[Higgs Physics Results from ATLAS]

P. Conde Muíño
on behalf of the ATLAS Collaboration

Probing the Higgs Boson at ATLAS

Became12 years old

The Higgs Boson

Couplings, mass, width, invisible decays, Higgs potential

EFT interpretation of Higgs measurements

Search for CP-Violating Higgs couplings

Lepton Flavour Violation

Searches for new Physics

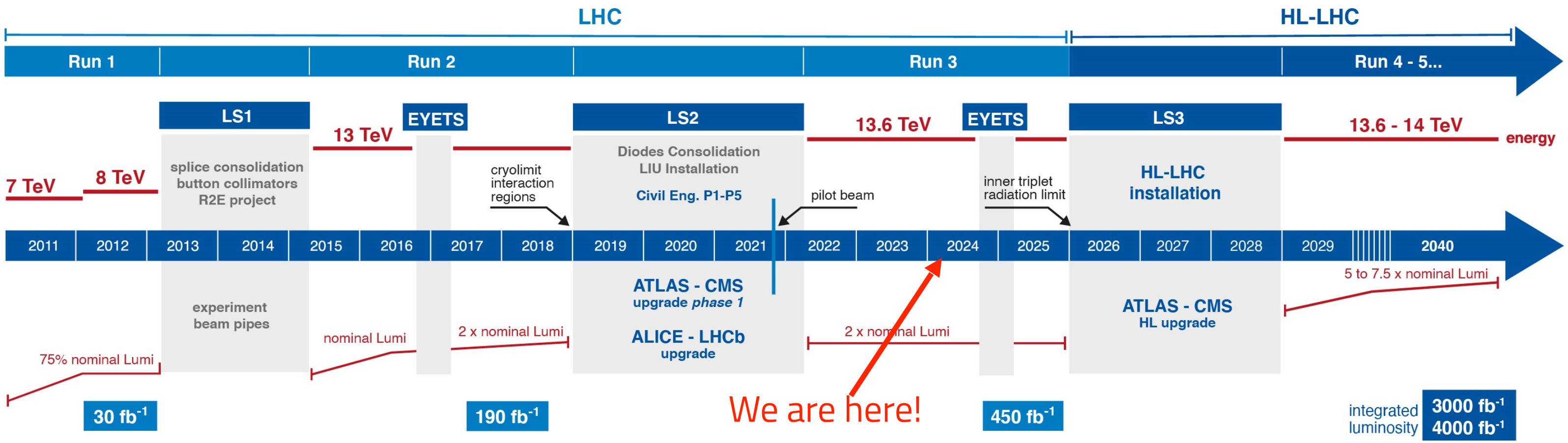
Charged Higgs searches

Di-Higgs resonances

Dark Matter

Low mass and high mass resonances

LHC schedule and ATLAS Data Taking statistics



	Center of mass energy	Period	<pp col/BX>	Accumulated luminosity
Run 1	7, 8 TeV	2010-2011	20	35 fb^{-1}
Run 2	13 TeV	2015-2018	34	147 fb^{-1}
Run 3	13.6 TeV	2022-2025	52/61	146 fb^{-1}
HL-LHC (Run 4 and beyond)	13.6-14 TeV	2029-2040	200	3000 fb^{-1}

ATLAS pp Run-3: 2023

Trigger	Inner Tracker			Calorimeters		Muon Spectrometer			Magnets	
L1+HLT	Pixel	SCT	TRT	LAr	Tile	MDT	RPC	TGC	Solenoid	Toroid
97.5-99.6	99.8	99.7	100	99.5	99.6	99.7	99.9	99.8	100	100
Good for physics: 94.6%-96.5% (27.2-27.8 fb^{-1})										

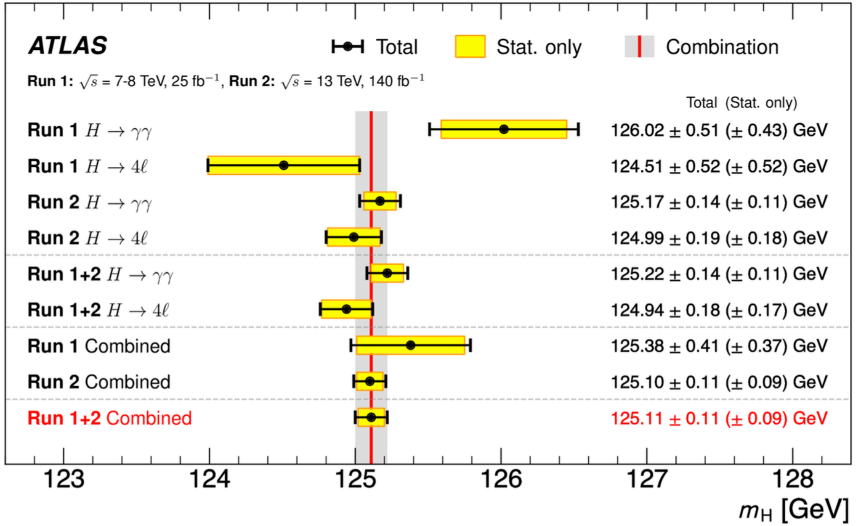
Phys. Rev. Lett. 131 (2023) 251802

Higgs Boson Mass

Fundamental parameter in the theory

Measured in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels

- Considerable effort to improve the $e/\gamma/\mu$ calibrations in Run 2
- e/γ calibration uncertainty reduced by a factor of 2-4
- μ momentum (resolution) precision down to 0.05% (0.1%)



Currently, most precise measurement:

$$m_H = 125.11 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.}) = 125.11 \pm 0.11\ \text{GeV}$$

Uncertainty < per-mill level (0.09%)

Phys. Lett. B 846 (2023) 138223

Higgs Boson Width

SM prediction: $\Gamma_H = 4.1\ \text{MeV}$

Indirect measurement through the on-shell and off-shell

$H \to ZZ^* \to 4\ell$ and $H \to ZZ^* \to 2\ell 2\nu$ production cross-section

$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

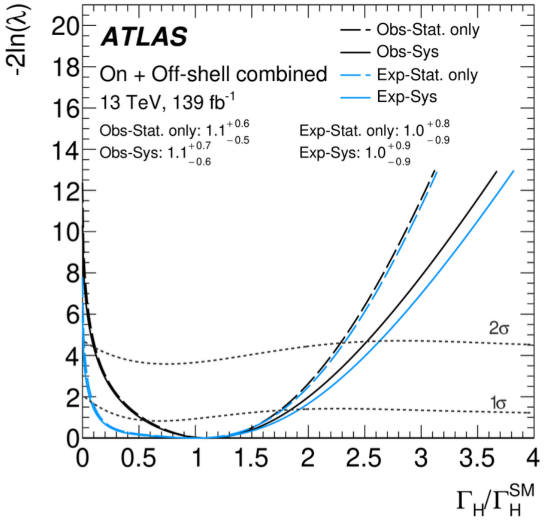
$\frac{g_{Hgg}^2 g_{HZZ}^2}{m_H\Gamma_H}$ On-shell

$\frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2)^2}$ Off-shell

- Assumes that Higgs production follows SM prediction

New off-shell Higgs production cross-section measurement

- Signal/background interference requires very good MC modelling
- Observed (expected) significance: $3.3\sigma\ (2.2\sigma)$

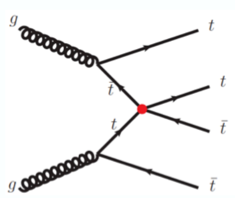


$$\Gamma_H = 4.5^{+3.3}_{-2.5}\ \text{MeV}$$

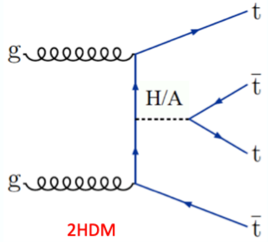
Observed (expected) 95% CL limits:

$$0.5(0.1) < \Gamma_H < 10.5(10.9)\ MeV$$

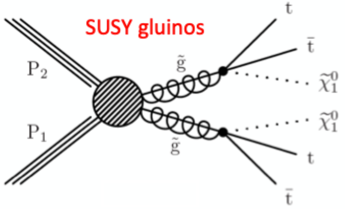
Observation $t\bar{t}t\bar{t}$ production and Higgs boson width



Four-fermion contact interaction



2HDM scalar/pseudoscalar



Very complicated process

- But sensitive to new physics
- Complicated final state with many jets

Observed (expected) significance $6.1\sigma(4.3\sigma)$

- Signal strength: $\mu = 1.9 \pm 0.4(\text{stat})^{+0.7}_{-0.4}(\text{sys})$
- Cross section: $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{4.3}(\text{stat})^{+4.6}_{-3.4}\text{sys fb}$

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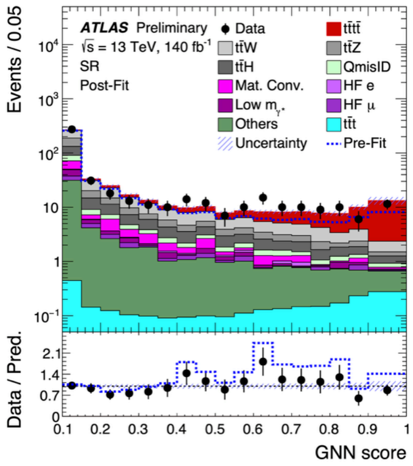
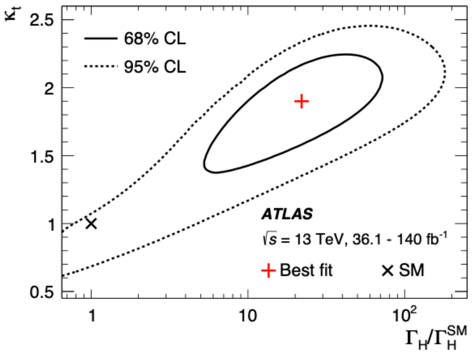


Determination of the Higgs width:

- Off-shell $t\bar{t}t\bar{t}$ production $\propto k_t$
- On-shell $t\bar{t}H$ production $\propto k_t/\Gamma_H$

ArXiv:2407.10631v1



- $\Gamma_H = 86^{+110}_{-46}$ MeV

2σ deviation from SM expectation

Top-quark, W and Higgs mass measurements

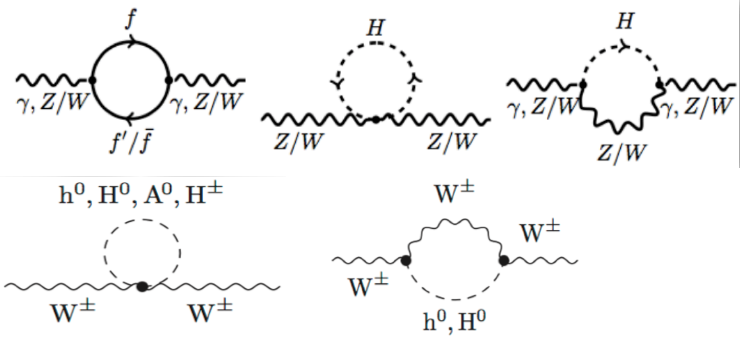
W-boson, top-quark and Higgs Boson mass interrelated in the SM

Tree level   Loop corrections

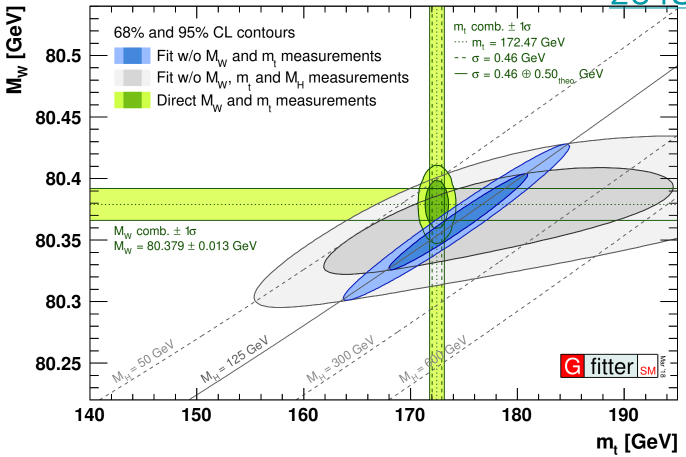
$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

Probe the coherence of the SM results

- Precise measurements needed



2018, Gfitter



Top-quark mass measurement

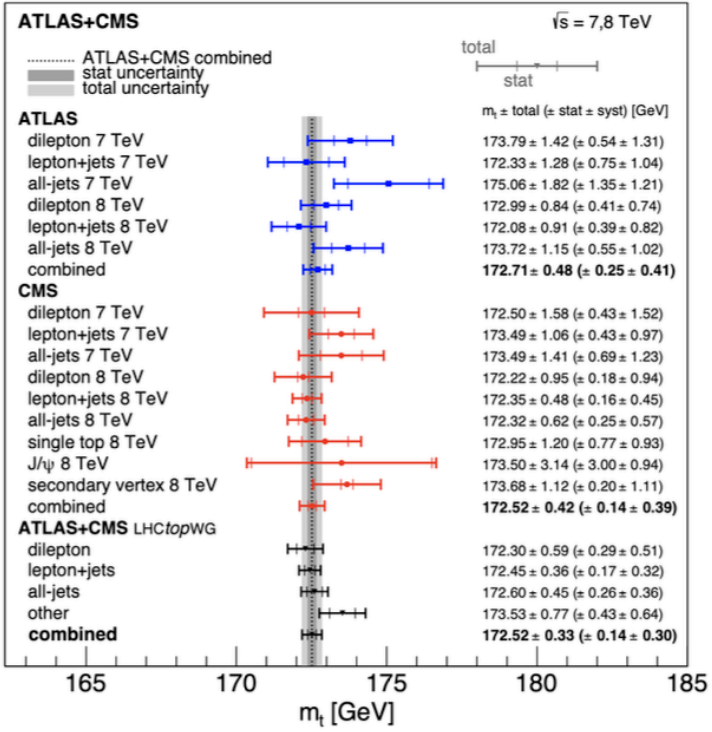
ATLAS and CMS mass combination using 7, 8 TeV analyses in different final states

- Using Best Linear Unbiased Estimator method (BLUE)

$$m_t = 172.52 \pm 0.14(\text{stat}) \pm 0.30(\text{syst}) = 172.52 \pm 0.33\ \text{GeV}$$

Best top quark mass measurement up-to-date

- Precision < 0.2%
- improvement of 31% in the total uncertainty relative to the most precise input measurement



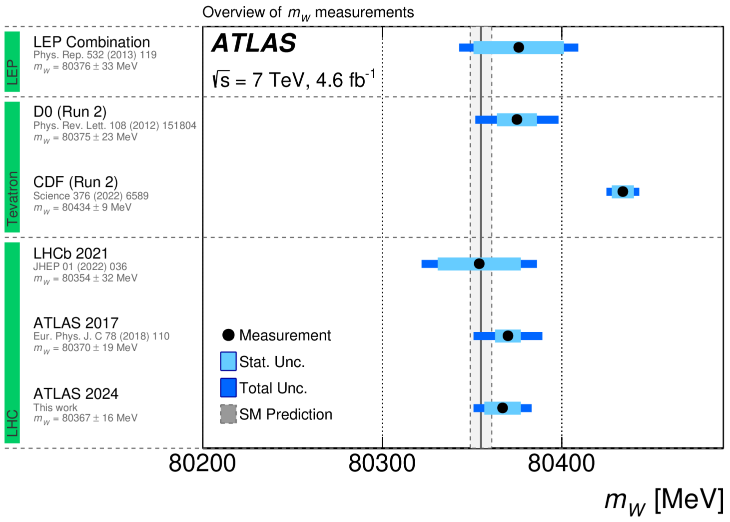
arXiv:2403.15085

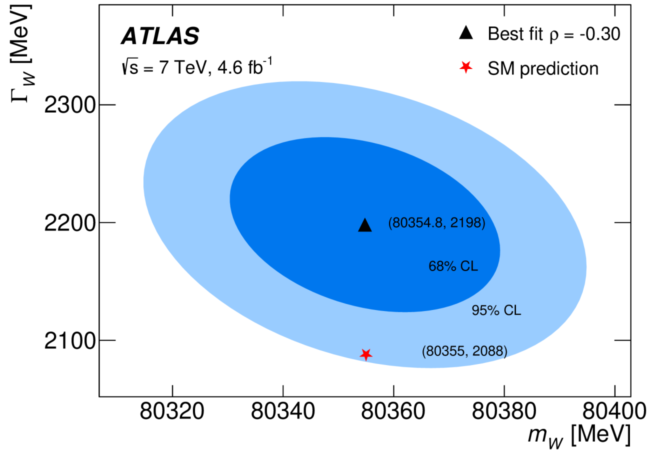
W-boson mass and Width

Combined measurement of the W boson mass and width

Using Run 1, 7 TeV data

- re-analysis with an extensive list of updates to reduce the uncertainties
  - Including PDF updates, improved p_T^W modelling and improved fit
- $m_W = 80360 \pm 5(\text{stat}) \pm 15(\text{syst}) = 80360 \pm 16\ \text{MeV}$
  - Even closer to Standard Model expectations
- $\Gamma_W = 2195.8 \pm 32.2(\text{stat.}) \pm 34.1(\text{syst.}) = 2195.8 \pm 46.8\ \text{MeV}$
  - Most precise Γ_W measurement

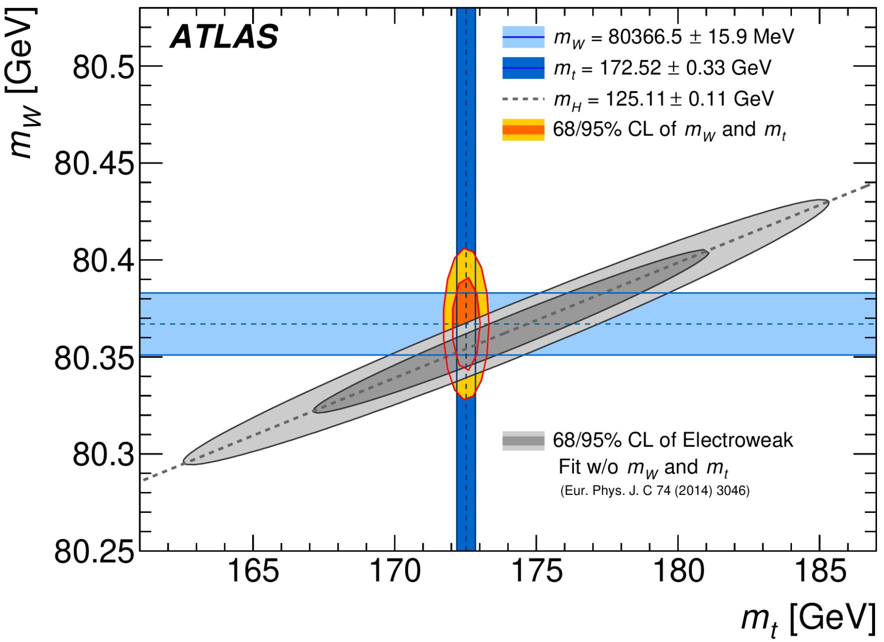




arXiv:2403.15085

ATLAS Top-quark, W and Higgs Bosons mass compatibility

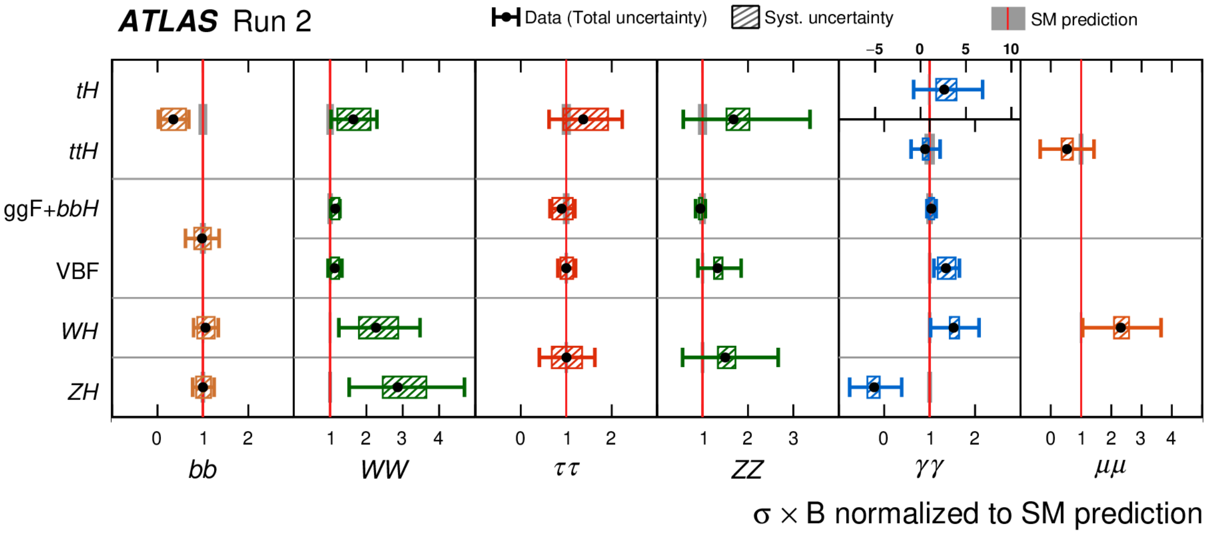
Electroweak fit without m_W and m_t masses (grey) compared to the ATLAS measurements of m_W, m_t and m_H



Higgs boson couplings combination

Direct measurement of $\sigma \times BR$

[Nature 607 (2022) 52-59]



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

Improved precision:

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

arXiv:2407.10904

ATLAS Run 2 Legacy ttH measurement

Measurement of ttH production with $H \rightarrow b\bar{b}$

Sensitivity improved by a factor of 2

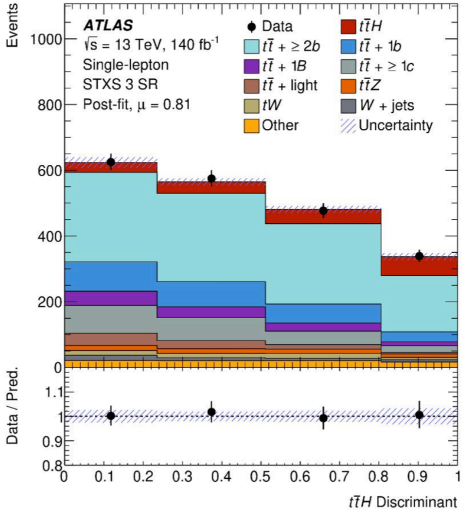
- Improved particle reconstruction & identification
- State-of-the-art Machine Learning: improved selection and Higgs boson reconstrution
- Improved $t\bar{t}bb$ background modelling (ATL-PHYS-PUB-2022-006)

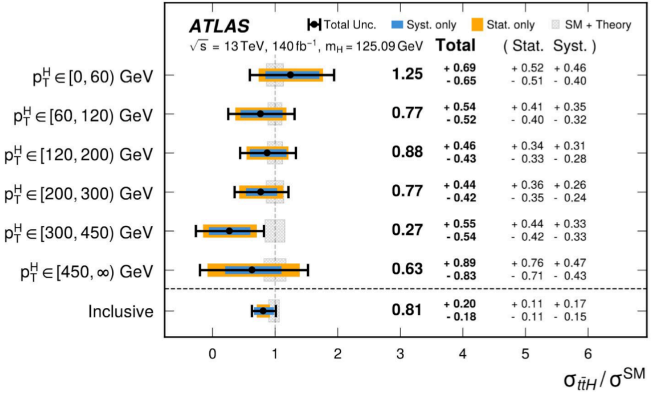
Profile likelihood fit

- Expected/observed significance: $5.4\sigma/4.6\sigma$
- Dominant uncertainties: $t\bar{t}H$ and $t\bar{t}bb$ modelling

Measurement of the p_T^H distribution (STXS)

- Only analysis probing the region $p_T^H > 450$ GeV in ttH production

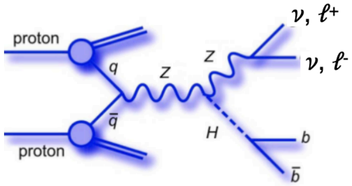


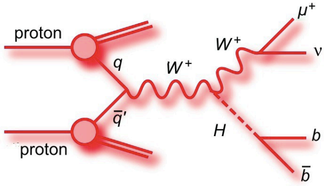


$p_T(H)$ measurement limited statistically

ATLAS-CONF-2024-010

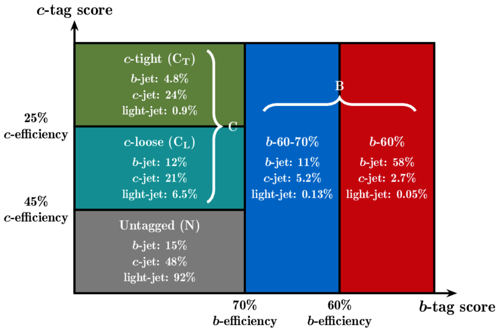
ATLAS Run 2 Legacy VH(bb) and VH(cc) analysis





Associated production of the Higgs with vector bosons

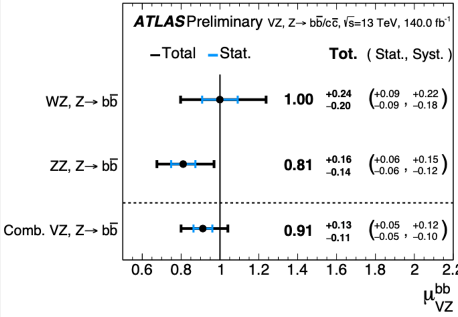
- Higgs decays to $b\bar{b}$ or $c\bar{c}$ pairs
  - Simultaneous extraction of both signals
  - Definition of orthogonal signal and control regions



Analysis strategy validated searching for diboson WZ and ZZ signal

(with $Z \rightarrow b\bar{b}$ or $Z \rightarrow c\bar{c}$)

$Z \rightarrow b\bar{b}$

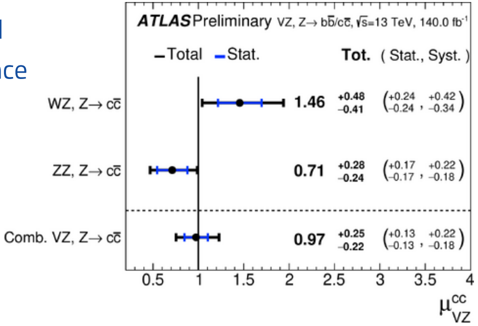


Observed significance

6.4σ

$> 10\sigma$

$Z \rightarrow c\bar{c}$



Observed significance

3.9σ

3.1σ

$> 5\sigma$

First ATLAS observation of VZ(cc) signal!

ATLAS-CONF-2024-010

ATLAS Run 2 Legacy VH(bb) and VH(cc) analysis

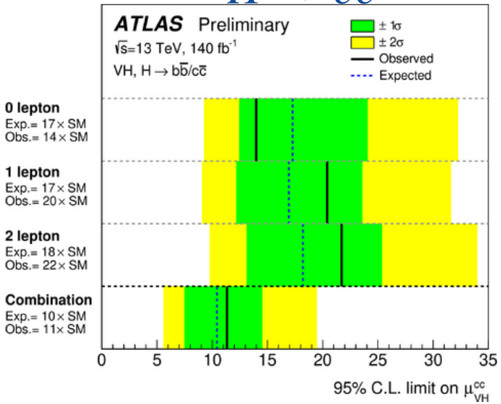
Sensitivity to $H \to c\bar{c}$ improved by a factor of 3

- 95% CL upper limit in the c-quark Yukawa coupling modifier:

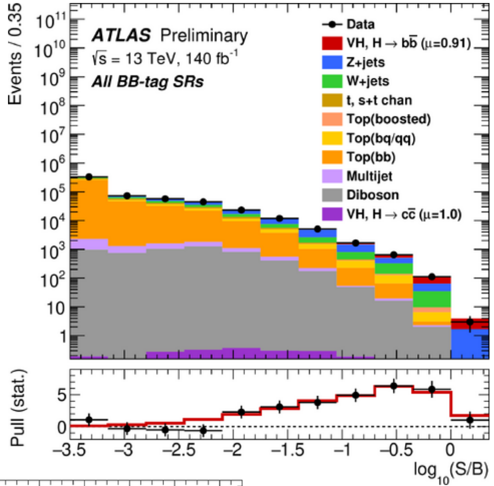
$$|k_c| < 4.2$$

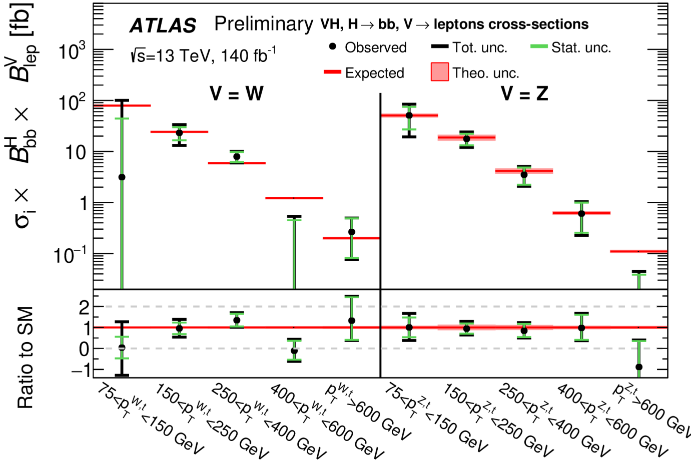
VH signal with $H \to b\bar{b}$ observed with 7.8σ (8.0σ) observed (expected) significance

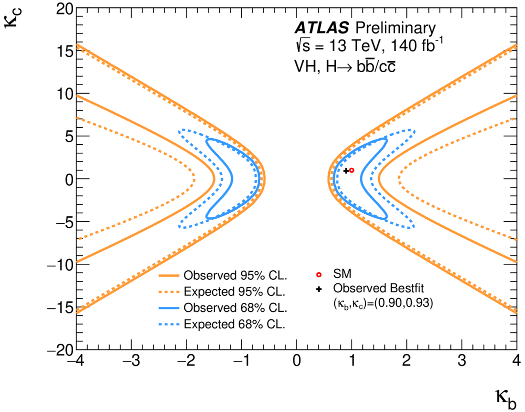
$H \to c\bar{c}$

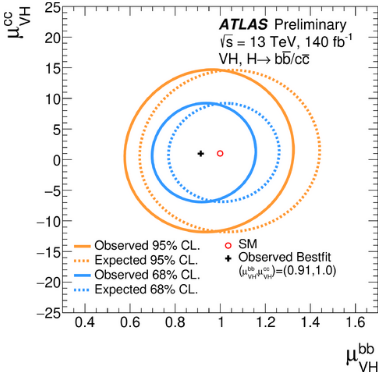


$H \to b\bar{b}$





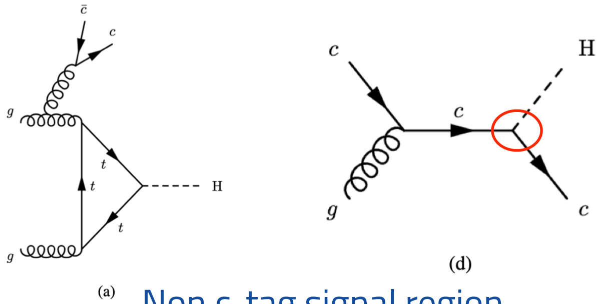




Search for Hc associated production, with $H \rightarrow \gamma\gamma$

Sensitive to the c-quark Higgs Yukawa coupling

Using a Gaussian process regression to extrapolate the background from the sidebands to the signal region

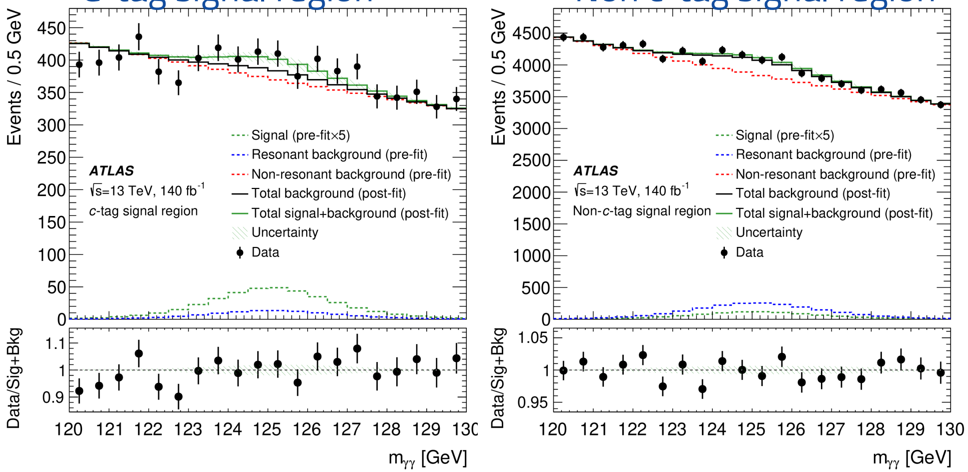


Best fit value:

- Observed: $\sigma(pp \rightarrow Hc) = 5.2 \pm 3.2$ pb
  - Significance: 1.7σ
- Expected: $\sigma(pp \rightarrow Hc) = 2.9 \pm 2.8$ pb
  - Significance: 1σ

C-tag signal region

Non c-tag signal region



Recent cross section measurements

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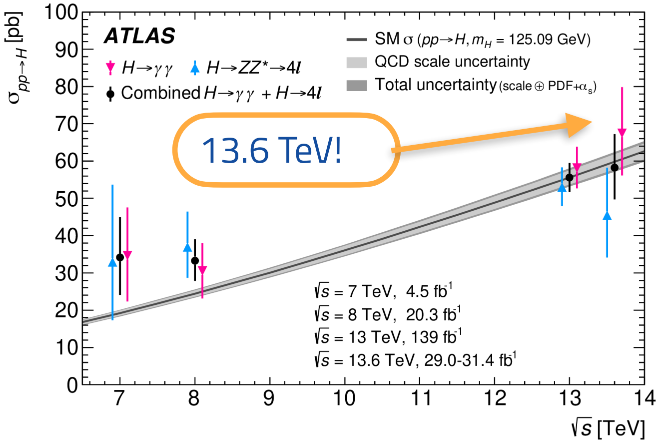

Total and differential cross-section measurements performed in different decay channels and for different variables

- Overall agreement with expectations within uncertainties

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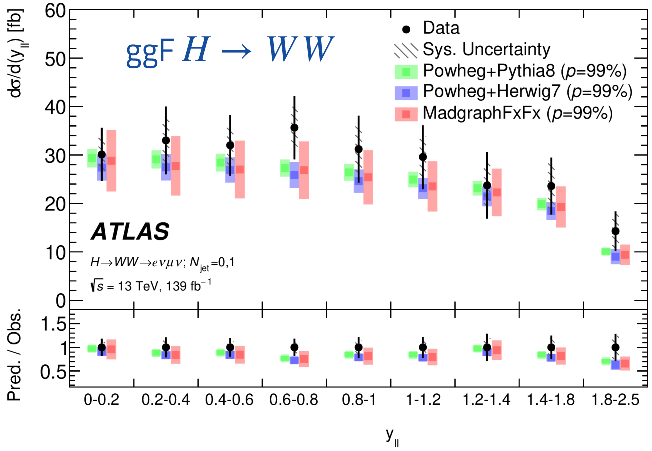
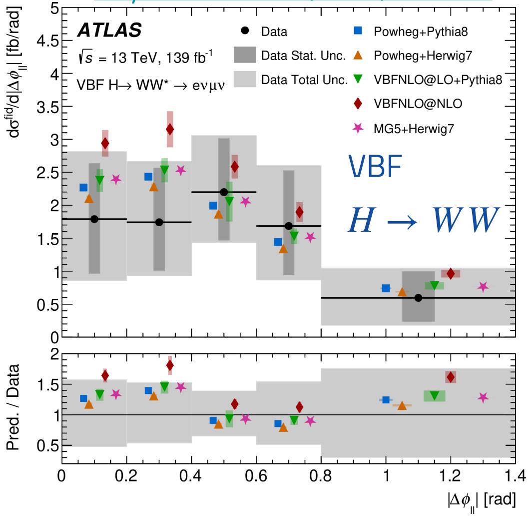
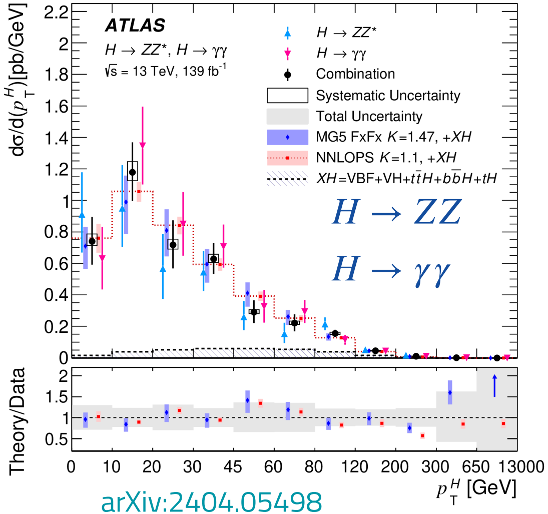


Phys. Rev. D 108 (2023) 072003





arXiv:2404.05498

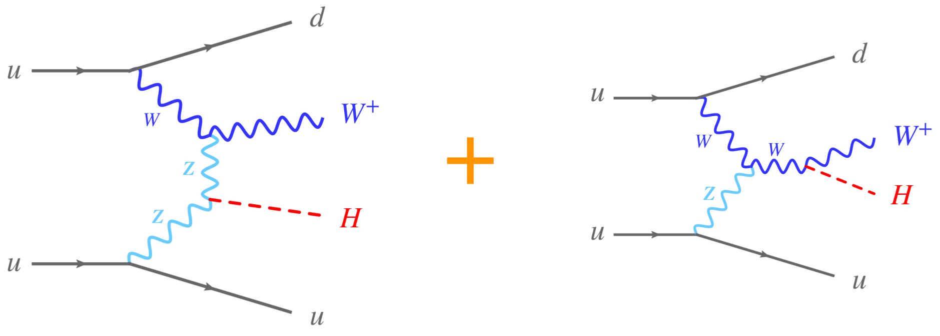
[arXiv:2402.00426](https://arxiv.org/abs/2402.00426)

Relative sign of the HWW and HZZ couplings

Vector boson fusion production of WH pairs disfavoured by the SM due to cancellation of two different contributions

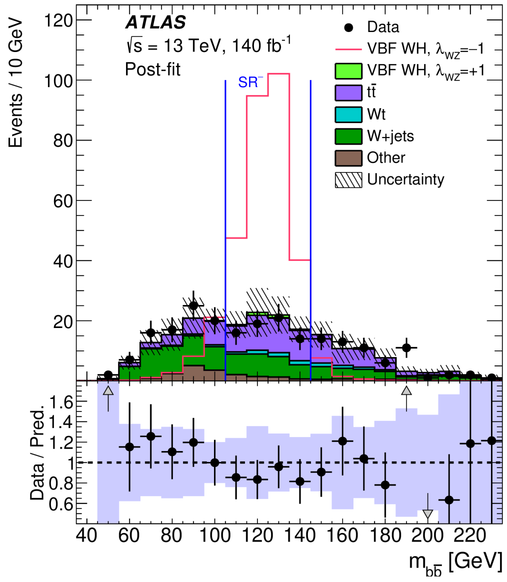
- Could be enhanced with opposite relative sign

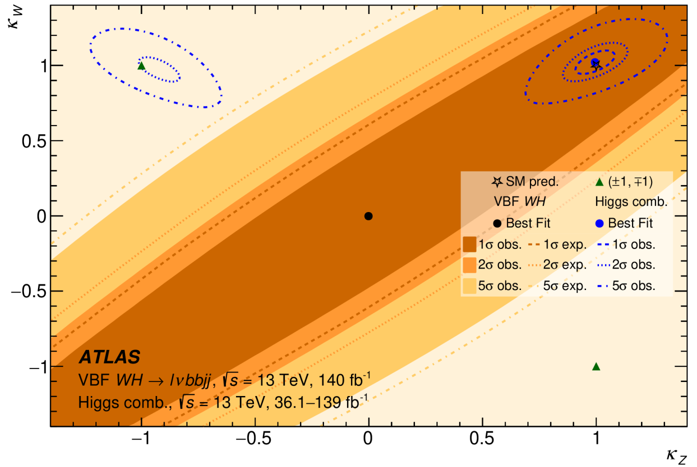
ATLAS Search for VBF WH production with $H \rightarrow bb$



$\sim \kappa_Z^2$ Interference $\sim \kappa_W \kappa_Z$ $\sim \kappa_W^2$

$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z\,\kappa_W\,\Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z^2\,\lambda_{WZ}\,\Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$





arXiv:2402.00426

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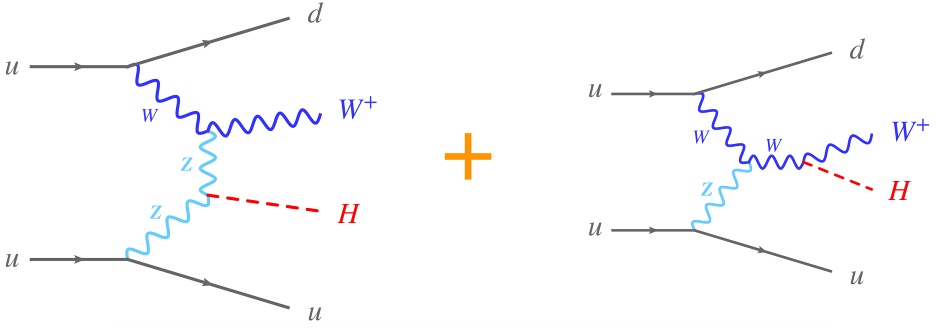
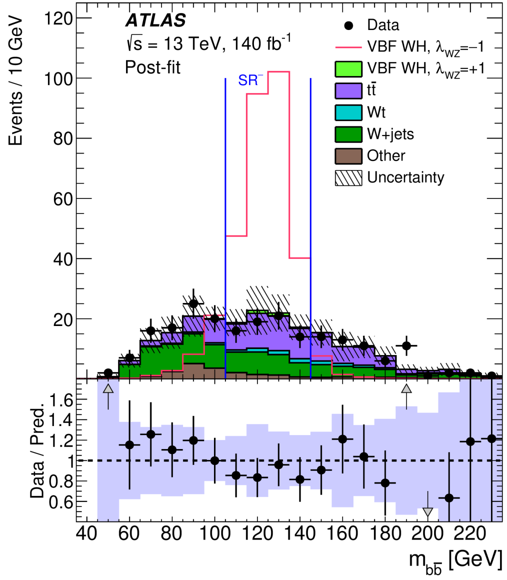
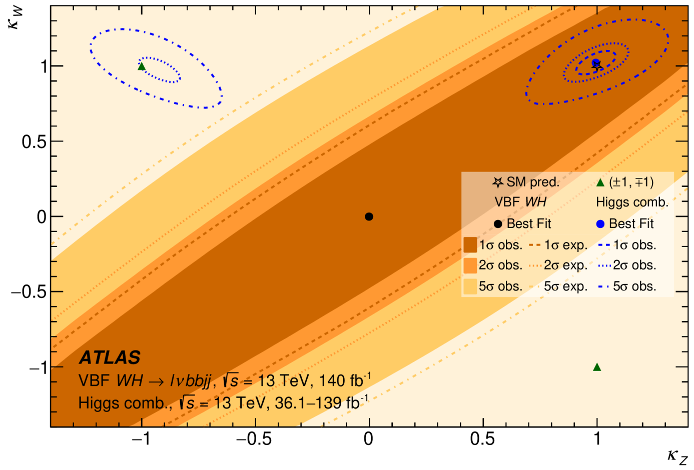




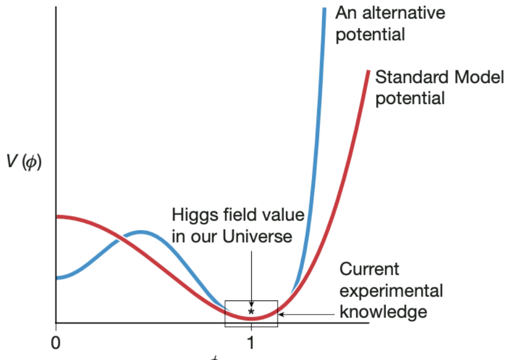


Opposite sign excluded with significance much better than 5σ

Higgs self coupling

- Determine the shape of the Higgs potential

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



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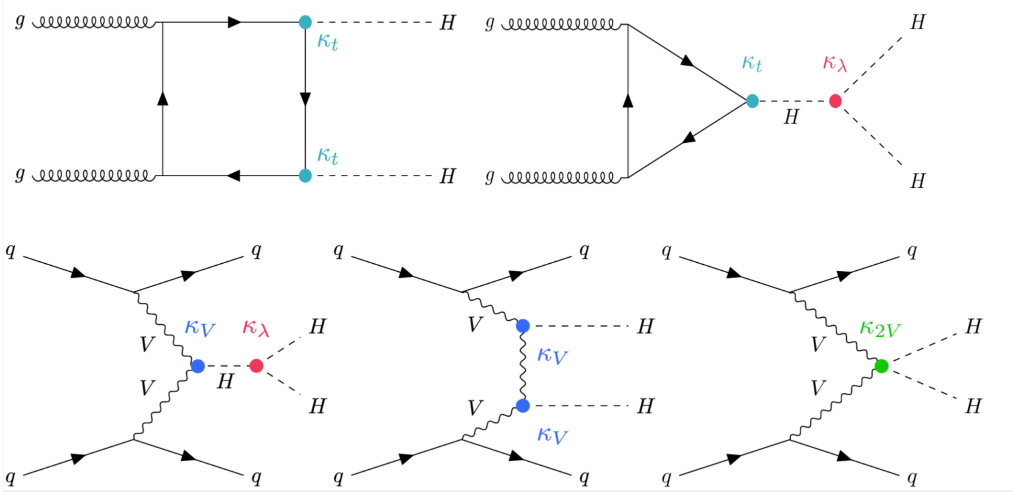
- Di-Higgs production



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

(Destructive interference in the SM)

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

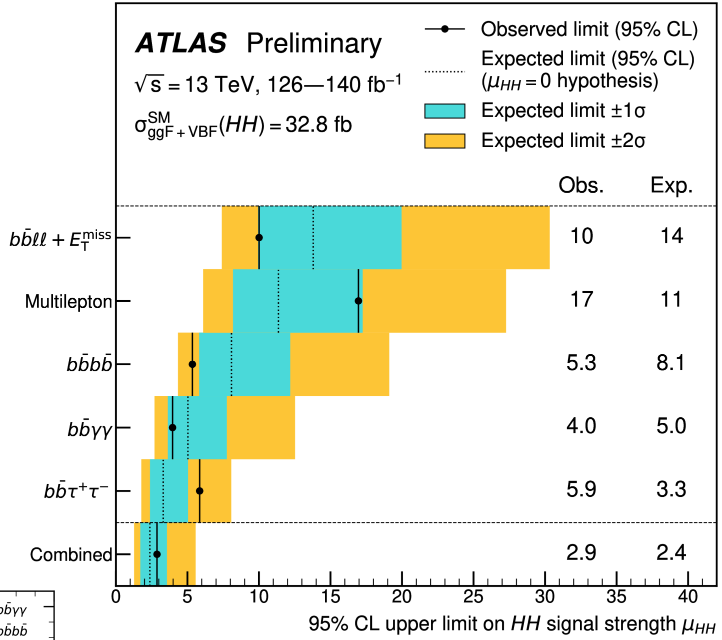
Di-Higgs production

Updated results in some channels:

- $b\bar{b}\gamma\gamma$: obs (exp) 95% CL limit on μ_{HH}: 4.0 (5.0)
- $b\bar{b}\tau^{+}\tau^{-}$: obs (exp) 95% CL limit on μ_{HH}: 5.9 (3.3)

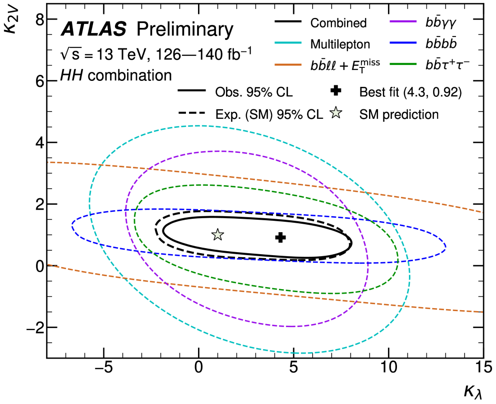
ATLAS di-Higgs search combination with Run 2 data:

- Using $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, multilepton and $b\bar{b}\ell\ell + E_T^{miss}$



Observed 95% CL constraints

$$-1.2 < \kappa_\lambda < 7.2$$
$$0.57 < k_{2V} < 1.48$$



$$\mu_{HH} = 0.5^{+0.9}_{-0.8}(\text{stat.})^{+0.7}_{-0.6}(\text{syst.})$$

Best expected sensitivity in κ_λ

Uncertainty on μ_{HH} ~1!

Probing the Higgs Boson at ATLAS

Searches for new Physics

Became12 years old

The Higgs Boson

Couplings, mass, width, invisible decays, Higgs potential

EFT interpretation of Higgs measurements

Search for CP-Violating Higgs couplings

Lepton Flavour Violation

arXiv:2402.05742

EFT interpretations of the Higgs measurements

Effective Field Theory interpretation

- Extend the SM Lagrangian with additional operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d=8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

c_i = Wilson coefficients

$\mathcal{O}^{(n)}$= operator of dimension n

Λ = new physics scale

- Calculate cross-sections: $$\sigma_{\mathrm{SMEFT}} = \sigma_{\mathrm{SM}} + \sigma_{\mathrm{int}} + \sigma_{\mathrm{BSM}},$$
- To reduce perturbative QCD uncertainties, use ratios:

$$\sigma^{i}_{\mathrm{SMEFT}} = \sigma^{i,\mathrm{((N)N)NLO}}_{\mathrm{SM}} \times \left(1 + \frac{\sigma^{i,\mathrm{(N)LO}}_{\mathrm{int}}}{\sigma^{i,\mathrm{(N)LO}}_{\mathrm{SM}}} + \frac{\sigma^{i,\mathrm{(N)LO}}_{\mathrm{BSM}}}{\sigma^{i,\mathrm{(N)LO}}_{\mathrm{SM}}}\right)$$

ATLAS EFT interpretation:

- Measurements from 17 different papers from all channels used in the combination
- Using ~50 dimension-6 CP-even dominant coefficients

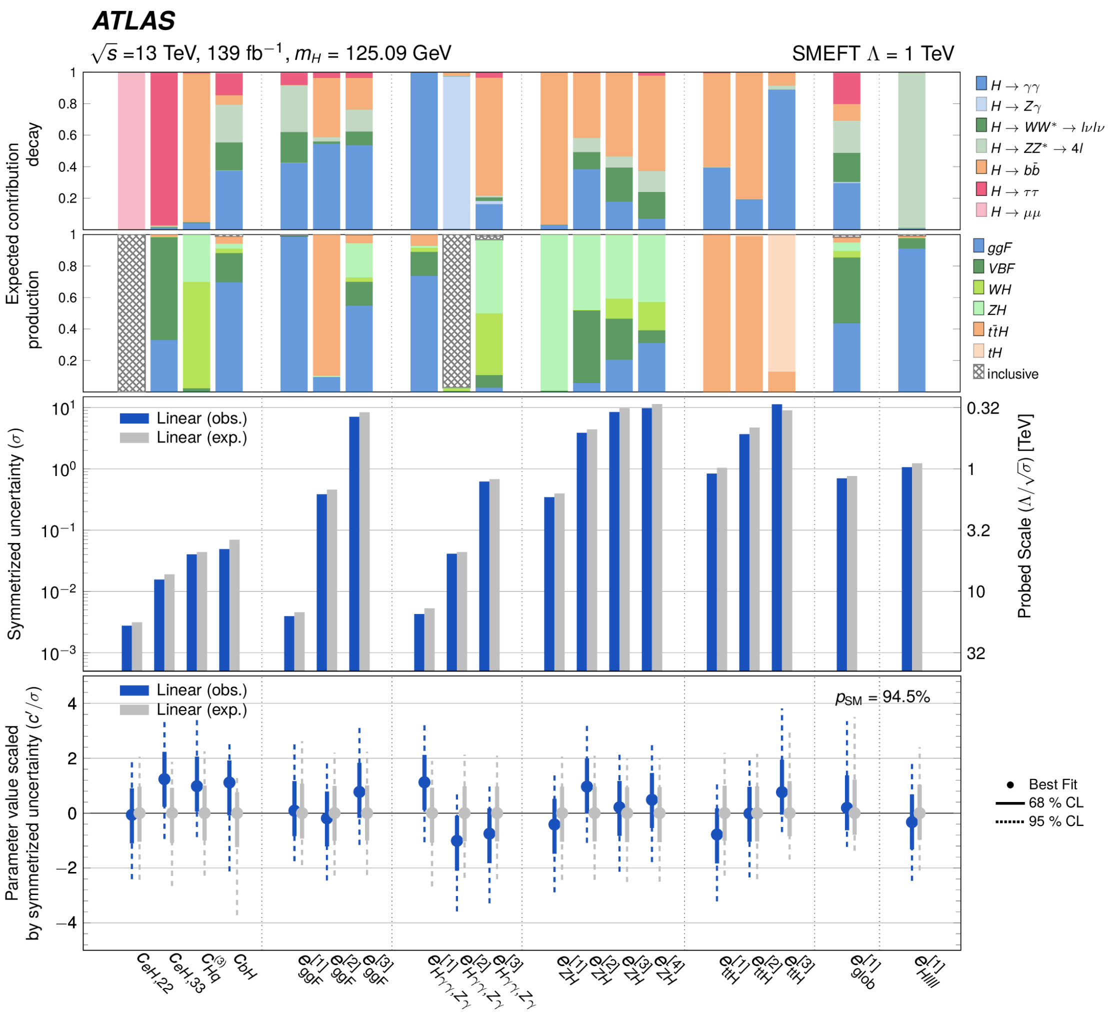
ATLAS EFT Higgs interpretation

Linearised model

Compatibility with the SM = 94.5%

Most parameters still dominated by statistical uncertainties

- But systematics might go up to 50% in some cases



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

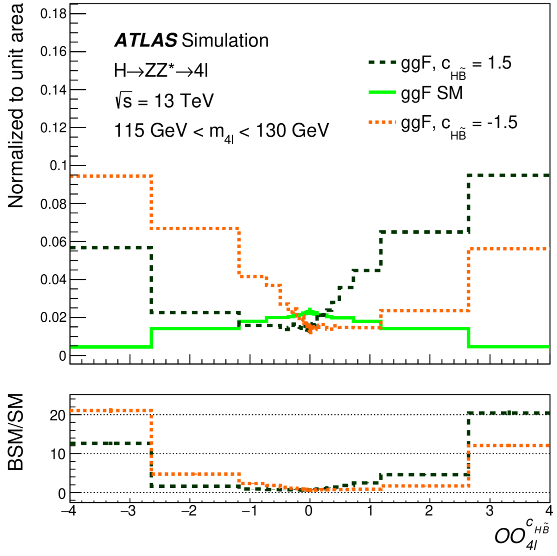
- There is still room for CP violation in the Higgs couplings

Searching for CP-odd components in the Higgs couplings

- Using CP-sensitive observables
  - Angular variables
  - Optimal observable: $OO = \dfrac{2Re(\mathscr{M}^*_{SM}\mathscr{M}_{CP-odd})}{|\mathscr{M}_{SM}|^2}$

Example OO in $H \to ZZ^* \to 4\ell$

JHEP 05 (2024) 105

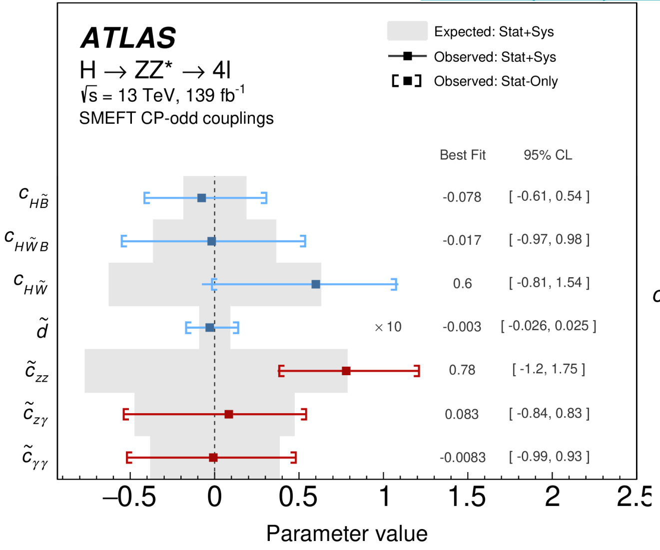


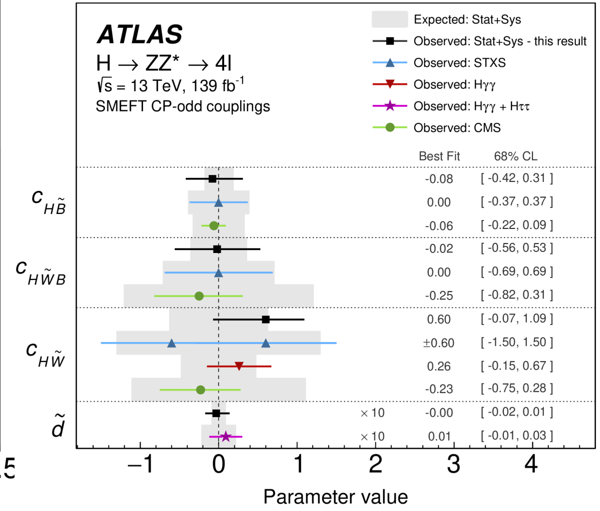
$$\sigma \sim |\mathscr{M}_{SM} + \mathscr{M}_{CP-odd}|^2 = |\mathscr{M}_{SM}|^2 + |\mathscr{M}_{CP-odd}|^2 + 2Re(\mathscr{M}^*_{SM}\mathscr{M}_{CP-odd})$$

Searching for CP Violation in the Higgs sector

Couplings involving vector bosons

$H \to ZZ^* \to 4\ell$ JHEP 05 (2024) 105





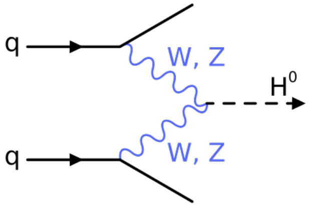
$H \to \gamma\gamma$

	95% (exp.)
$\tilde{d}$ (inter. only)	[−0.055, 0.055]
$\tilde{d}$ (inter.+quad.)	[−0.061, 0.060]
$\tilde{d}$ from $H \to \tau\tau$	–
Combined $\tilde{d}$	[−0.046, 0.045]
$c_{H\tilde{W}}$ (inter. only)	[−0.94, 0.94]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.95, 0.95]

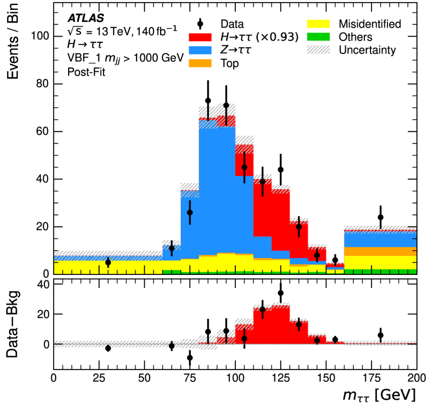
Phys. Rev. Lett. 131 (2023) 061802

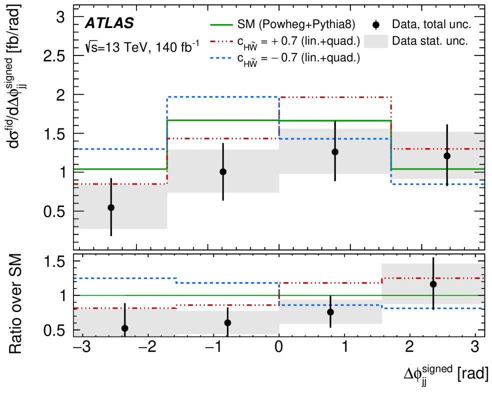
arXiv:2407.16320

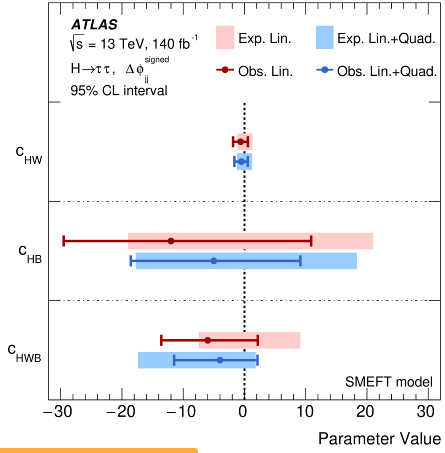
Constraints on c_{HW} and $c_{H\tilde{W}}$ from VBF $H \to \tau\tau$

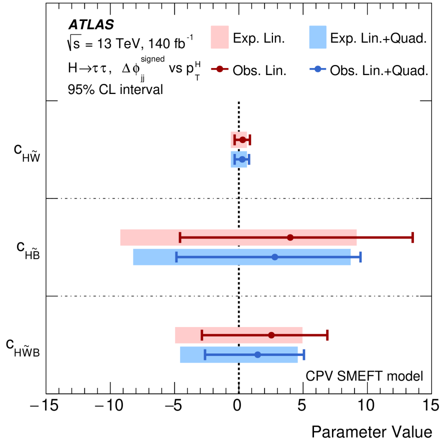


Differential measurements of $H \to \tau\tau$ in vector boson fusion production









Limits in

- $c_{H\tilde{W}}$: $[-0.31, 0.88]$ at 95% CL —> Best limits up to date
- c_{HW}: $[-1.85, 0.57]$ at 95% CL

Searching for CP Violation in the Yukawa couplings

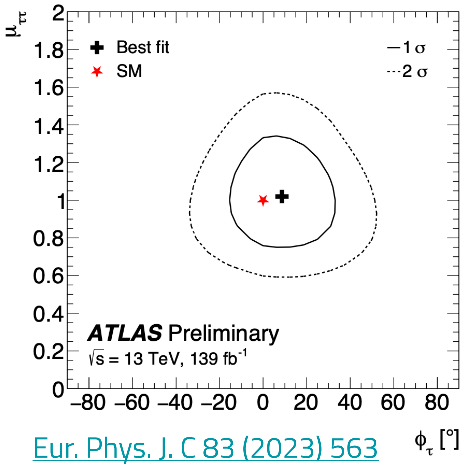
CP-violation might appear at tree level

- Typically parameterized with a mixing angle
- Using angular variables as observables

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

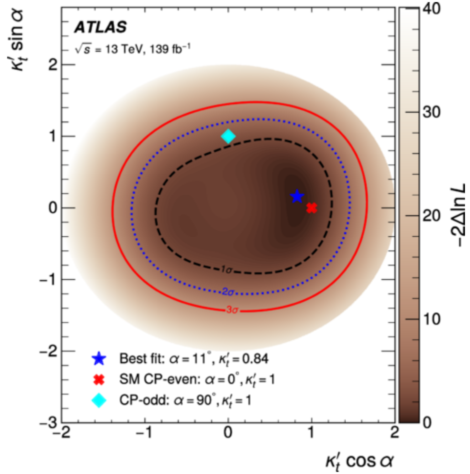
CP-even (SM) CP-odd

$H \rightarrow \tau\tau$



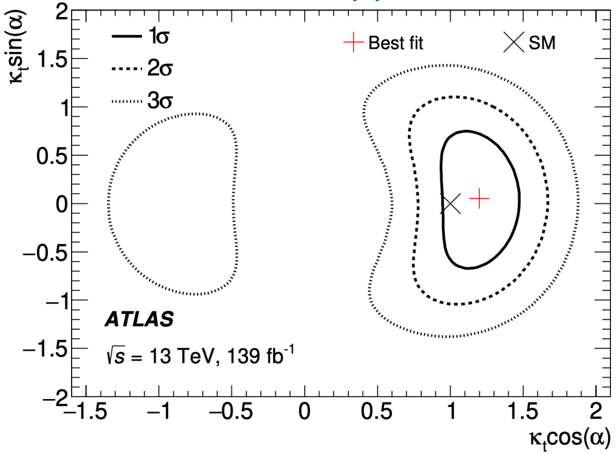
Eur. Phys. J. C 83 (2023) 563

$t\bar{t}H/tH$ with $H \rightarrow b\bar{b}$



Phys. Lett. B 849 (2024) 138469

$t\bar{t}H$ with $H \rightarrow \gamma\gamma$



Phys. Rev. Lett. 125 (2020) 061802

Probing the Higgs Boson at ATLAS

Searches for new Physics

Became12 years old

The Higgs Boson

Couplings, mass, width, invisible decays, Higgs potential

EFT interpretation of Higgs measurements

Search for CP-Violating Higgs couplings

Lepton Flavour Violation

Focus on recent results

Charged Higgs searches

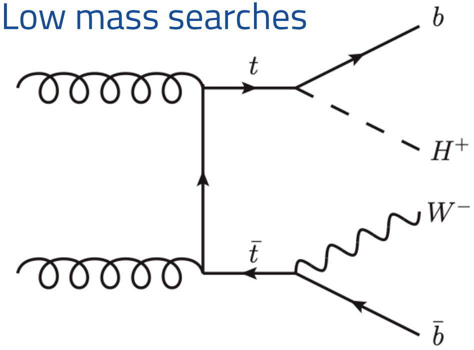
Di-Higgs resonances

Dark Matter

Low mass and high mass resonances

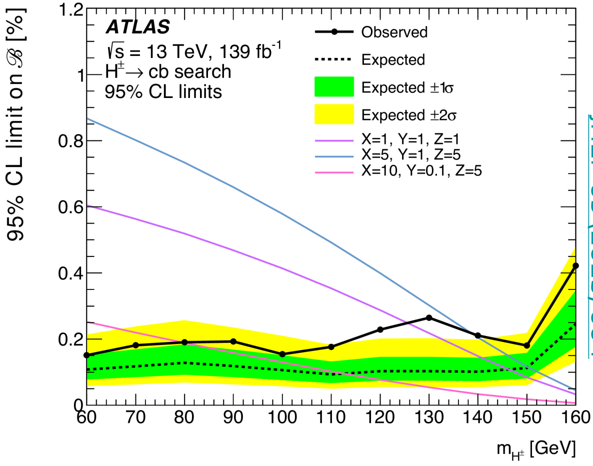
Searches for H^+ in top quark decays

Low mass searches



$H^+ \rightarrow cs$

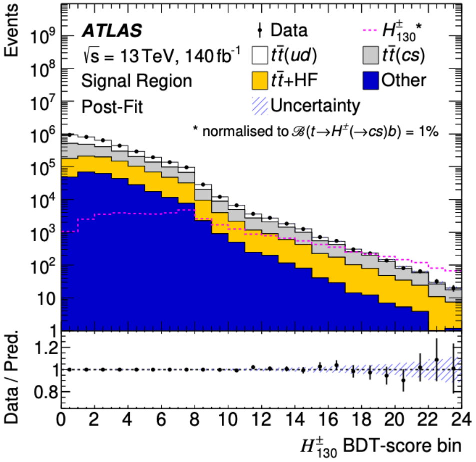
$H^+ \rightarrow cb$



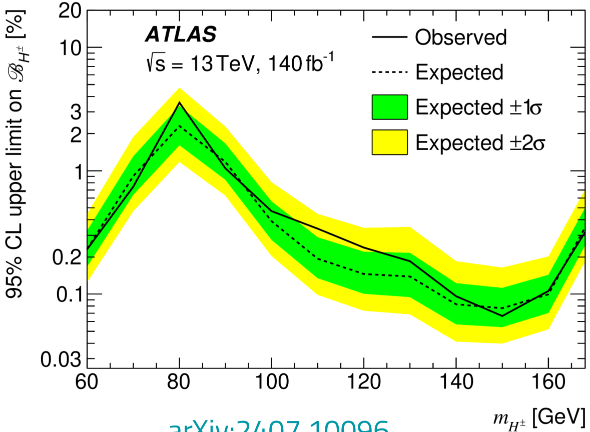
JHEP 09 (2023) 004

3σ excess at $m_{H+} \simeq 130$ GeV (2.4σ global)

BDT training depending on the H^+ mass



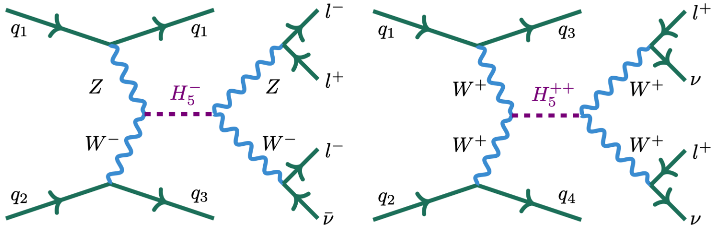
No excess found



arXiv:2407.10096

ArXiv: 2407.10798

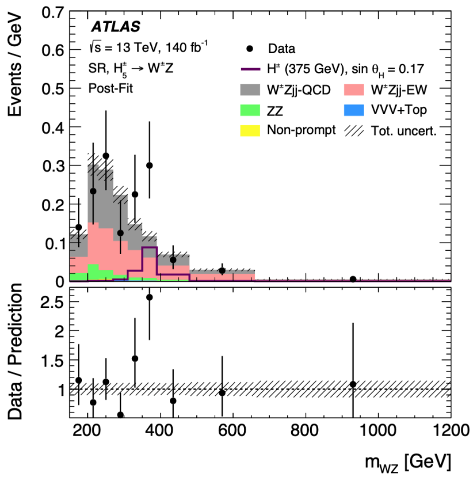
Combination of H^+ and H^{++} searches in VBF

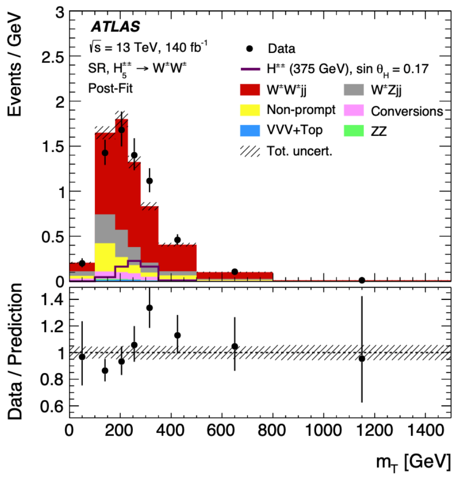


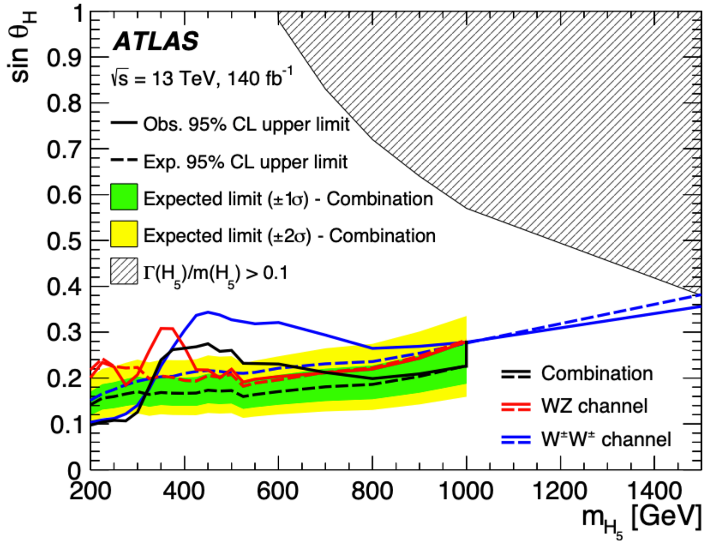
The Georgi–Machacek (GM) model used as benchmark

- One real + one complex tripplet
- Quintuplet $H_5^{\pm\pm}, H_5^{\pm}, H_5^0$ degenerate in mass

Final states with boson leptonic decays

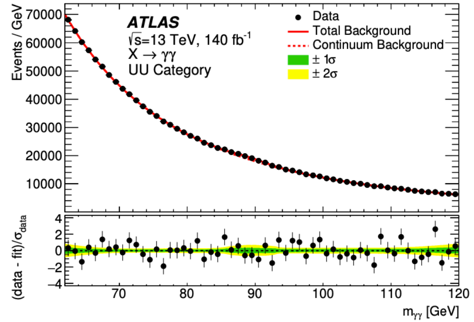


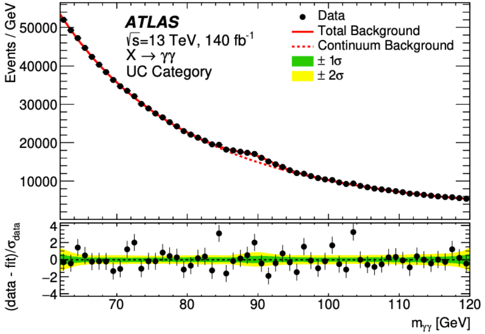




Low mass di-γ resonances

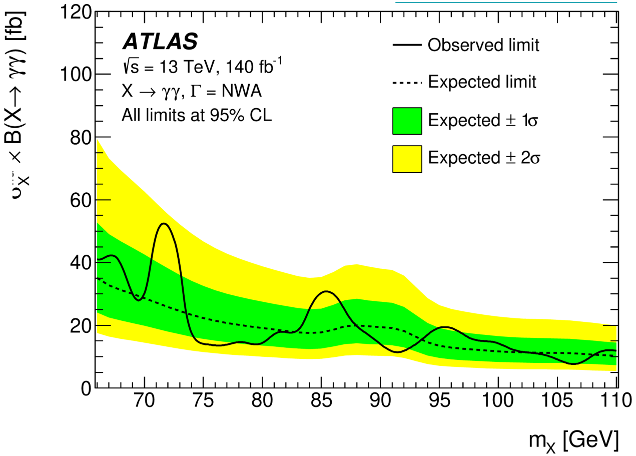
- Using a double sided Crystal Ball for the signal
- Events categories depending on number of converted photons





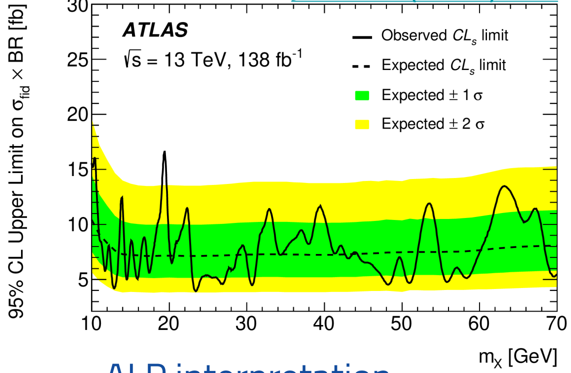
No significant excess observed

arXiv:2407.07546

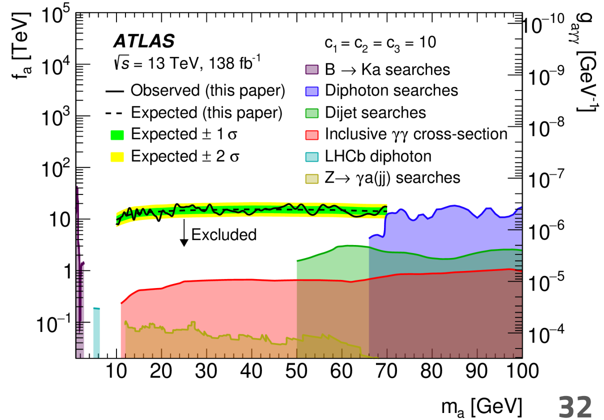


Boosted analysis:

JHEP 07 (2023) 155



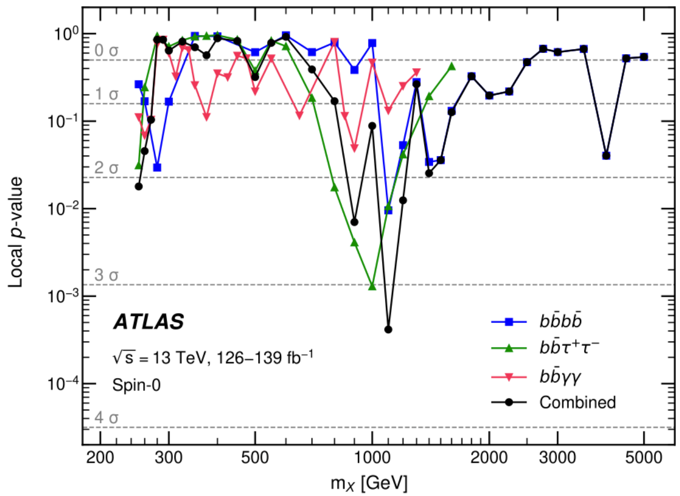
ALP interpretation

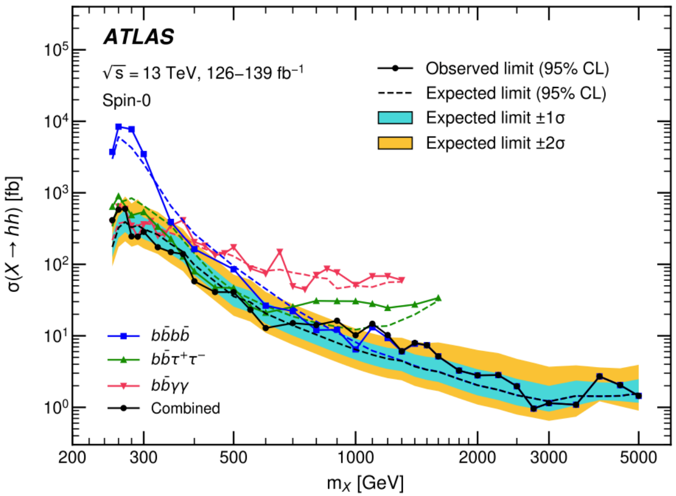


Search for $X \to HH$

Combination of results including $b\bar{b}b\bar{b}$, $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ final states

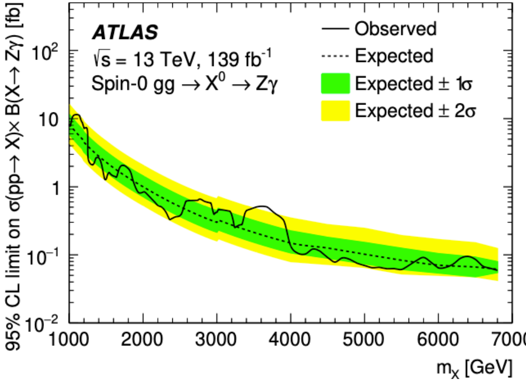
- Largest excess at 1.1 TeV with 3.3σ local (2.1σ global) significance driven by $b\bar{b}\tau\tau$

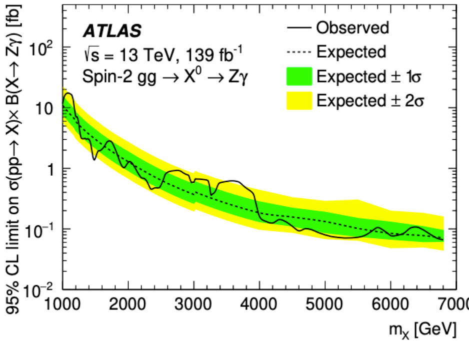




Boosted resonaces in hadronic final states

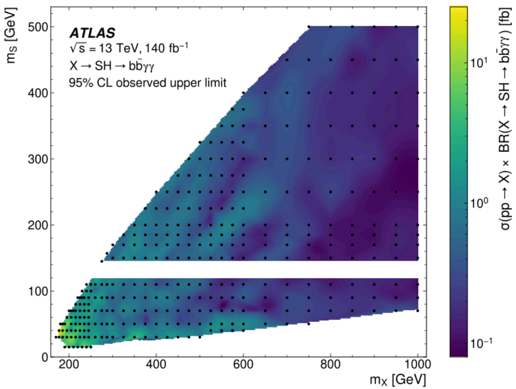
High mass $Z\gamma$ and $W\gamma$ resonances

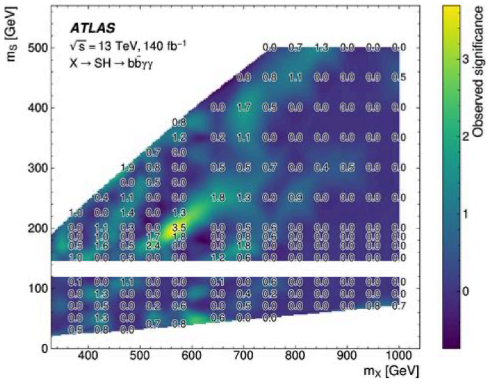




JHEP 2023, 125

$X \rightarrow SH \rightarrow bb\gamma\gamma$





arXiv:2404.12915v1

Anomaly Detection in boosted jets

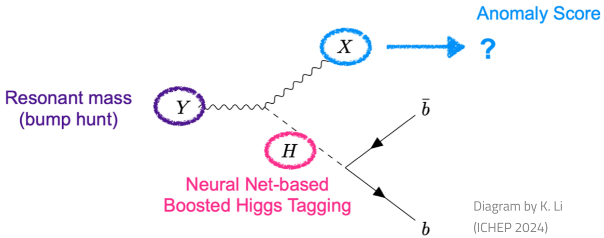
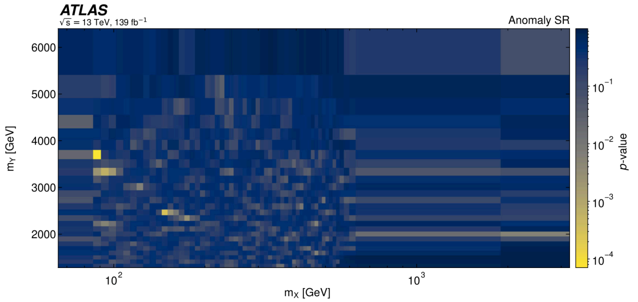
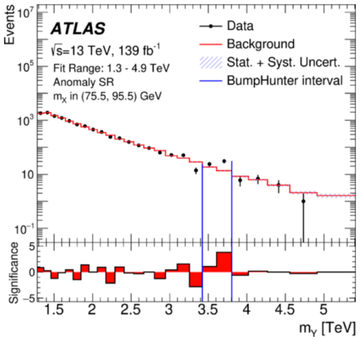


Diagram by K. Li (ICHEP 2024)



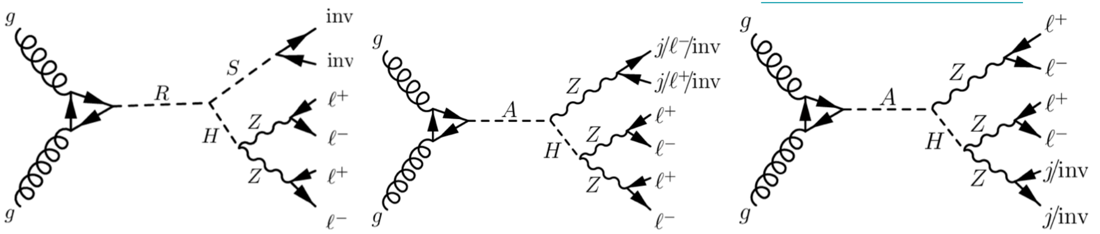


1.4σ global significance

Phys. Rev. D 108, 052009

arXiv:2401.04742

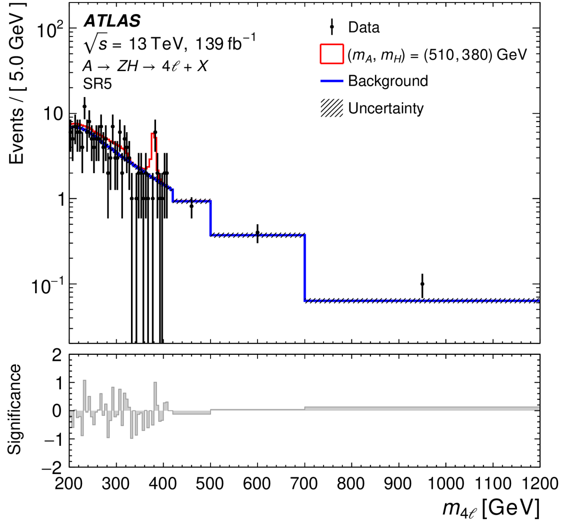
4ℓ+MET search

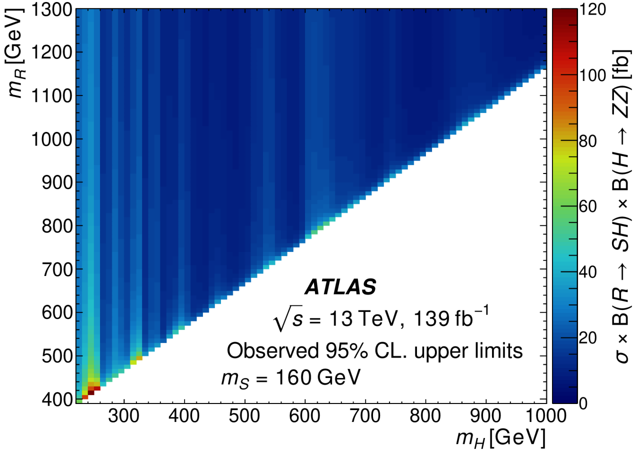


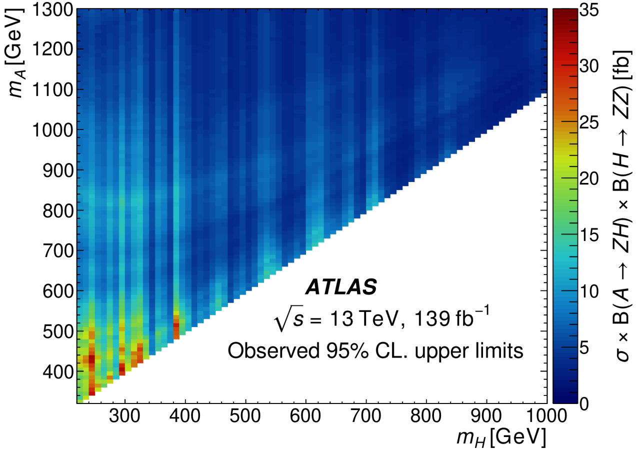
Two differen scenarios considered:

- Extended 2HDM+S with a heavy scalar R (H or S)
- 2HDM-based baryogenesis scenario

Highest excess: local significance 2.5σ, at (mA,mH) = (510, 380) GeV







Search for Dark Matter

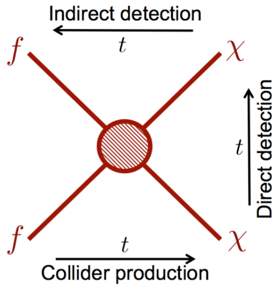
There is compelling cosmological evidence for the existence of Dark Matter

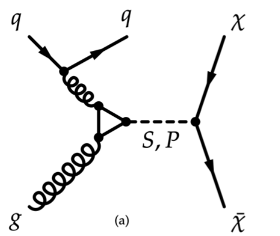
- Yet, we don't know anything about it

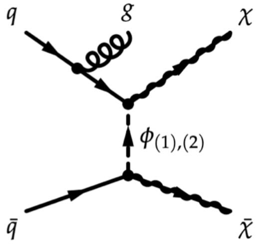
Searches at colliders are complementary to direct/indirect detection

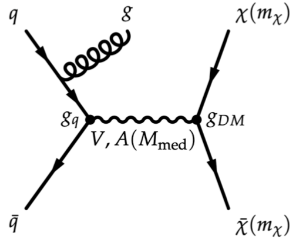
Simplified models

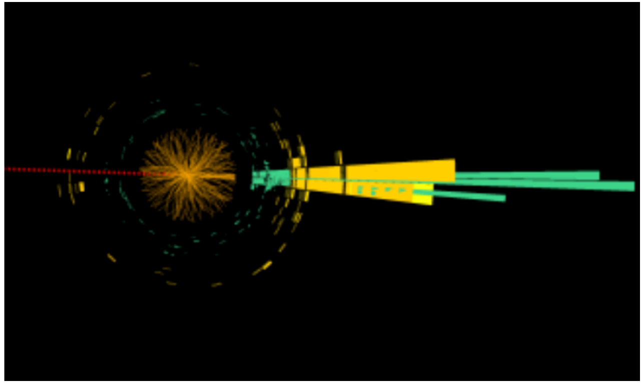
- DM assumed to be a Dirac fermion WIMP χ
- New particle mediator coupling χ to the SM
- Minimal set of parameters $\{M_{med}, m_\chi, g_\chi, g_q, g_\ell\}$









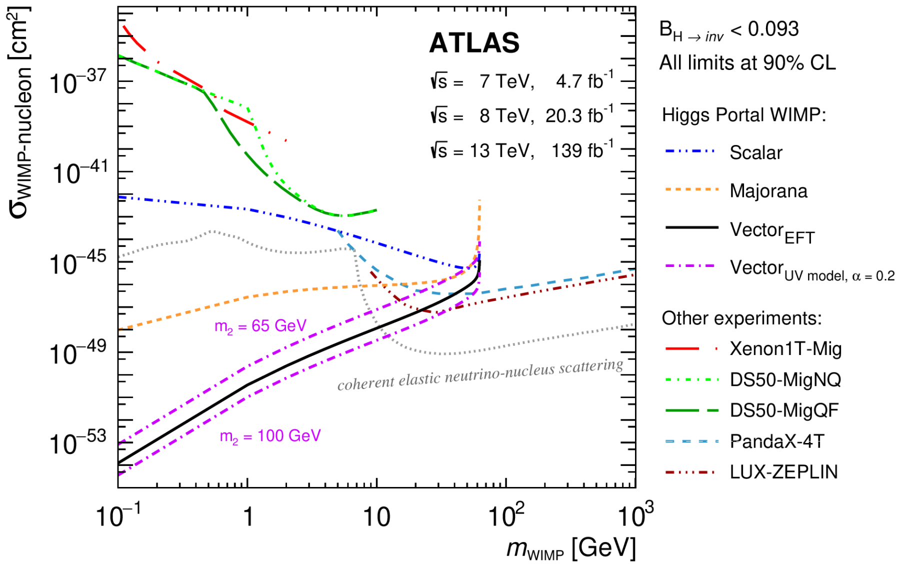


Dark matter searches

Higgs Portal WIMP

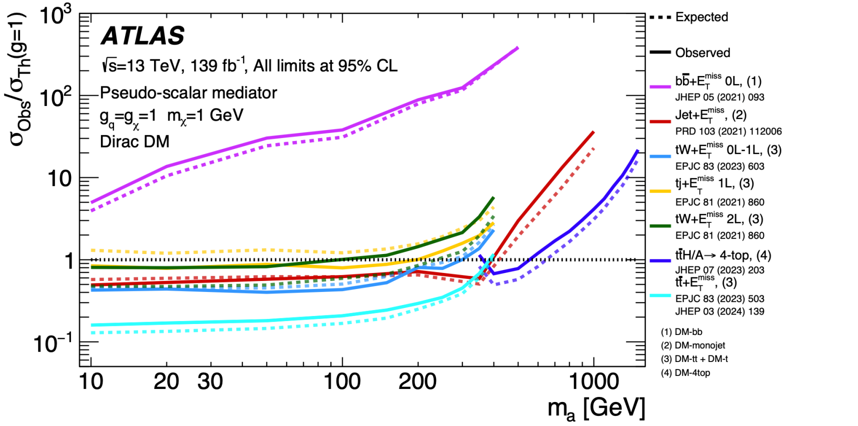
90% CL limits from $H \rightarrow invisible$ decays

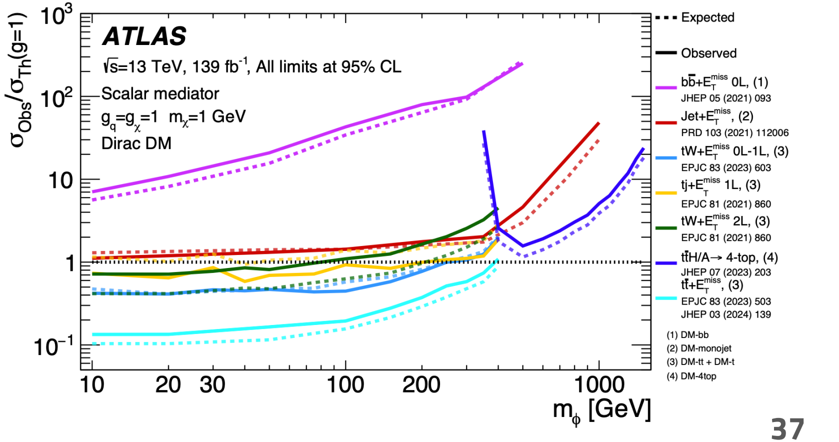
arXiv:2301.10731



Searches involving an s-channel mediator

arXiv:2404.15930v1



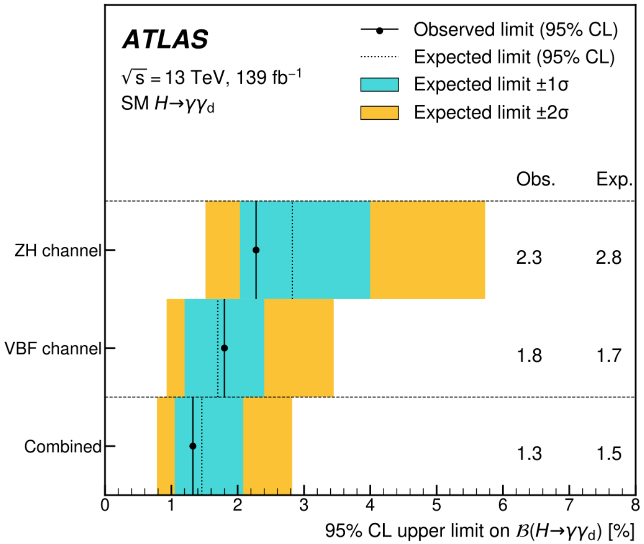


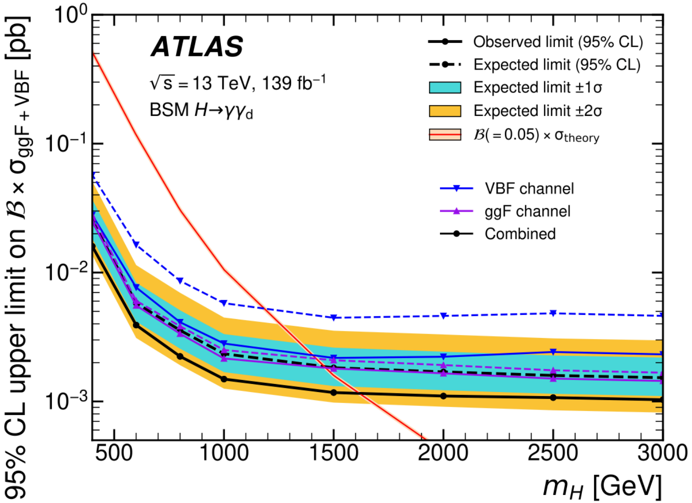
Combination of $H \to \gamma\gamma_D$ searches

Combined search for a massless dark photon in Higgs decays

- Includes ggF, VBF and ZH production

Best limits on Higgs decays to dark photons

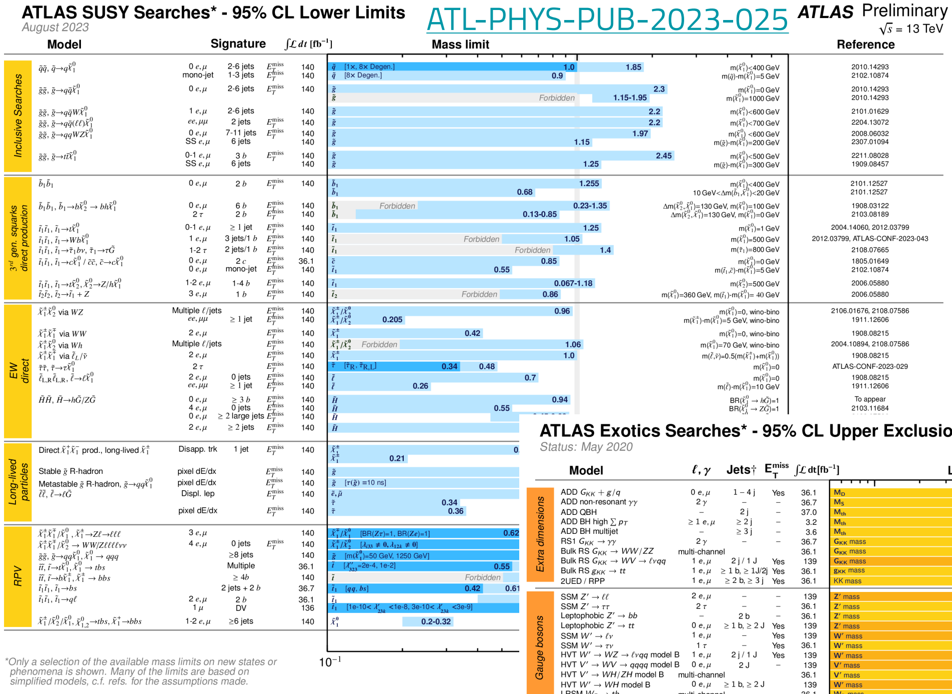




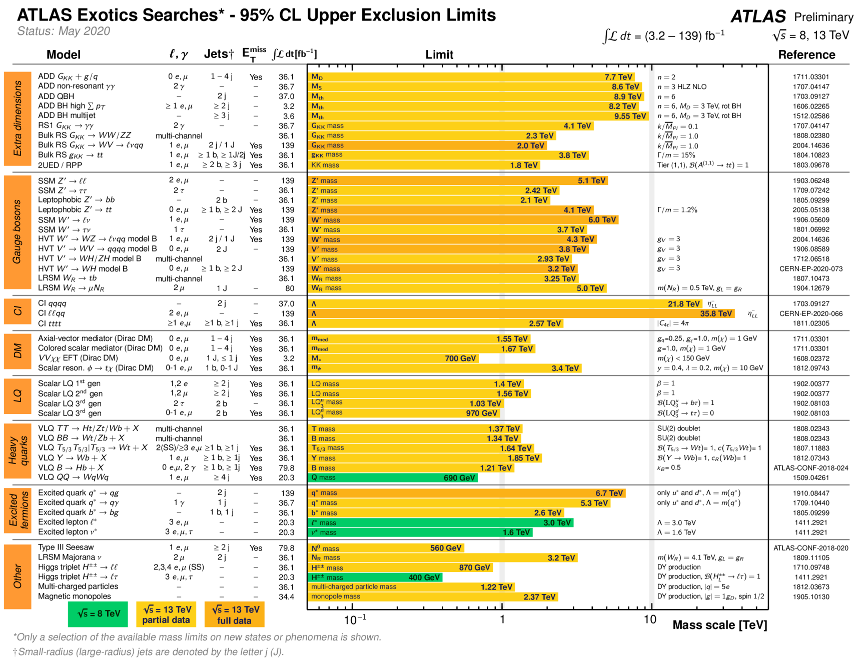
Plenty of other searches in ATLAS

Sorry if I haven't covered your favourite channel

ATL-PHYS-PUB-2023-025



ATLAS Exotics Summar Plots



Summary and conclusions

ATLAS is exploiting the Run 1, Run 2 and Run 3 pp collisions data with a comprehensive physics programme

- Standard Model measurements
- Searches for new physics

Measurements of the Higgs Boson are probing the Standard Model prediction and constraining new physics models

Direct searches for new physics have not yet shown any evidence for new particles

However

- The Run 3 and the HL-LHC period will provide a 10-fold increase in statistics

Thanks!

Acknowledgments:

REPÚBLICA PORTUGUESA

FCT Fundação para a Ciência e a Tecnologia

Search for Lepton Flavour Universality Violation

Used $t\bar{t}$ events to select a pure sample of W bosons

2021: most precise measurement of $R_{\tau/\mu} = \dfrac{BR(W \to \tau\nu)}{BR(W \to \mu\nu)}$ Nat. Phys. 17, 813–818 (2021)

- $R_{\tau/\mu} = 0.992 \pm 0.007(\text{stat}) \pm 0.011(syst) = 0.992 \pm 0.013$

Now: measurement of $R_{e/\mu} = \dfrac{BR(W \to e\nu)}{BR(W \to \mu\nu)}$

- Used the known ratio of $BR(Z \to e^+e^-)/BR(Z \to \mu^+\mu^-)$ to reduce uncertainties
- $R_{\mu/e} = 0.9995 \pm 0.0022(\text{stat}) \pm 0.0033(\text{syst}) \pm 0.0014(\text{ext})$
- Confirms the SM hypothesis at 0.5% precision

arXiv:2403.02133