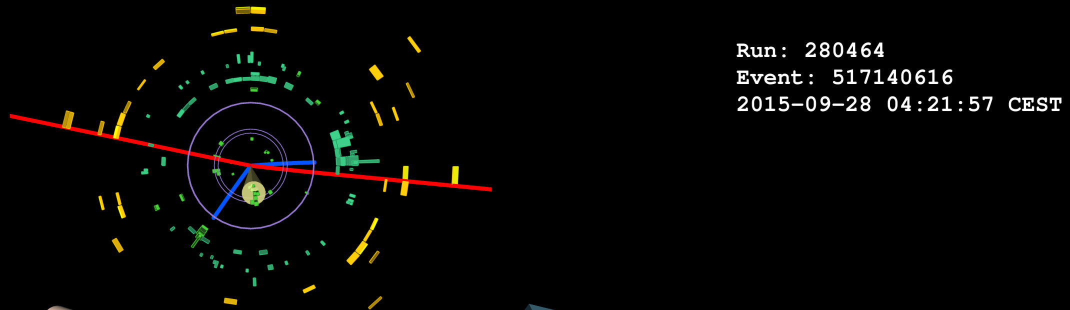
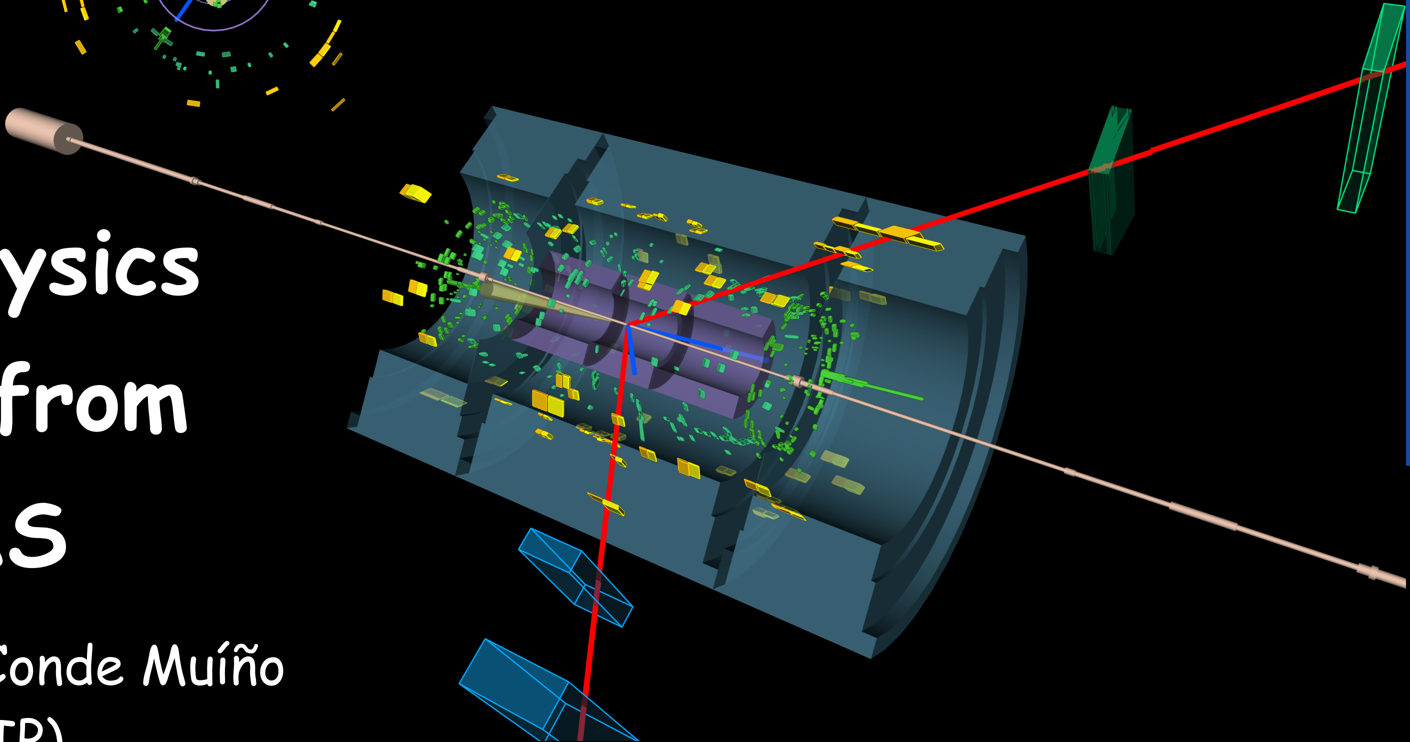
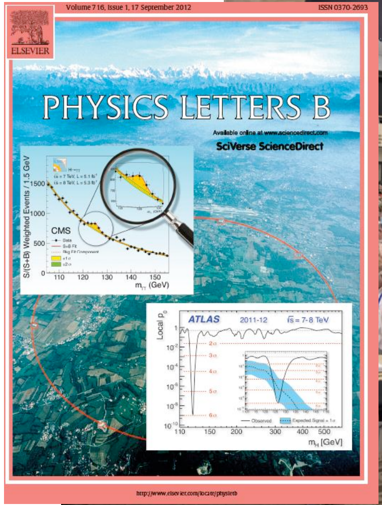


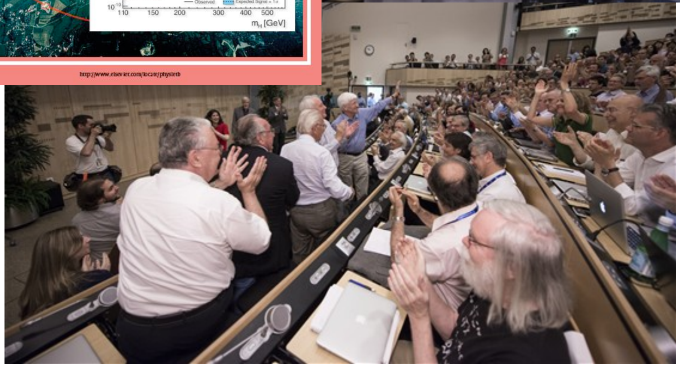


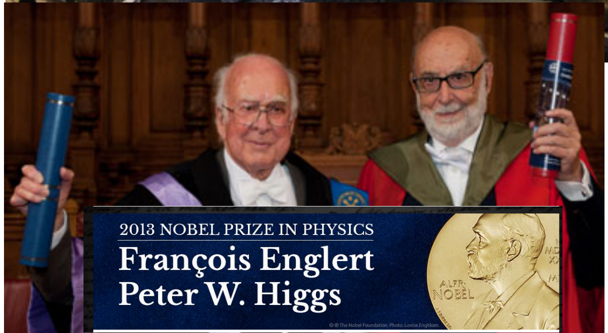
Higgs Physics Results from ATLAS

Patricia Conde Muíño
(IST & LIP)

years
HIGGS boson
discovery







SM Higgs Lagrangian after symmetry breaking

$$\mathscr{L}_{SM} = D_\mu H^\dagger D_\mu H - (y_{ij} H \bar{\psi}_i \psi_j + h.c.) + \mu^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$

Bosons

$$(m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0)(1 + \frac{h}{v})^2$$

Fermions

$$-\sum_f m_f \bar{f} f (1 + \frac{h}{v})$$

Higgs potential

$$\frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

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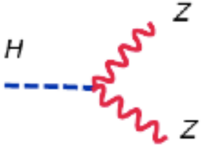
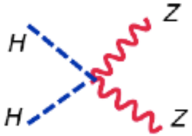
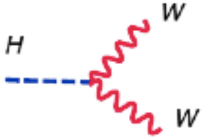


$$2i \frac{M_Z^2}{2v} g_{\mu\nu}$$



$$2i \frac{M_Z^2}{4v} g_{\mu\nu}$$



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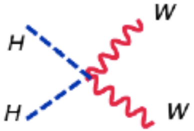

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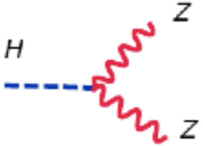

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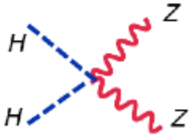

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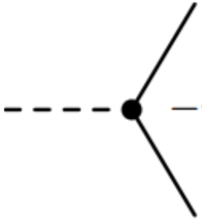
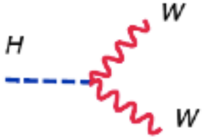
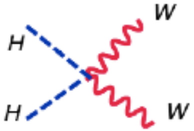


$-i \frac{m_f}{v}$



$2i \frac{M_W^2}{v} g_{\mu\nu}$



$2i \frac{M_W^2}{2v} g_{\mu\nu}$

I	II	III
u	c	t
d	s	b
ν_e	ν_μ	ν_τ
e	μ	τ

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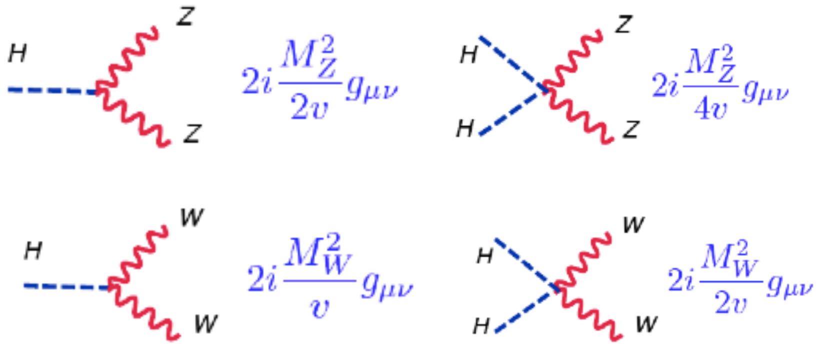

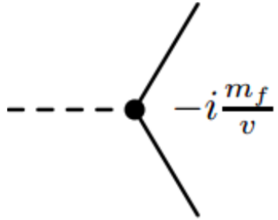

I	II	III
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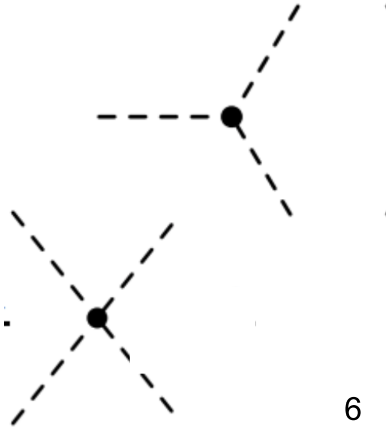

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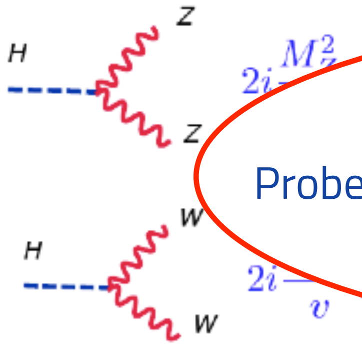
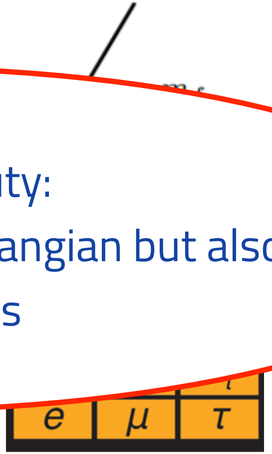
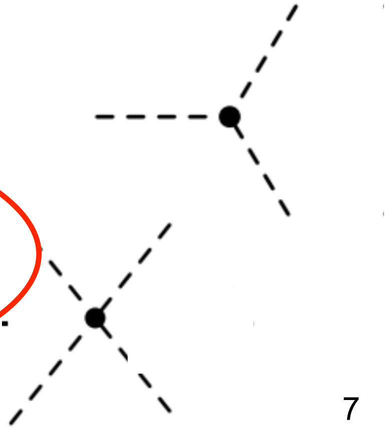




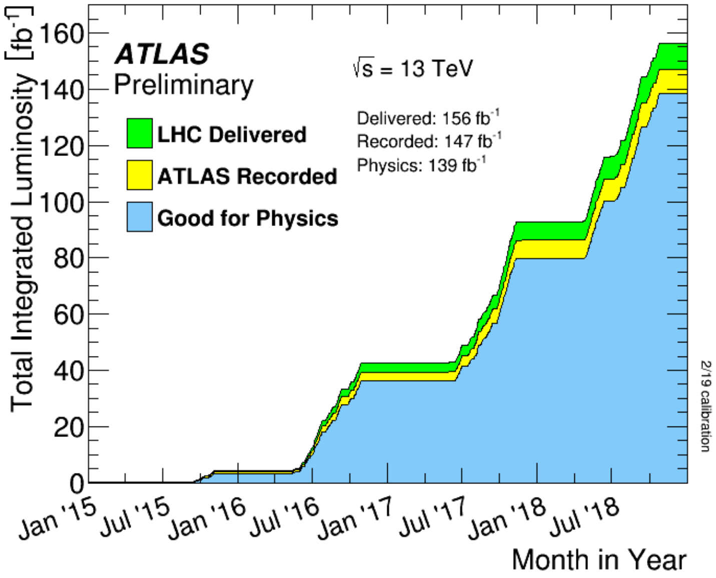


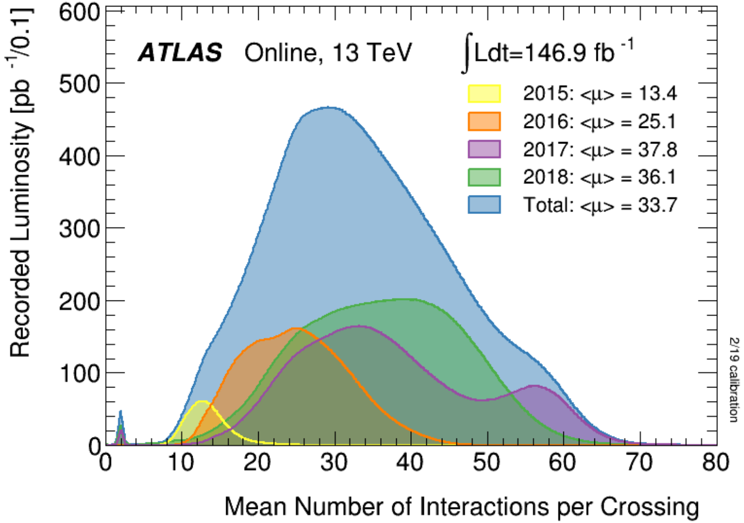
Experimental duty:
Probe the the SM Higgs boson Lagrangian but also search for new physics

ATLAS and LHC operation

$139\ \text{fb}^{-1}$ of good quality pp collisions at 13 TeV

- Average pile-up: 33.7 interactions/BX





ATLAS pp Run-2: July 2015 – October 2018										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.5	99.9	99.7	99.6	99.7	99.8	99.6	100	100	99.8	98.8
Good for physics: 95.6% (139 fb^{-1})										

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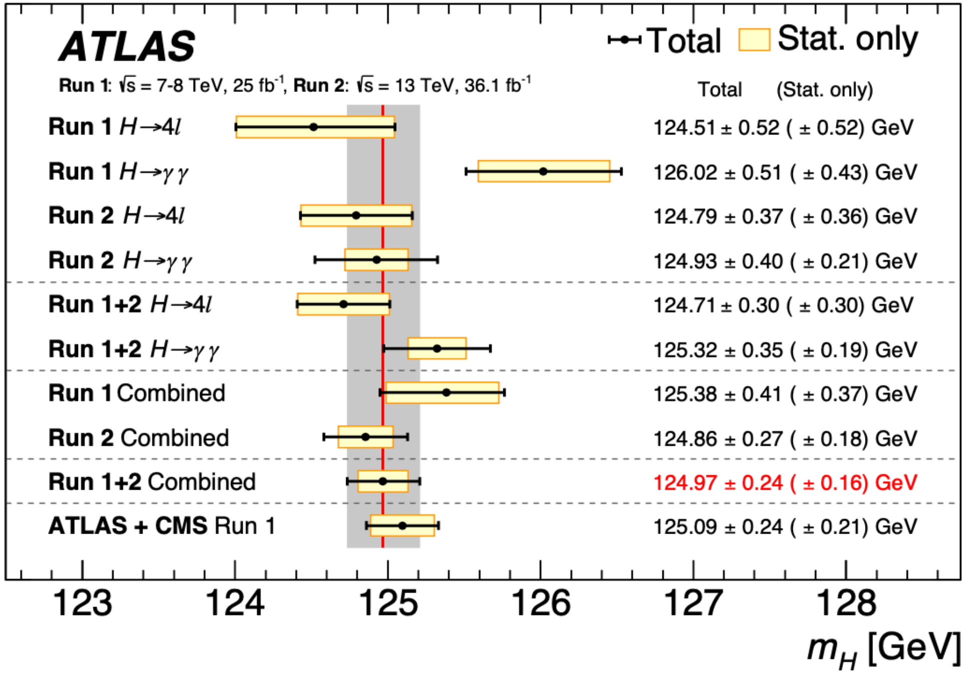
Higgs mass measurements

Higgs boson mass

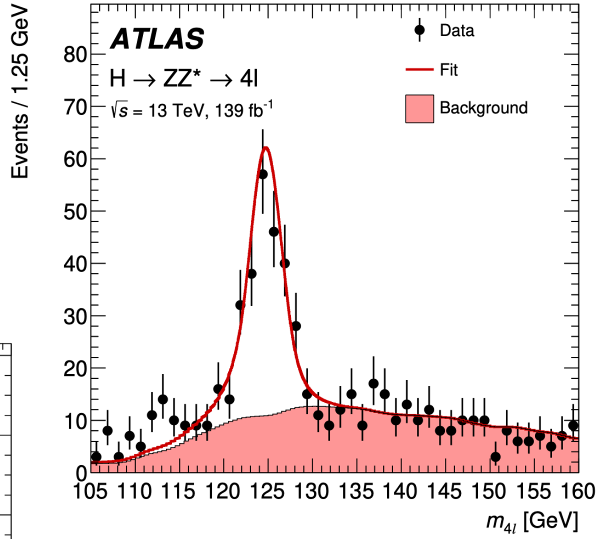
Phys. Lett. B 784 (2018) 345

- Fundamental parameter
  - Higgs couplings calculations
  - Precision global fit of the Standard Model
- ATLAS
  - Run I combination: 0.33% precision
  - Run 1+ partial Run 2 analysis: 0.23% precision

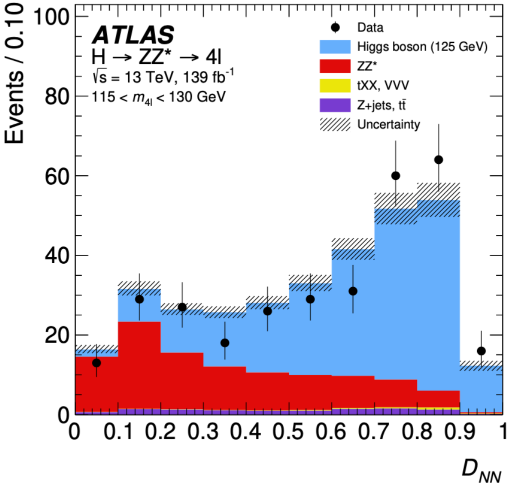


$H \rightarrow ZZ^* \rightarrow 4\ell$ new measurement $139\ \mathrm{fb}^{-1}$

- Improvements
  - μ momentum scale precision down to 0.05%
  - μ momentum resolution precision down to 0.1%
  - ML discriminant, $m_{4\ell}$ resolution estimated per-event (quantile regression NN)

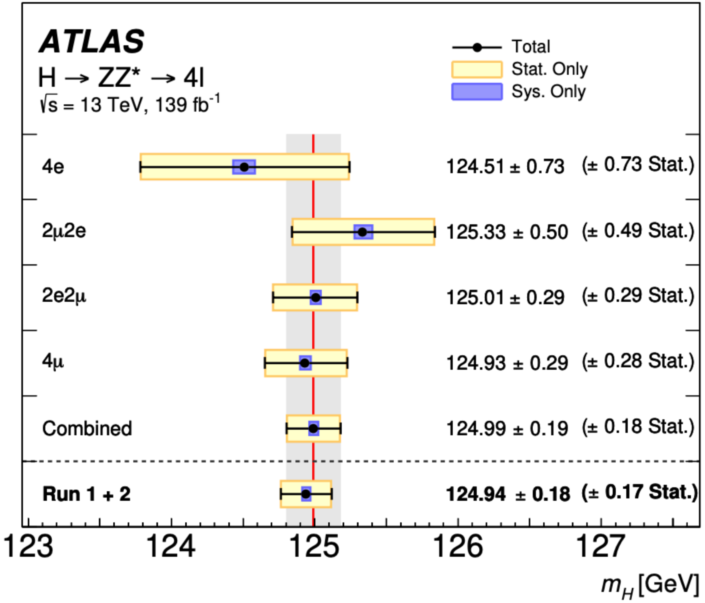


- Combined profile likelihood fit of $m_{4\ell}$ and D_{NN}
- $m_H = 124.99 \pm 0.18\ (stat.) \pm 0.04\ (syst.)\ GeV$
  - 0.15% accuracy!



$H \rightarrow ZZ^* \rightarrow 4\ell$ Run 1 and Run 2 Combination

- $m_H = 124.94 \pm 0.17\ (stat.) \pm 0.03\ (syst.)\ GeV$
  - 0.14% accuracy (limited by statistics)



$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H - (y_{ij} H \bar{\psi}_i \psi_j + h.c.) + \mu^2 H^\dagger H - \frac{\lambda}{2}$$

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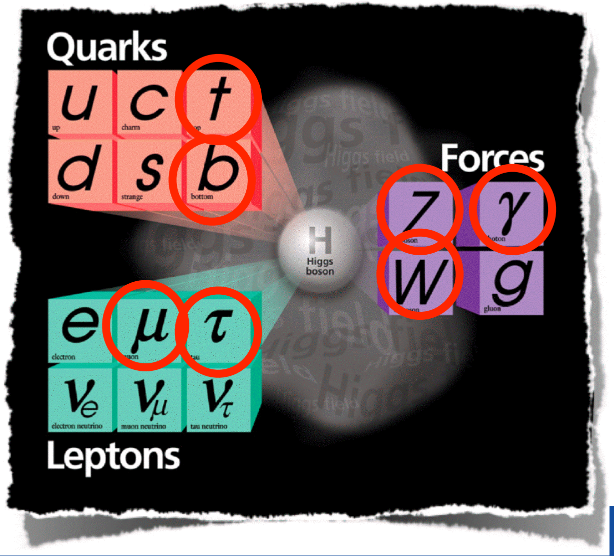
$$(m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0)(1 + \frac{h}{v})^2$$

Fermions

$$-\sum_f m_f \bar{f} f (1 + \frac{h}{v})$$

Higg

$$\frac{1}{2} m_h^2$$



Higgs couplings to bosons & fermions

Higgs boson couplings combination

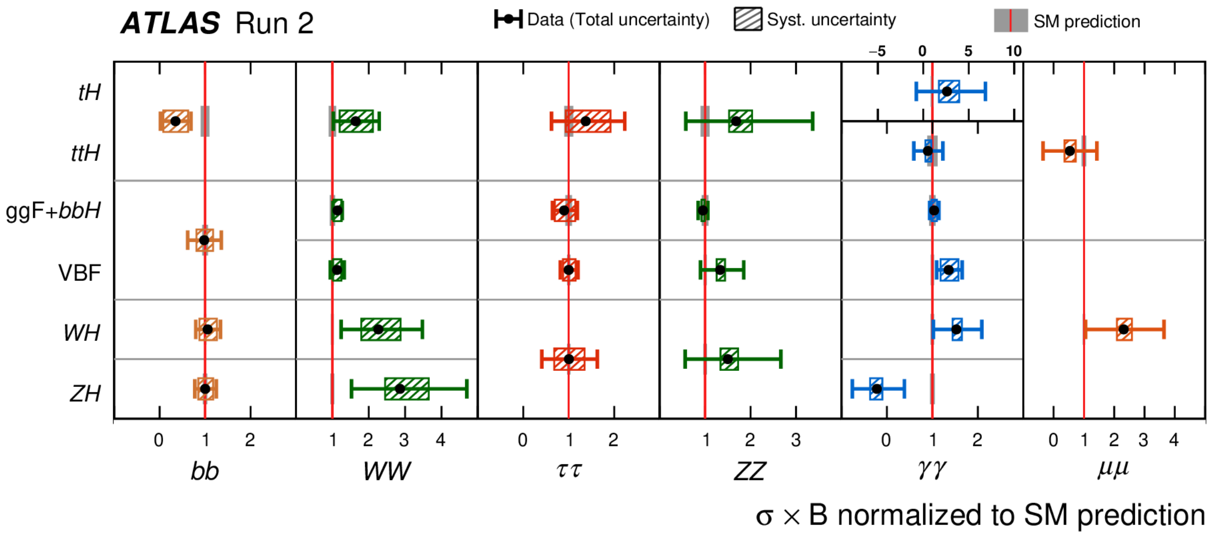
Long list of channels used

Nature **607**, 52–59 (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 $B_{u.}$ & $B_{inv.}$
	ZH	139	43	κ models with $B_{u.}$ & $B_{inv.}$

Higgs boson couplings combination

Direct measurement of $\sigma \times BR$



Good agreement with SM expectations (p-value 72%)

Improved precision:

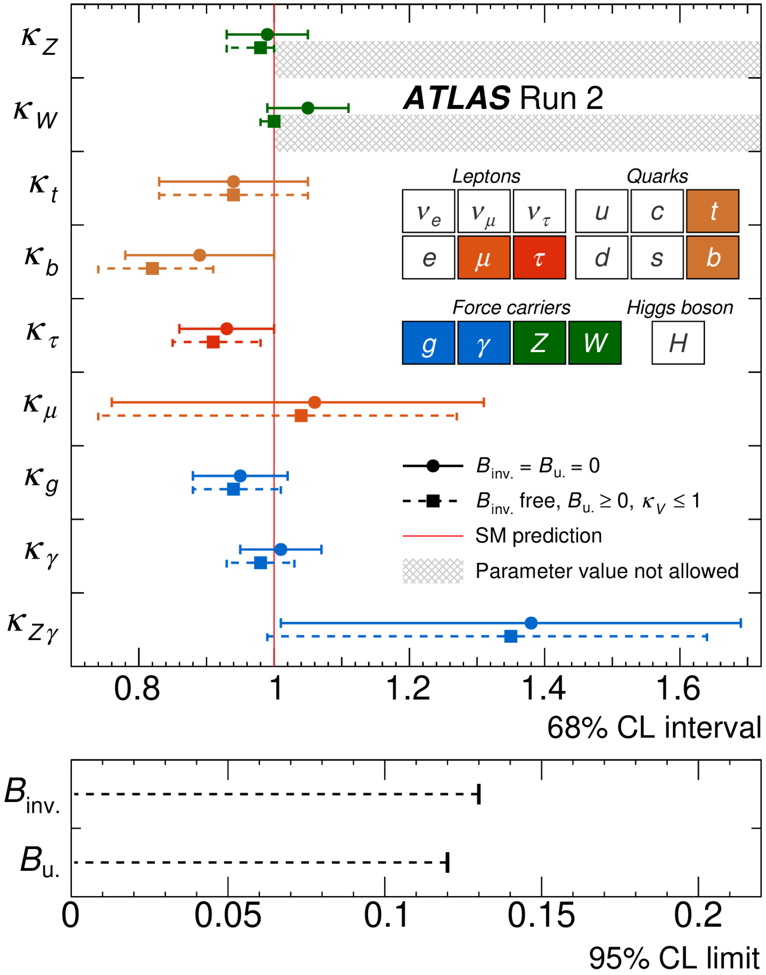
- Cross section: 7-12%
- Branching fractions:10-12%

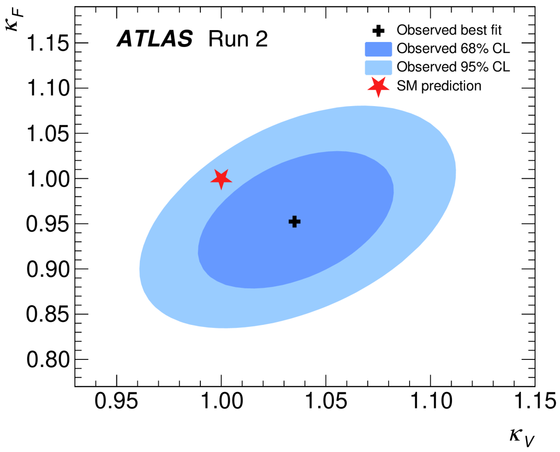
Higgs Couplings Combination

K-framework

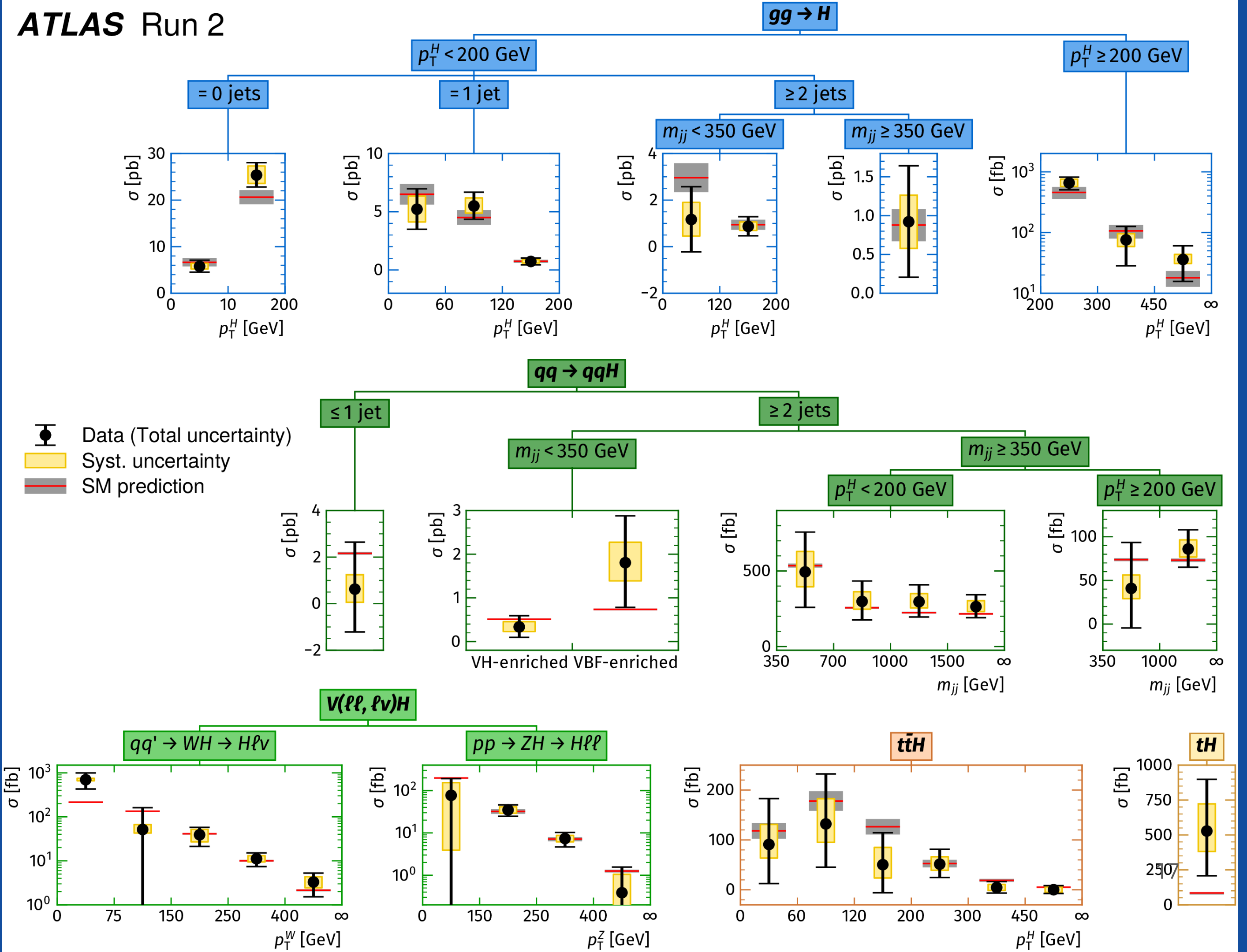
Best ATLAS limits in the BR to invisible modes

- $B_{inv.} < 0.13$ @ 95% CL
- (expected 0.08)





Cross section different kinematic regions



Proving larger kinematic region at high pT!

Combined p-value:

- 94%

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Bosons

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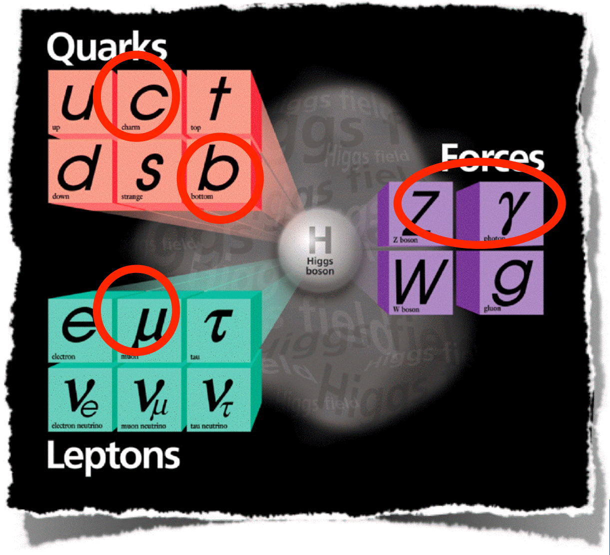
Fermions

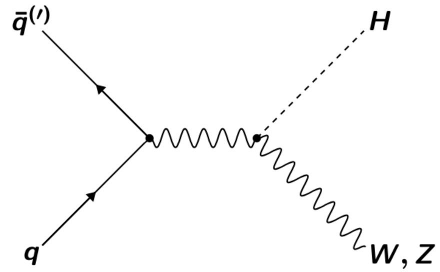
$$-\sum_f m_f \bar{f} f (1 + \frac{h}{v})$$



Higgs Rare Decays

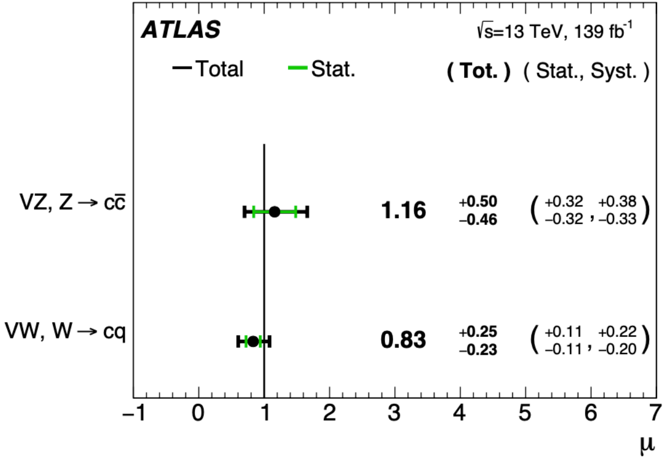
Eur. Phys. J. C 82 (2022) 717

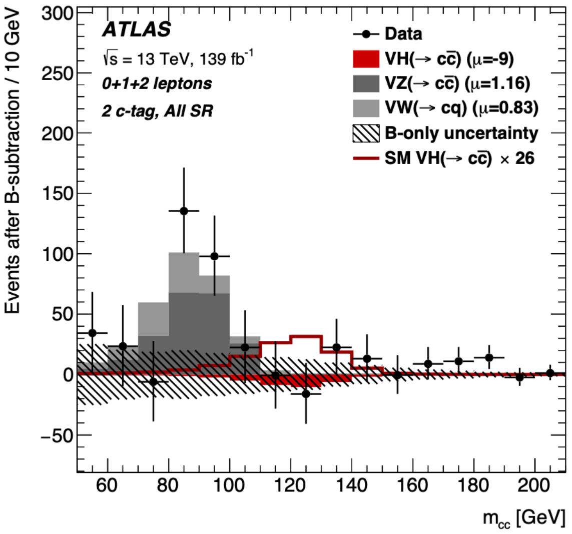
Second generation: $H \to c\bar{c}$



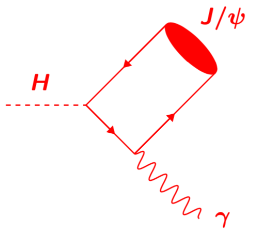
- Rate could be enhanced by BSM physics
- Extremely challenging: huge backgrounds
- 3 different channels: $WH \to \ell\nu c\bar{c}, ZH \to \ell\ell c\bar{c}, ZH \to \nu\nu c\bar{c}$

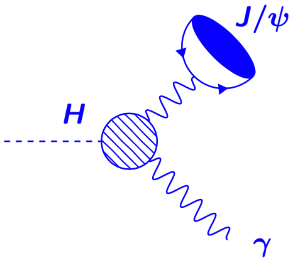
- Observed (expected) 95% CL limit: $26\ (31^{+12}_{-8})$
- $VW(cq)$ observed (expected) significance 3.8 (4.6)σ
- $VZ(c\bar{c})$ observed (expected) significance 2.6 (2.2)σ





$Hc\bar{c}$ and $Hb\bar{b}$ vertices

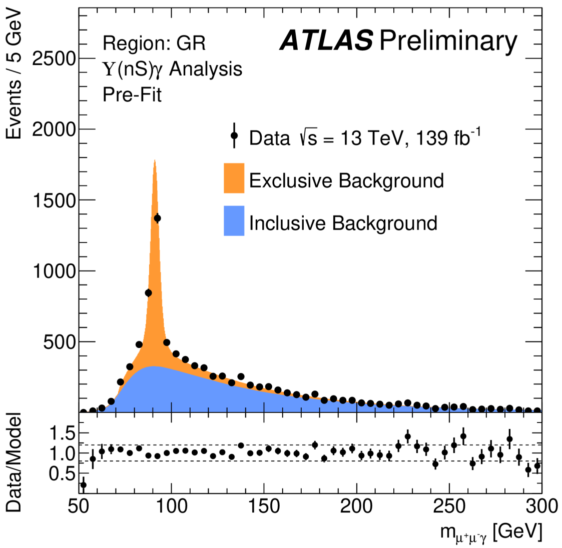




- Rare decays sensitive to Hcc or Hbb vertex
  - Direct and indirect contributions
- Could be enhanced due to BSM physics
- No signal observed → imposed limits on BR

BR (H→$\Upsilon\gamma$) ~9×10^{-8}

BR (H→J/$\Psi\gamma$) ~3×10^{-6}

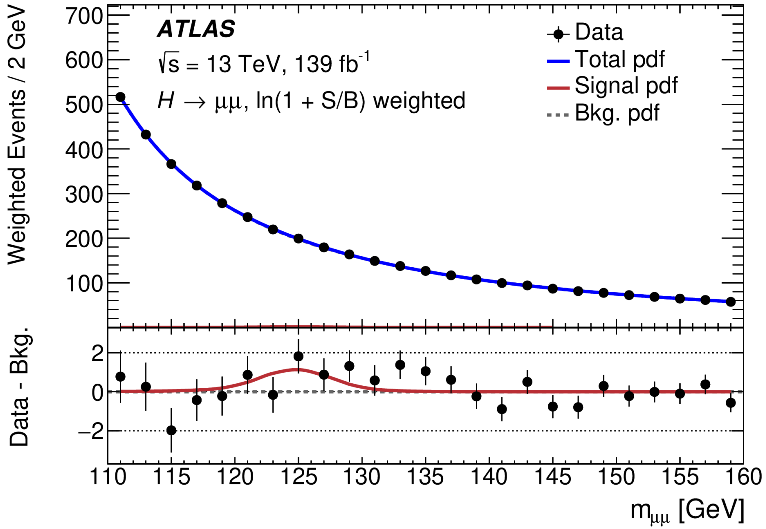


	95% CL_s upper limits					
	Branching fraction				$\sigma \times \mathcal{B}$	
Decay channel	Higgs boson [10^{-4}]		Z boson [10^{-6}]		Higgs boson [fb]	Z boson [fb]
	Expected	Observed	Expected	Observed	Observed	Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3	61	135
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0	14	59
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2	24	71
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3	19	135

Phys. Lett. B 812 (2021) 135980

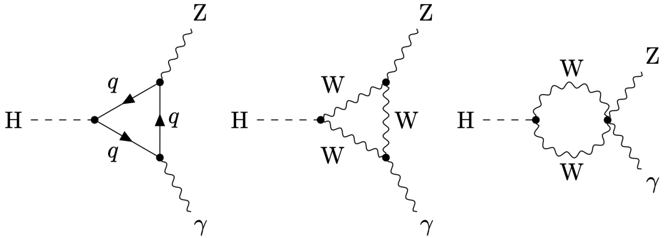
Second generation: $H \rightarrow \mu^+\mu^-$

- Very small BR and large backgrounds
- Dedicated BDTs trained for different production modes (20 categories)
  - Using muon and jet kinematics
- Simultaneous fit to $m_{\mu\mu}$ in all categories
- Signal strength:
  - $\mu = 1.2 \pm 0.6\ (stat.)^{+0.2}_{-0.1}\ (syst.)$
- Observed (expected) significance: 2σ (1.7σ).
- Upper limit:
  - $BR(H \rightarrow \mu\mu) < 4.7 \times 10^{-4} = 2.2 \times SM$

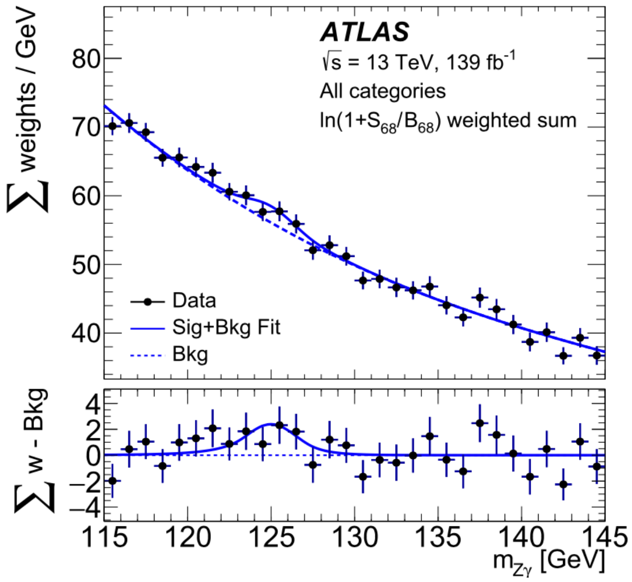


[Phys. Lett. B 809 (2020) 135754](#)

$H \rightarrow Z\gamma$



- Ratio $BR(H \rightarrow Z\gamma)/BR(H \rightarrow \gamma\gamma) = 0.69 \pm 0.04$ sensitive to new physics (composite Higgs, SUSY, …)
- Improved lepton/photon identification
- Constrained kinematic fit $Z \rightarrow \ell\ell$ improves invariant mass resolution by 10-14%
- 6 exclusive events categories depending on lepton flavour and event kinematics
    - BDT to separate VBF events
- Combined fit for all event categories to $m_{Z\gamma}$

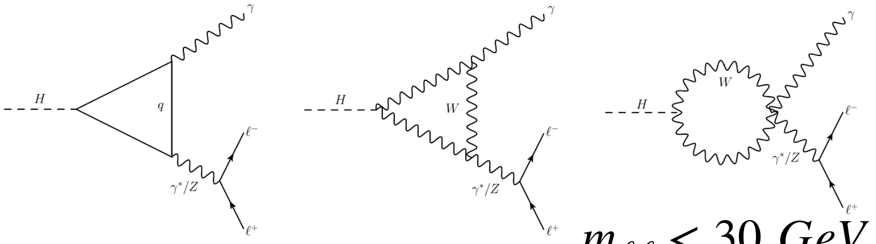


$\mu = 2.0 \pm 0.9\ (stat.)^{+0.4}_{-0.3}\ (syst.) = 2.0^{+1.0}_{-0.9}$

Obs (expect) significance: 2.2σ (1.2σ)

Phys. Lett. B 819 (2021) 136412

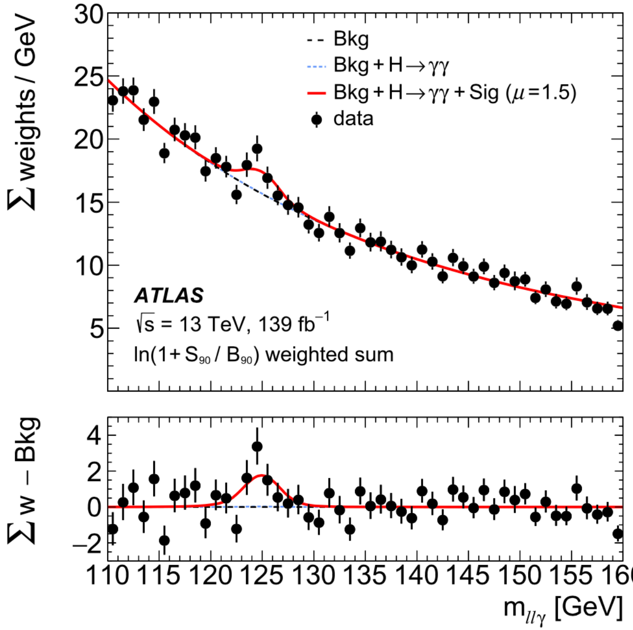
$H \to \gamma^*\gamma \to \ell\ell\gamma$

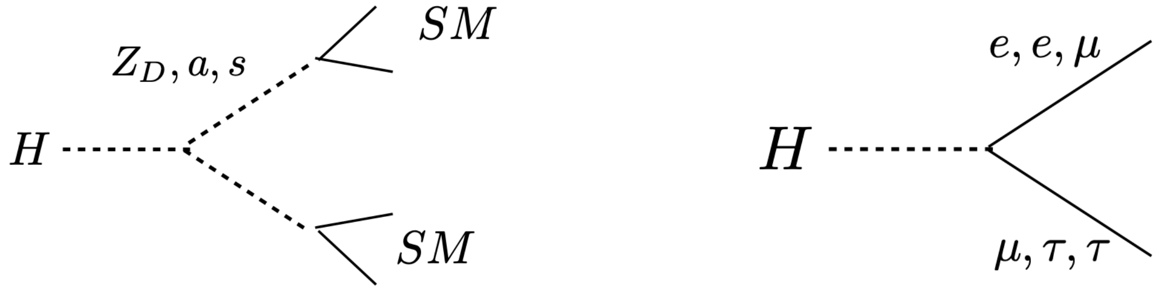


$m_{\ell\ell} < 30\ GeV$

- Sensitive to CP violation in the Higgs sector
- Dedicated trigger and reconstruction techniques for low p_T lepton pairs
- 9 event categories with different S/B
- First evidence observed: Obs(exp): 3.2σ (2.1σ)

$$\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5\ (\text{stat.})^{+0.2}_{-0.1}\ (\text{syst.})$$





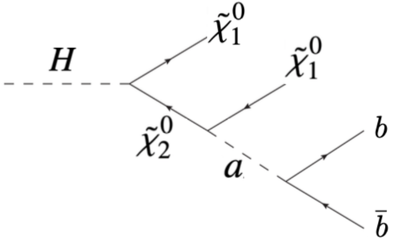
Search for exotic & LFV decays

[Phys. Rev. D 105 (2022) 012006]

Exotic decays

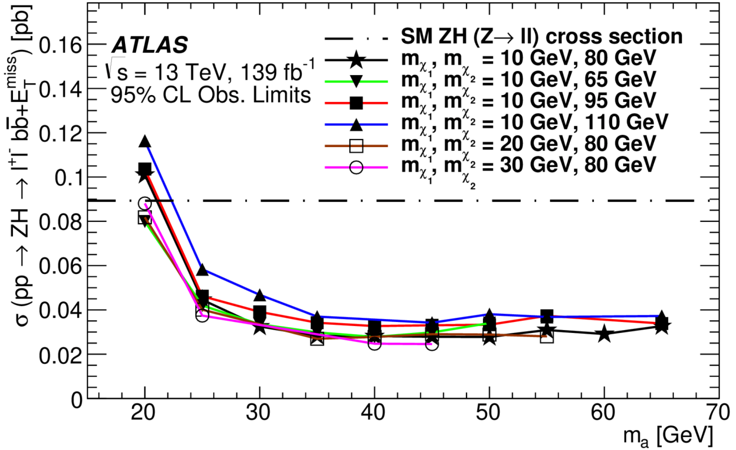
$H \rightarrow aa \rightarrow bb\mu\mu$

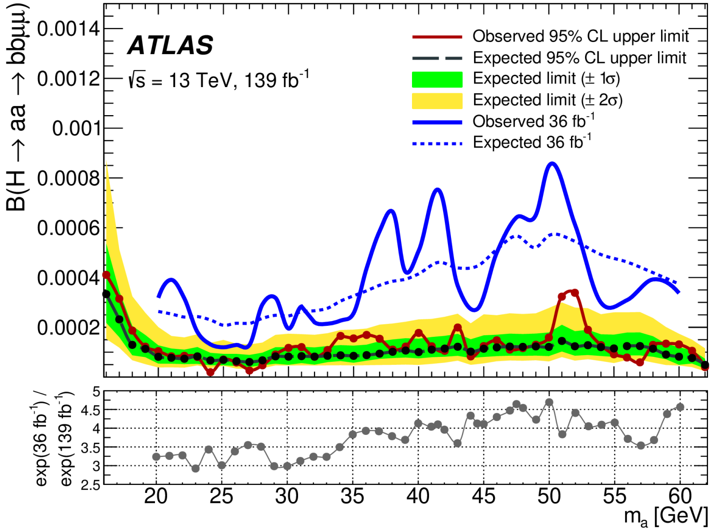
$H \rightarrow b\bar{b} + E_T^{miss}$



[JHEP 01 (2022) 063]

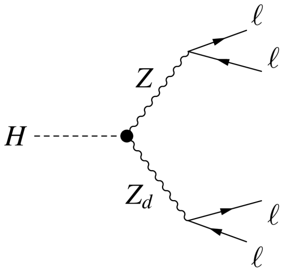
- Intermediate pseudo-scalars

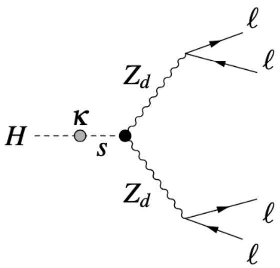




- Limits in cross section/BR as a function of $m_{\tilde{\chi}_1}, m_{\tilde{\chi}_2}$
- 3.3σ (1.7σ) local (global) excess observed at $m_a = 52$ GeV

Exotic decays

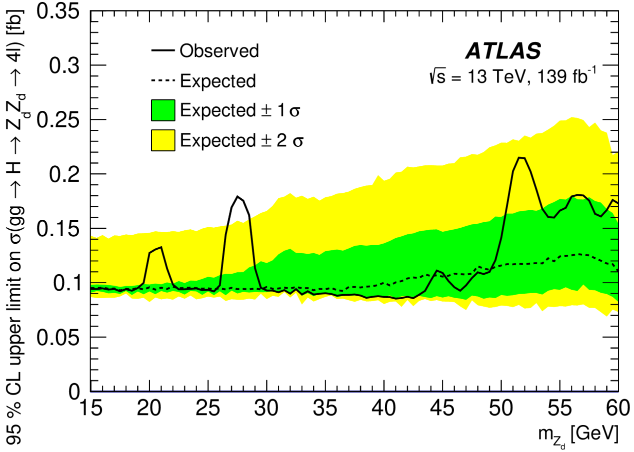




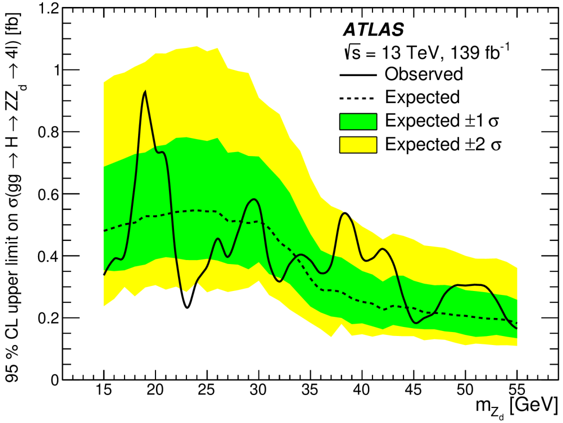
Z_d = dark photon

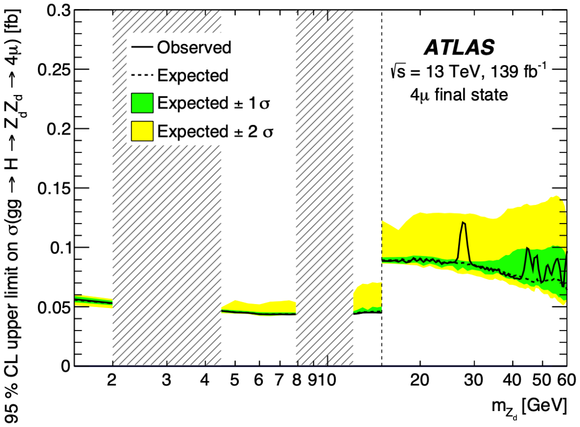
S = dark Higgs boson

$H \to Z_d Z_d \to 4\ell$



$H \to Z Z_d \to 4\ell$



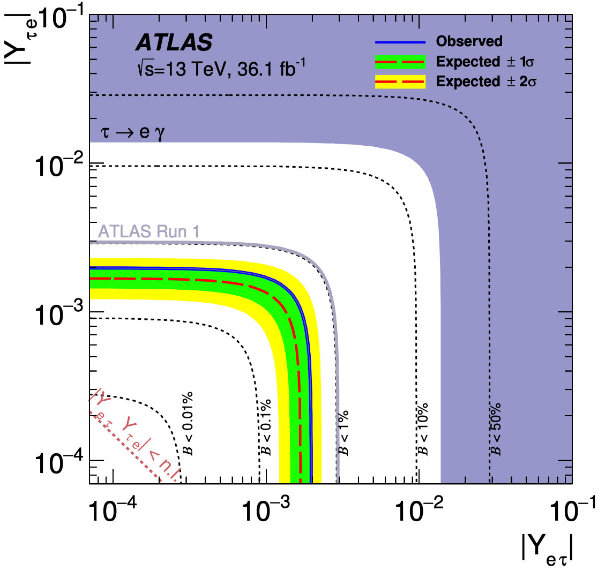


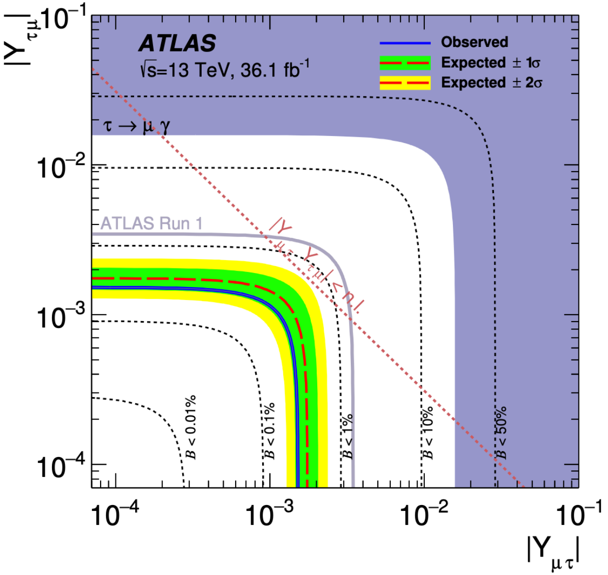
Lepton flavour violating Higgs decays searches

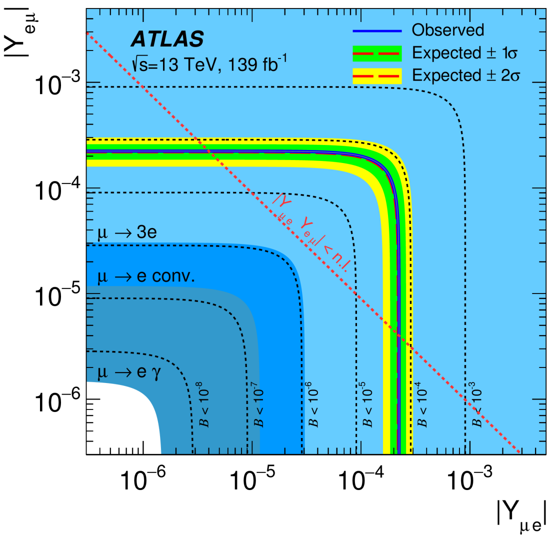
- Limits on the Yukawa couplings

Phys. Lett. B 800 (2020) 135069

Phys. Lett. B 801 (2020) 135148



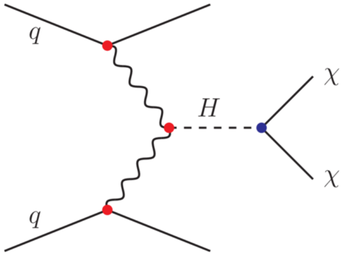




Searches for Higgs decaying to invisible particles

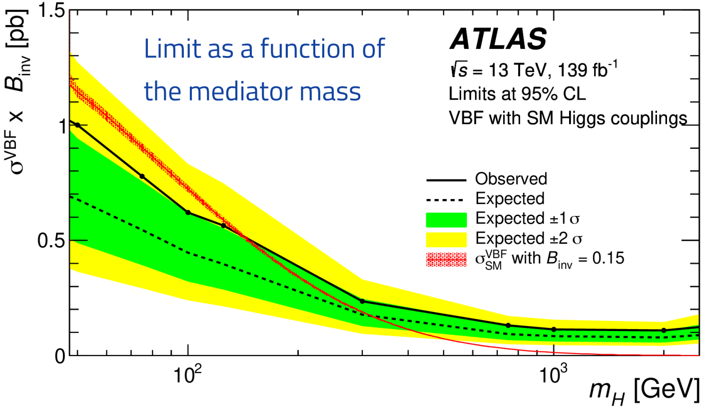
- VBF channel

arXiv:2202.07953



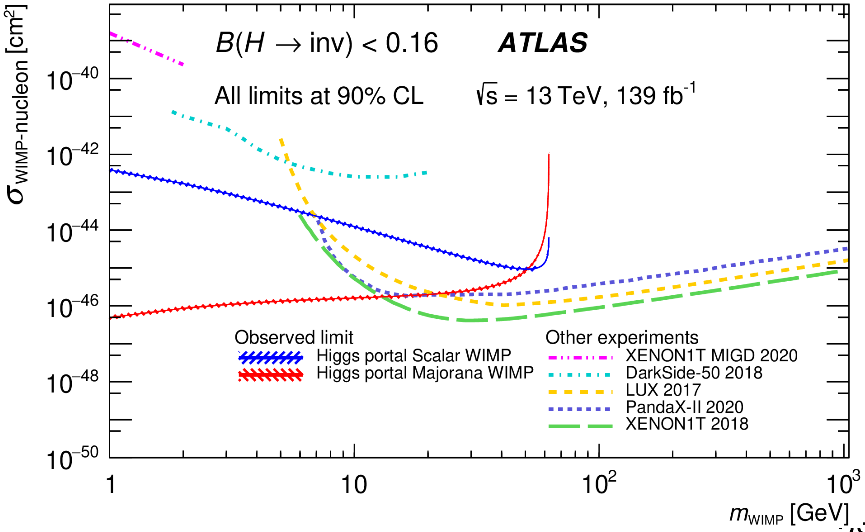
95% CL limits on $BR(H \to inv)$:

Observed	Expected	$+1\sigma$	-1σ	$+2\sigma$	-2σ
0.145	0.103	0.144	0.075	0.196	0.055



- ZH associated production searches
  - Interpretations for different models

[*Phys. Lett. B 829 (2022) 137066*](Phys. Lett. B 829 (2022) 137066)



$$\mathscr{L}_{SM} = D_\mu H^\dagger D_\mu H - (y_{ij} H \bar{\psi}_i \psi_j + h.c.) + \mu^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$

Bosons

$$(m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0)(1 + \frac{h}{v})^2$$

Fermions

$$-\sum_f m_f \bar{f} f (1 + \frac{h}{v})$$

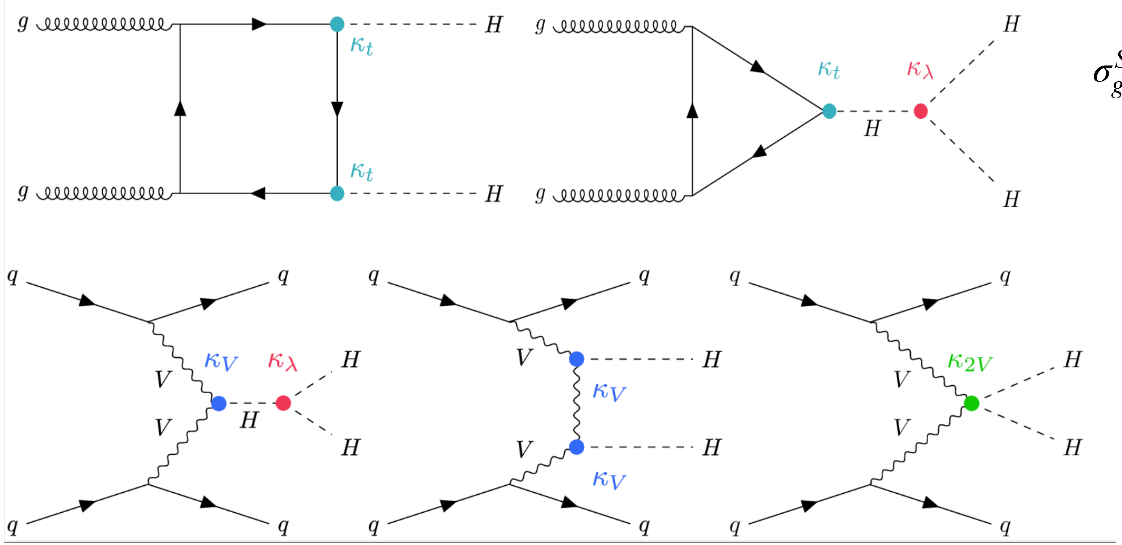
Higgs potential

$$\frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

Di-Higgs production

Higgs self coupling

- Determine the shape of the Higgs potential $\frac{1}{2}m_h^2h^2 + \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$
- Di-Higgs production



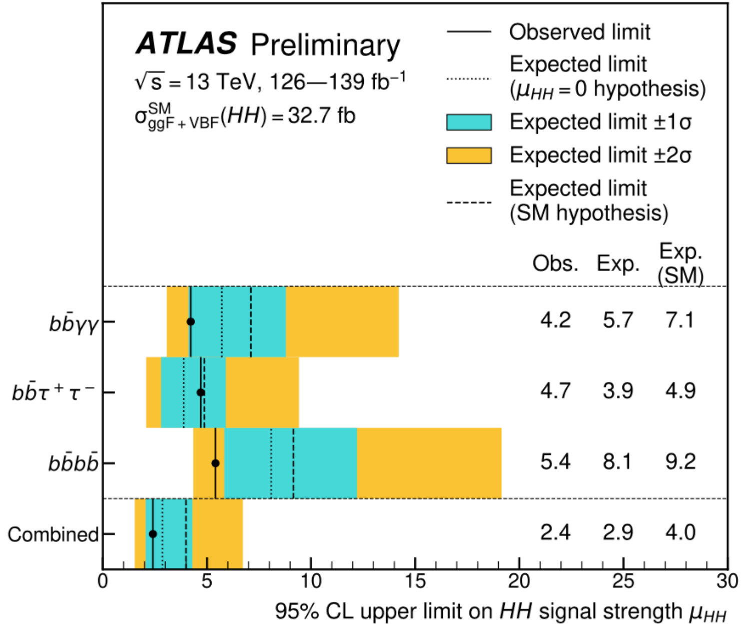
$$\sigma_{ggF}^{SM}(pp \to HH) = 31.05\ ^{+1.9}_{-7.1}\ fb$$

$$\sigma_{VBF}^{SM}(pp \to HH) = 1.72\ \pm 0.4\ fb$$

ATLAS HH combination

- Using $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$

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



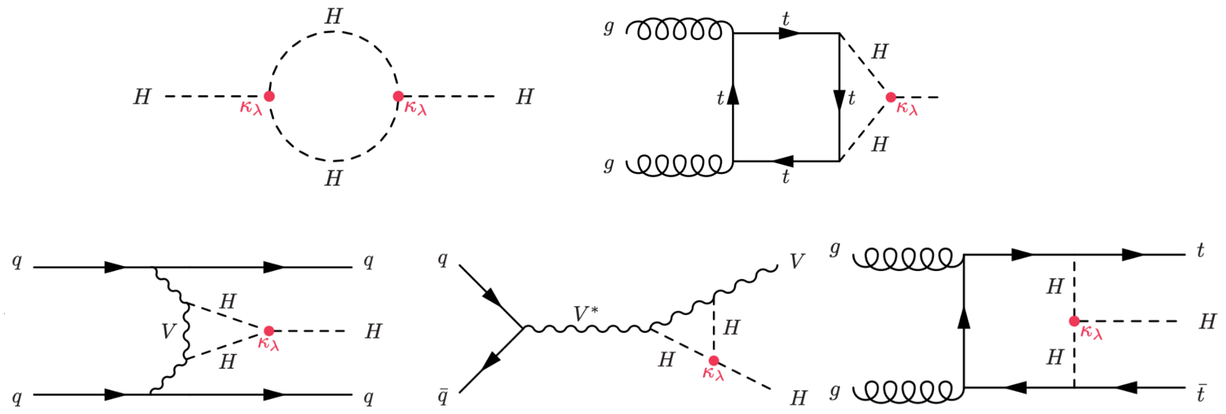
- 95% CL observed (expected) upper limit on HH production:

$$\mu_{HH} = \frac{\sigma^{HH}_{ggF+VBF}}{\sigma^{HH}_{ggF+VBF}|_{SM}} = 2.4\ (2.9)$$

- Using VBF channel extracted 95% CL limits on k_{2V}: $0.1 < k_{2V} < 2.0$

Higgs self-coupling

- Single Higgs production affected by k_λ via NLO EW corrections



ATLAS HH+H combination

- Using $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$ and single Higgs measurements

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

ATLAS HH+H combination

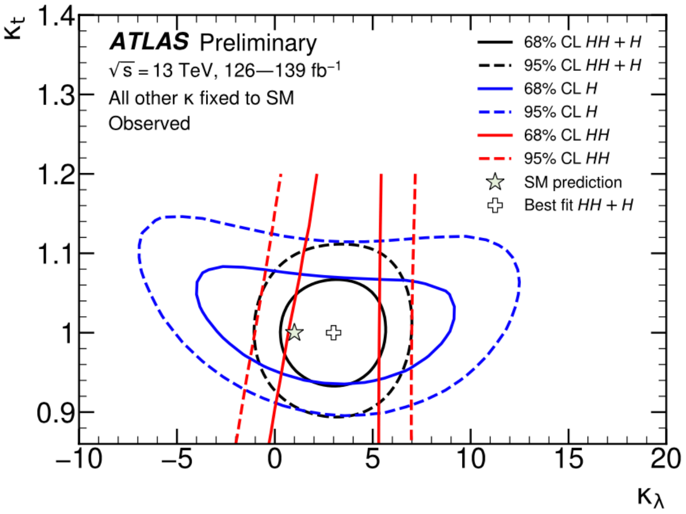
95% CL observed (expected) limits

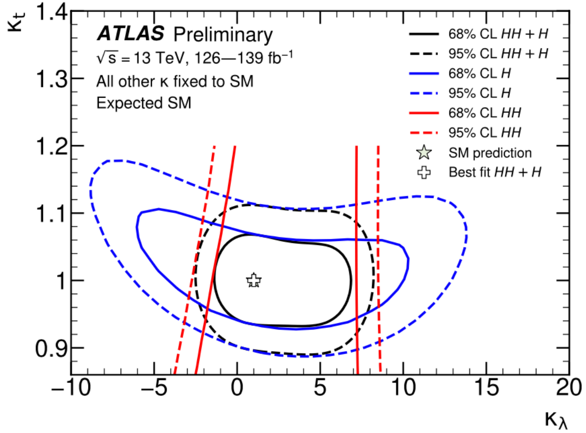
- Assuming all other SM couplings:

$$-0.4 < \kappa_\lambda < 6.3$$
$$(-1.9 < \kappa_\lambda < 7.5)$$

- No assumptions in other couplings

$$-1.3 < \kappa_\lambda < 6.1$$
$$(-2.1 < \kappa_\lambda < 7.6)$$





$$\mathscr{L}_{SM} = D_\mu H^\dagger D_\mu H - (y_{ij} H \bar{\psi}_i \psi_j + h.c.) + \mu^2 H^\dagger H - \frac{\lambda}{2}(H^\dagger H)^2$$

Bosons	Fermions	Higgs potential
$(m_W^2 W^{\mu+} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0)(1 + \frac{h}{v})^2$	$-\sum_f m_f \bar{f} f (1 + \frac{h}{v})$	$\frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$

CP Structure of Higgs Couplings

Searching for CP Violation in the Higgs sector

- Barion asymmetry of the Universe: still a mystery
- Combined results demonstrated H to be mainly CP-even scalar
  - There is still room for CP violation in the Higgs couplings
- Extend SM Lagrangian $\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$
- Effects:
  - Rates: don't allow to separate CP-even/odd
  - Identify CP-odd observables
    - Angular variables
    - Optimal observables

$$\sigma \sim |\mathscr{M}_{SM} + \mathscr{M}_{CP-odd}|^2 =$$
$$= |\mathscr{M}_{SM}|^2 + |\mathscr{M}_{CP-odd}|^2$$
$$+ 2Re(\mathscr{M}^*_{SM}\mathscr{M}_{CP-odd})$$

$$OO = \frac{2Re(\mathscr{M}^*_{SM}\mathscr{M}_{CP-odd})}{|\mathscr{M}_{SM}|^2}$$

arXiv:2208.02338

Vector Boson Fusion $H \to \gamma\gamma$

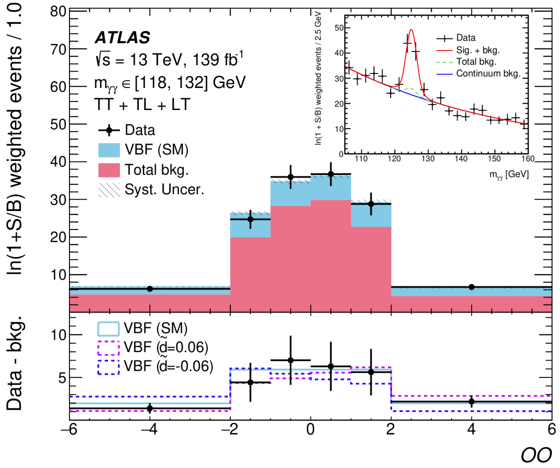
- VVH coupling
- Combination with $H \to \tau\tau$ ($36.1\ \text{fb}^{-1}$, OO)
- Results compatible with SM
  - Most stringent limits in HVV CP-violating couplings

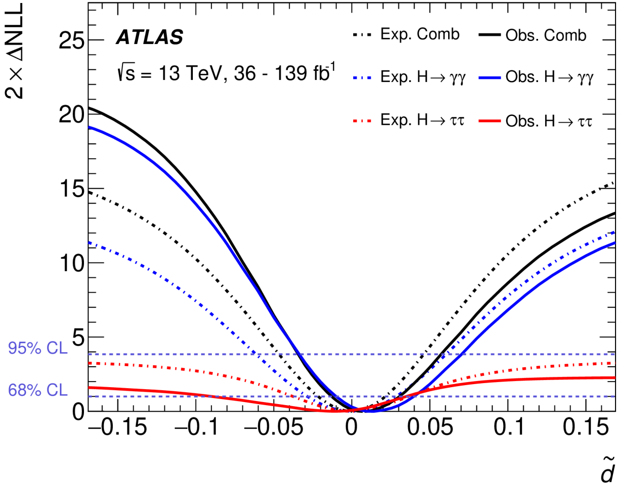
First time

	95% (exp.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.055, 0.055]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.061, 0.060]	[−0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	–	-
Combined $\tilde{d}$	[−0.046, 0.045]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.94, 0.94]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.95, 0.95]	[−0.55, 1.07]

HIGZ basis

Warsaw basis





ATLAS-CONF-2022-032

CP in $H \to \tau\tau$ coupling

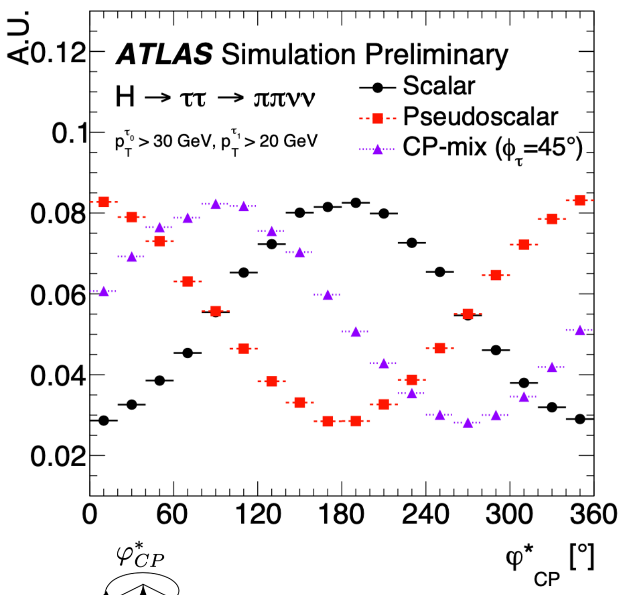
- Probe Yukawa coupling $H\tau\tau$
  - CP-odd contribution can be present at tree level
- Parametrisation

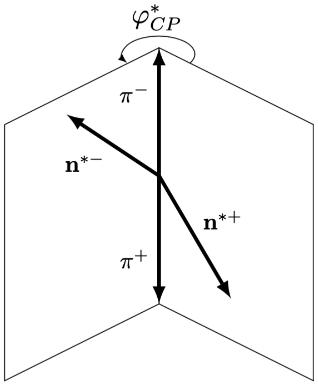
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

  - CP mixing angle ϕ_τ reflected in the directions of the decay products

$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

- Signed acoplanarity φ^*_{CP}
- Several analysis regions per channel



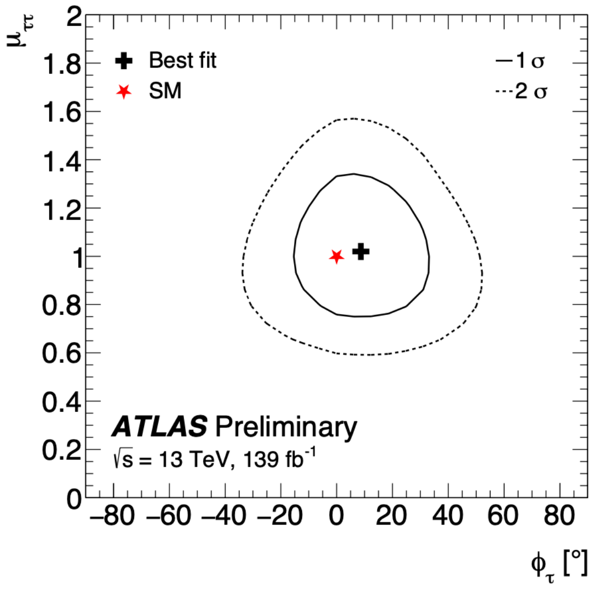


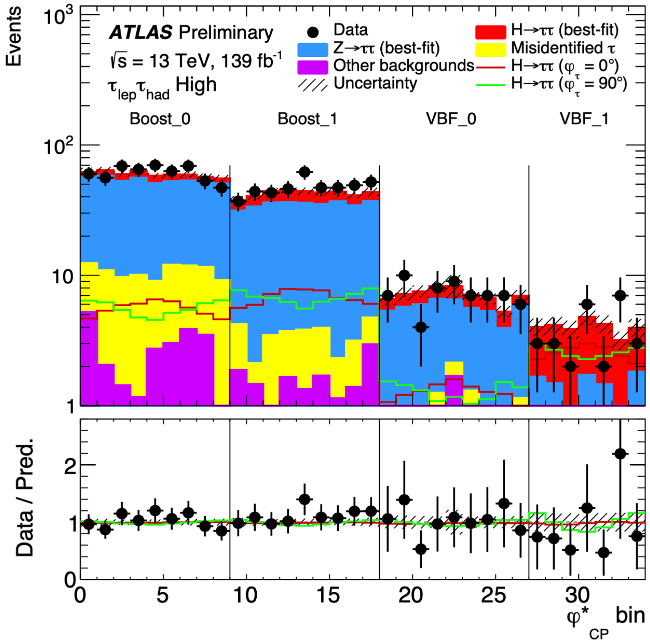
(a) $H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$

CP in $H \to \tau\tau$ coupling

- Disfavour pure CP-odd signal at 3.4σ
  - Results statistically limited

- Expected: $\phi_\tau = 0 \pm 28°$
- Observed: $\phi_\tau = 9 \pm 16°$





Phys. Rev. Lett. 125 (2020) 061802

Spin/CP in associated $t\bar{t}H/tH$ production ($H \rightarrow \gamma\gamma$)

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\} H$$

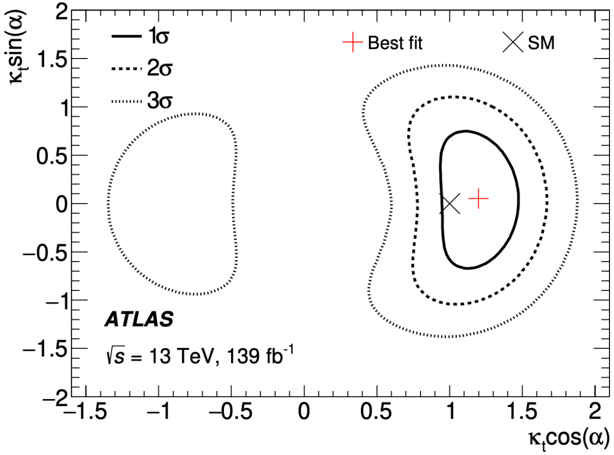
CP-even (SM) CP-odd

- Semileptonic and hadronic channels
- Event categories based on background rejection BDT and CP BDT trained to separate CP-even/CP-odd components
- Simultaneous fit to all event categories

- Measured ttH rate:

$$\mu = 1.43^{+0.33}_{-0.31}(stat.)^{+0.21}_{-0.15}(sys.)$$

- $|\alpha| < 43^\circ$ @95% CL
- $\alpha = 90^\circ$ excluded at 3.9σ (2.5σ) observed (expected)



Spin/CP in associated $t\bar{t}H/tH$ production ($H \rightarrow b\bar{b}$)

- Signal regions defined based on jet multiplicity, b-tagging conditions, number of boosted top candidates
  - Reconstruction and background rejection BDTs trained per region
- CP observables

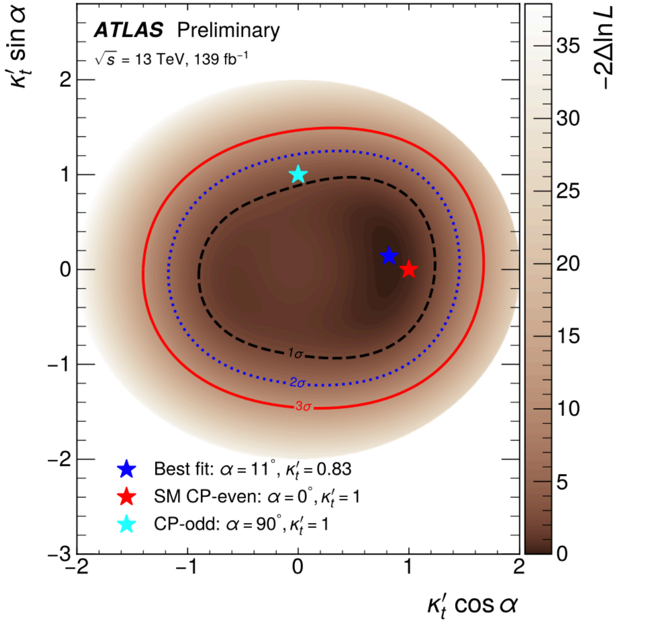
$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}$$

$$b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

- Results:
  - Assuming SM BR:

$$\alpha = 11^{\circ}{}^{+55^{\circ}}_{-77^{\circ}} \qquad \kappa_t' = 0.83^{+0.30}_{-0.46}$$

  - Data disfavours pure CP-odd at 1.2σ



Conclusions

- The Higgs boson provides an optimal ground to probe the SM predictions and search for new physics
- Outstanding performance of the LHC and the ATLAS detectors allows for an extensive Higgs Physics programme
- Selected recent results on the measurement of the Higgs couplings were presented
  - Increased precision and refined Run-2 data analysis
  - Overall agreement with the SM prediction

Thanks!

Acknowledgments

REPÚBLICA PORTUGUESA

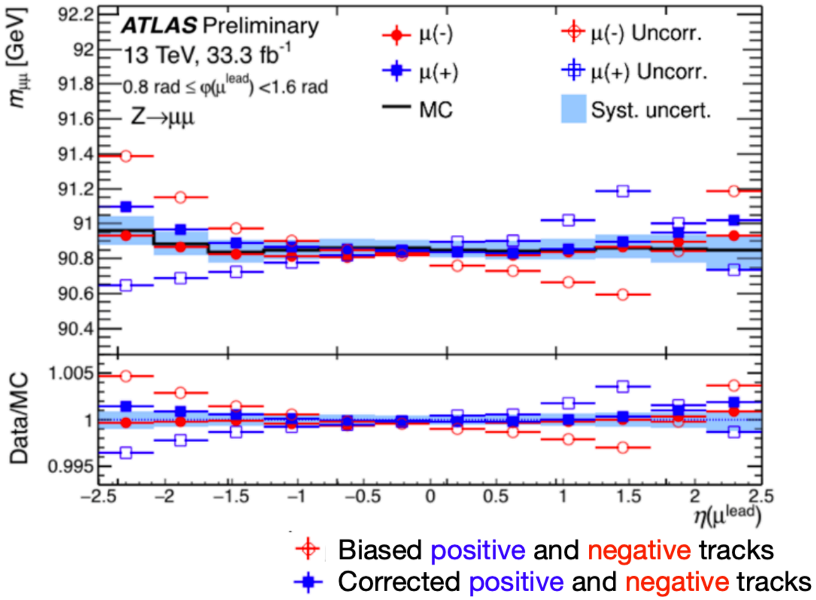
FCT Fundação para a Ciência e a Tecnologia

CERN/FIS-PAR/0010/2021

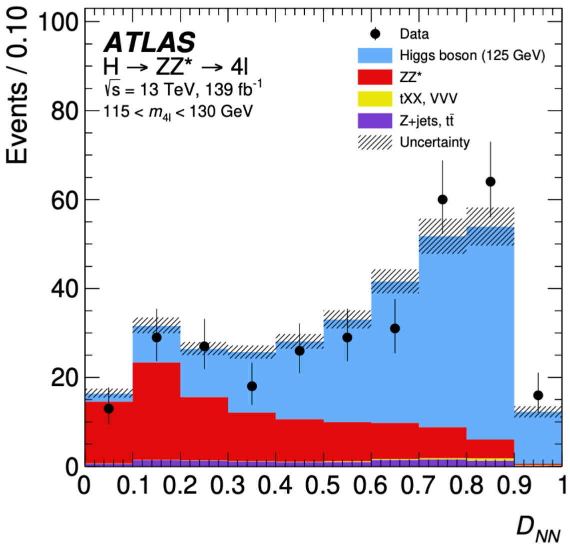
Backup

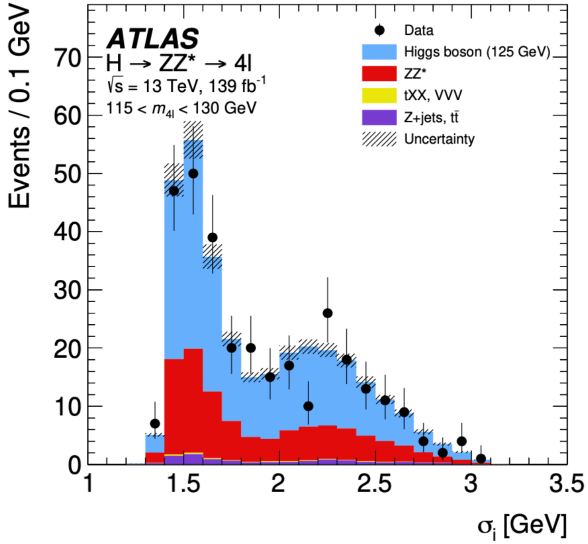
$H \rightarrow ZZ^* \rightarrow 4\ell$ new measurement $139\ \mathrm{fb}^{-1}$

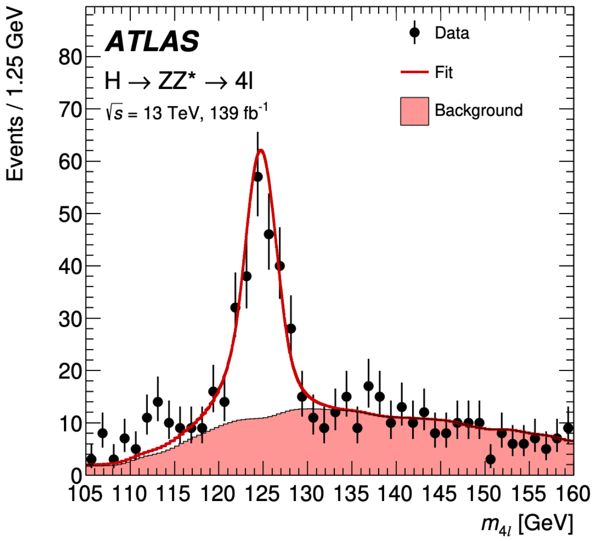
- Run 2 measurement, $139\ \mathrm{fb}^{-1}$
- Improvements
  - μ momentum scale precision down to 0.05%
  - μ momentum resolution precision down to 0.1%
  - ML discriminant to separate signal/background
    - $\mathrm{p_T}, \eta$ of the four leptons, kinematic discriminant $(ln(|\mathscr{M}_{HZZ*}|^2/|\mathscr{M}_{ZZ*}|^2)$
  - $m_{4\ell}$ resolution estimated per-event (quantile regression NN)



$H \rightarrow ZZ^* \rightarrow 4\ell$ new measurement $139\ \text{fb}^{-1}$







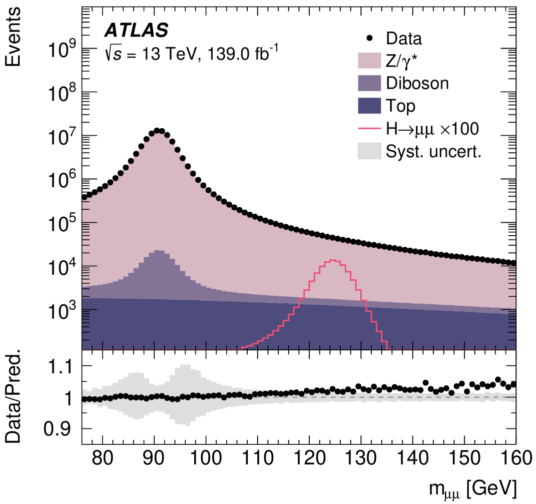
- Combined profile likelihood fit of $m_{4\ell}$ and D_{NN}
- $m_H = 124.99 \pm 0.18\ (stat.) \pm 0.04\ (syst.)\ GeV$
  - 0.15% accuracy!

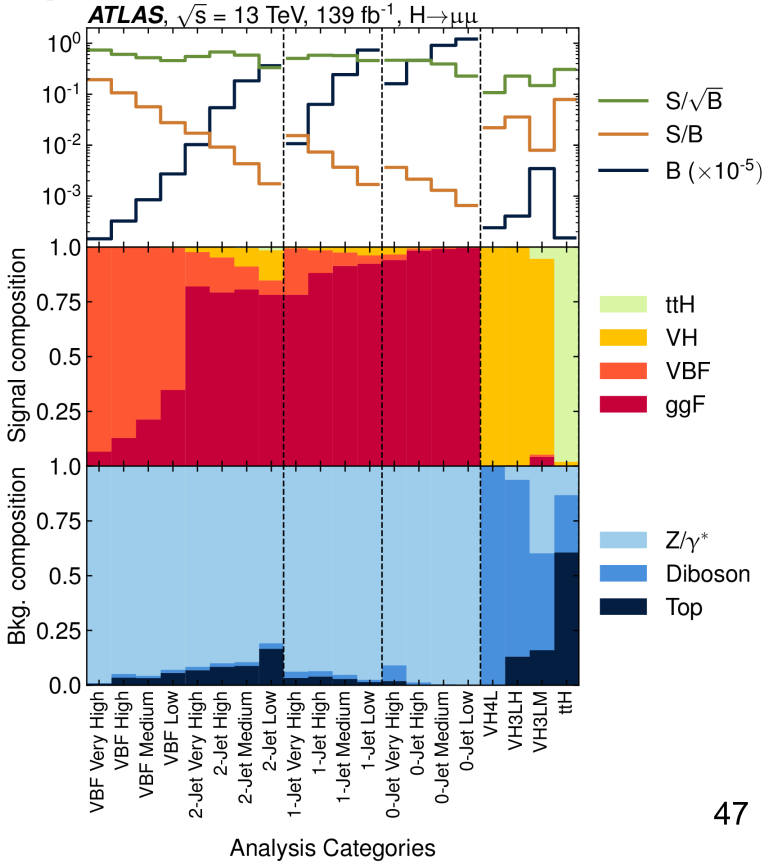
Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	±28
Electron energy scale	±19
Signal-process theory	±14

Phys. Lett. B 812 (2021) 135980

Second generation: $H \rightarrow \mu^+\mu^-$

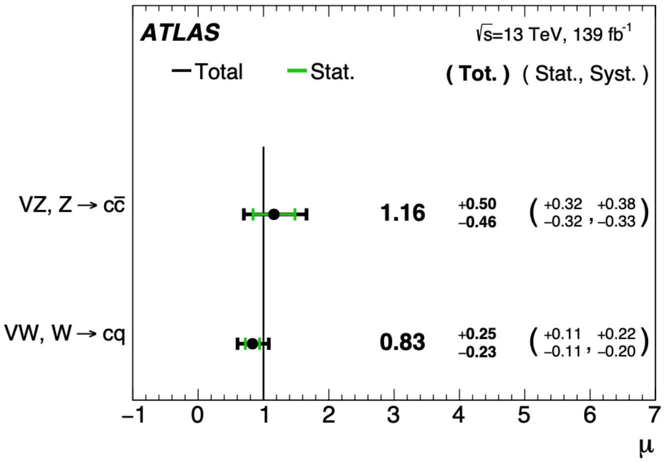
- Very small BR and large backgrounds
- Dedicated BDTs trained for different production modes (20 categories)
  - Using muon and jet kinematics

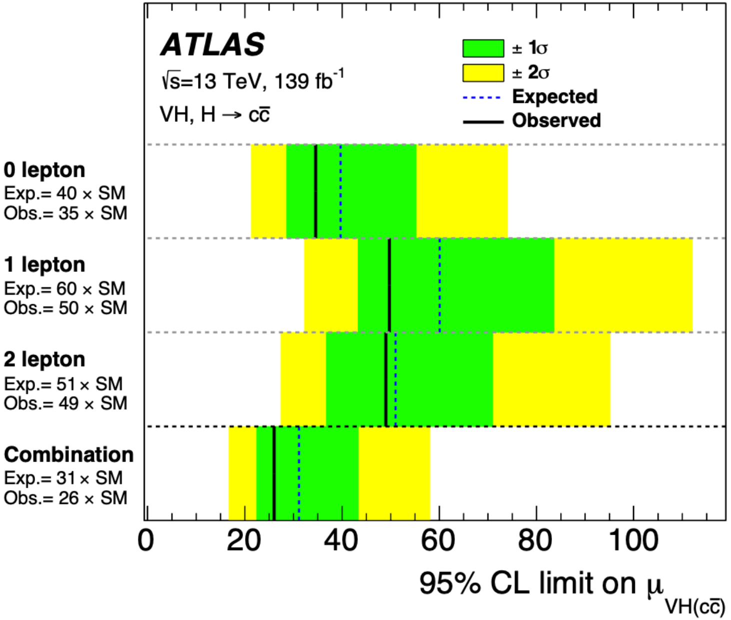




Second generation: $H \to c\bar{c}$

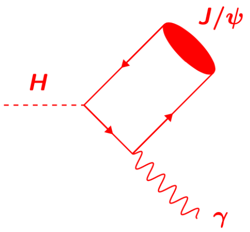
- Observed (expected) 95% CL limit: $26\ (31^{+12}_{-8})$
- $VW(cq)$ observed (expected) significance 3.8 (4.6)σ
- $VZ(c\bar{c})$ observed (expected) significance 2.6 (2.2)σ

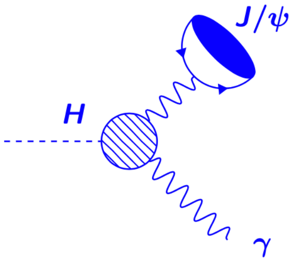




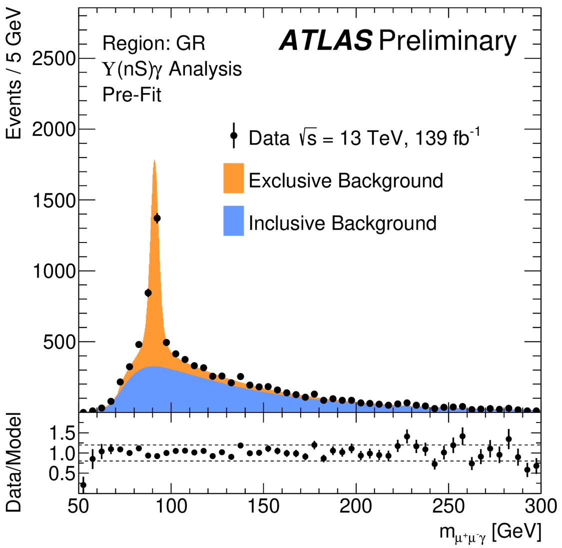
arXiv:2208.03122

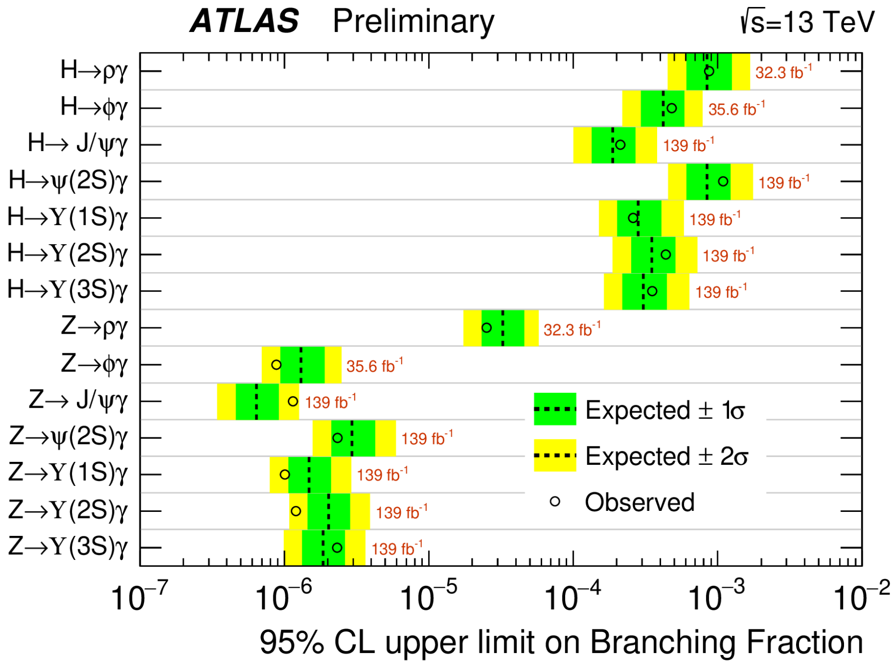
$Hc\bar{c}$ and $Hb\bar{b}$ vertices





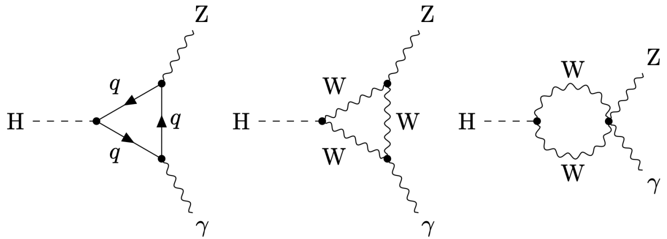
- Rare decays sensitive to Hcc or Hbb vertex
  - Direct and indirect contributions
- Could be enhanced due to BSM physics
- No signal observed → imposed limits on BR





Phys. Lett. B 809 (2020) 135754

$H \to Z\gamma$



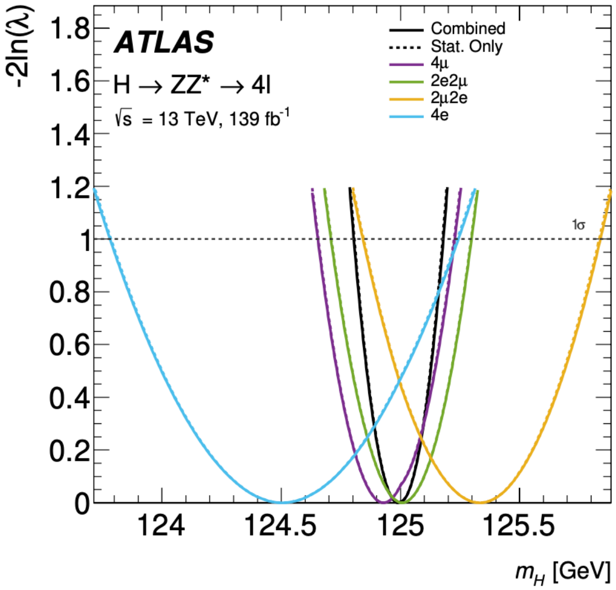
- Ratio $BR(H \to Z\gamma)/BR(H \to \gamma\gamma) = 0.69 \pm 0.04$ sensitive to new physics (composite Higgs, SUSY, ...)
- Improved lepton/photon identification
- Constrained kinematic fit $Z \to \ell\ell$ improves invariant mass resolution by 10-14%
- 6 exclusive events categories depending on lepton flavour and event kinematics
  - BDT to separate VBF events
- Combined fit for all event categories to $m_{Z\gamma}$

Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_T	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High p_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

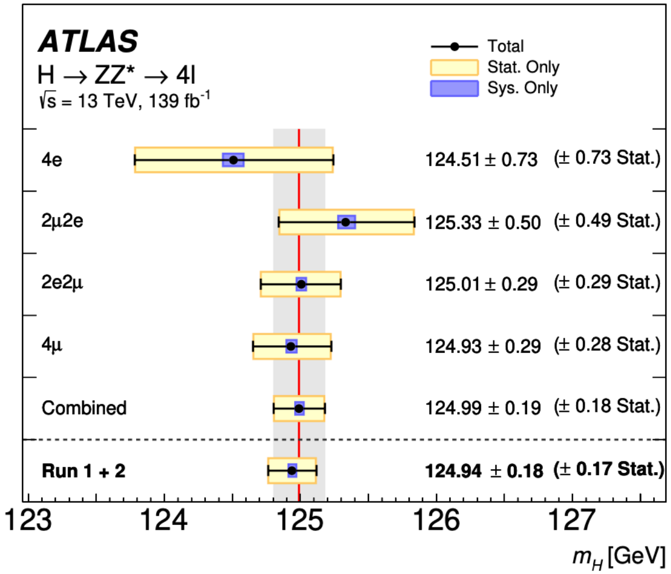
$$\mu = 2.0 \pm 0.9\ (stat.)^{+0.4}_{-0.3}\ (syst.) = 2.0^{+1.0}_{-0.9}$$

Obs (expect) significance: 2.2σ (1.2σ)

$H \to ZZ^* \to 4\ell$ new measurement $139\ \mathrm{fb}^{-1}$



(a)



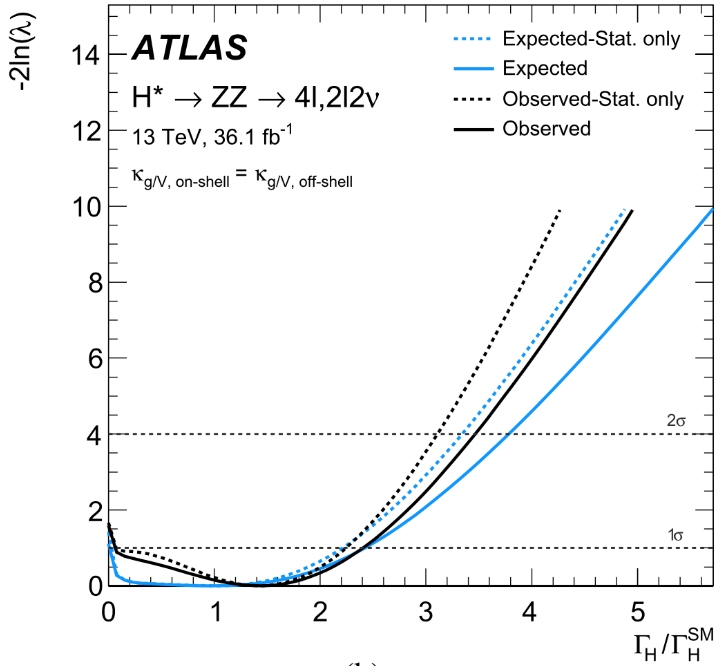
(b)

Higgs width

- On-shell and off-shell signal strength

$$\mu_{\text{off-shell}} = \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell,SM}}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{Z,\text{off-shell}}$$

$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell,SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$



(b)

- Includes $H \to 4\ell$ and $H \to 2\ell 2\nu$
- 95% CL observed (expected) upper limit: $\mu_{off-shell} < 3.8\ (3.4)$
- 95% CL observed (expected) upper limit: $\Gamma_H < 14.4\ (15.2)\ \text{MeV}$

$H \to Z\gamma$

Sources	$H \to Z\gamma$
Luminosity [%]	
Luminosity	1.7
Signal efficiency [%]	
Modelling of pile-up interactions	0.0–0.2
Photon identification efficiency	0.8–1.8
Photon isolation efficiency	0.7–1.9
Electron identification efficiency	0.0–2.3
Electron isolation efficiency	0.0–0.1
Electron reconstruction efficiency	0.0–0.5
Electron trigger efficiency	0.0–0.1
Muon selection efficiency	0.0–0.6
Muon trigger efficiency	0.0–1.6
Jet energy scale	0.0–3.5
Jet resolution	0.0–15
Jet pile-up	0.0–7.5
Jet flavor	0.0–11
Signal modelling on σ_{CB} [%]	
Electron and photon energy resolution	0.5–3.4
Muon – Inner detector resolution	0.0–1.2
Muon – Muon spectrometer resolution	0.0–3.4
Signal modelling on μ_{CB} [%]	
Electron and photon energy scale	0.09–0.15
Muon momentum scale	0.0–0.03
Higgs boson mass measurement	0.19
Background modelling [number of spurious signal events]	
Spurious signal	1.5–39

Sources	
Total cross-section and efficiency [%]	
ggF Underlying event	1.3
perturbative order	4.7–9.6
PDF and α_s	1.8–2.8
$B(H \to Z\gamma)$	5.7
Total (total cross-section and efficiency)	7.5–11
Category acceptance [%]	
ggF Underlying event	0.1–11
ggF H p_T perturbative order	0.3–0.4
ggF in VBF-enriched category	37
ggF in high relative p_T category	21
ggF in other categories	10–15
Other production modes	1.0–15
PDF and α_s	0.4–3.5
Total (category acceptance)	11–37

Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
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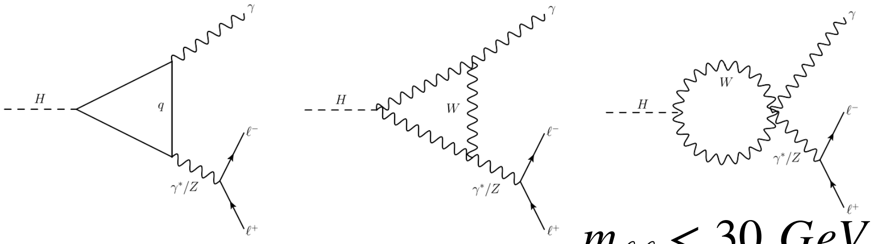
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

$$\mu = 2.0 \pm 0.9\ (stat.)^{+0.4}_{-0.3}\ (syst.) = 2.0^{+1.0}_{-0.9}$$

Obs (expect) significance: 2.2σ (1.2σ)

Phys. Lett. B 819 (2021) 136412

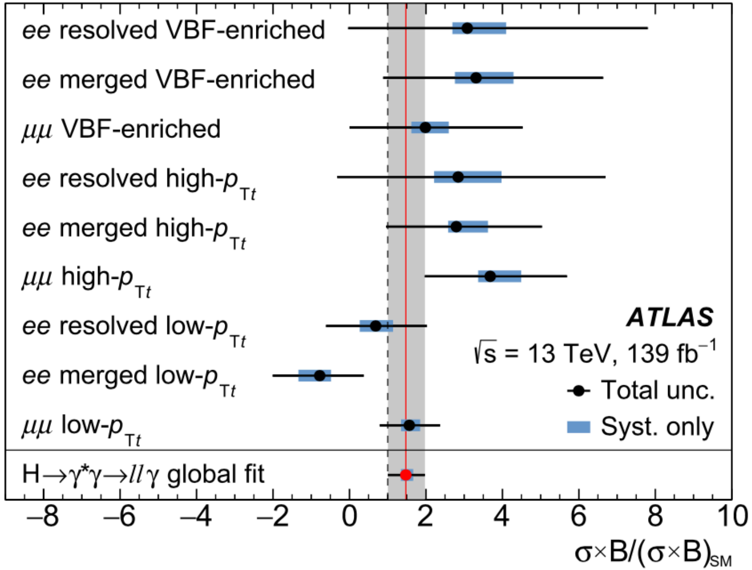
$H \to \gamma^*\gamma \to \ell\ell\gamma$

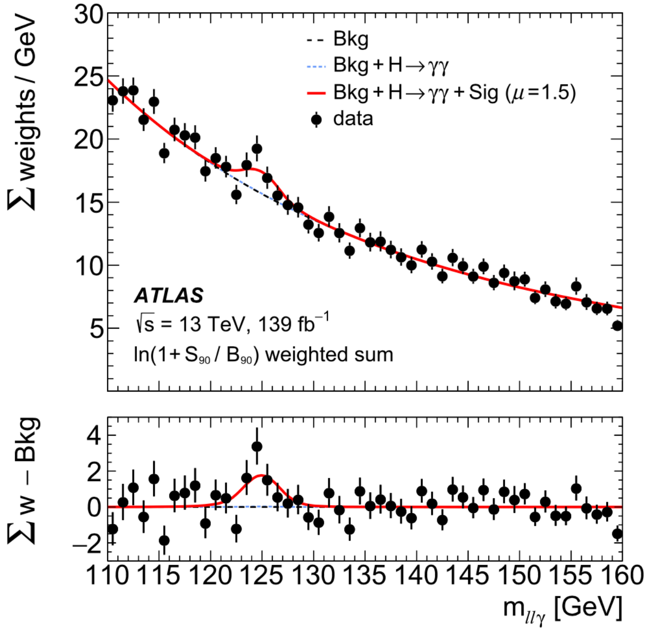


$m_{\ell\ell} < 30\ GeV$

- Sensitive to CP violation in the Higgs sector
- Dedicated trigger and reconstruction techniques for low p_T lepton pairs
- 9 event categories with different S/B

Obs(exp): 3.2σ (2.1σ)

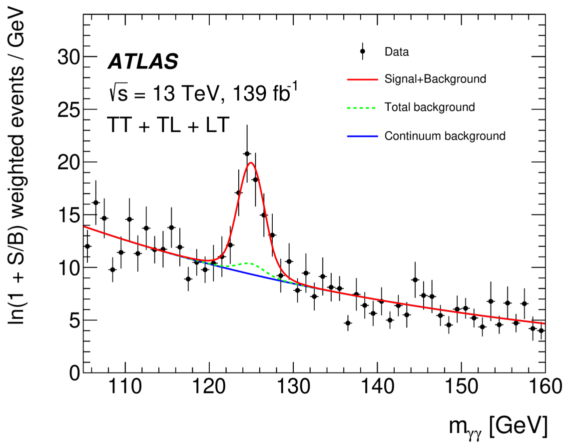




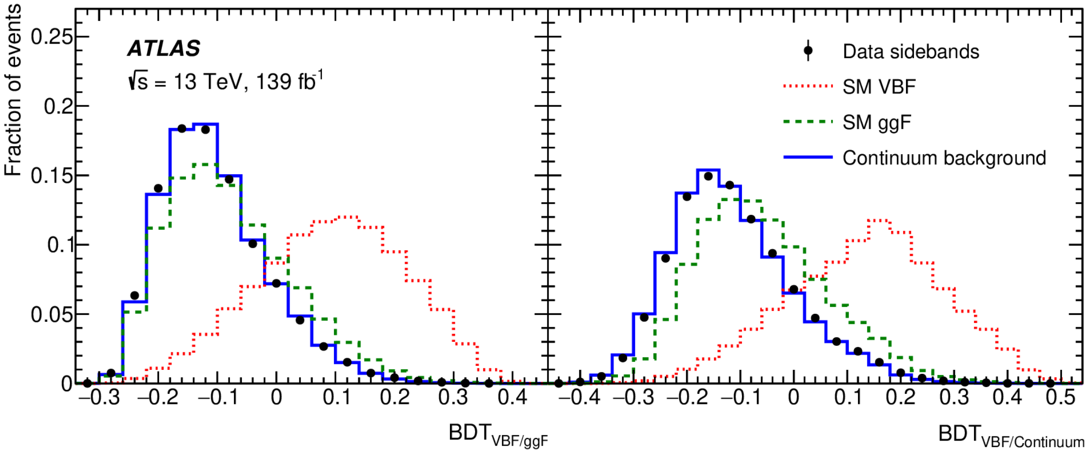
arXiv:2208.02338

Vector Boson Fusion $H \rightarrow \gamma\gamma$

- High statistics sample
- Using optimal observable (OO)
  - Calculated with the Higgs boson & VBF jets 4-momenta
  - Symmetric distribution if CP conserved
  - Simultaneous fit of $m_{\gamma\gamma}$ in bins of OO



- Interpretation in HIGZ /Warsaw basis
- Two BDTs used to separate gluon-gluon fusion Higgs production and continuous $\gamma\gamma$ production
  - Improve the results by a factor of 5

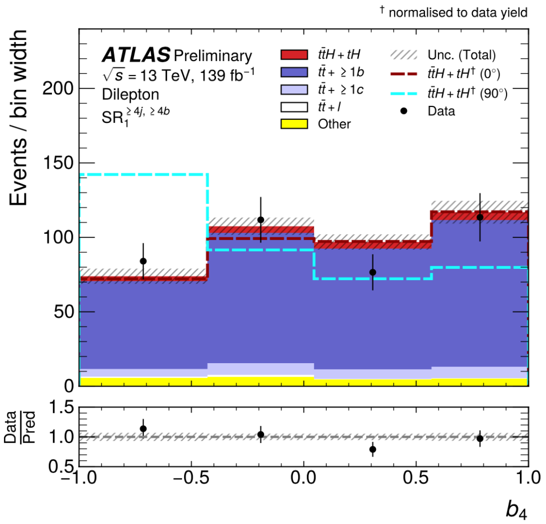


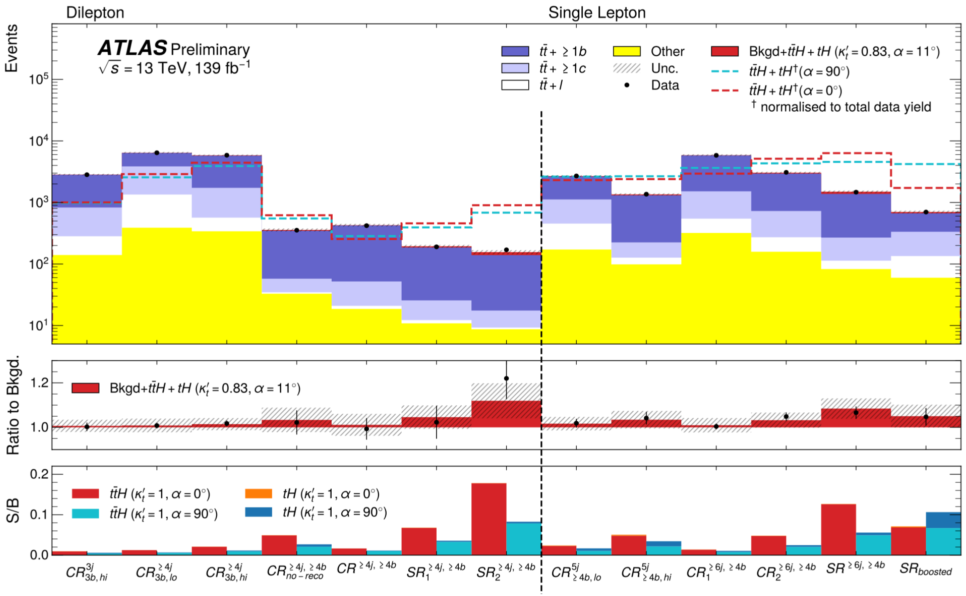
Spin/CP in associated $t\bar{t}H/tH$ production ($H \to b\bar{b}$)

- Signal regions defined based on jet multiplicity, b-tagging conditions, number of boosted top candidates
  - Reconstruction and background rejection BDTs trained per region
- CP observables

$$b_2 = \frac{(\vec{p}_1 \times \hat{n}) \cdot (\vec{p}_2 \times \hat{n})}{|\vec{p}_1||\vec{p}_2|}$$

$$b_4 = \frac{p_1^z p_2^z}{|\vec{p}_1||\vec{p}_2|}$$

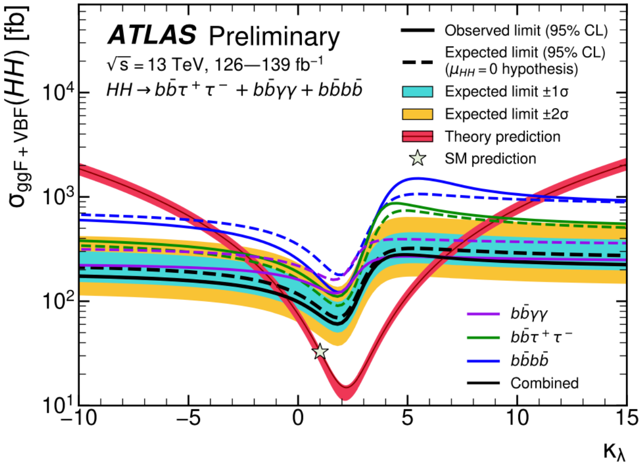


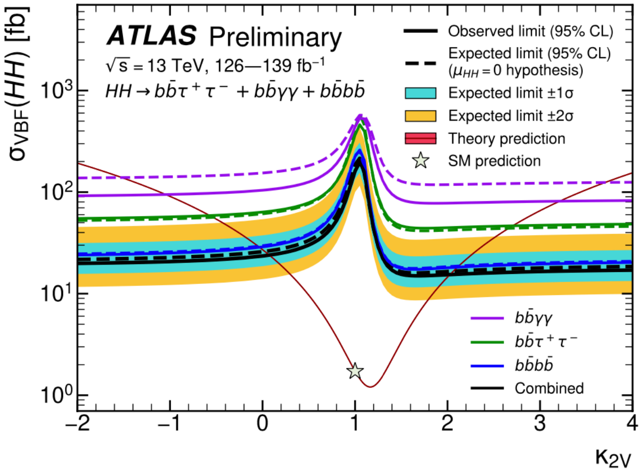


ATLAS double Higgs combination

- Using $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$

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





ATLAS HH+H combination

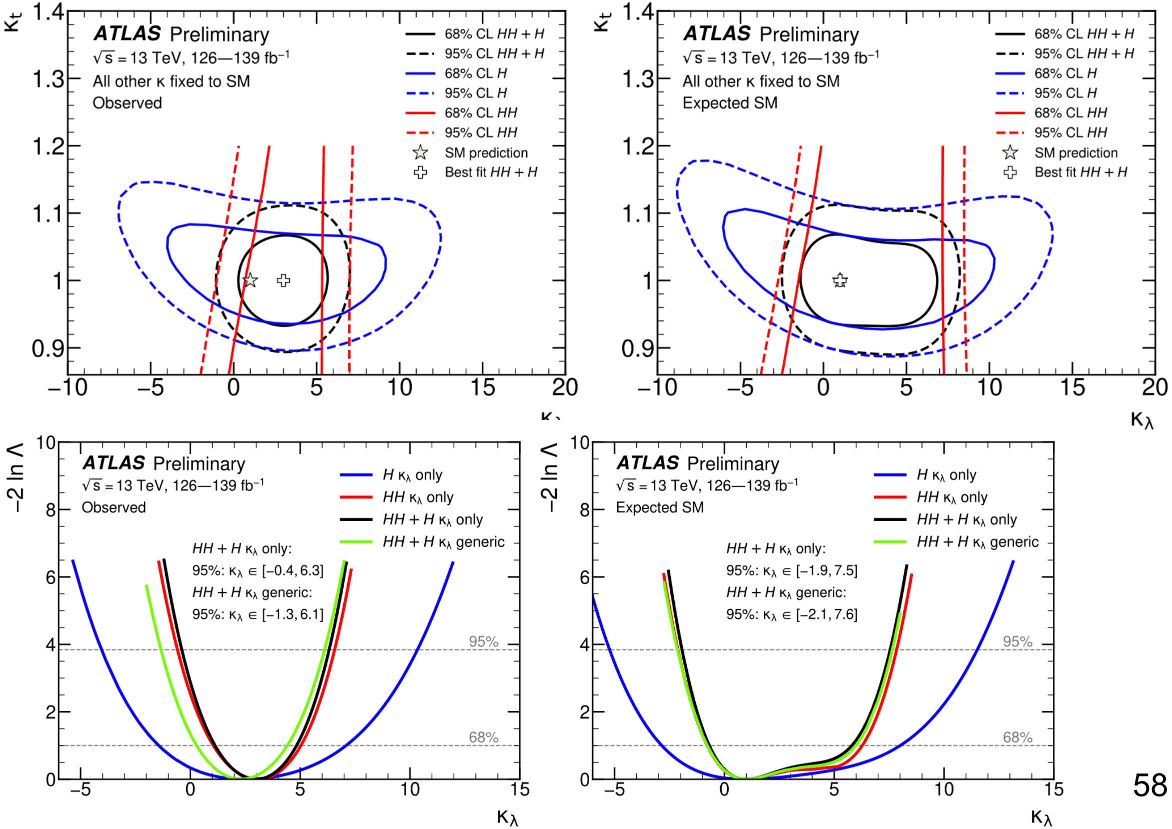
95% CL observed (expected) limits

- Assuming all other SM couplings:

$$-0.4 < \kappa_\lambda < 6.3$$
$$(-1.9 < \kappa_\lambda < 7.5)$$

- No assumptions in other couplings

$$-1.3 < \kappa_\lambda < 6.1$$
$$(-2.1 < \kappa_\lambda < 7.6)$$



ATLAS double Higgs combination

Table 2: Summary of κ_λ observed and expected constraints and corresponding observed best fit values with their uncertainties. In the first column, the coupling modifiers that are free floating in addition to κ_λ in the correspondent fit are reported.

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	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
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	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Phys. Rev. Lett. 125 (2020) 061802

Spin/CP in associated $t\bar{t}H/tH$ production ($H \to \gamma\gamma$)

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos(\alpha) + i \sin(\alpha)\gamma_5]\psi_t\} H$$

CP-even (SM) CP-odd

- Semileptonic and hadronic channels
- Event categories based on background rejection BDT and CP BDT trained to separate CP-even/CP-odd components
- Simultaneous fit to all event categories
- Measured ttH rate:

$$\mu = 1.43^{+0.33}_{-0.31}(stat.)^{+0.21}_{-0.15}(sys.)$$

- $|\alpha| < 43^{\circ}$ @95% CL
- $\alpha = 90^{\circ}$ excluded at 3.9σ (2.5σ) observed (expected)