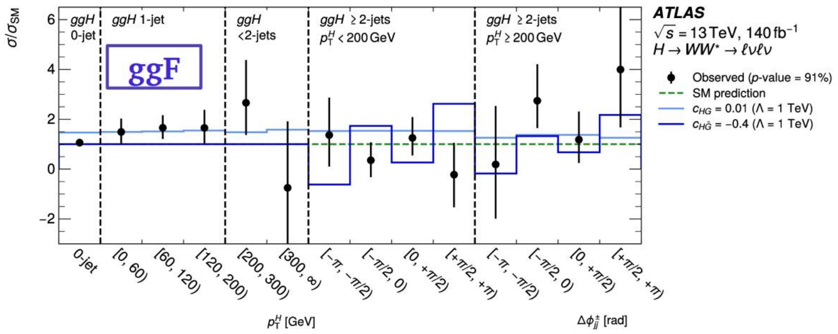
[Phys. Rev. D 108 (2023) 072003]

- ggF contamination large at low pTH



ggF contamination in the CP analysis

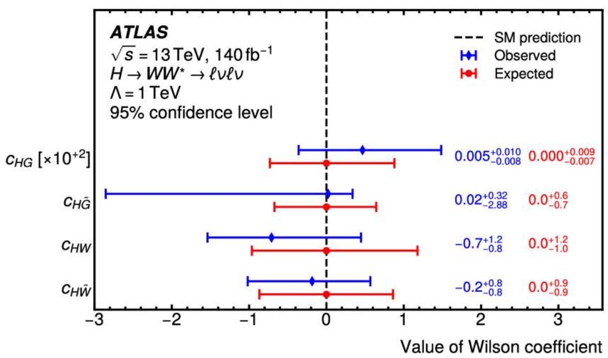
[Phys. Rev. D 108 (2023) 072003]

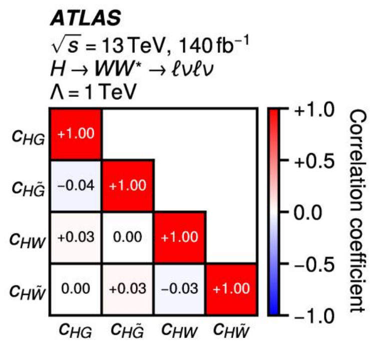


CPV results in the ggF+VBF $H \to WW^* \to l\nu l\nu$ channel

[Eur. Phys. J. C 85 (2025) 1403]

- All four Wilson coefficients are effectively constrained
- Strategy makes less assumption about the CP-even effect, yet the multi-dimensional differential (Higgs p_T vs signed $\Delta\phi_{jj}$) **improved the $c_{H\tilde{W}}$ limits by over 50%** compared to the 1-dimensional $\Delta\phi_{jj}$ sensitivity
- Distinct shapes of EFT impact from the four CP operators make their correlation small

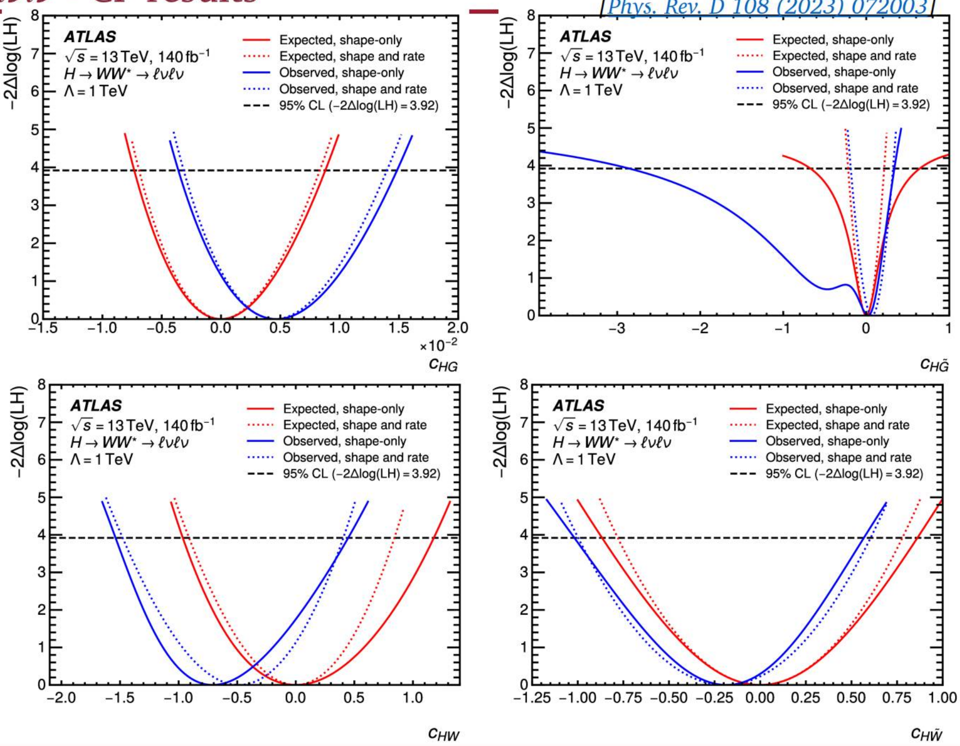




ggF+VBF $H \to WW^* \to l\nu l\nu$ - CP results

[Phys. Rev. D 108 (2023) 072003]

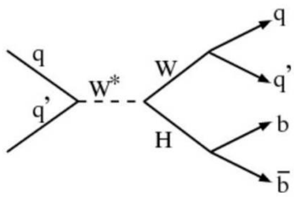
- Second local minimum for $c_{H\tilde{G}}$ and using only the shape of $\Delta\phi_{jj}$ induced the large asymmetric limits



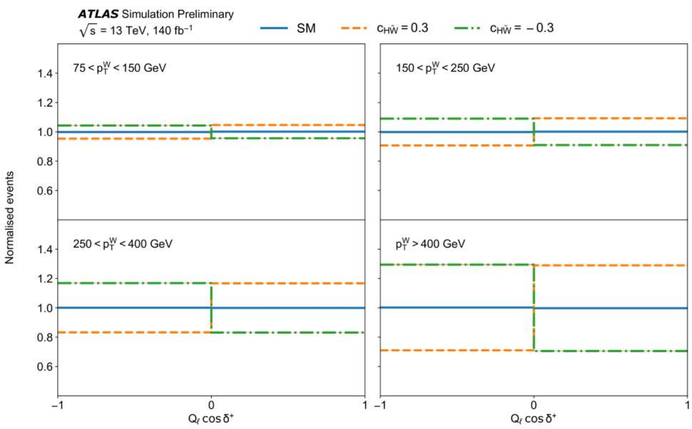
WH $H \to b\bar{b}$ CP

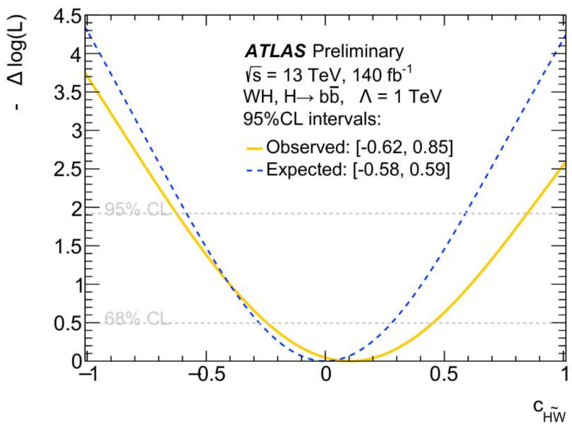
ATL-PHYS-PUB-2025-022

- *WH* particularly sensitive to $c_{H\tilde{W}}$ as the process is not diluted by *ZH*



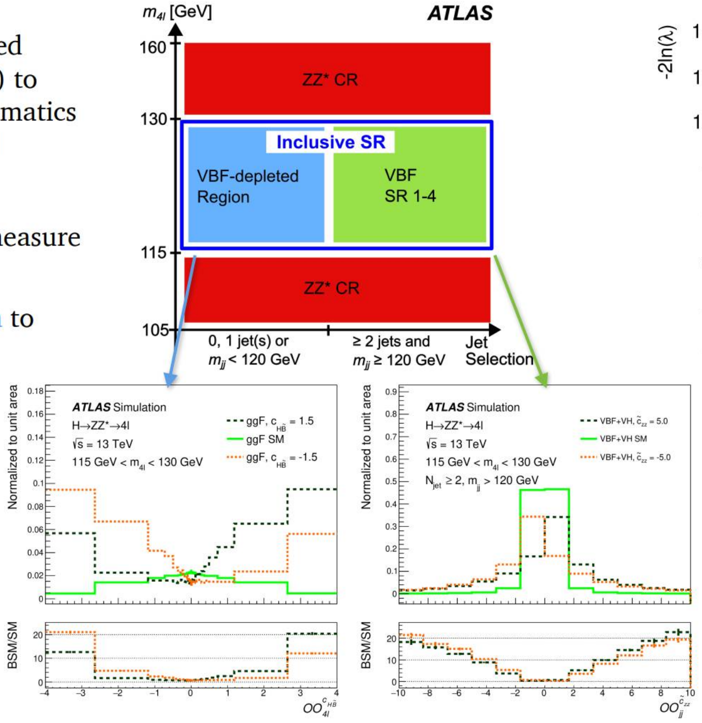
- Similar alternative STXS binning as HWW
- Only shape of the CP observable is used to constrain $c_{H\tilde{W}}$

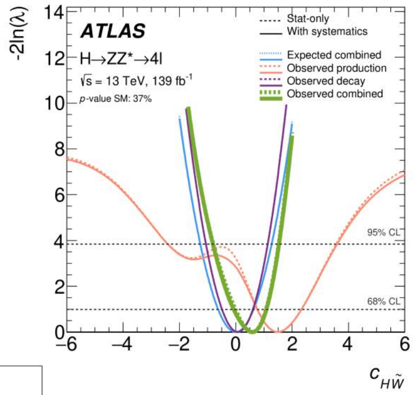




[JHEP 05 (2024) 105]

- Use Matrix-Element based optimal observable (OO) to compress full event kinematics into statistically optimal quantities
- Use VBF dominant SR measure production OO (VBF)
- Use VBF-depleted region to measure decay OO ($H \to ZZ^* \to 4l$)

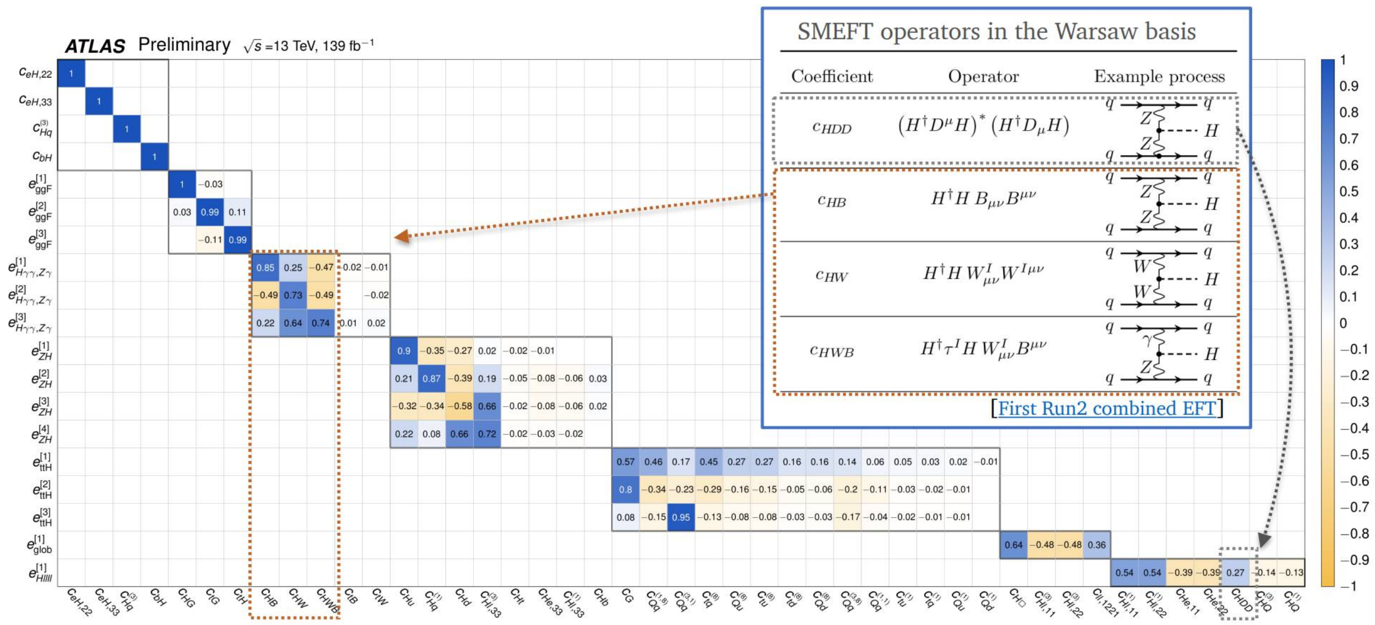




HVV EFT status from combined interpretation (I)

[HComb BSM interpretation]

- This talk will focus on the status of constraining $\mathcal{O}_{HW}$, $\mathcal{O}_{HB}$ and $\mathcal{O}_{HWB}$, and their CP odd counter parts
- $\mathcal{O}_{HDD}$ effect relatively small and similar effect as $HZee$ and $HZ\mu\mu$ anomalous coupling

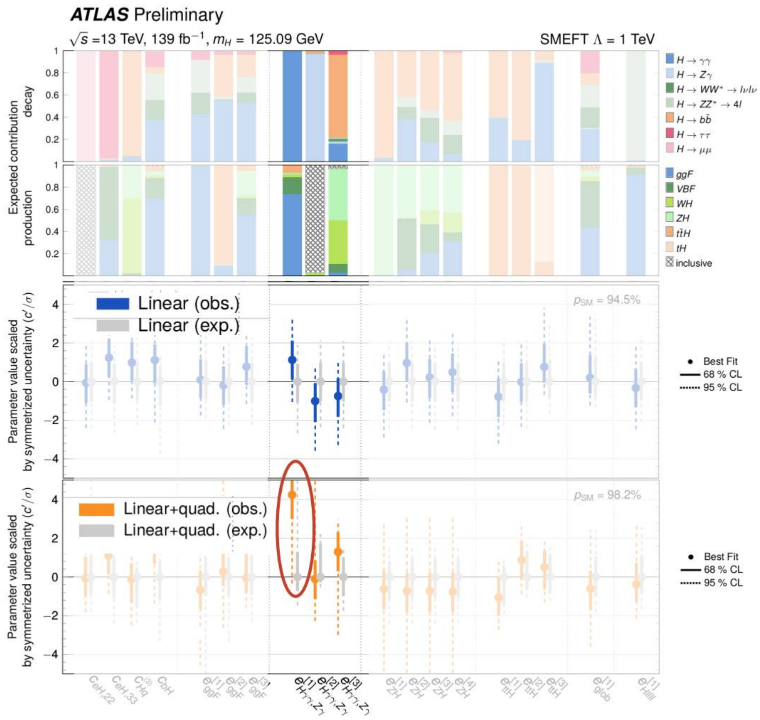


HVV EFT status from combined interpretation (II)

[HComb BSM interpretation]

- All HVV PCA directions are measured to be compatible with SM
- At linear+quadratic, the local minimum of $e^{[1]}_{H\gamma\gamma,Z\gamma}$ further from zero is also the global minimum
- The ggF, VBF and VH production modes plus $\gamma\gamma$, $Z\gamma$, bb decay channel contributed the most to constraining these HVV anomalous couplings

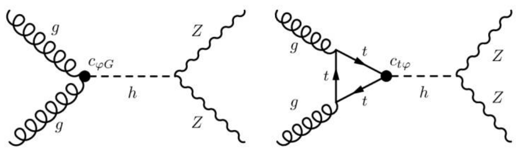
	CHB	CHW	CHWB	CtB	CtW
$e^{[1]}_{H\gamma\gamma,Z\gamma}$	0.85	0.25	−0.47	−0.02	−0.01
$e^{[2]}_{H\gamma\gamma,Z\gamma}$	−0.49	0.73	−0.49		−0.02
$e^{[3]}_{H\gamma\gamma,Z\gamma}$	0.22	0.64	0.74	0.01	0.02

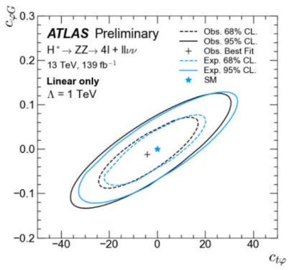


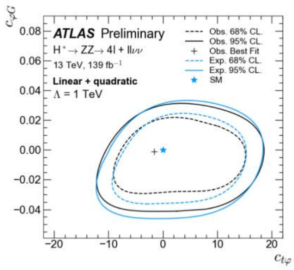
More recent/ongoing HVV EFT ideas - HVV off-shell and EFT

[HZZ off-shell EFT]

- HVV off-shell analysis probe higher energy regime and has the potential to decouple H-t and H-g anomalous coupling
- HZZ off-shell provided constraints on the two Wilson coefficients
- HWW off-shell is on-going and plan for a similar interpretation

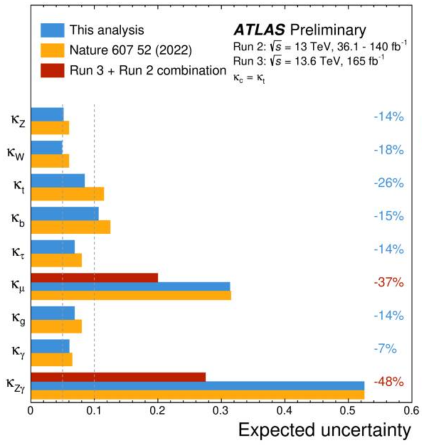






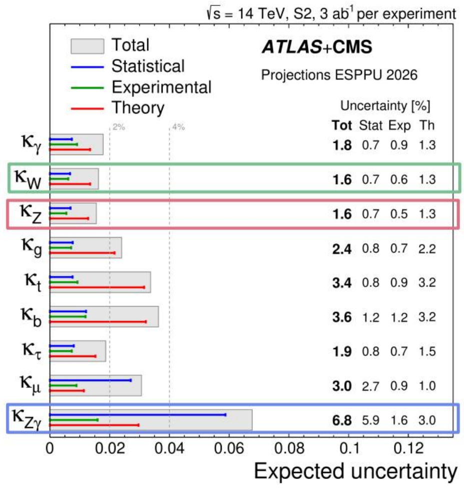
Higgs at High-Luminosity LHC

- **Projecting** the ATLAS Run-2 measurement (*Nature paper*) to HL-LHC (ATLAS+CMS), sensitivity improvements for Higgs coupling to
  - W boson, from 9% to *percent level*
  - Z boson, from 9% to *percent level*
  - $Z\gamma$, from >50% (~30% combined with partial Run3) to *<10%*



Parameter	Resolved $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$		Effective $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$
	Free κ_c	$\kappa_c = \kappa_t$	$\kappa_c = \kappa_t$
κ_Z	$0.97^{+0.09}_{-0.07}$	0.96 ± 0.05	0.96 ± 0.05
κ_W	$0.99^{+0.09}_{-0.06}$	0.99 ± 0.04	1.00 ± 0.05
κ_t	$0.99^{+0.10}_{-0.08}$	$0.99^{+0.06}_{-0.05}$	0.99 ± 0.09
κ_b	$0.90^{+0.12}_{-0.11}$	0.89 ± 0.09	$0.89^{+0.10}_{-0.09}$
κ_τ	$0.95^{+0.10}_{-0.08}$	0.94 ± 0.06	0.94 ± 0.06
κ_c	$1.1^{+1.6}_{-3.8}$	—	—
κ_μ	$1.05^{+0.25}_{-0.31}$	$1.04^{+0.24}_{-0.30}$	$1.04^{+0.23}_{-0.30}$
κ_g	—	—	$0.99^{+0.07}_{-0.06}$
κ_γ	—	—	0.97 ± 0.06
κ_{Z/γ^*}	—	—	$1.36^{+0.30}_{-0.36}$

[*ATLAS-CONF-2025-006*]



[Europe Strategy 2025]

Combination of search for di-Higgs

- Expected di-Higgs production cross-section is ~1000 times smaller than single-Higgs production
  - *combination of different decays is the key*

Symmetry 2022, 14(2), 260

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

- Combination sets upper limit on HH production at 2.9 (2.4) times SM value
- Self-coupling constrained to [-1.2,7.2] ([-1.6,7.2])

Phys. Rev. Lett. 133 (2024) 101801