A detailed picture of Higgs boson interactions from the ATLAS experiment

中国科学技术大学 学术报告

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Higgs Mechanism in the SM

- Introduced a field with ***a special potential***

$$V = \mu^2 \Phi^+ \Phi + \lambda(\Phi^+ \Phi)^2$$

- Lagrangian of the field has same symmetry as gauge theory

$$\mathcal{L} = T - V = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

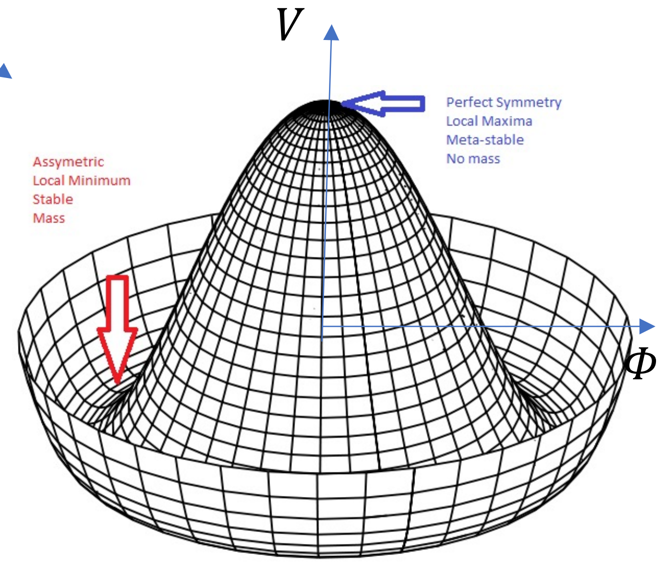
$$\text{where } D_\mu = \partial_\mu - ig\vec{W}_\mu \cdot \vec{\sigma} - ig' \frac{Y}{2} B_\mu$$

($\vec{W}_\mu$ & B_μ are gauge fields)

- If $\mu^2 < 0$, then spontaneous symmetry breaking → continuously degenerate ground state at non-zero field. The minimum of potential at

$$< \Phi > = \frac{1}{\sqrt{2}} \binom{0}{\nu}$$

Spontaneous Symmetry Breaking



Every ground state breaks the symmetry!

Expanding the Φ field around vacuum:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + H(x) \end{pmatrix}$$

Higgs boson interactions in the SM

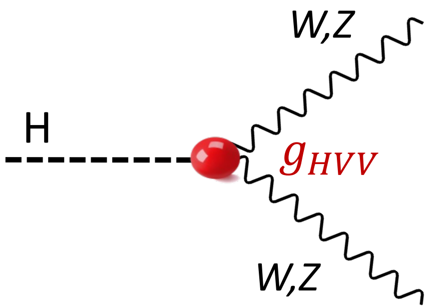
Higgs Potential $V = \mu^2 \Phi^+ \Phi + \lambda(\Phi^+ \Phi)^2$

→ **W & Z become massive & interacting with H**

$$(D^\mu \phi)^\dagger D_\mu \phi = \frac{1}{2}(\partial_\mu H)^2 + M_W^2 W^{\mu +} W_\mu^- \left(1 + \frac{H}{\nu}\right)^2 + \frac{1}{2} M_Z^2 Z^\mu Z_\mu \left(1 + \frac{H}{\nu}\right)^2$$

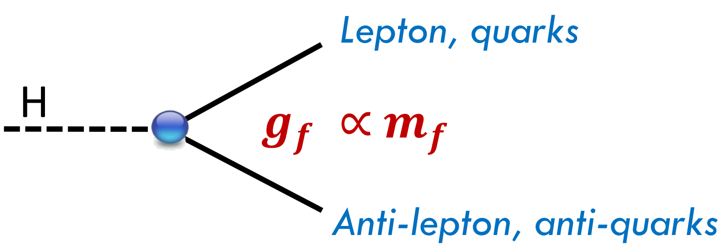
$$= \frac{1}{2}(\partial_\mu H)^2 + M_W{}^2 W^{\mu +} W_\mu^- + \frac{2M_W{}^2}{\nu} W^{\mu +} W_\mu^- H + \frac{M_W{}^2}{\nu^2} W^{\mu +} W_\mu^- H^2$$

$$+ \frac{1}{2} M_Z{}^2 Z^\mu Z_\mu + \frac{M_Z{}^2}{\nu} Z^\mu Z_\mu H + \frac{M_Z{}^2}{2\nu^2} Z^\mu Z_\mu H^2$$



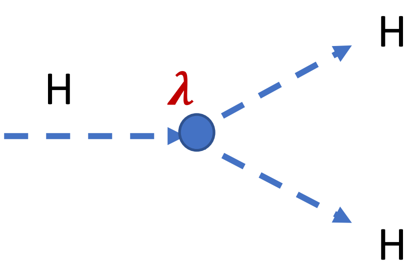
→ **Generate Fermion Mass**

$$\mathcal{L}^f_{\text{Yukawa}} = g_f(\bar{L}_f \Phi f_R^- + \Phi^\dagger \overline{f_R^-} L_f)$$

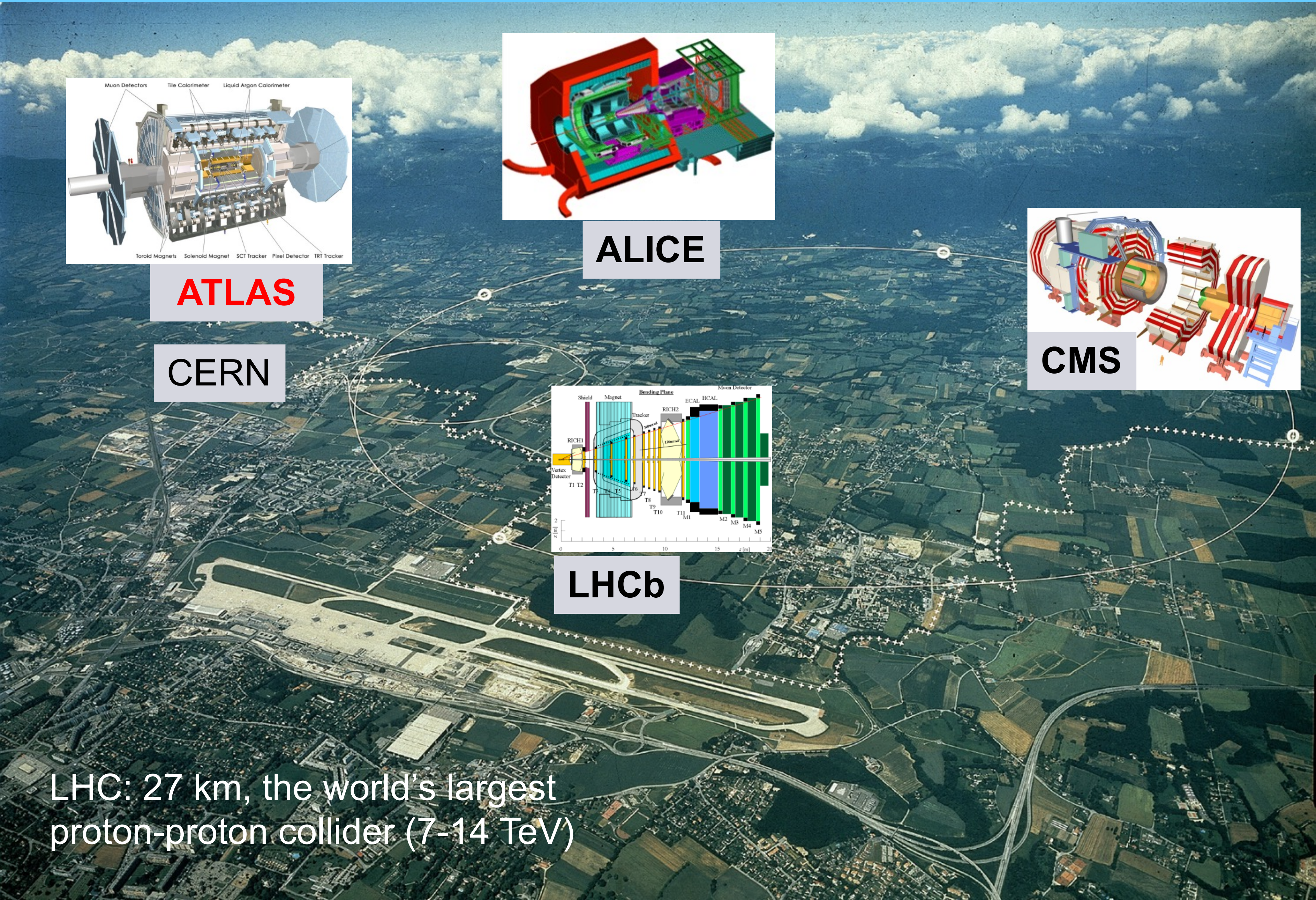


→ **Higgs boson massive; self-interactions**

$$V(\phi) = -\frac{\mu^4}{4\lambda} - \mu^2 H^2 + \lambda \nu H^3 + \frac{\lambda}{4} H^4$$



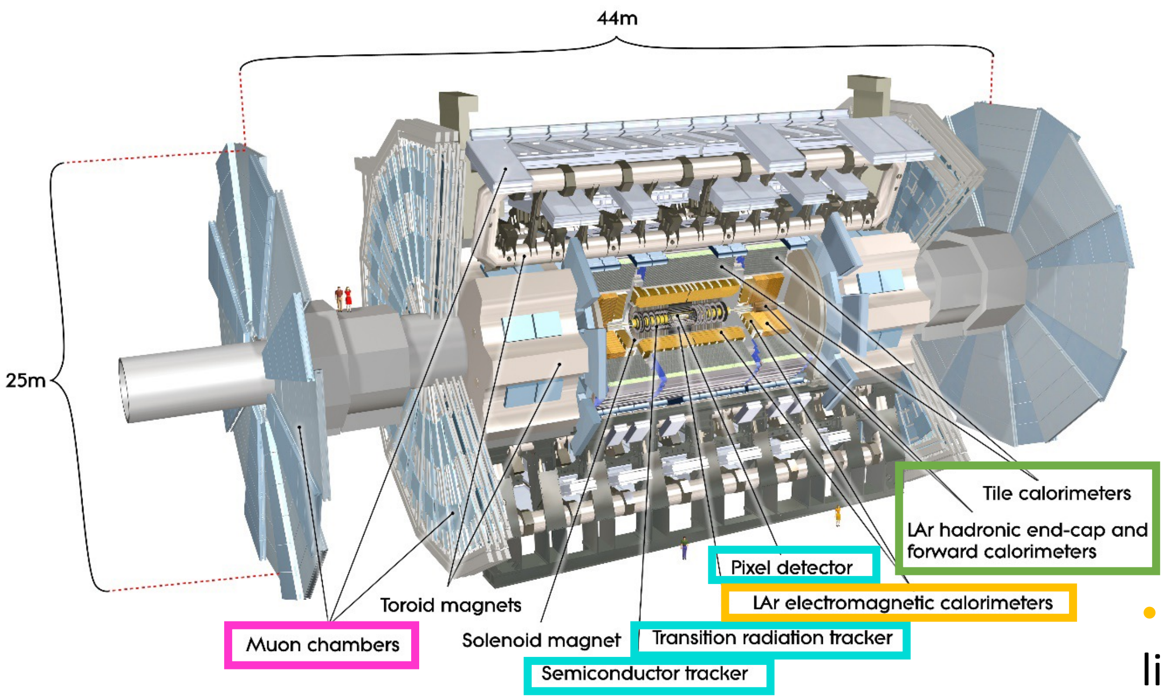
Large Hadron Collider at CERN



LHC: 27 km, the world's largest proton-proton collider (7-14 TeV)

ATLAS detector (Run 2)

- **Solenoid Magnet**: 2T
- **Toroid Magnets**: 0.5-1T



- **Hadronic calorimeter** (|η|<4.9):
Fe/scintillator Tiles (central)
Cu/W-LAr (foward)
Trigger and measurement of jets and E_T^{miss}.

- **EM calorimeter** (|η|<3.2):
liquid-argon
e/γ trigger, identification and measurement.

- **Muon Spectrometer** (|η|<2.7):
Monitored Drift Tubes, Cathode Strip Chambers, Resistive Plate Chambers, Thin Gap Chamber
Muon trigger and tracking.

- **Inner detector** (|η|<2.5):
Si Pixels, Si strips, Transition Radiation detector (straws),
Precise tracking and vertexing, e/π separation.

At Large Hadron Collider

Discovery of Higgs Boson

↓

Discovery production & decay modes

↓

Cross-section, **coupling**,
property measurements

↓

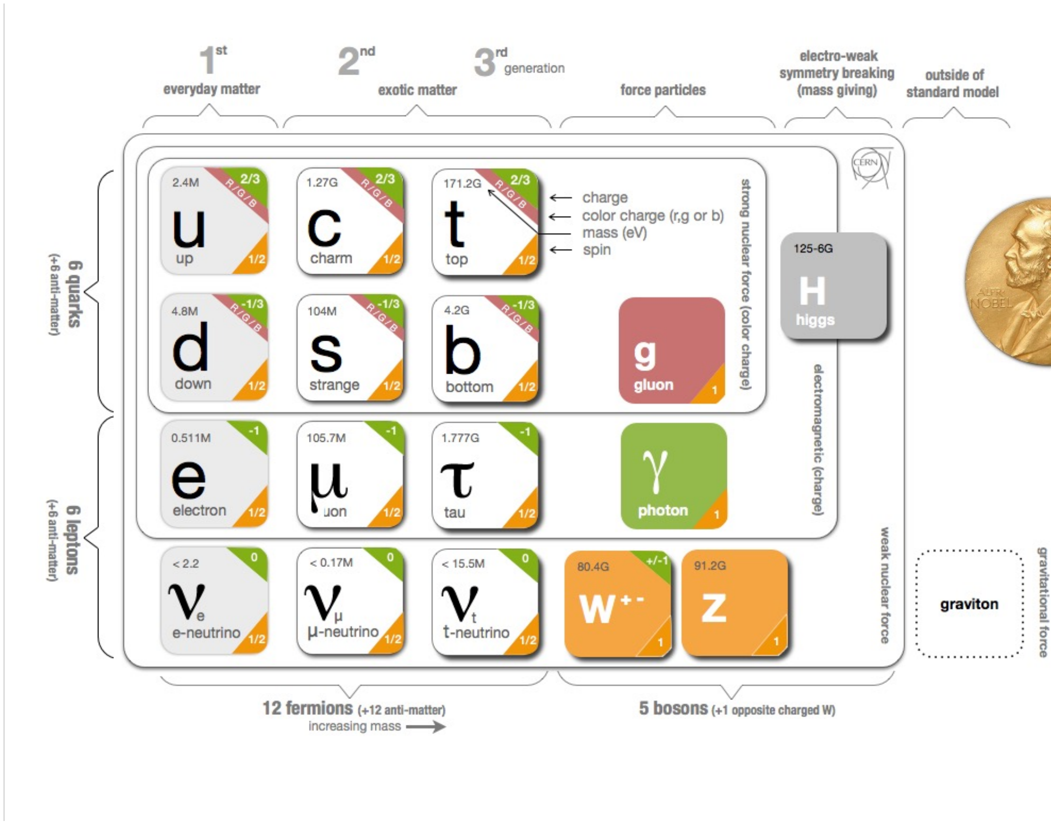
Explore the Higgs **self-interactions**

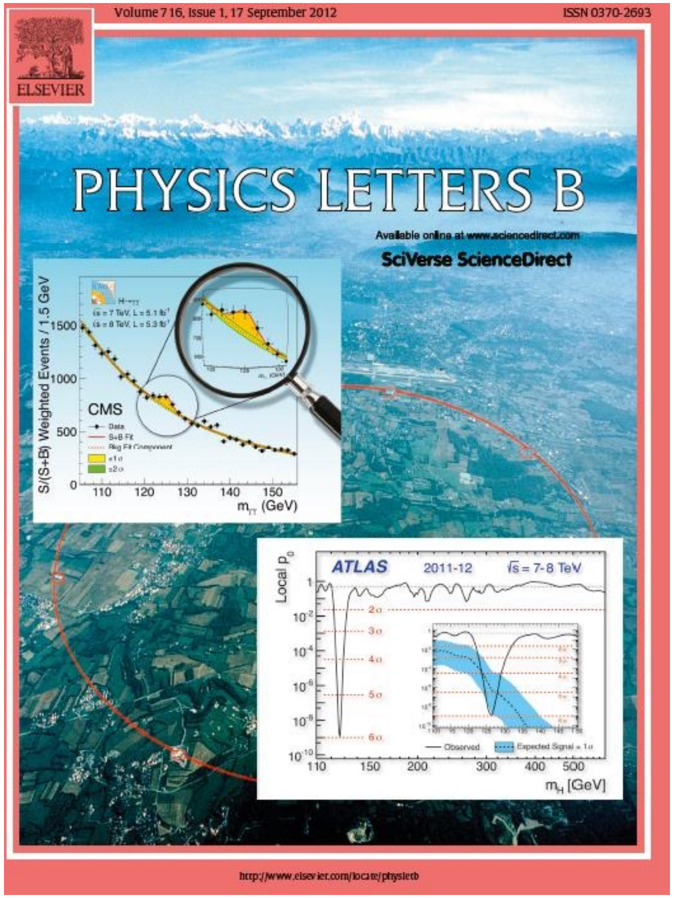
↓

Use Higgs as a tool to **search for new physics**

- **Mass** 0.09% precision: 125.11±0.11 GeV
- **Width** closing in on SM $4.6^{+2.6}_{-2.5}$ MeV
- Spin 1 and 2 excluded > 99.99%
- pure CP odd state excluded > 3σ

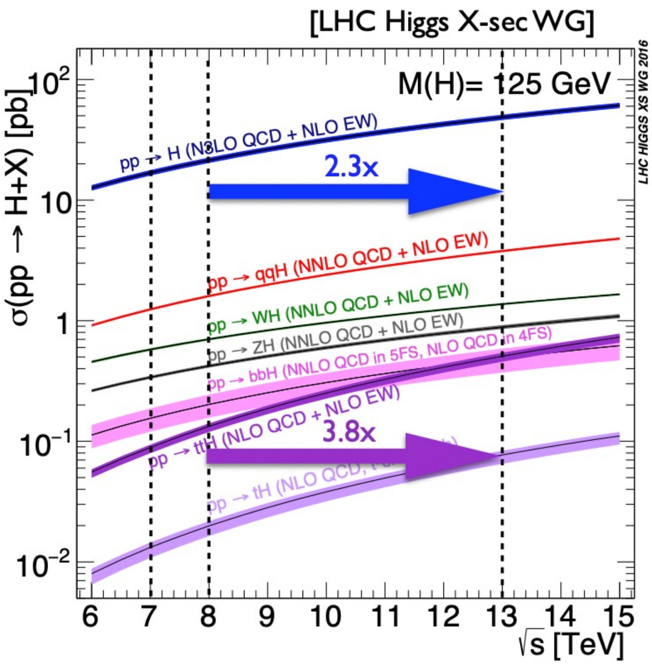
Higgs boson discovery



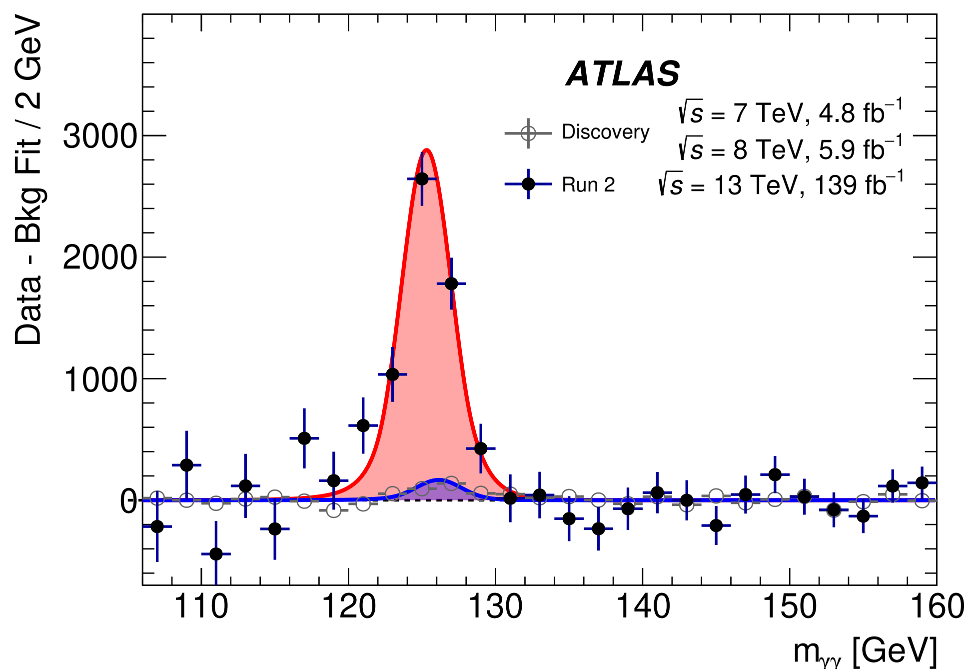


- July 4th 2012, **Discovery of Higgs boson** → **ATLAS** and **CMS** [PLB paper]
- Nobel Prize in Physics in 2013 → **Peter Higgs** and **François Englert**

- In LHC Run-2, 30x more Higgs recorded by the ATLAS detector, allows for **precise measurements** of cross-sections, couplings and properties, **search** for rare decay modes, and test phase space hasn't been probed before.

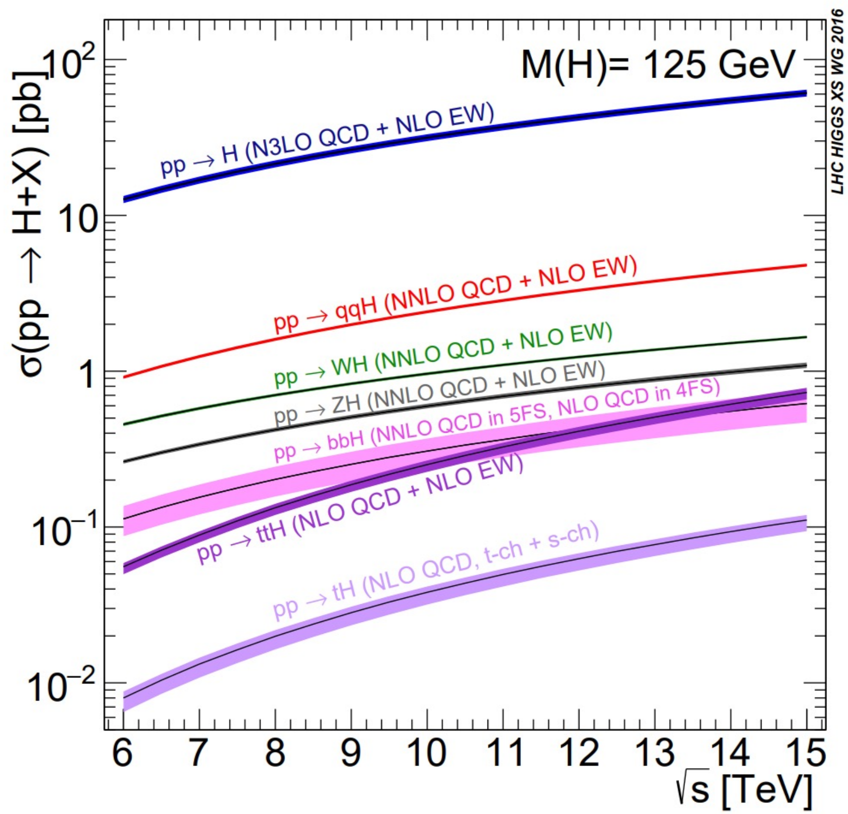


Significant increase in production rate from Run-1 to Run-2

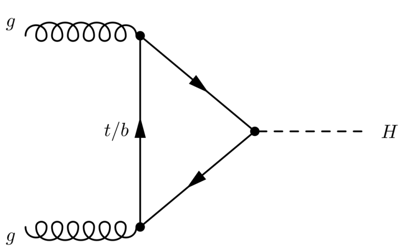


Comparison of $m_{\gamma\gamma}$ spectrum between discovery and full Run-2 datasets

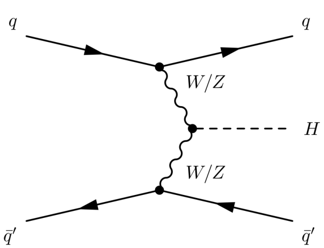
SM Higgs Production at LHC



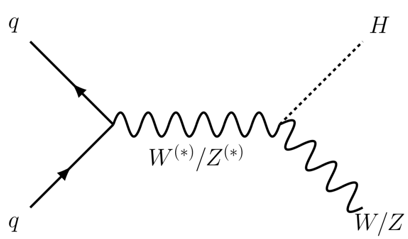
XS in pb	13 TeV	8 TeV	σ13/σ8
ggF	48.5	21.4	**2.3**
VBF	3.78	1.60	**2.4**
WH	1.37	0.70	**2.0**
ZH	0.88	0.42	**2.1**
bbH	0.49	0.20	**2.4**
ttH	0.51	0.13	**3.8**
tH	0.09	0.02	**3.9**



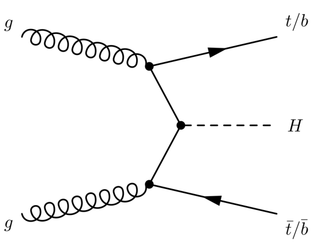
ggF



VBF

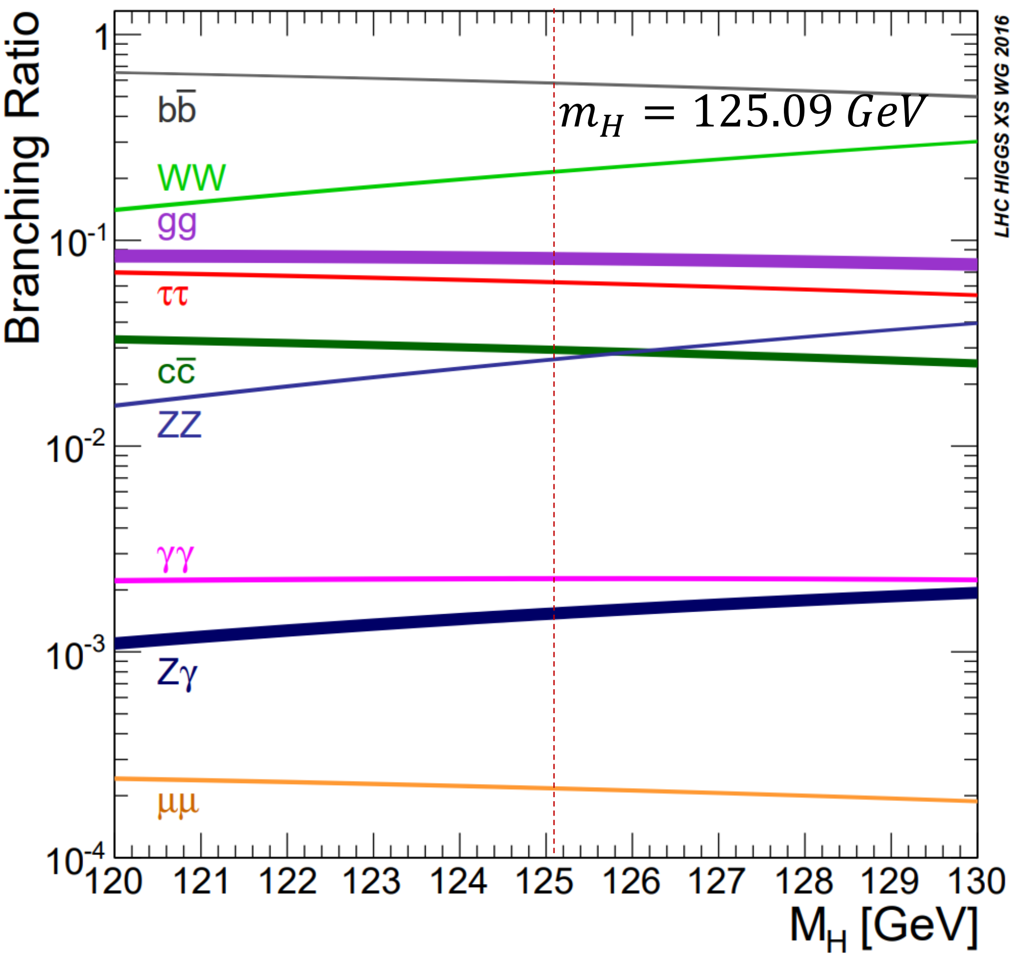


VH



ttH

SM Higgs Decay BR

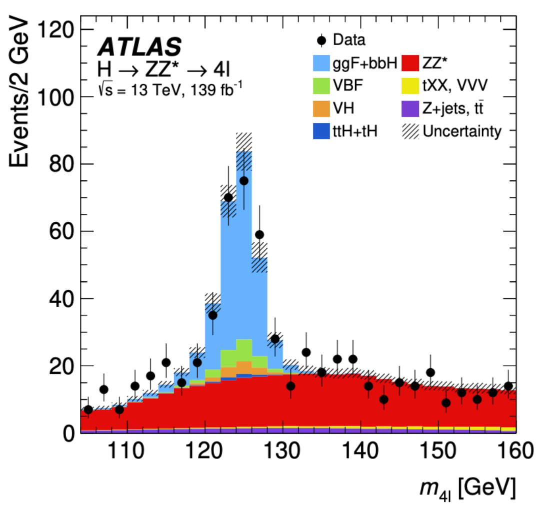


Decay channel	Branching Ratio[%]
H→bb	58
*H→WW**	22
H→gg	8.2
H→ττ	6.3
H→cc	2.9
*H→ZZ**	2.6
H→γγ	0.23
H→Zγ	0.15
H→μμ	0.02

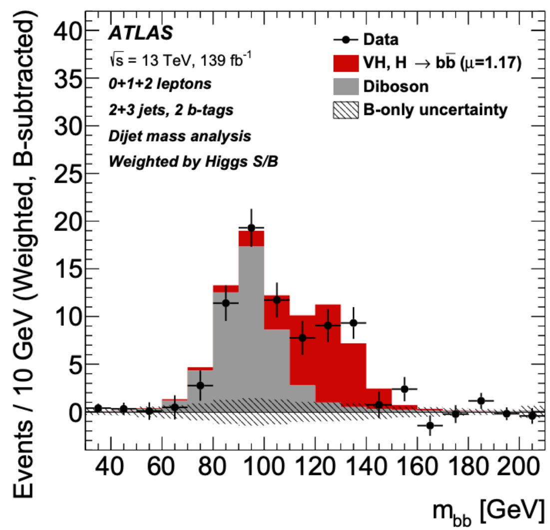
- *H→ZZ*→4l* (l=e,μ) and *H→γγ*: **low BR but clean signature, excellent mass resolution**
- *H→WW** : high BR but low mass resolution.
- *H→bb* and *H→ττ* : high BR, low S/B and low mass resolution at LHC.

Individual ATLAS Higgs analysis

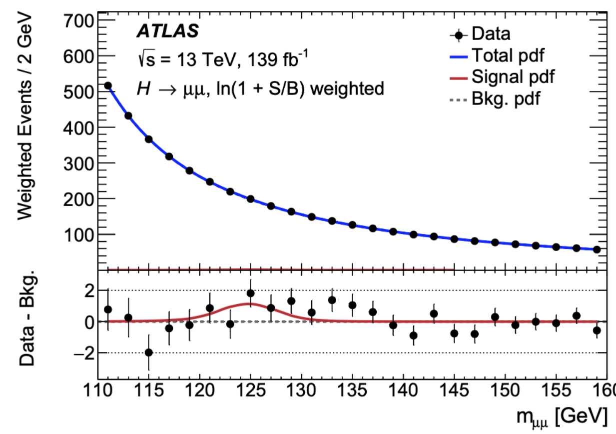
H→ZZ



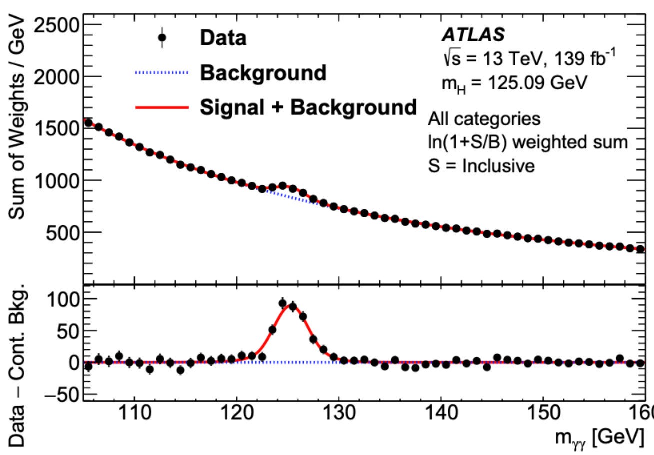
H→bb



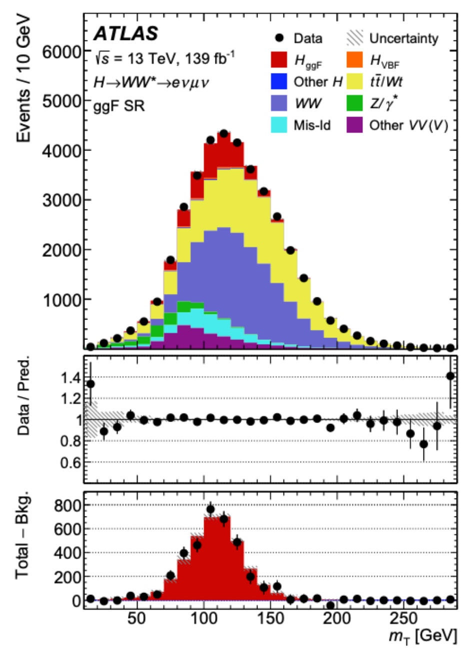
H→μμ



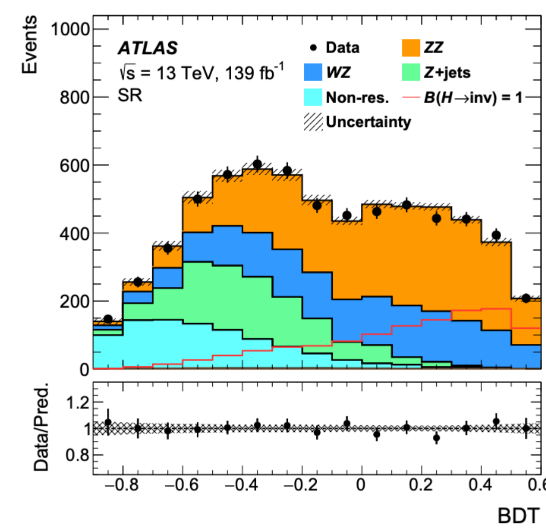
H→γγ



H→WW

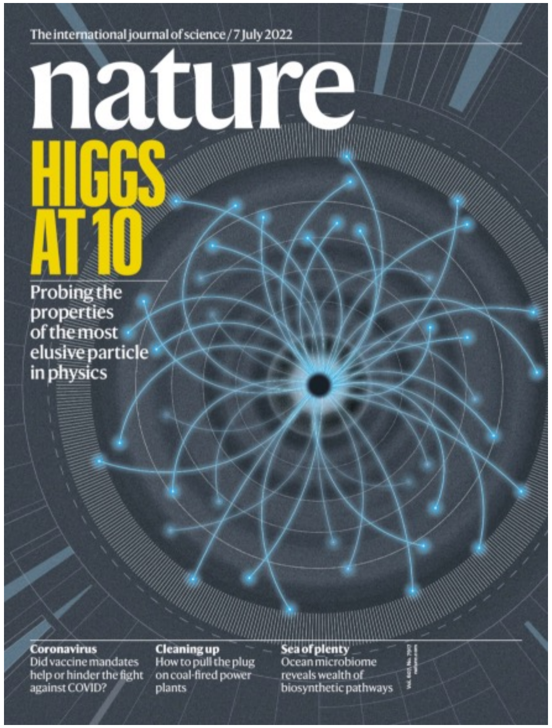


H→invisible



Combining productions and decays

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



Nature 607, 52–59 (2022)

A measurement based on **a combined likelihood** constructed from **all major ATLAS Higgs analyses**, to get **more sensitive** and **less model-dependent** results on Higgs interactions:

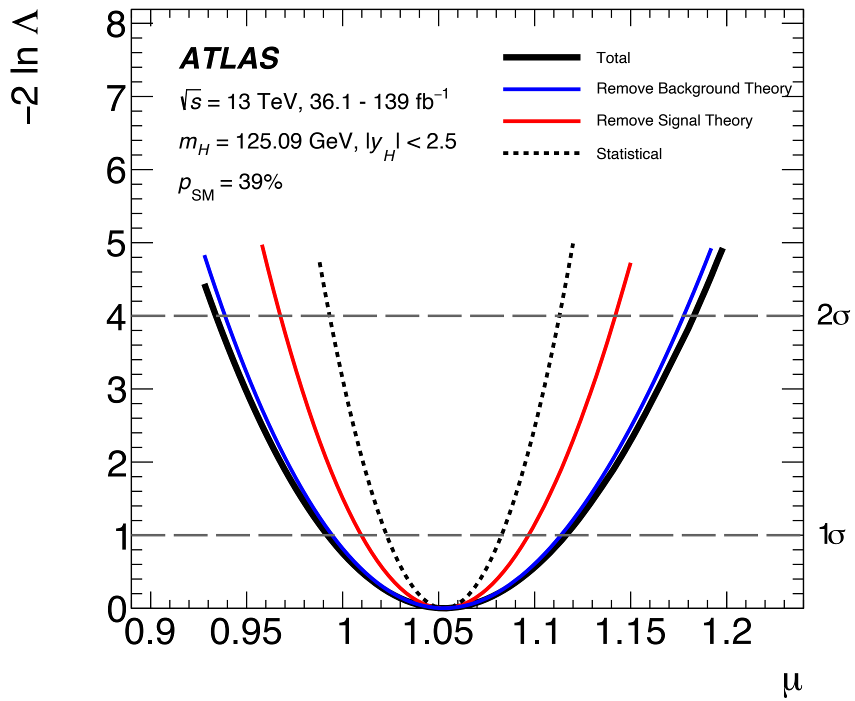
- Almost all measurements updated with the **LHC full Run-2** dataset

Global signal strength

- **Considering all production and decay modes together:** $\mu = \frac{\sigma \times B}{(\sigma \times B)_{SM}}$

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

- Experimental and theory uncertainties reduced by a factor of 2 wrt Run 1 result
- SM compatibility (p-value): 39%

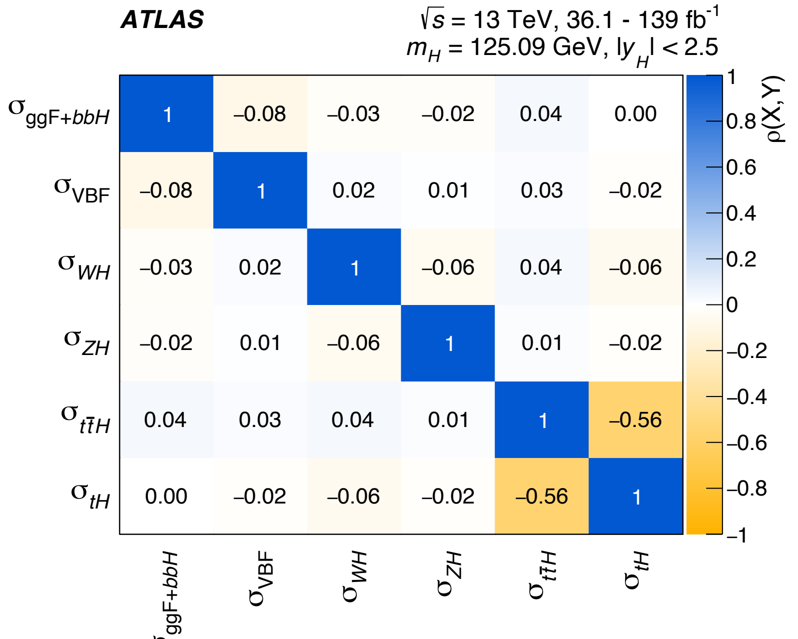


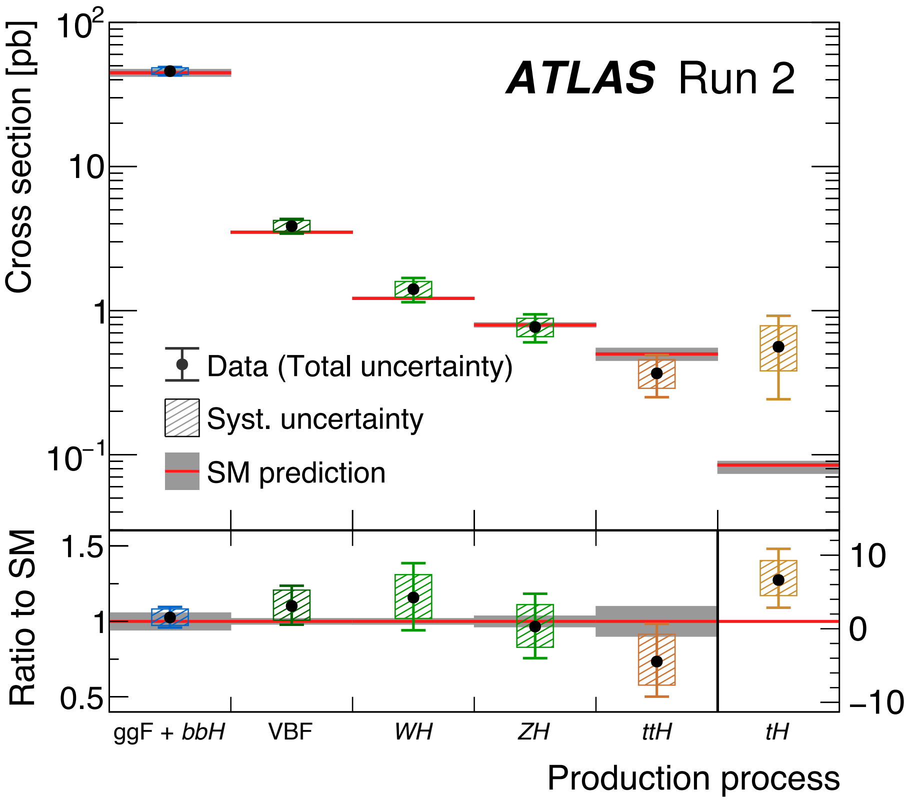
Previous results:

ATLAS+CMS (Run 1 combination): $1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}(\text{stat.})^{+0.04}_{-0.04}(\text{exp.})^{+0.07}_{-0.06}(\text{sig. th.})^{+0.03}_{-0.03}(\text{bkg. th.})$

Production cross-sections

- **Branching ratios are assumed to be SM-like** when combining processes and measurements
- SM compatibility (p-value): 65%

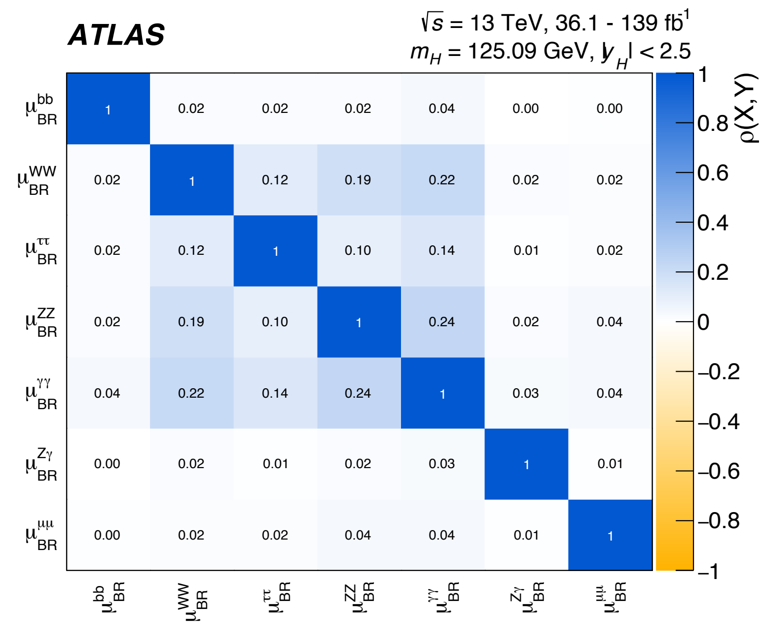


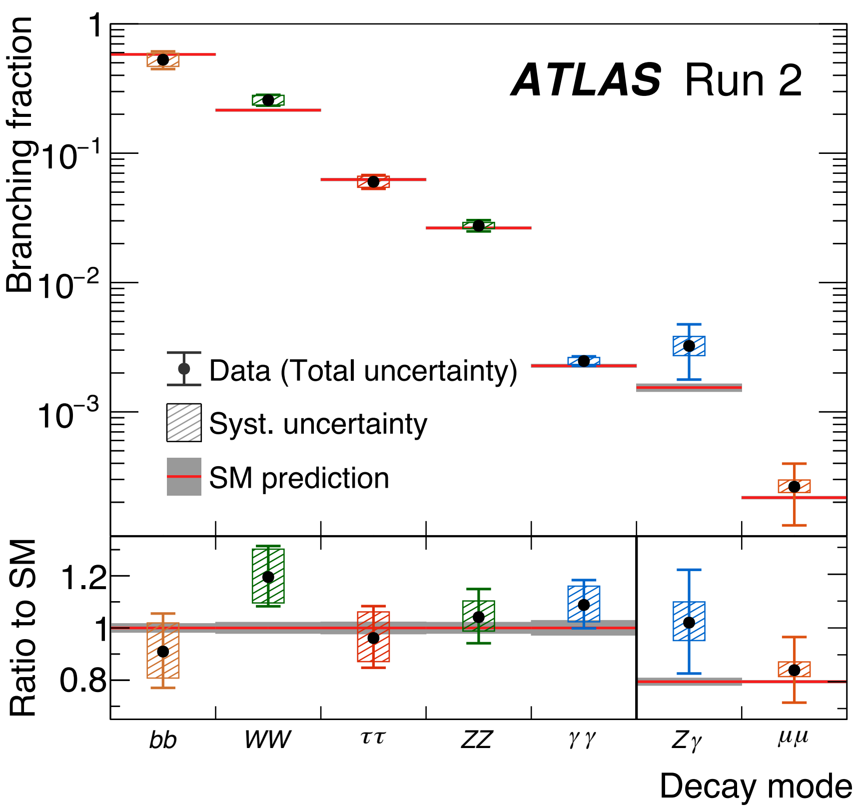


- **Better precision**:
  - ggF now at precision of 7%
  - VBF now at precision of 12%
- **All major production have been observed**:
  - *WH* is observed with 5.8σ (5.1σ), *ZH* with 5.0σ (5.5σ) and *ttH+tH* with 6.4σ (6.6σ)
- **Rare production mode**:
  - Upper limit on *tH* of 15(7) x SM at 95% C.L.
    - Strong correlation with *ttH*

Decay branching-ratios

- Branching ratios:
  - **Production cross sections are assumed to be SM-like** when combining processes/measurements
  - SM compatibility (p-value): 56%

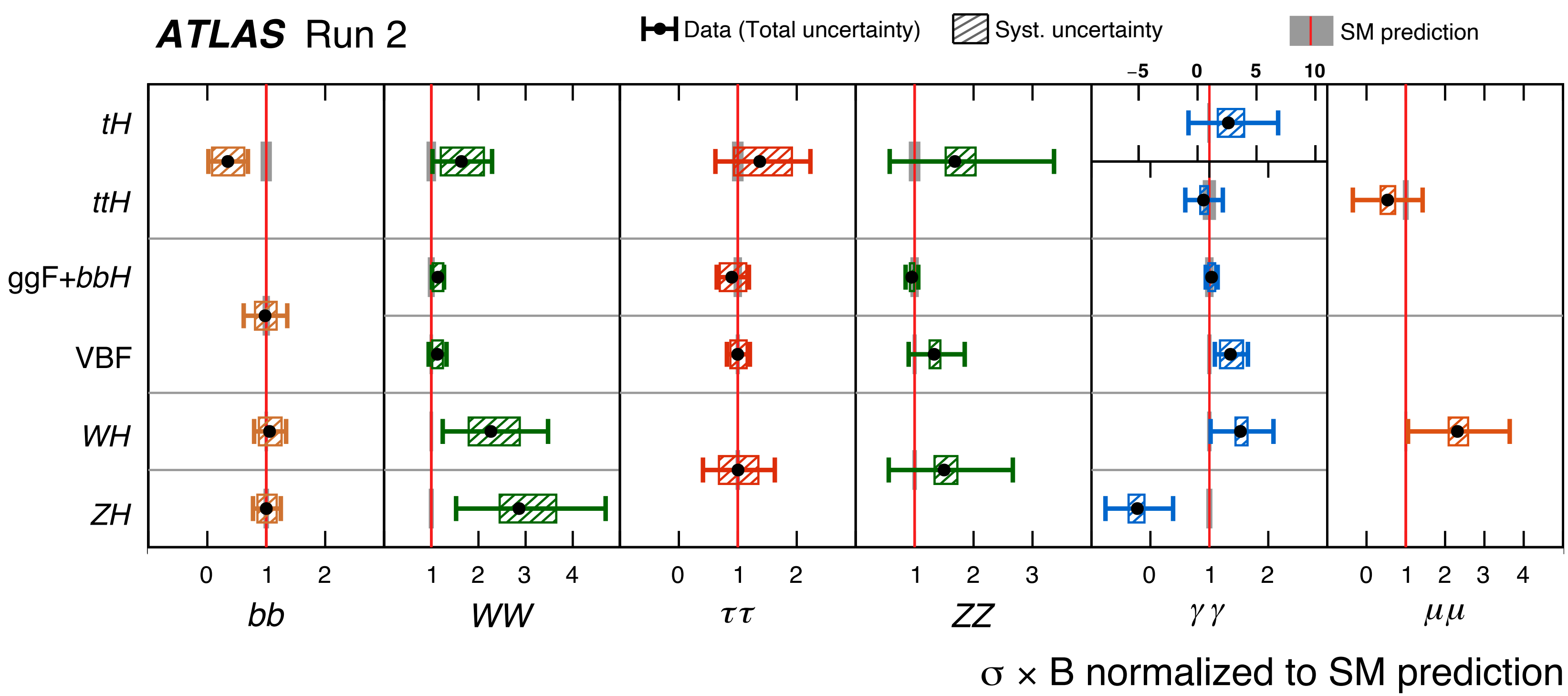




- **For decay BR:**
  - *H→WW, ττ, ZZ, γγ* now all at precisions between 10% and 12%
  - *H→bb* observed with 7.0σ (7.7σ)
  - *H→ μμ* with significances of 2.0σ (1.7σ) and *Zγ* with 2.3σ (1.1σ)

Production and Decay

- Cross sections times branching ratios:
  - Measurements for all available cross sections and branching ratios
  - **Assumptions on SM-BR relaxed**
  - SM compatibility (p-value): 72%

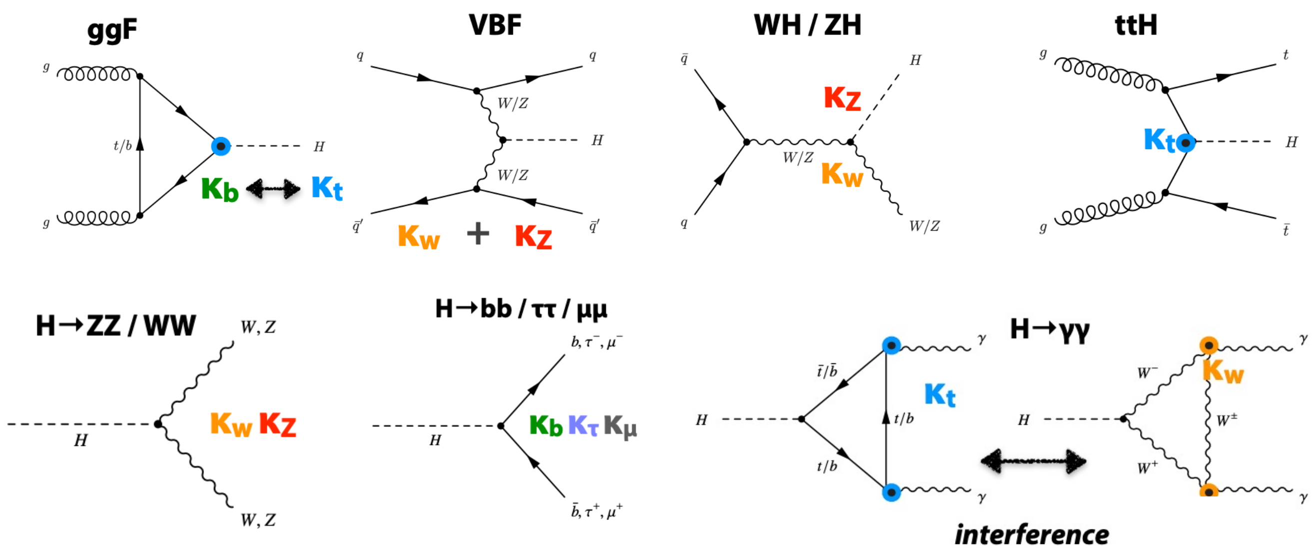


“kappa” framework

- With known Higgs boson mass, the SM Higgs sector is fixed.
- Use the **LO** coupling modifier to probe for rate deviations from the SM.
- Introduce one scale factor κ per SM particle with observable "Higgs coupling” at the LHC: κ_W, κ_Z, κ_t, κ_b, κ_τ, κ_μ, κ_γ, κ_g, etc.

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

- E.g.:



- Can handle other rare production and decay vertices in a similar way.

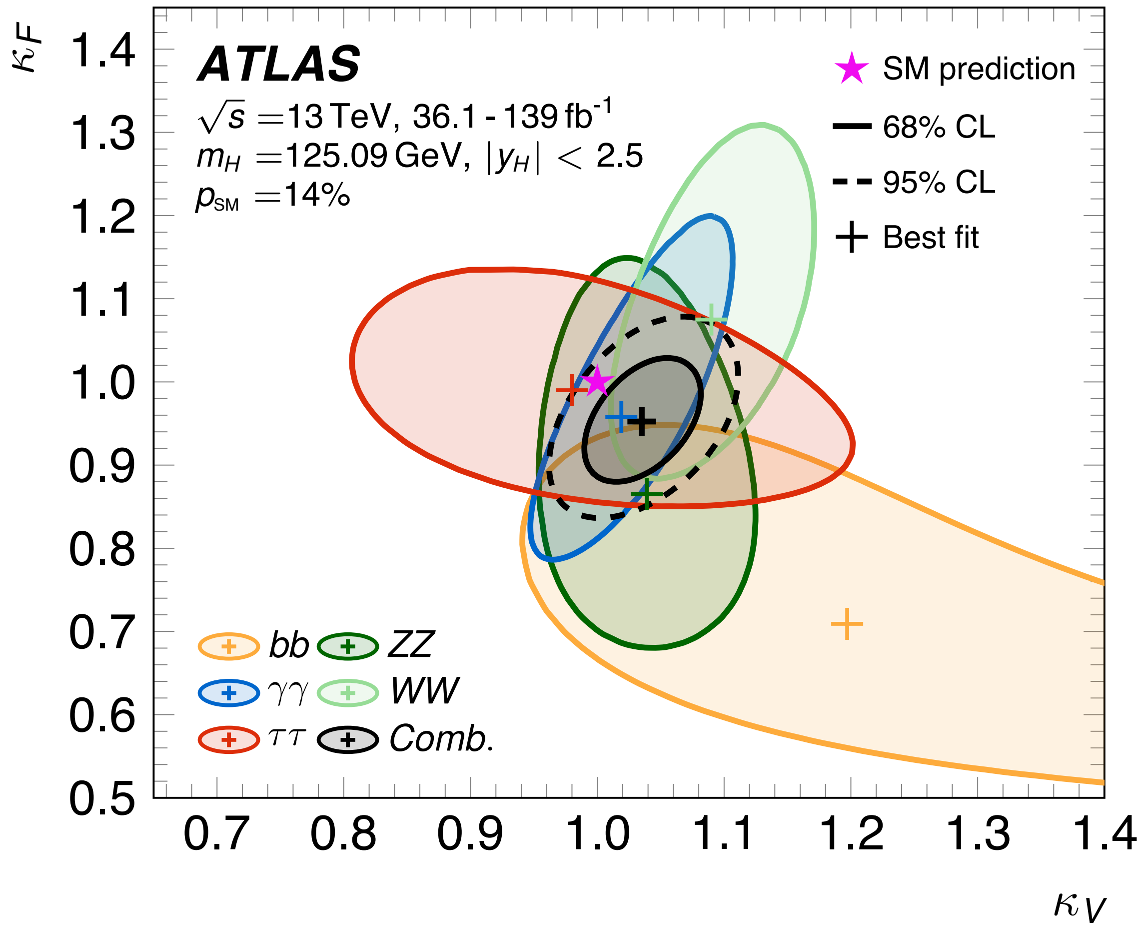
Fermion vs Vector boson coupling

κ_V vs κ_F : one coupling modifier for **vector boson coupling** and another for **fermions**

- Loop processes resolved according to the SM particles that contribute to them
- SM compatibility (p-value): 14%

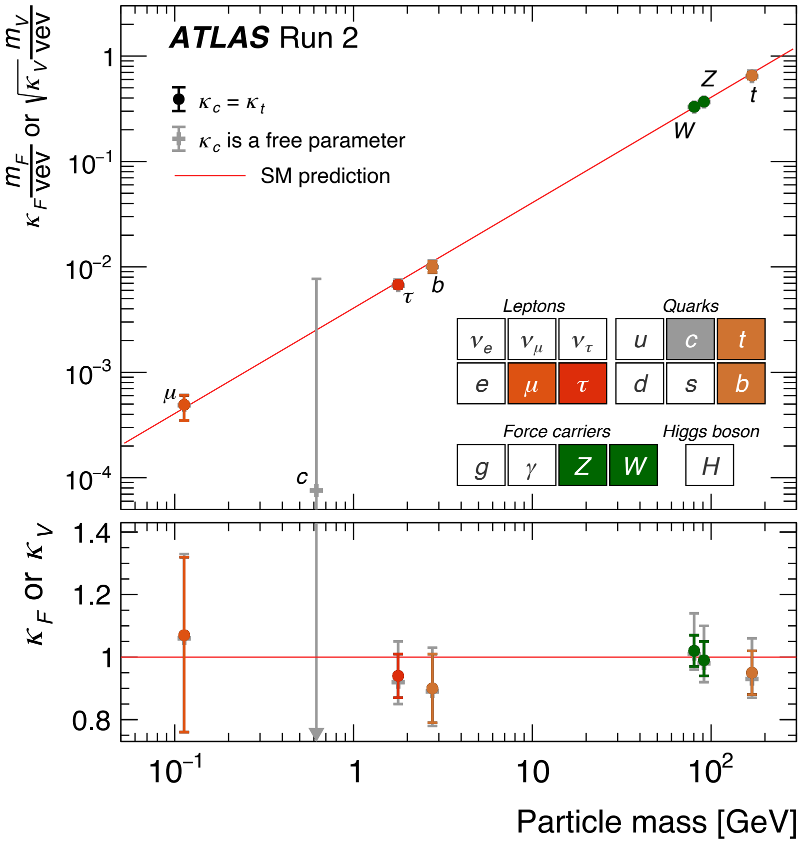
$$\kappa_V = 1.035^{+0.031}_{-0.031}$$
$$\kappa_F = 0.95^{+0.05}_{-0.05}$$

Vector-boson vs. fermion coupling in each decay channels



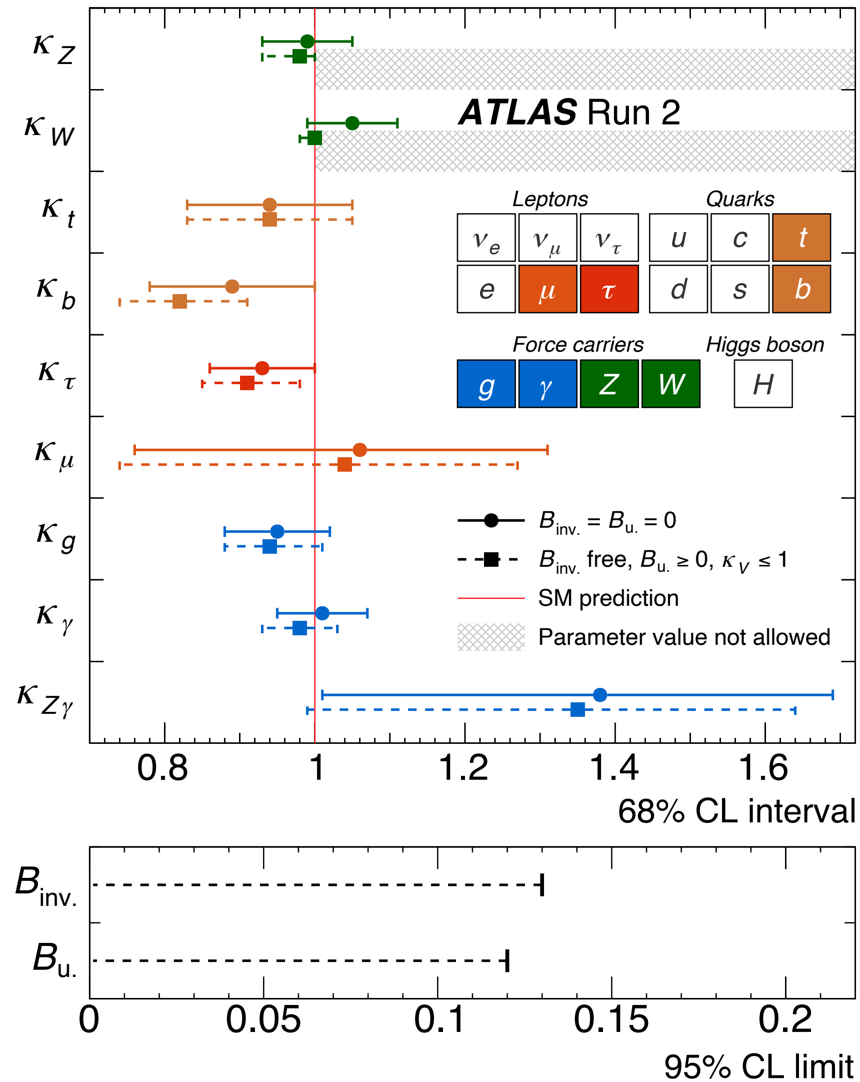
Coupling to each particle

- **All modifiers assumed to be positive**
- **Only SM particles in loop processes**
- **No invisible or undetected non-SM Higgs decays**
- Two setups: with and without κ_c to cope with low sensitivity
  - Upper limit on κ_c of 5.7 (7.6) x SM at 95% CL
- Coupling measurements:
  - Fermions (*t, b, τ*): precision between 7% and 12%
  - Vector bosons (W, Z): precision of 5%
  - SM compatibility (p-value): 56% (κ_c=κ_t) and 65% (κ_c free-floating)

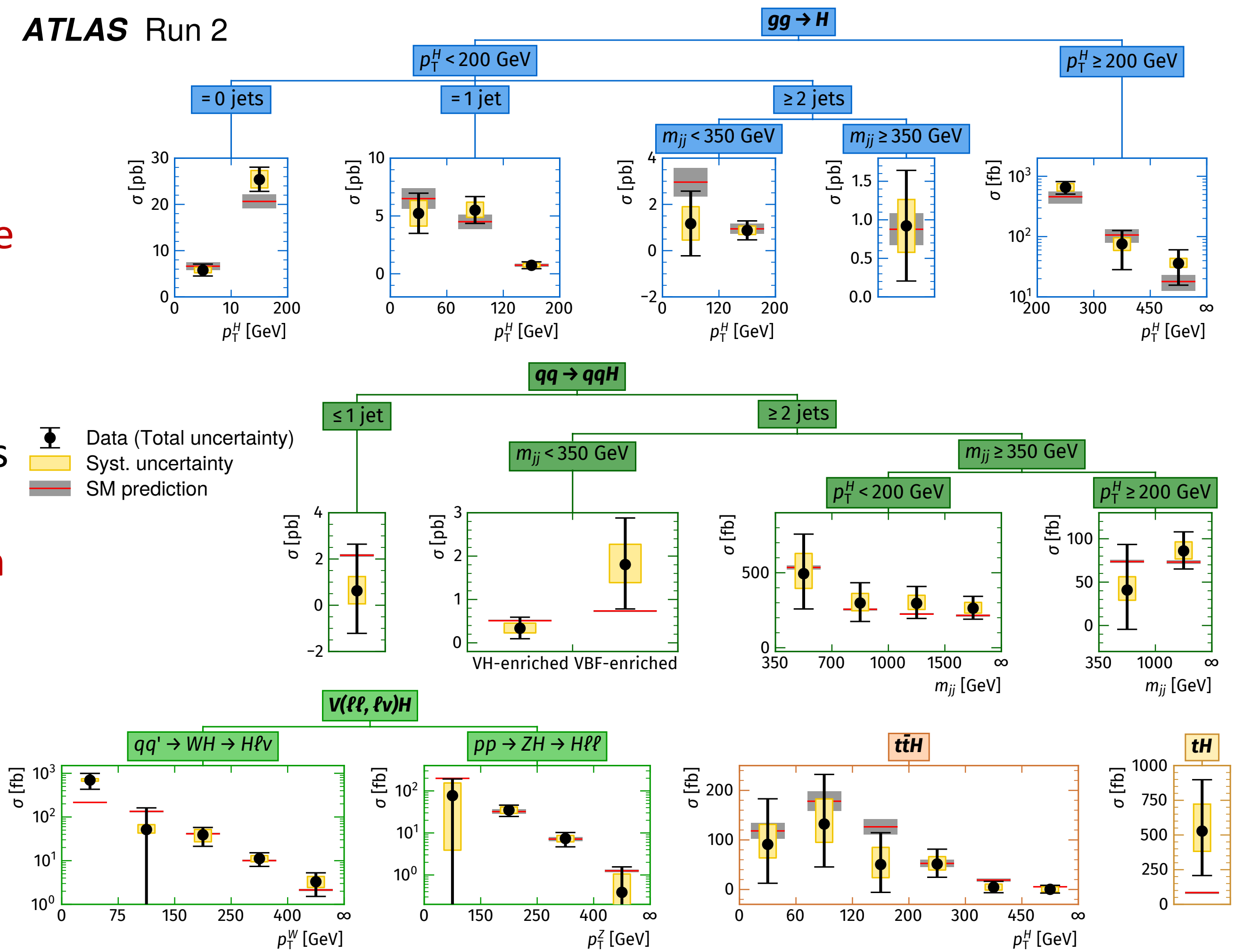


Generic coupling

- **Similar to previous setup with this time allowing for non-SM particles in loop processes, with effective coupling strengths.**
- **κ_t allowed to be negative.**
- Two scenarios: with and without invisible and undetected non-SM Higgs decays.
- SM compatibility (p-value):
  61% ($B_{inv} = B_u = 0$)
- Upper limits on B_{inv} of 0.13 (0.08) and B_u of 0.12 (0.21) at 95% CL



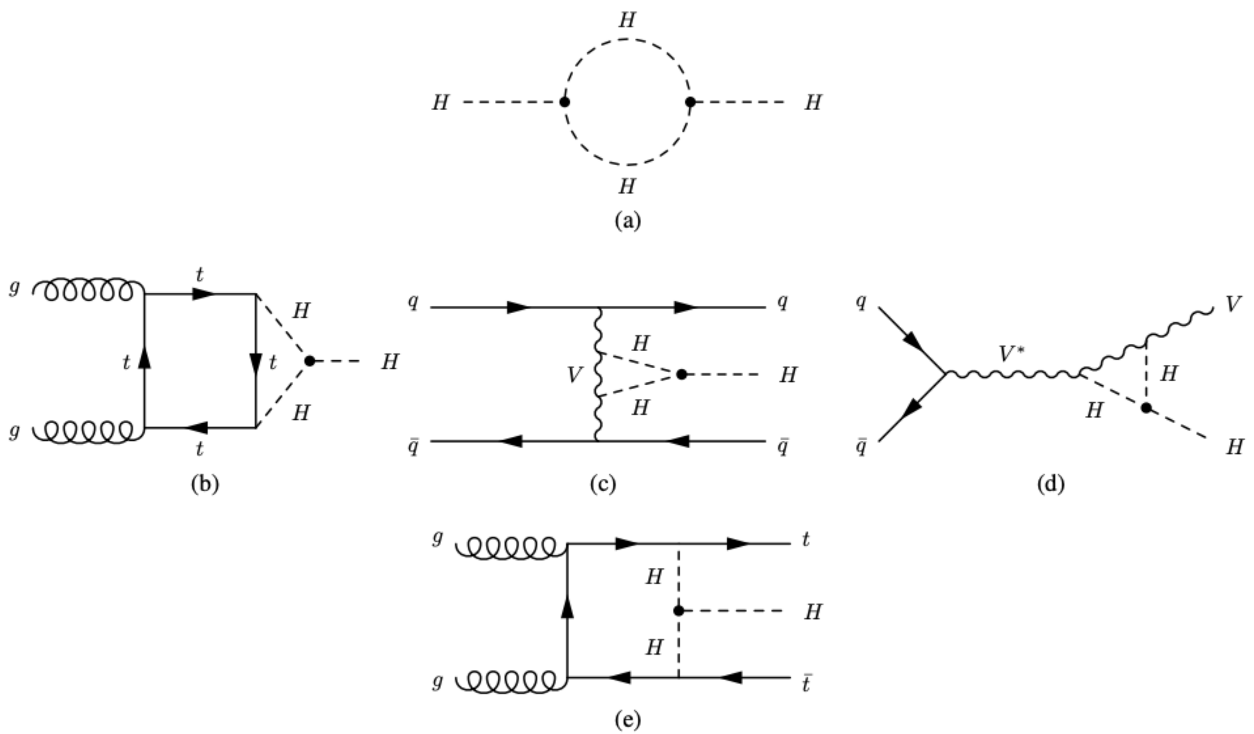
- STXS (Simplified Template Cross Sections)
- Split phase space of Higgs production processes into **36 kinematic regions**
  - Defined by kinematics of Higgs Boson and of associated jets, W, Z bosons where relevant



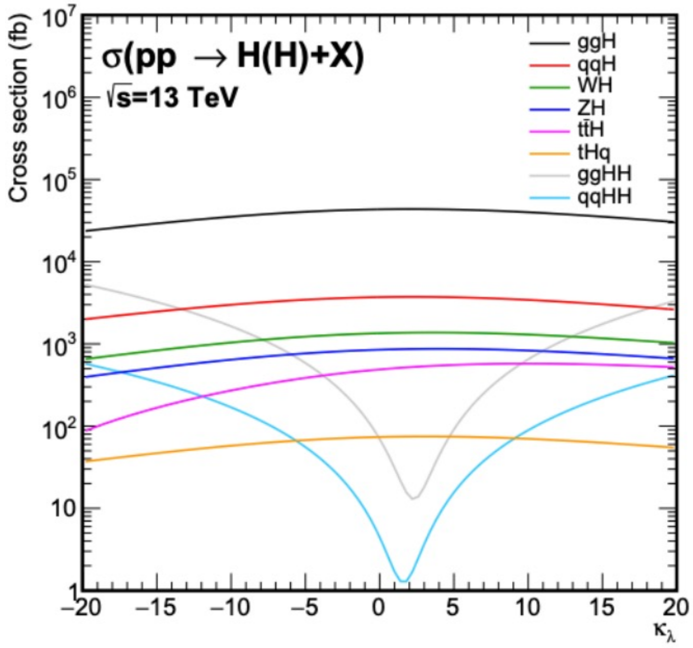
- **Goal:** provide sensitivity to BSM effects, avoid large theory uncertainties in predictions and minimise model-dependence from acceptance extrapolations
- Branching ratios and kinematics of Higgs Boson decays are assumed to be SM-like
- SM compatibility (p-value): 92%

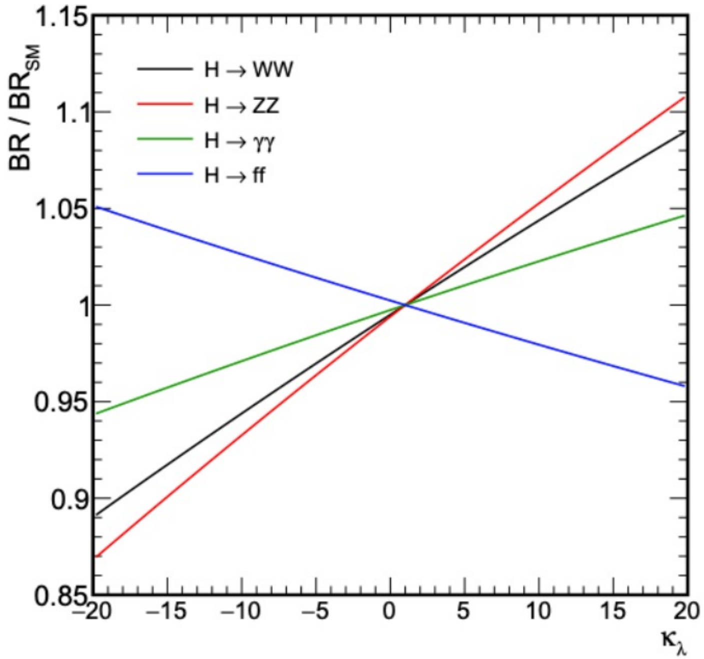
Extension 1: Probe Higgs self-coupling

- In SM, Higgs self-coupling λ_3 depends only on m_H and v: $\lambda_3 = \frac{{m_H}^2}{2v^2}$
  - BSM could modify the Higgs potential and alter λ_3
- Coupling modifier $\boldsymbol{\kappa_\lambda}$ used to express Higgs self coupling λ_3: $\boldsymbol{\kappa_\lambda = \lambda_3 / \lambda_3^{SM}}$
- Single Higgs production rate is much larger (> 1000x) than diHiggs on LHC. However, no direct constraint at LO on higgs self-coupling from single Higgs processes.
- An indirect constraint on κ_λ can be implemented in **single Higgs production** and **Higgs decays** via **NLO EW corrections** JHEP 1612, 080 (2016) , Eur. Phys. J. C (2017) 77



Probe self-coupling with single H processes



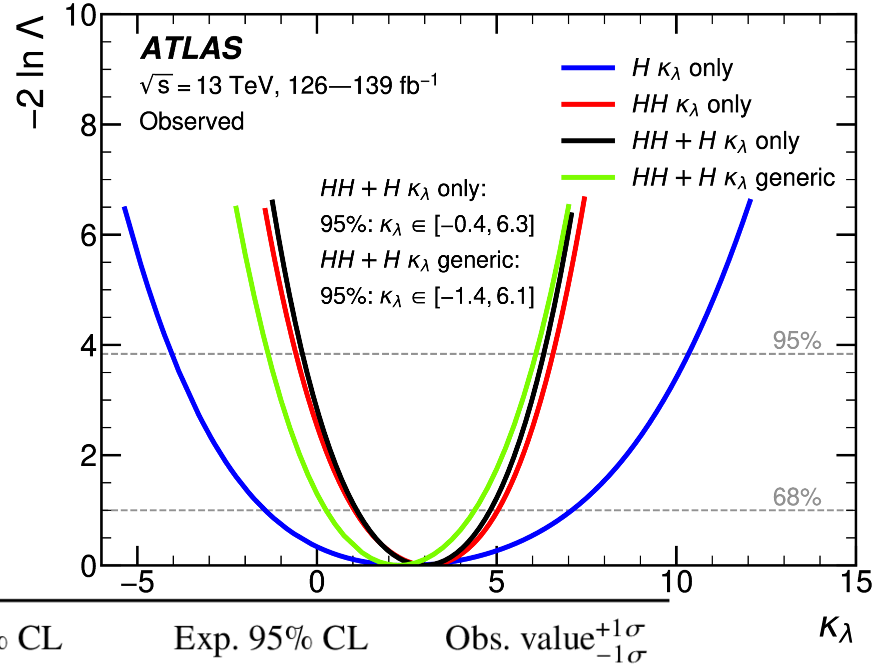


- **Production cross section** and **decay branching ratios** vary as a function of κ_λ
- A technical set up based on STXS using **differential information** to probe Higgs self-coupling via single Higgs processes: LHCHXSWG report
- Implement **universal correction on Higgs self-energy wavefunction renormalization** and **process and kinematic dependent corrections**.

Combining of diHiggs analyses and single Higgs measurement: Phys. Lett. B 843 (2023) 137745 , we provide more sensitive and less model-dependent results on Higgs trilinear self-coupling κ_λ

Combination benefits from complementary sensitivities from each channel.

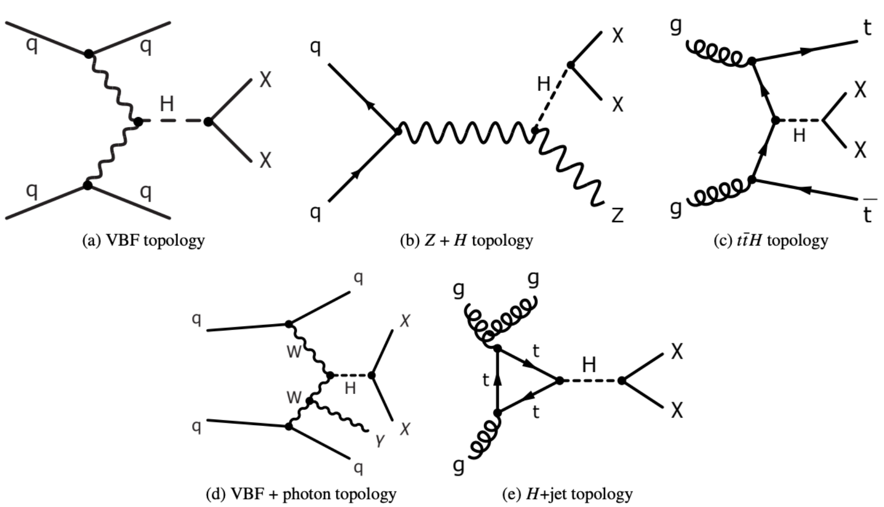
Channel	Integrated luminosity (fb^{-1})
$HH \to b\bar{b}\gamma\gamma$	139
$HH \to b\bar{b}\tau\bar{\tau}$	139
$HH \to b\bar{b}b\bar{b}$	126
$H \to \gamma\gamma$	139
$H \to ZZ^* \to 4\ell$	139
$H \to \tau^+\tau^-$	139
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139
$H \to b\bar{b}$ (VH)	139
$H \to b\bar{b}$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

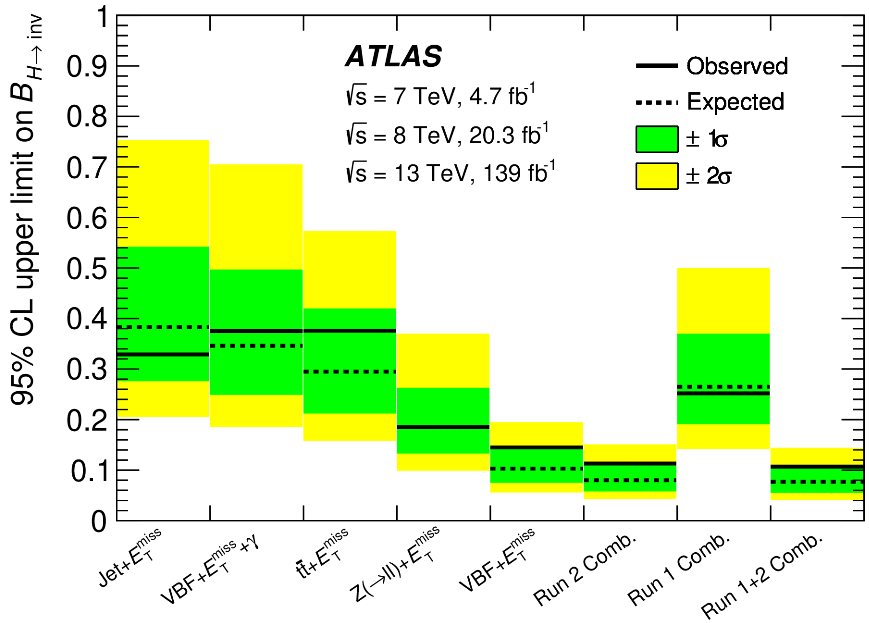


Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$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

DM Higgs portal models

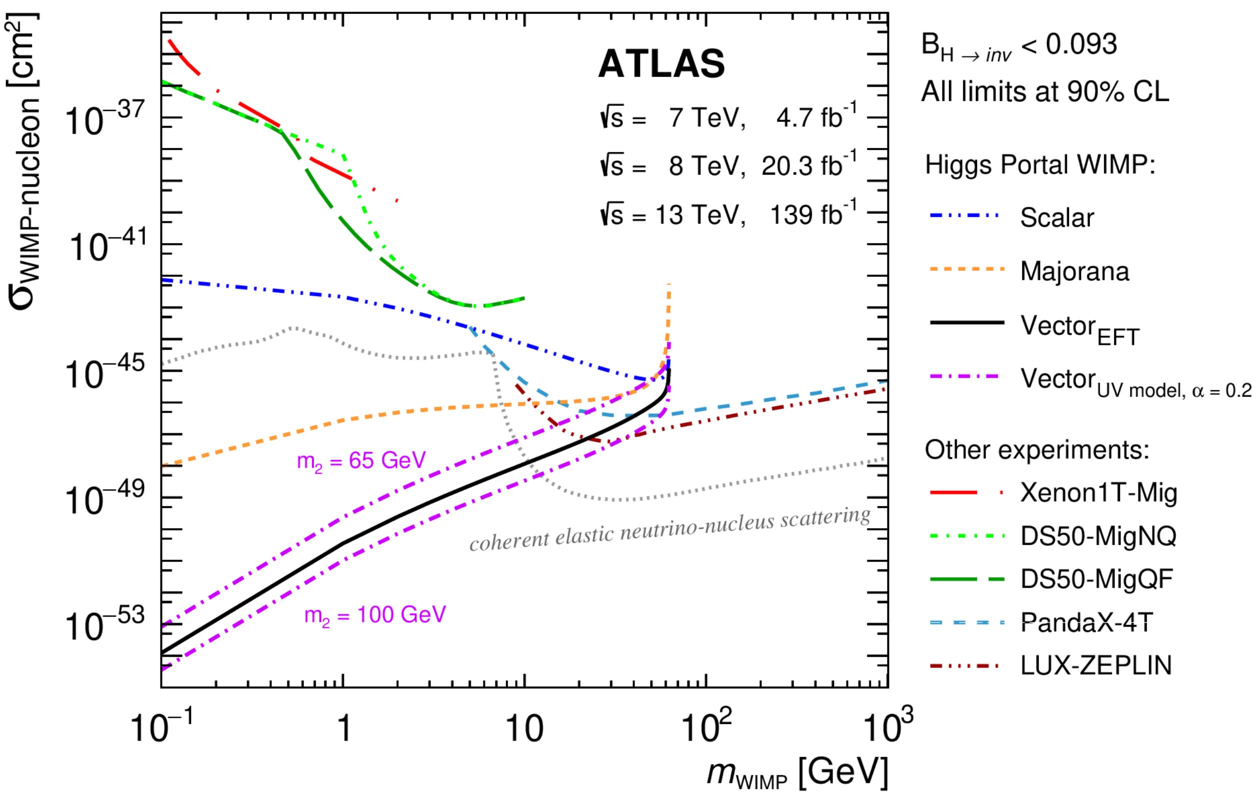
- Search for enhancement of invisibly decays which increase BR(H→inv) (~0.1% in SM).





- Combining direct measurements to probe with higher sensitivity ⇒ Statistically combining **ATLAS Run 2 major H → inv searches** and **Run1 combination results:** Phys. Lett. B 842 (2023) 137963 Observed BR(H→inv) < 0.107 @ 95% C.L. (~0.1% in SM).

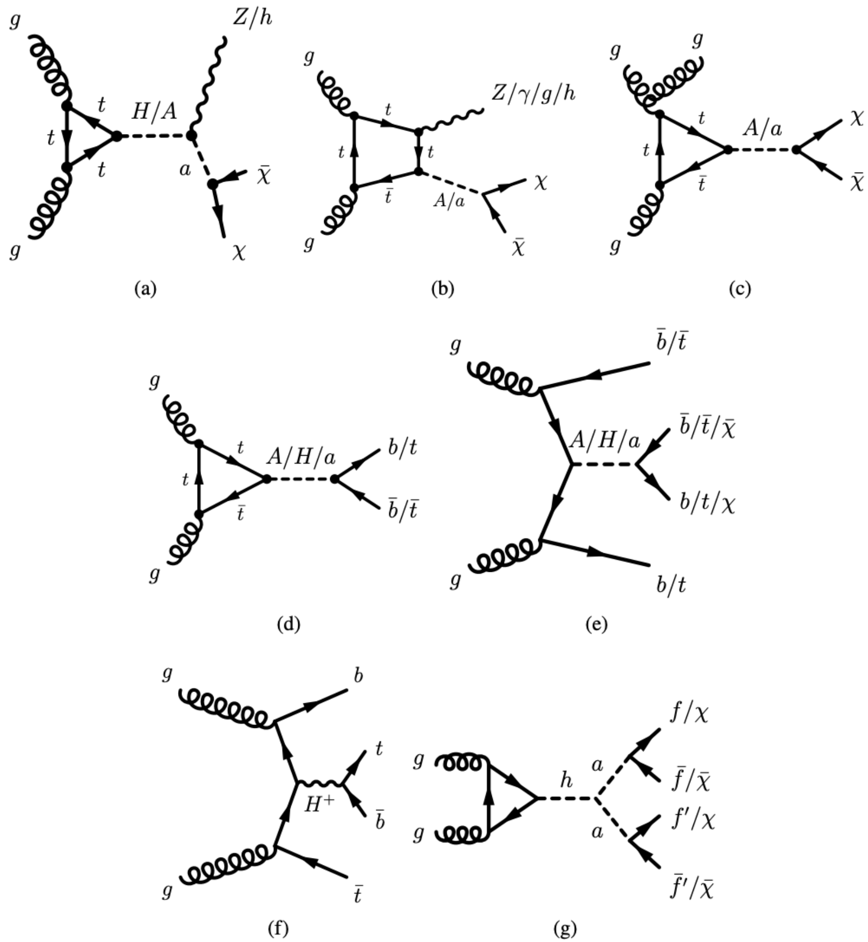
Higgs portal DM results



- **Significant complementarity** between LHC and direct detection experiments
- Caveat: Only VBF+MET and *Z(ll)*+MET results have been included in Nature 607, 52–59 (2022))

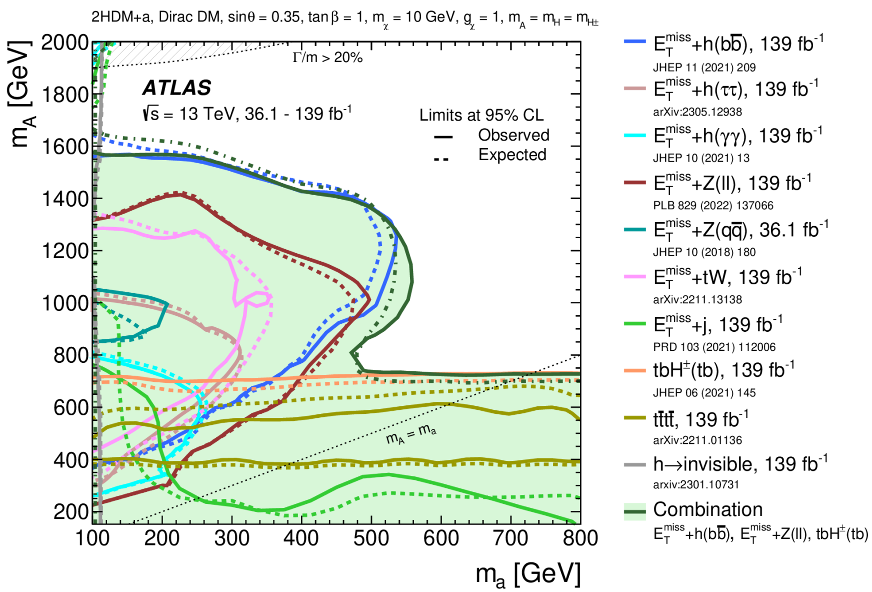
- **Simplest UV-complete model** with a new pseudoscalar DM mediator 'a' [1701.07427]
  - Recommended as **a benchmark model** by LHC DM WG for run 2 [1810.09420]
  - Rich phenomenology => One of the most explored DM models by ATLAS in Run 2.

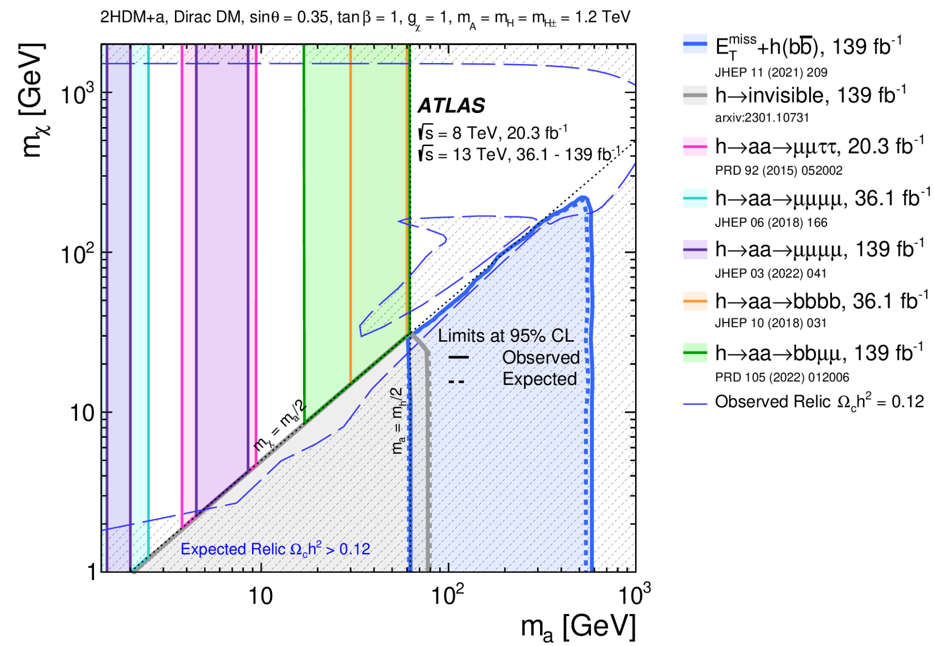
- Signatures with **SM Higgs** and **BSM Higgs** are both important in this model.
- ATLAS full run 2 summary/combination
  - Statistical combination of monoX (monoZ(ll)/monoH(bb)) and non-MET (tbH+(tb)) analyses.
  - Large project: Summary of **~20 analyses** across **4 ATLAS WGs** in **10+ parameter scans.**



2HDM+pseudo DM results

Full Run 2 2HDM+a summary paper has been submitted as the **1st ATLAS paper** to **Science Bulletin** (co-sponsored by the CAS and the NSFC): arXiv:2306.00641



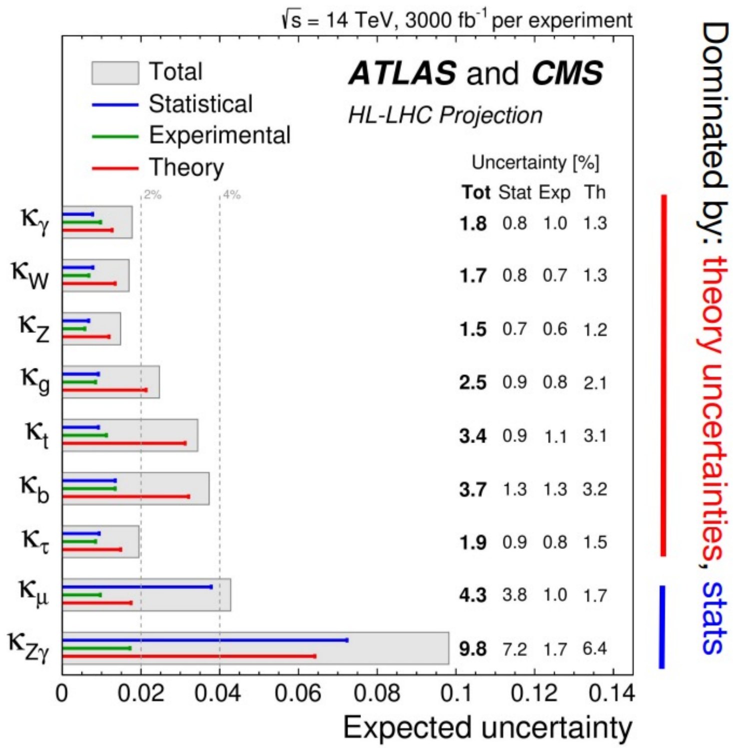


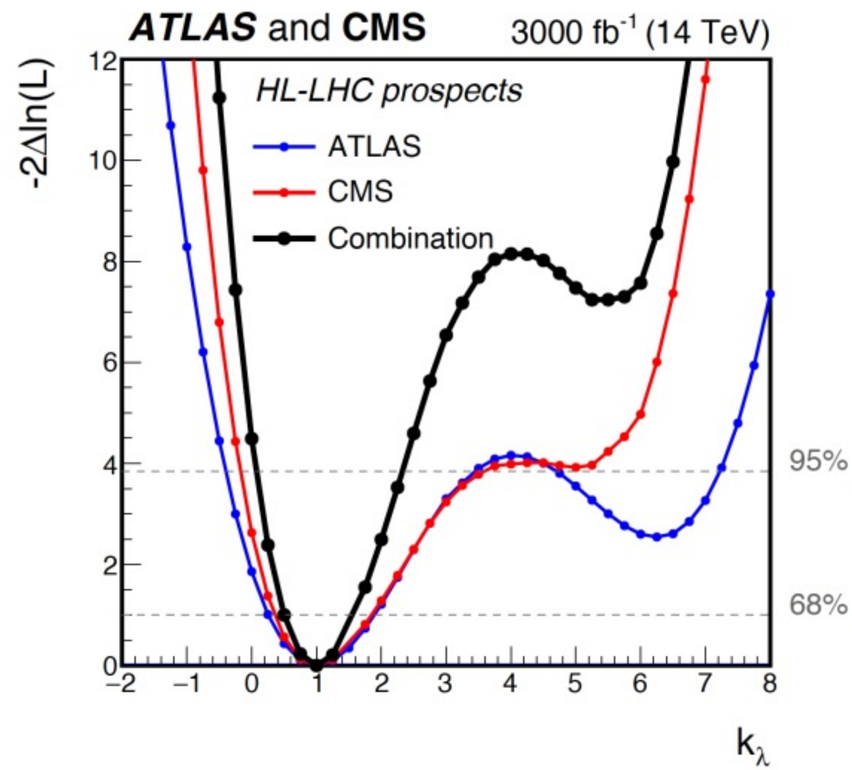
- **A large part of parameter space in benchmarks was excluded**.
- **Complementary** and **better** constrain reached by overlaying/combining of different signatures.
- **Higgs-related signatures place the most stringent constraints in benchmark scans.**

Outlook

- Measurements consistent with the Higgs boson predicted by the Standard Model, motivating **higher precision measurements.**
- 1st ATLAS **partial Run 3** H→ZZ + H→γγ fiducial cross-section measurement: arXiv:2306.11379
- LHC proton-proton dataset:
  - **Larger center-of-mass energy** and **20x** more dataset → To better probe Higgs couplings to other SM particles, Higgs self-coupling and the connections to new physics through Higgs sector.

- Efforts made for HL-LHC projections. Usually from published LHC Run 2 results, with **HL-LHC conditions** and **projections on uncertainties**
- [LHC Perspective report].





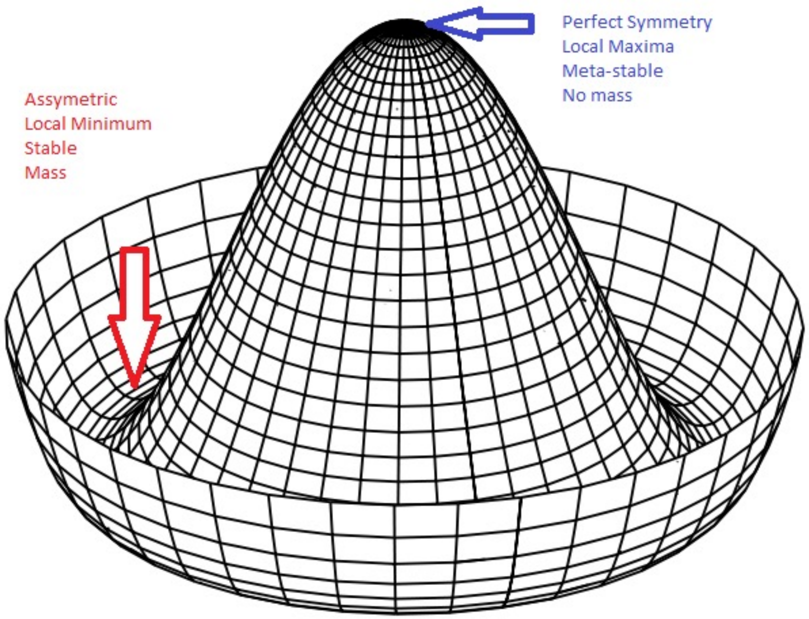
- With the future **HL-LHC** (3000 fb^{-1}), an unprecedented precision at a **percent level or better** for most of Higgs boson couplings, a 50% precision on Higgs self coupling will be reached!

Summary

- In the **10 years** since the Higgs discovery, many measurements have been performed by the ATLAS collaboration, with confirmation that the properties of this Higgs Boson show **good agreement with the SM**.
- A combined measurement of Higgs interactions has been presented
  - All main production and decay modes have been observed
  - Hints of rare Higgs decays have been seen
  - Kinematic dependence of production cross sections has been studied across a wide range of phase space
  - Unprecedented precision reached on coupling measurements including Higgs self-coupling.
  - Various searches have been made with Higgs to probe the potential BSM effect.
- Stay tuned for better results from LHC Run 3 and future experiment results!

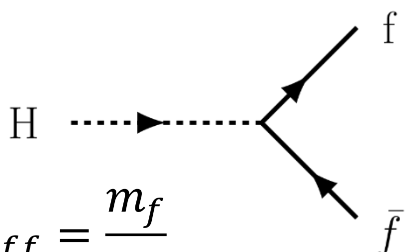
Backup

Higgs boson in the SM

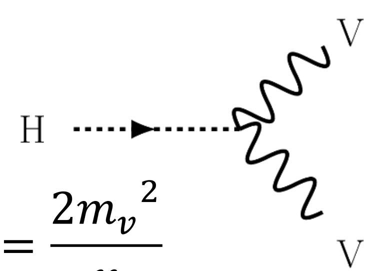


- Vector bosons masses → **spontaneous symmetry breaking**
- Fermions masses → **Yukawa couplings**
- The Higgs Boson couplings to other particles are set by their masses →determine all Higgs Boson production and decay.

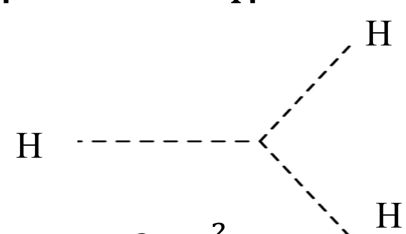
$$\mathcal{L} = -g_{Hff} f\bar{f}H + \delta_V V_\mu V^\mu \left(g_{HVV} H + \frac{g_{HHVV}}{2} H^2\right) + \frac{g_{HHH}}{3!} H^3 + \frac{g_{HHHH}}{4!} H^4$$



$$g_{Hff} = \frac{m_f}{v}$$



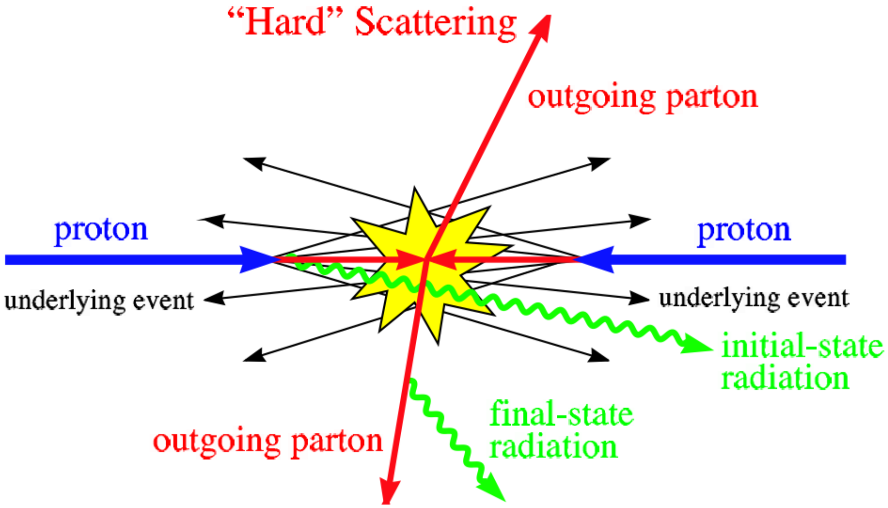
$$g_{HVV} = \frac{2m_v{}^2}{v}$$



$$g_{HHH} = \frac{3m_H{}^2}{v} = 6\lambda_3 v$$

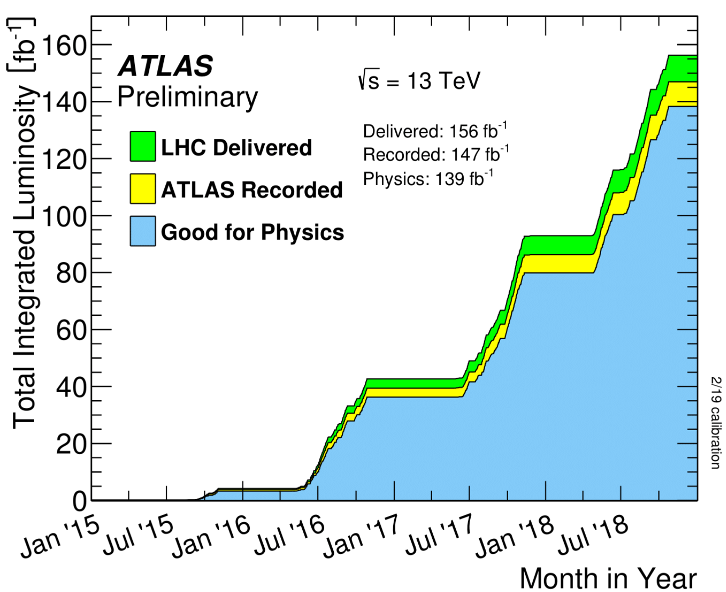
v = vacuum expectation value of the Higgs field

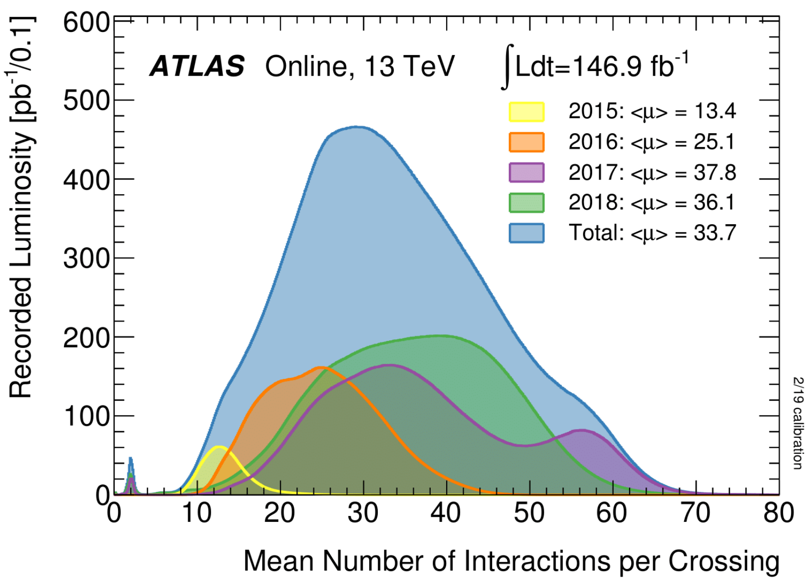
pp collisions and dataset at LHC



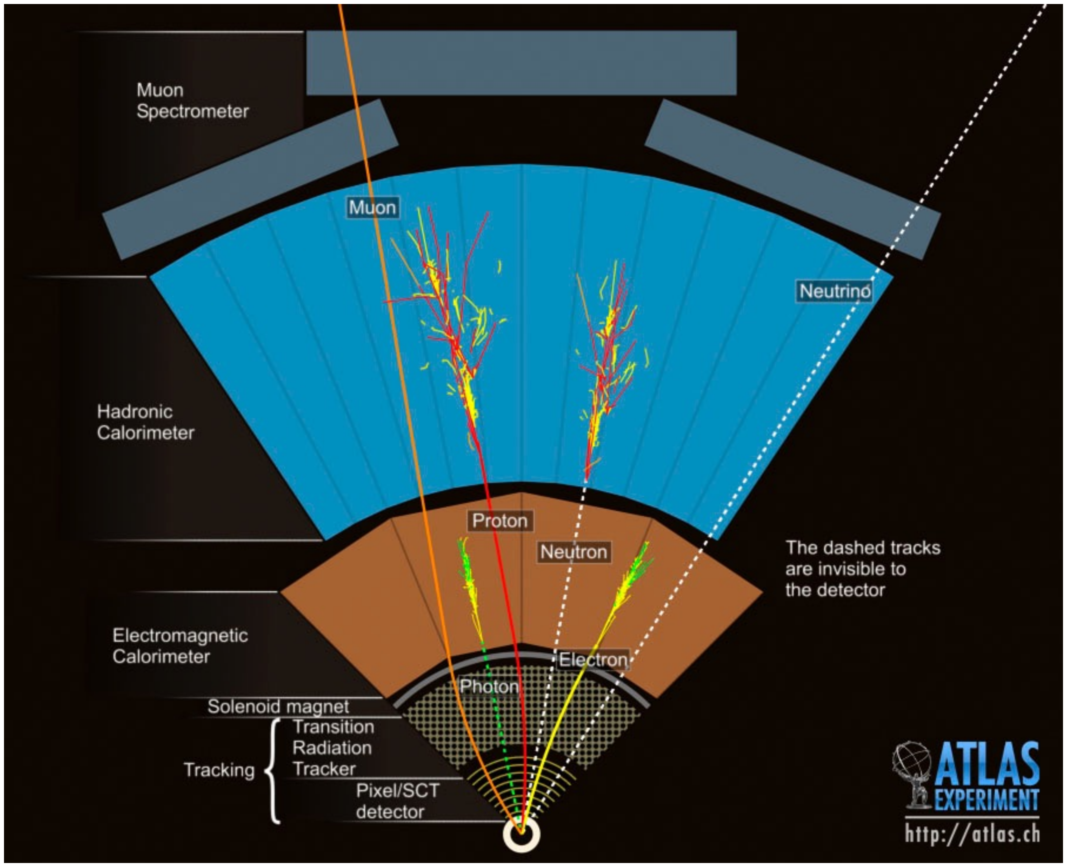
Integrated luminosity: 139 fb^{-1} after good quality requirement collected from 2015 to 2018.

Pile-up: additional pp collisions in the same (in-time) and surrounding (out-of-time) bunch crossings. More significant with the increasing luminosity.





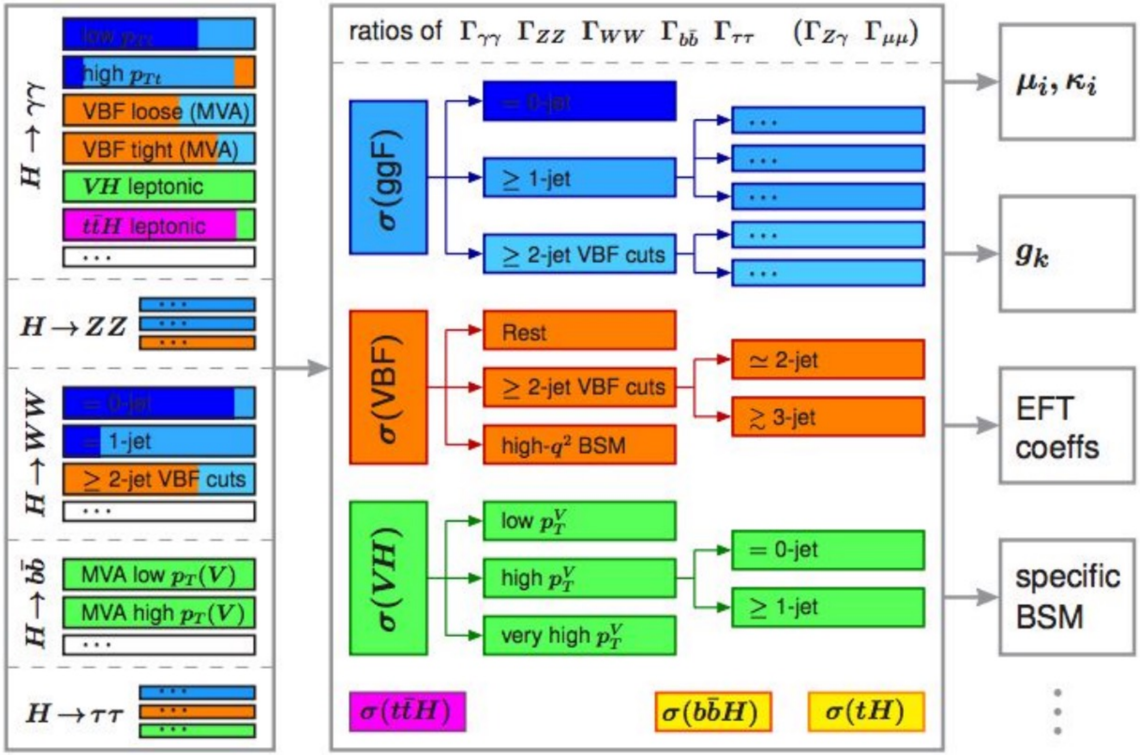
Reconstruction and identification



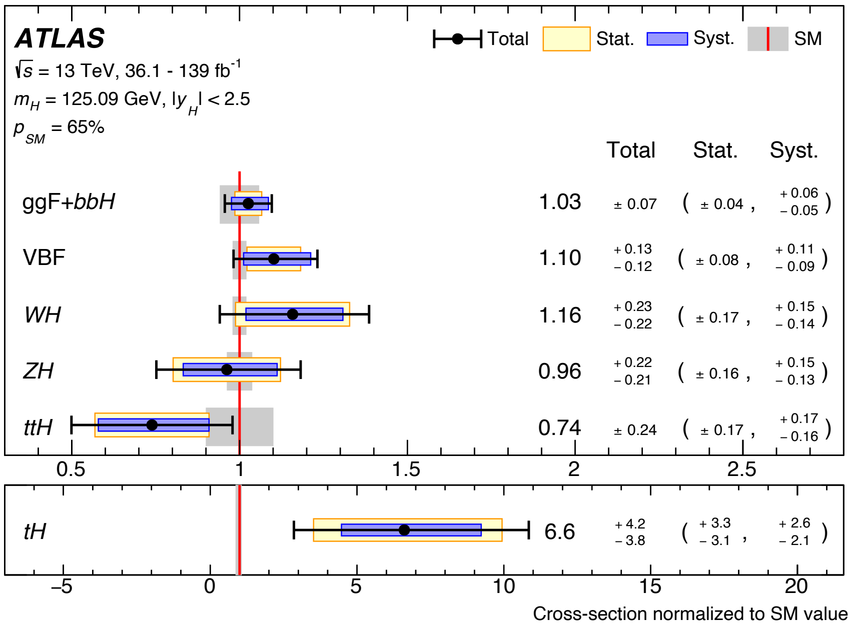
- **Each particle type has its own signature in the detector.**
- Reconstruction and identification algorithms of the major physics objects for analysis, such as vertices, tracks, photons, electrons, muons, jets and E_T^{miss} are developed by using the information from certain sensitive sub-detectors.

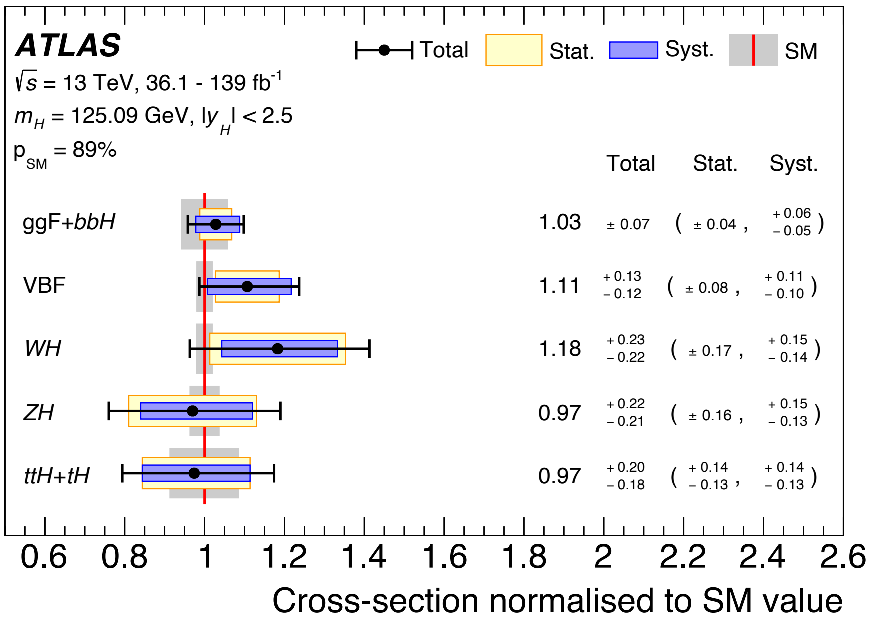
STXS can make Higgs measurements less model dependent than measurements during Run 1

- STXS (Simplified Template Cross Sections) splits Higgs productions into exclusive kinematic regions (Described in YellowReport4 (Section III.2).
- Instead of performing differential measurement in clean channels only, intend for **combination of all decay channels**.
- Minimize the dependence on theoretical uncertainties.



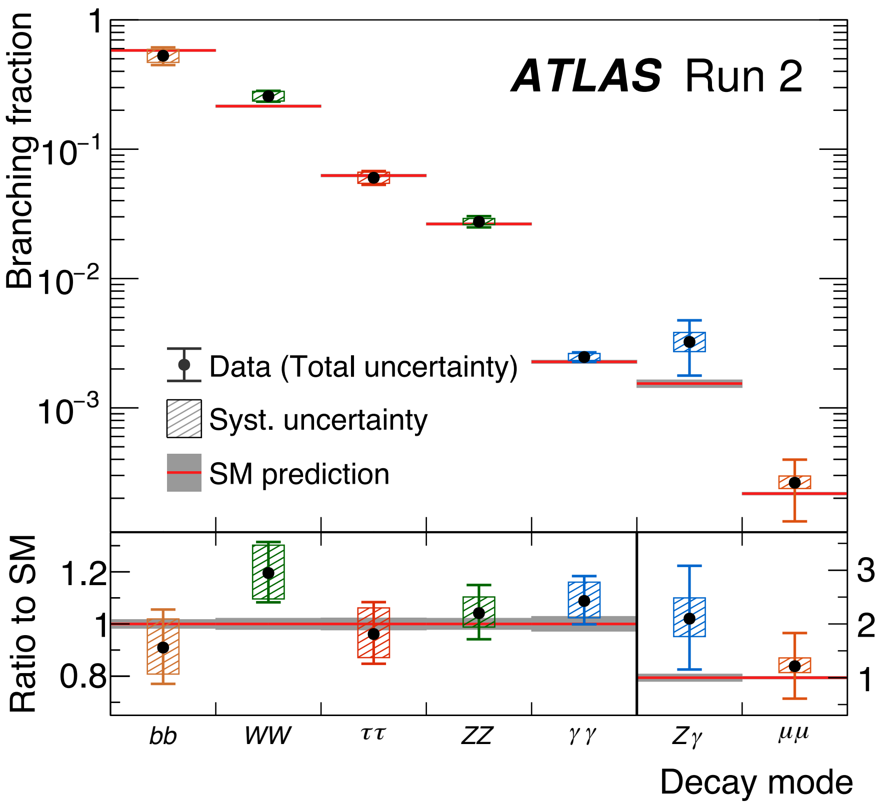
Cross section

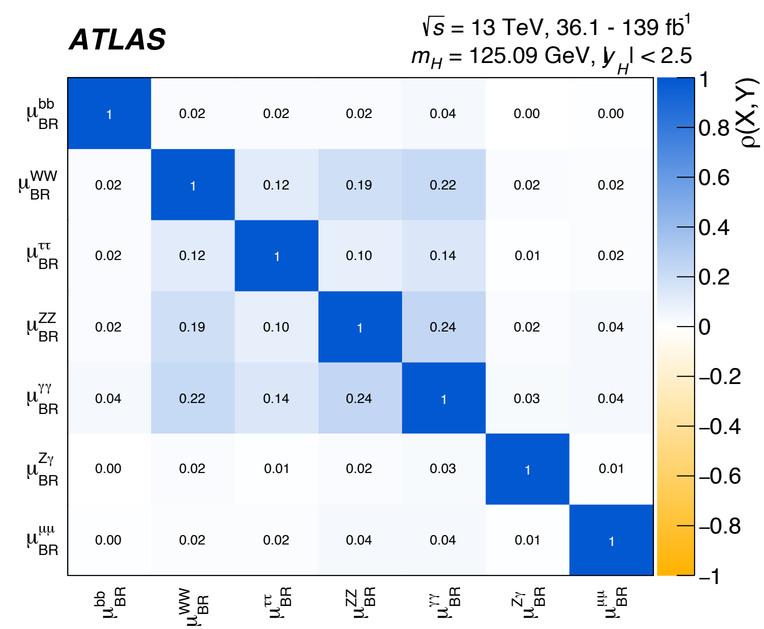


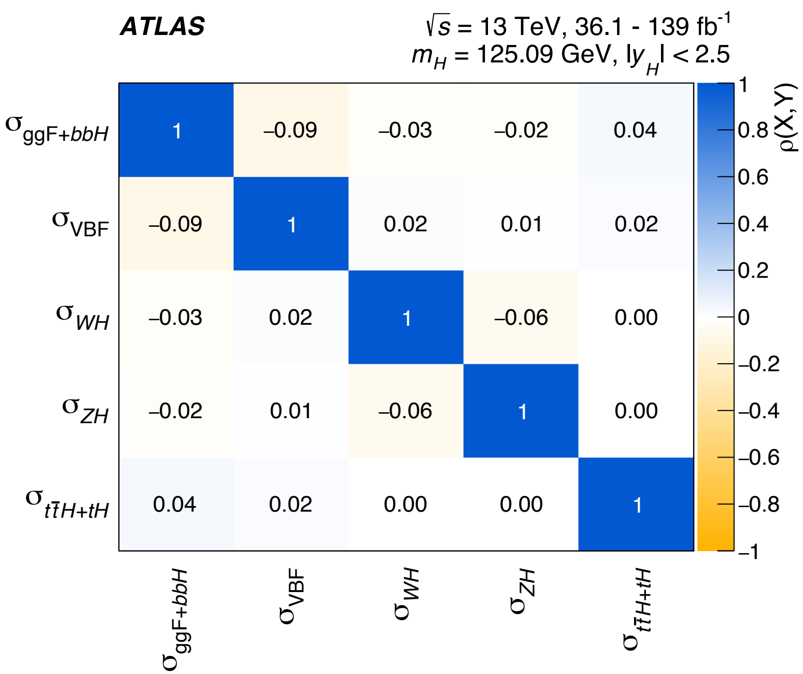


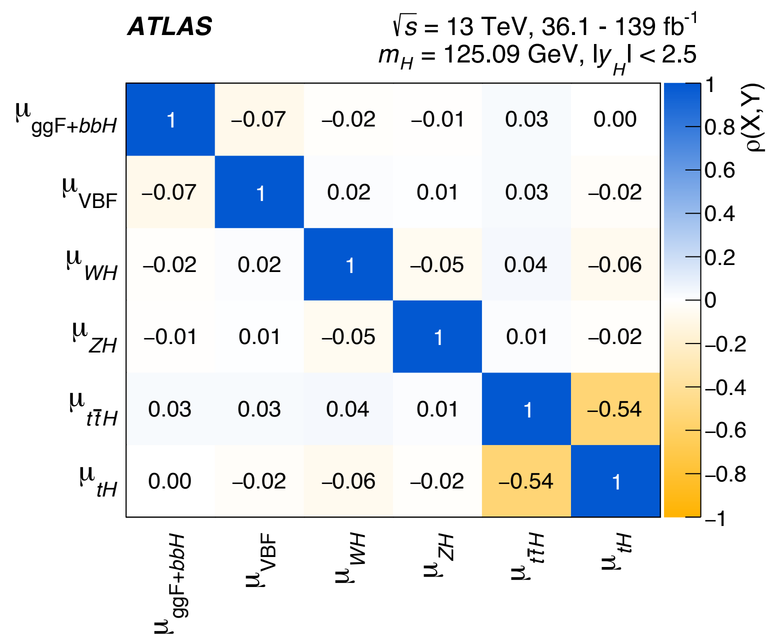
Decay branching-ratios

- Branching ratios:
  - **Production cross sections are assumed to be SM-like** when combining processes/measurements
  - SM compatibility (p-value): 56%

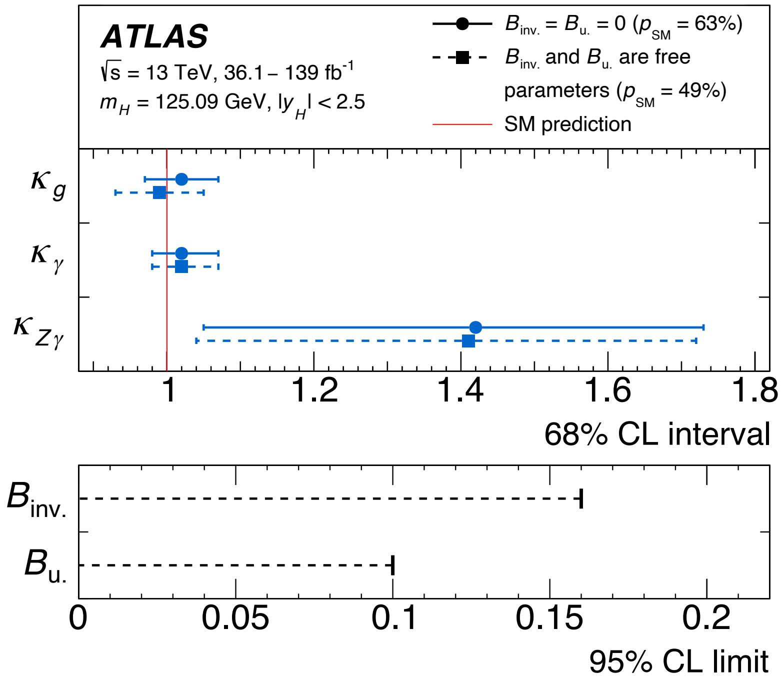


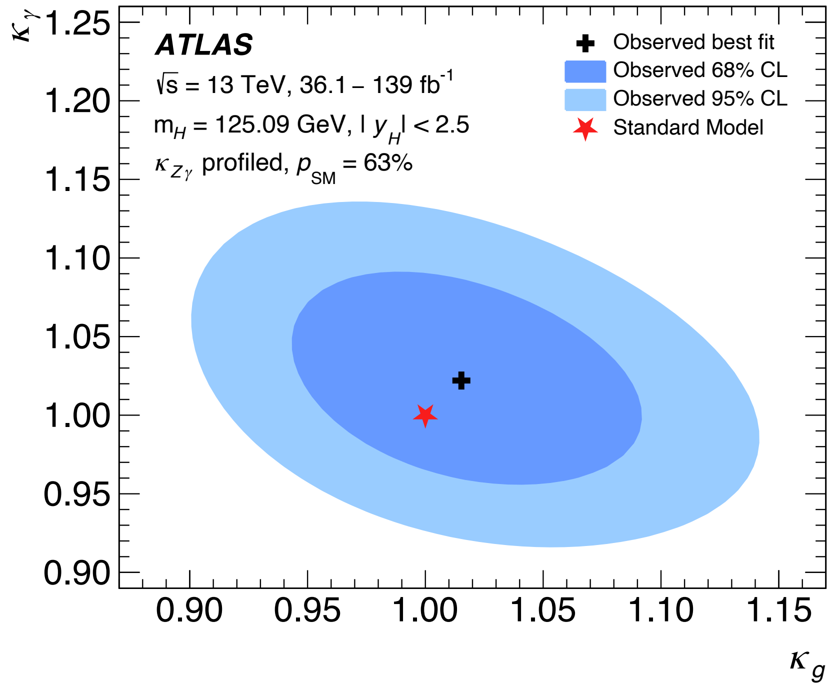



ATLAS
√s = 13 TeV, 36.1 - 139 fb-1
mH = 125.09 GeV, |yH| < 2.5
ρ(X,Y)
σggF+bbH 1 −0.09 −0.03 −0.02 0.04
σVBF −0.09 1 0.02 0.01 0.02
σWH −0.03 0.02 1 −0.06 0.00
σZH −0.02 0.01 −0.06 1 0.00
σtt̄H+tH 0.04 0.02 0.00 0.00 1


ATLAS
√s = 13 TeV, 36.1 - 139 fb-1
mH = 125.09 GeV, |yH| < 2.5
ρ(X,Y)
μggF+bbH 1 −0.07 −0.02 −0.01 0.03 0.00
μVBF −0.07 1 0.02 0.01 0.03 −0.02
μWH −0.02 0.02 1 −0.05 0.04 −0.06
μZH −0.01 0.01 −0.05 1 0.01 −0.02
μtt̄H 0.03 0.03 0.04 0.01 1 −0.54
μtH 0.00 −0.02 −0.06 −0.02 −0.54 1

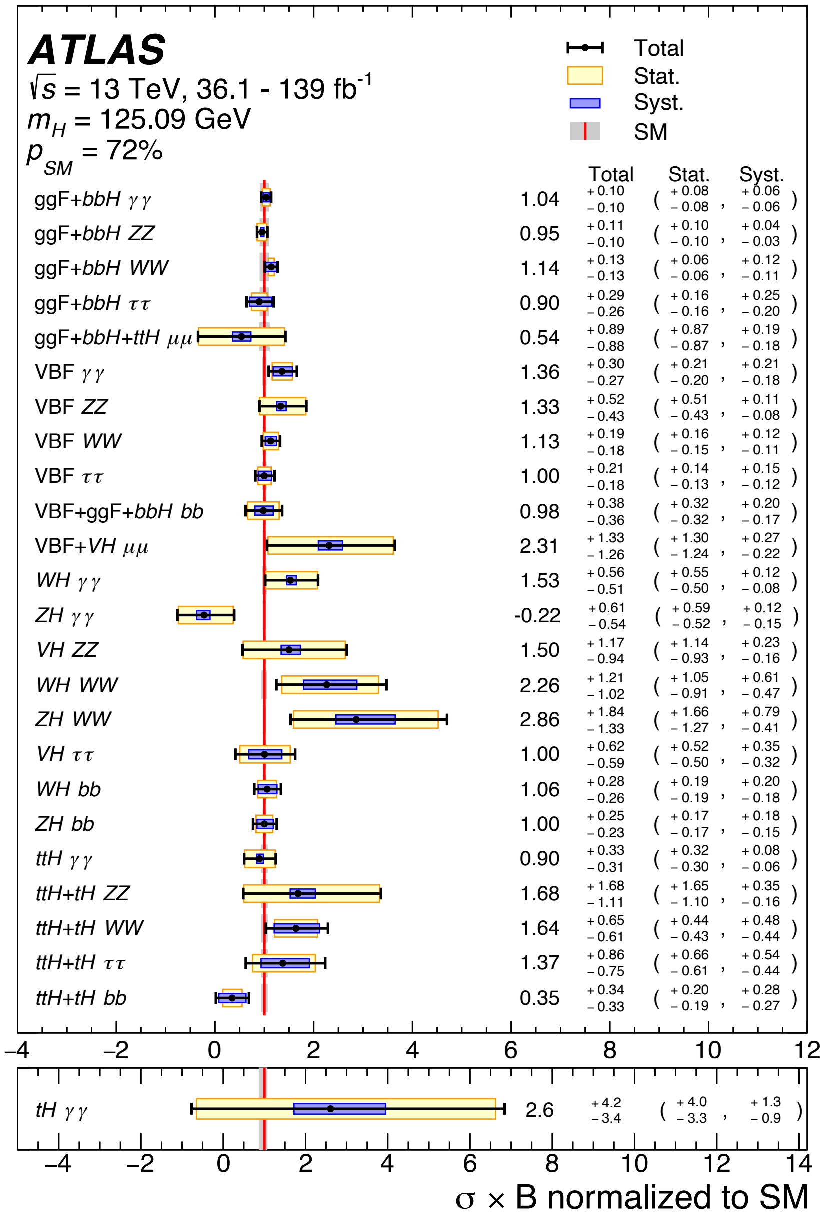
Effective coupling of loop contributions

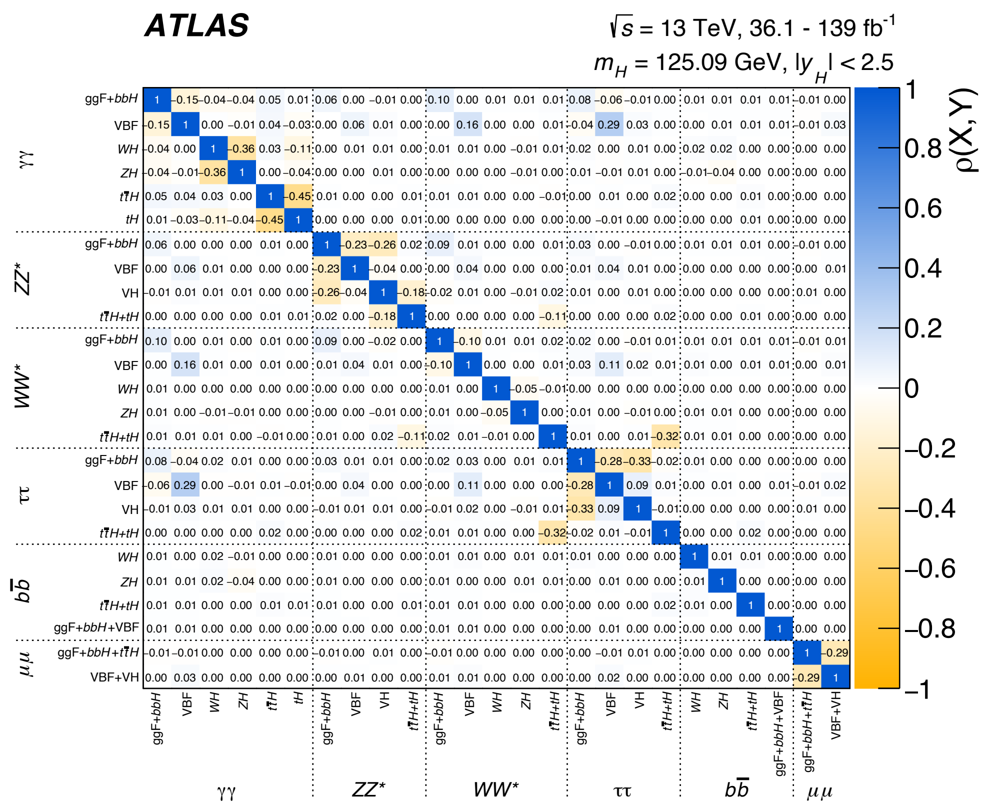




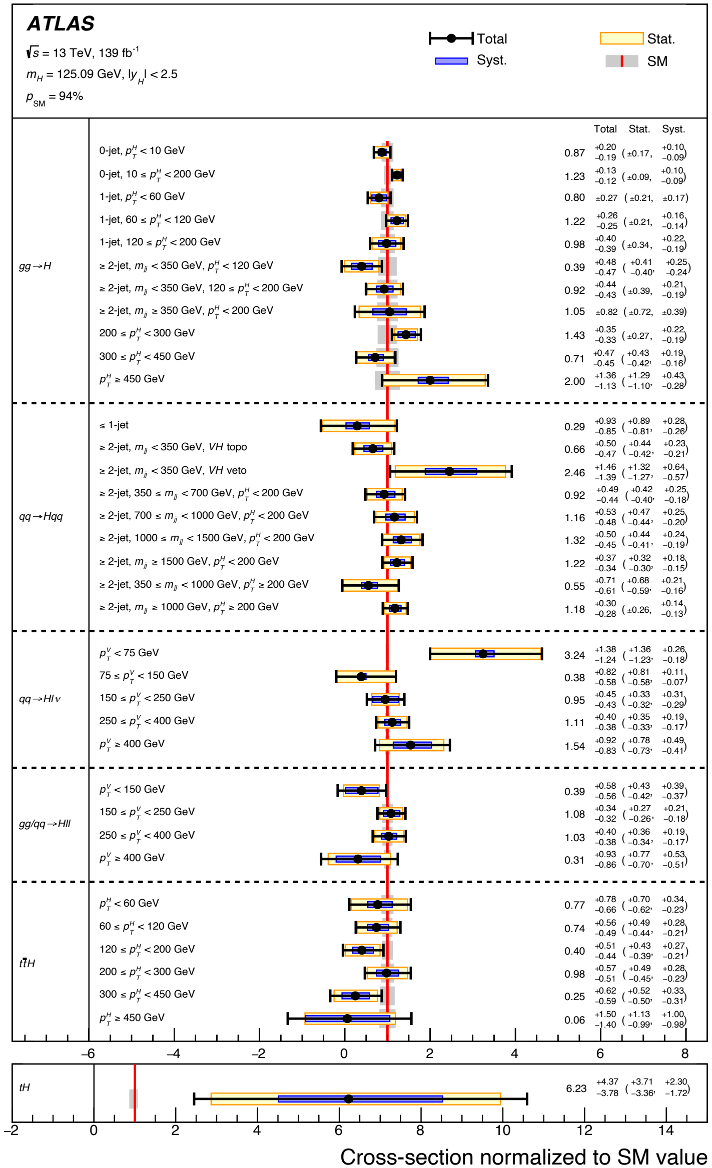
- Assign coupling modifiers of **ggF**, ***H→gg*** (κ_g), ***H→γγ*** (κ_γ) and ***H→Zγ*** ($\kappa_{Z\gamma}$)
  - capture all loop contributions to the Higgs interaction with gluons and photons
- Two scenarios: with and without invisible and undetected non-SM Higgs decays.
- SM compatibility (p-value): 63% ($B_{inv} = B_u = 0$)
- Upper limits on B_{inv} of 0.16 (0.09) and B_u of 0.10 (0.18) at 95% CL

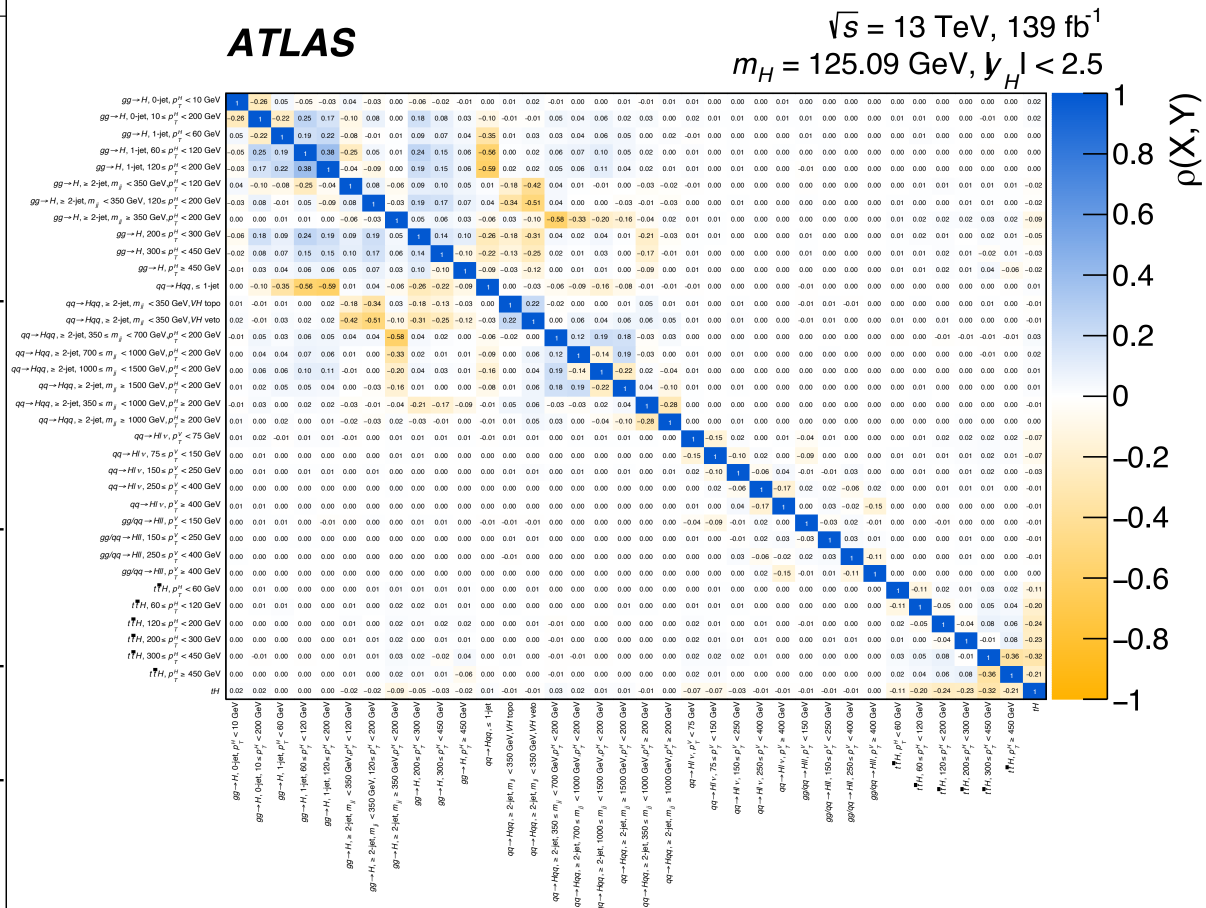
Cross section tims BR



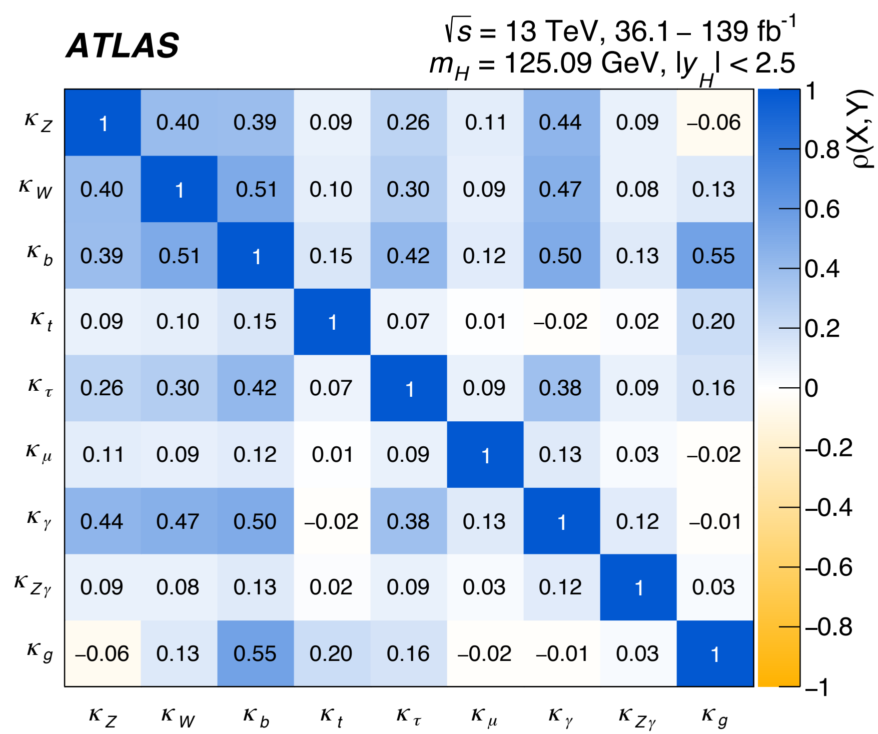


STXS


ATLAS
√s = 13 TeV, 139 fb⁻¹
m_H = 125.09 GeV, |y_H| < 2.5
p_SM = 94%
Total
Stat.
Syst.
SM
gg→H
qq→Hqq
qq→Hlν
gg/qq→Hll
ttH
tH
Cross-section normalized to SM value

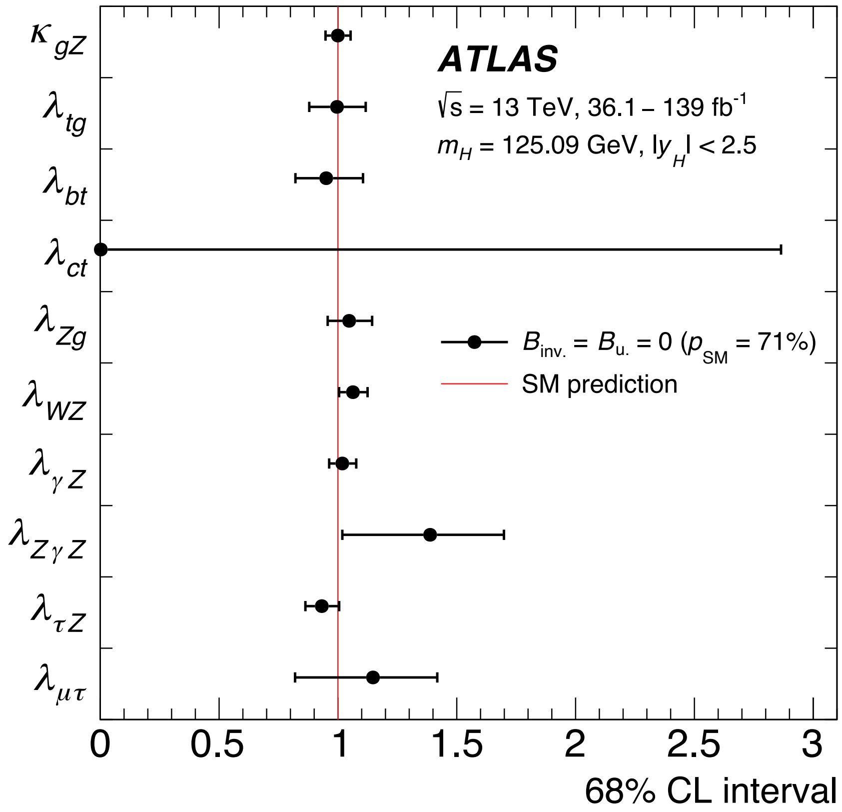

ATLAS
√s = 13 TeV, 139 fb⁻¹
m_H = 125.09 GeV, |y_H| < 2.5
ρ(X, Y)

	(a) $B_{inv.} = B_{u.} = 0$	(b) $B_{inv.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	$0.99^{+0.06}_{-0.06}$	$0.98^{+0.02}_{-0.05}$
κ_W	$1.05^{+0.06}_{-0.06}$	$1.00_{-0.02}$
κ_t	$0.94^{+0.11}_{-0.11}$	$0.94^{+0.11}_{-0.11}$
κ_b	$0.89^{+0.11}_{-0.11}$	$0.82^{+0.09}_{-0.08}$
κ_τ	$0.93^{+0.07}_{-0.07}$	$0.91^{+0.07}_{-0.06}$
κ_μ	$1.06^{+0.25}_{-0.30}$	$1.04^{+0.23}_{-0.30}$
κ_g	$0.95^{+0.07}_{-0.07}$	$0.94^{+0.07}_{-0.06}$
κ_γ	$1.01^{+0.06}_{-0.06}$	$0.98^{+0.05}_{-0.05}$
$\kappa_{Z\gamma}$	$1.38^{+0.31}_{-0.37}$	$1.35^{+0.29}_{-0.36}$
$B_{inv.}$	-	< 0.13
$B_{u.}$	-	< 0.12



Ratio kappa model

Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g \kappa_Z / \kappa_H$	1.00 ± 0.05
λ_{tg}	κ_t / κ_g	1.00 ± 0.12
λ_{bt}	κ_b / κ_t	$0.95\ ^{+\ 0.15}_{-\ 0.13}$
λ_{ct}	κ_c / κ_t	$0.00\ ^{+\ 2.86}$
λ_{Zg}	κ_Z / κ_g	$1.05\ ^{+\ 0.10}_{-\ 0.09}$
λ_{WZ}	κ_W / κ_Z	1.06 ± 0.06
$\lambda_{\gamma Z}$	κ_γ / κ_Z	1.02 ± 0.06
$\lambda_{Z\gamma Z}$	$\kappa_{Z\gamma} / \kappa_Z$	$1.39\ ^{+\ 0.31}_{-\ 0.37}$
$\lambda_{\tau Z}$	κ_τ / κ_Z	0.93 ± 0.07
$\lambda_{\mu\tau}$	κ_μ / κ_τ	$1.15\ ^{+\ 0.27}_{-\ 0.33}$



Input likelihood modification

- In the combination, a **full model** with **BR uncertainty** split into different sources

Channel	BR	α_s	m_b	m_c	TH bb	TH $\tau\tau$	TH $\mu\mu$	TH cc	TH gg	TH VV	TH $\gamma\gamma$	TH $Z\gamma$
$H \to bb$	5.81E-01	-0.78	0.71	-0.15	0.21	-0.03	<0.01	-0.01	-0.26	-0.12	<0.01	-0.01
$H \to \tau\tau$	6.26E-02	0.63	-0.99	-0.15	-0.29	0.47	<0.01	-0.01	-0.26	-0.12	<0.01	-0.01
$H \to \mu\mu$	2.17E-04	0.63	-0.99	-0.15	-0.29	-0.03	0.50	-0.01	-0.26	-0.12	<0.01	-0.01
$H \to cc$	2.88E-02	-0.38	-0.99	5.18	-0.29	-0.03	<0.01	0.49	-0.26	-0.12	<0.01	-0.01
$H \to gg$	8.18E-02	3.65	-0.99	-0.15	-0.29	-0.03	<0.01	-0.01	2.94	-0.12	<0.01	-0.01
$H \to \gamma\gamma$	2.27E-03	0.63	-0.99	-0.15	-0.29	-0.03	<0.01	-0.01	-0.26	-0.12	1.00	-0.01
$H \to Z\gamma$	1.54E-03	0.63	-0.99	-0.15	-0.29	-0.03	<0.01	-0.01	-0.26	-0.12	<0.01	4.99
$H \to VV$	2.42E-01	0.63	-0.99	-0.15	-0.29	-0.03	<0.01	-0.01	-0.26	0.38	<0.01	-0.01

- **Scale Higgs mass** to 125.09 GeV
  - Besides HGam, Htautau, Hmumu and HZy, other channels are based on $m_H = 125$ GeV rather than 125.09 GeV, prod. XS and BR need to be corrected
  - **Prod. XS**
    - The XS difference between 125 and 125.09 GeV is well below theory unc. (0.1-0.2%), thus is **neglected**
  - **BR**
    - BR correction is neglected as well except for $\boldsymbol{H \to VV(WW, ZZ)}$, which is ~1%

Input likelihood modification

- **Luminosity:**
  - Two kinds of datasets included with different lumi uncer. (15-16: 2.1%, 15-18: 1.7%).
  - Simplified approach to consider lumi uncertainty correlations in each dataset:

    Splitting sources to correlated and uncorrelated terms, with a good closure reached.

	36 fb^{-1}	139 fb^{-1}
Uncorr36	1.558	0.406
Uncorr44-58	0	0.794
Correlated	1.459	1.459
Total	2.135	1.710

- **NLO EW corrections for VBF/VH processes**
  - Corrections are calculated with HAWK, available at LHCHXSWG.
  - Corrections already considered in HGam, Htautau, (boosted, VBF, VH) bb, VHcc and (VBF/VH) Hinv channels
  - Implemented corrections by us in HZZ and HWW.

Correlation and systematic impact

- **Experimental uncertainties.**
  - Correlate CP NPs where possible following recommendations
  - Decorrelate different analysis releases (20.7 VS 21)
  - Decorrelate NPs from different schemes, calibrations and WPs
- **Theory uncertainties**
  - Correlate signal uncertainties where possible
  - Decorrelate bkg. uncertainties as they are evaluated in different phase spaces in input channels
- **Special treatments**
  - Study over-constrained (<70%) or pulled (>0.5) NPs. Decorrelate as baseline.

	μ_{mu}	
Uncertainty source	$\Delta\sigma_{\text{low}}$ [%]	$\Delta\sigma_{\text{high}}$ [%]
Theory Signal	3.8	4.1
Theory Background	1.7	1.7
Luminosity	1.6	1.8
Jet/E_T^{miss}	0.78	0.86
Flavour Tag	0.88	0.84
EGamma	1.2	1.3
Tau	0.28	0.3
MC Stat	0.99	0.95

Technical improvement

- **Motivation**
  - More and more channels included in combination, fitting time consumption is becoming a bottleneck (In total, over 2600 sources of systematic uncertainty are included in the combined likelihood. **>24 hrs** single MIGRAD+HESSE fit)
- Optimize fitting procedure together with **CERN RooFit devs** using **toy ATLAS workspaces**
  - RooFit were not designed with such huge likelihoods
  - Typically, **RooArgSet** are implemented as **std::vector**. But lookups are then in linear time, causing huge time consumption in likelihood creation.
  - RooFit devs implemented a **new caching mechanism** with dedicated lookup tables
- **Outcome:**
  1. Many features has been released as a part of ROOT master/6.26 in March 2022.
  2. HComb has validated and used a "preview" ROOT version (via docker images) to produce all results.
  3. ~3X faster in fitting workflows (createNLL, RooMinimizer creation, NLL minimization, etc.)

Recap of κ_λ parameterization in single H

- The κ_λ –dependent implementation can be expressed as

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\text{BSM}}}{\sigma^{\text{SM}}} = Z_H^{\text{BSM}}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\text{EW}}^i}\right]$$

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\text{BR}_f^{\text{BSM}}}{\text{BR}_f^{\text{SM}}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \text{BR}_j^{\text{SM}}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

$$Z_H^{\text{BSM}}(\kappa_\lambda) = \frac{1}{1 - (\kappa_\lambda^2 - 1)\delta Z_H}, \text{with } \delta Z_H = -1.536 \times 10^{-3}$$

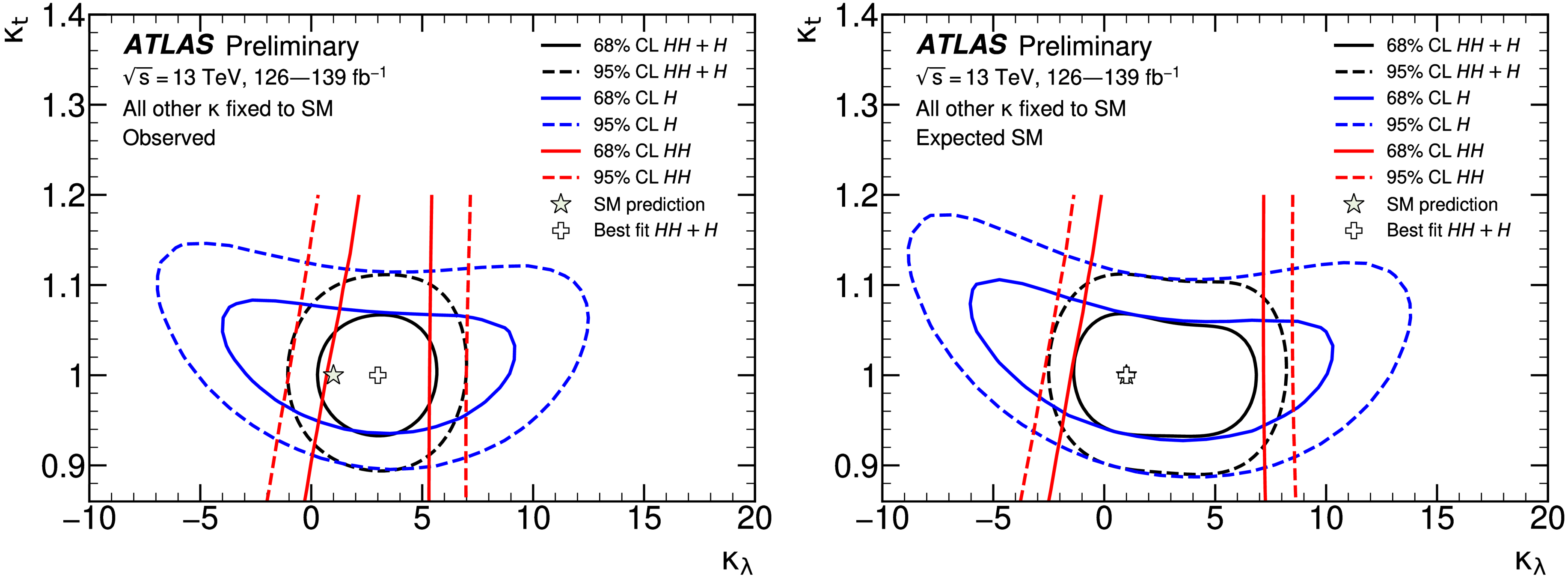
- $\boldsymbol{Z_H^{BSM}}$ represents the effect of the Higgs self-energy wavefunction renormalization (**same for all the Higgs mechanisms**)
- $\boldsymbol{C_1^{\text{i}}}$ describes the magnitude of the correction (**process-dependent**)
- $\boldsymbol{K_{EW}^{\text{i}}}$ is the k-factor for the full set of NLO electroweak correction (**process-dependent**)

κ_λ parameterization in single H

- In this round, $\boldsymbol{C_1^i}$ on single Higgs production has been extended to **STXS 1.2** granularity, to use more differential information for additional sensitivity LHCHXSWG-Pubnote
- Technically, MG5 was used to generate events at LO. Events are then classified into STXS bins via Rivet. In each STXS bin, C_1^{i} is computed as

$$C_1^i = \frac{\sum_j w_{NLO}^j}{\sum_j w_{LO}^j}$$

  - Where $\boldsymbol{w_{NLO}^{\mathrm{j}}}$ is the weight from LO cross section corrected for the κ_λ-effect through NLO EW correction
  - $\boldsymbol{w_{LO}^j}$ is the weight corresponding to LO cross section
- C_1^{i} calculation at STXS 1.2 is available for *ttH, V(lep)H,* and *Hjj* processes.
- C_1^{i} of ggH and *tHj* is still at inclusive level due to the missing theoretical calculations at the differential level.
- No available C_1^{i} calculation on *tHW*, *bbH* and *ggZH* processes.



- $\kappa_\lambda - \kappa_t$ **2D contours** from the fit with the only these two parameters floating.
- Major constraints on κ_t from single Higgs measurements.