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

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Collider Physics in the Northwest

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TRIUMF

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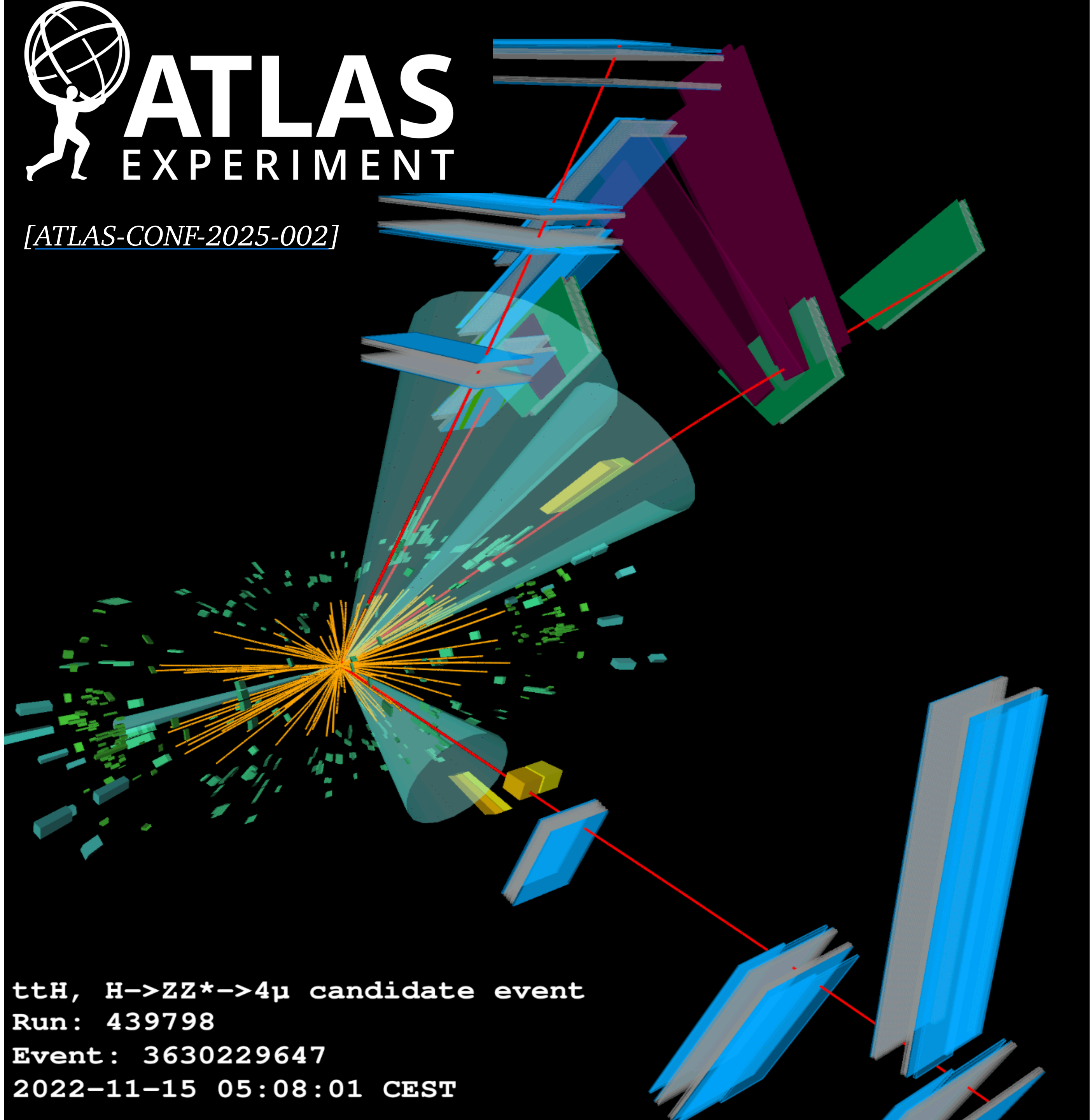
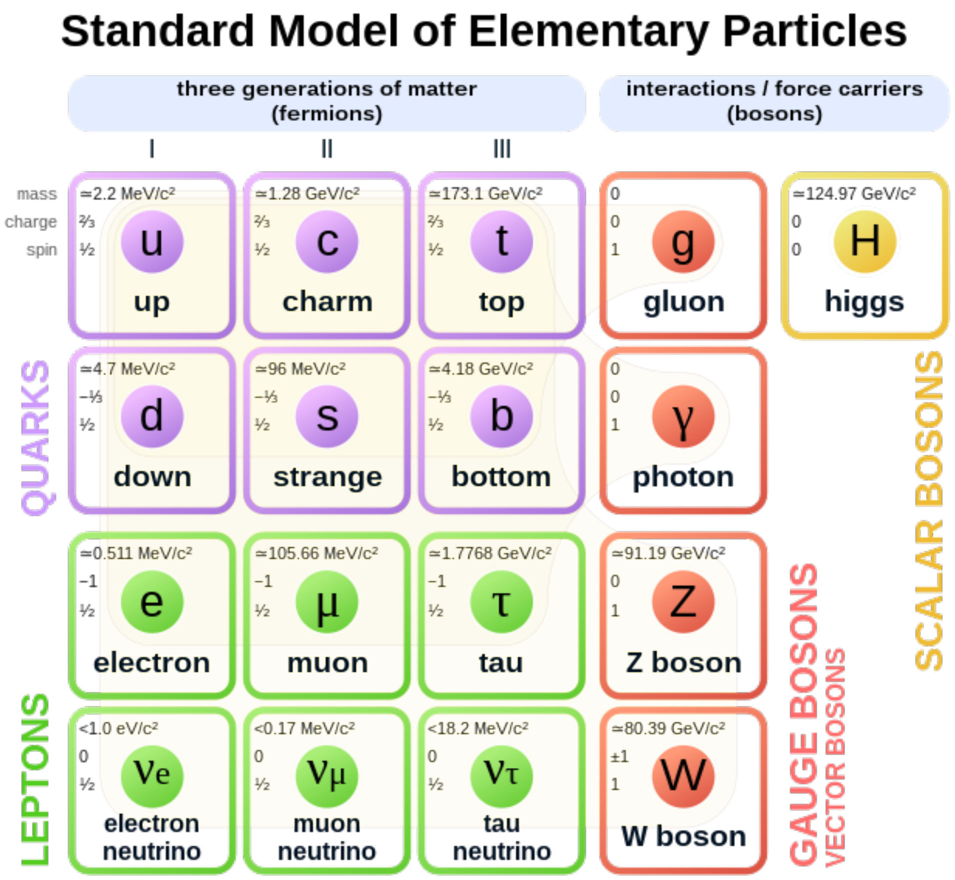
ATLAS EXPERIMENT

[ATLAS-CONF-2025-002]



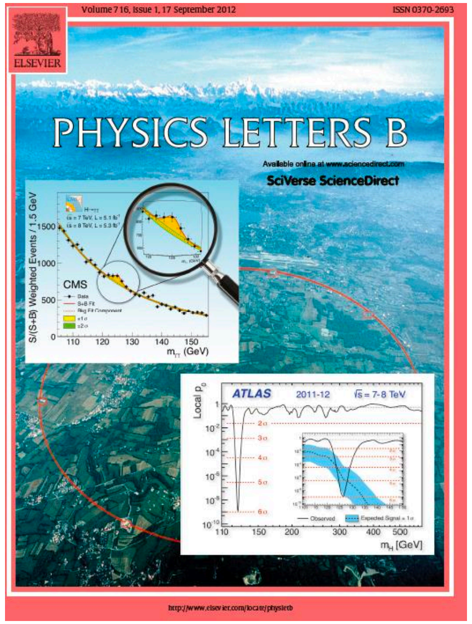
Introduction

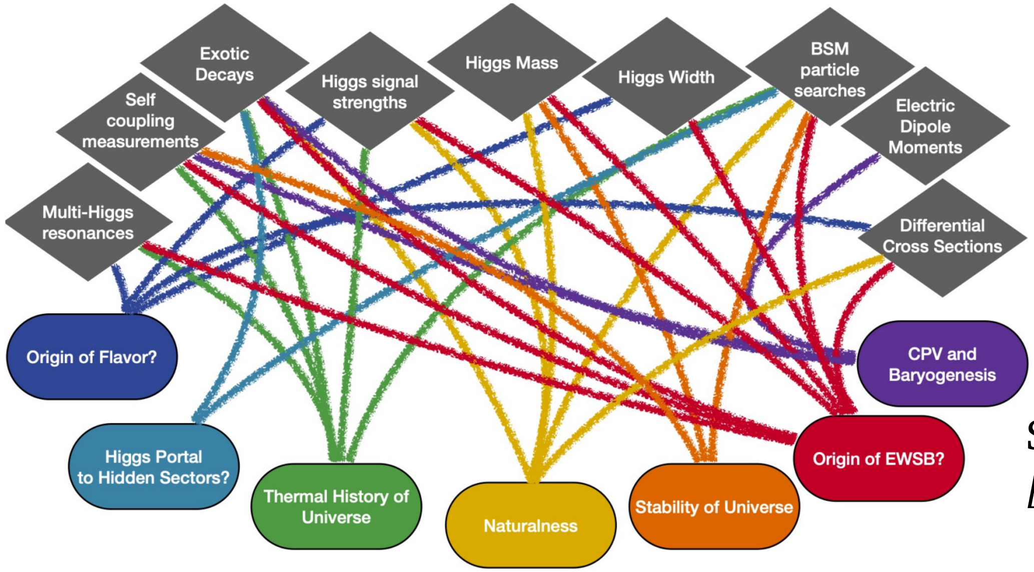
- The Standard Model (SM) is a successful model describing the past 50 years of experimental data



[Wikipedia contributors.](https://en.wikipedia.org)

- **Higgs**, the last missing piece co-discovered by ATLAS and CMS collaborations in 2012 - a particle that gives mass to fermions and gauge bosons
- Many unexplained physics phenomena call for the precise determination of the Higgs boson nature





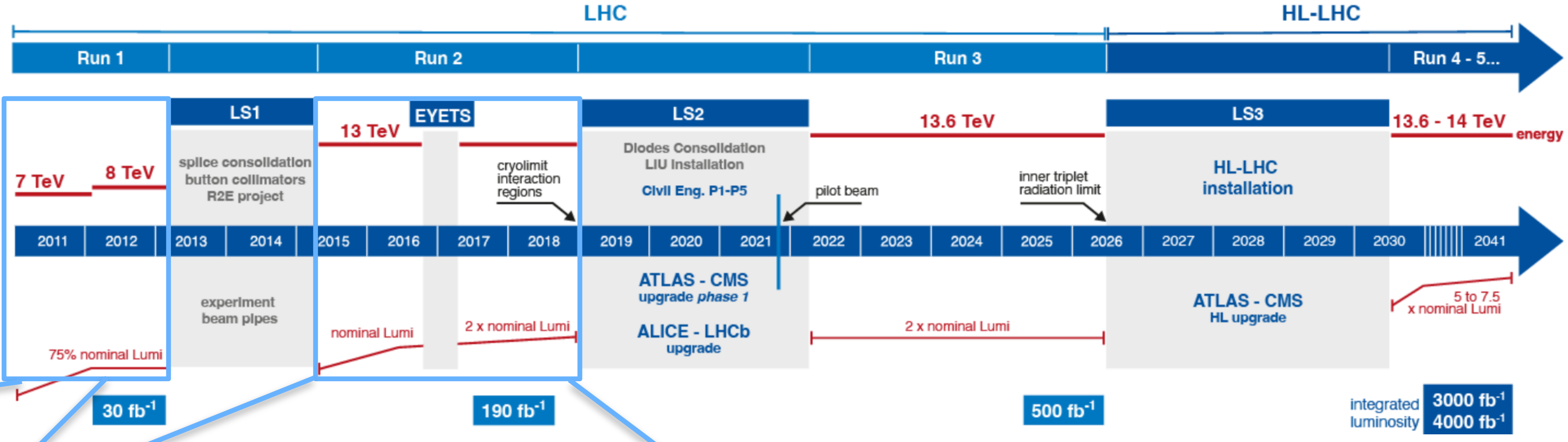
Snowmass [arXiv:2209.07510]

Higgs measurements - past, present and future

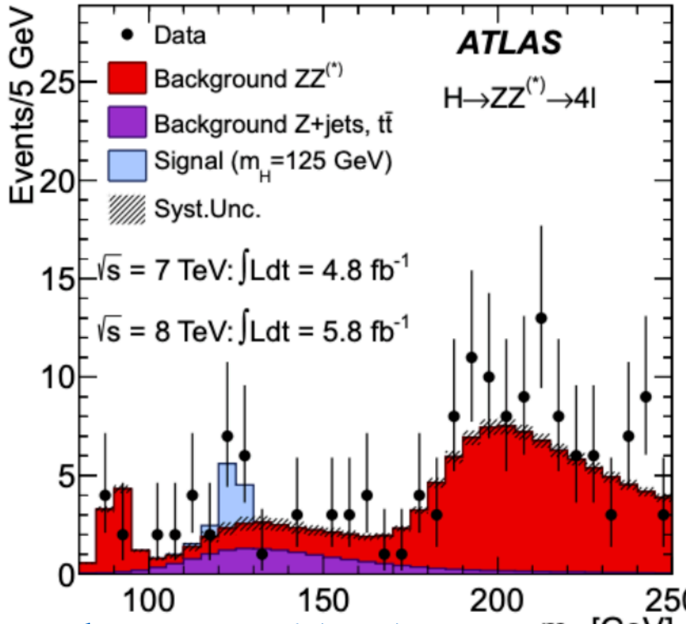
[High Lumi LHC Project]

- During Run-2, expected amount of Higgs boson events is ~30 times larger than at the time of its discovery

  * $1\ fb^{-1} \sim 100$ trillion pp interactions

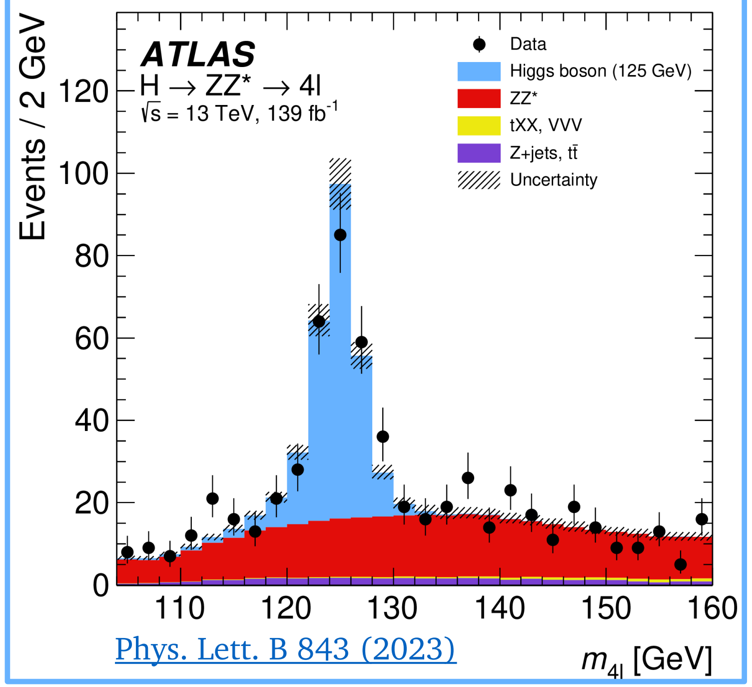


Run-1



Phys. Lett. B 716 (2012)

Run-2



Phys. Lett. B 843 (2023)

Higgs measurements - past, present and future

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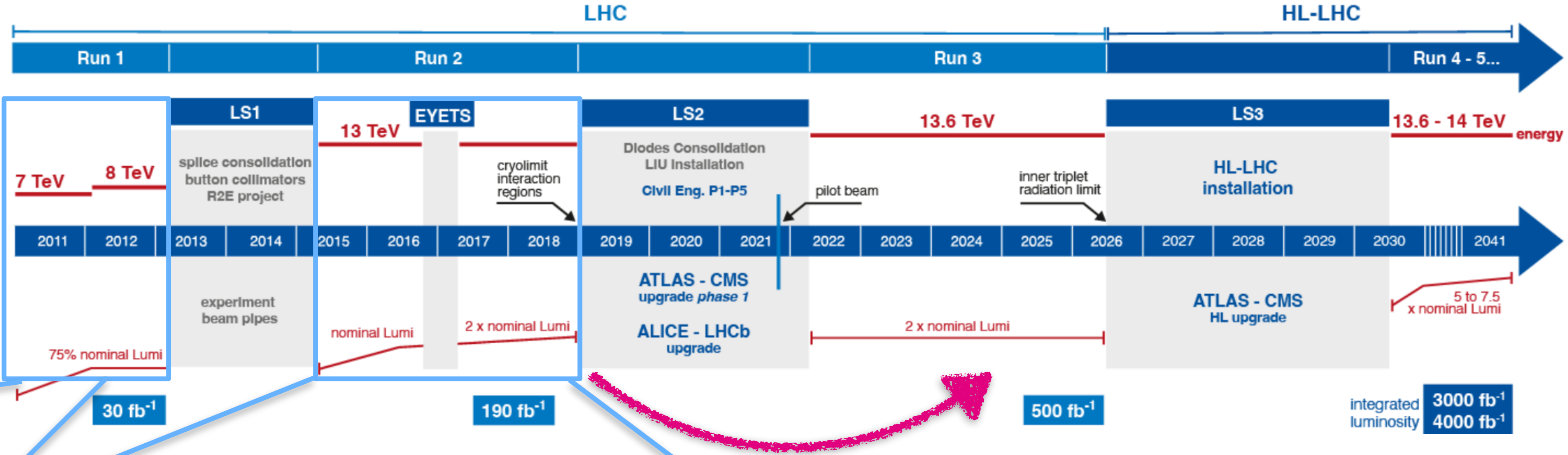

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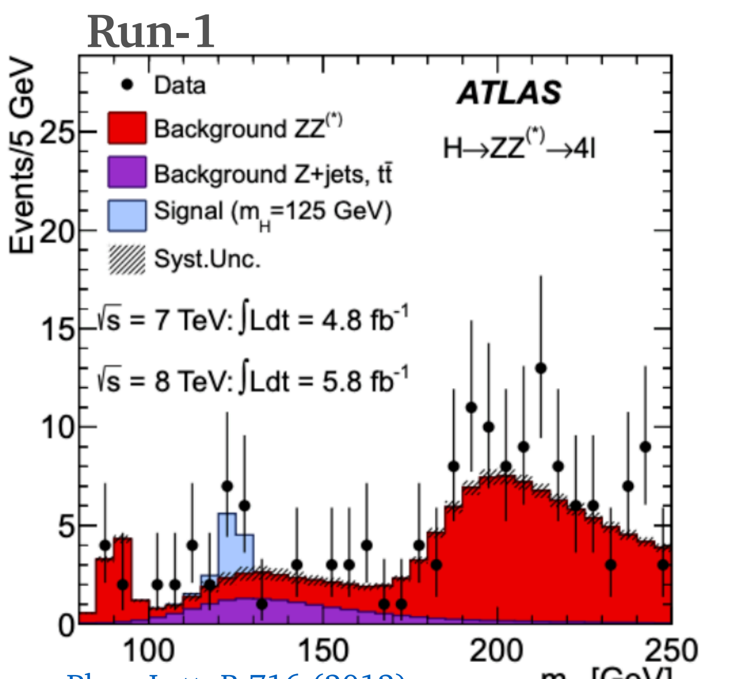

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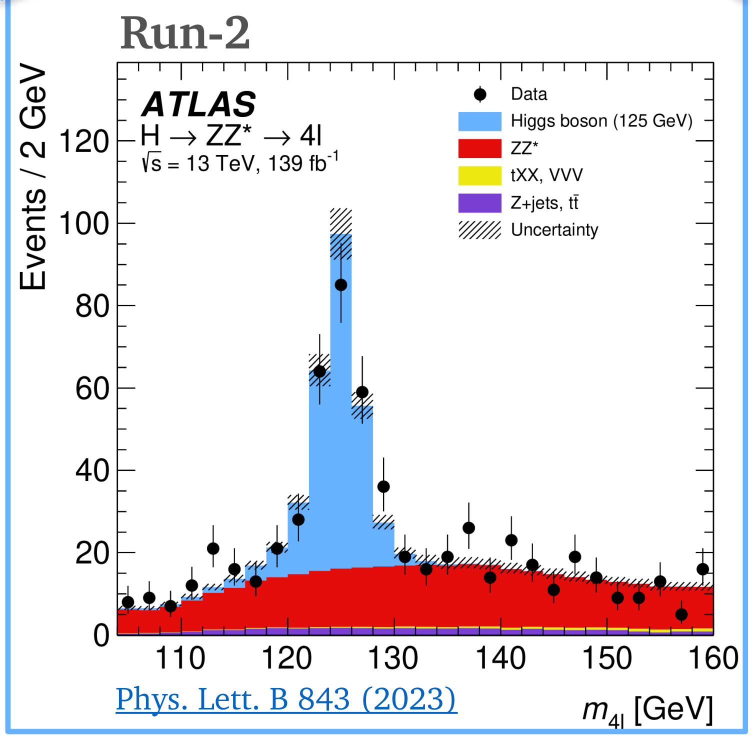


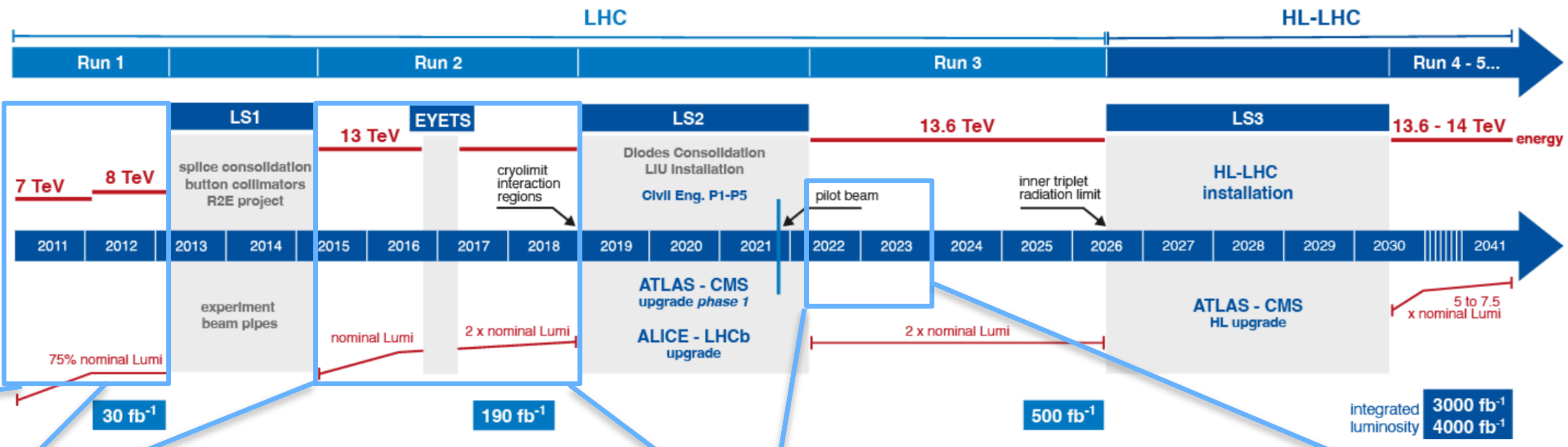
Phys. Lett. B 843 (2023)

Many channel published re-analysis with improved technique and strategy using the same Run-2 dataset

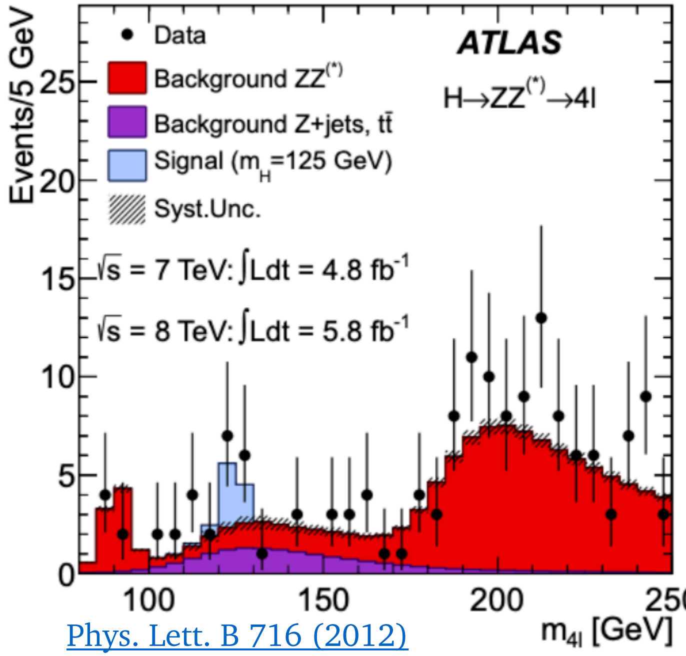
Higgs measurements - past, present and future

[High Lumi LHC Project]

- During Run-2, expected amount of Higgs boson events is ~30 times larger than at the time of its discovery
- Partial Run-3 analysis are reported



Run-1



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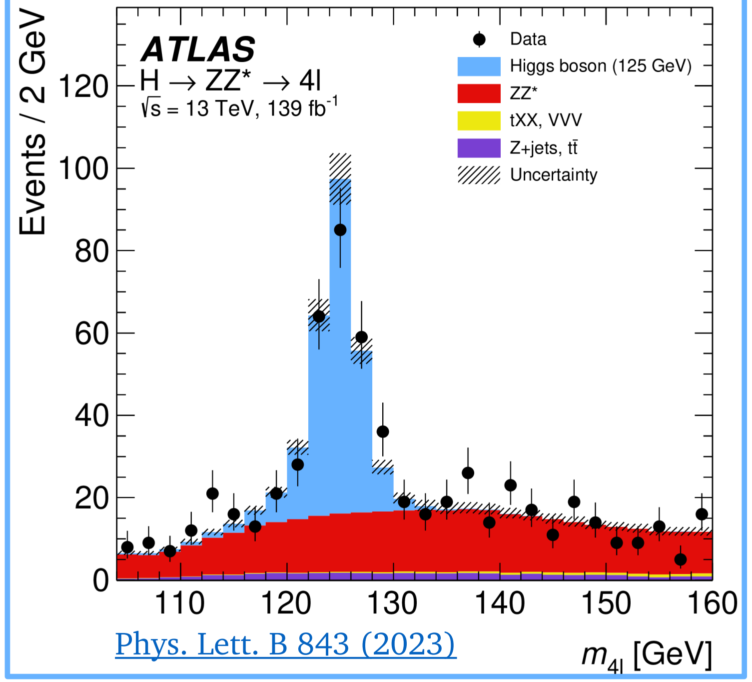
Run-2



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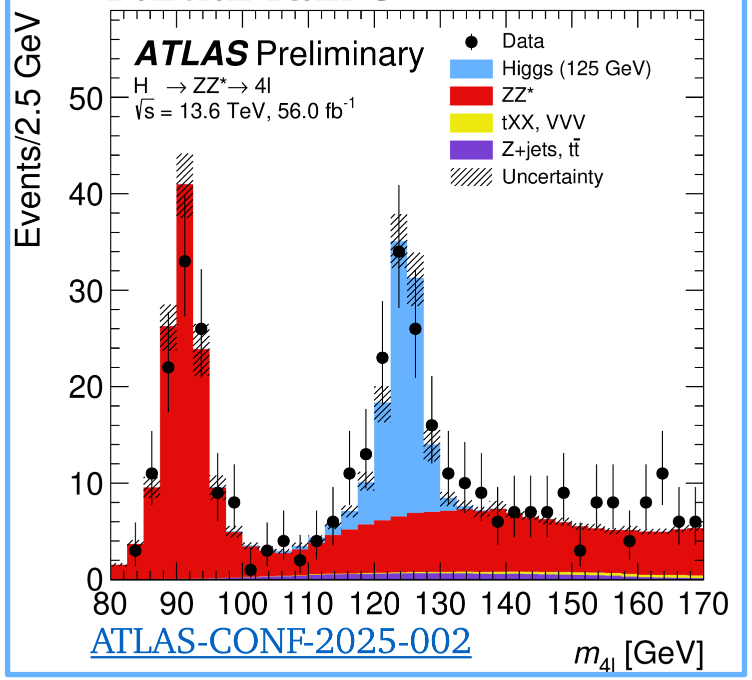
Partial Run-3

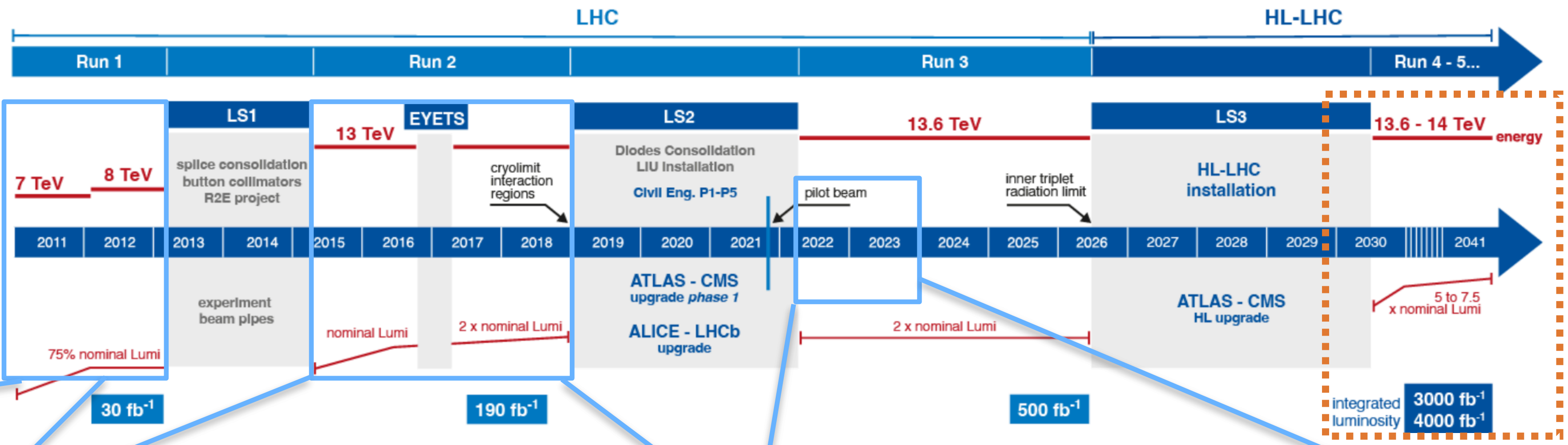


ATLAS-CONF-2025-002

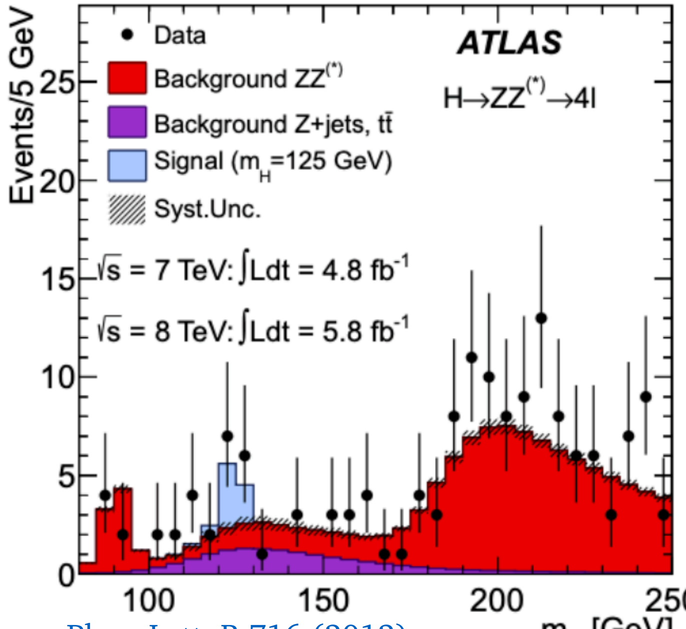
Higgs measurements - past, present and future

[High Lumi LHC Project]

- During Run-2, expected amount of Higgs boson events is ~30 times larger than at the time of its discovery
- Partial Run-3 analysis are reported
- HL-LHC increment the data statistics by 10 folds

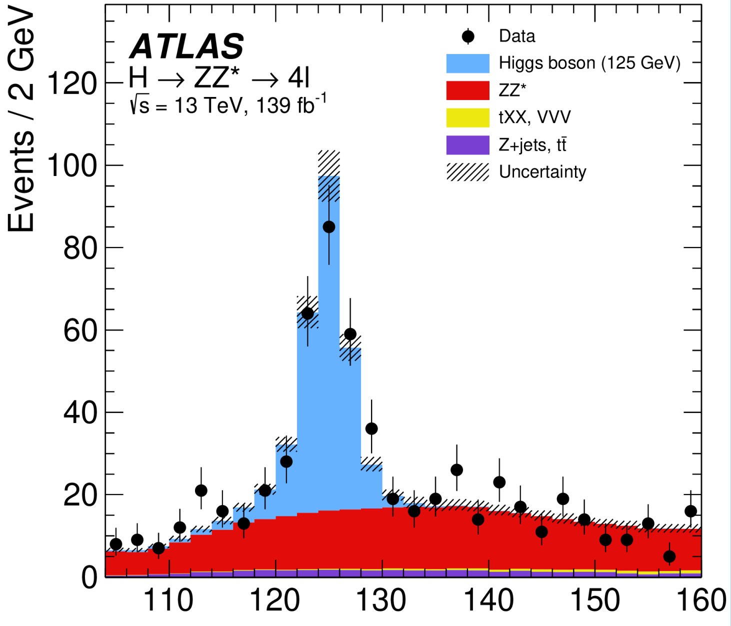


Run-1



Phys. Lett. B 716 (2012)

Run-2



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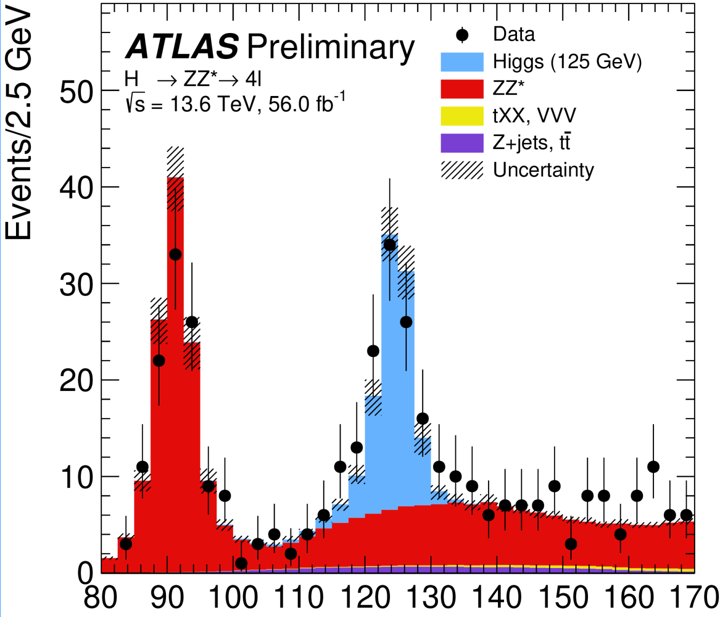
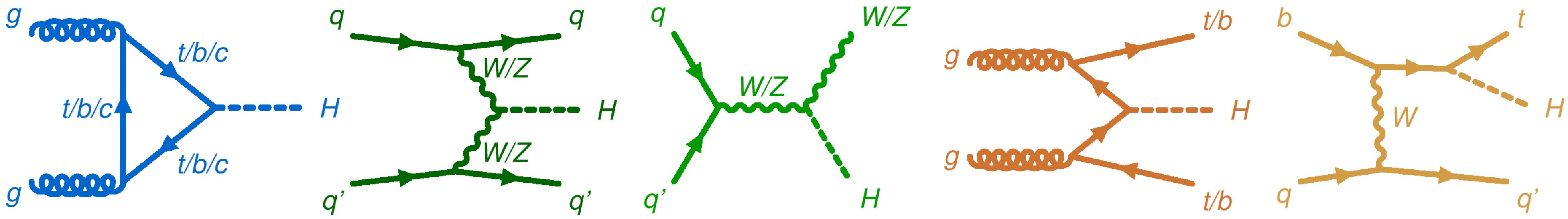
Partial Run-3



ATLAS-CONF-2025-002

- Experimental data further verified this 125 GeV particle follows the predicted production and decay mechanism



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

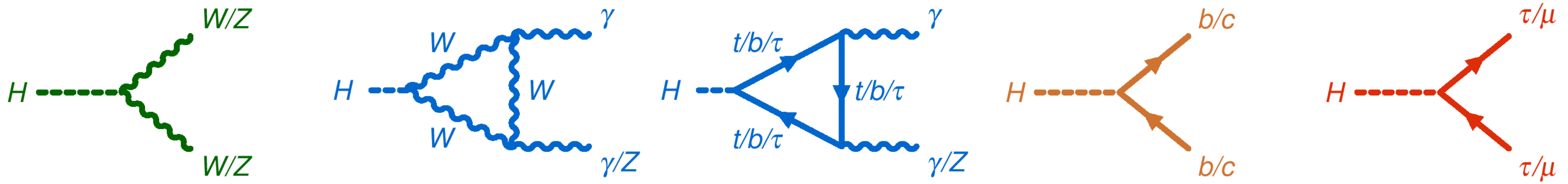
gluon-gluon fusion (ggF): 87%

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:

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

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

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

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

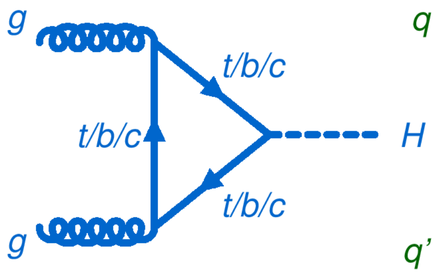
This talk has particular focus to H-V coupling vertices

Higgs boson production and decay modes

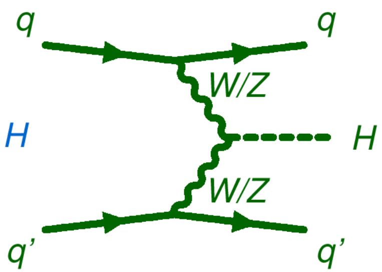
[Nature 607 (2022)]

- Experimental data further verified this 125 GeV particle follows the predicted production and decay mechanism

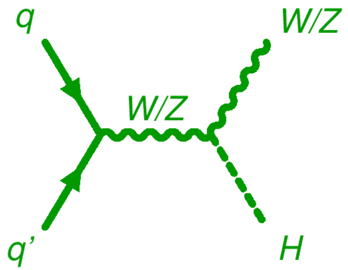
Dominant production modes (at *13 TeV* center-of-mass energy):



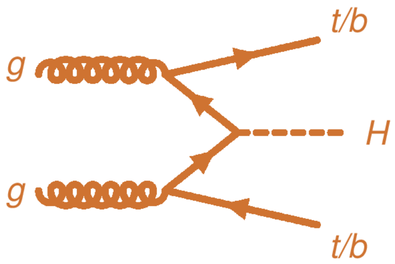
gluon-gluon fusion (ggF): 87%



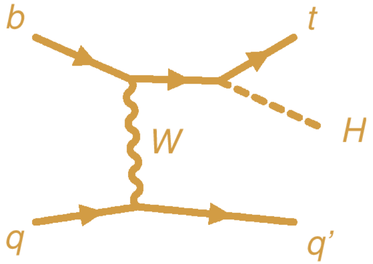
vector boson fusion (VBF): 7%



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

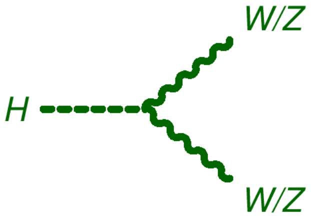


in-association with t/b-quark pair ($t\bar{t}H/b\bar{b}H$): 1%

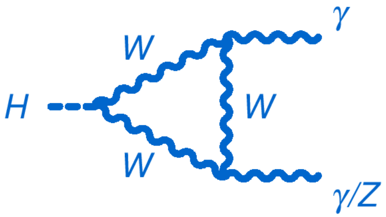


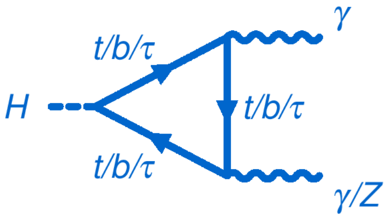
in-association with single top (tH): 0.05%

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

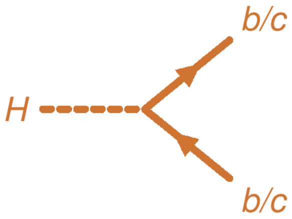


$H \to WW$: 22%
$H \to ZZ$: 3%

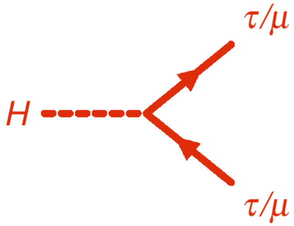




$H \to \gamma\gamma$: 0.2%
$H \to Z\gamma$: 0.2%



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



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

This talk has particular focus to H-V coupling vertices

Single-Higgs combined measurement

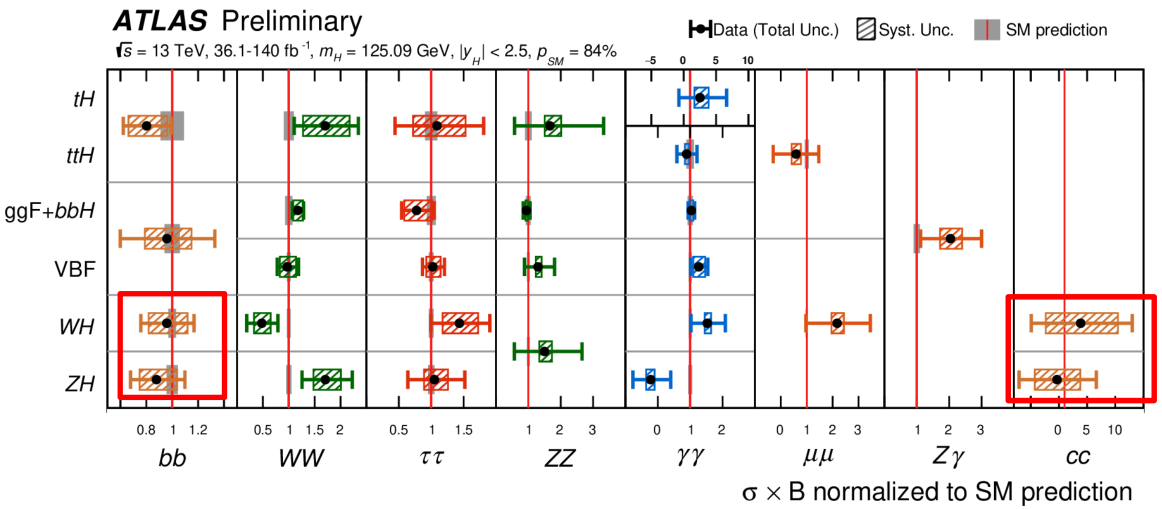
[ATLAS-CONF-2025-006]

- 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

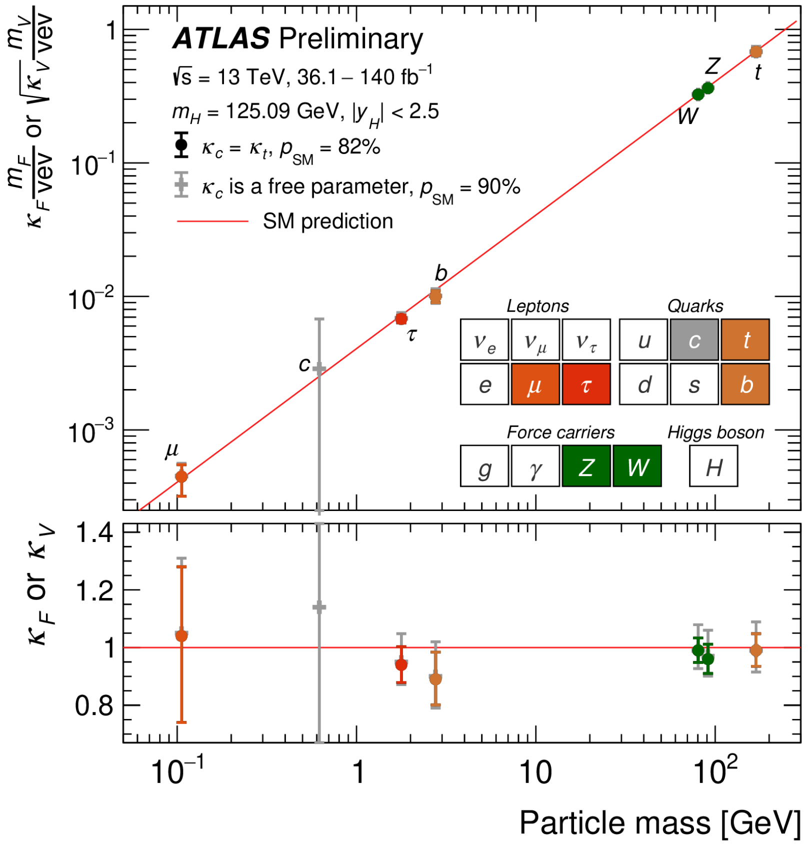
The κ-framework

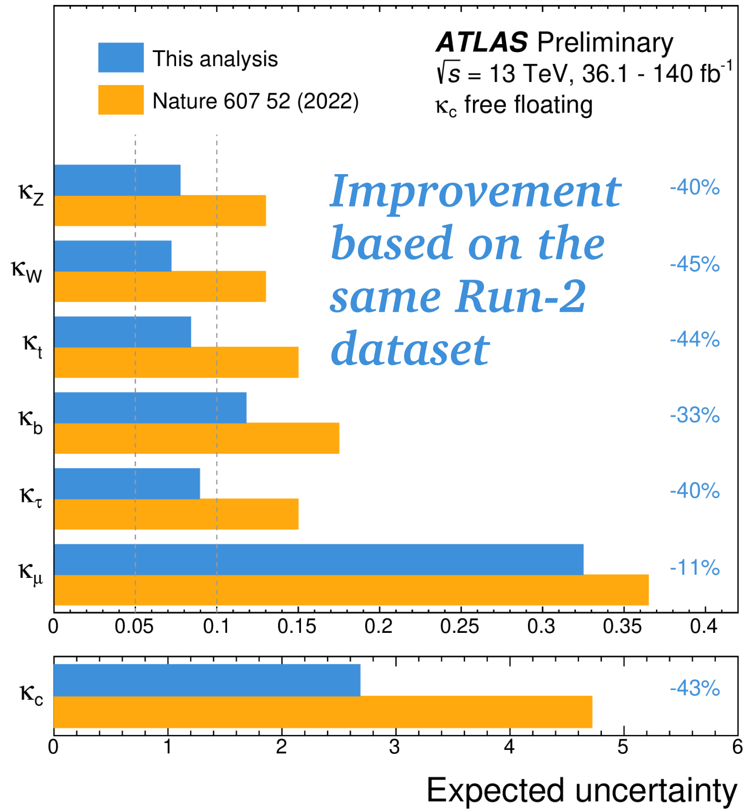
[ATLAS-CONF-2025-006]

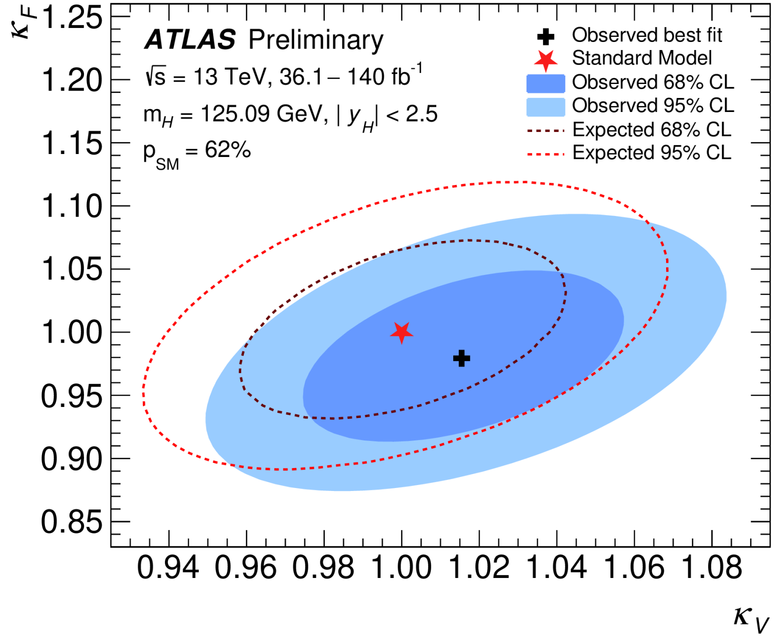
- The **κ-framework** introduces coupling modifiers for the Higgs coupling with the fermions (κ_f) and bosons (κ_V)

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

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



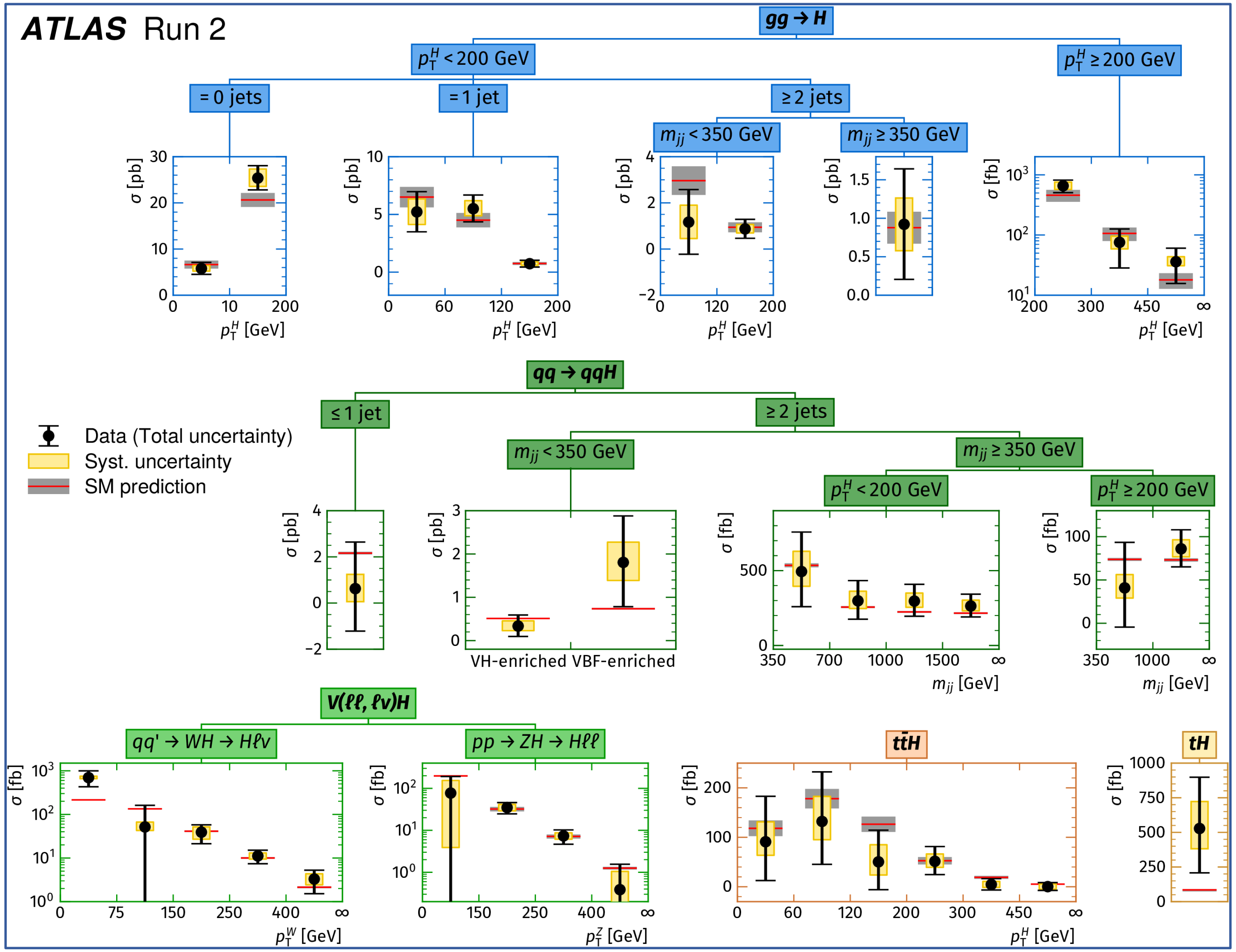


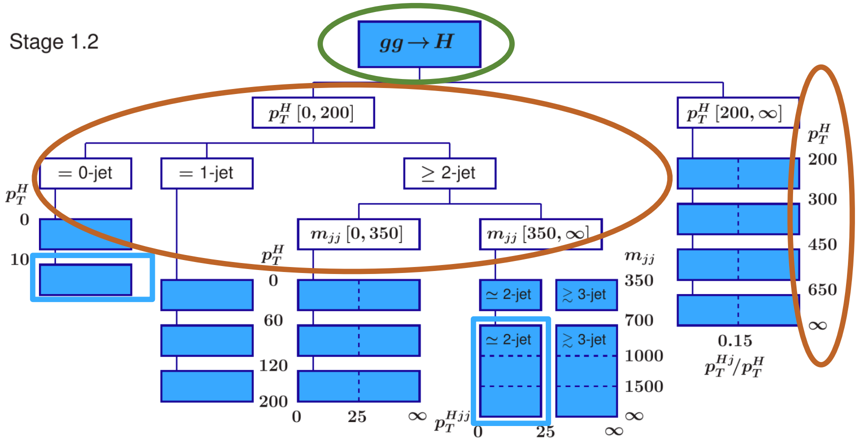


Simplified Template Cross Sections (STXS)

[Nature 607 (2022)]

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



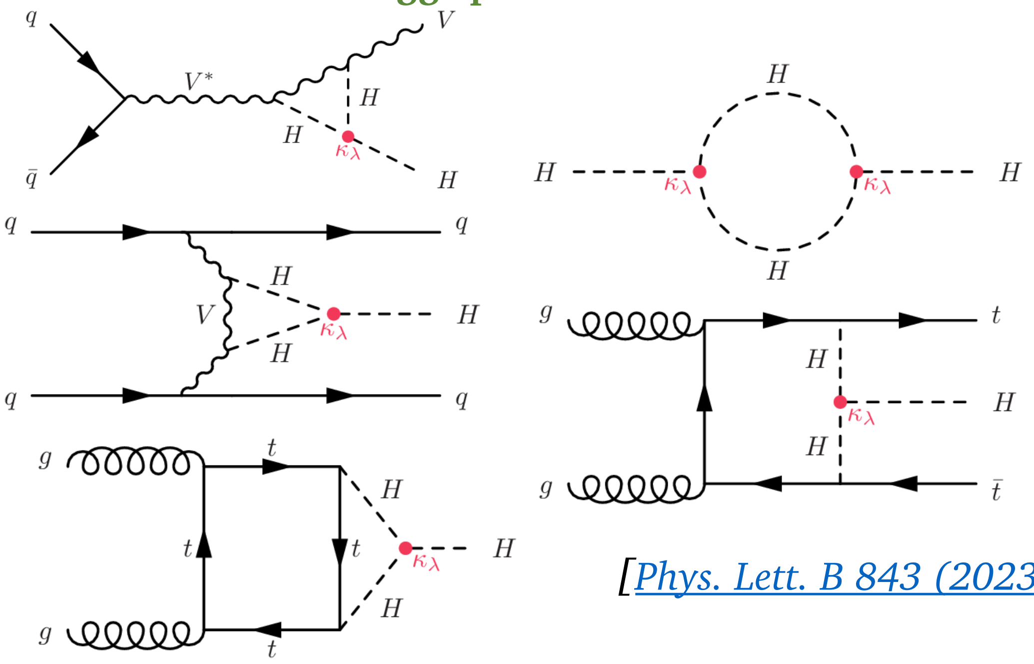


- The STXS binning minimize measurement dependency on theory predictions
- STXS also maximize BSM sensitivity
- Run2 measurements are designed around Stage1.2 of the STXS
- Run3 with planned Stage1.3 and HL-LHC with Stage2.0

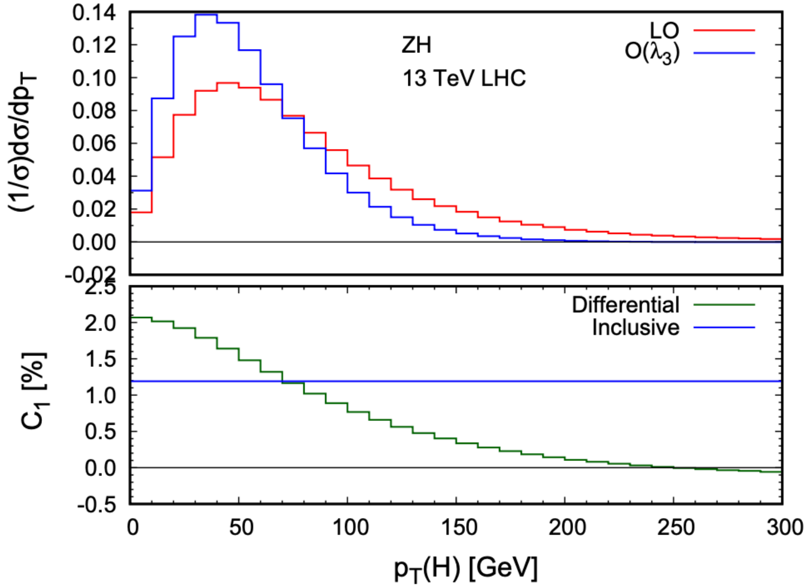
Single-Higgs helping to constrain Higgs self-coupling

- 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)

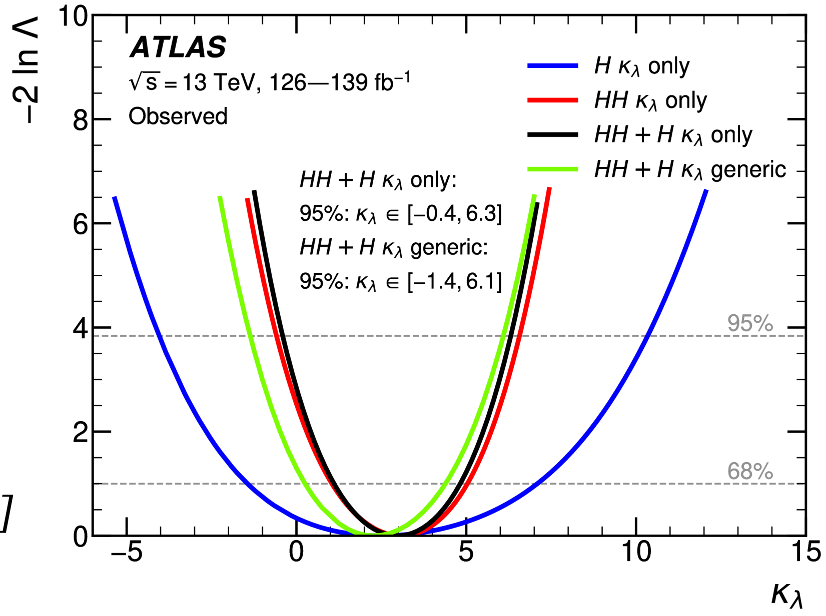
One-loop κ_λ dependent diagrams of single-Higgs production



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

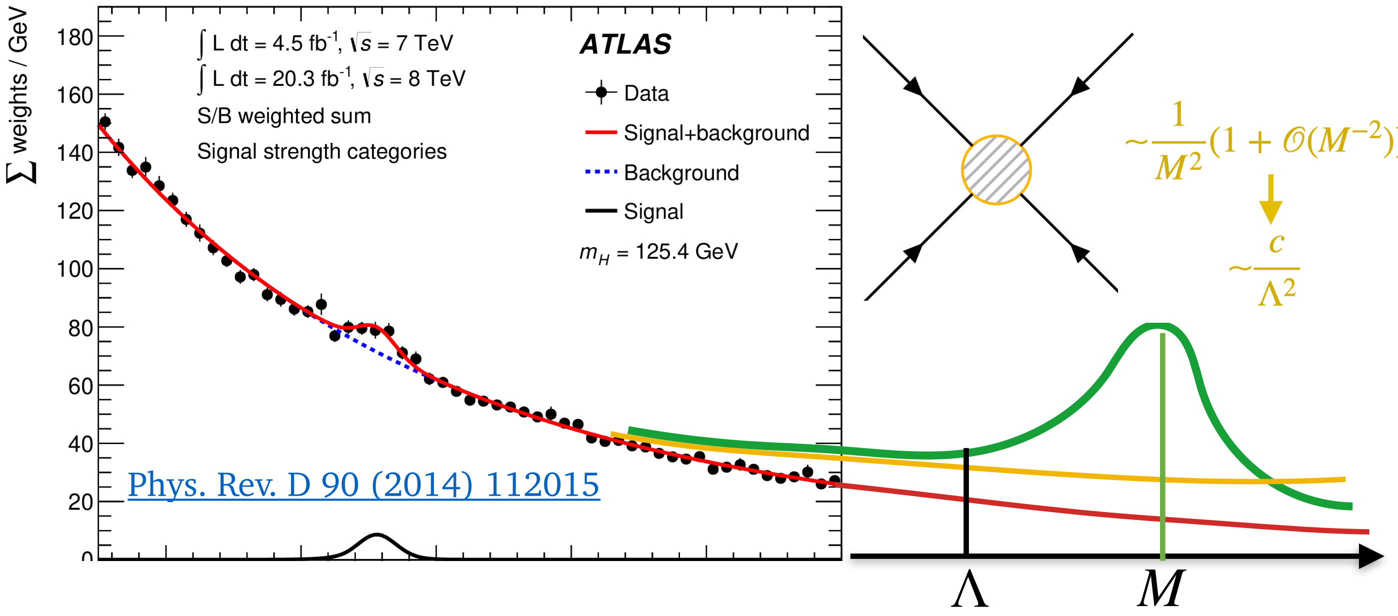


[Eur. Phys. J. C 77, 887 (2017)]

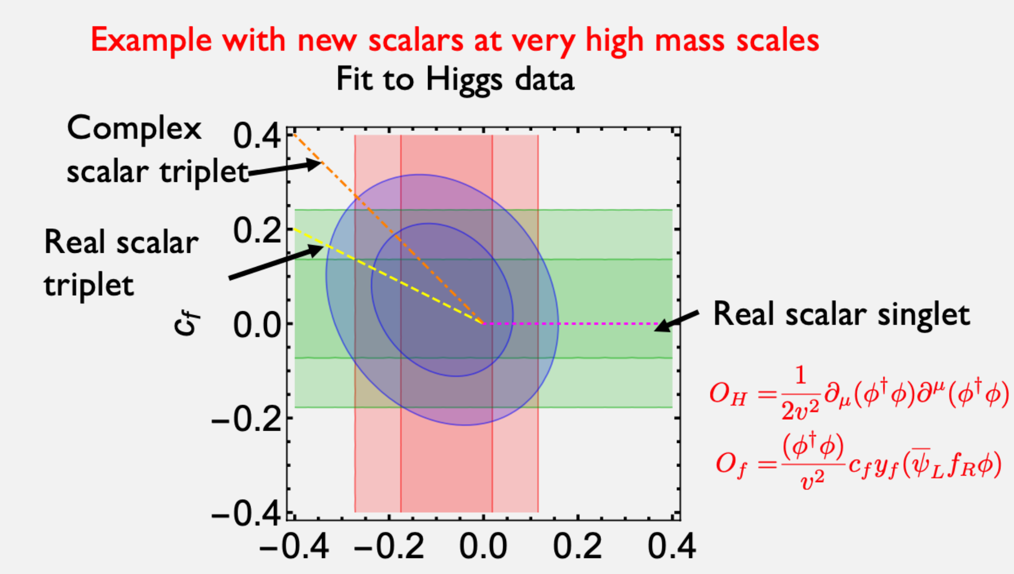


Effective Field Theory framework

- 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; equivalently describes the phenomena below cut-off scale Λ
- Precision measurement of the Higgs helps to narrow the window of new physics (constrain the Wilson coefficients c)
- One can "translate" EFT constraint to specific new physics model



Phys. Rev. D 90 (2014) 112015



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

Standard Model EFT framework

- Expand SM Lagrangian with higher dimensional operators (assuming conservation laws, such as baryon/lepton number) using SM gauge fields - SM-EFT framework

Dimensional-6 operators

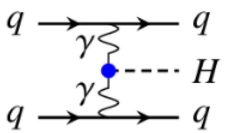
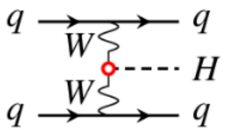
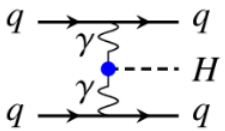
$$|\mathcal{M}_{\text{SMEFT}}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2\sum_i \frac{c_i}{\Lambda^2} Re(\mathcal{M}^*_{\text{SM}}\mathcal{M}_i) + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} Re(\mathcal{M}^*_i \mathcal{M}_j)$$

SM contribution

Interference between SM and EFT operators (linear)

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

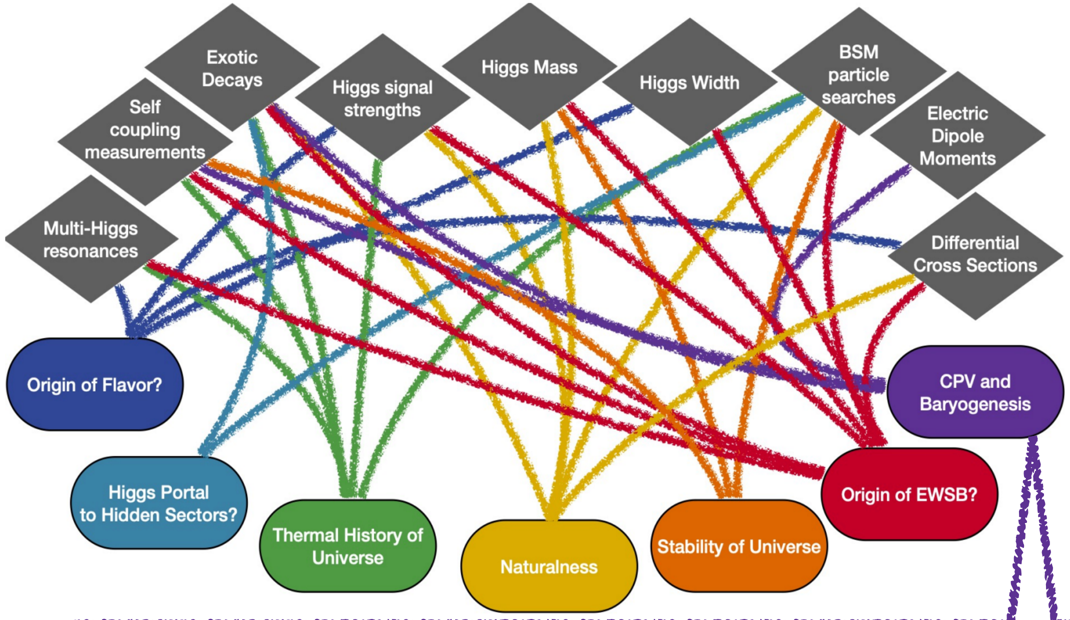
- Anomalous (CP-conserving) couplings of the *H-V* vertices in the Warsaw basis:

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

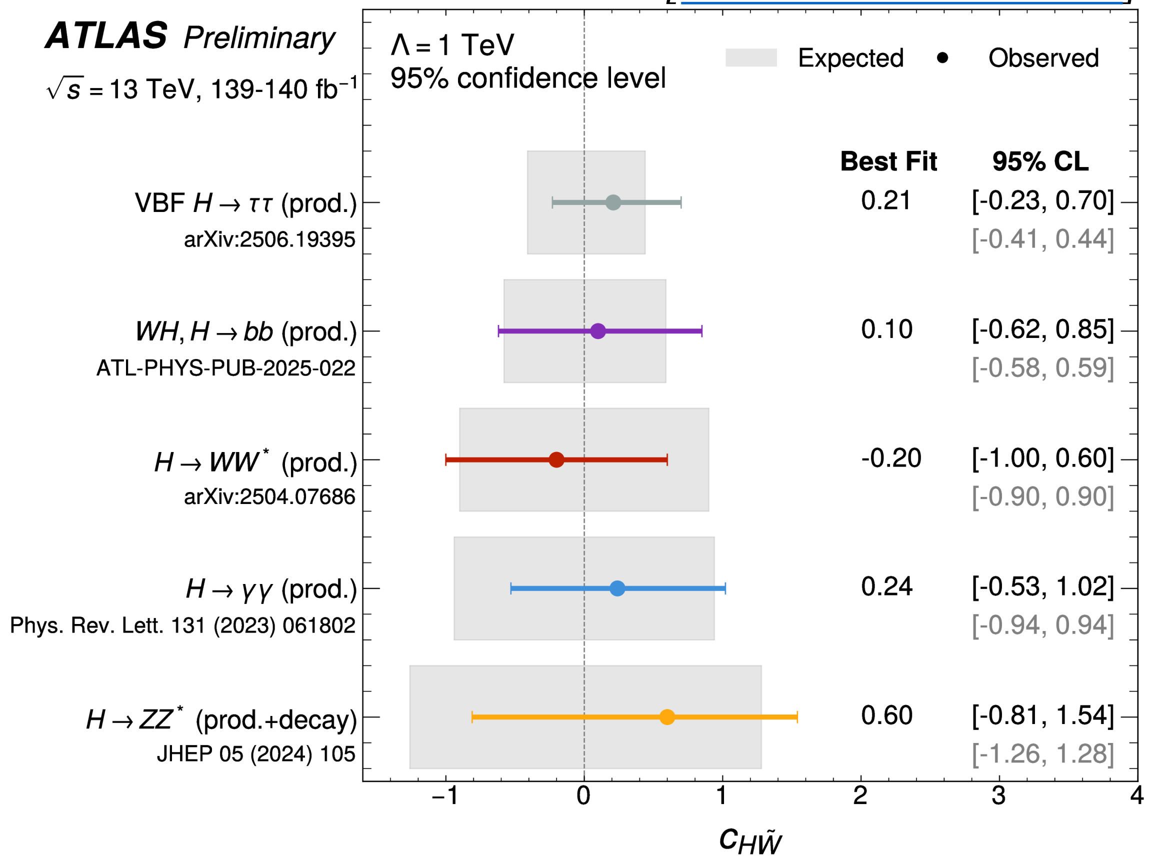
Zoom in on the Higgs charge-parity property



- Key ingredient to forbid same amount of anti-matter at early Universe by breaking **charge-parity (CP)** symmetry.
- But CP-violating component in the SM is too small (via CKM mixing matrix for the three generations of quarks).
- **Higgs CP-violating coupling is considered Beyond Standard Model.**

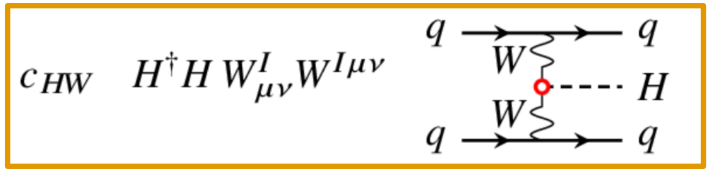
- CP property studied in 5 different decay channels using the Run-2 ATLAS dataset under the SMEFT framework
- This talk will highlight techniques for $H \rightarrow WW^*$, WH $H \rightarrow bb$, and $H \rightarrow ZZ^*$

[ATL-PHYS-PUB-2025-031]

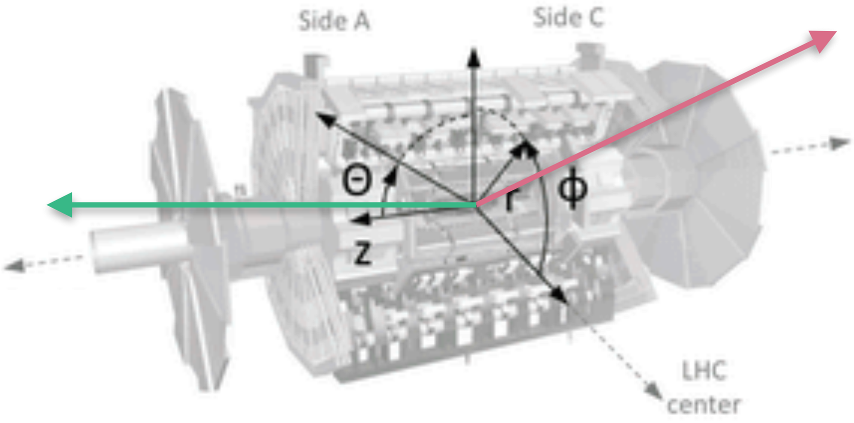


Signed $\Delta\phi_{jj}$ as the CP-sensitive observable

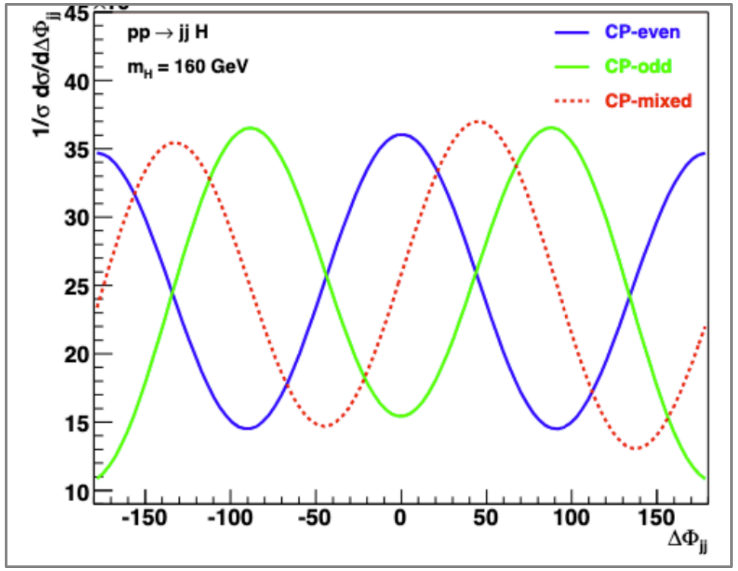
- Wilson coefficient that characterize the CP coupling of the *H-W* vertex
  - Warsaw basis CP even: c_{HW}; CP odd: $c_{H\tilde{W}}$



- 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



[hep-ph/0703202]

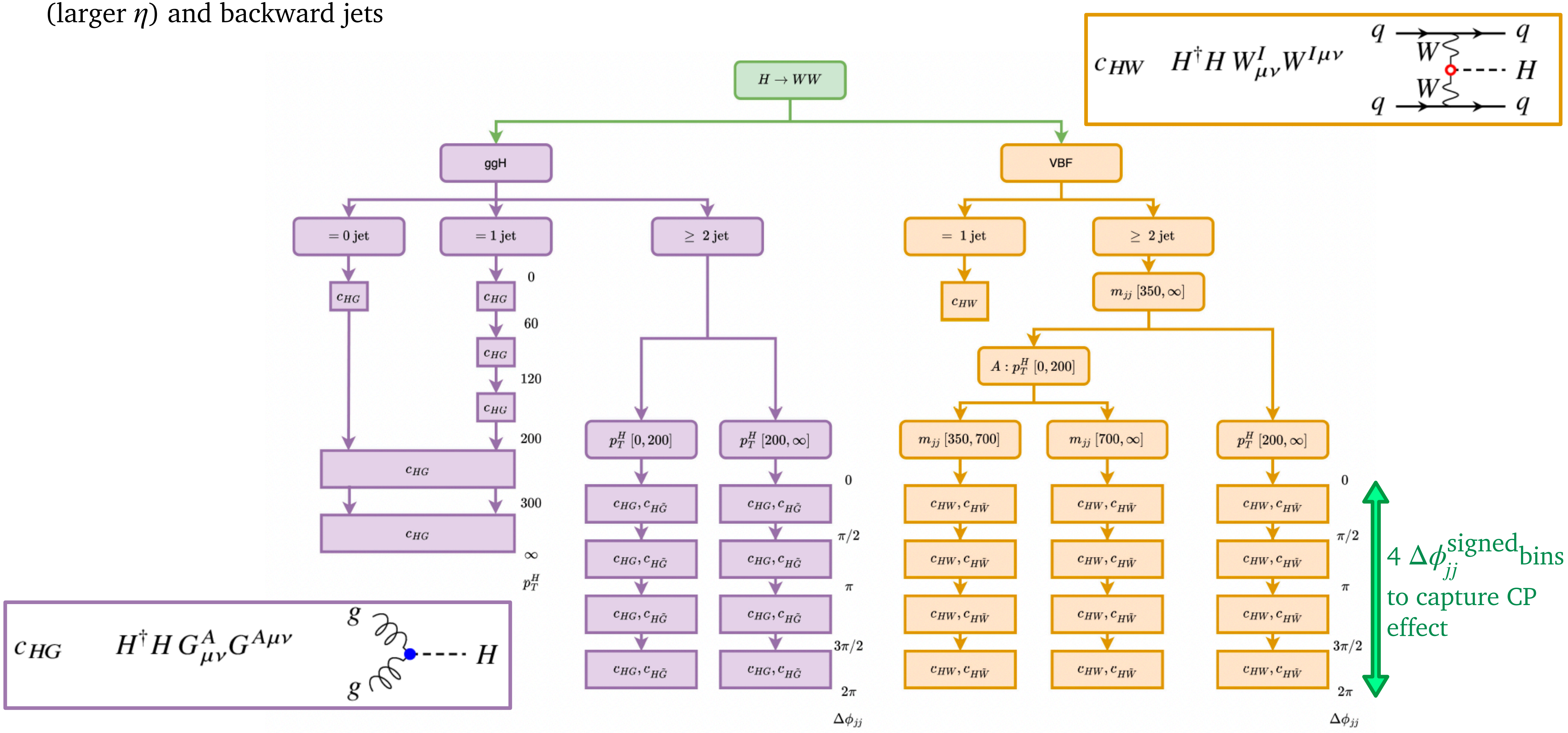


Pure CP-even and CP-odd symmetric about $\Delta\phi_{jj}^{\text{signed}}$=0 with phase shift

CP-mixed asymmetric

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

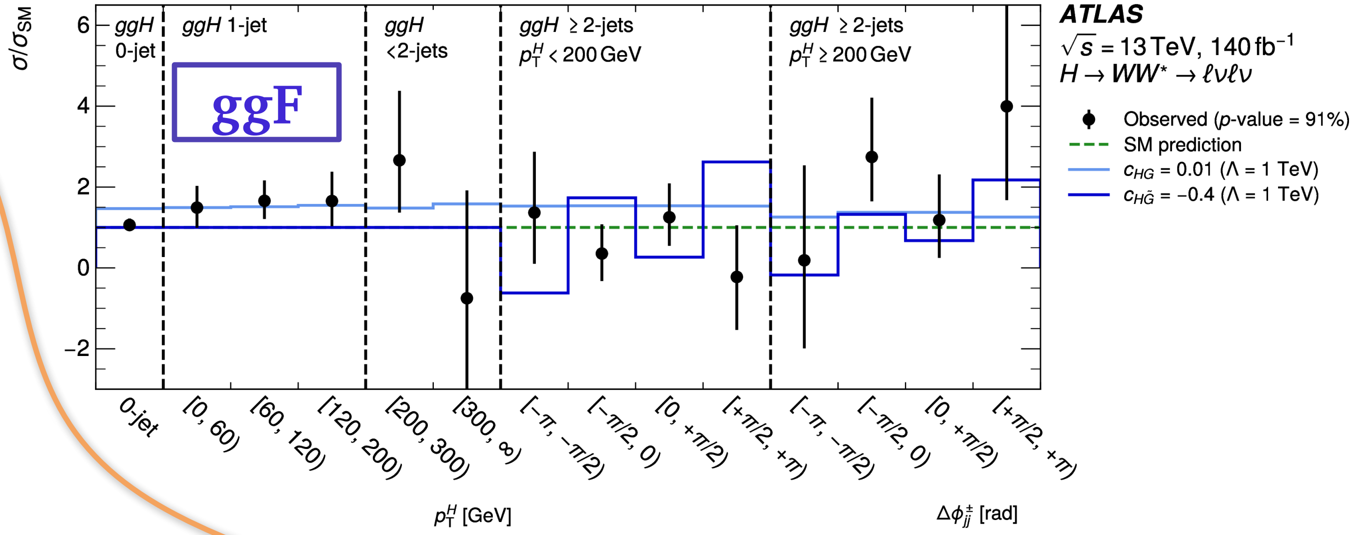
- An alternative STXS scheme is developed to probe the Higgs CP property: p_T^H vs m_{jj} vs $\Delta\phi_{jj}^{\text{signed}}$
  - $\Delta\phi_{jj}^{\text{signed}}$ is a charge-parity (CP) sensitive observable, which is defined as azimuthal angle difference between the forward (larger η) and backward jets

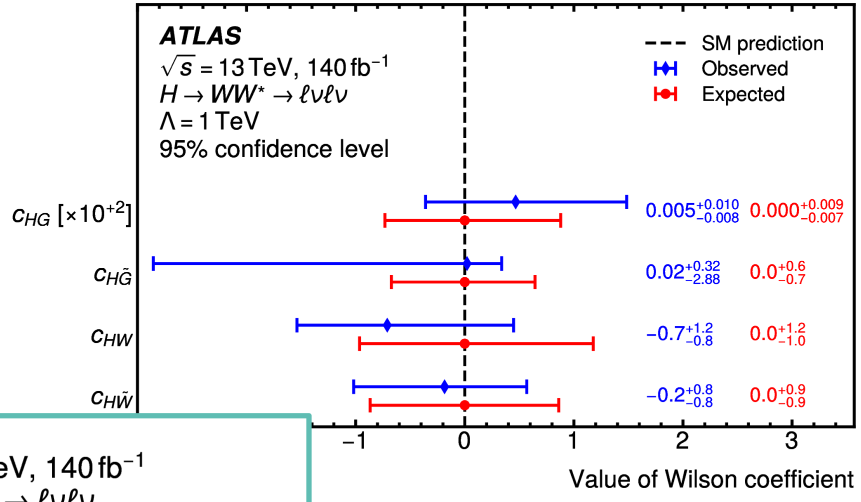


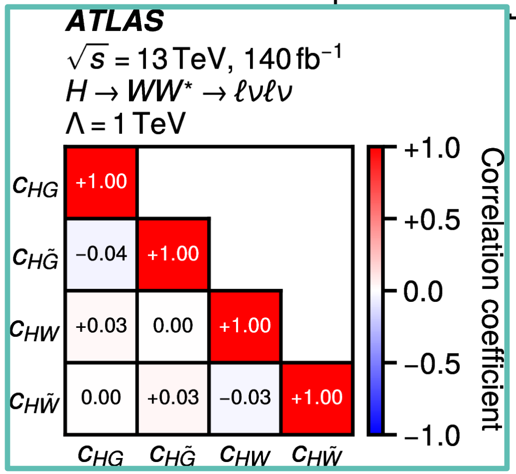
CPV strategy in the ggF+VBF $H \to WW^* \to l\nu l\nu$ channel

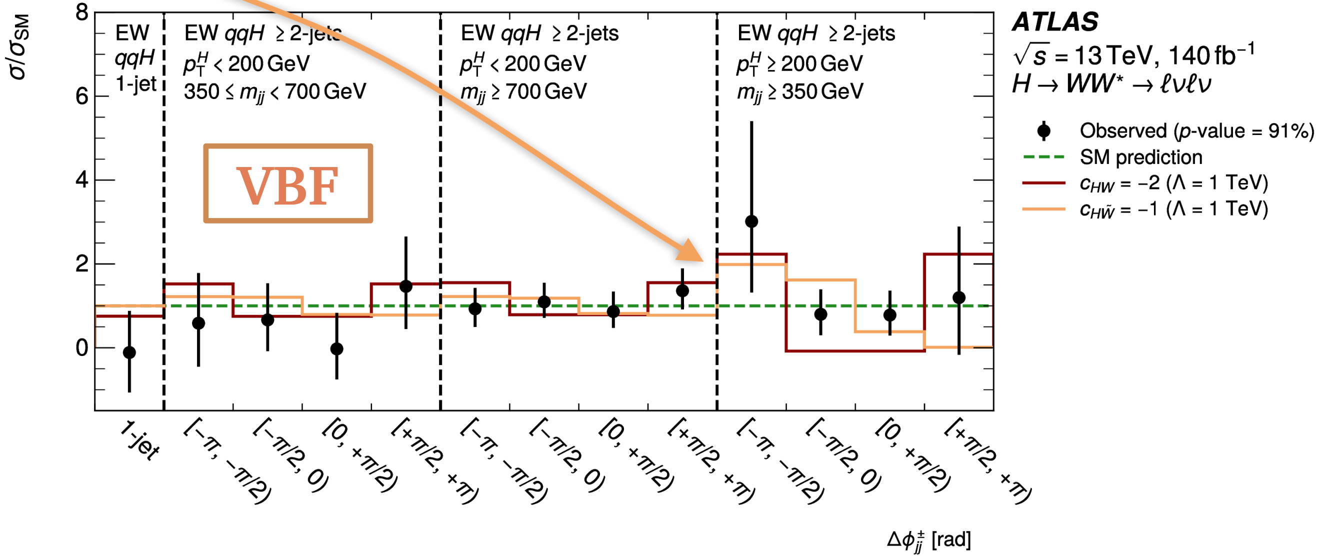
[Phys. Rev. D 108 (2023) 072003]

- Multi-dimensional differential **improved** $c_{H\tilde{W}}$ **limits by >50%** compared to the 1-dimensional $\Delta\phi_{jj}$ sensitivity
- *H-W* CP-odd effect is magnified at high Higgs p_T (>3times larger effect than low Higgs p_T)
- Distinct shapes of EFT impact from the four CP operators make their correlation small





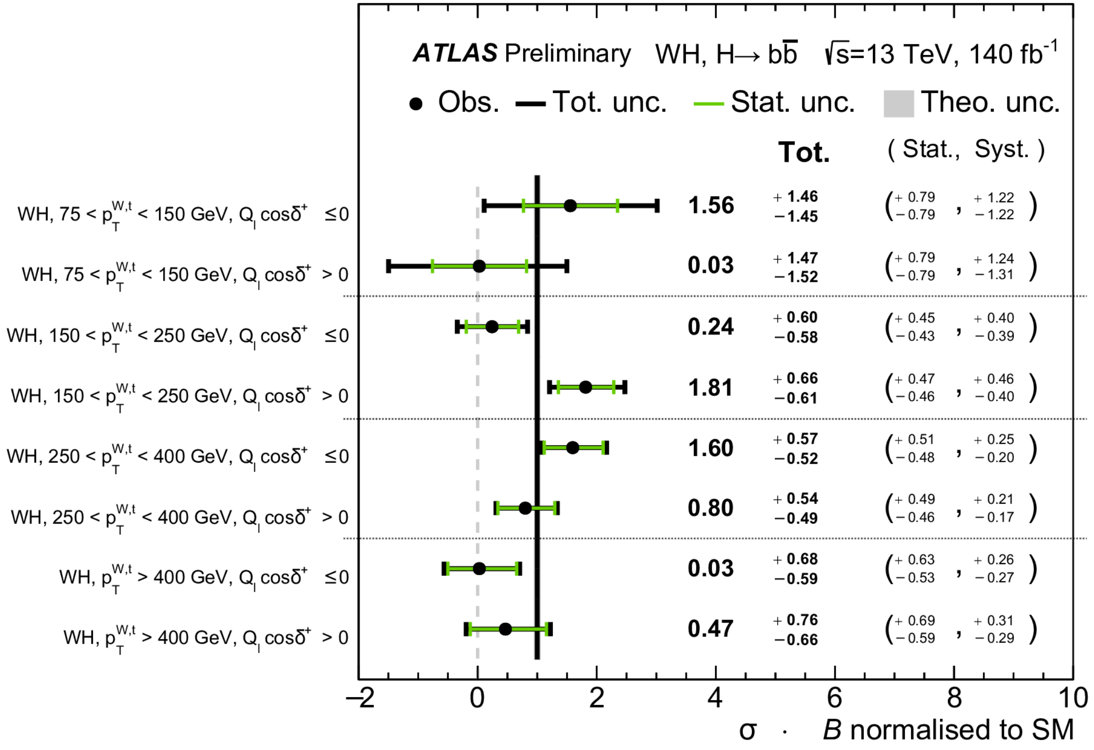


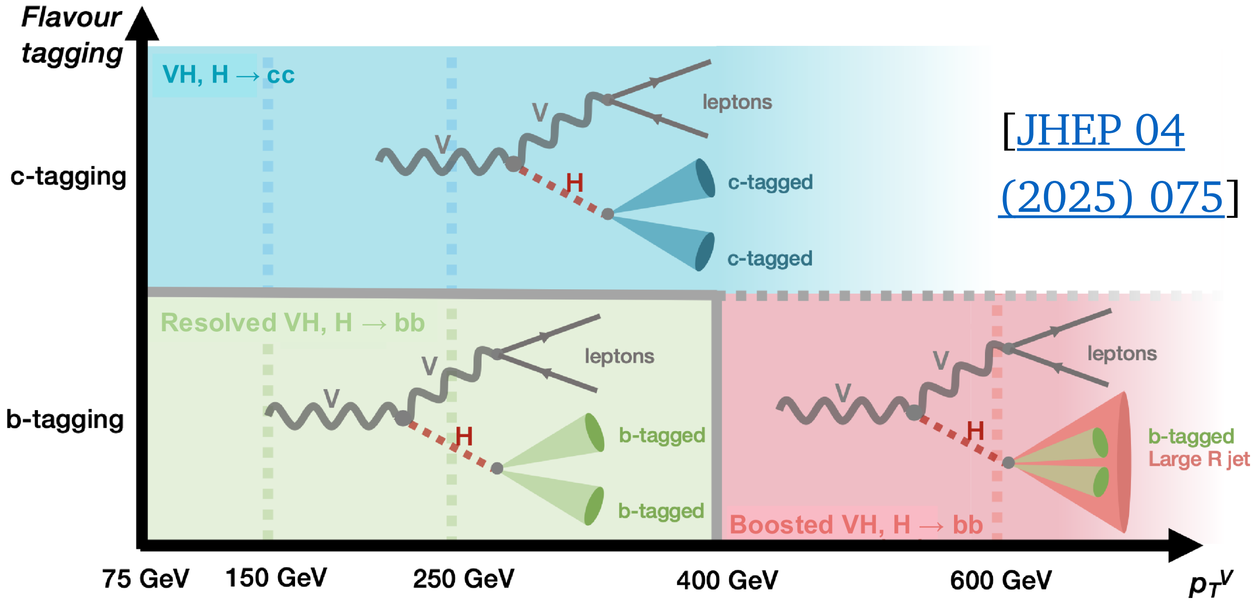


WH $H \rightarrow b\bar{b}$ CP

[ATL-PHYS-PUB-2025-022]

- The object definition and event selection follows the improved VH bb/cc analysis closely
  - Including improved b/c-tagger as well as optimized MVA strategy





[JHEP 04 (2025) 075]

- Similar strategy as HWW: STXS measurement with the addition of CP-sensitive observable:

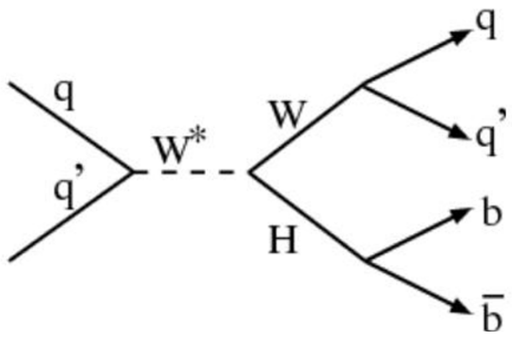
$$Q_\ell \cos\delta^+ = Q_\ell \frac{\overrightarrow{p_\ell}^{(W)} \cdot (\overrightarrow{p_H} \times \overrightarrow{p_W})}{\left|\overrightarrow{p_\ell}^{(W)}\right| \left|\overrightarrow{p_H} \times \overrightarrow{p_W}\right|}$$

- Cross-section measurement compatible with SM prediction

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

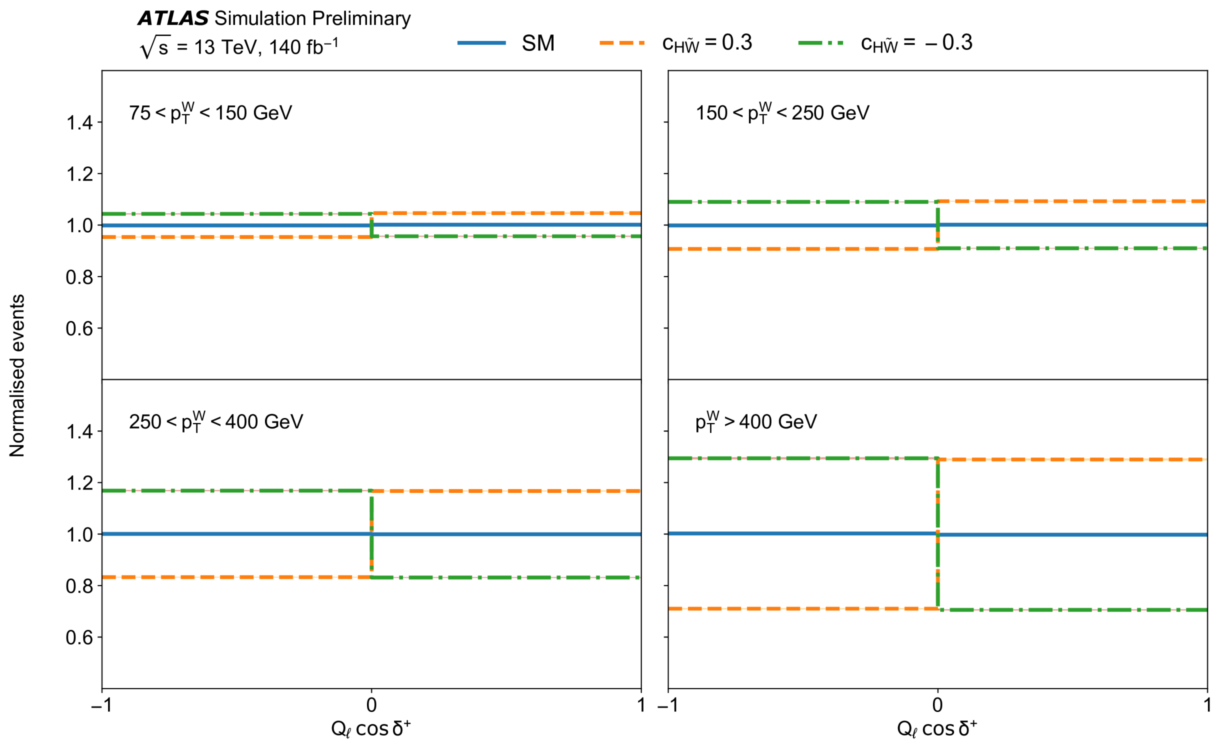
[ATL-PHYS-PUB-2025-022]

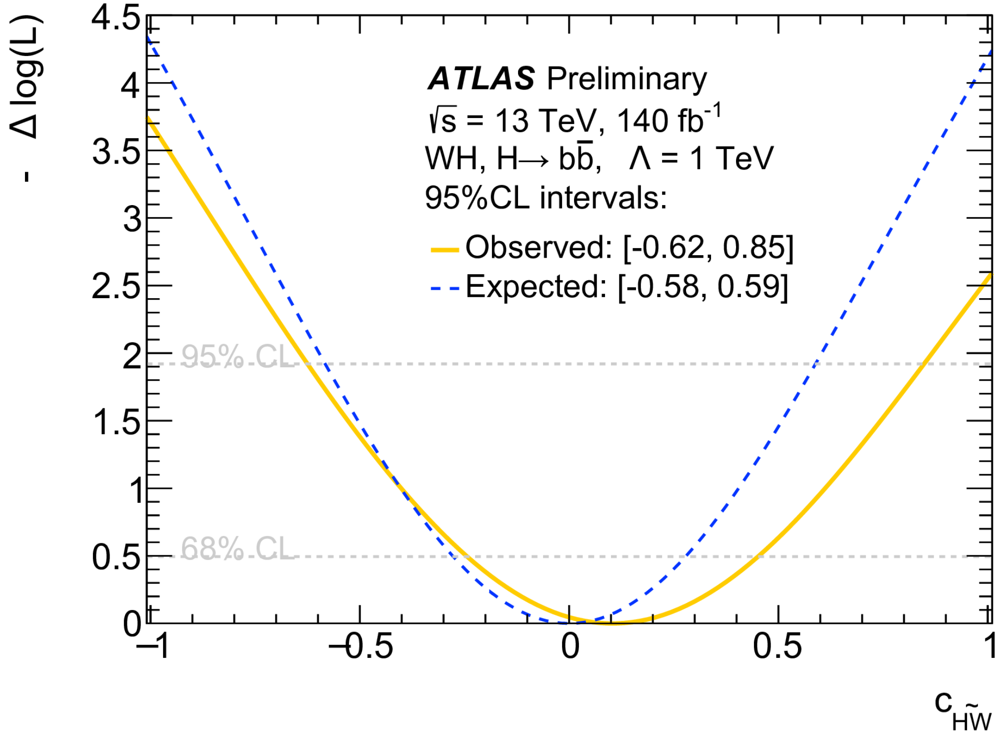
- WH particularly sensitive to $c_{H\tilde{W}}$ as the process is not diluted by ZH



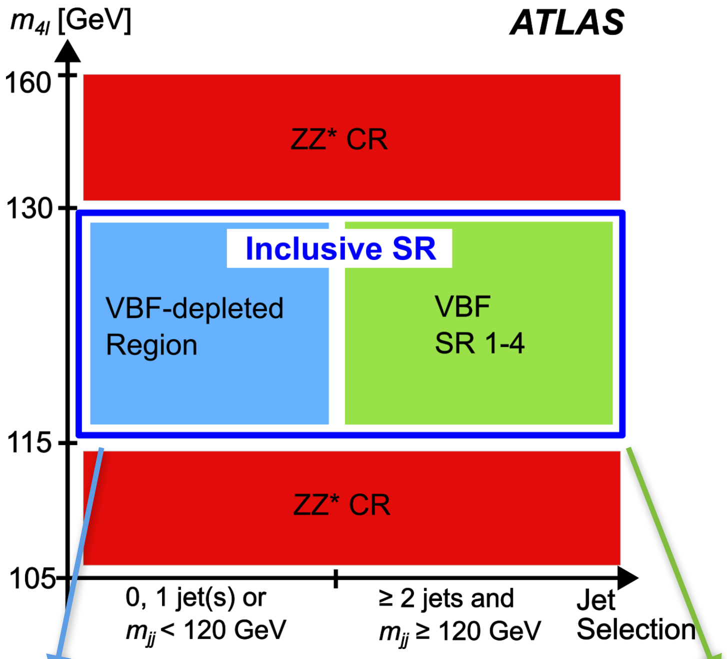
- Only shape of the CP observable is used to constrain $c_{H\tilde{W}}$

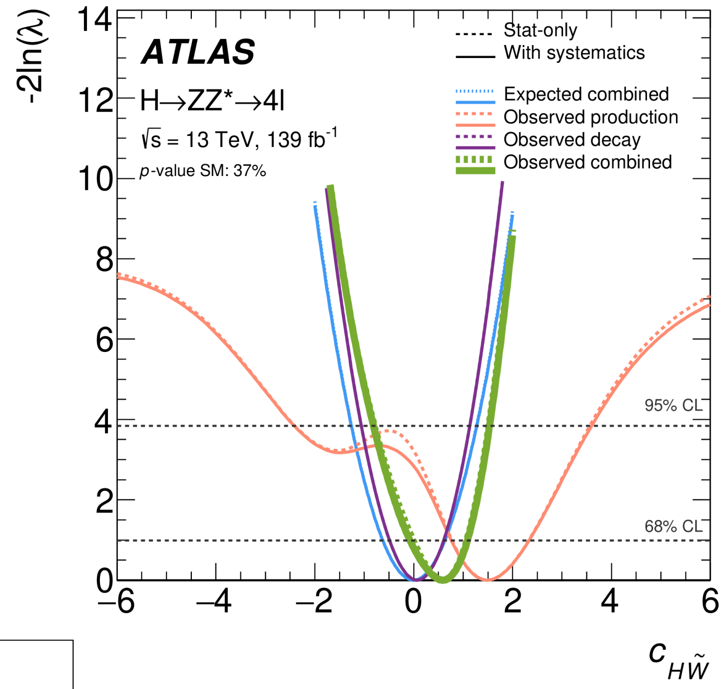
Most stringent limits on $c_{H\tilde{W}}$

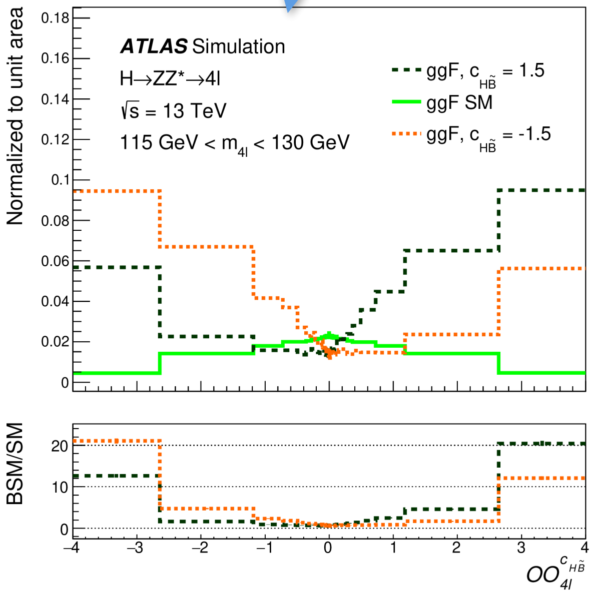


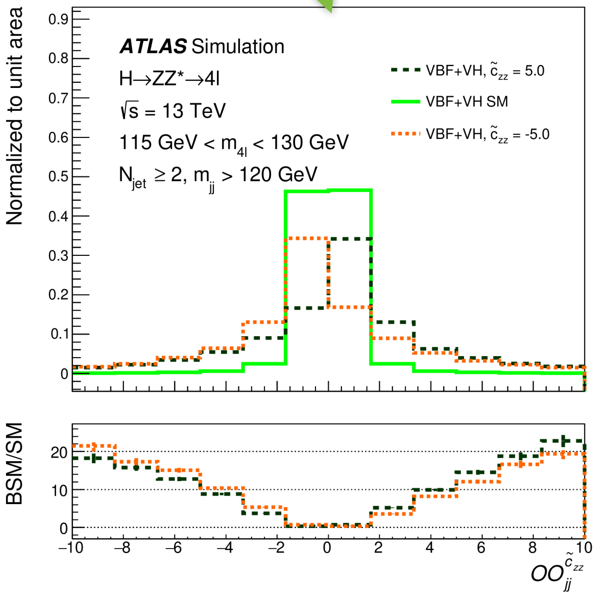


- Use Matrix-Element based optimal observable (*OO*) to compress full event kinematics into statistically optimal quantities
- Use VBF dominant SR measure production *OO* (VBF)
- Use VBF-depleted region to measure decay *OO* ($H \rightarrow ZZ^* \rightarrow 4l$)



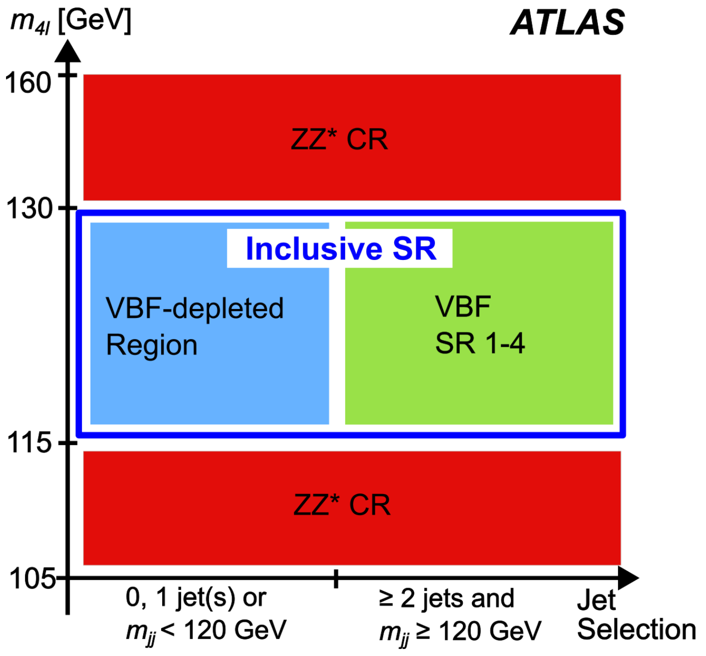


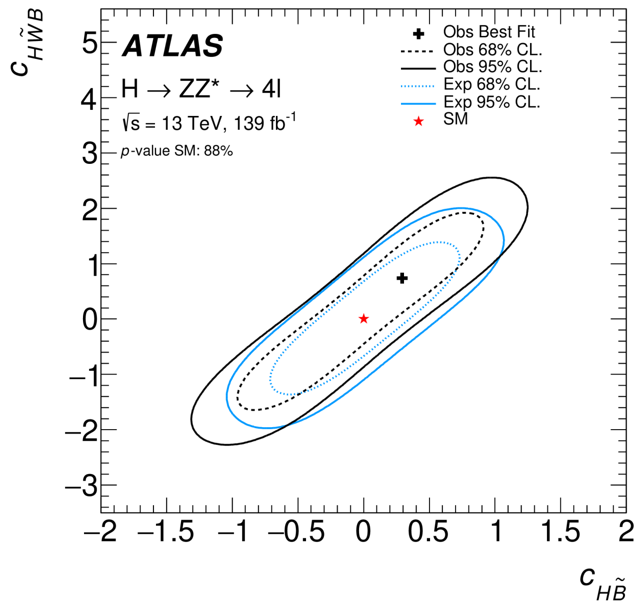




Inclusive $H \to ZZ^*$ CP

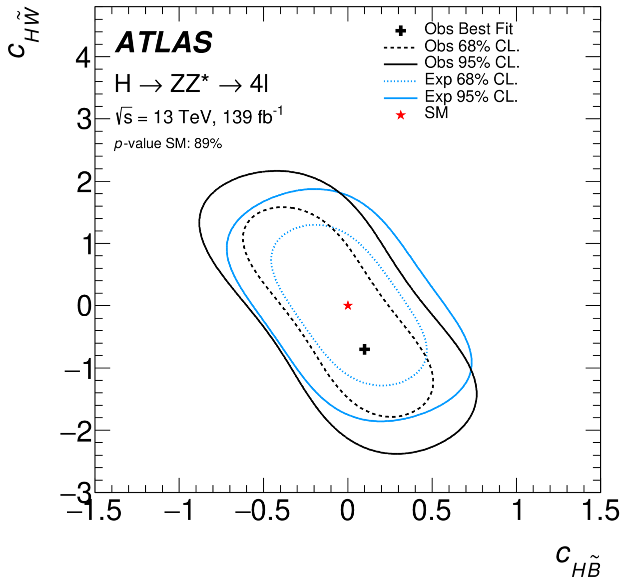
- Use Matrix-Element based optimal observable (OO) to compress full event kinematics into statistically optimal quantities

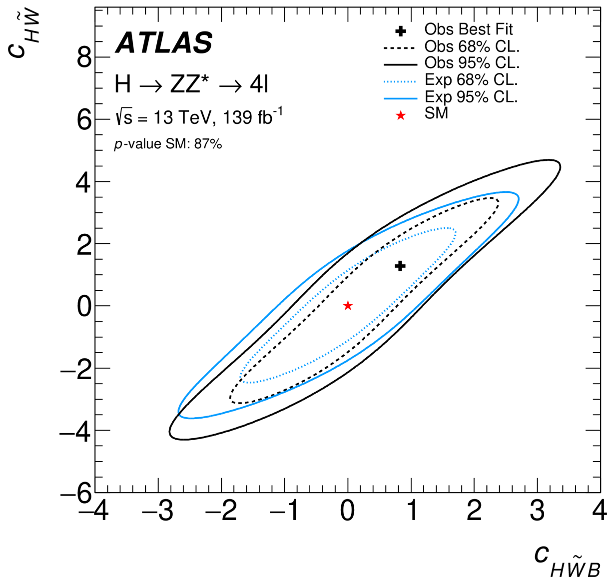




- Use Inclusive region to measure decay OO ($H \to ZZ^* \to 4l$)

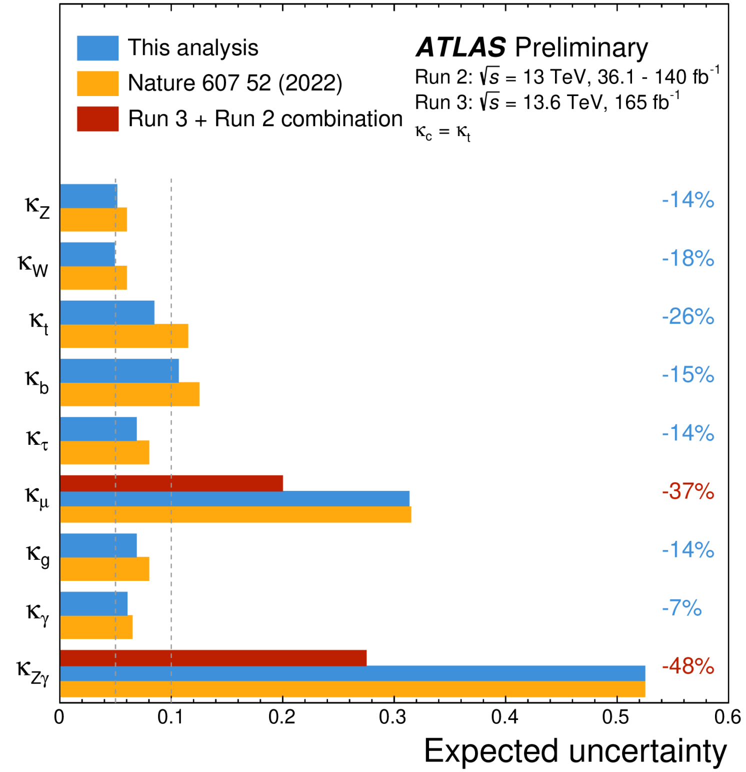
- 2-dimensional OOs for $c_{H\tilde{W}}$ and $c_{H\tilde{B}}$ used to constrain three CP-odd H-V anomalous couplings





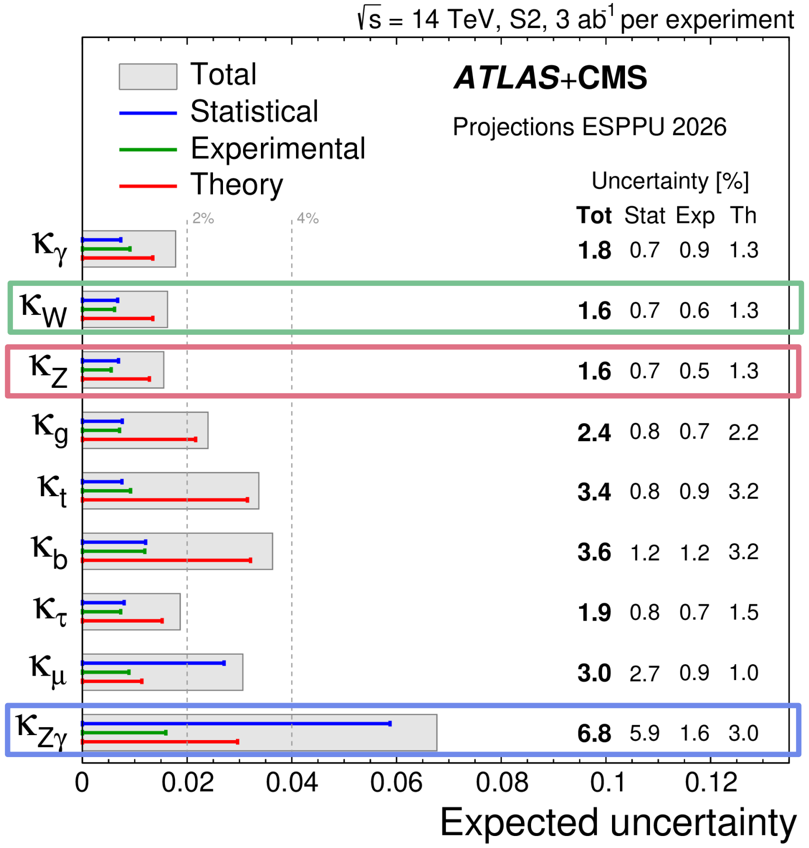
Higgs at High-Luminosity LHC

- **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]

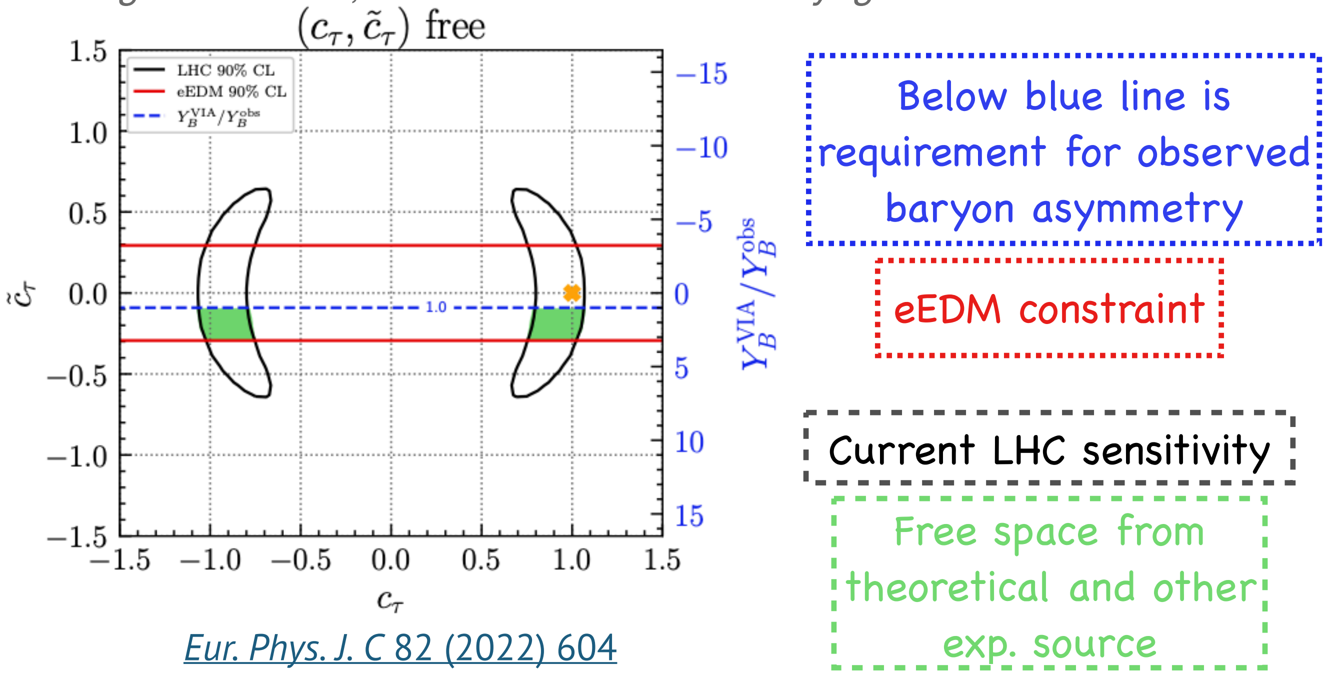


[Europe Strategy 2025]

Summary and outlook on single-Higgs

- Lessons from Run-2 to carry to Run-3 and HL-LHC:
  - Experimental advancement: analysis improvements alone can deliver sensitivity comparable to (very roughly) ~3x more data (such as $H \to b\bar{b}/c\bar{c}$)
  - Higgs self-coupling: Single-Higgs (in particular *VH*) can help to constrain Higgs self-coupling on top of di-Higgs productions
  - Evolution of STXS: constant evolution of STXS staging is needed to improve BSM sensitivity (boosted region, self-coupling) and add CP-sensitive splitting
- Natural future directions include:
  - Combined Run-2 CPV interpretations
  - $Z\gamma$ for a more global constraints on all *H-V* anomalous couplings
  - Dedicated *H-g* and Higgs-lepton CPV analysis and combination
- Final remark: can we map the current *HVV* CP constraints onto specific benchmark scenarios, so we can quantify the physics reach from constraints on EFT Wilson coefficients?

*"Constraining the CP structure of **Higgs-fermion** couplings with a global LHC fit, the electron EDM and baryogenesis"*



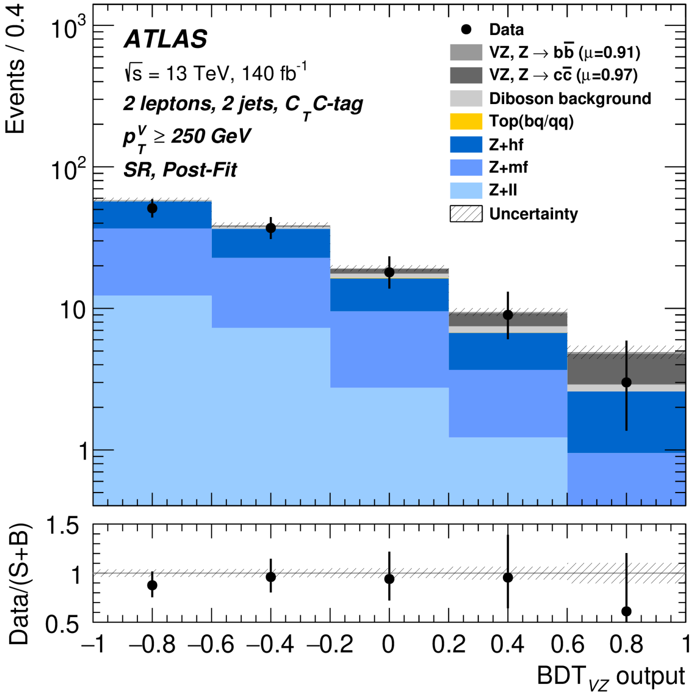
Eur. Phys. J. C 82 (2022) 604

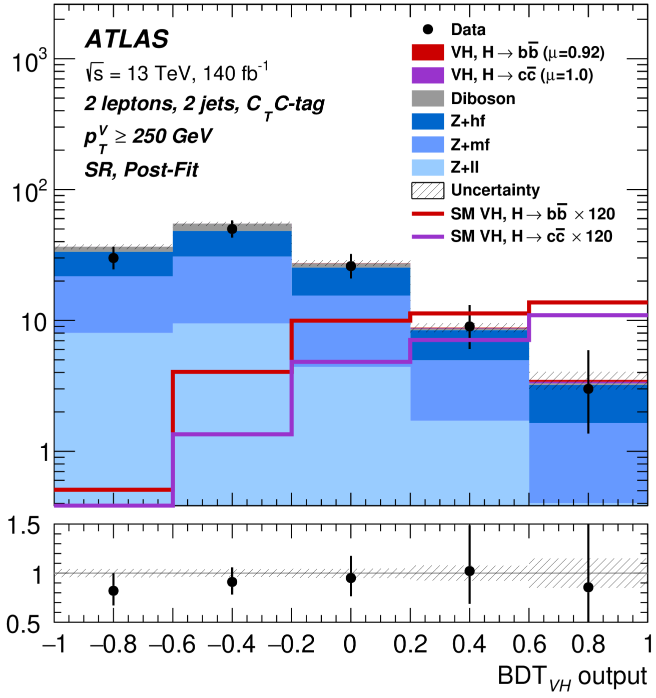
Backup

VH $H \to b\bar{b}/c\bar{c}$ analysis - and VZ $Z \to b\bar{b}/c\bar{c}$

[JHEP 04 (2025) 075]

- Improvement from previous Run-2 analyses:
  - combined resolved and boosted $H \to bb$ as well as $H \to cc$; new flavor tagger; new or re-optimized MVA; better control of the background through updated analysis categorization
- Categorization based on number of leptons, number of b/c-tagged jets, flavor tagging efficiency and p_T^V
- Simultaneous fit from 59 signal regions and 97 control regions
- Analysis strategy verified with $VZ, Z \to bb/cc$ using the same categorization but switch between two BDTs which treat either VH or VZ as the signal against the background processes
  - First observation of $WZ, Z \to bb$ 6.4 (6.5)σ and $VZ, Z \to cc$ 5.2 (5.3)σ





$VZ, Z \to b\bar{b}/c\bar{c}$ signal strength

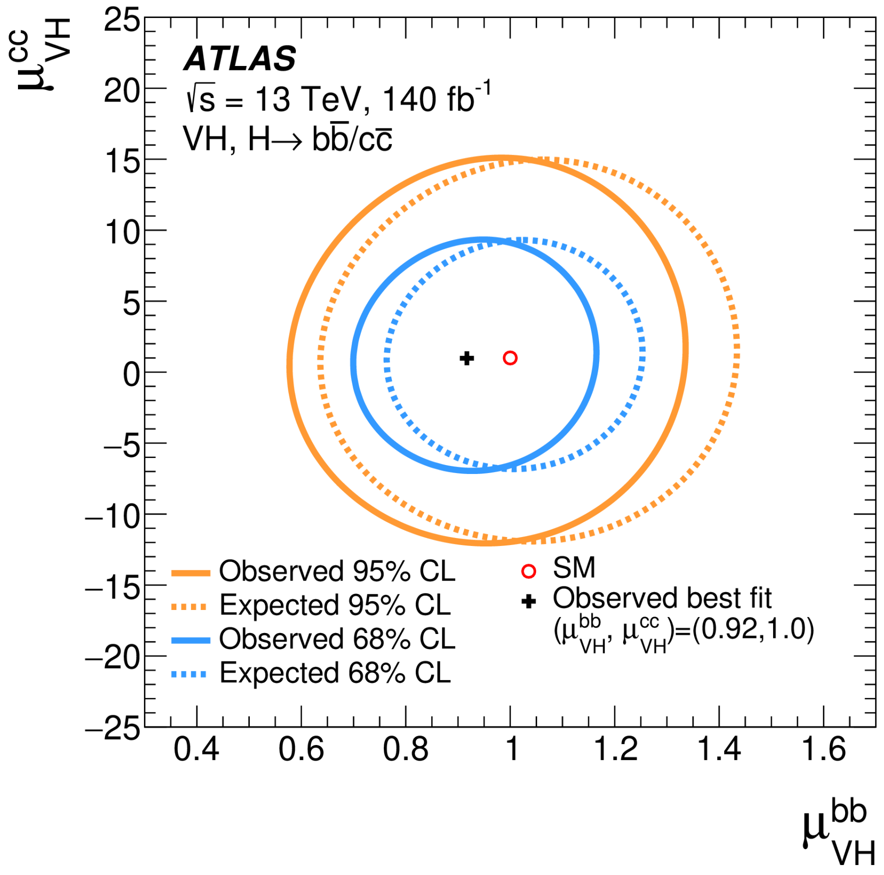
$$\mu_{VZ}^{bb} = 0.92^{+0.13}_{-0.11} = 0.92 \pm 0.05\,(\text{stat.})^{+0.12}_{-0.10}\,(\text{syst.})$$
$$\mu_{VZ}^{cc} = 0.98^{+0.25}_{-0.22} = 0.98 \pm 0.13\,(\text{stat.})^{+0.22}_{-0.18}\,(\text{syst.})$$

$VH, H \to b\bar{b}/c\bar{c}$ signal strength

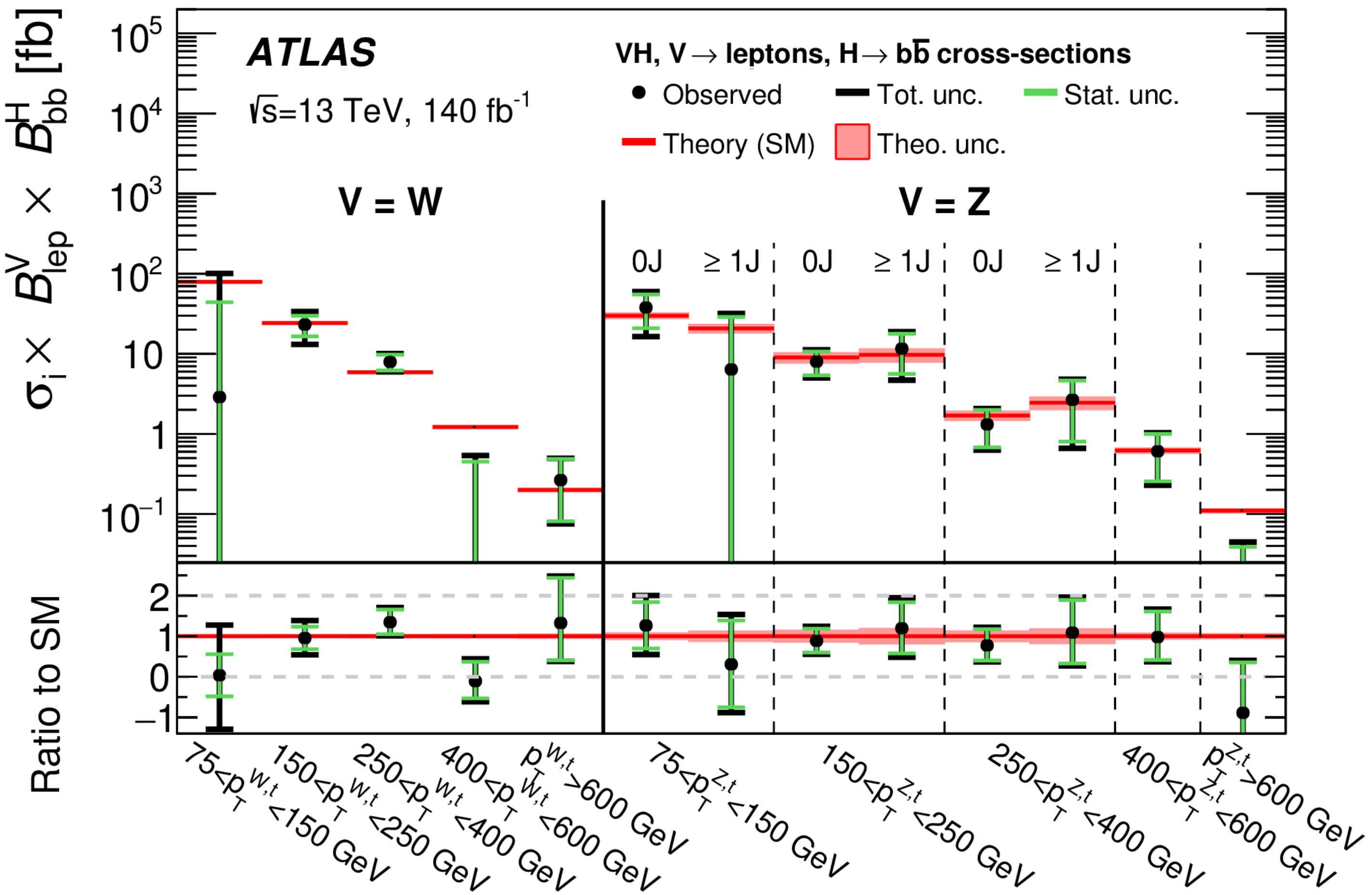
$$\mu_{VH}^{bb} = 0.92^{+0.16}_{-0.15} = 0.92 \pm 0.10\,(\text{stat.})^{+0.13}_{-0.11}\,(\text{syst.}),$$
$$\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\,(\text{stat.})^{+3.7}_{-3.5}\,(\text{syst.}).$$

$VH\ H \to b\bar{b}/c\bar{c}$ - results

- Measured $H \to b\bar{b}/c\bar{c}$ signal strengths agree with SM and have also small correlation: 5%

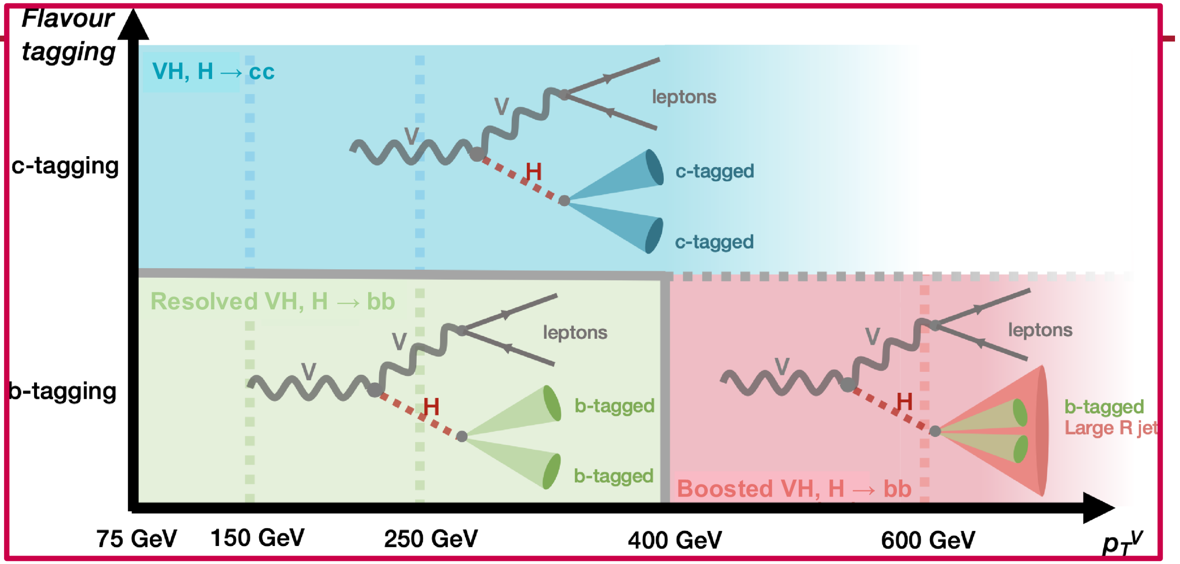


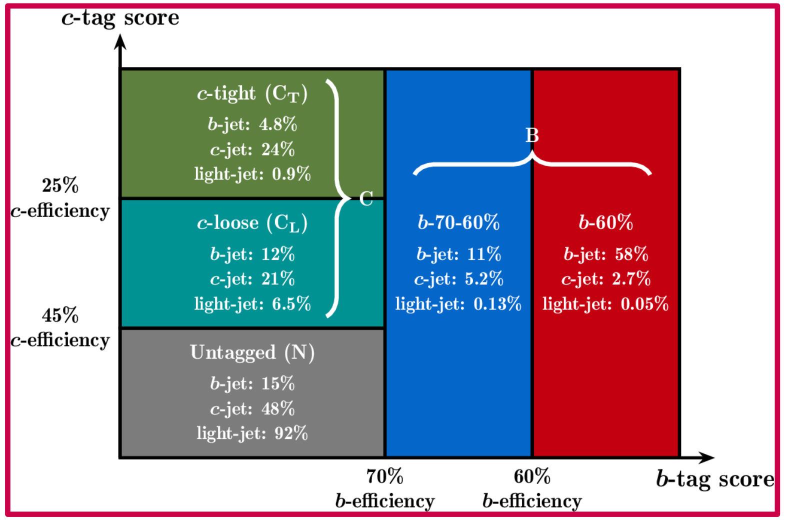
- $H \to b\bar{b}$ channel measured in very granular STXS bins also agree with SM
  - Dominated by statistical uncertainty

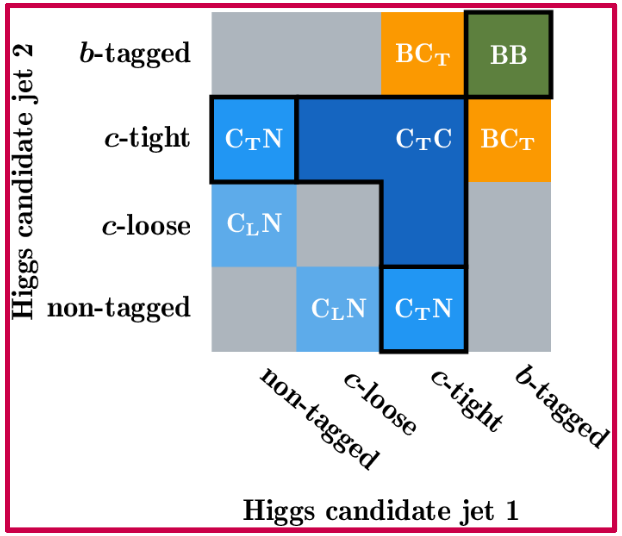


$VH\ H \to b\bar{b}/c\bar{c}$ - strategy overview

- Improvement from previous Run-2 analyses:
  - combined resolved and boosted *Hbb* as well as *Hcc*; new flavor tagger; re-optimized or new MVA; better constraint on background through updated analysis categorization
  - *Hbb*: extended STXS on pTV and 0 or >=1 additional jet
  - *Hcc*: large improvement in limit and kappaC





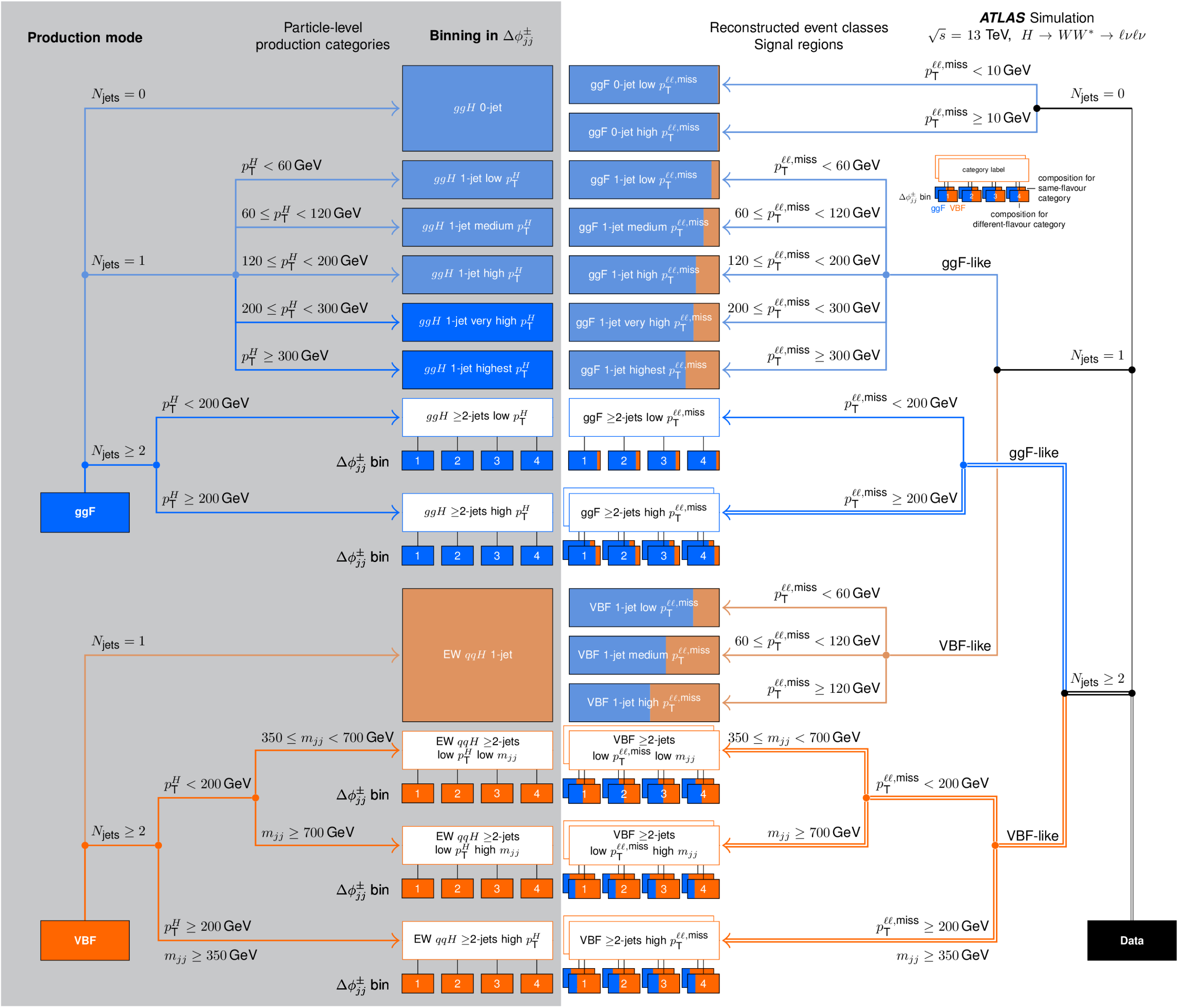


- Categorization based on number of leptons, number of b/c-tagged jets, flavor tagging efficiency and p_T^V
- Simultaneous fit from 59 signal regions and 97 control regions

ggF contamination in the CP analysis

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

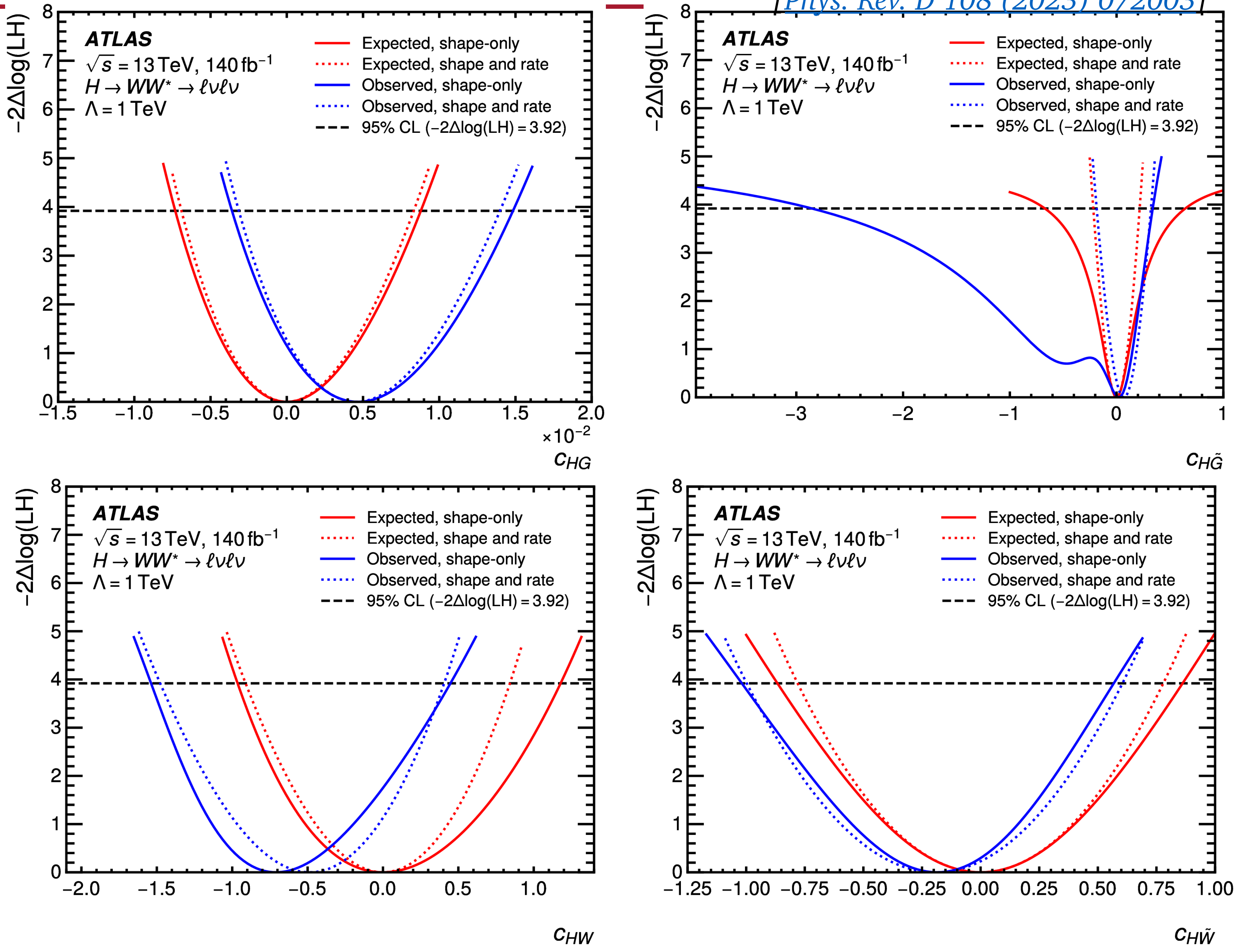
- ggF contamination large at low pTH



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

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

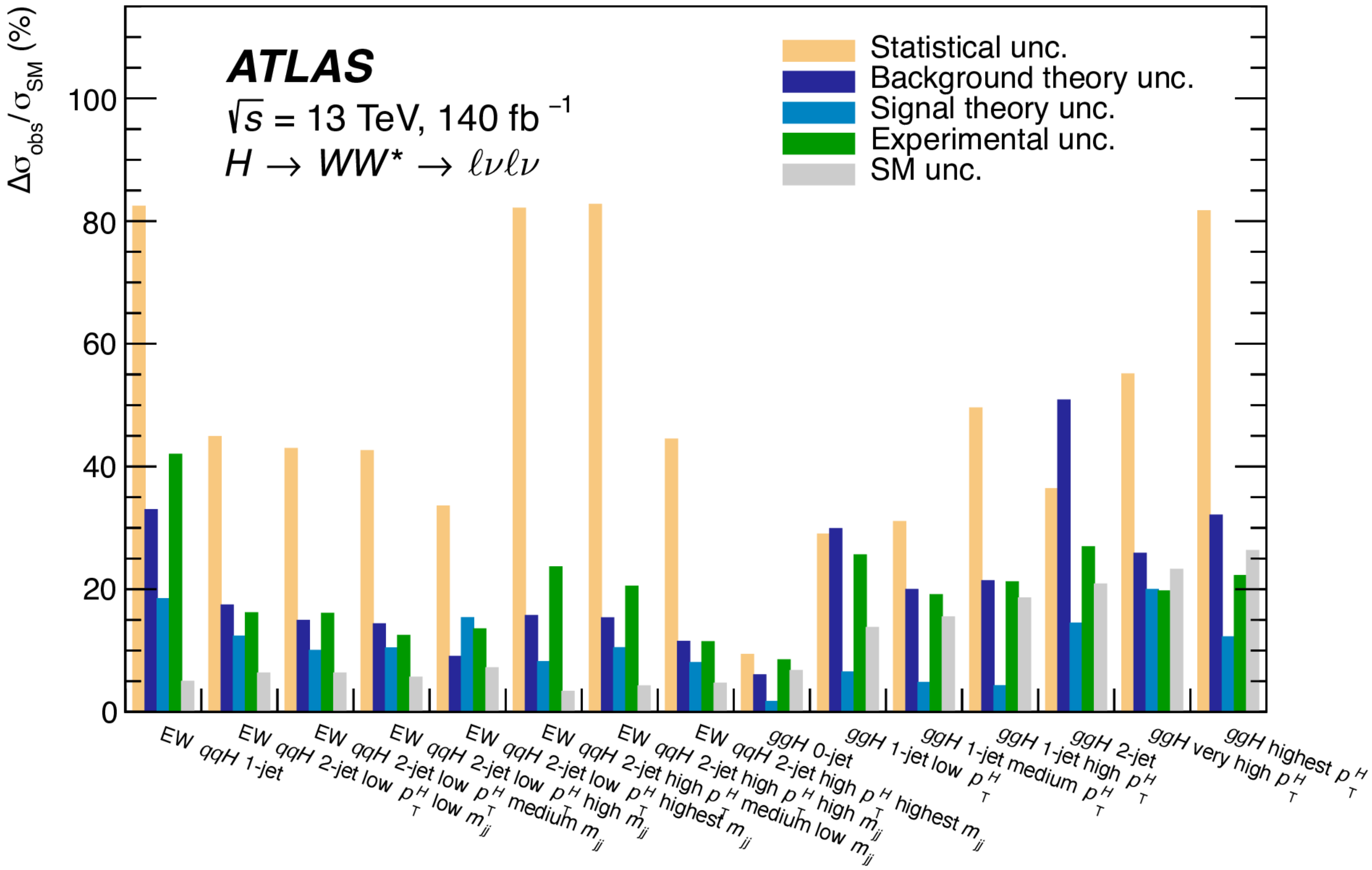
- Second local minimum for $c_{H\tilde{G}}$ and using only the shape of $\Delta\phi_{jj}$ induced the large asymmetric limits



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

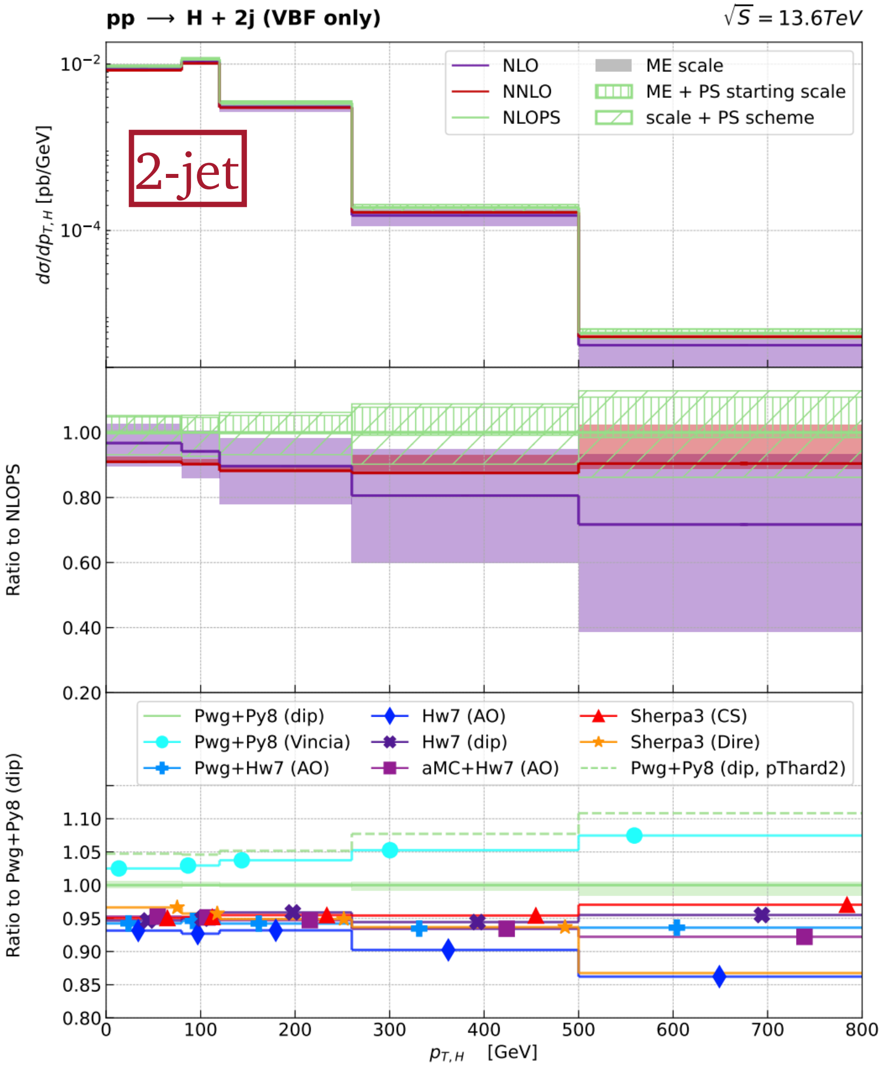
[Phys. Rev. D 108 (2023) 072003]

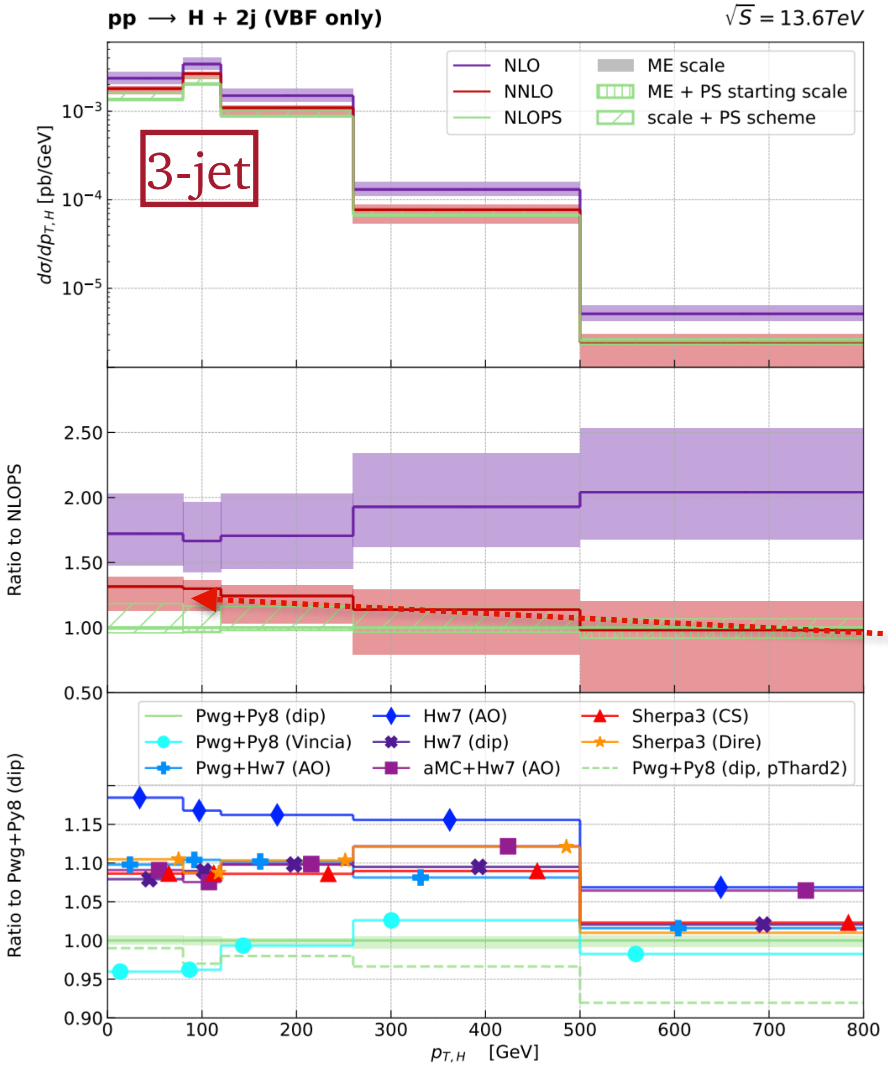
- Dominated by statistical uncertainty

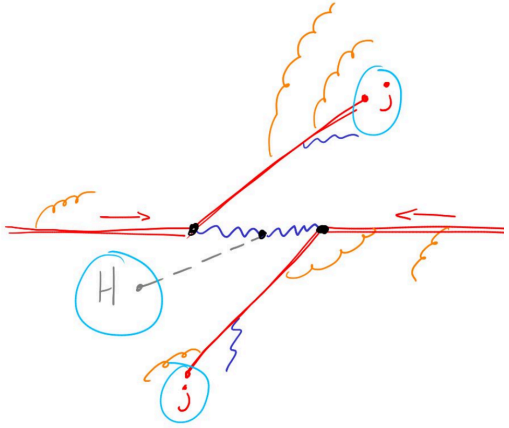


Systematic comparison of theoretical modeling

[LHC Higgs Working Group Reports Series]





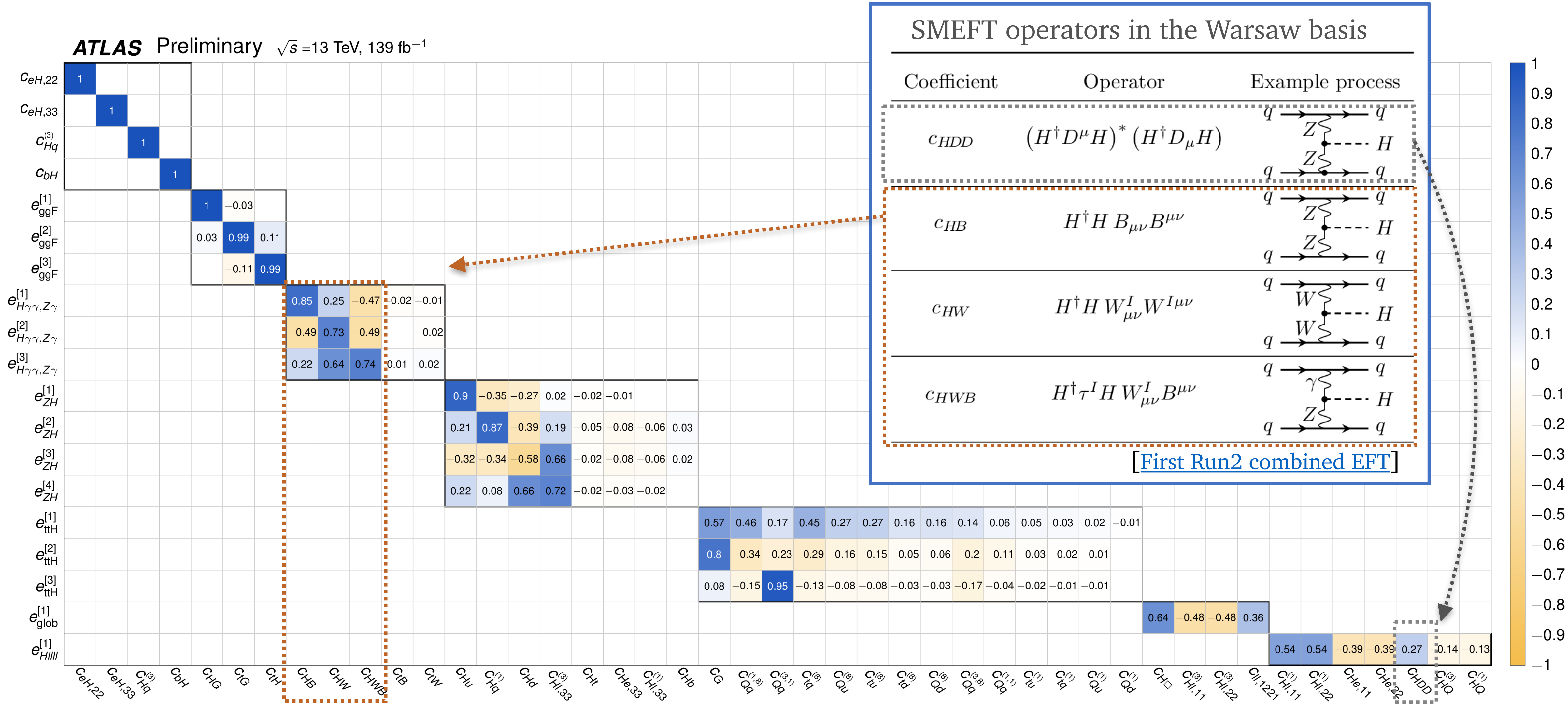


- Modeling of the 3rd jet with NLOPS problematic
- PS uncertainty doesn't cover the difference between NLOPS and NNLO
- Uncertainty reaches >15%
- Experimental measurements need to reconsider the central jet veto selection for next round

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

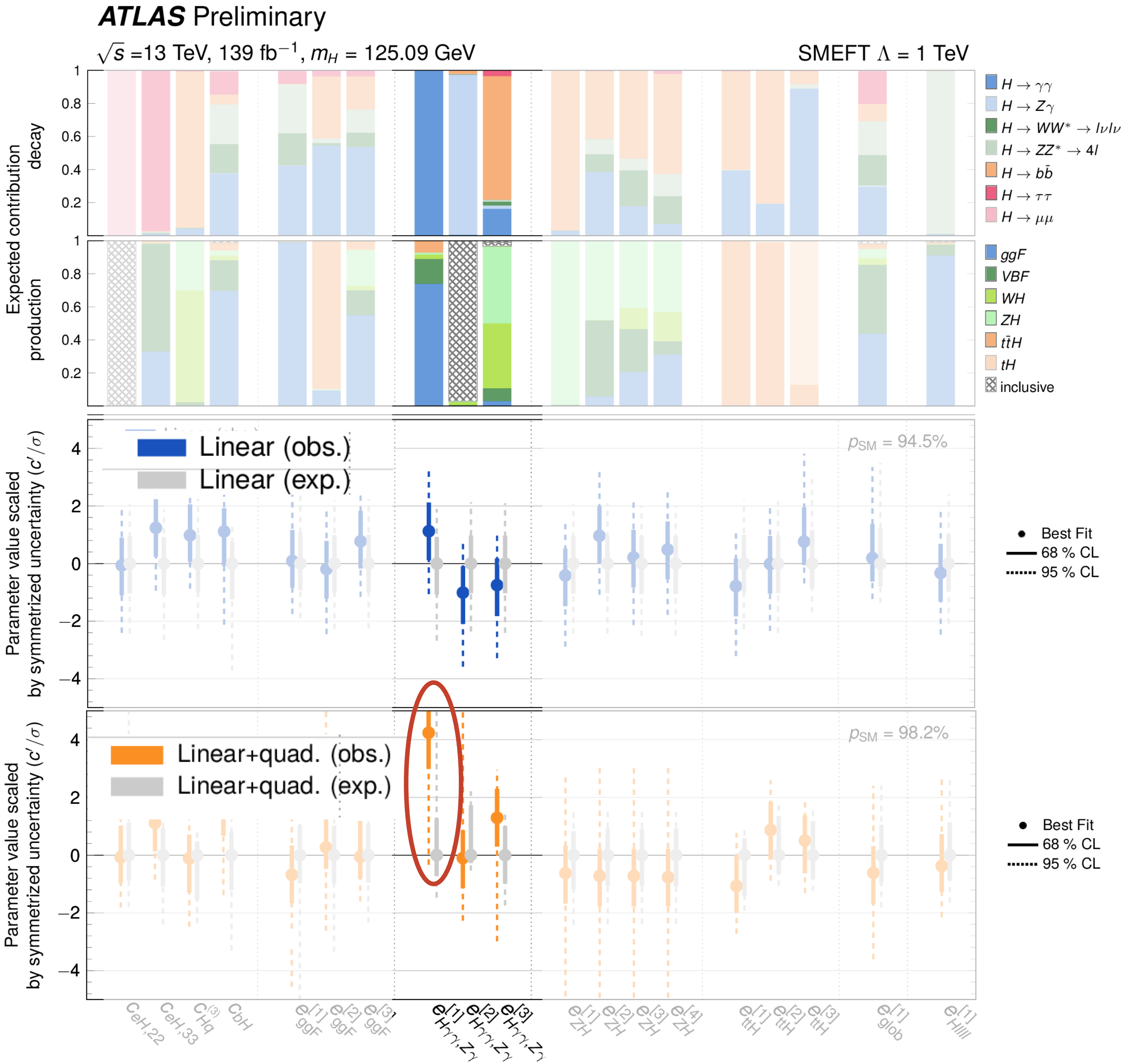


HVV EFT status from combined interpretation (II)

[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

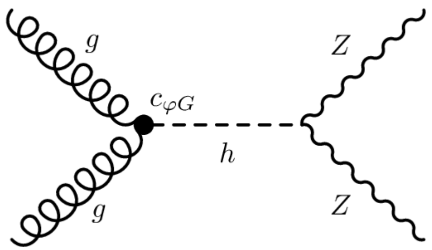
	CHB	CHW	CHWB	CtB	CtW
$e^{[1]}_{H\gamma\gamma,Z\gamma}$	0.85	0.25	−0.47	−0.02	−0.01
$e^{[2]}_{H\gamma\gamma,Z\gamma}$	−0.49	0.73	−0.49		−0.02
$e^{[3]}_{H\gamma\gamma,Z\gamma}$	0.22	0.64	0.74	0.01	0.02

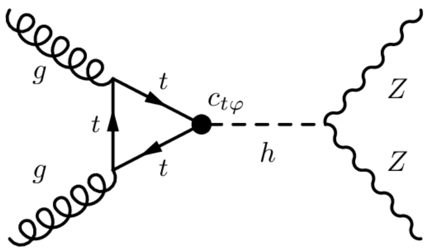


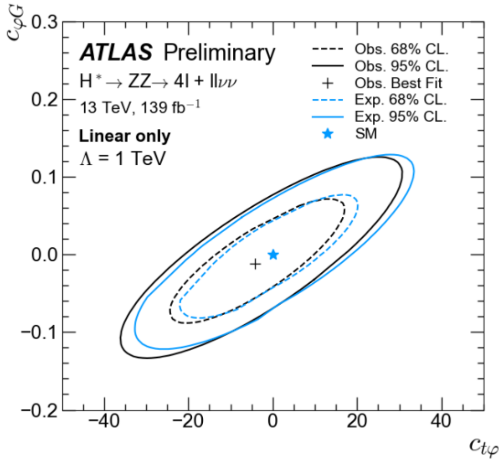
More recent/ongoing HVV EFT ideas - HVV off-shell and EFT

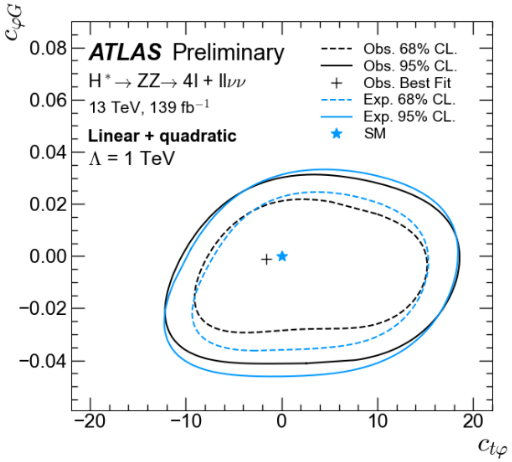
[HZZ off-shell EFT]

- 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

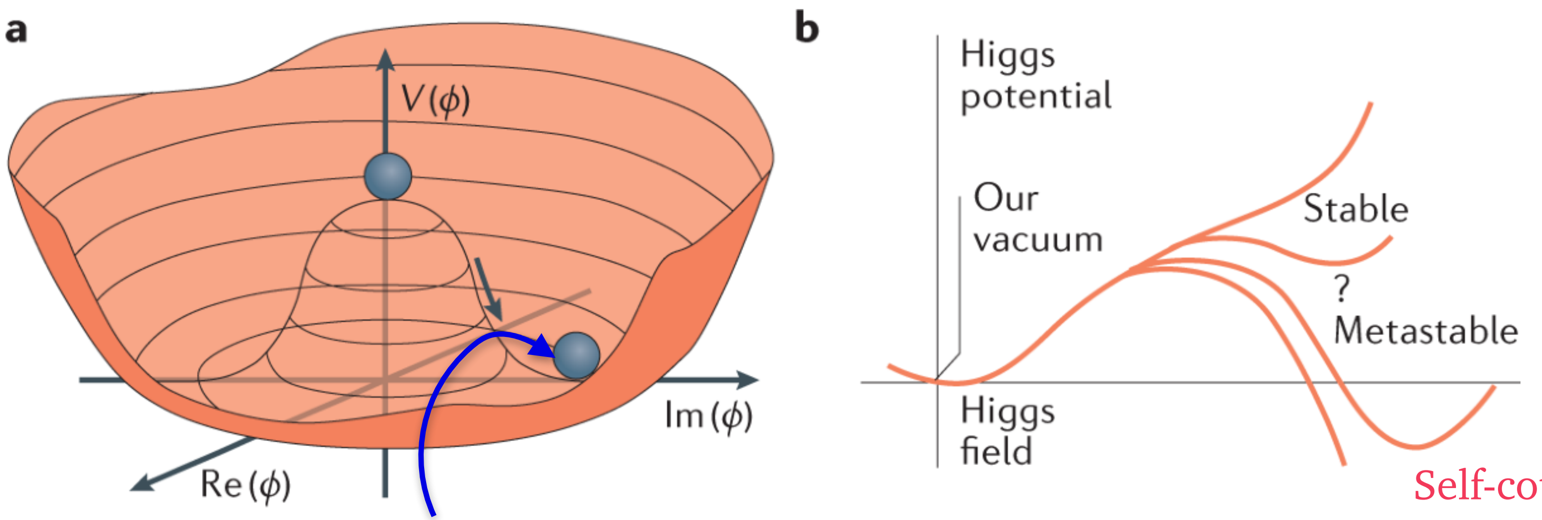




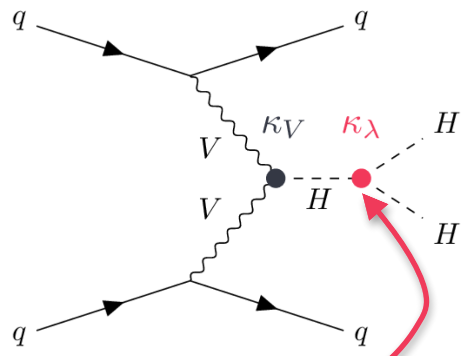




Di-Higgs search



Mass: minimum of the potential



Self-coupling (κ_λ): shape of the potential

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

Phys. Rev. Lett. 133 (2024) 101801

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