Combined Higgs boson measurements and their interpretations with the ATLAS experiment

(will focus on results new since DIS2022)

ATLAS EXPERIMENT

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Introduction

	SM	BSM
H_{125}	μ_i, μ_f κ STXS	2HDM EFT invisible
$H_{125}H_{125}$	μ_{HH}, κ_λ, κ_{2V}	resonant HH
$H_{125}H_{125}+H_{125}$	κ_λ	

Run 1: $\sqrt{s}$=7 TeV, L=4.7 fb^{-1},
$\sqrt{s}$=8 TeV, L=20.3 fb^{-1}
Run 2: $\sqrt{s}$=13 TeV, L=139 fb^{-1}

$1\text{-}H_{125}$

Production modes & decays

- Inputs

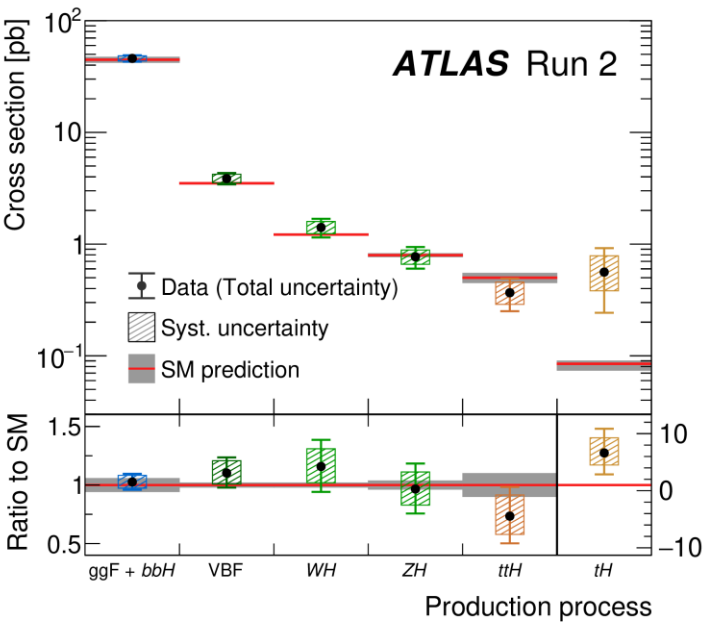
ATLAS, Run 2, L=36.1-139 fb^{-1}, Nature, 607, 52 (2022)

H→γγ, H→ZZ, H→WW, H→Zγ, H→bb, H→ττ, H→μμ

- Signal strength

$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\ (\text{stat.}) \pm 0.03\ (\text{exp.}) \pm 0.04\ (\text{sig. th.}) \pm 0.02\ (\text{bkg. th.})$

- Production modes



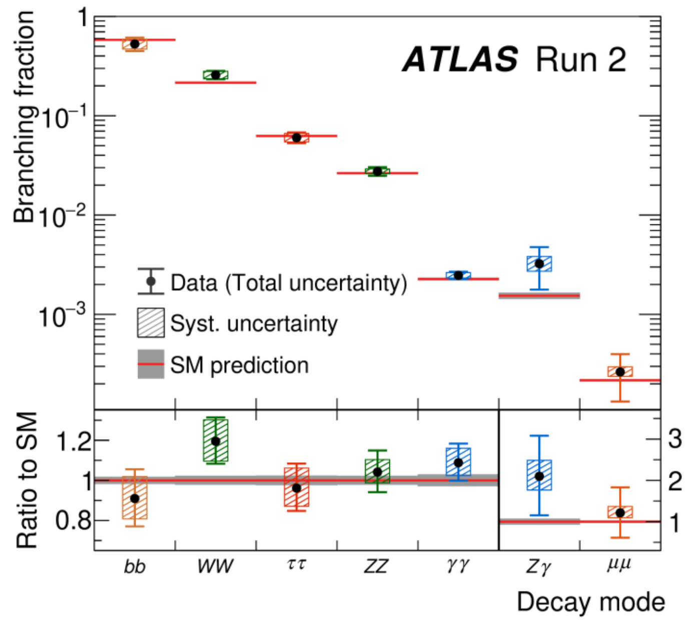
Z_{obs}=5.8 Z_{obs}=5.0 Z_{obs}=6.4

Z_{exp}=5.1 Z_{exp}=5.5 Z_{exp}=6.6

tH 95 % limit

obs: 15 x SM (exp: 7 x SM)

- Decay channels



Z_{obs}=7.0

Z_{exp}=7.7

Z_{obs}=2.3 Z_{obs}=2.0

Z_{exp}=1.1 Z_{exp}=1.7

+others measurements ($\sigma_i BR_f$, ratio σ/σ_{ggF}, BR/BR_{ZZ}, etc.)

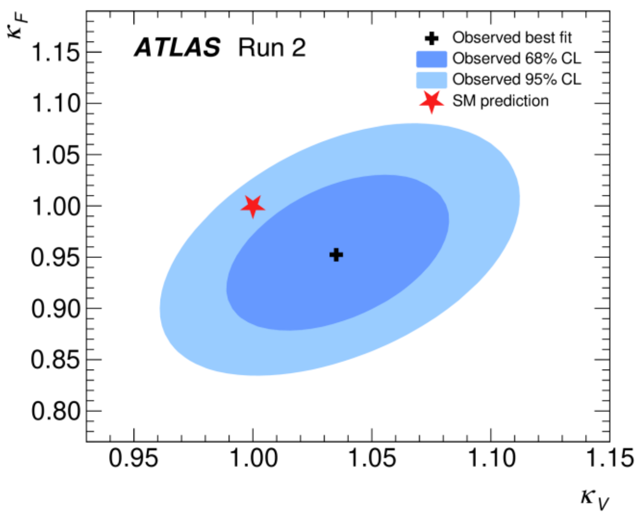
Coupling strength modifiers

- coupling strength modifiers (κ framework, no Zγ, μμ)

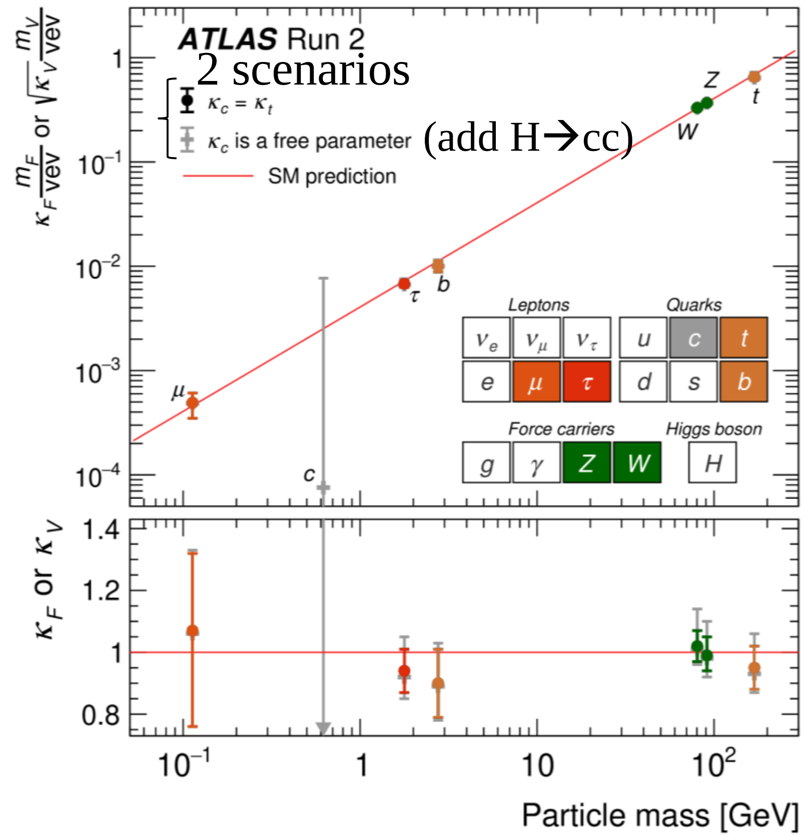
3 scenarios, increasingly reducing assumptions

(1) boson/fermion symmetry

$\kappa_V = 1.035 \pm 0.031$, $\kappa_F = 0.95 \pm 0.05$



(reduced H couplings to f, V)



2 scenarios

(add H→cc)

(2) κ treated independently

(no invisible/undetected)

Scaling of coupling with mass

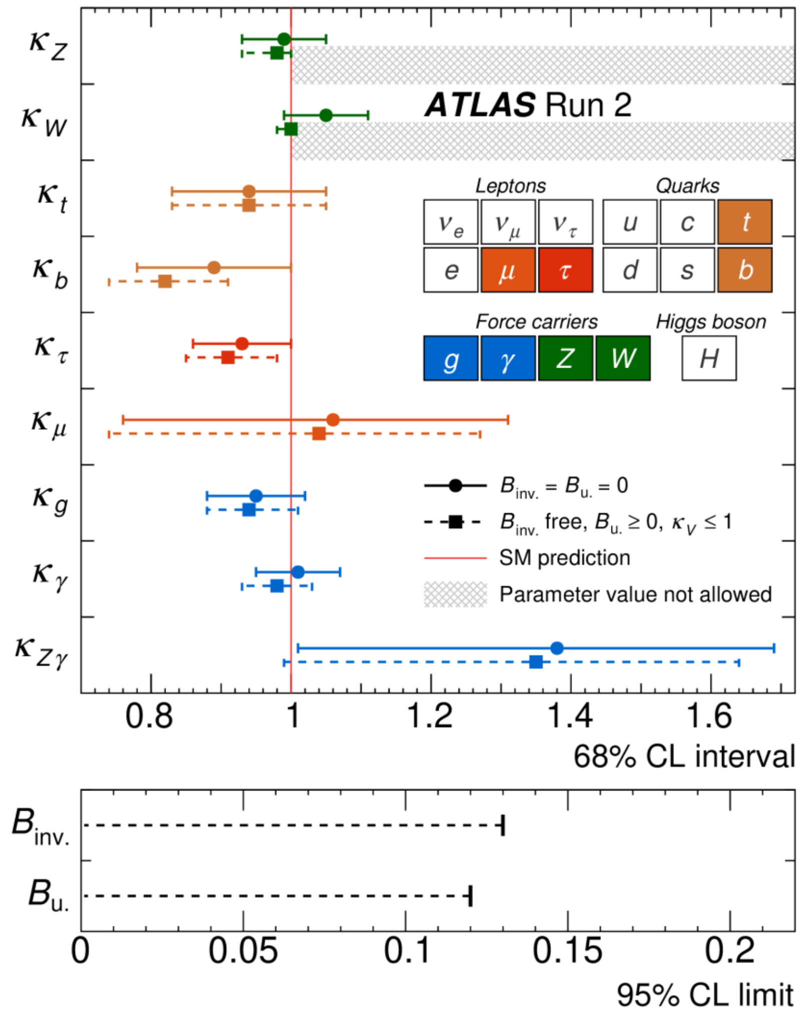
95 % CL limit on κ_c

obs: <5.7xSM (exp: <7.6xSM)

Coupling strength modifiers

3) generic parametrisation: allow non-SM: effective couplings for loops

-wo/ invisible/undetected



-w/ invisible/undetected

(add H→inv)

$$\kappa_H^2(\kappa, B_{i.}, B_{u.}) = \frac{\sum_j B_j^{SM}\kappa_j^2}{(1 - B_{i.} - B_{u.})}$$

BR_i (≠SM), BR_u (light q, low MET)

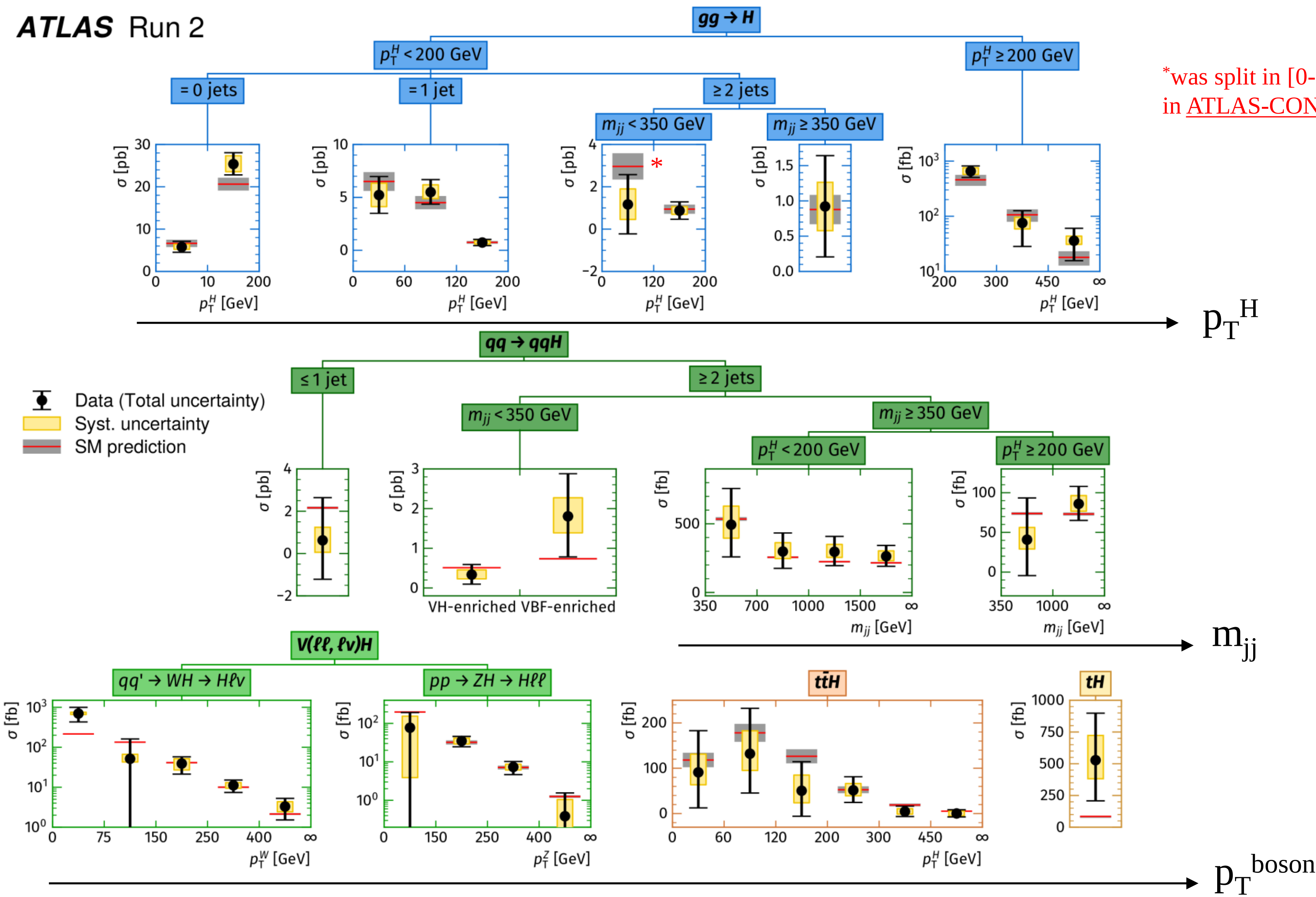
degeneracy: $\kappa_W \leq 1$, $\kappa_Z \leq 1$

BR_{inv} obs: <0.13 (exp: <0.08)

BR_{un} obs: <0.12 (exp: <0.21)

Kinematic properties (STXS) No {Zγ, cc, μμ}

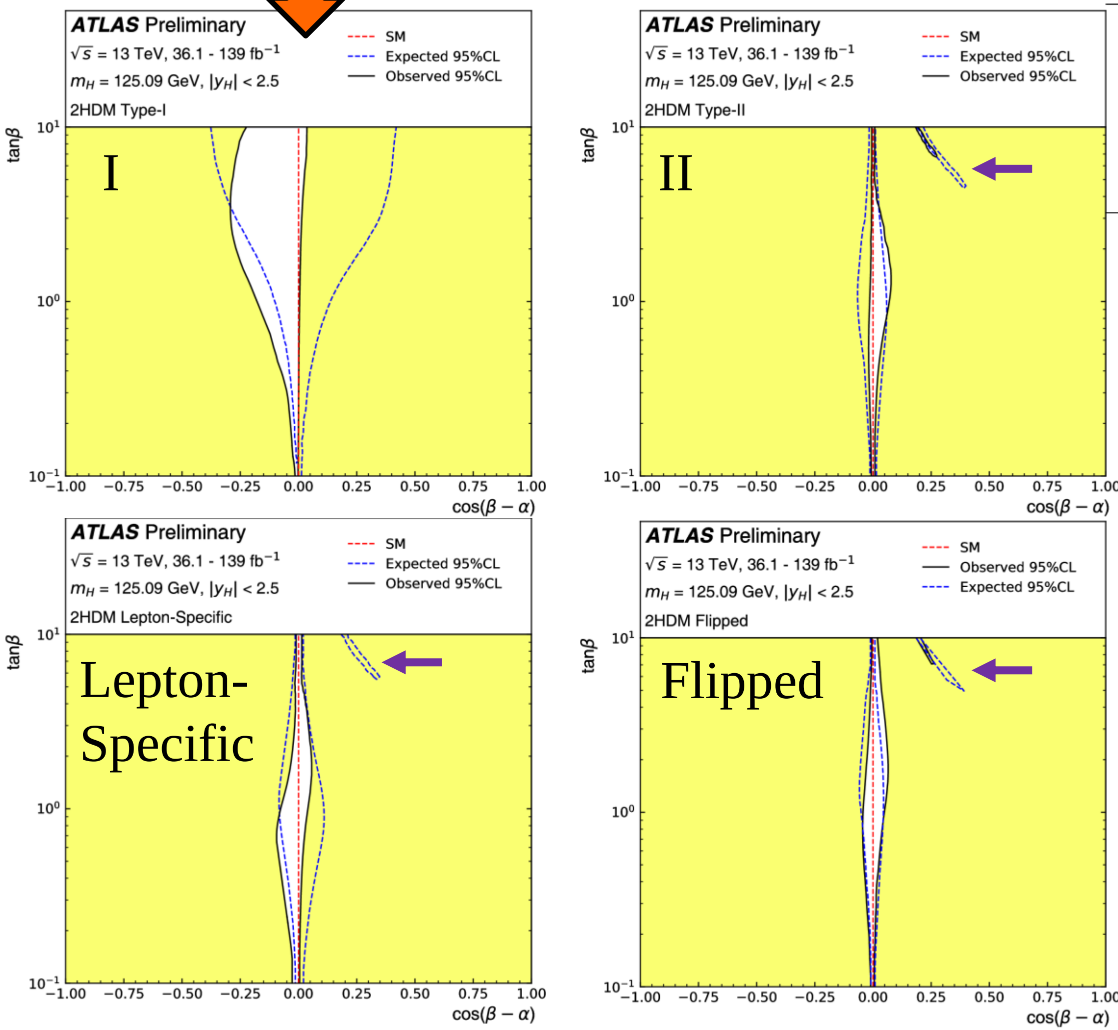
- Kinematic properties, STXS stage 1.2, 36 truth bins



- $\kappa \rightarrow$2HDM

ATLAS, Run 2, L=36.1-139 fb^{-1}, ATLAS-CONF-2021-053

Coupling modifiers→2HDMs, H_{125}: assumed≈couplings H_{SM}, changes: f(α, tan β)
Limits Couplings=f(cos(β-α), tan β)



	type I	type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

- Compatible w/ alignment limit:

cos (β-α)=0 $H_{VV}=H_{VV}^{SM}$, $Hff=H_{ff}^{SM}$

- Best fit not shown

(limited sensitivity in tan β)

- petals: Hff: same magnitude, sign≠

Combination STXS+decay→SMEFT, Warsaw basis

- EFT

ATLAS, Run 2, L=36-139 fb^{-1}, ATL-PHYS-PUB-2022-037

$$\sigma = |\mathcal{A}_{SM}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{SM}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right)$$

interf. SM-d6 — Linear (in c_i)

pure d6 — Quadratic (in c_i)

interf. d6-d6 — Cross-terms

+pure Λ^{-4}
+interf SM-dim 8
→neglected

- Inputs

ATLAS:
- -Higgs: H→γγ, H→ZZ*, H→WW*, H→ττ, H→bb
- -dσ/dX EW

24 c_i/eigenvectors(c_i): linear+quadratic

LEP, SLD: EW observables

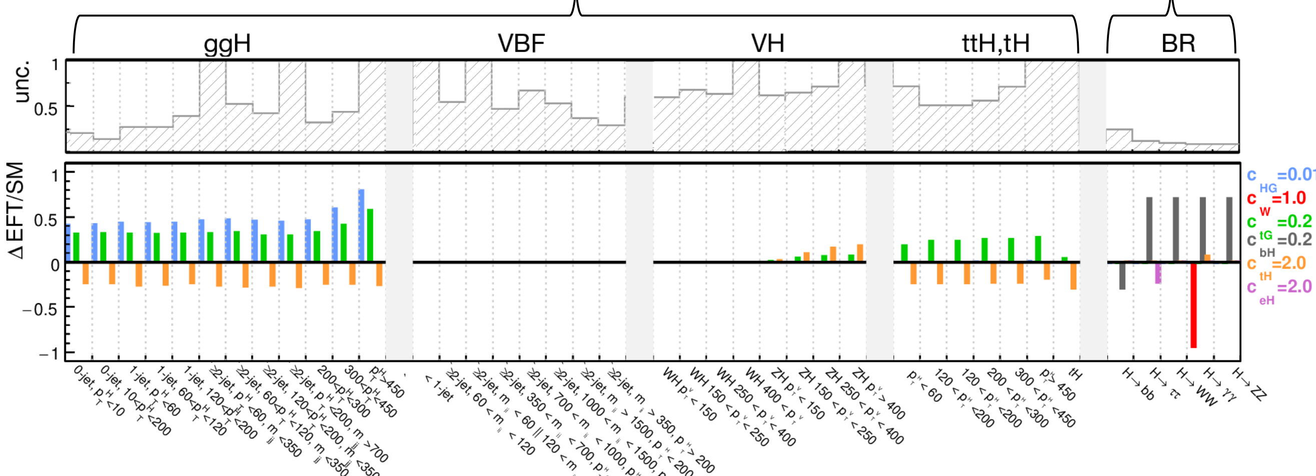
28 linear

- Symmetry: $U(2)_q \times U(2)_u \times U(2)_d \times U(3)_l \times U(3)_e$
- Impact c_i (linear) on STXS & BR

STXS — BR

Rel. uncertainty measurement →

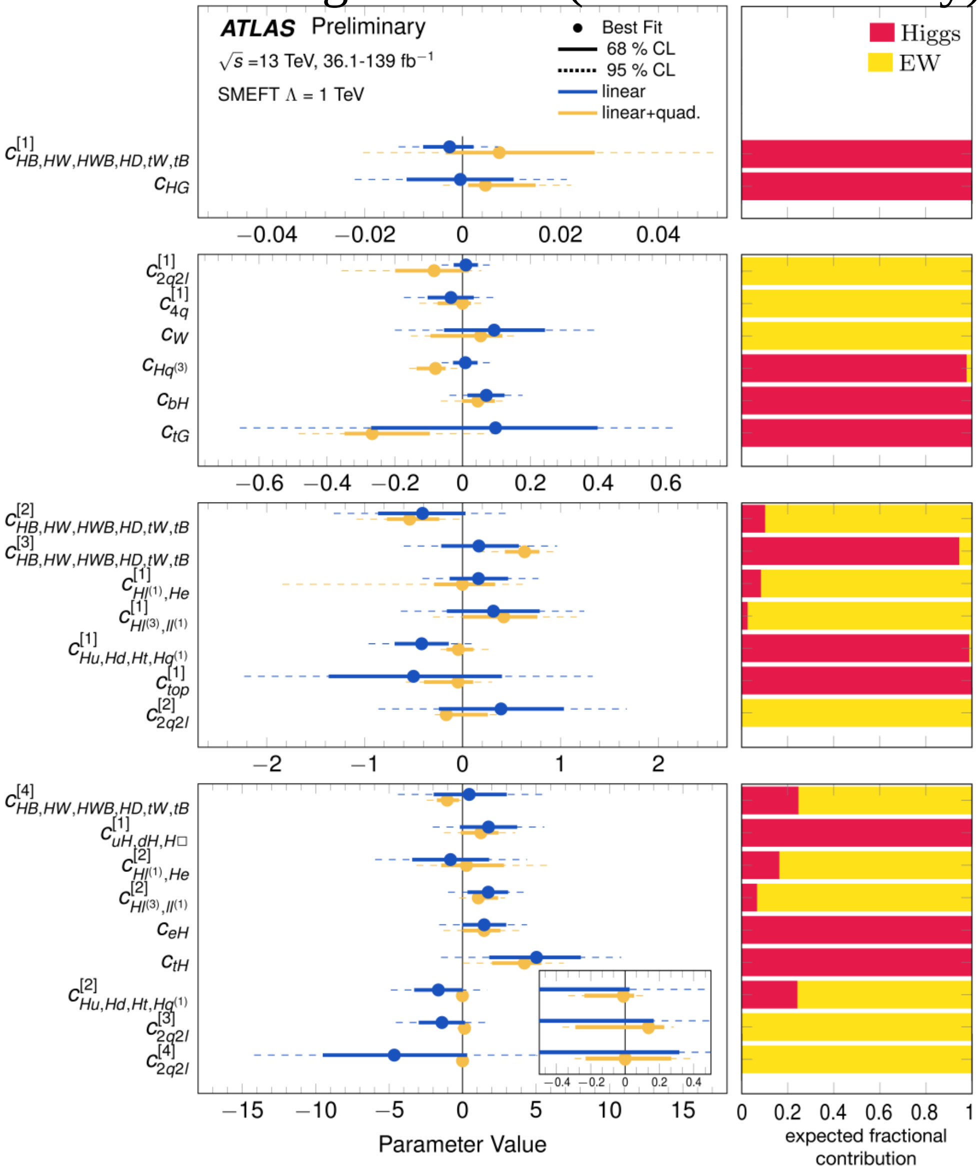
Impact c_i →



Combination STXS→SMEFT

- Results ATLAS inputs (Higgs + dσ/dX EW)

individual and eigenvectors (else no sensitivity)



- additional results: …+LEP+SLD

σ_{fid}

- Inputs

ATLAS, Run 2, L=139 fb[-1], CERN-EP-2022-143

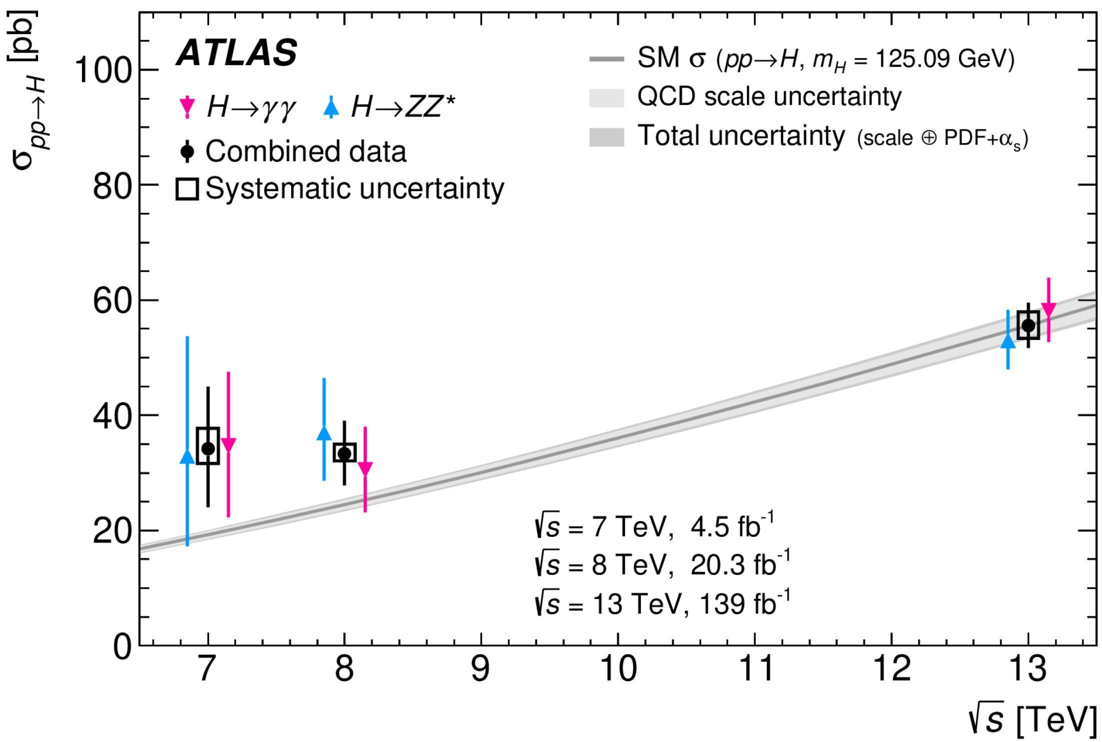
$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$

Channels compatible

- Systematics

Dominated by stat. uncertainties ;experimental & theoretical uncertainties correlated

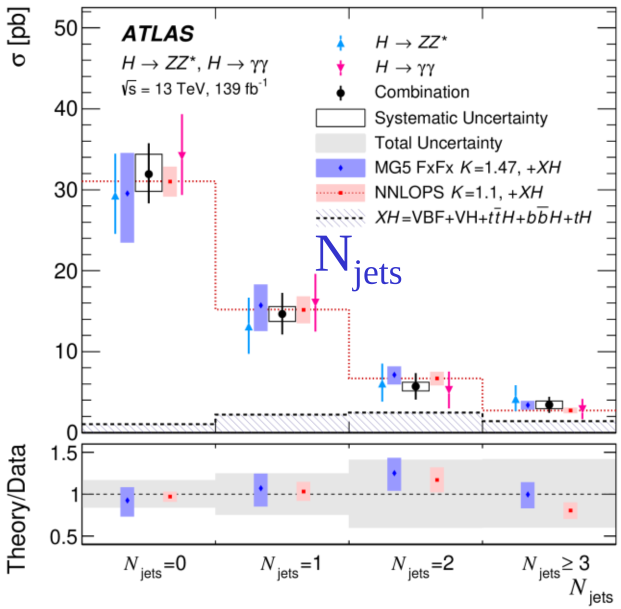
- σ_{fid}

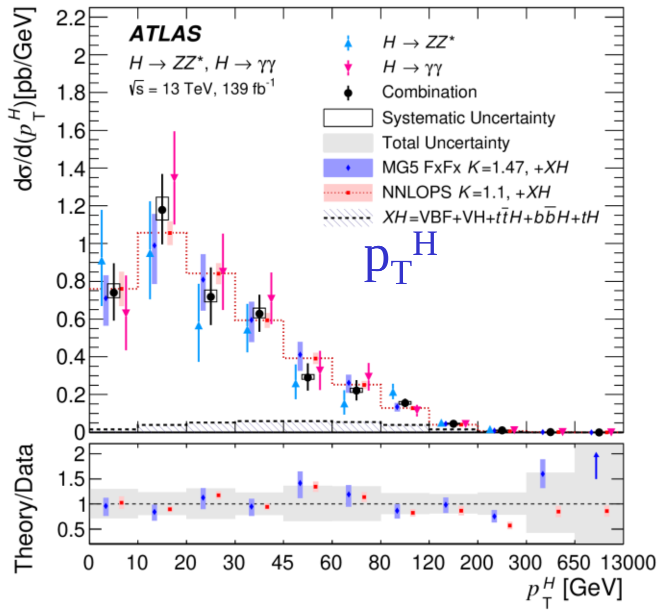


$d\sigma_{fid}/dX$

- $d\sigma/dX$

ATLAS, Run 2, L=139 fb^{-1}, CERN-EP-2022-143





+others

(N_{jets}, $p_T^{lead. jet}$, $|y_H|$, p_T^H)

model. QCD rad., prod. modes

JES/JER important

perturbative QCD

- Sensitivity p^T_H to Yukawa Hcc, Hbb

loop(ggH, Γ(H→γγ), thus BRs), qq, qg

normalization & shape of p_T^H

Channel	Parameter	Observed 95% confidence interval	Expected 95% confidence interval
Combined	κ_b	$[-1.09, -0.86] \cup [0.81, 1.09]$	$[-1.14, -0.92] \cup [0.86, 1.15]$
	κ_c	$[-2.27, 2.27]$	$[-2.77, 2.75]$

- Combination w/ VH(bb, cc)

Jet energy, flav. tagging not correlated: (clustering ≠)

Scenario	Observed 68% confidence interval	Observed 95% confidence interval
$B_{BSM} = 0$	$[-1.61, 1.70]$	$[-2.47, 2.53]$
No assumption on B_{BSM}	$[-2.63, 3.01]$	$[-4.46, 4.81]$

Best κ_c constraint

H→invisible

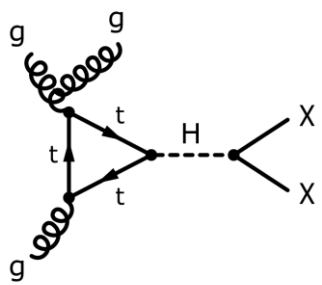
- SM: BR(H→ZZ*→4ν)=0.1 %

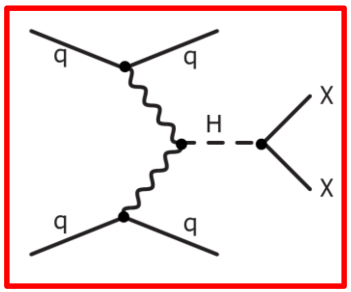
Run 1+2, L=4.7+20.3+139 fb^{-1}, arxiv:2301.10731

Higgs portal SM⇔dark sector

DM χ: MET: indirect

H+j VBF VBF+γ ZH ttH





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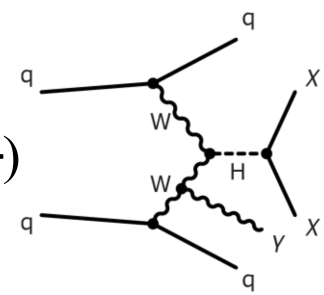
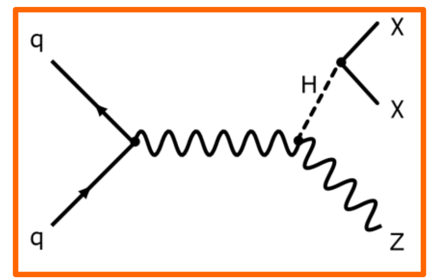
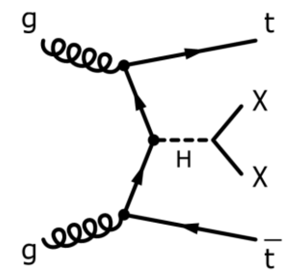






- Correlations

Run 2 : most experim. systematics correlated among channels

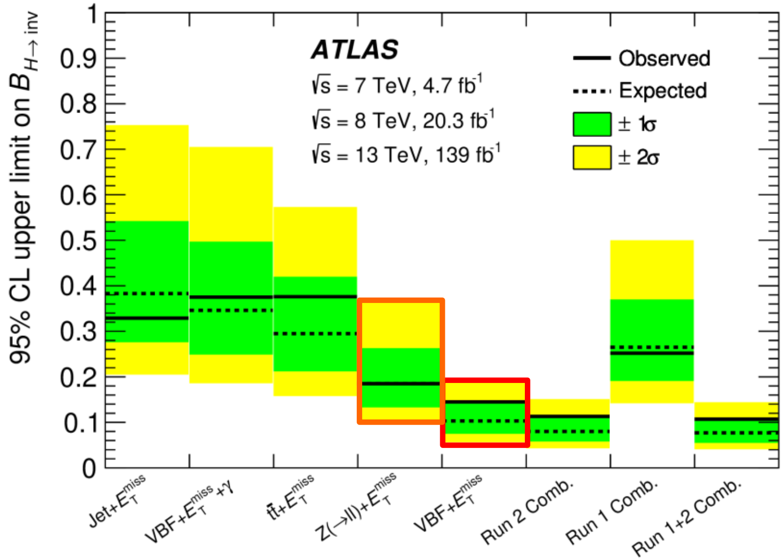
Run 1-Run 2: most experim. systematics uncorrelated

detector layout ≠, data-taking ≠⇔data-driven calibration ≠

bkg modelling: improvement in MC & theory

H→invisible

- Limit BR H→inv (95 % CL)



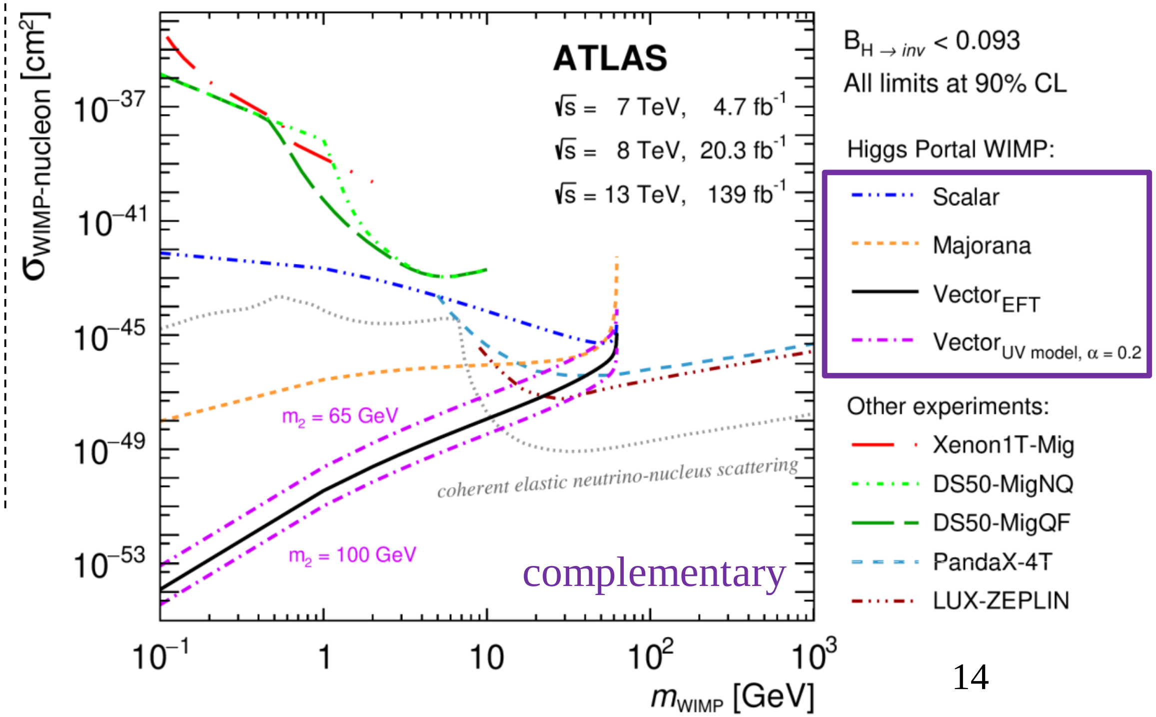
obs: 0.107

exp: 0.077

(most stringent results to date)

- EFT and UV models explored

$m_H \geq 2m_{WIMP}$

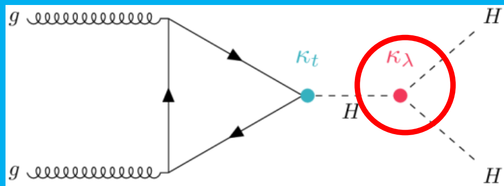


HH Higgs self-coupling

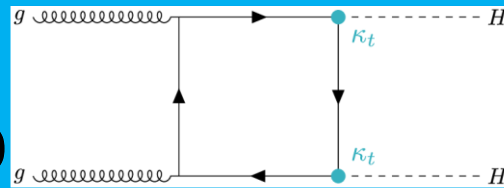
examples

- **Non-resonant** (in the HH)

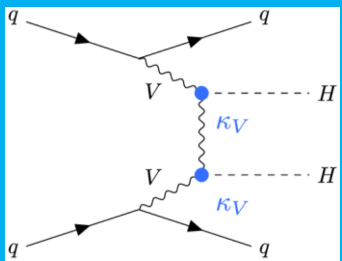
ggF

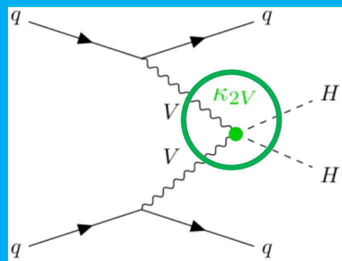


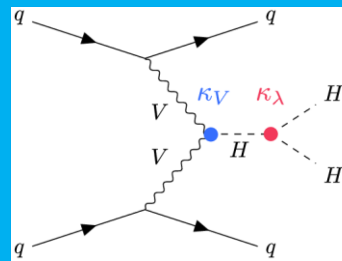
« - »
(SM)



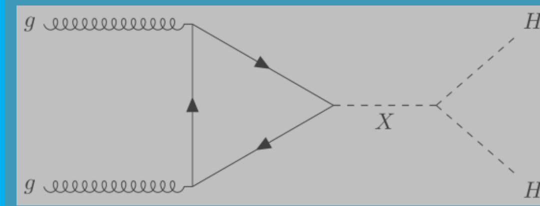
VBF

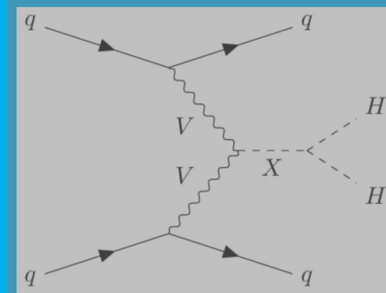






- **Resonant (backup), extension**

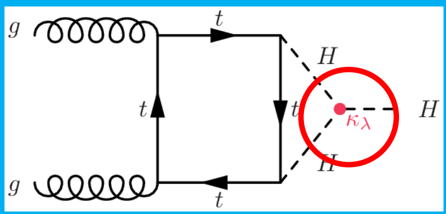




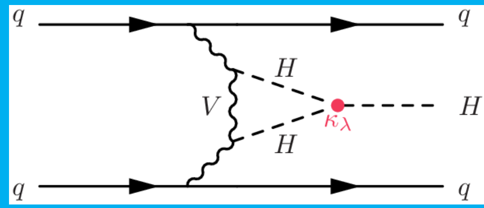
1-H

Exploits higher EW correction

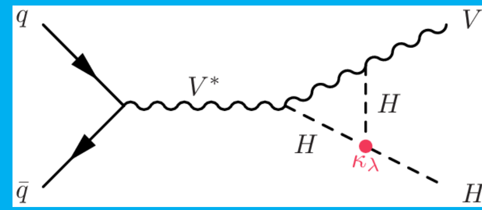
ggF



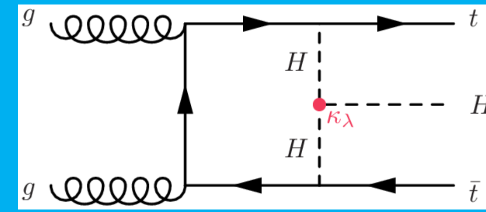
VBF



VH

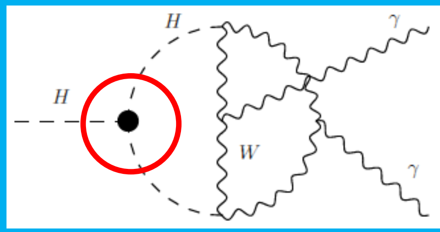


ttH



BR

H→γγ



(many other diagrams)

HH & Higgs self-coupling (κ_λ)

Run 2, $\sqrt{s}$=13 TeV, L=126-139 fb^{-1}, CERN-EP-2022-149

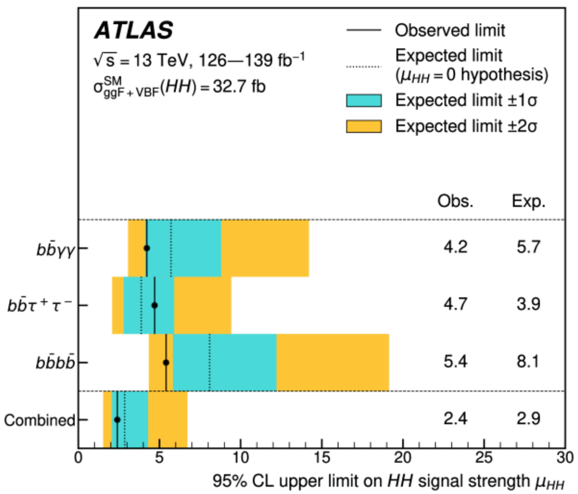
(from paper draft $H_{125}H_{125}+H_{125}$)

- Inputs

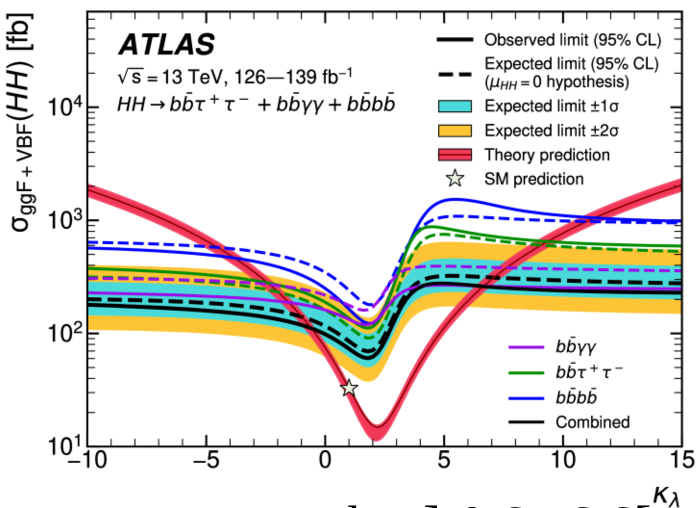
Channel	Integrated luminosity [fb^{-1}]
$HH \to b\bar{b}\gamma\gamma$	139
$HH \to b\bar{b}\tau^+\tau^-$	139
$HH \to b\bar{b}b\bar{b}$	126

- Limit μ_{HH} (95 % CL)

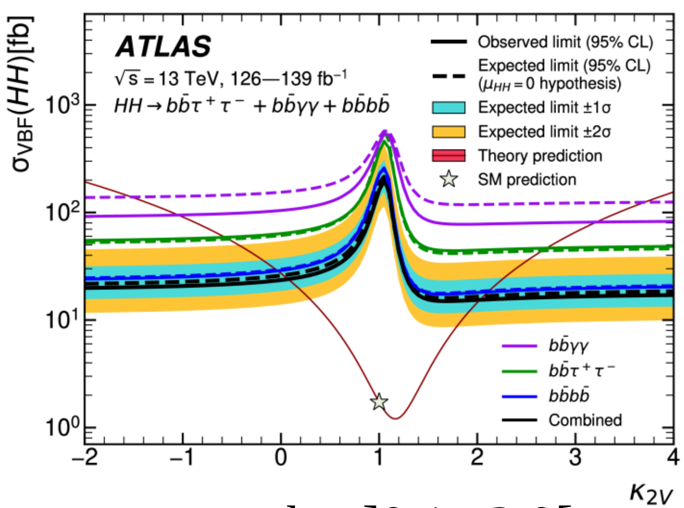
HH=f(κ_λ, κ_{2V}, …)



obs: 2.4xSM, exp: 2.9xSM
(if no HH)
(4.0 if SM)



κ_λ: obs:]-0.6 ; 6.6[
(exp:]-2.1 ; 7.8[)



κ_{2V}: obs:]0.1 ; 2.0[
(exp:]0.0 ; 2.1[)

HH+H: probing further κ_λ

- Inputs

Run 2, $\sqrt{s}$=13 TeV, L=126-139 fb^{-1}, CERN-EP-2022-149

HH ($bb\gamma\gamma$, $bb\tau\tau$, bbbb) + 1-H ($\gamma\gamma$, $ZZ^* \rightarrow 4l$, $\tau\tau$, $WW^* \rightarrow e\nu\mu\nu$, bb) (exploit loop from higher order)

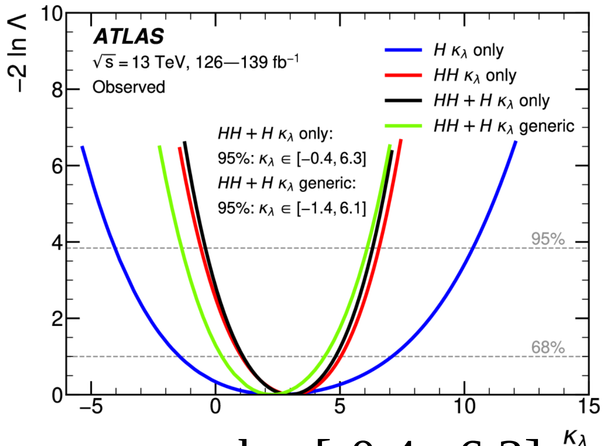
Negligible overlap channels, removed ttH($\tau\tau$) : 4 % in HH

- Parametrisation

-σ HH: $f(\kappa_\lambda, \kappa_t, \kappa_V, \kappa_{2V})$ -BR(κ_λ, κ_m) -A$\times\varepsilon$: $f(\kappa_\lambda)$

1-H STXS: sensitivity ↑ for κ_λ, κ_m (κ_t, κ_b, κ_τ, κ_V) -A$\times\varepsilon$: $f(\kappa_\lambda)$: ≈1

(ggF=$f(\kappa_\lambda)$) inclusive : not exploiting STXS granularity)



κ_λ: obs: [-0.4 ; 6.3]

exp: [-1.9 ; 7.6]

- add 1-H : relax assumptions Higgs couplings
- as strong as wo/ κ_t
- Less model dependent

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Conclusion

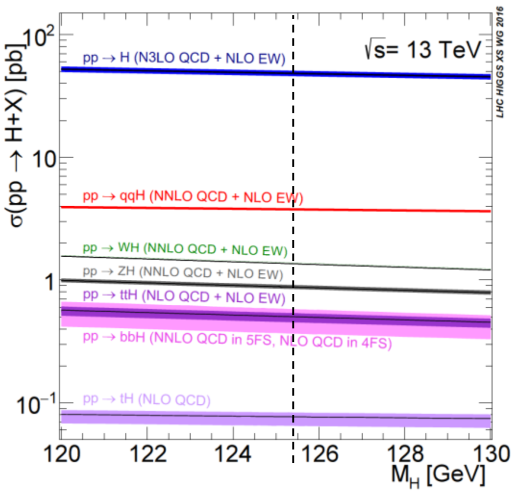
Object	analysis	Reference & comment
H_{125}	μ_i, μ_f, STXS, κ	Nature, 607, 52 (2022), Run 2, L=36-139 fb^{-1} 36 truth bins ATLAS-CONF-2021-053: less channels, one truth bin more (split) κ: add generic ratio f coupling modifiers
H_{125}	κ→BSM: 2HDM	ATLAS-CONF-2021-053, Run 2, L=36.1-139 fb^{-1}
H_{125}	STXS→EFT SMEFT, Warsaw	ATL-PHYS-PUB-2022-037, Run 2, L=36-139 fb^{-1} topU3l: relax t, b: $U(2)_q \times U(2)_u \times U(2)_d \times U(3)_l \times U(3)_e$ ATLAS-CONF-2021-053: only linear, flav. symmetry $U(3)^5$
σ_{H125}, $d\sigma_{H125}/dX$		CERN-EP-2022-143, Run 2, L=139 fb^{-1}
H_{125}→inv		arxiv:2301.10731, Run 1+2, L=4.7+20.3+139 fb^{-1}
$H_{125}H_{125}$		CERN-EP-2022-149, non resonant HH combination part of HH+H ATLAS-CONF-2021-052, Run 2, √s=13 TeV, L=126-139 fb^{-1} -Non-resonant: superseeded by HH part of CERN-EP-2022-149 -Resonant: not new since DIS2022: backup, ATLAS-CONF-2021-052
$H_{125}H_{125}+H_{125}$	μ_{HH}, κ_λ	CERN-EP-2022-149, Run 2, √s=13 TeV, L=126-139 fb^{-1}
$H_{125}H_{125}$ prospects	μ_{HH}, κ_λ	ATL-PHYS-PUB-2022-005, Prospects HL-LHC, √s=14 TeV, L=3000 fb^{-1} Not new since DIS2022: in backup

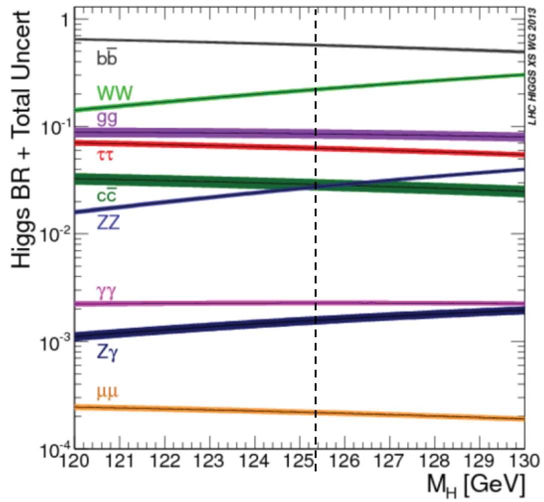
Backup

Abstract: Combining measurements of many production and decay channels of the observed Higgs boson allows for the highest possible measurement precision for the properties of the Higgs boson and its interactions. These combined measurements are interpreted in various ways; specific scenarios of physics beyond the Standard Model are tested, as well as a generic extension in the framework of the Standard Model Effective Field Theory. The latest highlight results of these measurements and their interpretations performed by the ATLAS Collaboration will be discussed.

Generalities (flashed slide)

- Production (SM)
- Decay (SM)





YR4, arxiv: 1610.07922 [hep-ph]
YR3, arxiv: 1307.1347 [hep-ph]

H→γγ : tiny interference signal/bkg

Signal strengths, scale factor μ, κ framework

- Direct (dis-)agreement SM 🙂
- f(ref.): model, precision ☹
- higher sys. error ☹

$\mu = (\sigma x BR)/(\sigma x BR)_{SM}$

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

Simplified Template Cross-Section (STXS)

- 'Simplified' : indep. decay mode 🙂
  →easy to combine $\sigma(i \to H)_{\text{phase space (truth bins)}}$
- $(\varepsilon x A)_{if}$ from SM : assummed template in fits
- Reduced th. sys. error 🙂
- region detector acceptance $|y_H|<2.5$ 🙂

no extrapolation full phase space
→reduced model dependency 🙂

- Enhance sensitivity for BSM models
- =f(experimental acceptance simulation)

Fiducial / differential cross-sections

- Specific to decay mode ☹
  →not easy to combine

$\sigma(i \to H \to j)_{\text{phase space}}$ 🙂

- region detector acceptance

no extrapolation full phase space 🙂
Fiducial region as close as reco selection level→tiny model dependency

- Reduced th. syst. error (no ref.)

Inputs : ATLAS-CONF-2021-053 vs Nature

ATLAS, Run 2, L=36.1-139 fb^{-1}, ATLAS-CONF-2021-053

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]	Ref.	Used in combined measurement
$H\to\gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	[10]	Everywhere
$H\to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139	[11]	Everywhere
	$t\bar{t}H$	36.1	[19]	Everywhere but STXS and SMEFT
$H\to WW^*$	ggF, VBF	139	[12]	Everywhere
	$t\bar{t}H$	36.1	[19]	Everywhere but STXS and SMEFT
$H\to\tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139	[13]	Everywhere
	$t\bar{t}H$	36.1	[19]	Everywhere but STXS and SMEFT
$H\to b\bar{b}$	WH, ZH	139	[14,15,16]	Everywhere
	VBF	126	[17]	Everywhere
	$t\bar{t}H$	139	[18]	Everywhere
$H\to\mu\mu$	ggF, VBF, $VH, t\bar{t}H$	139	[20]	Everywhere but STXS and SMEFT
$H\to Z\gamma$	ggF, VBF, $VH, t\bar{t}H$	139	[21]	Everywhere but STXS and SMEFT
$H\to inv$	VBF	139	[22]	Sec. 6.2 & 6.3

ATLAS, Run 2, L=36.1-139 fb^{-1}, Nature, 607, 52 (2022)

Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]	Ref.	Fits deployed in
$H\to\gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	[31]	All
$H\to ZZ$	ggF, VBF, $WH+ZH, t\bar{t}H+tH$	139	[28]	All
	$t\bar{t}H+tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H\to WW$	ggF, VBF	139	[29]	All
	WH, ZH	36.1	[30]	All but fit of kinematics
	$t\bar{t}H+tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H\to Z\gamma$	inclusive	139	[32]	All but fit of kinematics
$H\to b\bar{b}$	WH, ZH	139	[33, 34]	All
	VBF	126	[35]	All
	$t\bar{t}H+tH$	139	[36]	All
	inclusive	139	[37]	Only for fit of kinematics
$H\to\tau\tau$	ggF, VBF, $WH+ZH, t\bar{t}H+tH$	139	[38]	All
	$t\bar{t}H+tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H\to\mu\mu$	ggF + $t\bar{t}H+tH$, VBF + $WH+ZH$	139	[40]	All but fit of kinematics
$H\to c\bar{c}$	$WH+ZH$	139	[41]	Only for free-floating κ_c
$H\to$ invisible	VBF	139	[42]	κ models with $B_{\text{u.}}$ & $B_{\text{inv.}}$
	ZH	139	[43]	κ models with $B_{\text{u.}}$ & $B_{\text{inv.}}$

Higgs detailed map (STXS, κ)

- Inputs pp→ii→ff

ATLAS, Run 2, L=36-139 fb^{-1}, Nature 607, 52 (2022)

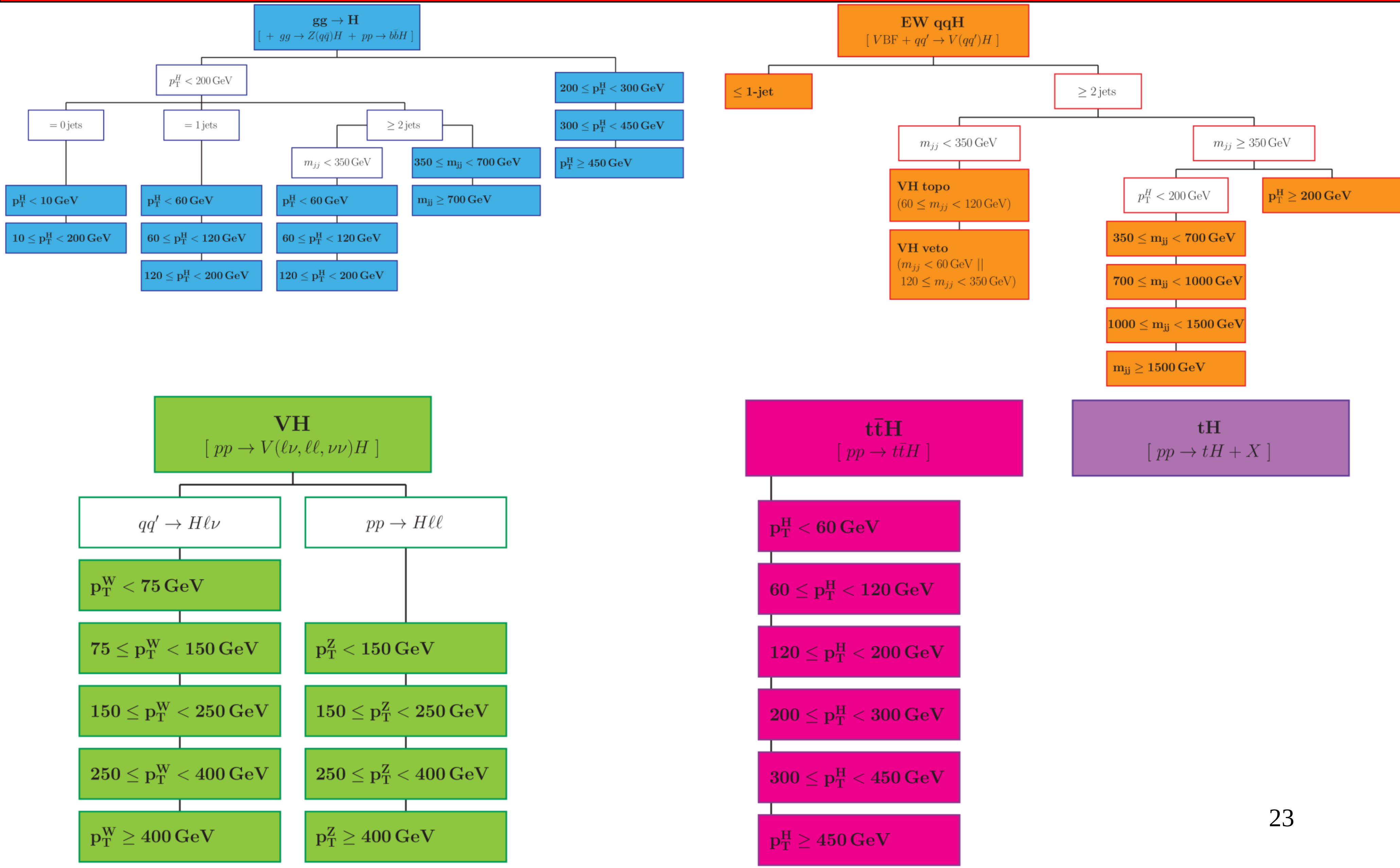
-Higgs

Various prod. modes & kinematics (STXS) various decays Luminosity application

(allows dσ/dX per prod. mode)

Targeted production processes	Decay mode	$\mathcal{L}$ [fb^{-1}]	Fits deployed in
ggF, VBF, $WH, ZH, t\bar{t}H, tH$	$H \to \gamma\gamma$	139	All
ggF, VBF, $WH+ZH, t\bar{t}H+tH$	$H \to ZZ$	139	All
$t\bar{t}H+tH$ (multilepton)		36.1	All but fit of kinematics
ggF, VBF	$H \to WW$	139	All
WH, ZH		36.1	All but fit of kinematics
$t\bar{t}H+tH$ (multilepton)		36.1	All but fit of kinematics
inclusive	$H \to Z\gamma$	139	All but fit of kinematics
WH, ZH	$H \to b\bar{b}$	139	All
VBF		126	All
$t\bar{t}H+tH$		139	All
inclusive		139	Only for fit of kinematics
ggF, VBF, $WH+ZH, t\bar{t}H+tH$	$H \to \tau\tau$	139	All
$t\bar{t}H+tH$ (multilepton)		36.1	All but fit of kinematics
ggF + $t\bar{t}H+tH$, VBF + $WH+ZH$	$H \to \mu\mu$	139	All but fit of kinematics
$WH+ZH$	$H \to c\bar{c}$	139	Only for free-floating κ_c
VBF	$H \to$ invisible	139	κ models with $B_{u.}$ & $B_{inv.}$
ZH		139	κ models with $B_{u.}$ & $B_{inv.}$

Couplings Combination Run 2

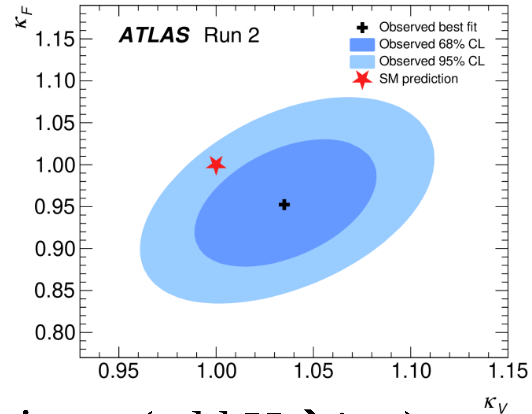


Coupling strength modifiers

- coupling strength modifiers (κ framework, no $Z\gamma$, $\mu\mu$)

1) boson/fermion symmetry

κ_V=1.035 ± 0.031, κ_F=0.95 ± 0.05



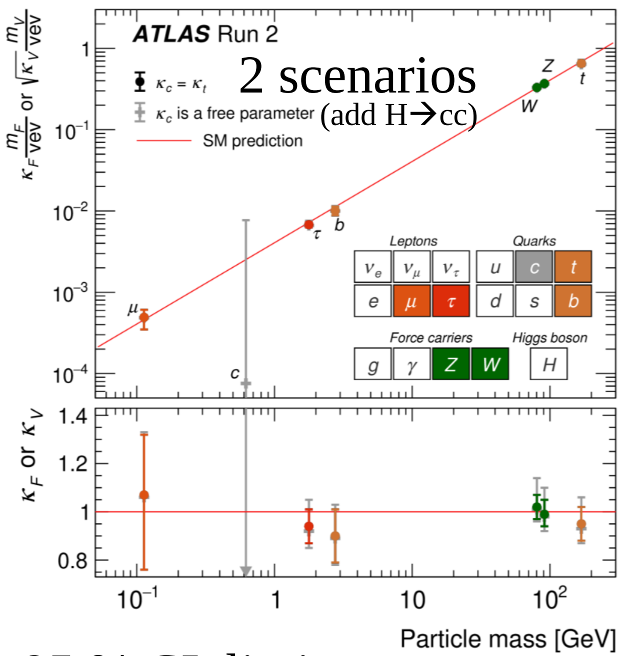
2) κ treated independently (no invisible/undetected)

Scaling of coupling with mass

(reduced H couplings to f, V)

2 scenarios

(add H→cc)

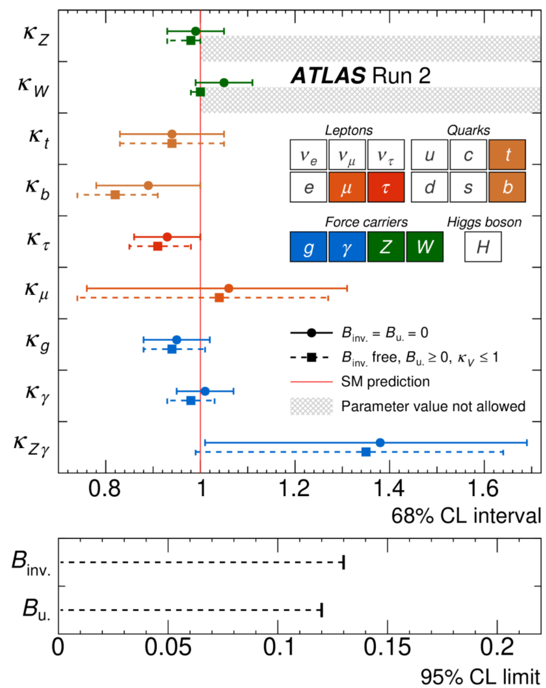


95 % CL limit on κ_c

obs: <5.7xSM (exp: <7.6xSM)

3) generic parametrisation (add H→inv)

allow non-SM: effective couplings for loops



-wo/ invisible/undetected

$$\kappa_H^2(\boldsymbol{\kappa}, B_{i.}, B_{u.}) = \frac{\sum_j B_j^{SM}\kappa_j^2}{(1 - B_{i.} - B_{u.})}$$

-w/ invisible/undetected

BR_i (≠SM), BR_u (light q, low MET)

degeneracy: $\kappa_W \leq 1$, $\kappa_Z \leq 1$

BR_{inv} obs: <0.13 (exp: <0.08)

BR_{un} obs: <0.12 (exp: <0.21)

κ→2HDM

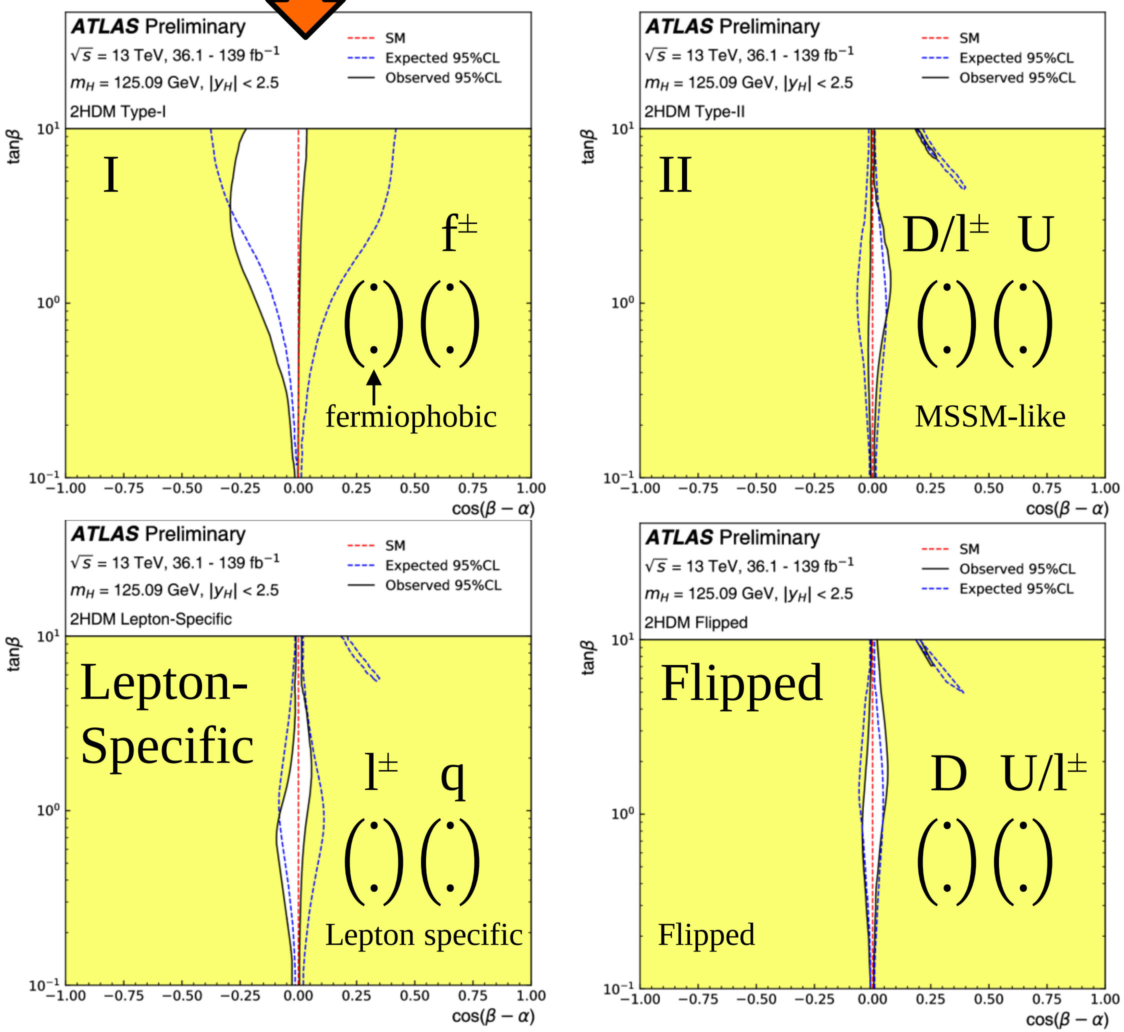
(inputs: no H→cc)
a bit less prod. modes

- κ→2HDM

ATLAS, Run 2, L=36.1-139 fb^{-1}, ATLAS-CONF-2021-053

Coupling modifiers→2HDMs, H_{125}: assumed≈couplings H_{SM}, changes: f(α, tan β)
Limits Couplings=f(cos(β-α), tan β)

	type I	type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$



- Compatible w/ alignment limit:
  cos (β-α)=0
  $H_{VV}=H_{VV}^{SM}$, $Hff=H_{ff}^{SM}$
- Best fit not shown
(limited sensitivity in tan β)
- petals: Hff: same magnitude, sign≠

Combination STXS→SMEFT

- Inputs   pp→ii→ff   ATLAS, Run 2, L=36-139 fb^{-1}, ATL-PHYS-PUB-2022-037

-Higgs

Various production modes & kinematics (STXS)   various decays

(allows dσ/dX per prod. mode)

Target Production Modes	Decay channel	$\mathcal{L}$ [fb^{-1}]
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \to \gamma\gamma$	139
ggF, VBF, WH, ZH, $t\bar{t}H$ (4ℓ)	$H \to ZZ^*$	139
ggF, VBF	$H \to WW^*$	139
ggF, VBF, WH, ZH, $t\bar{t}H$ ($\tau_{\text{had}}\tau_{\text{had}}$)	$H \to \tau\tau$	139
WH, ZH		139
VBF	$H \to b\bar{b}$	126
$t\bar{t}H$		139

-≠Higgs (-dσ/dX EW, EW observables : LEP, SLD)

Prod. & decay : parametrised→ c_i (CP-even, real), SMEFT, Warsaw basis

ATLAS constraints on 24 c_i/eigenvectors(c_i) : linear+quadratic

(28 when adding LEP+SLD) : linear

Combination STXS→SMEFT

ATLAS, Run 2, L=36-139 fb^{-1}, ATL-PHYS-PUB-2022-037

$$\sigma = |\mathcal{A}_{SM}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_{SM}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4} \left|\mathcal{A}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)*}\right)$$

interf. SM-d6 — Linear (in c_i)

pure d6 — Quadratic (in c_i)

interf. d6-d6 — Cross-terms

+pure Λ^{-4}
+interf SM-dim 8
→neglected

- Linear vs linear+quadratic: qualitative measure of missing $O(\Lambda^{-4})$
- NWA: factorize production/decays

$$O_b = O_b^{SM}\left(1 + \sum_i A_{bi} c_i + \sum_i B_{bi} c_i^2 + \sum_{i<j} C_{bi} c_i c_j\right)$$

linear — quadratic — cross-terms

- Input parameter scheme: m_W, m_Z, G_F
- Symmetry topU3l: relax t, b

$$U(2)_q \times U(2)_u \times U(2)_d \times U(3)_l \times U(3)_e$$

2 first generations quarks treated similarly
3rd generation quarks: no symmetry

All lepton generations treated similarly

Λ=1 TeV, reinterpretation Λ': $c_i \rightarrow x(\Lambda/\Lambda')^2$

Combination STXS→SMEFT

Wilson coefficients/operators probed by Higgs channels

pure bosonic

$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$
c_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$
c_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
c_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$

3H+f

c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
c_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u\tilde{H})$
c_{tH}	$(H^\dagger H)(\bar{Q}\tilde{H}t)$
c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$

2H+f

$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l)$
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$
$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$

1H+G+f

c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{H}\,G_{\mu\nu}^A$
c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\tilde{H}\,W_{\mu\nu}^I$
c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\tilde{H}\,B_{\mu\nu}$

light q & Q

$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$
$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$
$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$
$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$
$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$
$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$
$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$
$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$
$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$

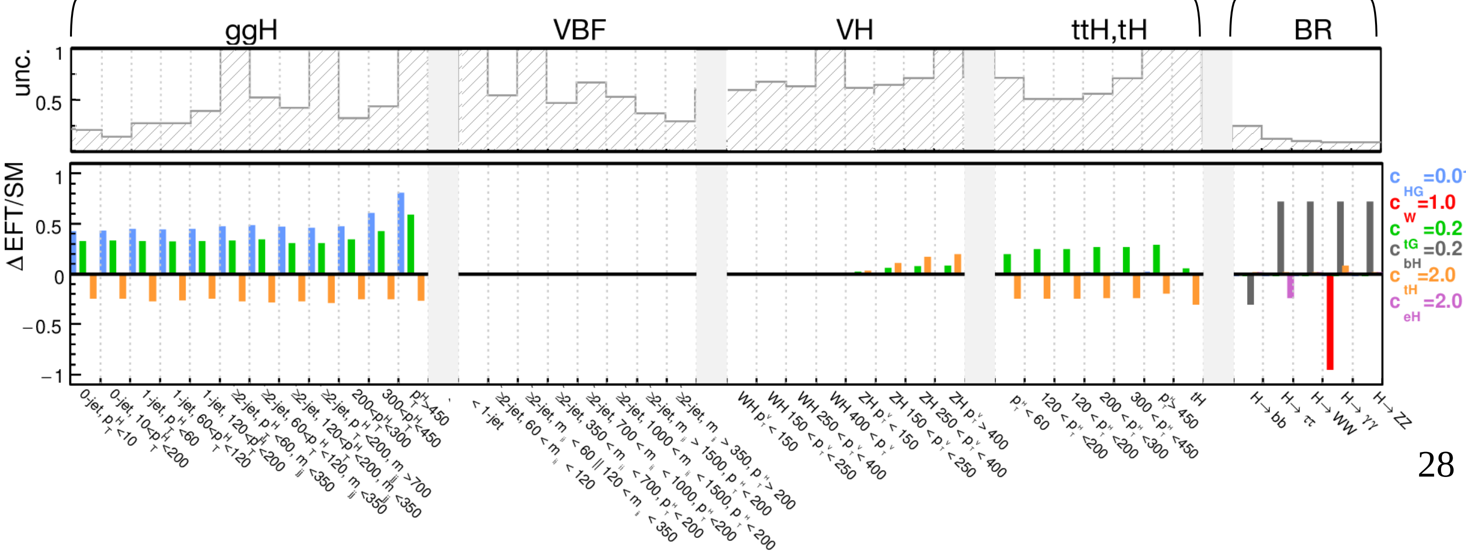
Some common & additional c_i for dσ/dX EW (ATLAS), EW observables (LEP, SLD)

- Impact c_i (linear) on STXS & BR

STXS　　BR

rel. uncertainty measurement →

Impact c_i →



Combination STXS+decay→SMEFT, Warsaw basis

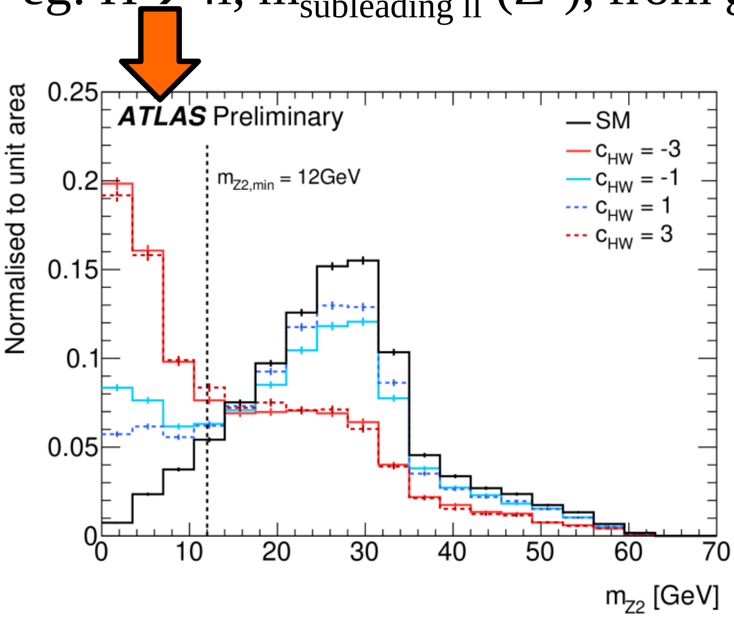
Assumptions STXS : independent of c_i: {signal acceptance/efficiency, signal shape, bkg}

≈ true: partition in regions of similar kinematics

no more true for decay:

eg: H→4l, $m_{\text{subleading ll}}$ (Z^*), from gg→H→4l, assumed valid for all prod. modes)

parametrise in fiducial cuts



- Simulation EFT

Basis samples c_i

Tree level/LO: Madgraph/SMEFTSim

Loops gg→H, gg→ZH, H→gg: SMEFT@NLO

H→γγ: analytic computation

Higher order corrections : factorize from SM

- Systematics

Common systematics treated correlated among channels

Combination EFT

ATLAS, Run 2, L=36-139 fb^{-1}, ATL-PHYS-PUB-2022-037

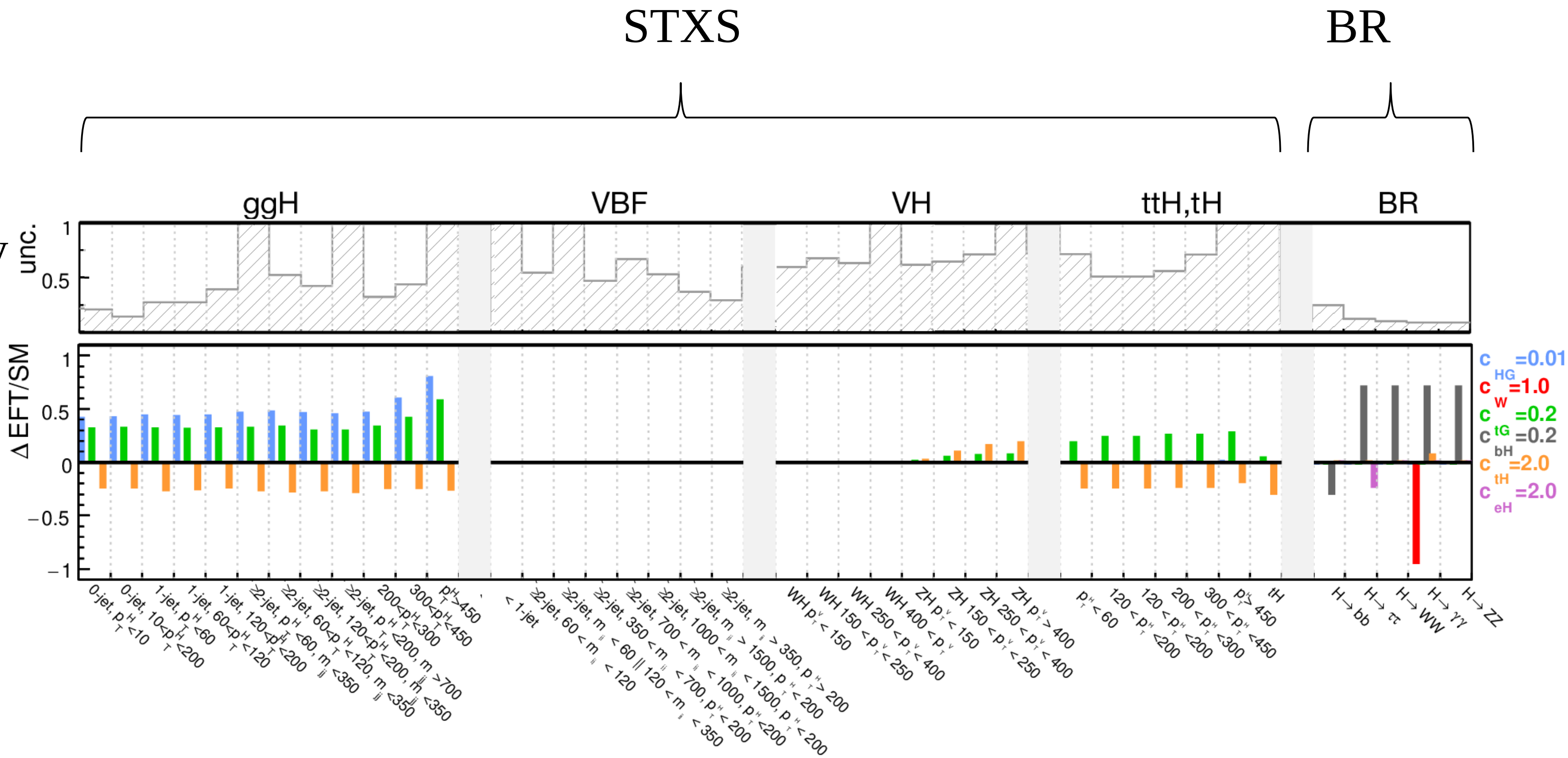
Wilson coefficient and operator		Affected process group: LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$		✓	
c_G	$f^{abc}G_\mu^{a\nu}G_\nu^{b\rho}G_\rho^{c\mu}$		✓	✓
c_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$		✓	✓
c_{HD}	$\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D_\mu H\right)$		✓	✓
c_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$		✓	
c_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$		✓	
c_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$		✓	
c_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	✓	✓	✓
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$		✓	
c_{uH}	$(H^\dagger H)(\bar{q}Y_u^\dagger u\widetilde{H})$		✓	
c_{tH}	$(H^\dagger H)(\bar{Q}\widetilde{H}t)$		✓	
c_{bH}	$(H^\dagger H)(\bar{Q}Hb)$		✓	
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$	✓	✓	✓
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l)$	✓	✓	✓
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$	✓	✓	✓
$c_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q)$	✓	✓	✓
$c_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q)$	✓	✓	✓
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$	✓	✓	✓
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$	✓	✓	✓
$c_{HQ}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$	✓	✓	
$c_{HQ}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$	✓	✓	
c_{Hb}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{b}\gamma^\mu b)$	✓		
c_{Ht}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$	✓	✓	
c_{tG}	$(\bar{Q}\sigma^{\mu\nu}T^A t)\widetilde{H}\, G_{\mu\nu}^A$		✓	
c_{tW}	$(\bar{Q}\sigma^{\mu\nu}t)\tau^I\widetilde{H}\, W_{\mu\nu}^I$		✓	
c_{tB}	$(\bar{Q}\sigma^{\mu\nu}t)\widetilde{H}\, B_{\mu\nu}$		✓	
c_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	✓		✓

Wilson coefficient and operator		Affected process group: LEP/SLD EWPO	ATLAS Higgs	ATLAS electroweak
$c_{lq}^{(1)}$	$(\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q)$			✓
$c_{lq}^{(3)}$	$(\bar{l}\gamma_\mu\tau^I l)(\bar{q}\gamma^\mu\tau^I q)$			✓
c_{eu}	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$			✓
c_{ed}	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$			✓
c_{lu}	$(\bar{l}\gamma_\mu l)(\bar{u}\gamma^\mu u)$			✓
c_{ld}	$(\bar{l}\gamma_\mu l)(\bar{d}\gamma^\mu d)$			✓
c_{qe}	$(\bar{q}\gamma_\mu q)(\bar{e}\gamma^\mu e)$			✓
$c_{qq}^{(1,1)}$	$(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$			✓
$c_{qq}^{(1,8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{q}T^a\gamma^\mu q)$			✓
$c_{qq}^{(3,1)}$	$(\bar{q}\sigma^i\gamma_\mu q)(\bar{q}\sigma^i\gamma^\mu q)$			✓
$c_{qq}^{(3,8)}$	$(\bar{q}\sigma^i T^a\gamma_\mu q)(\bar{q}\sigma^i T^a\gamma^\mu q)$			✓
$c_{uu}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$			✓
$c_{uu}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{u}T^a\gamma^\mu u)$			✓
$c_{dd}^{(1)}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$			✓
$c_{dd}^{(8)}$	$(\bar{d}T^a\gamma_\mu d)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{ud}^{(1)}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$			✓
$c_{ud}^{(8)}$	$(\bar{u}T^a\gamma_\mu u)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{qu}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{u}\gamma^\mu u)$			✓
$c_{qu}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{u}T^a\gamma^\mu u)$			✓
$c_{qd}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{d}\gamma^\mu d)$			✓
$c_{qd}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{d}T^a\gamma^\mu d)$			✓
$c_{Qq}^{(1,1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q)$		✓	
$c_{Qq}^{(1,8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{q}T^a\gamma^\mu q)$		✓	
$c_{Qq}^{(3,1)}$	$(\bar{Q}\sigma^i\gamma_\mu Q)(\bar{q}\sigma^i\gamma^\mu q)$		✓	
$c_{Qq}^{(3,8)}$	$(\bar{Q}\sigma^i T^a\gamma_\mu Q)(\bar{q}\sigma^i T^a\gamma^\mu q)$		✓	
$c_{tu}^{(1)}$	$(\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u)$		✓	
$c_{Qu}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$		✓	
$c_{Qu}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{u}T^a\gamma^\mu u)$		✓	
$c_{Qd}^{(1)}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$		✓	
$c_{Qd}^{(8)}$	$(\bar{Q}T^a\gamma_\mu Q)(\bar{d}T^a\gamma^\mu d)$		✓	
$c_{tq}^{(1)}$	$(\bar{q}\gamma_\mu q)(\bar{t}\gamma^\mu t)$		✓	
$c_{tq}^{(8)}$	$(\bar{q}T^a\gamma_\mu q)(\bar{t}T^a\gamma^\mu t)$		✓	

Appendix impact c_i (linear) on STXS & BR

rel. uncertainty measurement

Impact c_i



EFT implementation

- Higgs sector

Category b, considered as an histogram bin

$$L(N|\boldsymbol{c},\boldsymbol{\theta}) = \prod_{b}^{n_{\text{bins}}} \text{Poisson}\left(N_b \middle| N_b^{\text{pred}}(\boldsymbol{c},\boldsymbol{\theta})\right) \times \prod_{i}^{n_{\text{syst}}} f_i(\theta_i)$$

constraints on systematics

pp→ii→ff

$$N_b^{\text{pred}}(\boldsymbol{c},\boldsymbol{\theta}) = \sum_p \sum_d N_b^{pd,\text{SM}}(\boldsymbol{\theta}) \left(1 + \sum_i A_{bi}^{pd} c_i + \sum_i B_{bi}^{pd} c_i^2 + \sum_{i<j} C_{bij}^{pd} c_i c_j\right) + N_b^{\text{bkg,SM}}(\boldsymbol{\theta})$$

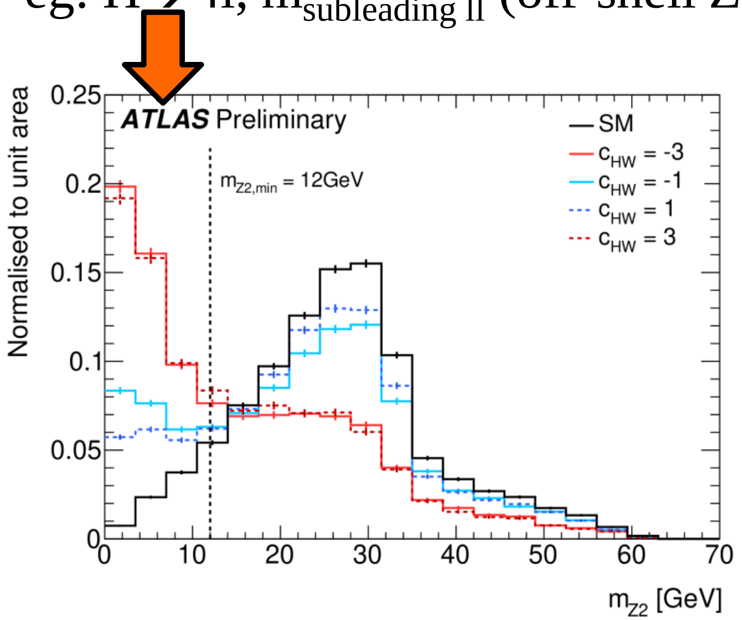
signal ... bkg

Assumptions STXS : signal acceptance/efficiencies, signal shape, bkg independent: c_i

≈ true for H→2 bodies: partition in regions of similar kinematics

Decays : no more true : parametrise EFT effect acceptance & shape

eg: H→4l, $m_{\text{subleading ll}}$ (off-shell Z), from gg→H→4l, assumed valid for all prod. modes)



EW sector: some exceptions of parametrisation acceptance

- Simulation EFT

Basis samples c_i

Tree level/LO: Madgraph/SMEFTSim

Loops gg→H, gg→ZH, H→gg: SMEFT@NLO

H→γγ: analytic computation

Higher order corrections : factorize from SM

Propagators corrections linear expansion

(quadratic neglected)

EFT implementation

- EW sector: likelihood from gaussian from $\sigma_{fit}=f(c_i, \theta)$
- Scan test stat: profile likelihood ratio

$$q(c_i) = -2\log \frac{L\left(\boldsymbol{x}\middle|c_i, \hat{\hat{\theta}}\right)}{L\left(\boldsymbol{x}\middle|\hat{c}_i, \hat{\theta}\right)}$$

→Confidence Interval (Wilks theorem, χ^2 distribution)

- Systematics

Common nuisance parameters for systematics of various channels

Luminosity : split : 1 correlated, 1 for 2015/2016, 1 for 2017/2018

PU modelling/eff PU suppression: correlated

Some uncertainties correlated among sectors (some components of JES, etc.)

Combination STXS→SMEFT

- Results ATLAS inputs (Higgs + dσ/dX EW):

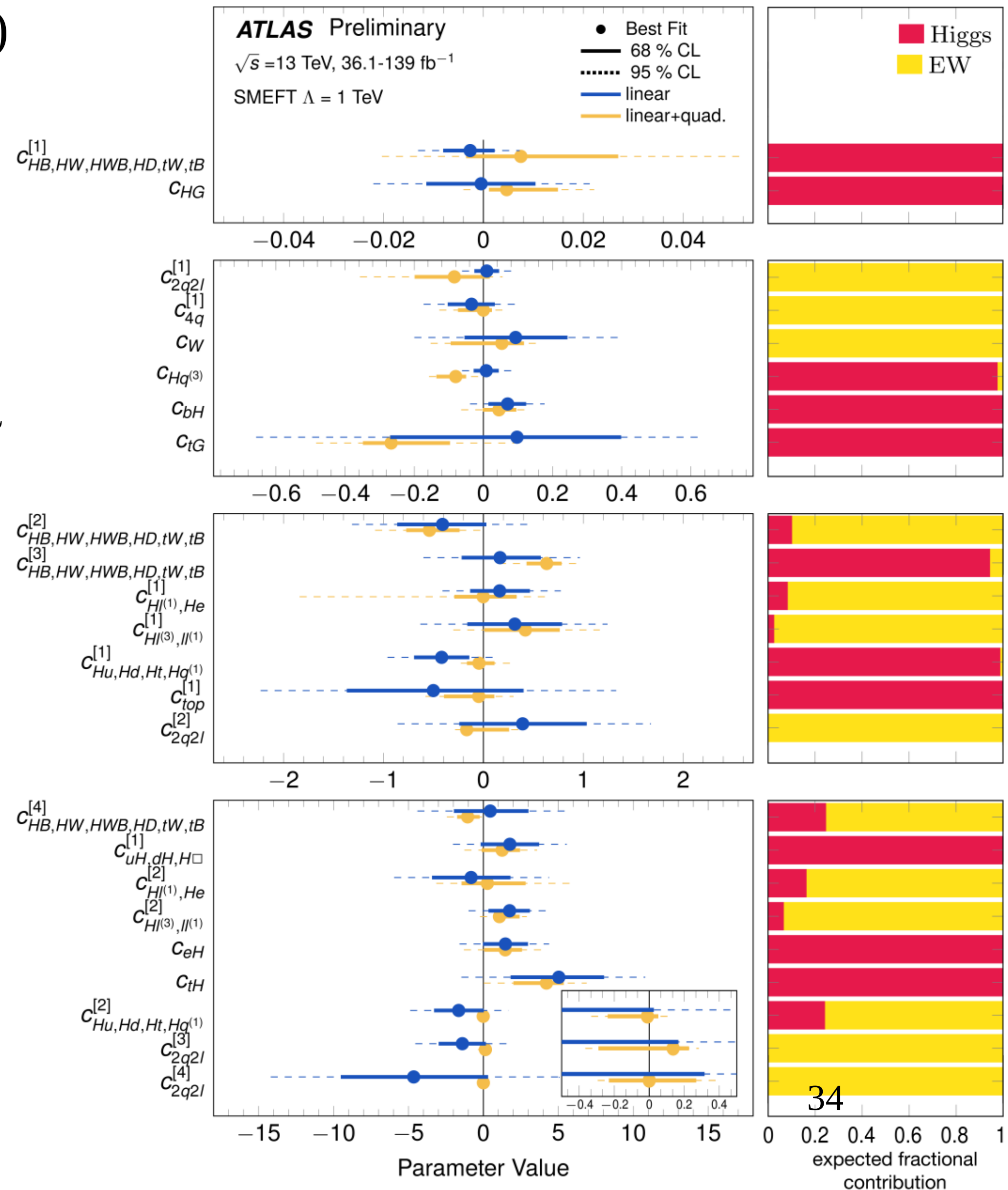
individual and eigenvectors (else no sensitivity)
-orthogonal subsets affecting some observable
-PCA operators within group
$f(c_i) \rightarrow \mu_b$
Hessian matrix H_μ, change of basis matrix A
$H_{SMEFT} = A^T H_\mu A$
expected uncertainty σ; eigenvalues λ: $\sigma = 1/\sqrt{\lambda}$

- additional results: …+LEP+SLD
- Simplified likelihood: very good agreement

$$L(\mu) = \frac{1}{\sqrt{(2\pi)^{n_\mu} \det(V_\mu)}} \exp\left(-\frac{1}{2}\Delta\mu^T V_\mu^{-1} \Delta\mu\right)$$

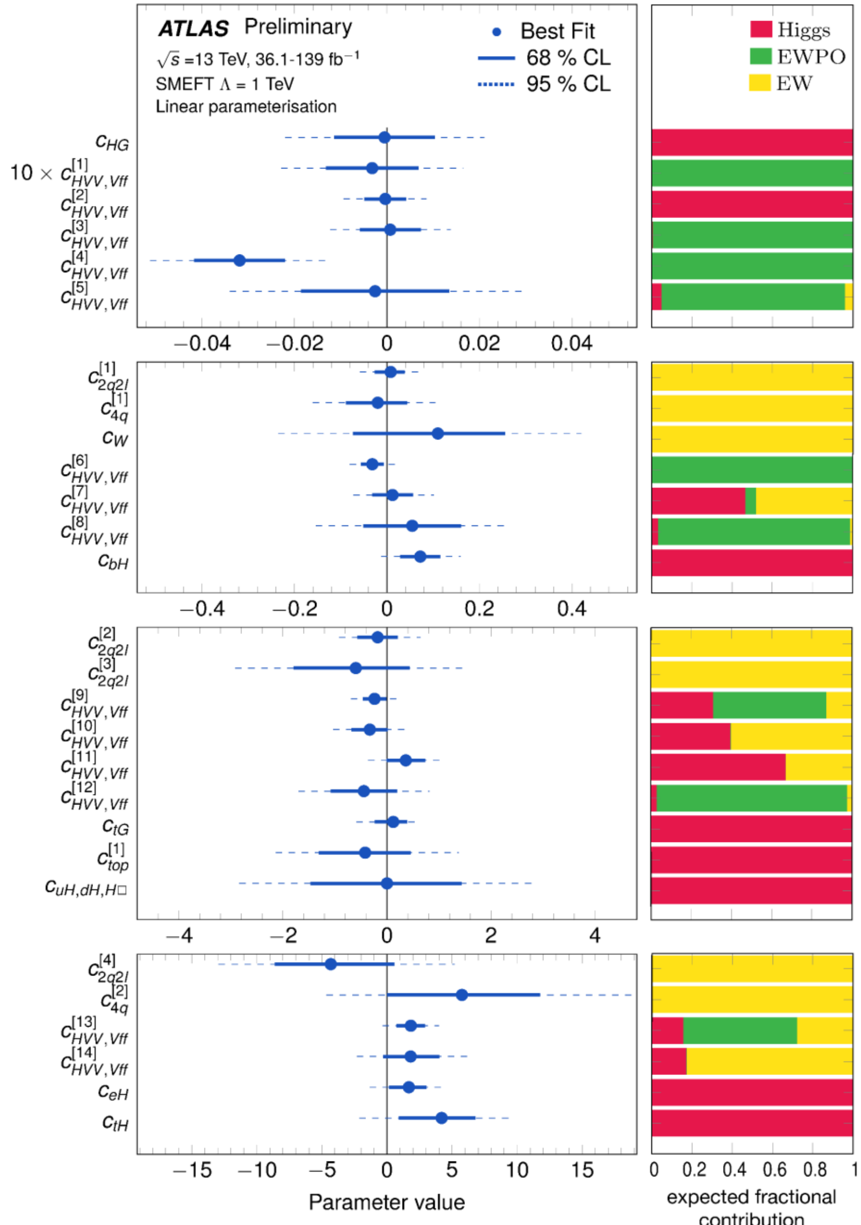
$$\Delta\mu = \mu - \hat{\mu}$$

μ=f(SMEFT)

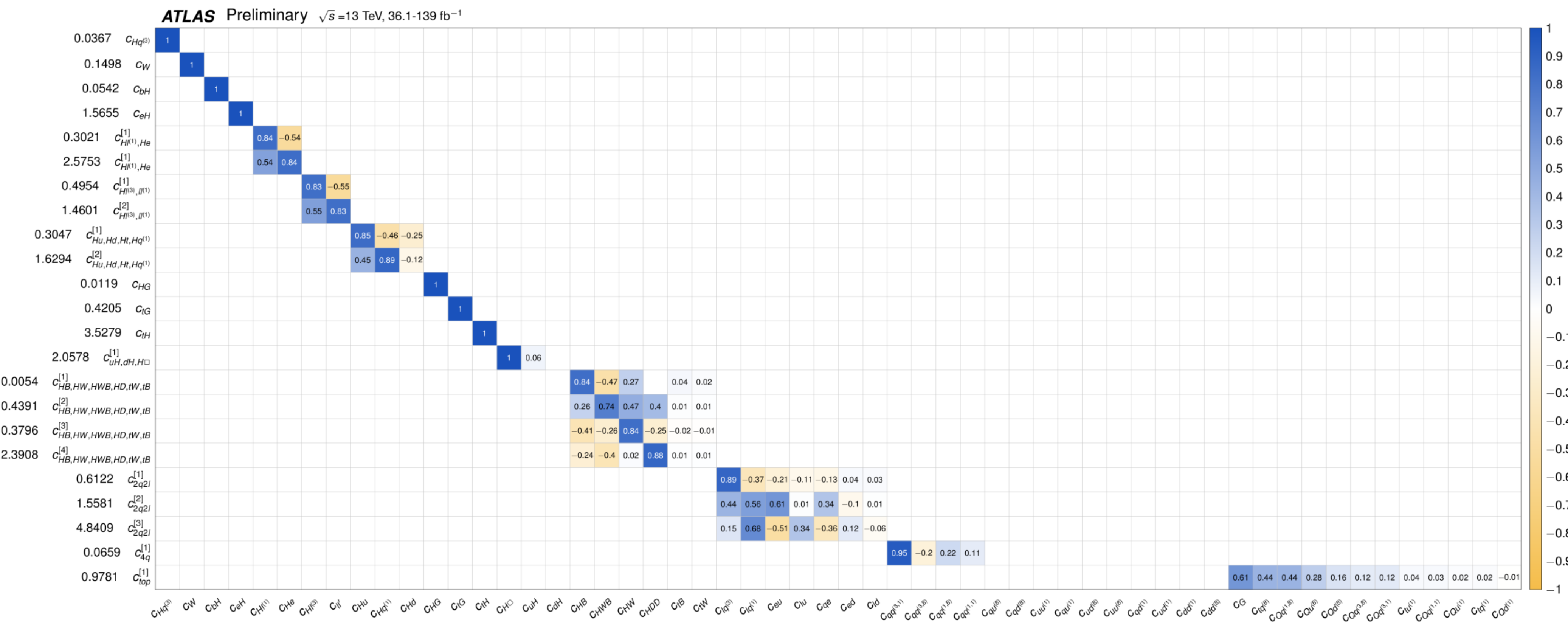


Combination EFT

ATLAS, Run 2, L=36-139 fb^{-1}, ATL-PHYS-PUB-2022-037



Appendix combination STXS→SMEFT



σ_{fid}, $d\sigma_{fid}/dX$

ATLAS, Run 2, L=139 fb^{-1}, CERN-EP-2022-143

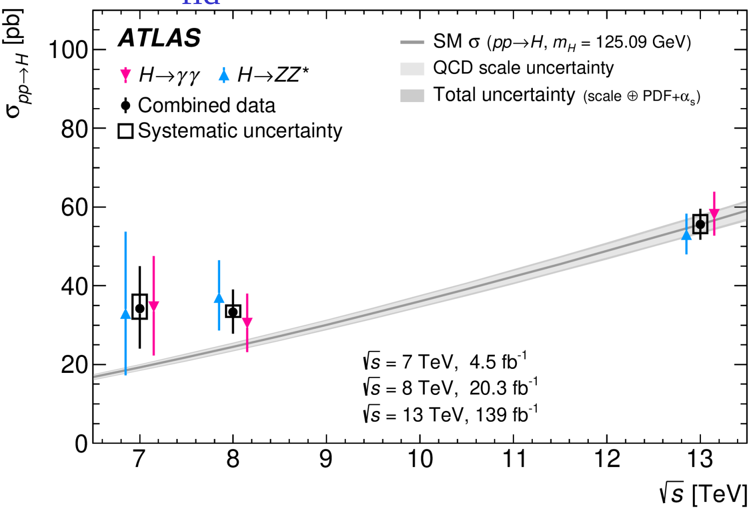
- Inputs

H→γγ, H→ZZ*→4l   Channels compatible

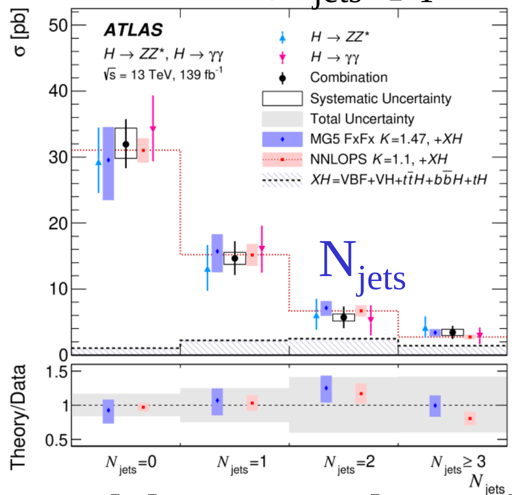
- Systematics

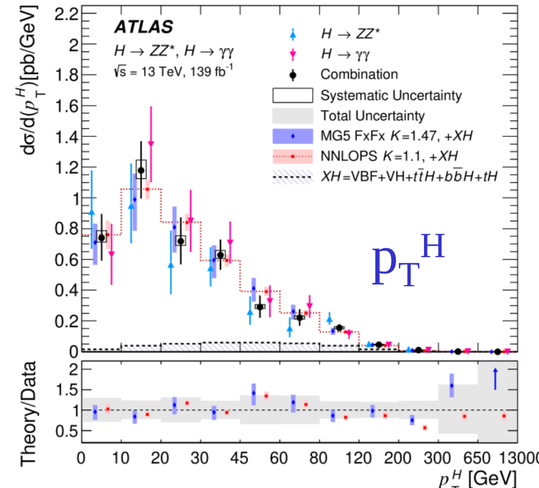
Dominated by stat. uncertainties ; Experimental & theoretical uncertainties correlated

- σ_{fid}



- $d\sigma/dX$ (N_{jets}, $p_T^{lead.\ jet}$, $|y_H|$, p_T^H)





model. QCD rad., prod. modes   perturbative QCD

JES/JER important

- Sensitivity Yukawa Hcc, Hbb

loop(ggH, Γ(H→γγ), thus BRs), qq, qg

normalization & shape of p_T^H

Channel	Parameter	Observed 95% confidence interval	Expected 95% confidence interval
Combined	κ_b	[−1.09, −0.86] ∪ [0.81, 1.09]	[−1.14, −0.92] ∪ [0.86, 1.15]
	κ_c	[−2.27, 2.27]	[−2.77, 2.75]

- Combination w/ VH(bb, cc)

Jet energy, flav. tagging not correlated: (clustering ≠)

Scenario	Observed 68% confidence interval	Observed 95% confidence interval
$B_{BSM} = 0$	[−1.61, 1.70]	[−2.47, 2.53]
No assumption on B_{BSM}	[−2.63, 3.01]	[−4.46, 4.81]

Best κ_c constraint

σ_{fid}, $d\sigma_{fid}/dX$

ATLAS, Run 2, L=139 fb^{-1}, CERN-EP-2022-143

- Inputs

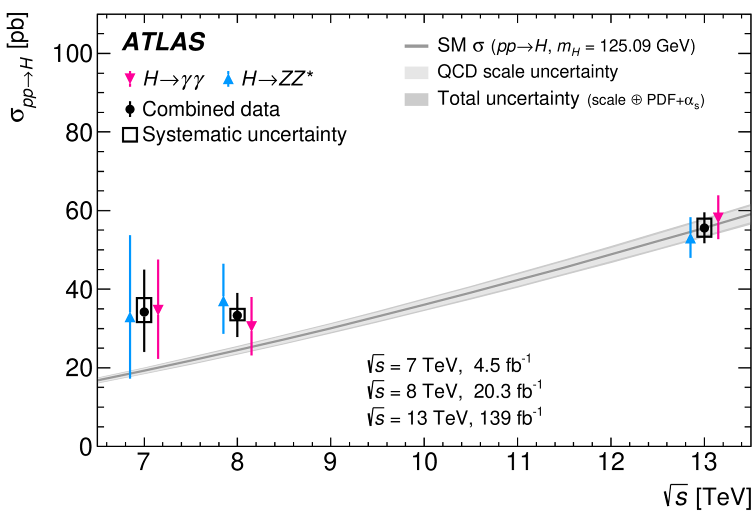
$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$

- Systematics

Acceptance/response matrix: correlate theory unc. (QCD, pdf, PS, composition signal)
Experimental & theoretical uncertainties correlated
Dominated by stat. uncertainties
Dominant systematics: bkg modelling ($H \rightarrow \gamma\gamma$), luminosity
N_{jets}, $p_T^{lead. jet}$: JES/JER important
Dominant th: PS ggF

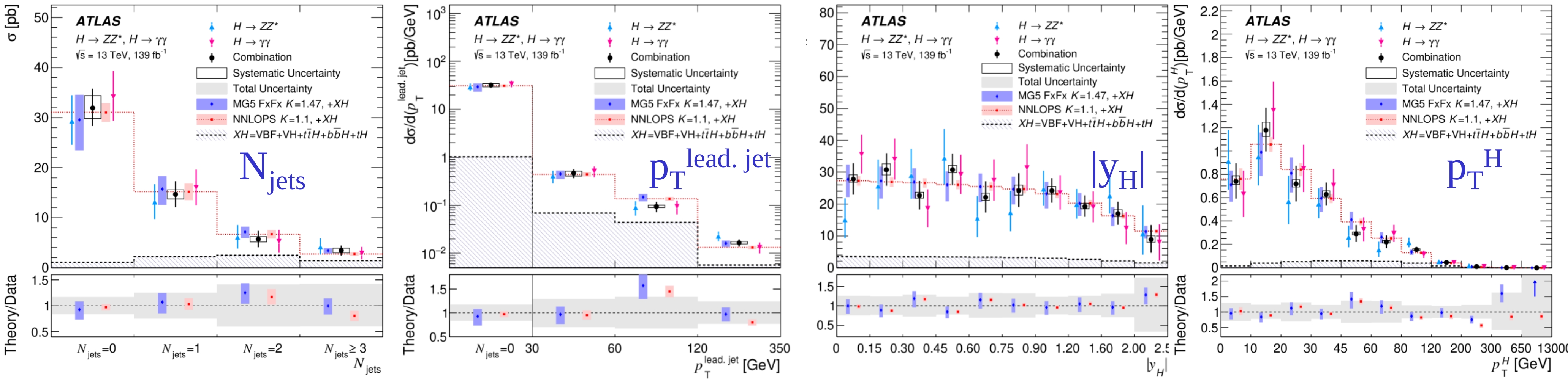
- Fiducial cross-section

Compatibility p-value=0.98



σ_{fid}, $d\sigma_{fid}/dX$

- $d\sigma/dX$



th. model. QCD radiation, prod. modes — pdf — perturbative QCD

Channels compatible

- Sensitivity Yukawa Hcc, Hbb:

loop(ggH, Γ(H→γγ), thus BRs), qq, qg
normalization & shape of p_T^H (variante : shape only)

- Combination w/ VH(bb, cc)

Jet energy & flavour tagging not correlated: ≠jet clustering

Channel	Parameter	Observed 95% confidence interval	Expected 95% confidence interval
Combined	κ_b	$[-1.09, -0.86] \cup [0.81, 1.09]$	$[-1.14, -0.92] \cup [0.86, 1.15]$
	κ_c	$[-2.27, 2.27]$	$[-2.77, 2.75]$

Scenario	Observed 68% confidence interval	Observed 95% confidence interval
$B_{BSM} = 0$	$[-1.61, 1.70]$	$[-2.47, 2.53]$
No assumption on B_{BSM}	$[-2.63, 3.01]$	$[-4.46, 4.81]$

Most stringent constraint κ_c

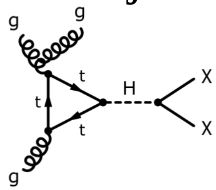
H→invisible

- SM: BR(H→ZZ*→4ν)=0.1 %

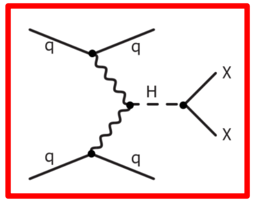
Run 1+2, L=4.7+20.3+139 fb^{-1}, arxiv:2301.10731

Higgs portal SM⇔dark sector, DM χ: MET: indirect

H+j

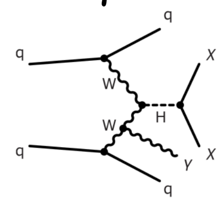


VBF

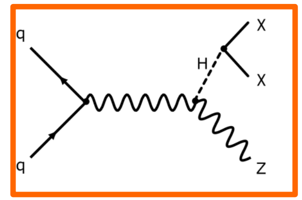


(⊥)

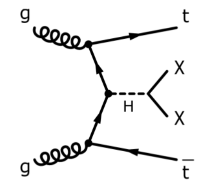
VBF+γ



ZH



ttH



- Correlations

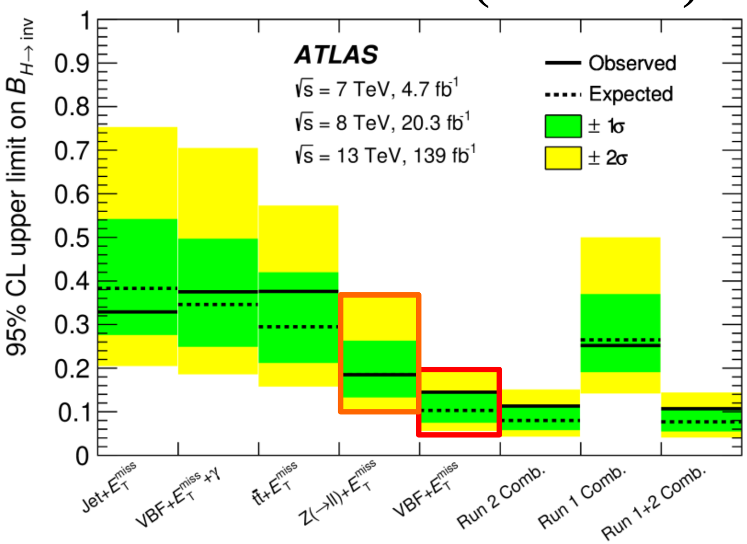
Run 2 : most experim. systematics correlated among channels

Run 1-Run 2: most experim. systematics uncorrelated

detector layout ≠, data-taking ≠⇔data-driven calibration ≠

bkg modelling: improvement in MC & theory

- Limit BR H→inv (95 % CL)

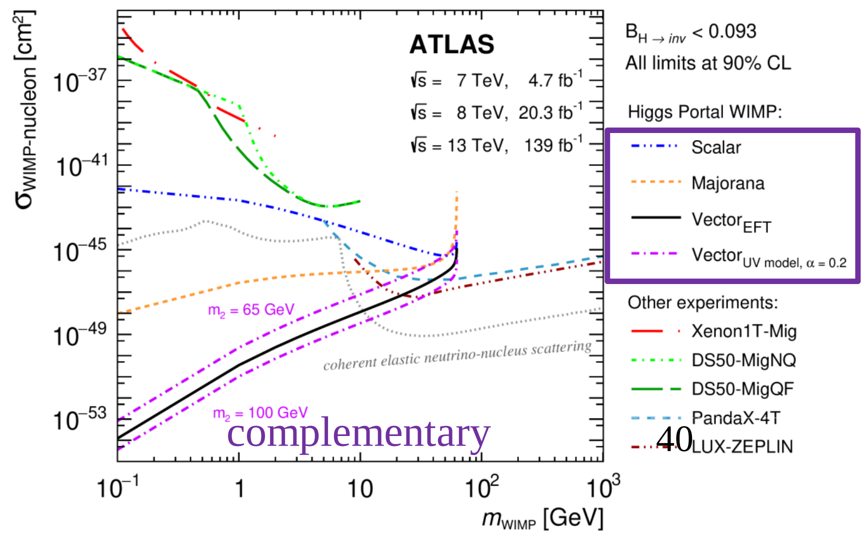


(most stringent results to date)

obs: 0.107

exp: 0.077

- EFT and UV models explored, $m_H \geq 2m_{WIMP}$

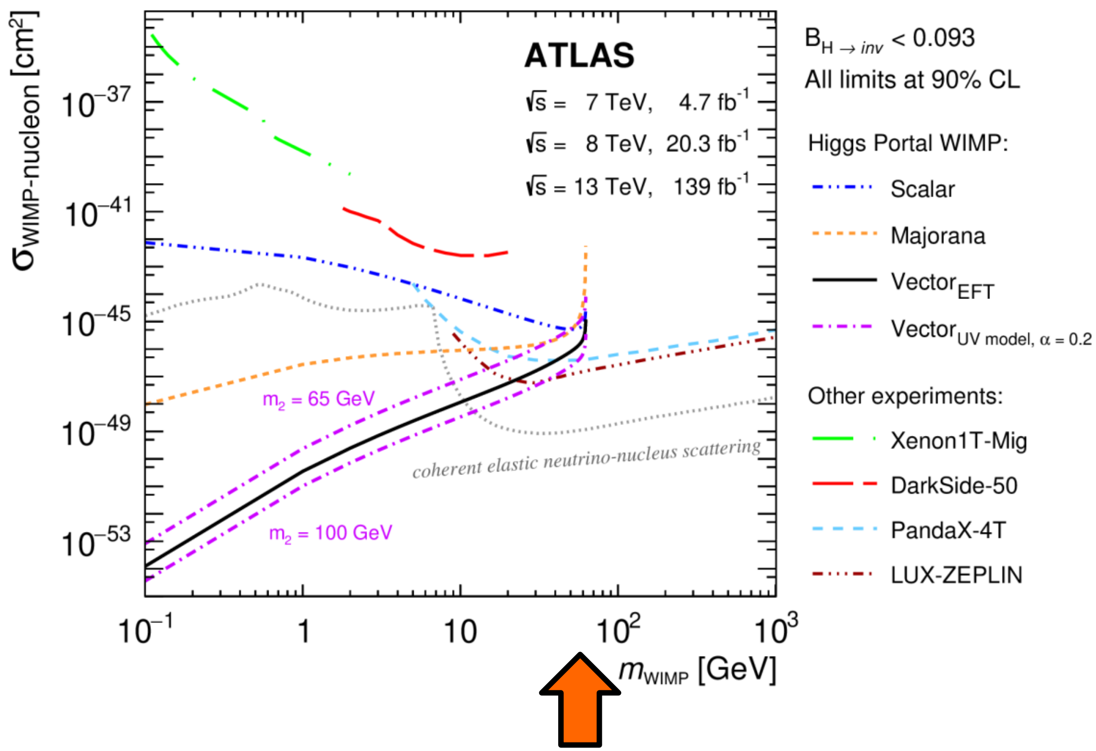


complementary

H→invisible

ATLAS, Run 1+2, L=4.7+20.3+139 fb^{-1}, arxiv:2301.10731

Translated by EFT in spin-independent $\sigma_{\text{WIMP-nucleon}}$
mediator new interactions > TeV>>m_H
Scalar, Majorana, vector



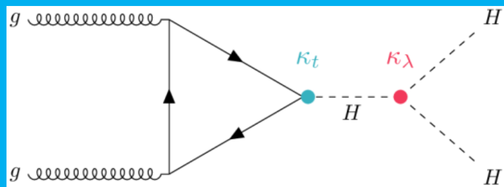
Complementary to direct searches

kinematics: assume $m_{\text{WIMP}}<m_H/2$

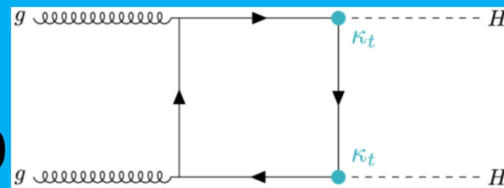
$H_{125}H_{125}$

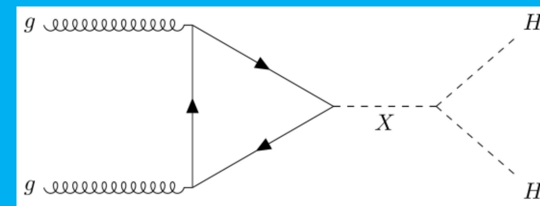
- **Non-resonant** (in the HH)
- **Resonant**

ggF

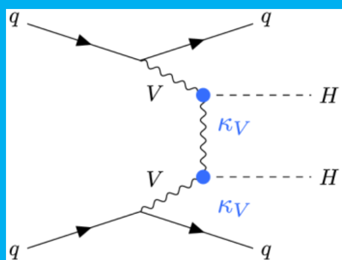


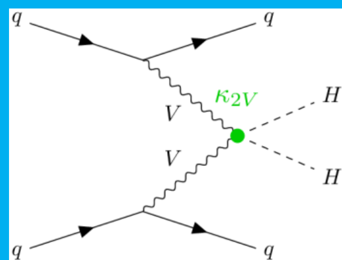
« - »
(SM)

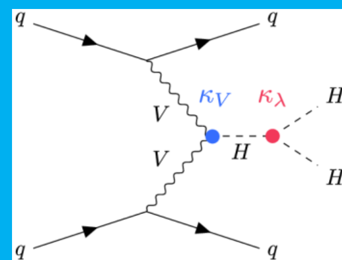


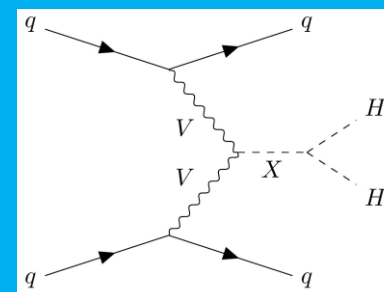


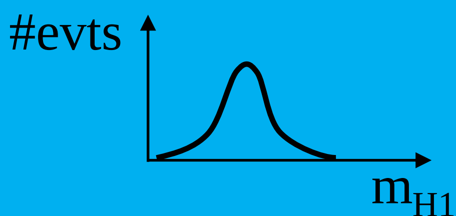
VBF

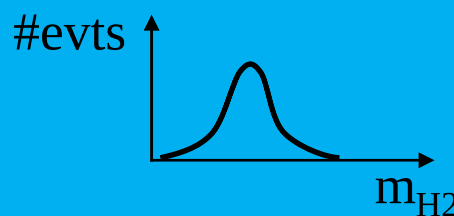


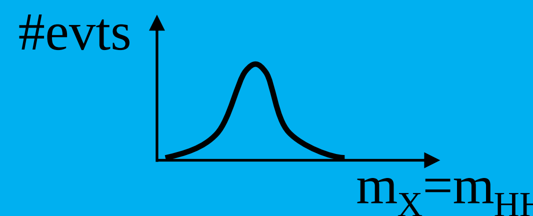












$H_{125}H_{125}$ non resonant: selection

backup

- bbbb

Very high BR (33.9 %)
Largest background (QCD)
=4 b-jets (DL1r, WP 77 %)
top-veto discriminant X_{Wt},
HH discriminant X_{HH}
Final discriminant variable: m_{HH}
-Resonant: resolved (R=0.4)
boosted (R=1.0)
(anti-k_T jets)

- bbγγ

Very low BR (0.26 %)
cleanest signature
=2 γ, 2 b-jets (DL1r, WP 77 %)
Veto e, μ (⊥ other HH w/ leptons)
bkg: continuum γγjj, 1-H
Resonant analysis:
continuum γγjj, non-resonant HH, 1-H
Categories: $m_{\gamma\gamma jj}$, MVA
Final discriminant variable: $m_{\gamma\gamma}$
Resonant : NWA

- bbττ

Large BR (7.3 %)
=2 b-jets (DL1r, WP 77 %)
$\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$: {=1 e/μ + τ_{had}, OS}, or {2 τ_{had} OS, veto e, μ}
Bkg: tt, Z+HF
Final discriminant variable: MVA

Non-Resonant $H_{125}H_{125}$

- Systematics

Data-taking, pile-up mis-modelling, luminosity : correlated
Physics objects : correlated, m_H : correlated
Different methodologies : uncorrelated
Theoretical: correlated ; 1-H vs HH: uncorrelated

Systematics constrained significantly: checked correlation effect: < 2%: take conservative
HH: dominant bkg estimates data-driven: uncorrelated w/ 1-H
negligible impact choice, apart ggF HH: correlation ↓ 7 %: take conservative

HH

Run 2, $\sqrt{s}$=13 TeV, L=126-139 fb^{-1}, CERN-EP-2022-149

(from paper draft $H_{125}H_{125}+H_{125}$)

- Inputs

Channel	Integrated luminosity [fb^{-1}]
$HH \to b\bar{b}\gamma\gamma$	139
$HH \to b\bar{b}\tau^+\tau^-$	139
$HH \to b\bar{b}b\bar{b}$	126

- Systematics

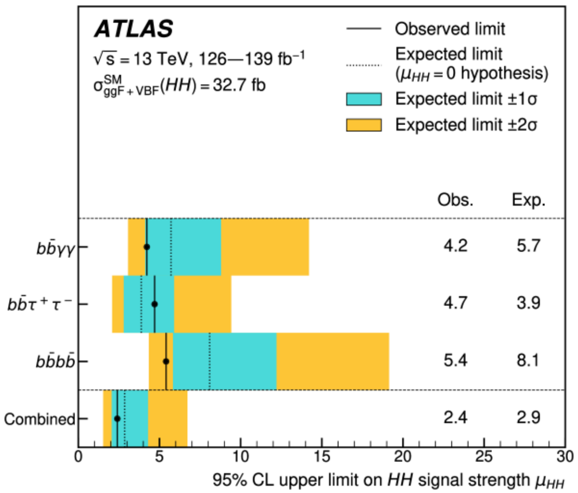
Physics objects : correlated, Δm_H : correlated

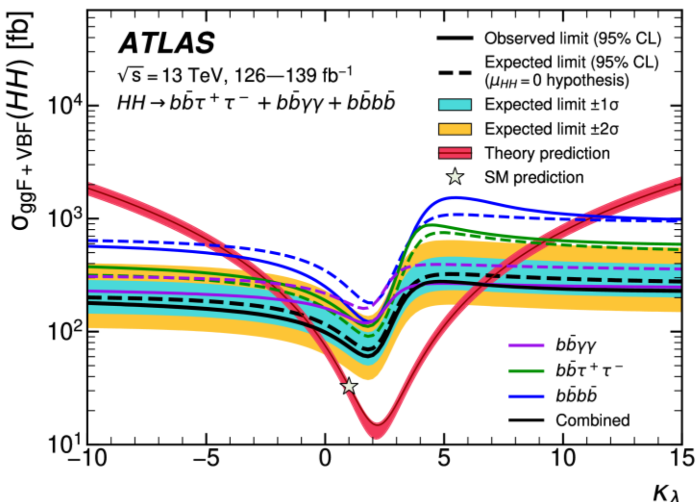
methodologies ≠ : uncorrelated

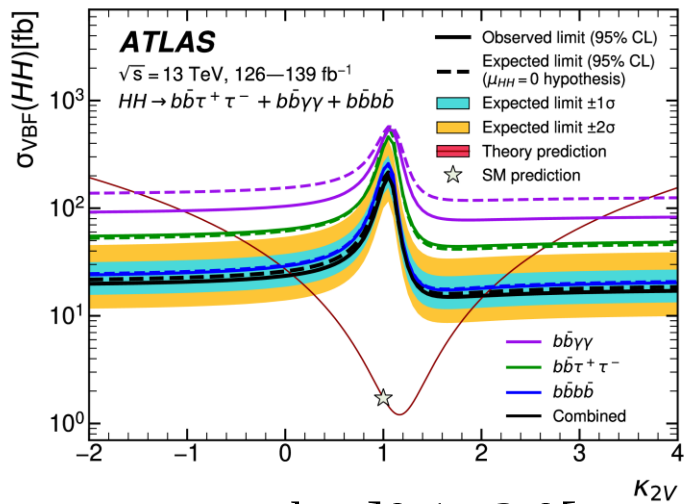
Theoretical: correlated ; 1-H vs HH: uncorrelated

- Limit μ_{HH} (95 % CL)

HH=f(κ_λ, κ_{2V}, …)







obs: 2.4xSM, exp: 2.9xSM
(if no HH)
(4.0 if SM)

κ_λ: obs:]-0.6 ; 6.6[
(exp:]-2.1 ; 7.8[)

κ_{2V}: obs:]0.1 ; 2.0[
(exp:]0.0 ; 2.1[)

Resonant $H_{125}H_{125}$

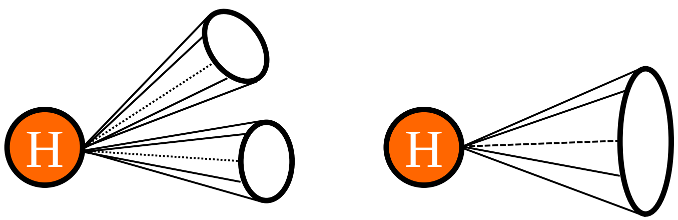
ATLAS, Run 2, √s=13 TeV, L=126-139 fb^{-1}, ATLAS-CONF-2021-052
(non resonant superseeded by HH content of HH+H paper draft)

- Resonant analysis

$m_X \in [251 ; 3000]$ GeV, NWA

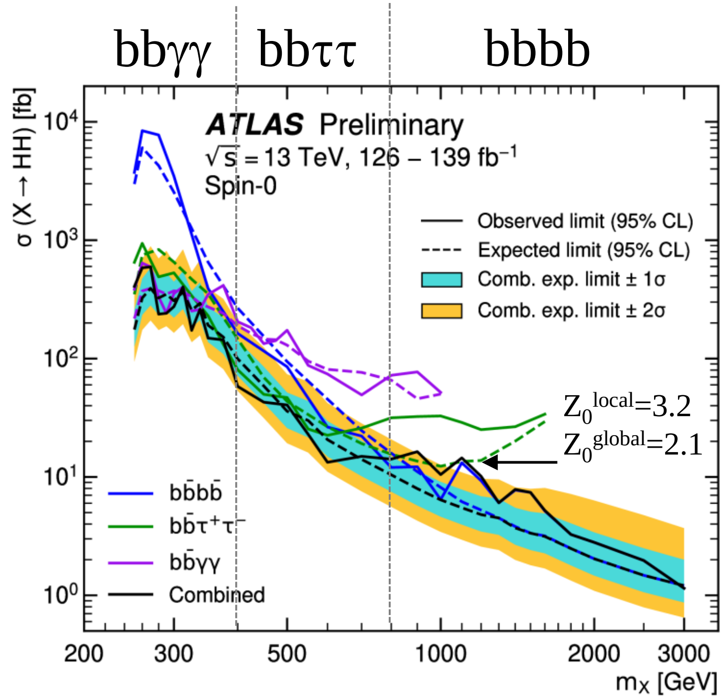
	final DV
bbγγ: 251-1000 GeV	$m_{\gamma\gamma}$
bbττ: 251-1600 GeV	MVA
bbbb:	m_{HH}

resolved (R=0.4): 251-1500 GeV
boosted (R=1.0): 900-3000 GeV



⊥: veto resolved events from boosted selection

sensitivity dominated by…



$H_{125}H_{125}$: prospects HL-LHC

- Correlation

correlate systematics among channels

Source	**Scale factor**	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$
Experimental Uncertainties			
Luminosity	0.6	*	*
b-jet tagging efficiency	0.5	*	*
c-jet tagging efficiency	0.5	*	*
Light-jet tagging efficiency	1.0	*	*
Jet energy scale and resolution, E_T^{miss}	1.0	*	*
κ_λ reweighting	0.0	*	*
Photon efficiency (ID, trigger, isolation efficiency)	0.8	*	
Photon energy scale and resolution	1.0	*	
Spurious signal	0.0	*	
Value of m_H	0.08	*	
τ_{had} efficiency (statistical)	0.0		*
τ_{had} efficiency (systematic)	1.0		*
τ_{had} energy scale	1.0		*
Fake-τ_{had} estimation	1.0		*
MC statistical uncertainties	0.0		*
Theoretical Uncertainties	0.5	*	*

$H_{125}H_{125}+H_{125}$

Exploits higher EW correction in 1-H, BR

G. Degrassi, P. P. Giardino, F. Maltoni and D. Pagani, *Probing the Higgs self coupling via single Higgs production at the LHC*, JHEP **12** (2016) 080, arXiv: 1607.04251 [hep-ph].

F. Maltoni, D. Pagani, A. Shivaji and X. Zhao, *Trilinear Higgs coupling determination via single-Higgs differential measurements at the LHC*, Eur. Phys. J. C **77** (2017) 887, arXiv: 1709.08649 [hep-ph].

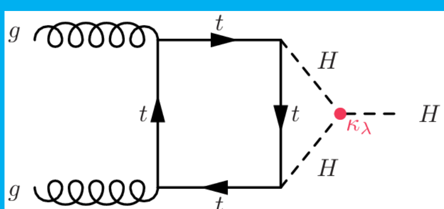
S. Di Vita, C. Grojean, G. Panico, M. Riembau and T. Vantalon, *A global view on the Higgs self-coupling*, JHEP **09** (2017) 069, arXiv: 1704.01953 [hep-ph].

M. Gorbahn and U. Haisch, *Indirect probes of the trilinear Higgs coupling: $gg \to h$ and $h \to \gamma\gamma$*, JHEP **10** (2016) 094, arXiv: 1607.03773 [hep-ph].

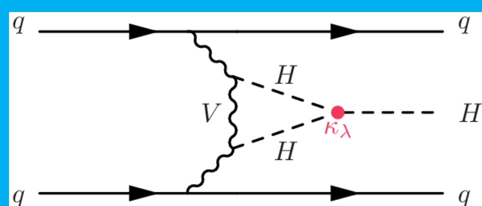
W. Bizon, M. Gorbahn, U. Haisch and G. Zanderighi, *Constraints on the trilinear Higgs coupling from vector boson fusion and associated Higgs production at the LHC*, JHEP **07** (2017) 083, arXiv: 1610.05771 [hep-ph].

M. McCullough, *An Indirect Model-Dependent Probe of the Higgs Self-Coupling*, Phys. Rev. D **90** (2014) 015001, [Erratum: Phys. Rev. D **92** (2015) 039903], arXiv: 1312.3322 [hep-ph].

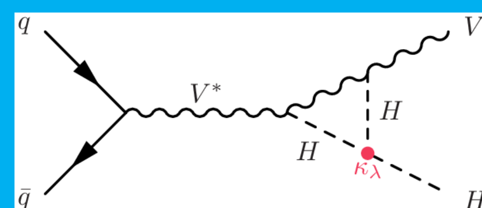
ggF



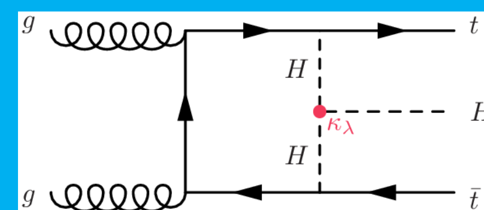
VBF



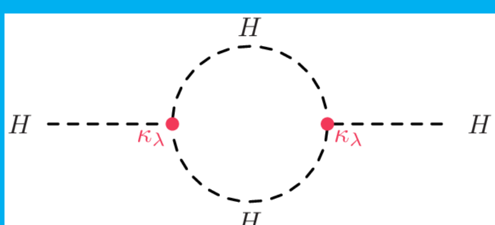
VH



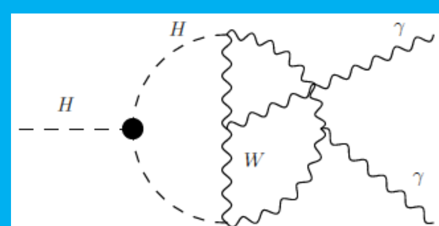
ttH



self-energy



H→γγ



(many other diagrams)

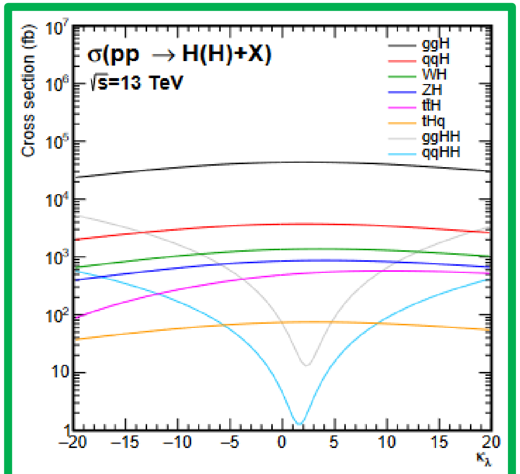
$H_{125}H_{125}+H_{125}$

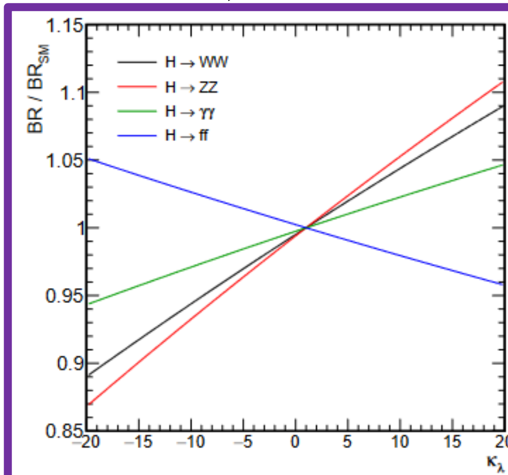
- **Inputs**

ATLAS, Run 2, $\sqrt{s}$=13 TeV, L=126-139 fb^{-1}, CERN-EP-2022-149

Channel	Integrated luminosity [fb^{-1}]
$HH \to b\bar{b}\gamma\gamma$	139
$HH \to b\bar{b}\tau^+\tau^-$	139
$HH \to b\bar{b}b\bar{b}$	126
$H \to \gamma\gamma$	139
$H \to ZZ^* \to 4\ell$	139
$H \to \tau^+\tau^-$	139
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139
$H \to b\bar{b}$ (VH)	139
$H \to b\bar{b}$ (VBF)	126
$H \to b\bar{b}$ $(t\bar{t}H)$	139

m_H=125.09 ± 0.24 GeV
(LHCHWG-2022-002)





- **Parametrisation of 1-H and BR**

-1-H: exploits STXS granularity: increase sensitivity to κ_λ, κ_m (κ_t, κ_b, κ_τ, κ_V)
accept. x efficiency : negligible dependence κ_λ

$$n_{i,f}^{\text{signal}}(\kappa_\lambda, \kappa_m) \propto \mu_i(\kappa_\lambda, \kappa_m) \times \mu_f(\kappa_\lambda, \kappa_m) \times \sigma_{\text{SM},i} \times \mathcal{B}_{\text{SM},f} \times (\epsilon \times A)_{if}$$ f(process, STXS)

f (κ_λ):
$$\frac{\sigma^i_{NLO_{EW}}}{\sigma^i_{NLO_{EW},SM}} = Z_{\text{H}}^{BSM}\left[\frac{(\kappa_\lambda - 1)C_1^i}{K^i_{EW}} + \kappa_i^2\right]$$
$$Z_{\text{H}}^{BSM} = \frac{1}{1-({\kappa_\lambda}^2-1)\delta Z_{\text{H}}}$$

ggF: κ_λ dependence only + not using STXS depence

1-H=f(κ_V, κ_{2V}): prospects, although small sensitivity (arXiv:2208.09334)

-BR(κ_λ) taken into account

$H_{125}H_{125}+H_{125}$

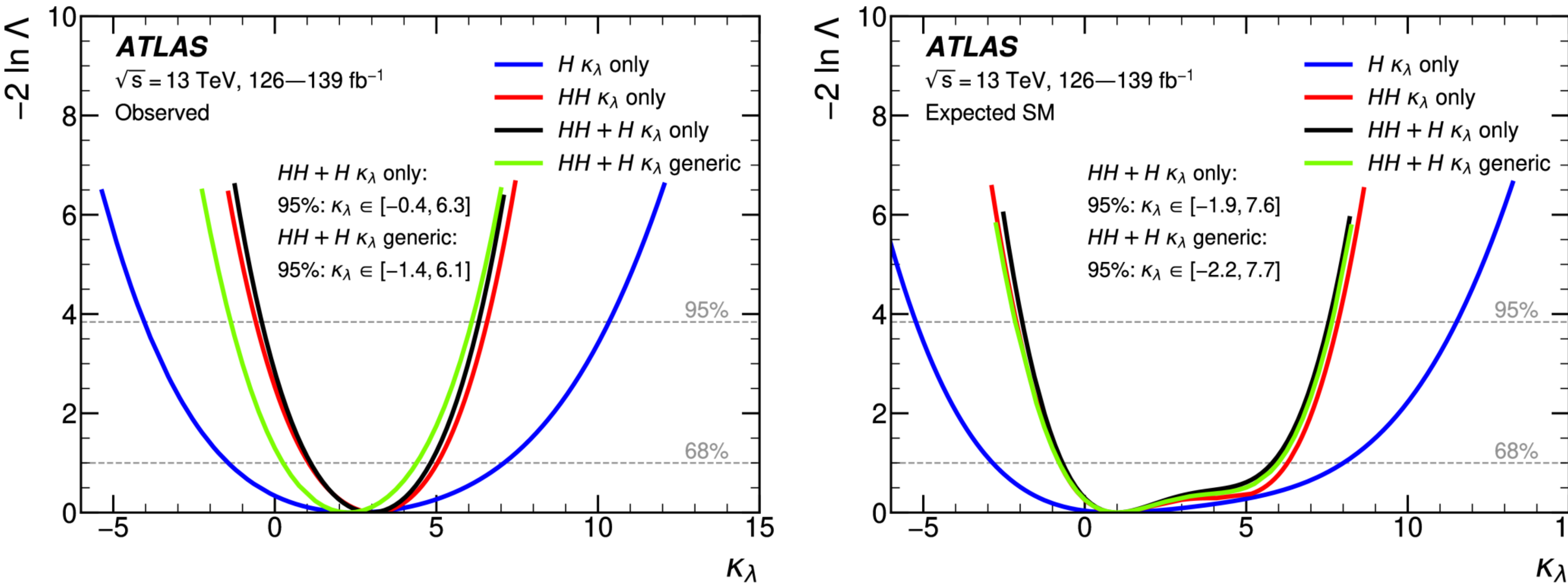
- Systematics

Data-taking, pile-up mis-modelling, luminosity : correlated
Physics objects : correlated, m_H : correlated
Different methodologies : uncorrelated
Theoretical: correlated ; 1-H vs HH: uncorrelated
Systematics constrained significantly: checked correlation effect: < 2%: take conservative
HH: dominant bkg estimates data-driven: uncorrelated w/ 1-H
negligible impact choice, apart ggF HH: correlation ↓ 7 %: take conservative

- Combination H+HH

Treated statistically independent
Consider further HH=f(κ_λ, κ_t, κ_V, κ_{2V})
Search overlap (1-H : négligeable, HH : <0.1 %, H-HH: <1 % apart H→ττ, HH→bbττ:
removed ttH(ττ) : 4 % in HH
κ_λ: obs:]-0.4 ; 6.3[
exp:]-1.9 ; 7.6[

$H_{125}H_{125}+H_{125}$

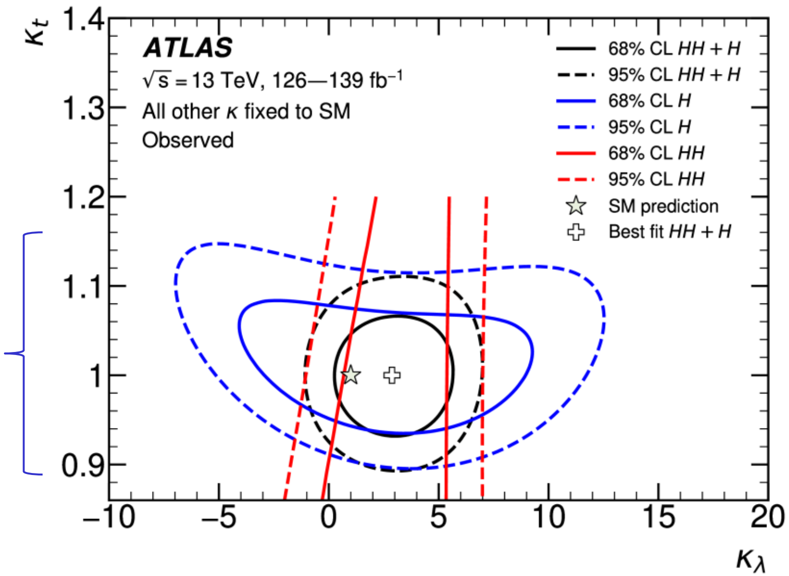


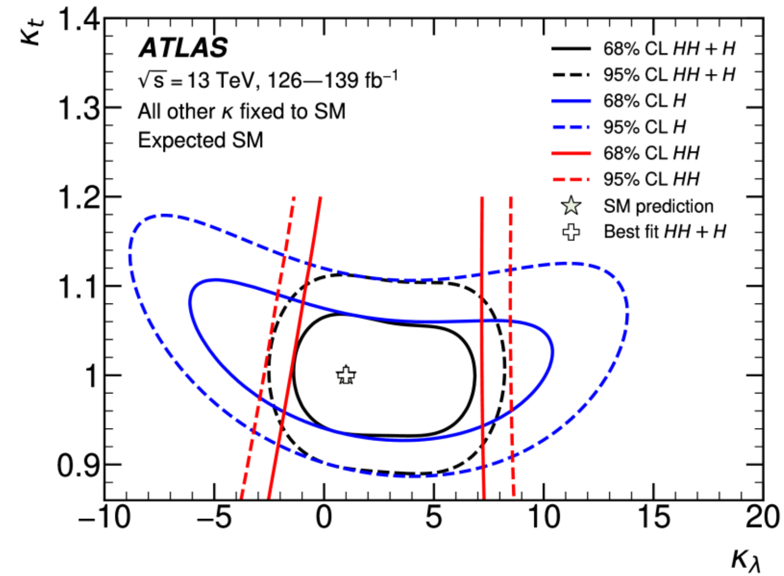
gg HH : $A(\kappa_t, \kappa_\lambda)=\kappa_\lambda\kappa_t\Delta + \kappa_t^2\Box$ $\rightarrow \sigma(\kappa_t, \kappa_\lambda)=\kappa_\lambda^2\kappa_t^2|\Delta|^2 + \kappa_t^4|\Box|^2+\kappa_t^3\kappa_\lambda f(\Delta,\Box)$

$H_{125}H_{125}+H_{125}$

+1-H allows to relax assumptions on Higgs couplings to other particles

1-H
strong constraint κ_t
as strong wo/ κ_t





(1) CL_s treatment
(2) Profile likelihood ratio scan

	Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
(1)	*HH* combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
(2)	Single-*H* combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
(2)	*HH*+*H* combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
(2)	*HH*+*H* combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
(2)	*HH*+*H* combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Less model dependent (HH parametrisation)

Prospects HL-LHC

$H_{125}H_{125}$: prospects HL-LHC

- Inputs

Run 2 bbγγ, bbττ

- Extrapolation

-m_H=125.00 GeV (negligible)

-L

-σ: √s=14 TeV

Prospects HL-LHC, √s=14 TeV, L=3000 fb^{-1}, ATL-PHYS-PUB-2022-005

Process	Scale factor
Signals	
ggF HH	1.18
VBF HH	1.19
Backgrounds	
ggF H	1.13
VBF H	1.13
WH	1.10
ZH	1.12
$t\bar{t}H$	1.21
Others	1.18

gluon luminosity

bbττ : {Z+HF, tt}: norm: data

→additive x factor: {1.37, 1}

- Systematic scenarios

-Baseline:

stat: x 1/√L

L: 1% (Run 2 : 1.7 %)

Theory: /2 ('continuous progress')

MC stat: ø (cpu for generation)

κ_λ samples reweighting: non-closure: ø (cpu for generation)

spurious signal : ø ('progress in modelling')

object performance: f(upgrade)

bbγγ: m_H: 240 MeV→20 MeV

- Alternative systematics

-No syst. uncertainties

-Theoretical unc. halved: th / 2, exp : / 1

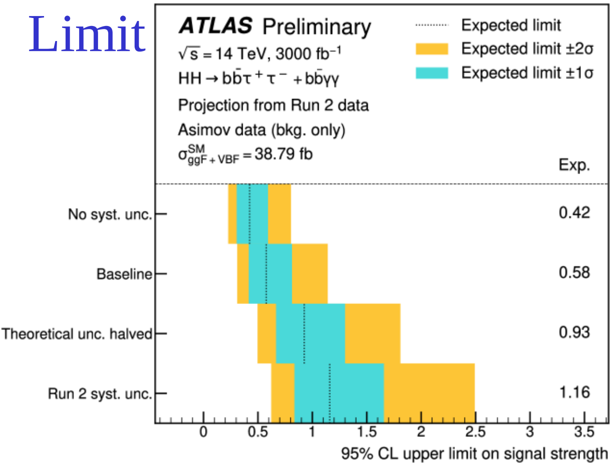
-Run 2 syst. unc.

envelope⇔uncertainty on prospects

- correlate systematics among channels

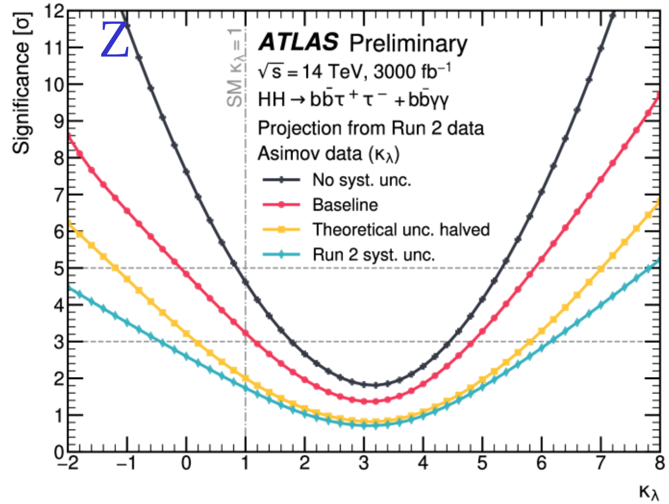
$H_{125}H_{125}$: prospects HL-LHC

Limit

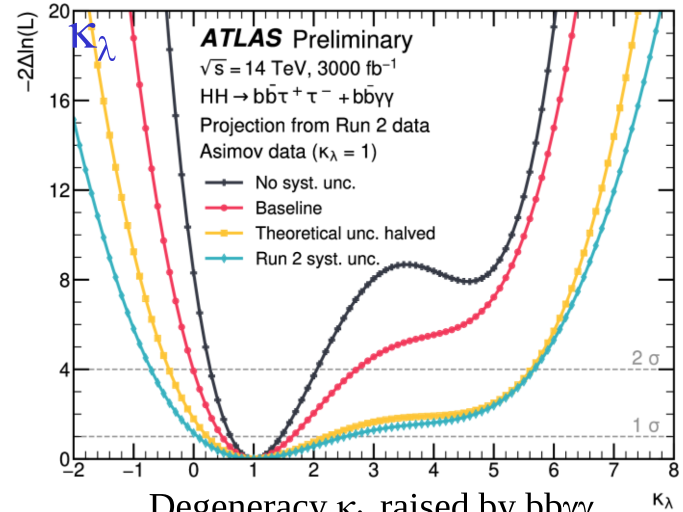


(SM)

Z



κ_λ



Degeneracy κ_λ raised by bbγγ

Uncertainty scenario	Significance [σ] $b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	Combination	Combined signal strength precision [%]	Likelihood scan 1 σ CI
No syst. unc.	2.3	4.0	4.6	$-23/+23$	$[0.6, 1.5]$
Baseline	2.2	2.8	3.2	$-31/+34$	$[0.5, 1.6]$
Theoretical unc. halved	1.1	1.7	2.0	$-49/+51$	$[0.2, 2.2]$
Run 2 syst. unc.	1.1	1.5	1.7	$-57/+68$	$[0.1, 2.5]$

bbγγ: dominant systematic: spurious signal

bbττ: dominant systematic : MC stat: -not in baseline

-in Theoretical unc. halved ; Run 2 systematics unc.

Comb.: dominant systematic: -100 % uncertainty HF → 1-H background

$-\sigma_{HH}$ theory