A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

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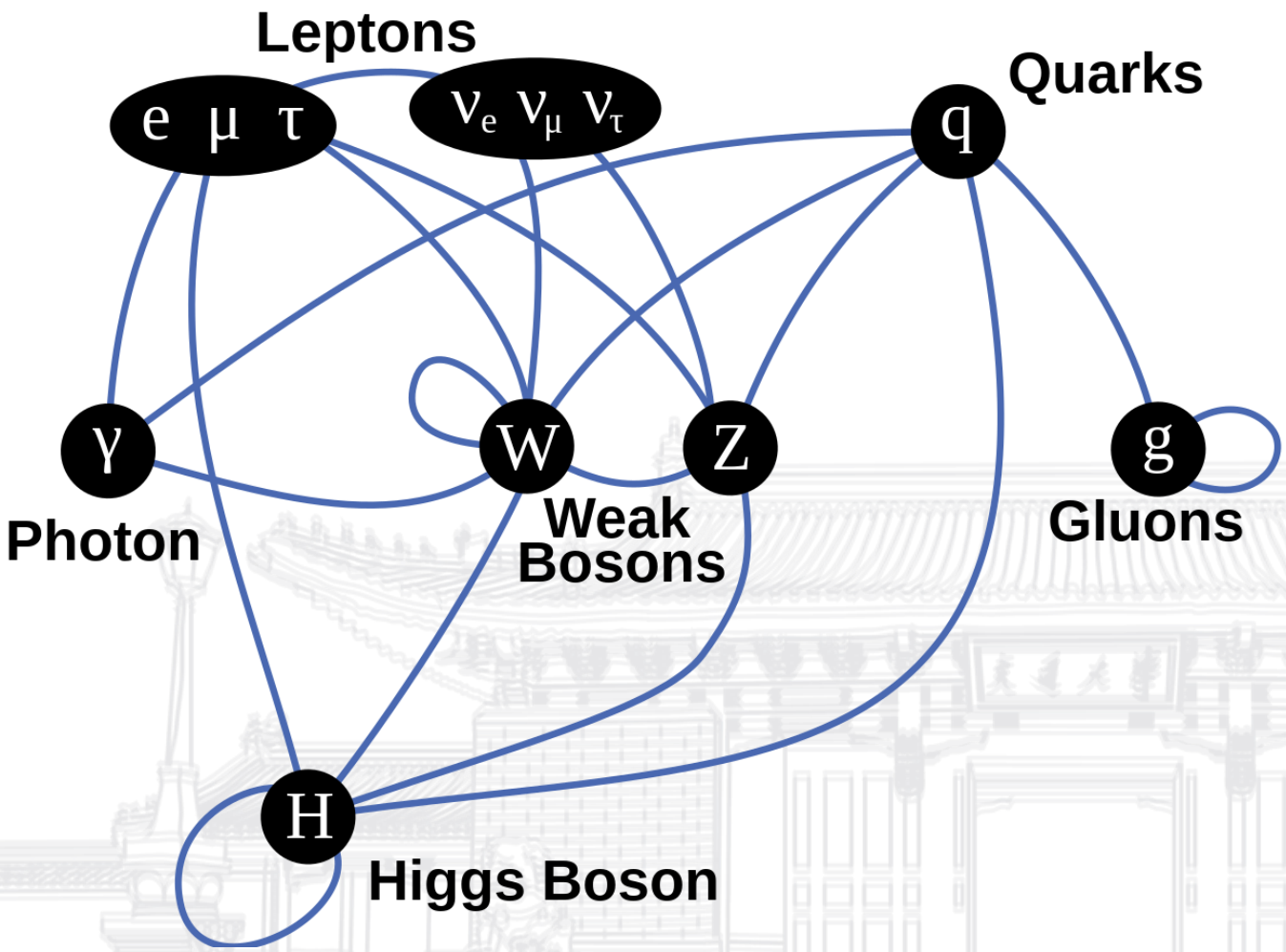
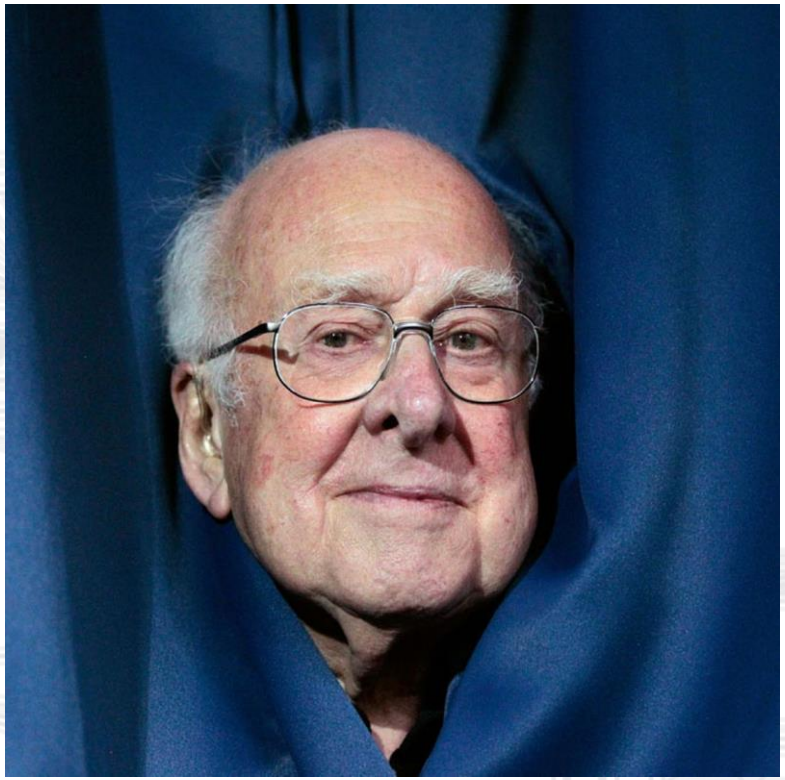
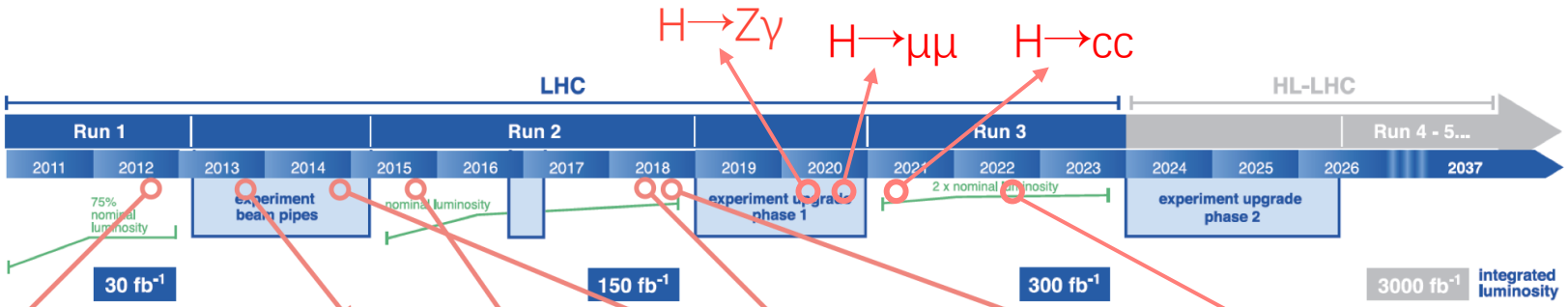
ATLAS EXPERIMENT

10 years of Higgs @ ATLAS

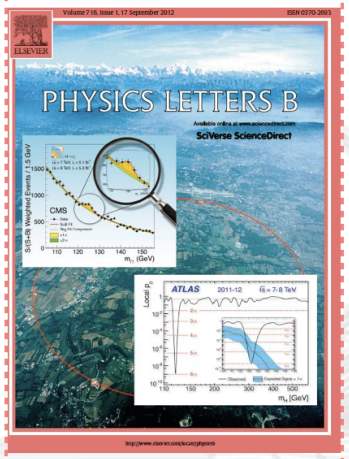




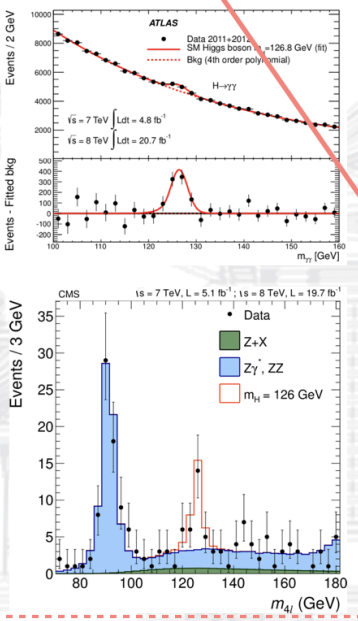
10 years of Higgs @ ATLAS



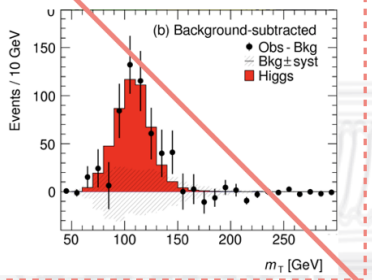
SM-like Higgs discovery (ggF → γγ + ZZ + WW)



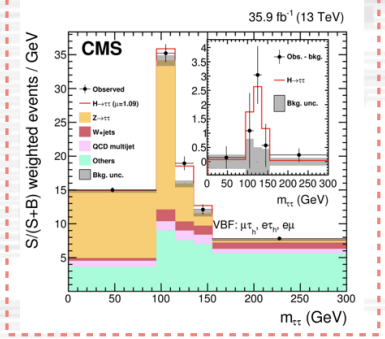
H→γγ, ZZ→4l observation (spin-0 and parity +)



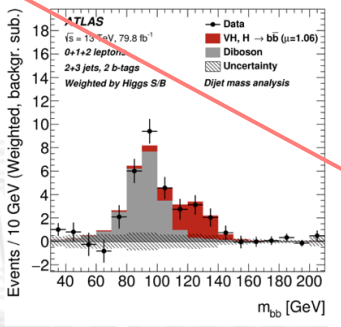
H→WW observation



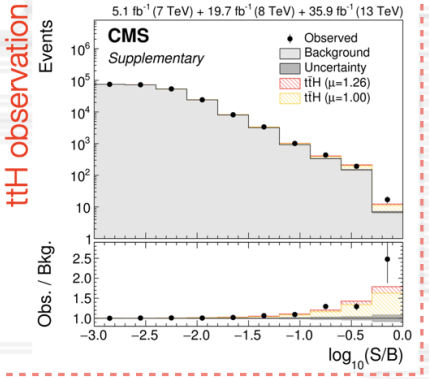
VBF, H→ττ observation



VH, H→bb observation



ttH observation



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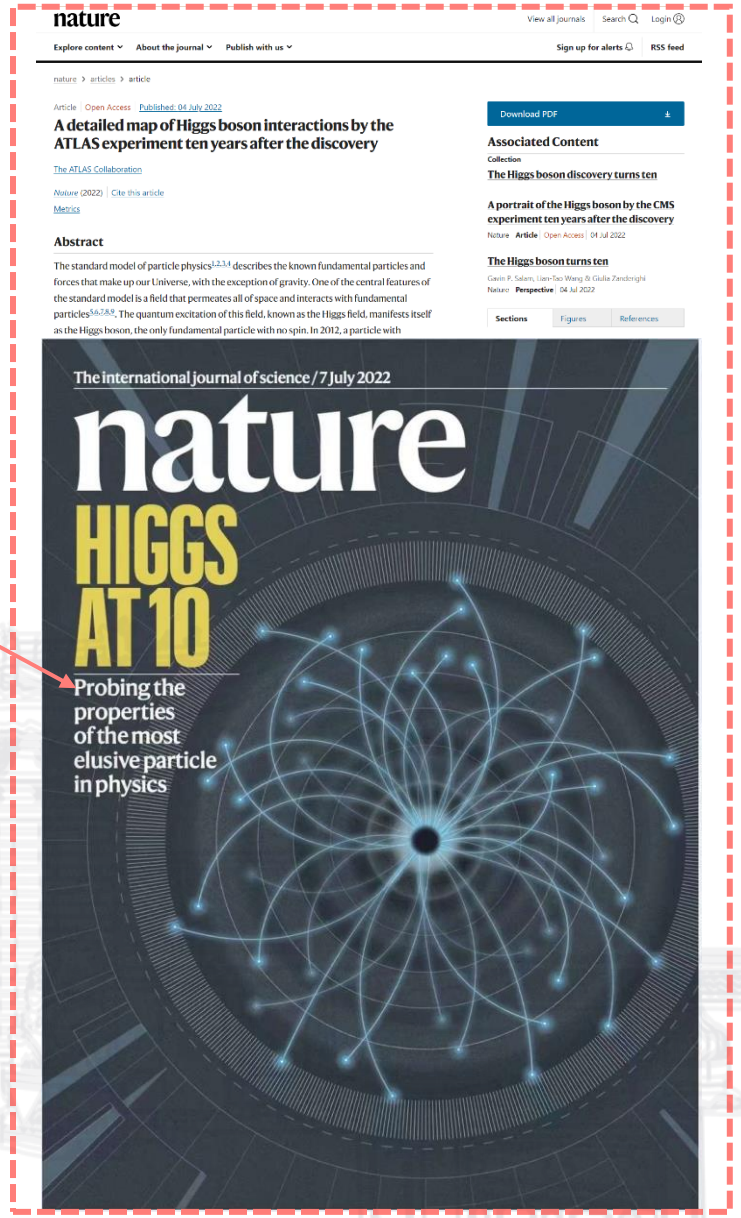
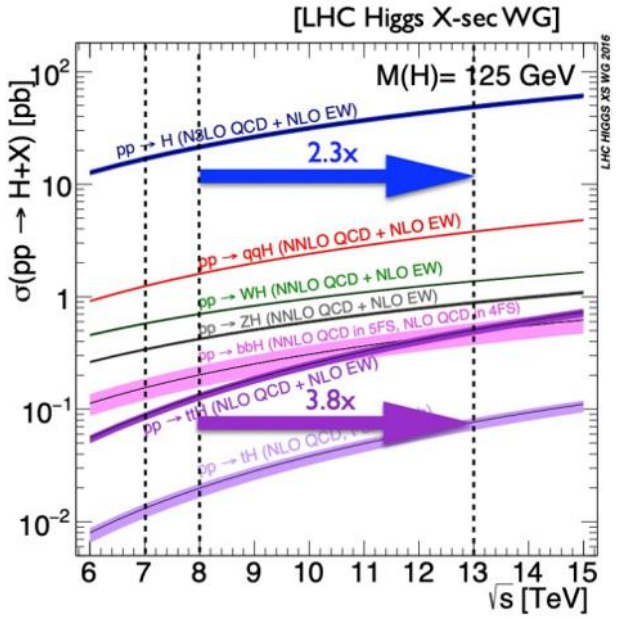


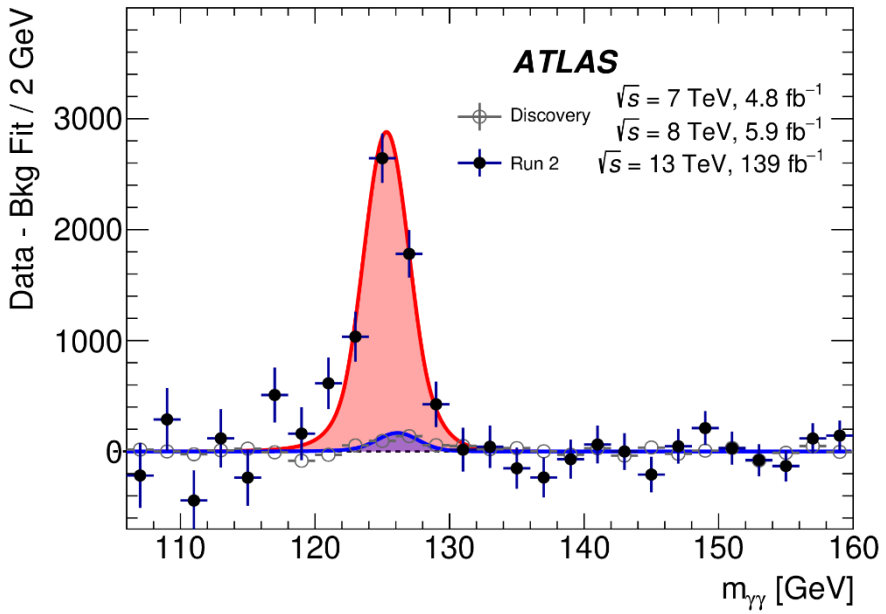
10 years of Higgs @ ATLAS

- In LHC Run-2, 30x more Higgs recorded by the ATLAS detector, allows for
  - Precise measurements of cross-sections, couplings and other properties
  - Search for rare decay modes
  - Hints of BSM effects
- A combination of these novel work make an examination of the Standard Model expectation with unprecedented precision possible



←Significant increase in production data from Run-1 to Run-2

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



Input analyses

Analysis	Production modes	Integrated lumi (fb^{-1})	Used in
H→γγ	All	139	All
H→ZZ→4l	All	139	All
H→ττ	All	139	All
H→WW	ggF, VBF	139	All
H→bb	VH	139	All
	VBF	126	All
	ttH	139	All
H→bb boosted	ggF, VBF, VH, ttH	139	STXS
H→WW	VH	36.1	All but STXS
H→multilepton	ttH	36.1	All but STXS
H→invisible	VBF	139	κ
H→invisible	ZH	139	κ
H→Zγ	All	139	All but STXS
H→μμ	All	139	All but STXS
H→cc	qq→WH/ZH	139	κ

New wrt combination 2021

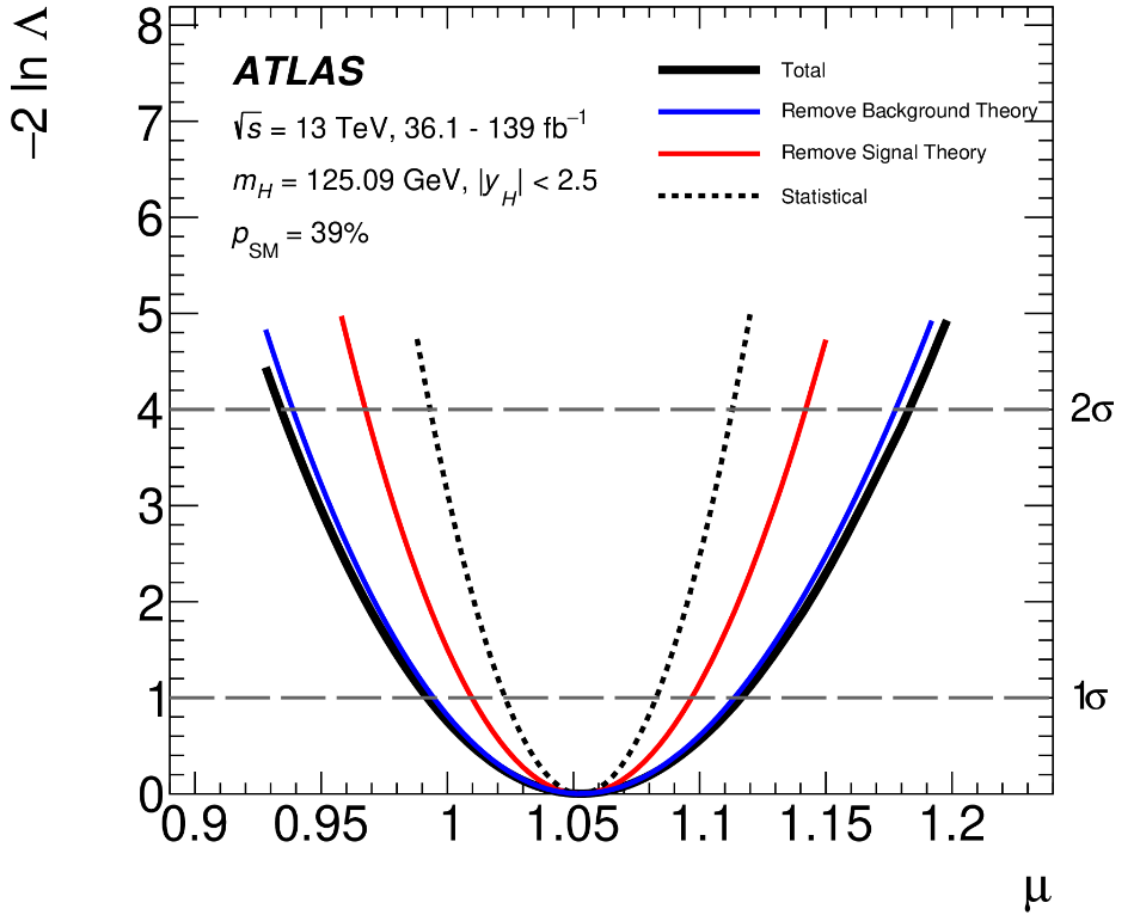
New wrt combination Run-1

- Almost all measurements updated to **full Run-2** dataset
- A combination of all major ATLAS Higgs analyses to get **more sensitive** and **less model-dependent** results on Higgs interactions

Global signal strength

- Combination of all production/decay

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



$$\mu = \frac{\sigma \times \mathrm{B}}{(\sigma \times \mathrm{B})_{\mathrm{SM}}}$$

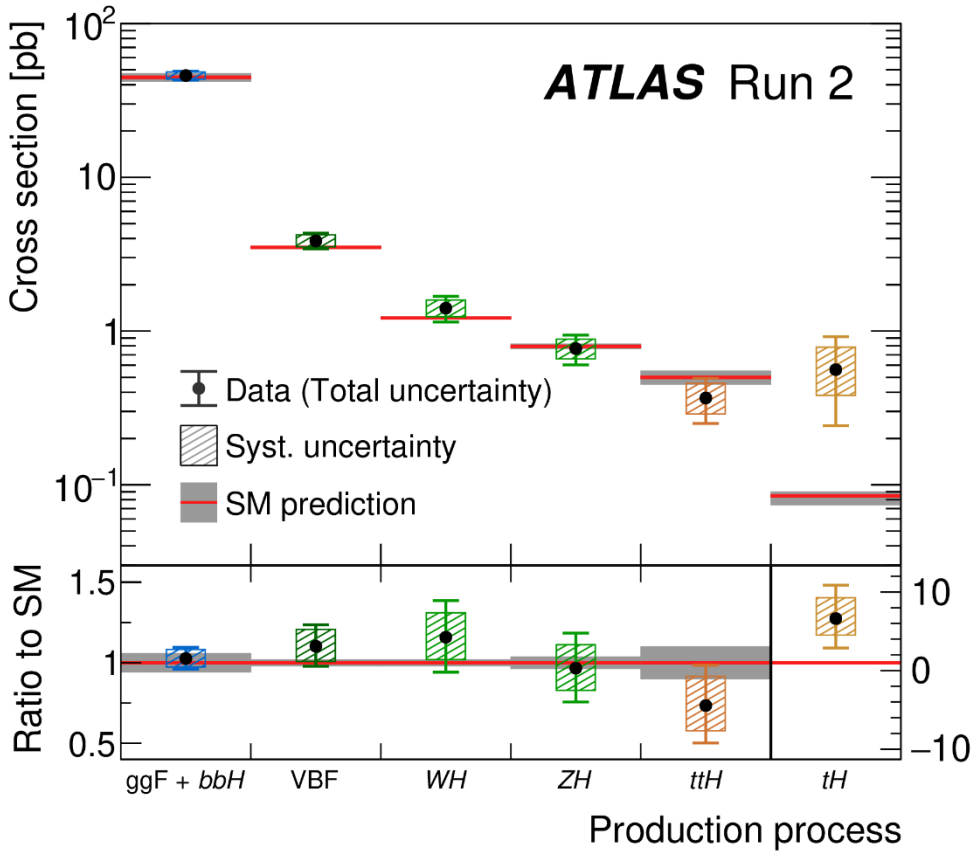
- SM compatibility: p_{SM}=39%
- Compared to ATLAS+CMS Run-1, uncertainties reduced significantly

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig}),$$

Production and decay

- Measurements of production cross sections

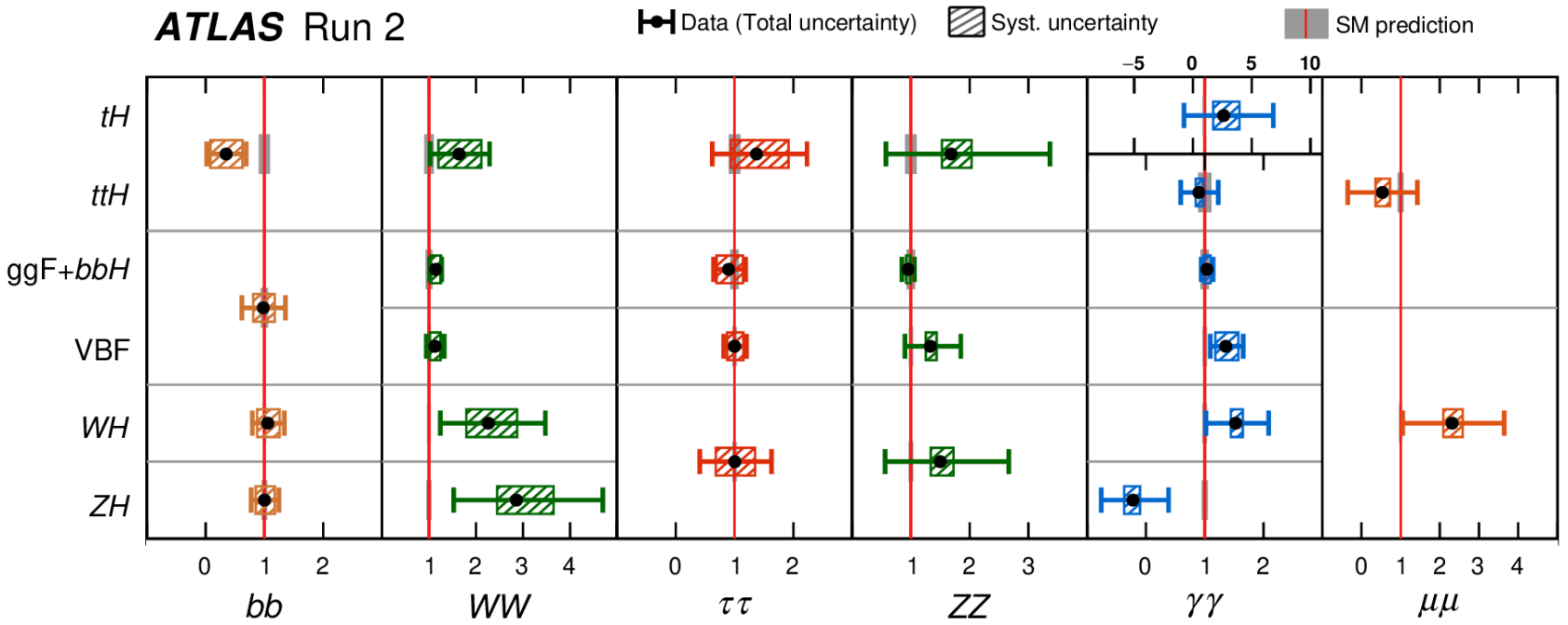
- SM compatibility: p_{SM}=65%
- Compared to Run-1 combination
  - Observation of WH & ZH
    - σ_{WH}: 3.51 σ⟶5.8 σ
    - σ_{ZH}: 3.63 σ⟶5.0 σ
  - Better precision
    - σ_{ggF}: 9%⟶7%
    - σ_{VBF}: 19%⟶12%
  - Independent tH measurement
    - Upper limit on tH of 15(7) x SM at 95% CL



Production and decay

- Measurements of all cross sections and branching ratios available

  SM compatibility (p-value): 72%

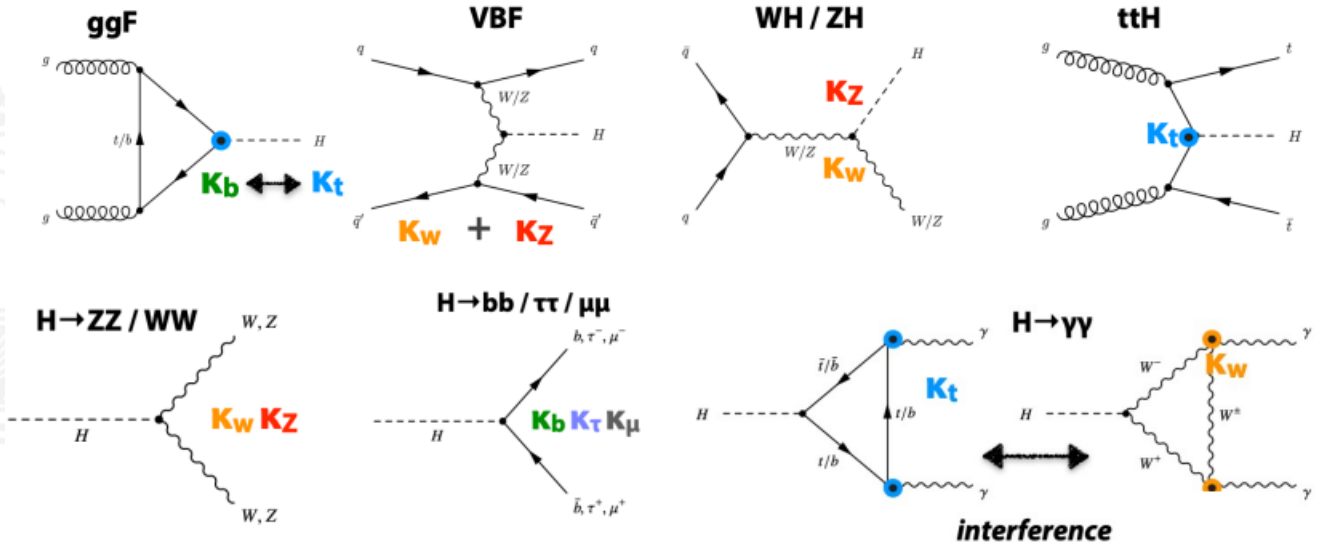


- Thanks to updated analyses, the granularity is improved compared to Run-1 combination
  - Split of VH production in bb, WW & γγ channels
  - Rare production of tH mode in γγ channel
  - Rare decay: μμ

Couplings to particles-κ framework

- Introduce one scale factor κ per SM particle with observable "Higgs coupling" at LHC
  - Bosons: κ_W, κ_Z, κ_γ, κ_g
  - Fermions: κ_t, κ_b, κ_τ, κ_μ
- Considering LO modifiers, they are parameterized as:

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



Couplings to particles-κ framework

- κ_V vs κ_F : use one uniform modifier for vector boson coupling and another for fermions
- Consider only SM particles contributions to the total width of Higgs

- SM compatibility: p-value = 14.3%
- Linear correlation between κ_V & κ_F : 39%

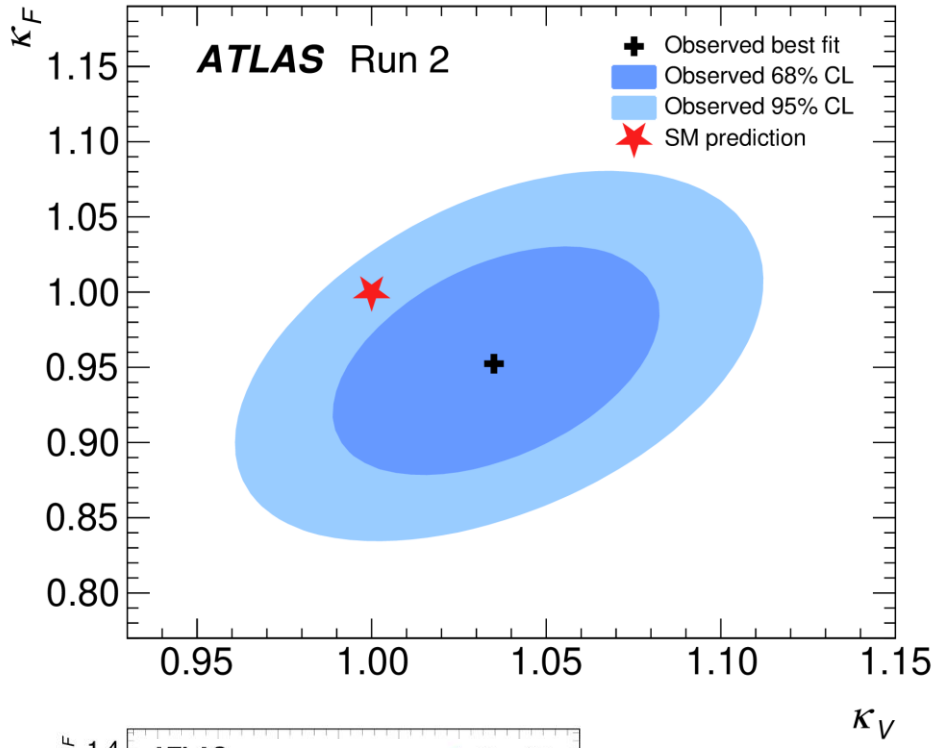
		measurements
κ_V	obs.	$1.04^{+0.03}_{-0.03}$
	exp.	$1.00^{+0.03}_{-0.03}$
κ_F	obs.	$0.95^{+0.05}_{-0.05}$
	exp.	$1.00^{+0.05}_{-0.05}$

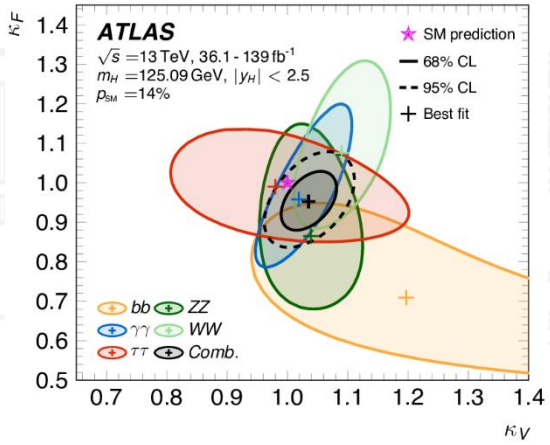
VS

		Measurements
κ_V	obs.	$1.05^{+0.04}_{-0.04}$
	exp.	$1.00^{+0.04}_{-0.04}$
κ_F	obs.	$1.05^{+0.09}_{-0.09}$
	exp.	$1.00^{+0.09}_{-0.09}$

Run-1 combination

- Uncertainties reduced compared to Run-1 combination



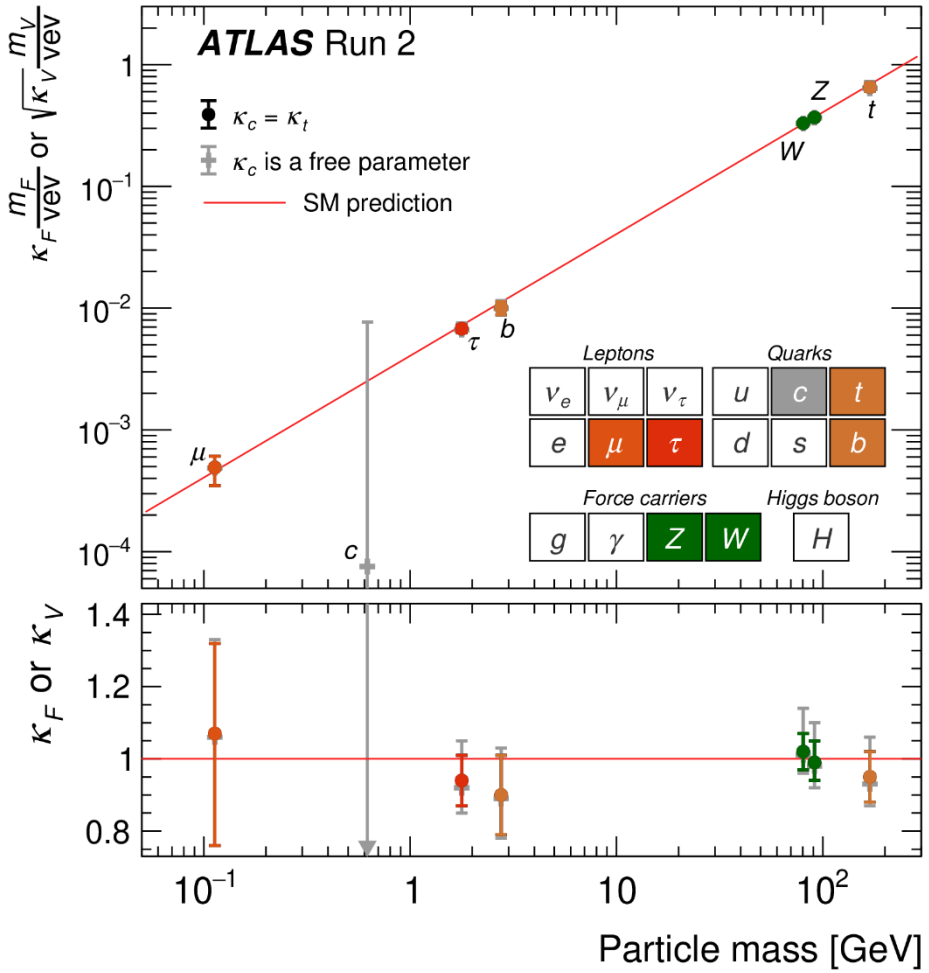


- Sensitivities from each channel

Couplings to particles-κ framework

- All modifiers assumed to be positive & only SM particles in loop processes
- No invisible or undetected non-SM Higgs decays

- Scaled by $\kappa_F m_F/v$ for fermions and $\sqrt{\kappa_V} m_V/v$ for bosons, measurements are nicely plotted as a function of the particles' mass to display the expected mass dependence in SM
- Upper limit on κ_c of 5.7 (7.6) x SM at 95% CL
- SM compatibility:
  - p-value = 56% ($\kappa_c = \kappa_t$)
  - p-value = 65% (κ_c float)



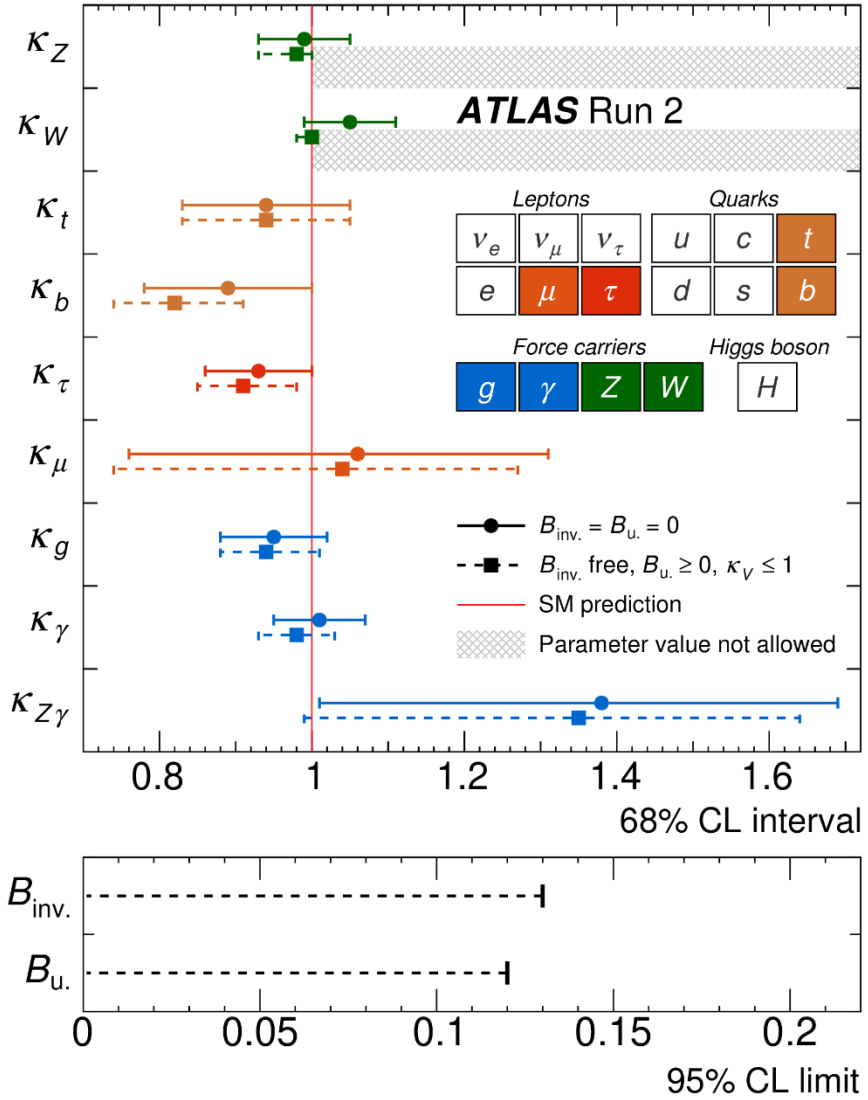
Couplings to particles-κ framework

- Allowing for non-SM particles in loop processes, with effective coupling strengths
- κ_t allowed to be negative

$$\Gamma_H(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}}) = \kappa_H^2(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}})\,\Gamma_H^{\text{SM}}$$

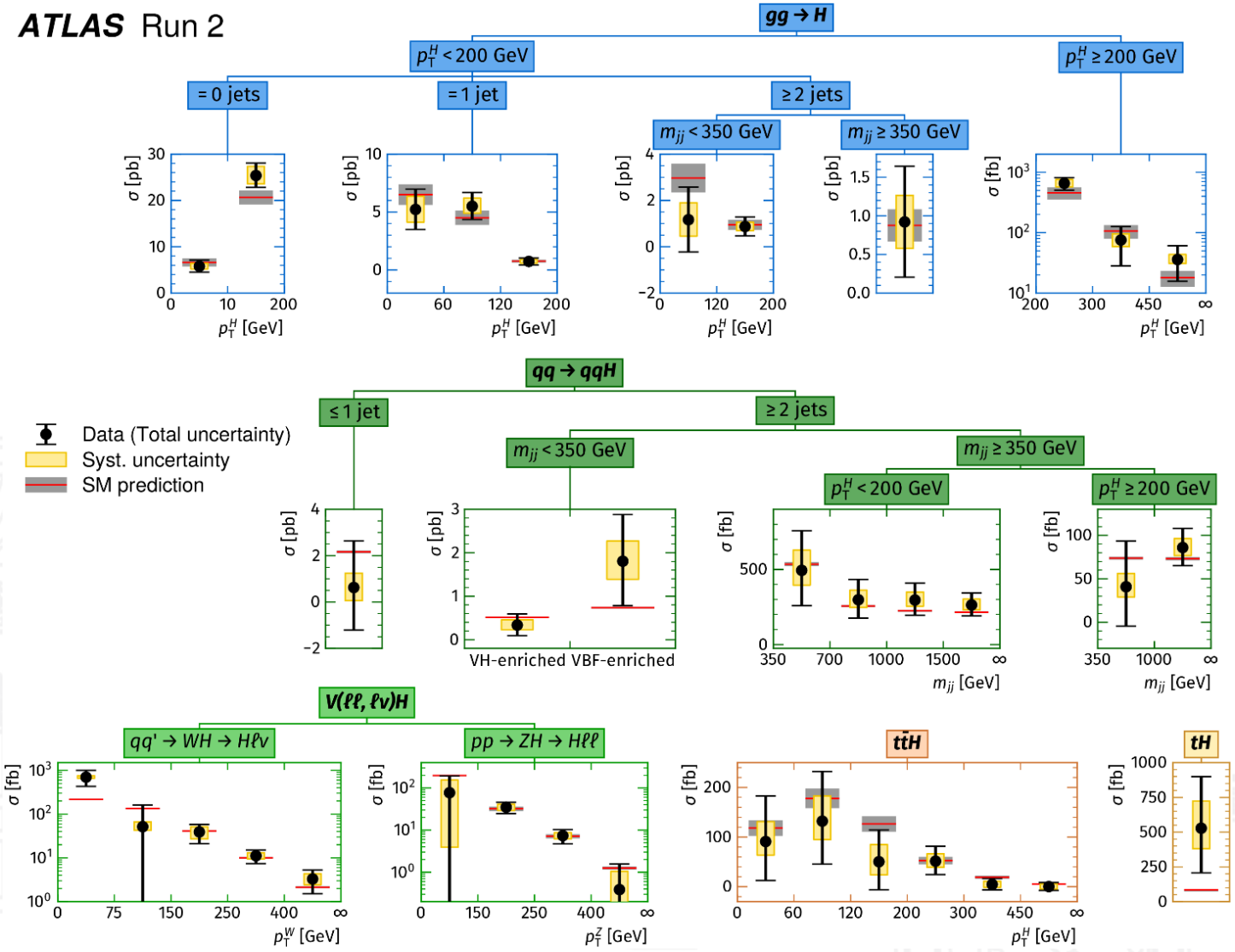
$$\kappa_H^2(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}}) = \frac{\sum_p B_p^{\text{SM}} \kappa_p^2}{(1 - B_{\text{inv.}} - B_{\text{u.}})}.$$

- Upper limit on
  - $B_{\text{invisible}}$: 0.13 (0.08)
  - $B_{\text{undetected}}$: 0.12 (0.21)
- SM compatibility:
  - p-value = 56% ($\kappa_c = \kappa_t$)
  - p-value = 65% (κ_c float)



Simplified Template Cross Section

- Split phase space of Higgs production processes into 36 kinematic regions defined by kinematics of Higgs and associated jets, W, Z bosons
- Goal:
  - Provide sensitivity to BSM ✓
  - Avoid large theory uncertainties in predictions ✓
  - Minimize model-dependence from acceptance extrapolations ✓
- SM compatibility (p-value): 92%



Crucial contributions from China

- China high-energy physics community made crucial contribution to the Higgs combination measurement:

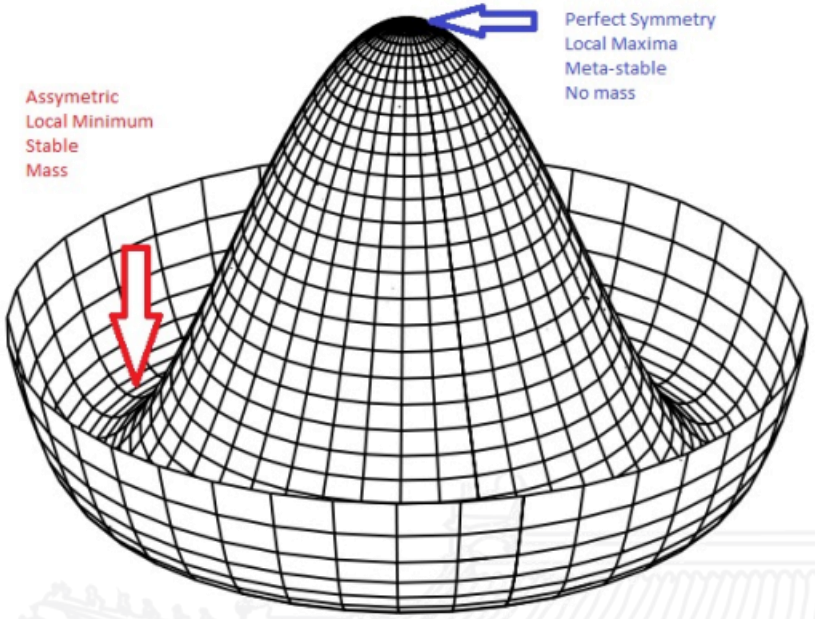
- **SJTU/TDLi**: **INT note editor**, input validation, **production mode and BR**
- **IHEP**: **analysis contact**, input & validation, workspace preparation, **global signal strength**, **STXS**
- **Nanjing University**: input liaison & validation, **2HDM interpretation**
- **Shandong University**: input & validation, **production mode and BR**
- **USTC**: input liaison & validation

Conclusions

- In the 10 years since the discovery of Higgs boson, many measurements have been performed by the ATLAS collaboration
  - All main production and decay modes @ LHC have been observed
  - Hints of rare decays have been seen
- A combined measurement of Higgs interactions has been presented
  - Unprecedented precision reached on cross-section, branching ratio & coupling measurements
  - Kinematic dependence of production cross sections has been studied across a wide range of phase space
  - Limits on BSM effect revealed
- The properties of Higgs boson show good agreement with Standard Model expectation!

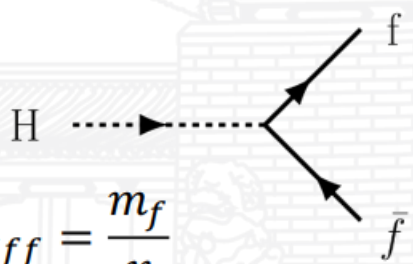
- Looking forward to future ATLAS results of more precise measurements and observation of rare processes!

Backup

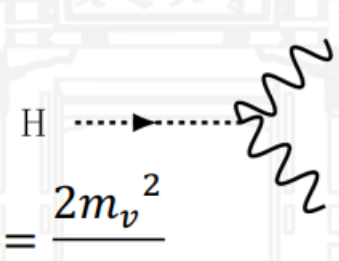


- Vector bosons masses → **spontaneous symmetry breaking**
- Fermions masses → **Yukawa couplings**
- The Higgs Boson couplings to other particles are set by their masses →determine all Higgs Boson production and decay.

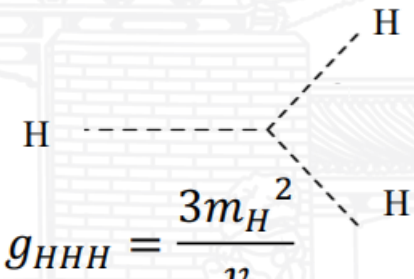
$$\mathcal{L} = -g_{Hff} f \bar{f} H + \delta_V V_\mu V^\mu \left(g_{HVV} H + \frac{g_{HHVV}}{2} H^2 \right) + \frac{g_{HHH}}{6} H^3 + \frac{g_{HHHH}}{6} H^4$$



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

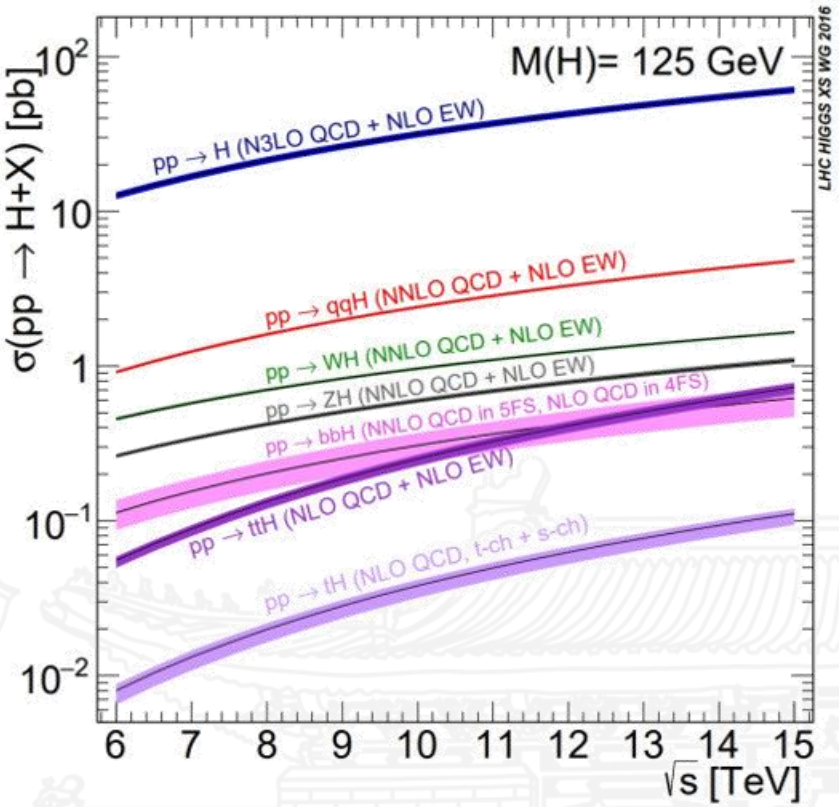


$$g_{HVV} = \frac{2{m_v}^2}{v}$$



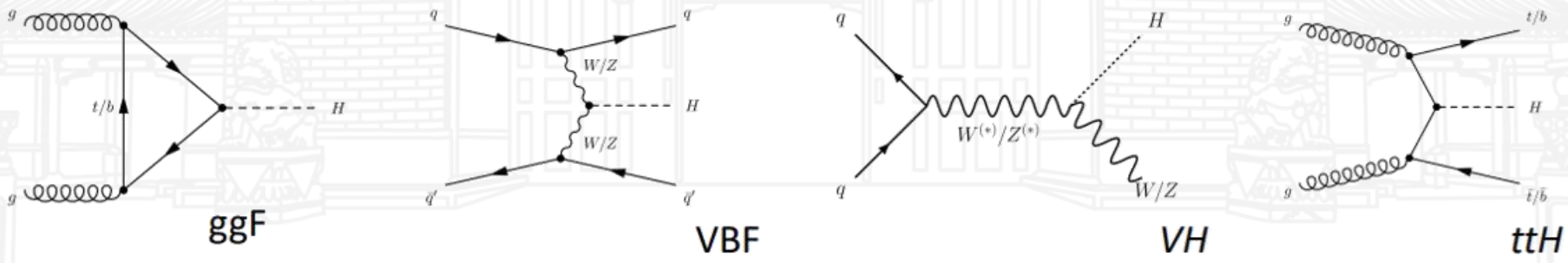
$$g_{HHH} = \frac{3{m_H}^2}{v}$$

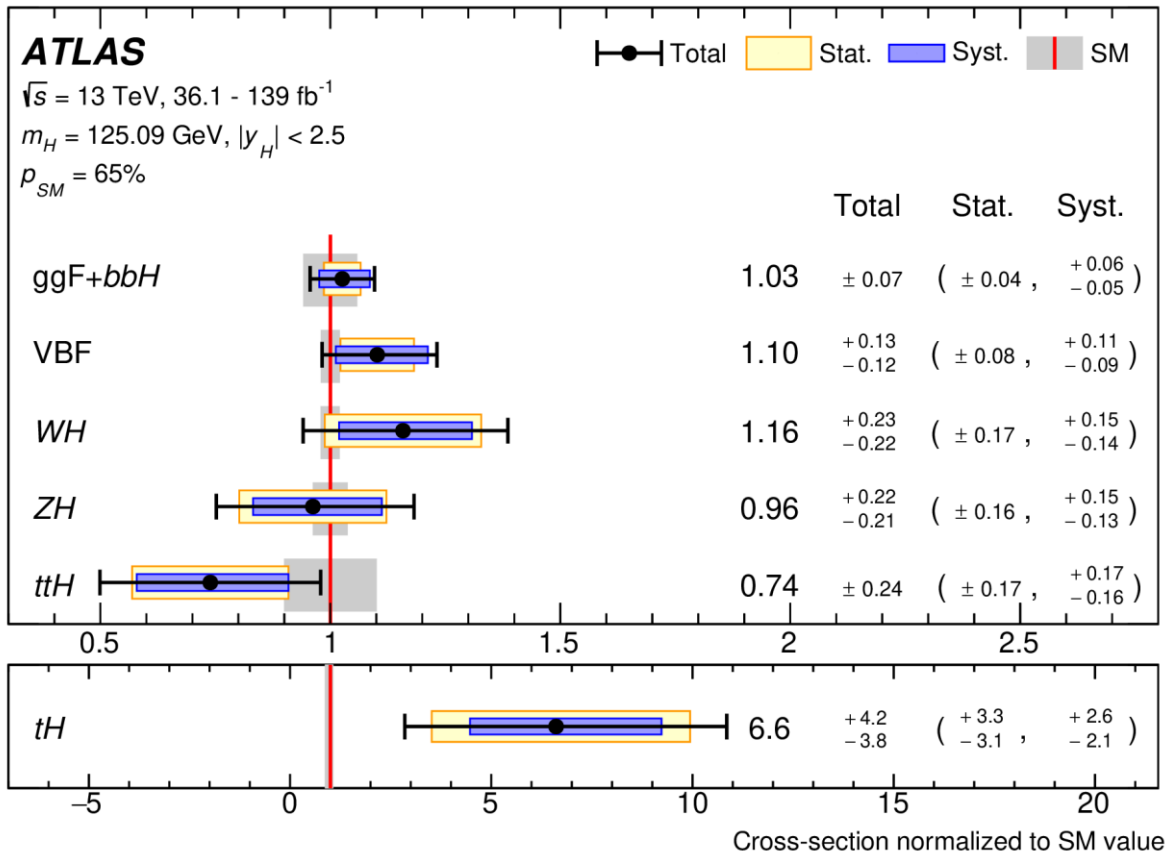
v = vacuum expectation value of the Higgs field

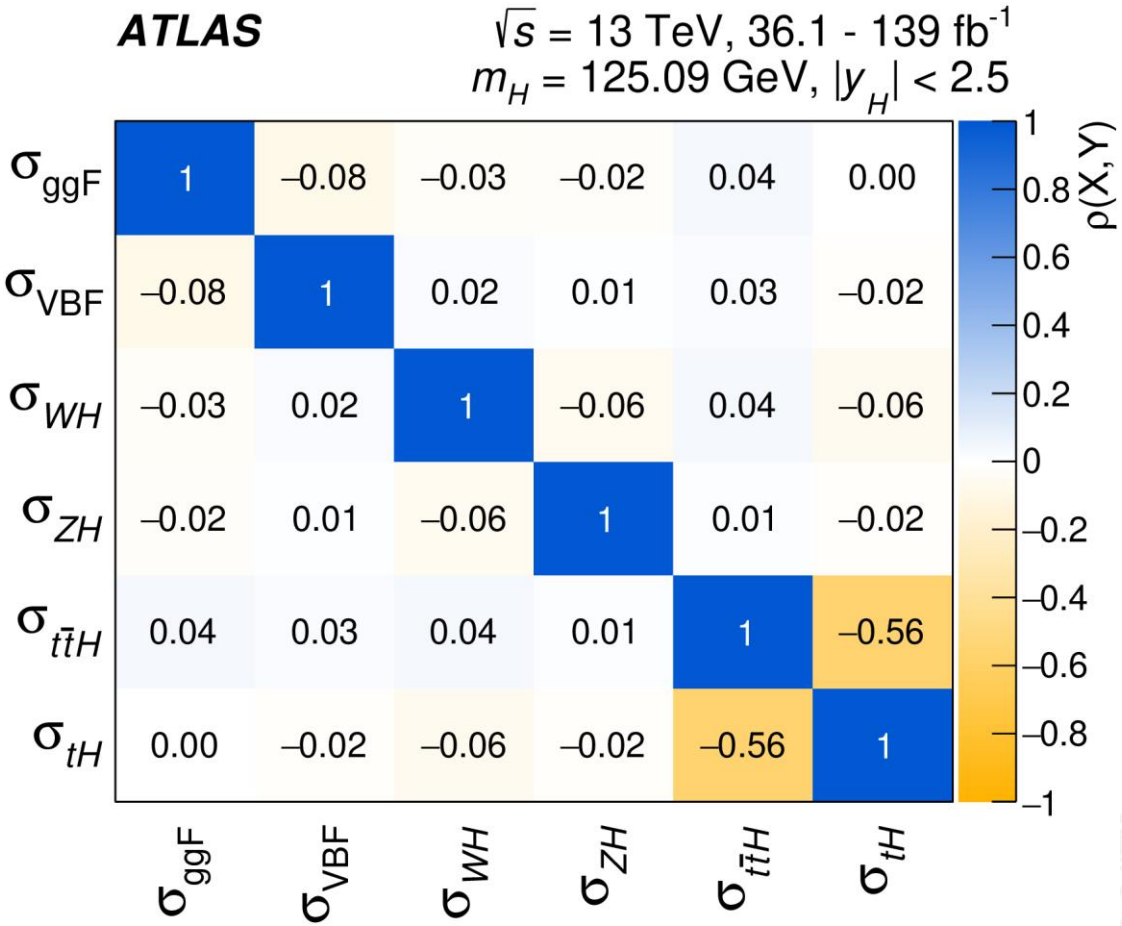


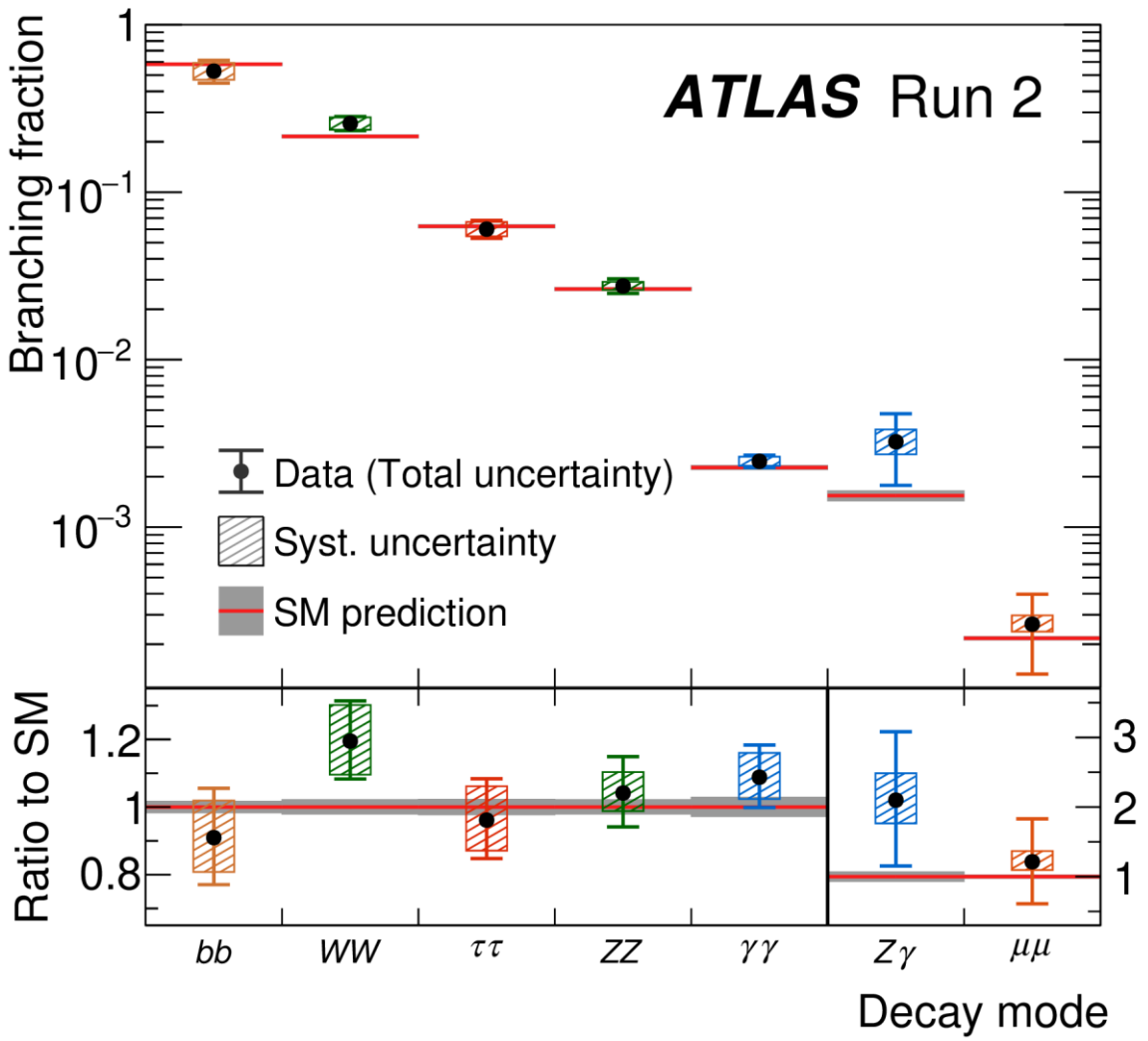
XS in pb	13 TeV	8 TeV	σ13/σ8
ggF	48.5	21.4	**2.3**
VBF	3.78	1.60	2.4
WH	1.37	0.70	2.0
ZH	0.88	0.42	2.1
bbH	0.49	0.20	**2.4**
ttH	0.51	0.13	**3.8**
tH	0.09	0.02	**3.9**

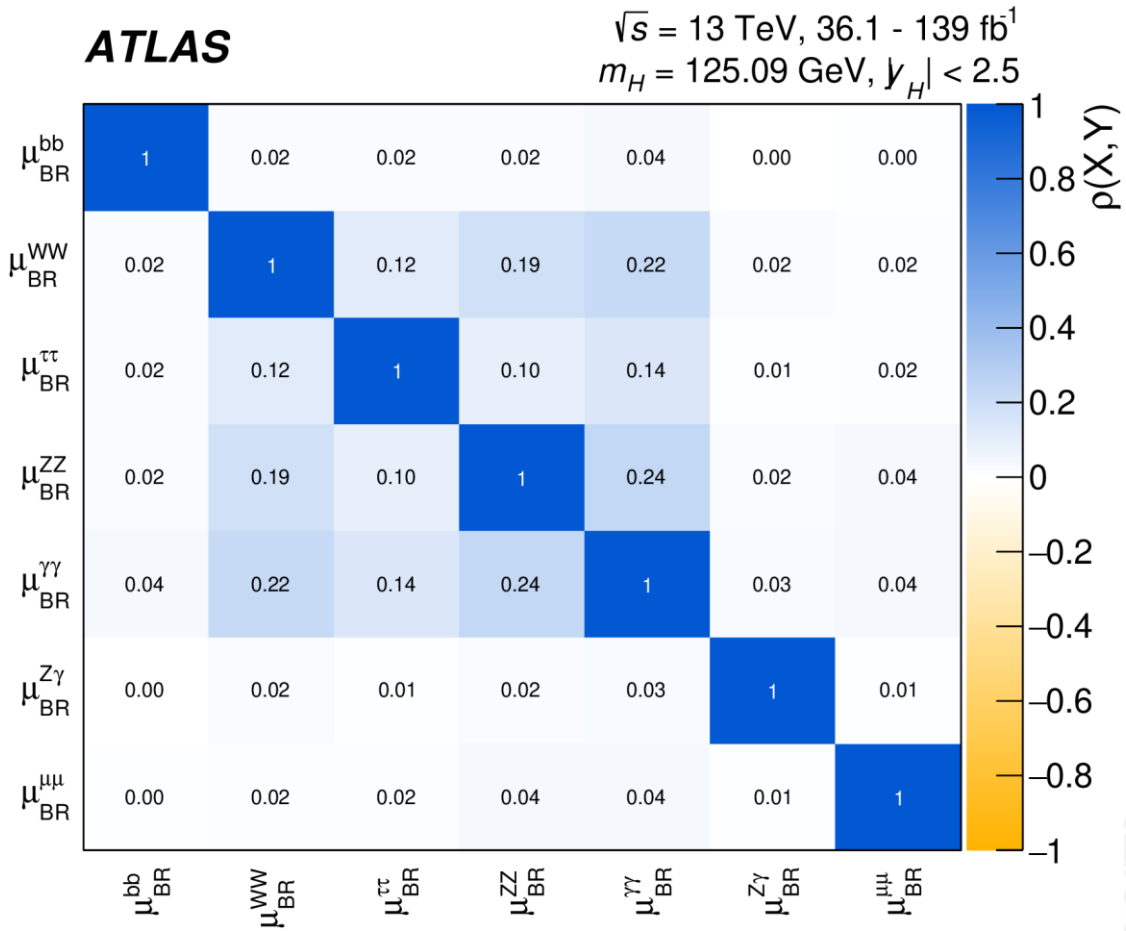
- There is **an increase** in production cross sections from increased center-of-mass energy.

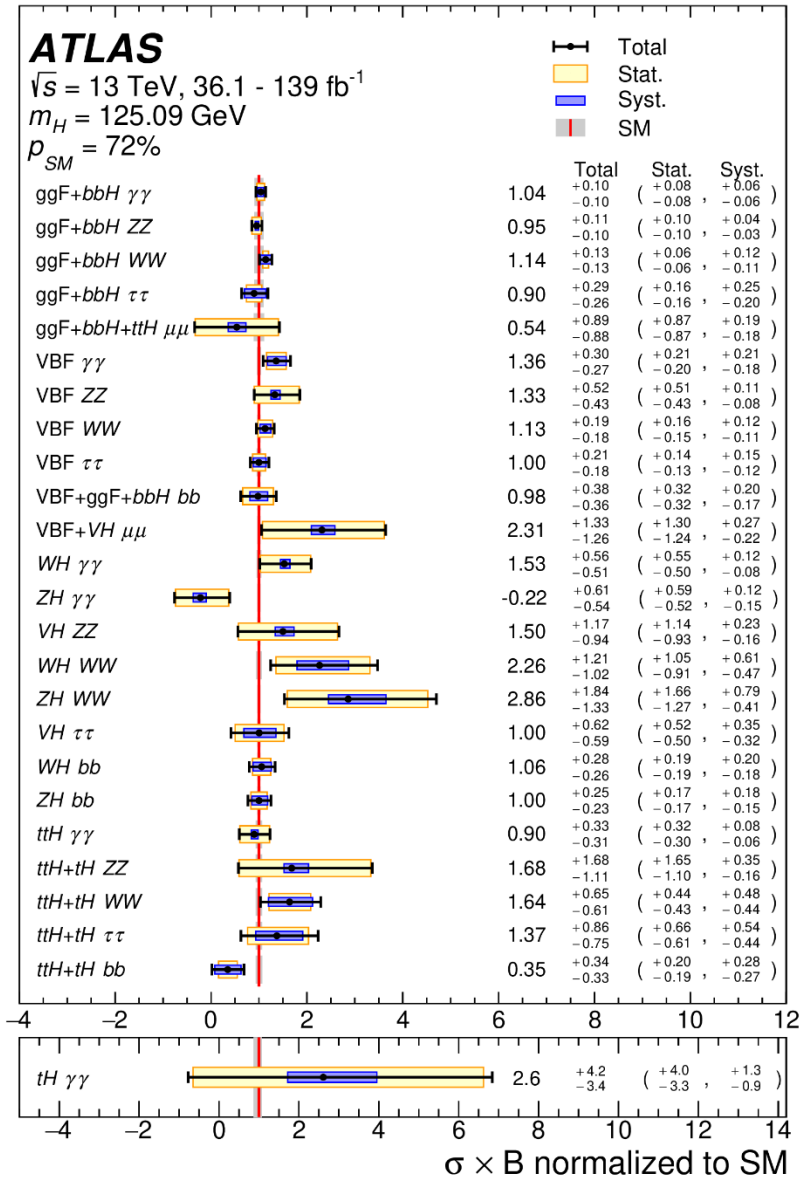


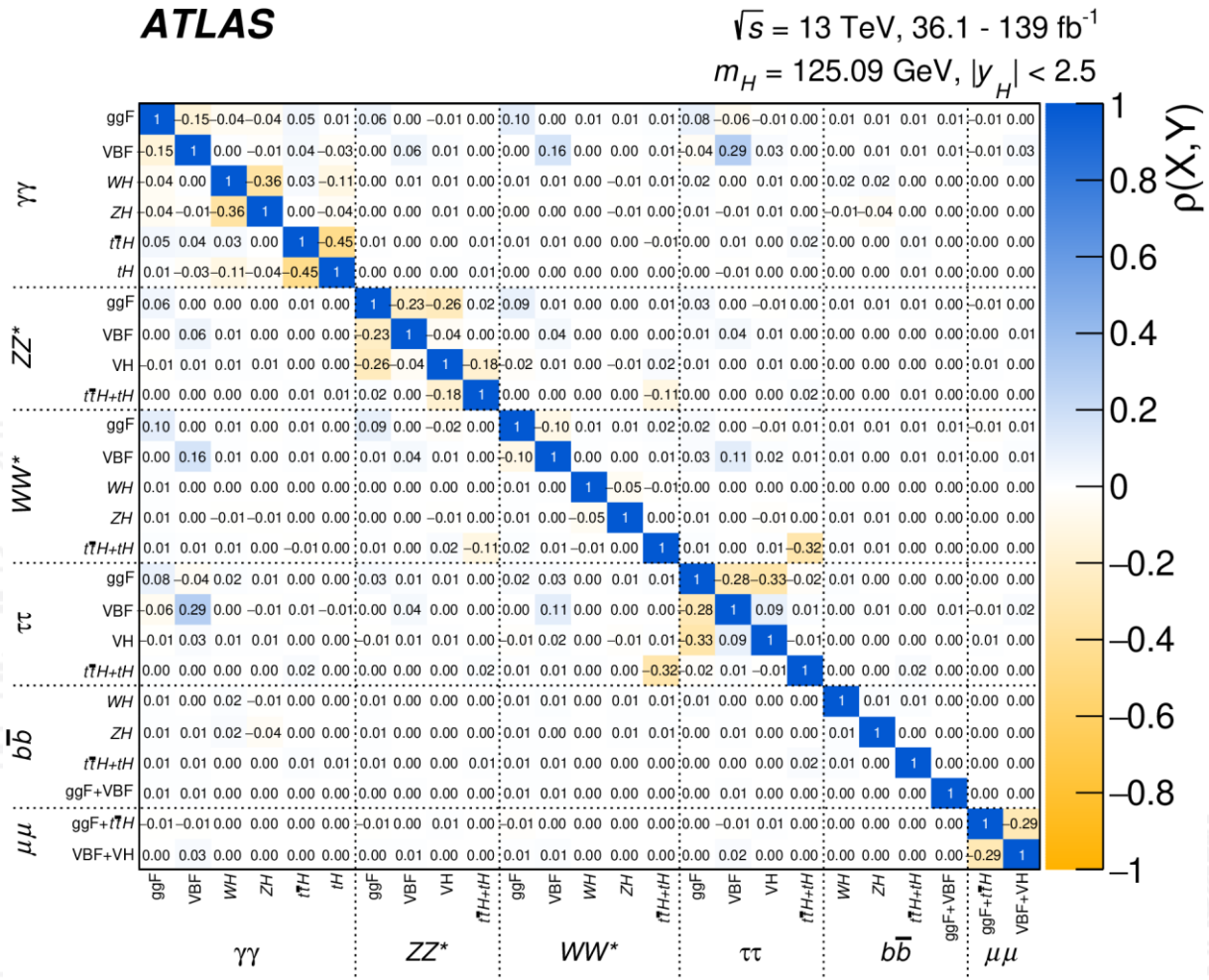

ATLAS
Total
Stat.
Syst.
SM
$\sqrt{s}$ = 13 TeV, 36.1 - 139 fb^{-1}
m_H = 125.09 GeV, $|y_H| < 2.5$
p_{SM} = 65%
Total
Stat.
Syst.
ggF+bbH
1.03 ± 0.07 (± 0.04 , +0.06 −0.05)
VBF
1.10 +0.13 −0.12 (± 0.08 , +0.11 −0.09)
WH
1.16 +0.23 −0.22 (± 0.17 , +0.15 −0.14)
ZH
0.96 +0.22 −0.21 (± 0.16 , +0.15 −0.13)
ttH
0.74 ± 0.24 (± 0.17 , +0.17 −0.16)
0.5
1
1.5
2
2.5
tH
6.6 +4.2 −3.8 (+3.3 −3.1 , +2.6 −2.1)
−5
0
5
10
15
20
Cross-section normalized to SM value

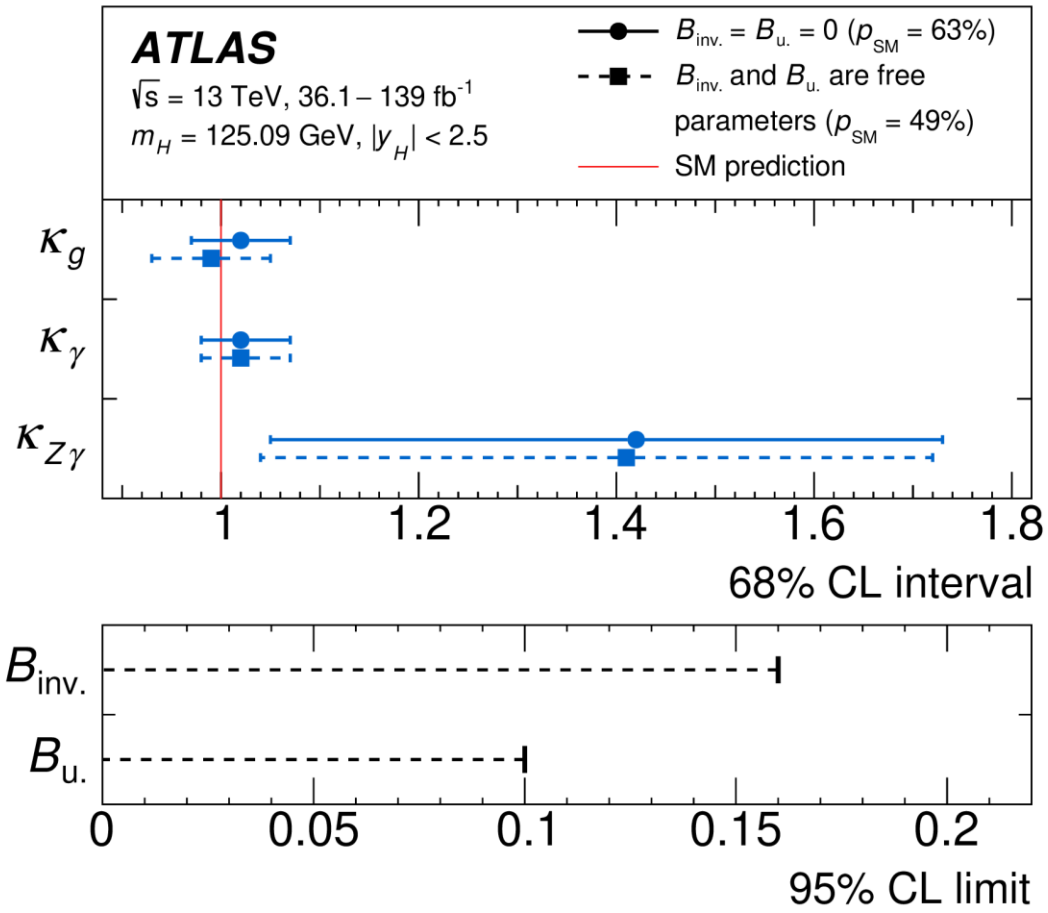

ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 - 139 fb^{-1}
m_H = 125.09 GeV, $|y_H| < 2.5$
σ_{ggF} 1 −0.08 −0.03 −0.02 0.04 0.00
σ_{VBF} −0.08 1 0.02 0.01 0.03 −0.02
σ_{WH} −0.03 0.02 1 −0.06 0.04 −0.06
σ_{ZH} −0.02 0.01 −0.06 1 0.01 −0.02
$\sigma_{t\bar{t}H}$ 0.04 0.03 0.04 0.01 1 −0.56
σ_{tH} 0.00 −0.02 −0.06 −0.02 −0.56 1
σ_{ggF}
σ_{VBF}
σ_{WH}
σ_{ZH}
$\sigma_{t\bar{t}H}$
σ_{tH}
ρ(X,Y)
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1

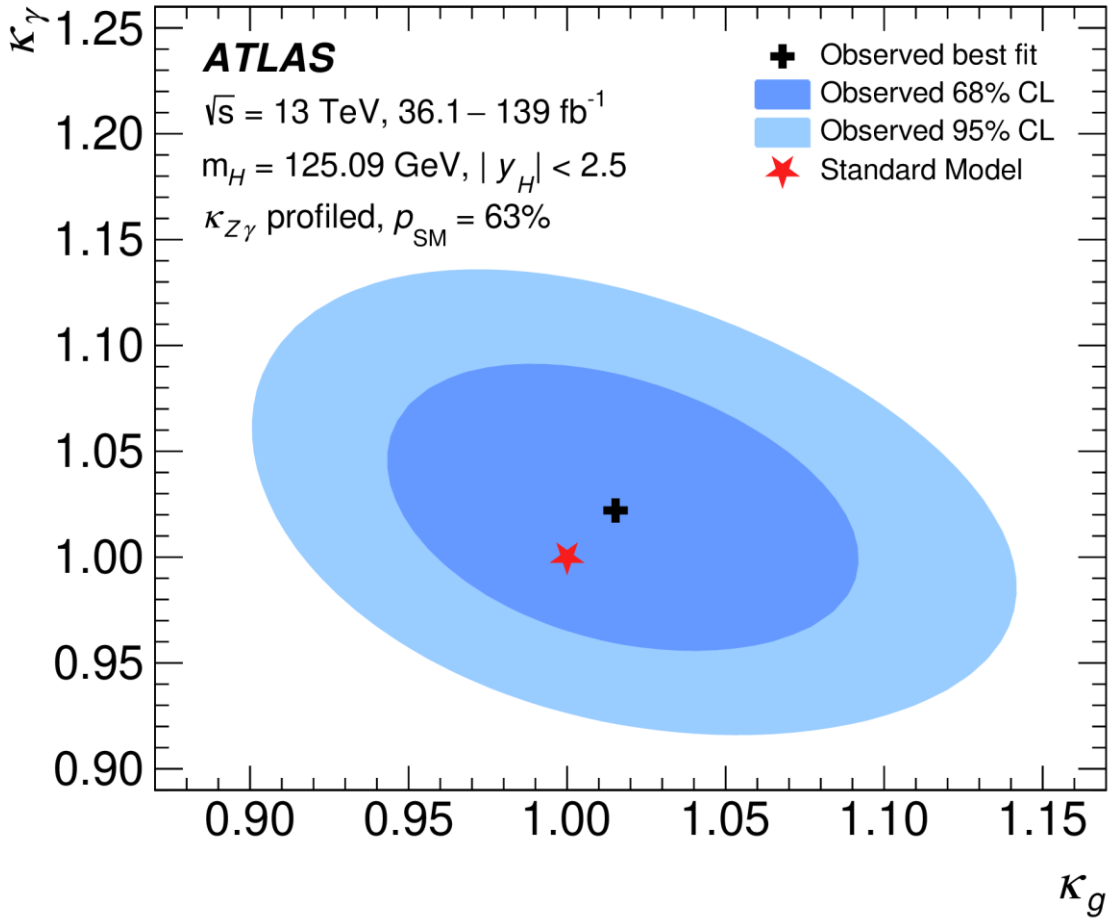

ATLAS Run 2
Branching fraction
Data (Total uncertainty)
Syst. uncertainty
SM prediction
Ratio to SM
bb
WW
ττ
ZZ
γγ
Zγ
μμ
Decay mode

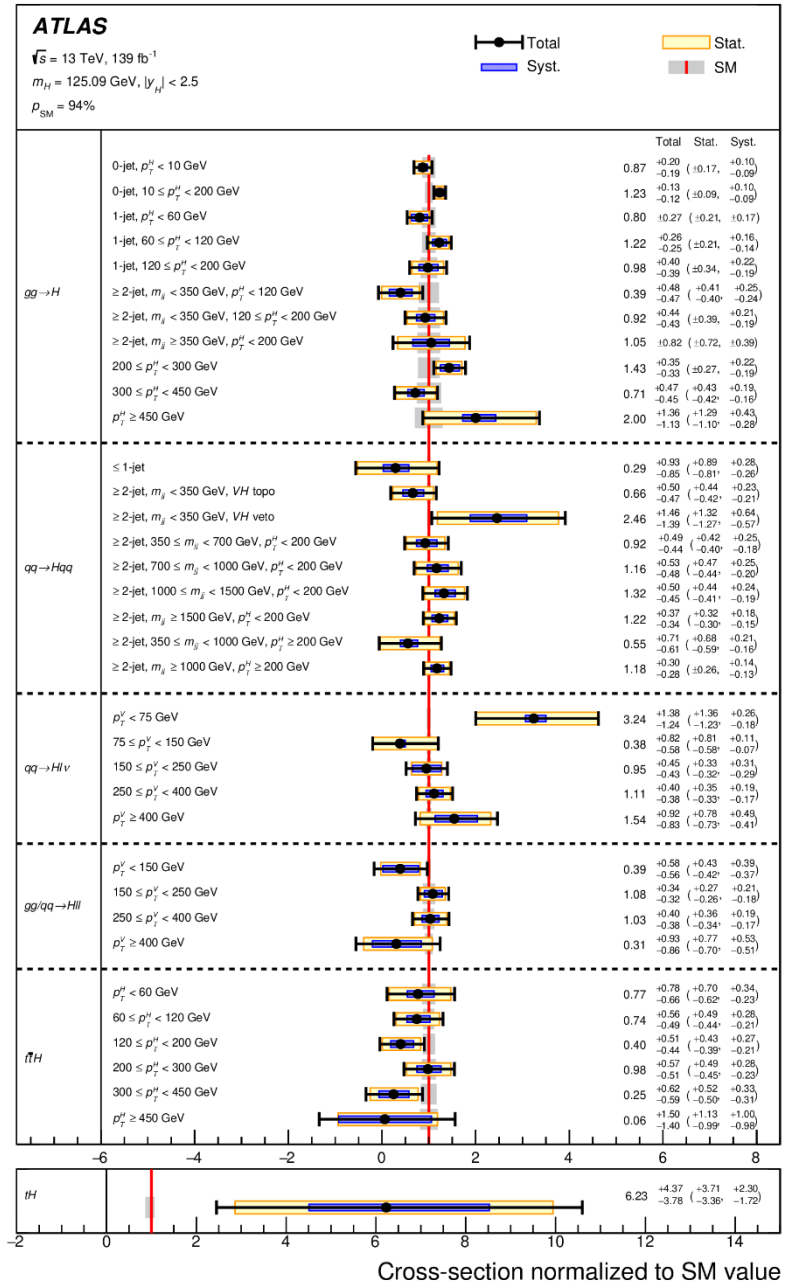

ATLAS
√s = 13 TeV, 36.1 - 139 fb-1
mH = 125.09 GeV, |yH| < 2.5
ρ(X,Y)

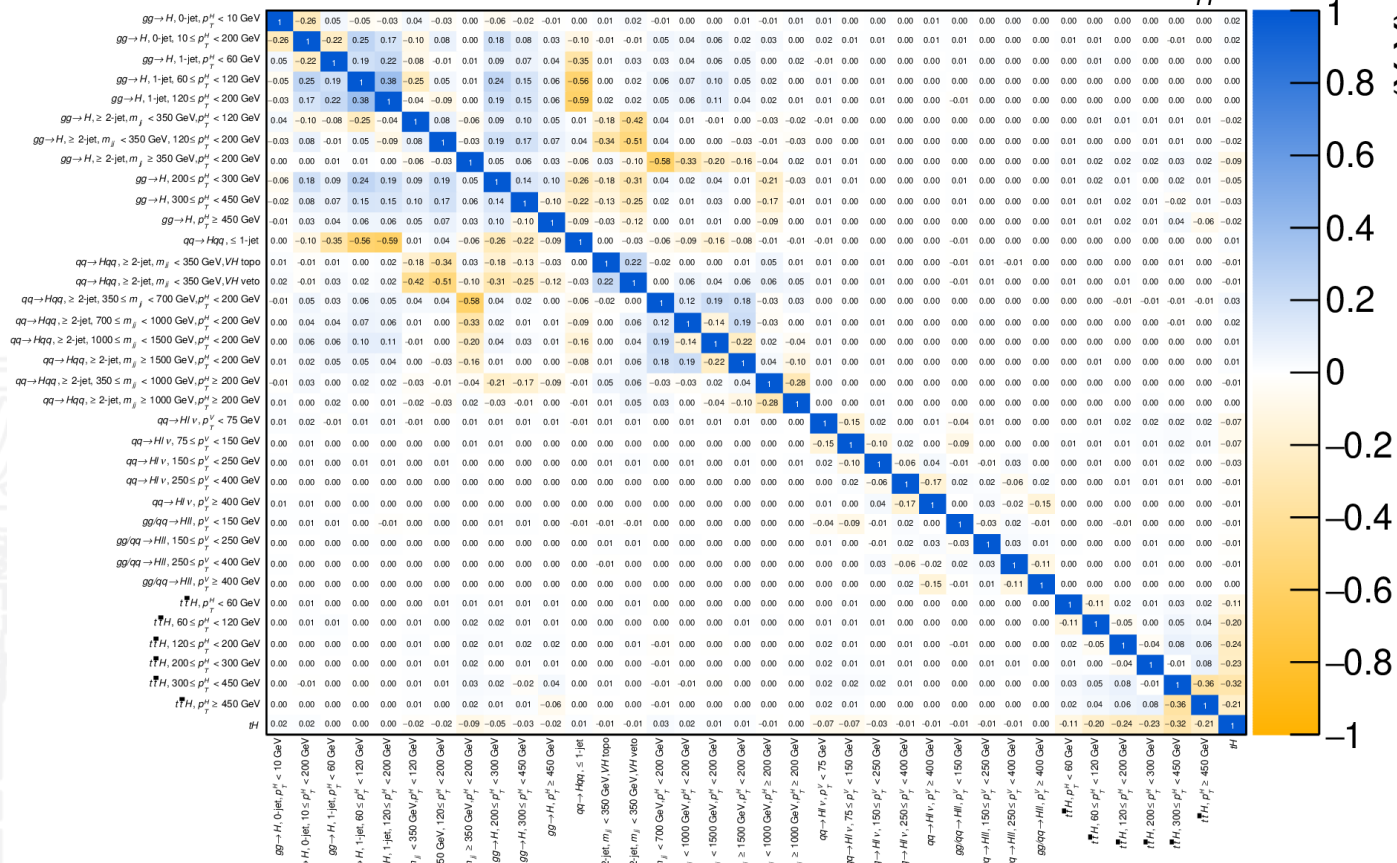

ATLAS
√s = 13 TeV, 36.1 - 139 fb-1
mH = 125.09 GeV
pSM = 72%
Total
Stat.
Syst.
SM
Total Stat. Syst.
ggF+bbH γγ 1.04 +0.10 −0.10 (+0.08 −0.08 , +0.06 −0.06)
ggF+bbH ZZ 0.95 +0.11 −0.10 (+0.10 −0.10 , +0.04 −0.03)
ggF+bbH WW 1.14 +0.13 −0.13 (+0.06 −0.06 , +0.12 −0.11)
ggF+bbH ττ 0.90 +0.29 −0.26 (+0.16 −0.16 , +0.25 −0.20)
ggF+bbH+ttH μμ 0.54 +0.89 −0.88 (+0.87 −0.87 , +0.19 −0.18)
VBF γγ 1.36 +0.30 −0.27 (+0.21 −0.20 , +0.21 −0.18)
VBF ZZ 1.33 +0.52 −0.43 (+0.51 −0.43 , +0.11 −0.08)
VBF WW 1.13 +0.19 −0.18 (+0.16 −0.15 , +0.12 −0.11)
VBF ττ 1.00 +0.21 −0.18 (+0.14 −0.13 , +0.15 −0.12)
VBF+ggF+bbH bb 0.98 +0.38 −0.36 (+0.32 −0.32 , +0.20 −0.17)
VBF+VH μμ 2.31 +1.33 −1.26 (+1.30 −1.24 , +0.27 −0.22)
WH γγ 1.53 +0.56 −0.51 (+0.55 −0.50 , +0.12 −0.08)
ZH γγ -0.22 +0.61 −0.54 (+0.59 −0.52 , +0.12 −0.15)
VH ZZ 1.50 +1.17 −0.94 (+1.14 −0.93 , +0.23 −0.16)
WH WW 2.26 +1.21 −1.02 (+1.05 −0.91 , +0.61 −0.47)
ZH WW 2.86 +1.84 −1.33 (+1.66 −1.27 , +0.79 −0.41)
VH ττ 1.00 +0.62 −0.59 (+0.52 −0.50 , +0.35 −0.32)
WH bb 1.06 +0.28 −0.26 (+0.19 −0.19 , +0.20 −0.18)
ZH bb 1.00 +0.25 −0.23 (+0.17 −0.17 , +0.18 −0.15)
ttH γγ 0.90 +0.33 −0.31 (+0.32 −0.30 , +0.08 −0.06)
ttH+tH ZZ 1.68 +1.68 −1.11 (+1.65 −1.10 , +0.35 −0.16)
ttH+tH WW 1.64 +0.65 −0.61 (+0.44 −0.43 , +0.48 −0.44)
ttH+tH ττ 1.37 +0.86 −0.75 (+0.66 −0.61 , +0.54 −0.44)
ttH+tH bb 0.35 +0.34 −0.33 (+0.20 −0.19 , +0.28 −0.27)
tH γγ 2.6 +4.2 −3.4 (+4.0 −3.3 , +1.3 −0.9)
σ × B normalized to SM


ATLAS
√s = 13 TeV, 36.1 - 139 fb-1
mH = 125.09 GeV, |yH| < 2.5
ρ(X,Y)
γγ
ZZ*
WW*
ττ
bb̄
μμ
ggF
VBF
WH
ZH
ttH
tH
VH
ttH+tH
ggF+VBF
ggF+ttH
VBF+VH


ATLAS
√s = 13 TeV, 36.1 – 139 fb-1
mH = 125.09 GeV, |yH| < 2.5
Binv. = Bu. = 0 (pSM = 63%)
Binv. and Bu. are free parameters (pSM = 49%)
SM prediction
κg
κγ
κZγ
1
1.2
1.4
1.6
1.8
68% CL interval
Binv.
Bu.
0
0.05
0.1
0.15
0.2
95% CL limit


ATLAS
√s = 13 TeV, 36.1 – 139 fb-1
mH = 125.09 GeV, | yH| < 2.5
κZγ profiled, pSM = 63%
Observed best fit
Observed 68% CL
Observed 95% CL
Standard Model
κγ
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.90
0.95
1.00
1.05
1.10
1.15
κg


ATLAS
√s = 13 TeV, 139 fb-1
mH = 125.09 GeV, |yH| < 2.5
pSM = 94%
Total
Syst.
Stat.
SM
Total Stat. Syst.
gg→H
0-jet, pTH < 10 GeV
0-jet, 10 ≤ pTH < 200 GeV
1-jet, pTH < 60 GeV
1-jet, 60 ≤ pTH < 120 GeV
1-jet, 120 ≤ pTH < 200 GeV
≥ 2-jet, mjj < 350 GeV, pTH < 120 GeV
≥ 2-jet, mjj < 350 GeV, 120 ≤ pTH < 200 GeV
≥ 2-jet, mjj ≥ 350 GeV, pTH < 200 GeV
200 ≤ pTH < 300 GeV
300 ≤ pTH < 450 GeV
pTH ≥ 450 GeV
qq→Hqq
≤ 1-jet
≥ 2-jet, mjj < 350 GeV, VH topo
≥ 2-jet, mjj < 350 GeV, VH veto
≥ 2-jet, 350 ≤ mjj < 700 GeV, pTH < 200 GeV
≥ 2-jet, 700 ≤ mjj < 1000 GeV, pTH < 200 GeV
≥ 2-jet, 1000 ≤ mjj < 1500 GeV, pTH < 200 GeV
≥ 2-jet, mjj ≥ 1500 GeV, pTH < 200 GeV
≥ 2-jet, 350 ≤ mjj < 1000 GeV, pTH ≥ 200 GeV
≥ 2-jet, mjj ≥ 1000 GeV, pTH ≥ 200 GeV
qq→Hlν
pTV < 75 GeV
75 ≤ pTV < 150 GeV
150 ≤ pTV < 250 GeV
250 ≤ pTV < 400 GeV
pTV ≥ 400 GeV
gg/qq→Hll
pTV < 150 GeV
150 ≤ pTV < 250 GeV
250 ≤ pTV < 400 GeV
pTV ≥ 400 GeV
ttH
pTH < 60 GeV
60 ≤ pTH < 120 GeV
120 ≤ pTH < 200 GeV
200 ≤ pTH < 300 GeV
300 ≤ pTH < 450 GeV
pTH ≥ 450 GeV
tH
Cross-section normalized to SM value


ATLAS
√s = 13 TeV, 139 fb-1
mH = 125.09 GeV, |yH| < 2.5
ρ(X,Y)