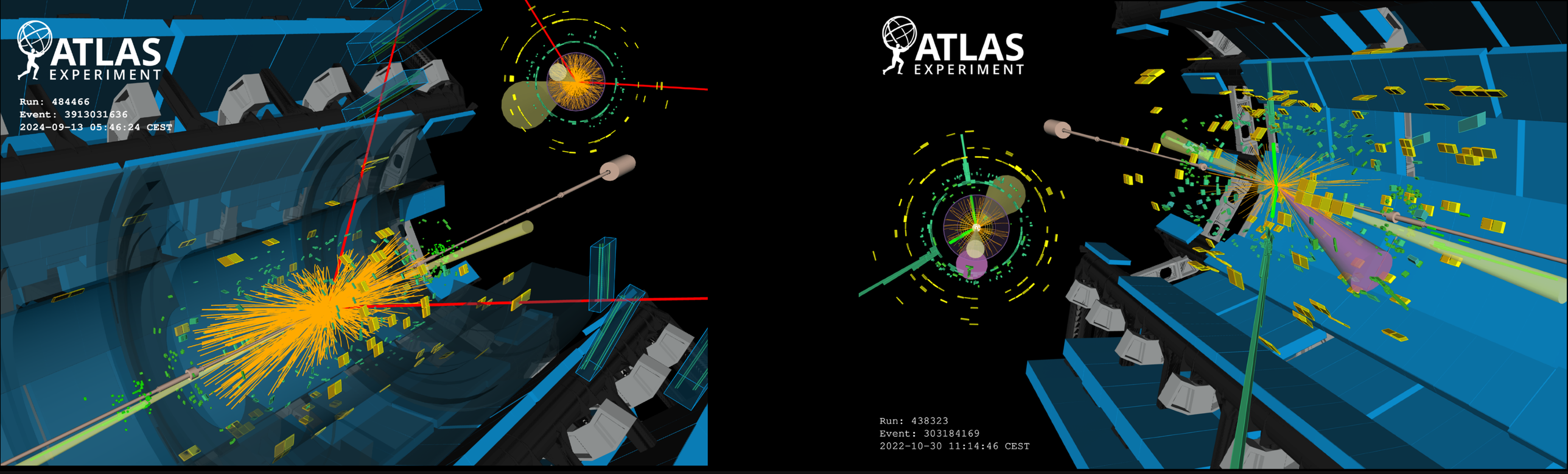


Higgs boson measurements and searches for new scalars with ATLAS

Trevor Vickey
on behalf of the ATLAS Collaboration

September 25, 2025

Scalars 2025 — Warsaw, Poland

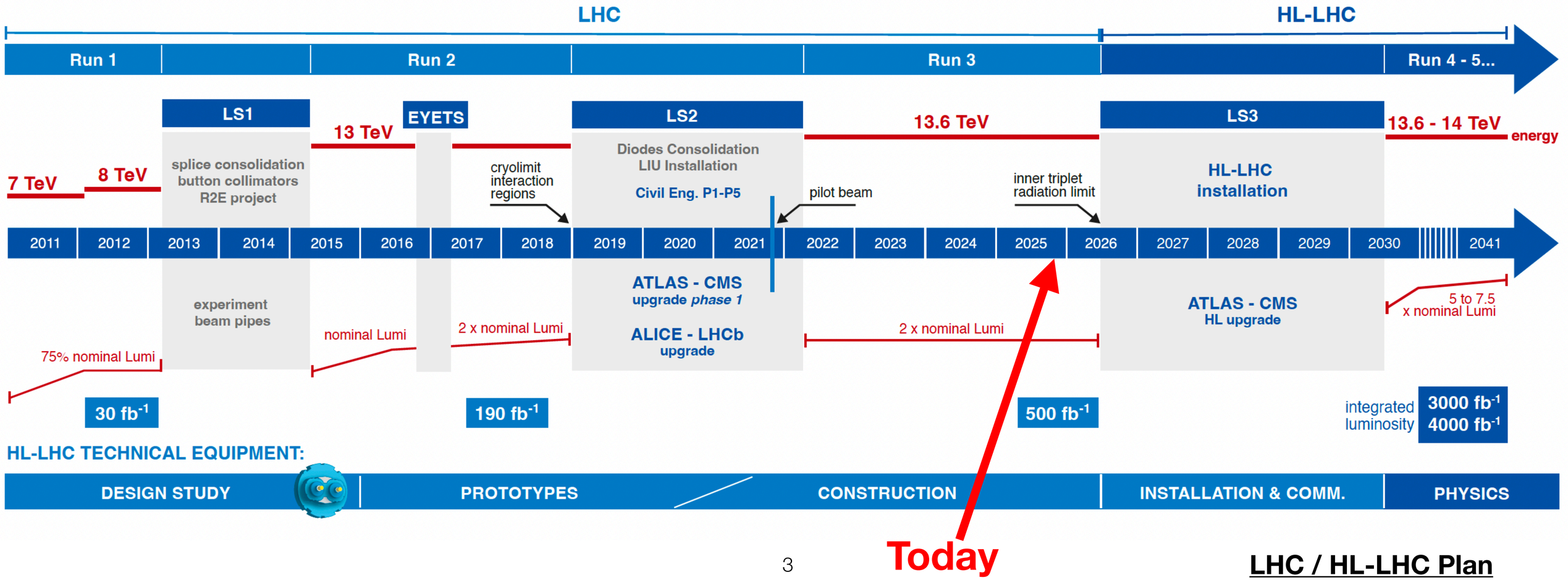
ATLAS EXPERIMENT

University of Sheffield

The LHC is terra incognita… “Here be dragons”

LHC Plan ("break physics")

- The world's highest-energy particle collider, just outside of Geneva, CH
  - Home to four major experiments (and a number of smaller ones too…)



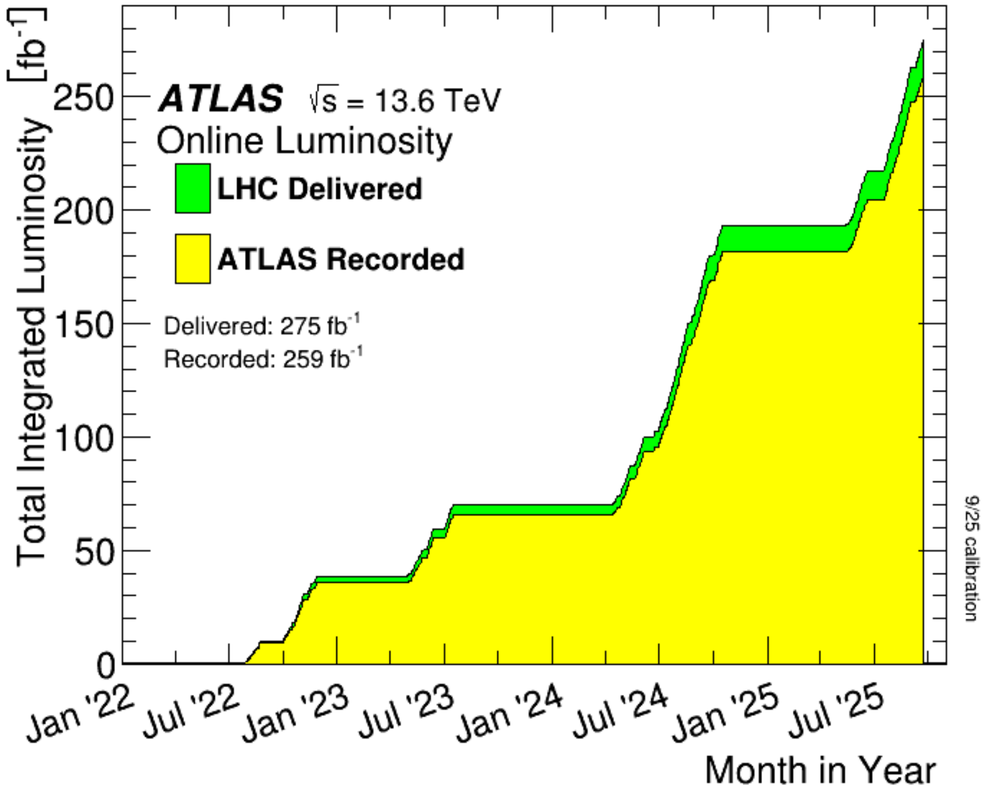
LHC / HL-LHC Plan

LHC Point-1: The ATLAS Experiment

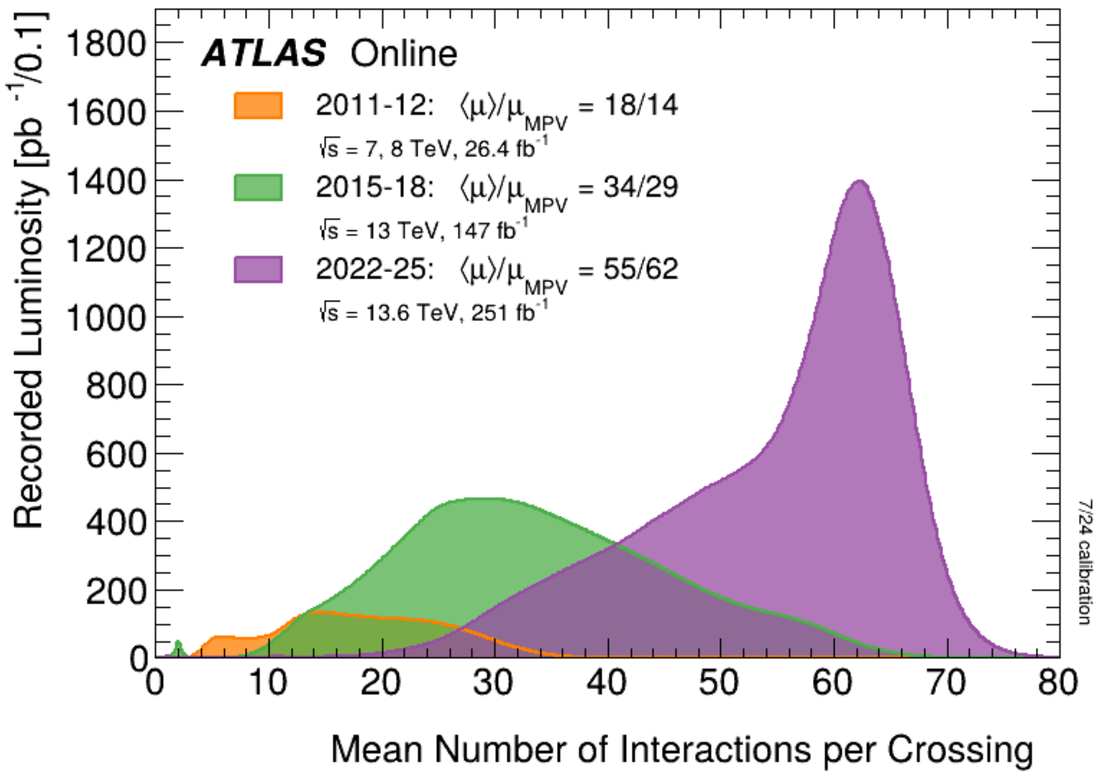
Integrated Luminosity and Pile-Up

- ATLAS recorded ~26 fb^{-1} during Run-1 ($\sqrt{s}$ = 7 and 8 TeV) and 147 fb^{-1} at $\sqrt{s}$ = 13 TeV (Run-2)
- Total integrated luminosity from $\sqrt{s}$ = 13.6 TeV pp collisions delivered to ATLAS so far in Run-3: 275 fb^{-1}
- Average pile-up in Run-3: ~55 interactions per bunch crossing, about 60% higher than Run-2
  - Fills with μ in the high-end tail are challenging: detector 'busy' more often, then readout must recover

Run-3 Integrated Luminosity

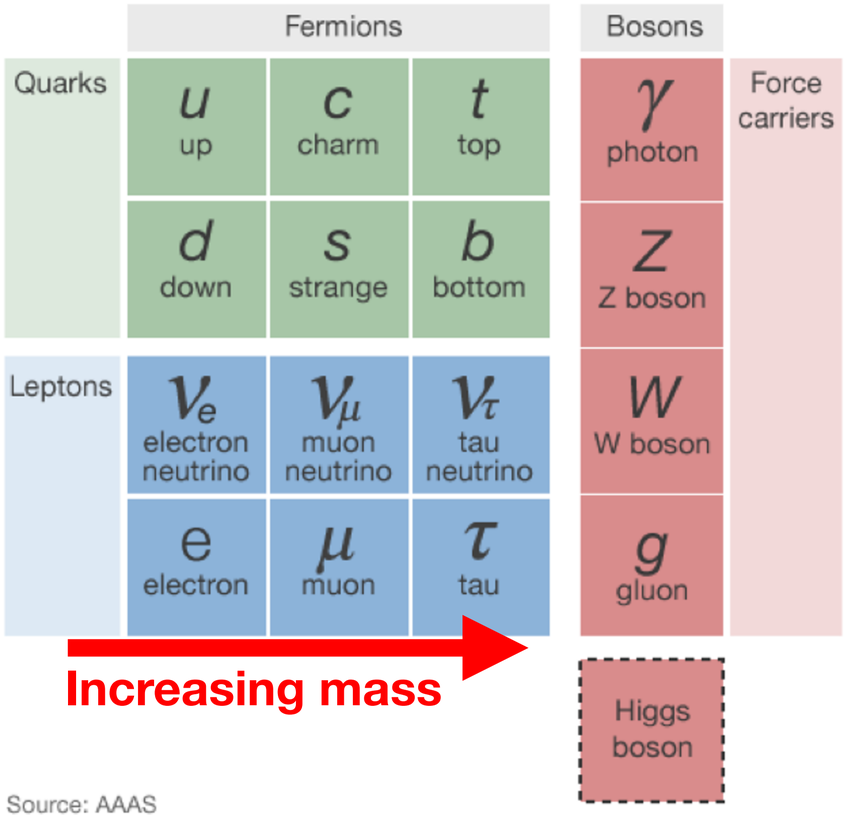


Luminosity-weighted Pile-up Distributions



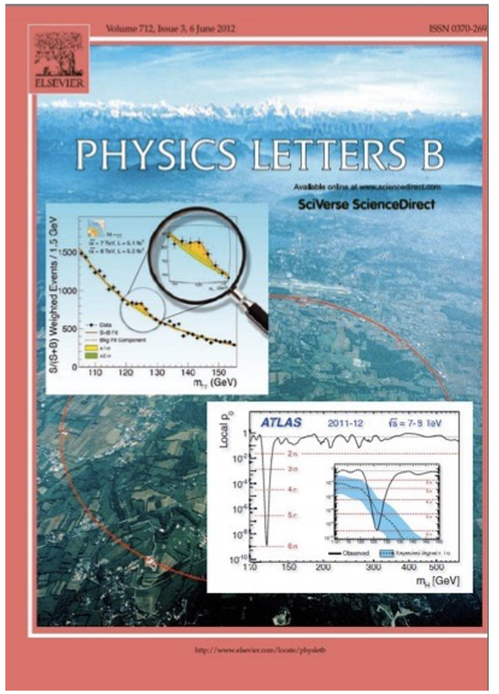
Brout-Englert-Higgs Mechanism

- The BEH complex scalar field
  - Permeates the entire universe
  - Gives mass to the elementary particles
- To verify its existence, we must find the associated Higgs boson



Source: AAAS

July 4, 2012



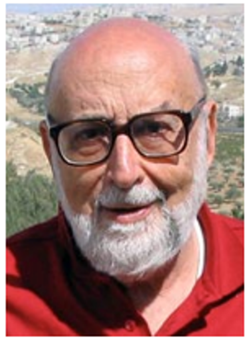


Photo: Pnicolet via Wikimedia Commons

François Englert

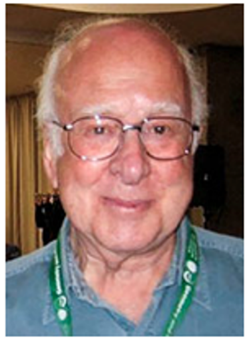
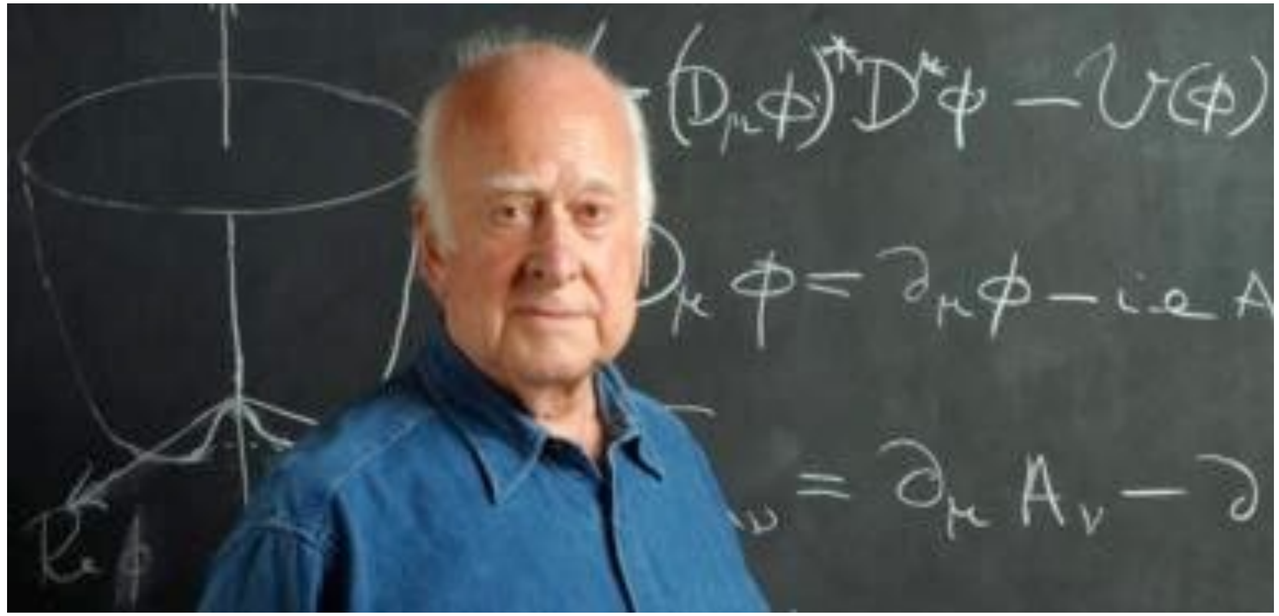


Photo: G-M Greuel via Wikimedia Commons

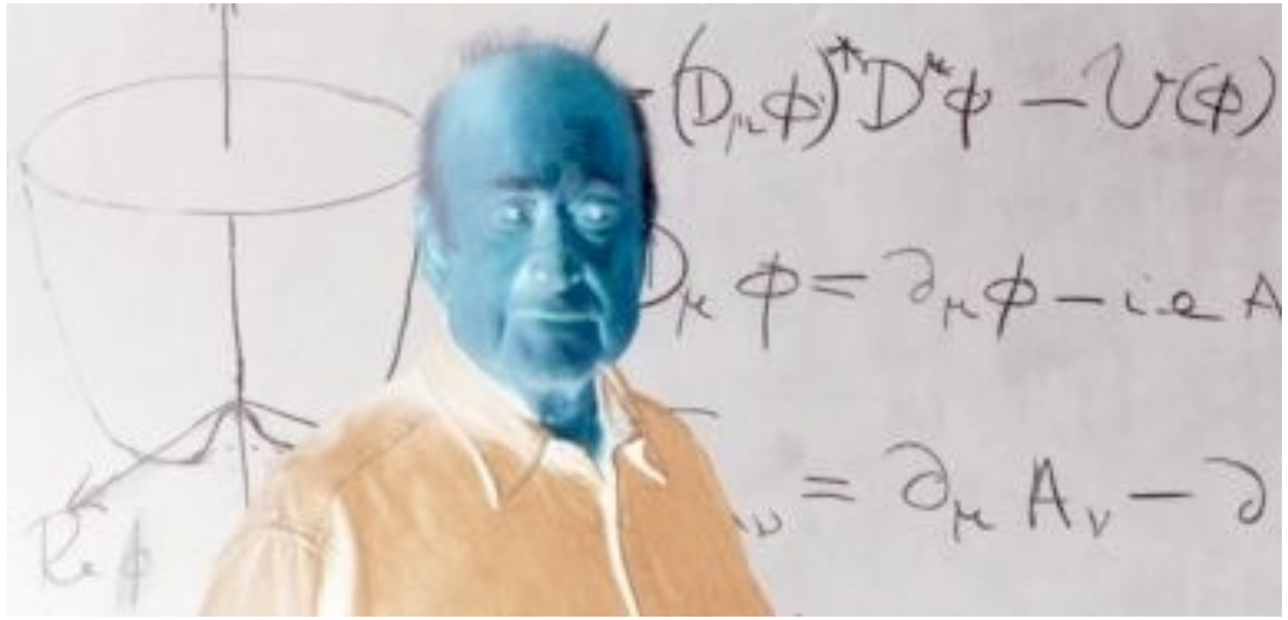
Peter W. Higgs

October 2013

But… What Kind Of Higgs Is It?



Standard Model Higgs

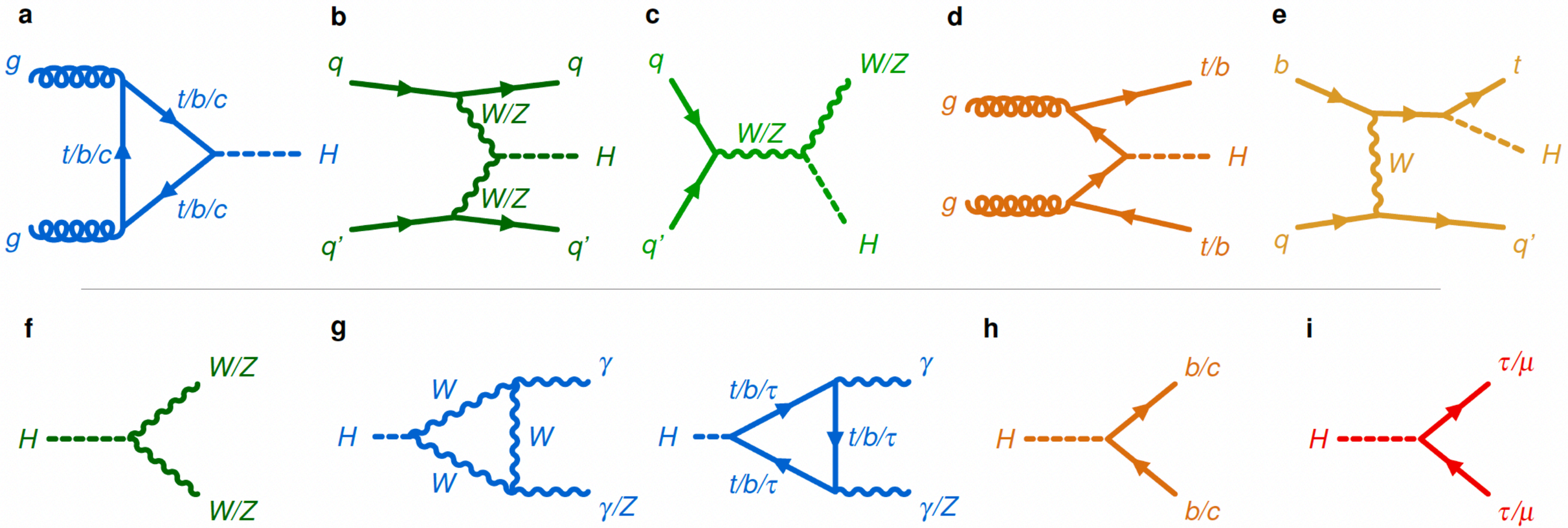


Beyond the SM Higgs

- Higgs boson properties (many of which are predicted by the Standard Model):
  - Electric charge
  - Spin angular momentum
  - Parity
  - Charge conjugation
  - Mass
  - Width
  - Cross-sections, branching ratios and signal strength
  - Couplings

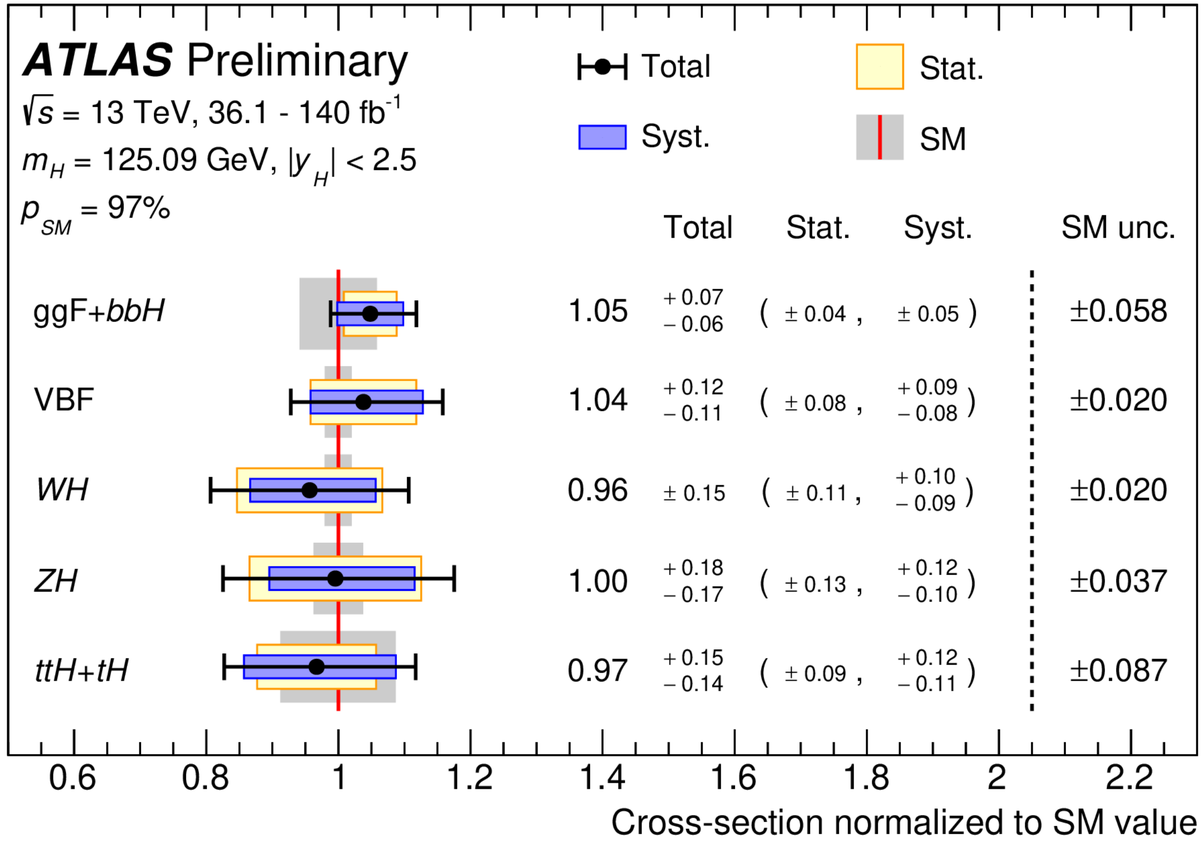
Nature 607, pages 52-59 (2022)

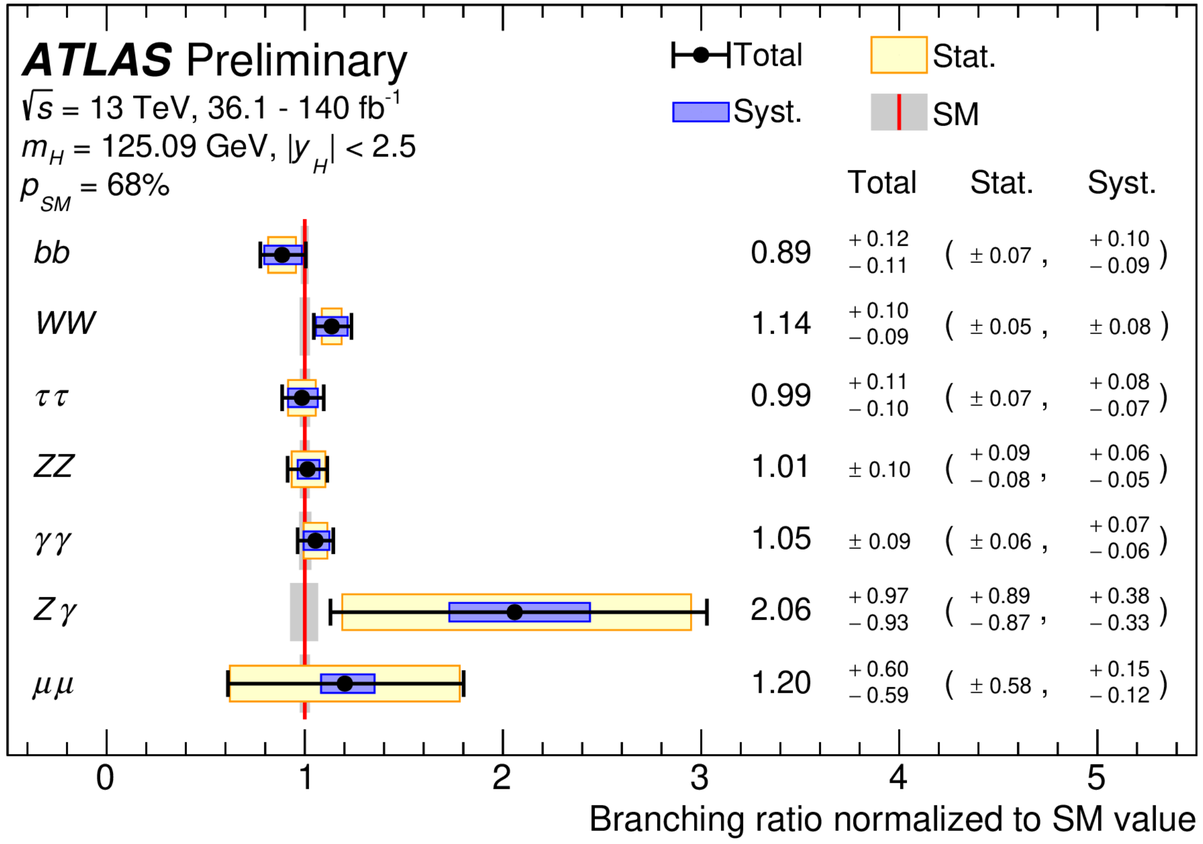
Higgs Production and Decay



ATLAS Run-2 Higgs Production and Decay Results

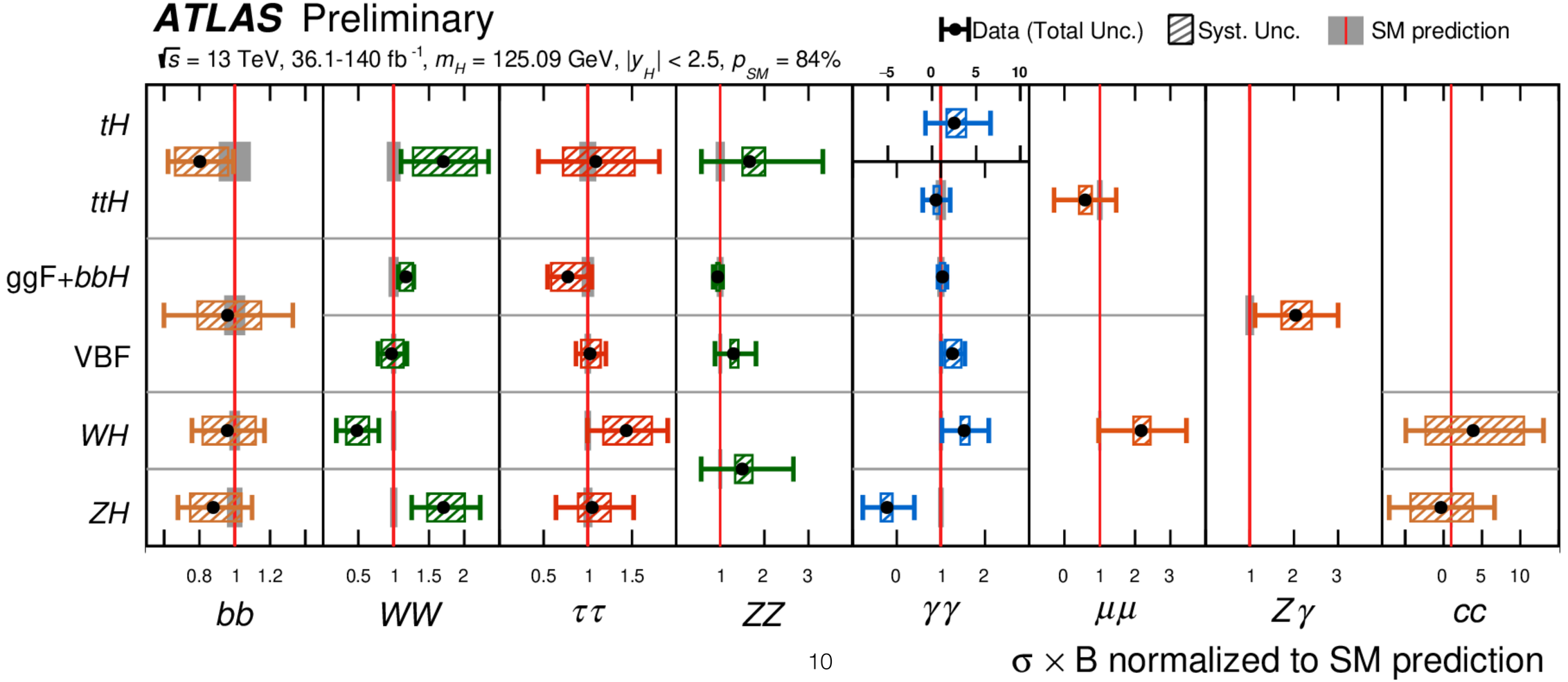
- Precise measurements of Higgs boson properties provide a test of the consistency of the SM
  - Observed cross-sections, with branching ratios assumed to be equal to their SM predictions
  - Observed branching ratios, with production cross-sections assumed to be equal to their SM predictions





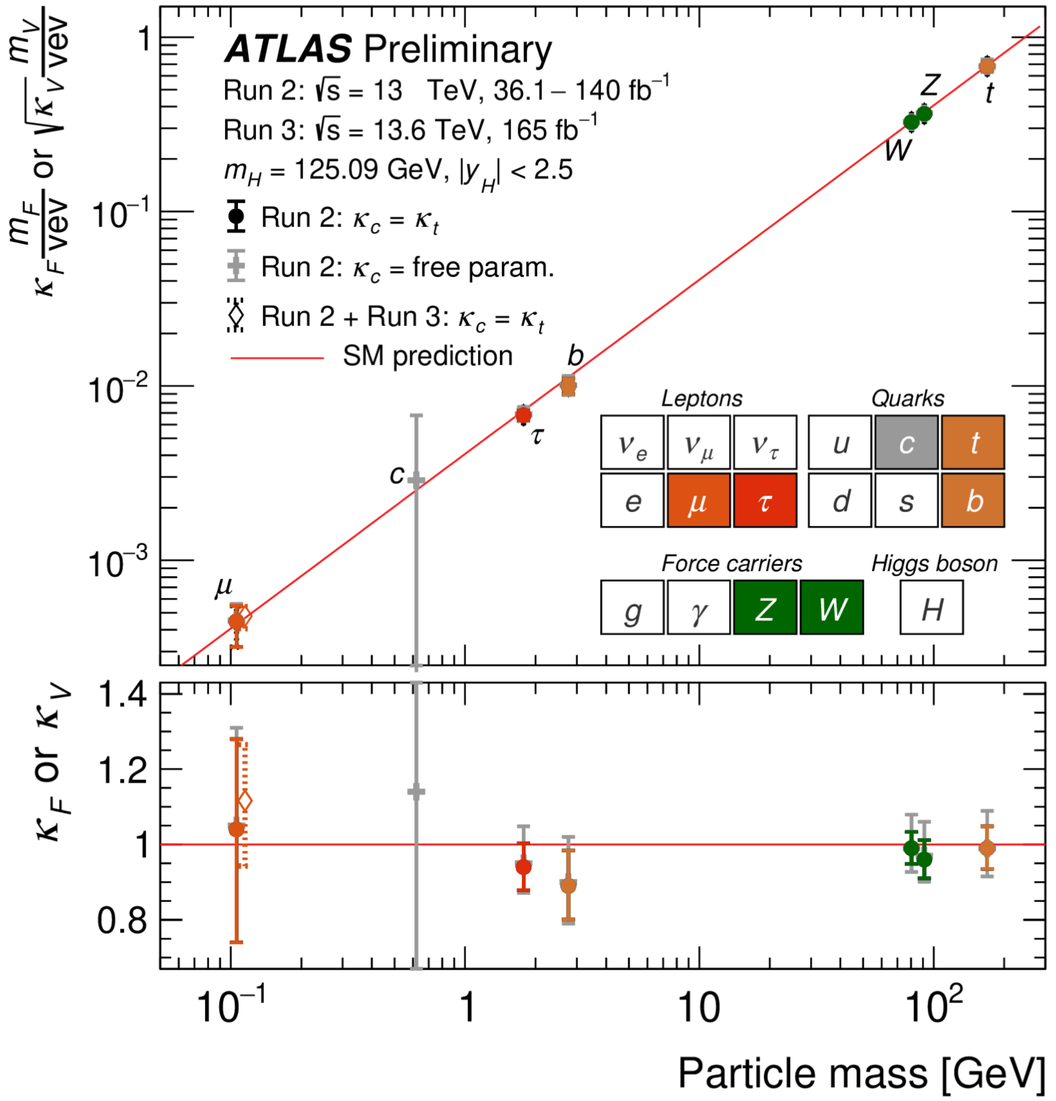
ATLAS Run-2 Higgs Production and Decay Results

- Can also examine the ratio of observed rate to predicted SM event rate for different combinations of Higgs boson production and decay processes



ATLAS Higgs Couplings Overview

- Direct measurements of all particles with mass ≥m_τ
- Includes 140 fb^{-1} (Run-2) and 165 fb^{-1} (Run-3)
- Indirect constraints for many in addition
- Limits on charm and 3.4σ measurement of muon
- Testing 3 orders of magnitude in coupling and 4 orders in mass

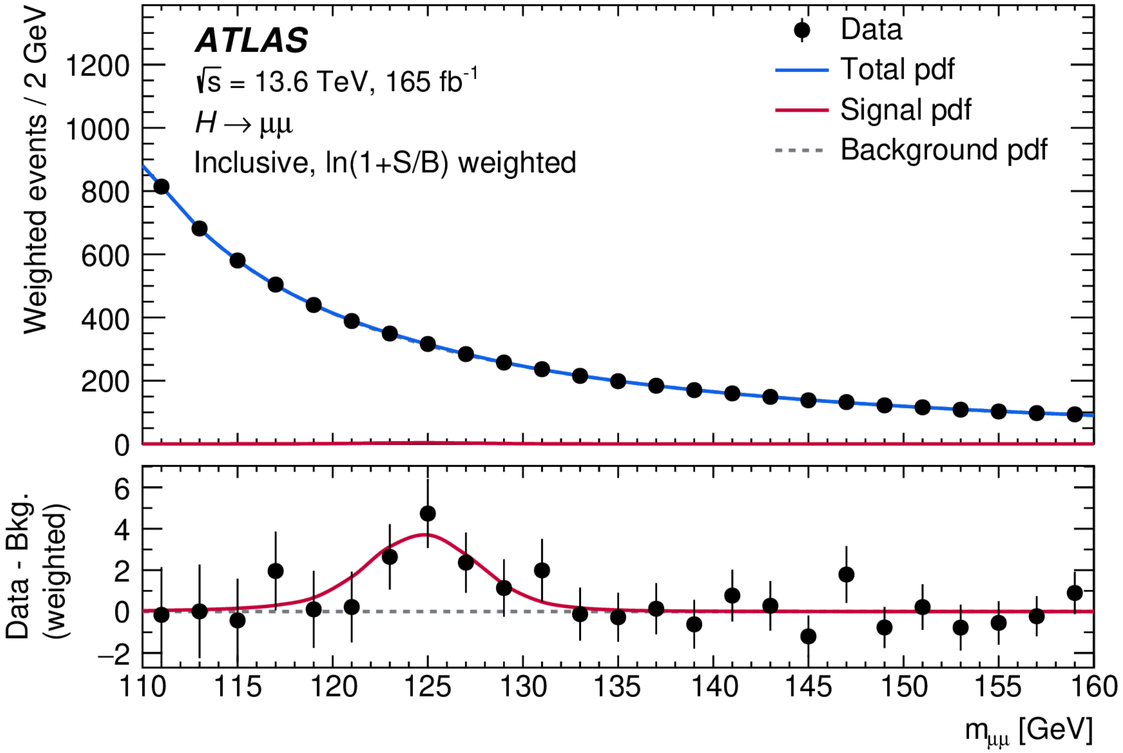


arXiv:2507.03595

ATLAS Higgs to mu-mu evidence

- A search for the dimuon decay of the Higgs boson is carried out based on pp collision data recorded by ATLAS during Run-3 of the Large Hadron Collider, corresponding to an integrated luminosity of 165 fb^{-1} at $\sqrt{s}$=13.6 TeV

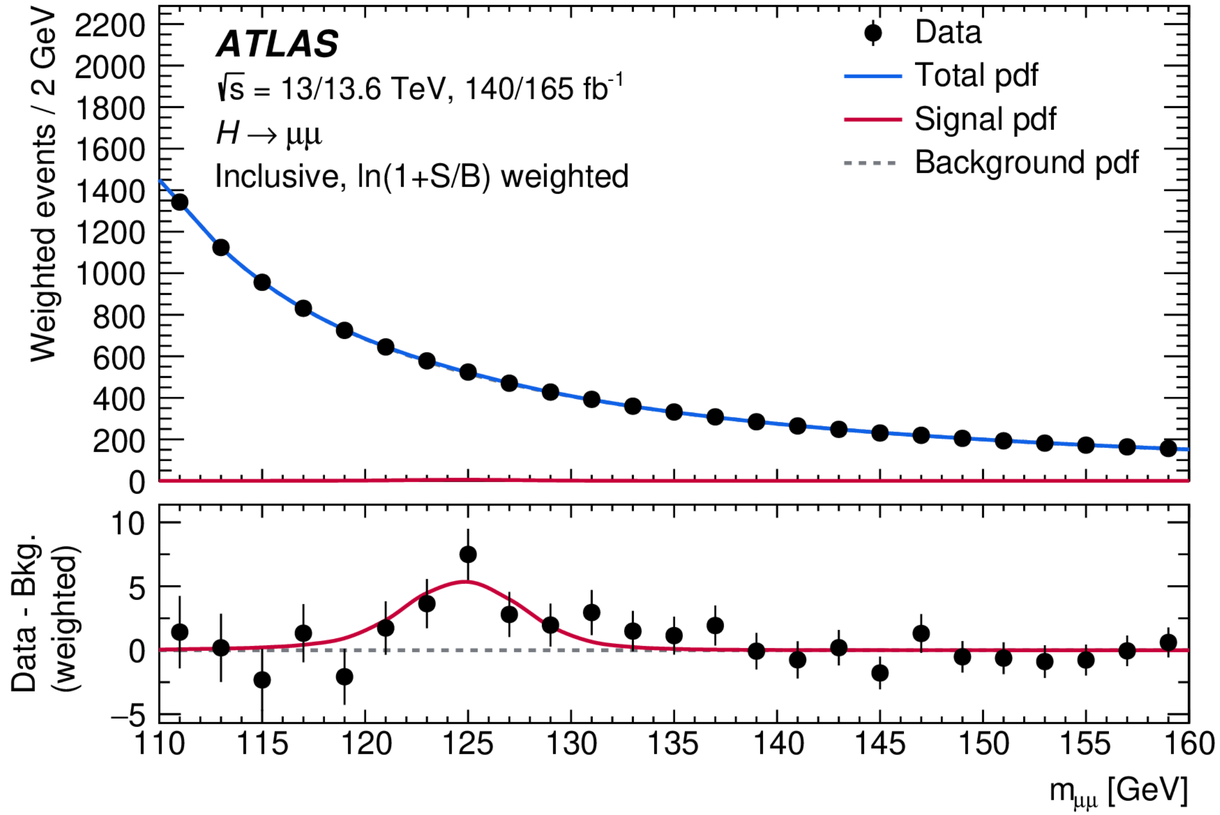
	Selection
Common preselection	Primary vertex Two opposite-charge muons Muons: $\|\eta\| < 2.5$, $p_T^{lead} > 27$ GeV, $p_T^{sublead} > 15$ GeV
Fit region	$m_{\mu\mu} = 110 - 160$ GeV
Jets	$p_T > 25$ GeV and $\|\eta\| < 2.4$ or with $p_T > 30$ GeV and $2.4 < \|\eta\| < 4.5$
b-tagged jets	$p_T > 25$ GeV and $\|\eta\| < 2.4$ or with $p_T > 30$ GeV and $2.4 < \|\eta\| < 2.5$ Tagging efficiency working point of 85%
$t\bar{t}H$ categories	At least one b-jet
VH 4-lepton category	Exactly two additional e or μ with $p_T > 8$ GeV, 5 GeV (μ) / 7 GeV (e), no b-jets
VH 3-lepton categories	Exactly one additional e or μ with $p_T > 15$ GeV, no b-jets
VH 2-lepton categories	No additional lepton, no b-jets, $E_T^{miss} > 120$ GeV
VBF and ggF categories	No additional lepton, no b-jets, $E_T^{miss} < 120$ GeV

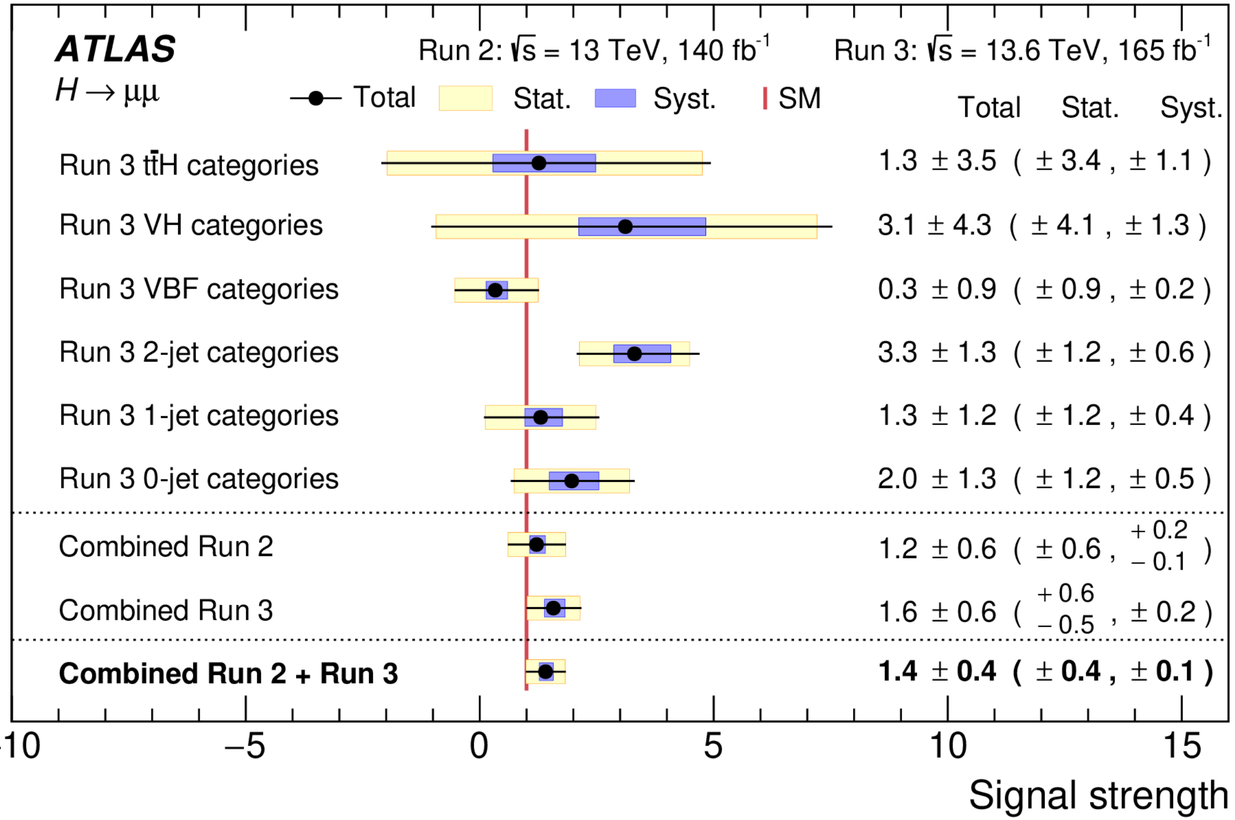


arXiv:2507.03595

ATLAS Higgs to mu-mu evidence

- Results from Run-2 and Run-3 are statistically combined
  - An excess of events over the background is observed with a significance of 3.4σ (2.5σ expected). Best-fit signal strength is μ = 1.4 ± 0.4.
  - Provides evidence for the H → μμ decay with ATLAS data and offers a direct probe of the Higgs-boson Yukawa coupling to second-generation fermions.

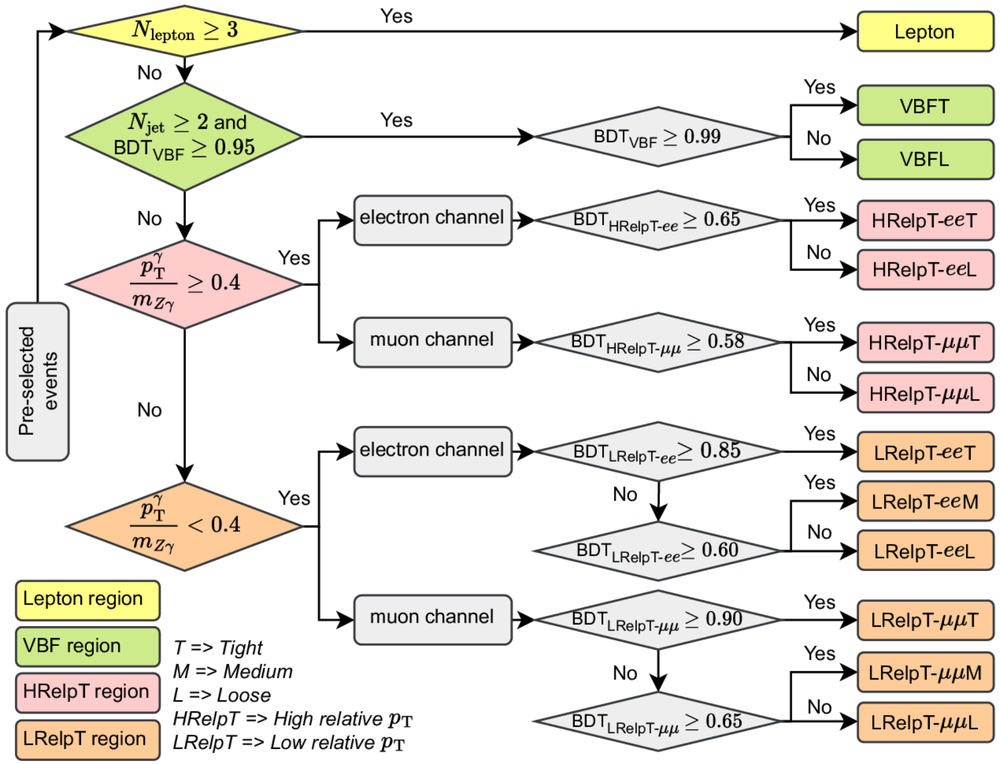




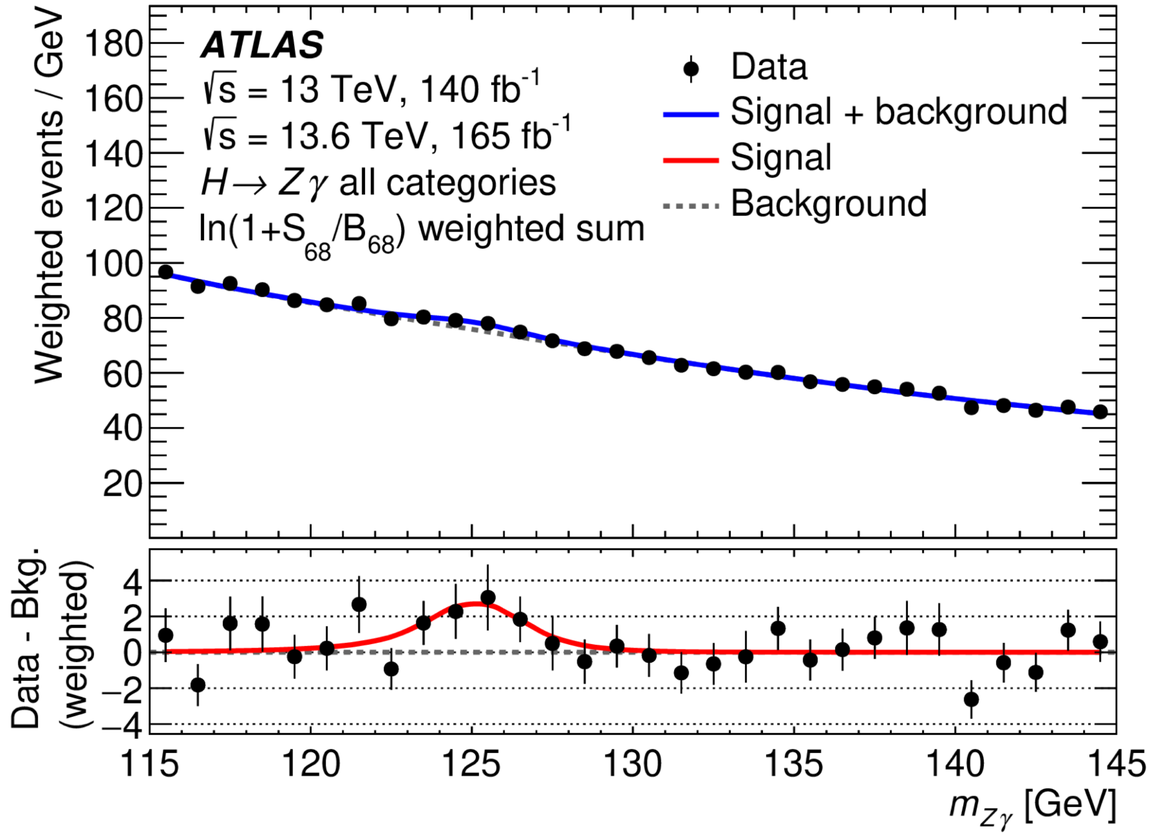
arXiv:2507.12598

ATLAS Higgs to $Z\gamma$ search

- Search for Higgs decays to $Z\gamma$ (Z to $\ell\ell$, ℓ = e or μ) is carried out on 165 fb^{-1} of Run-3 data
- Results statistically combined with those from earlier search on 140 fb^{-1} of Run-2 data
- Total statistical significance is observed (expected) significance of 2.5σ (1.9σ expected)
- Observed signal strength is μ = 1.3 +0.6 -0.5



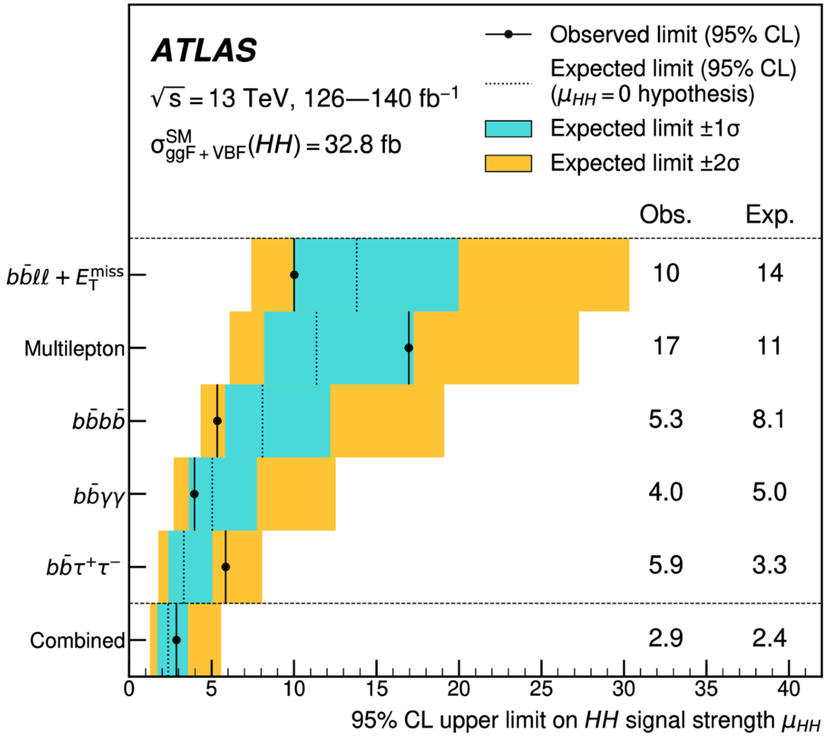
Analysis considers a total of 13 categories

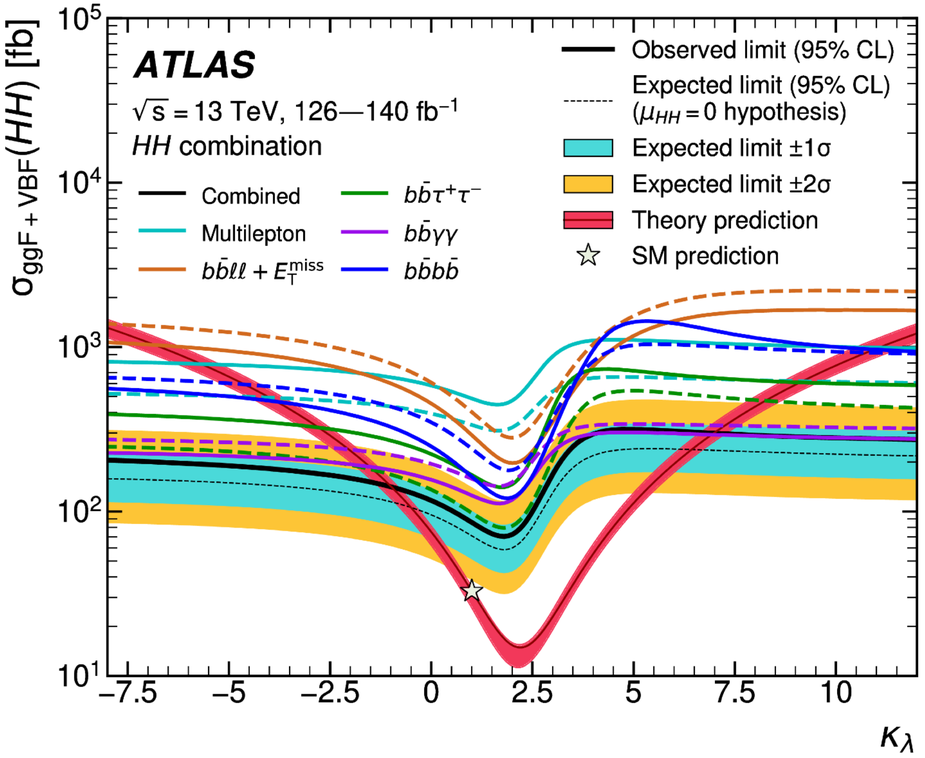


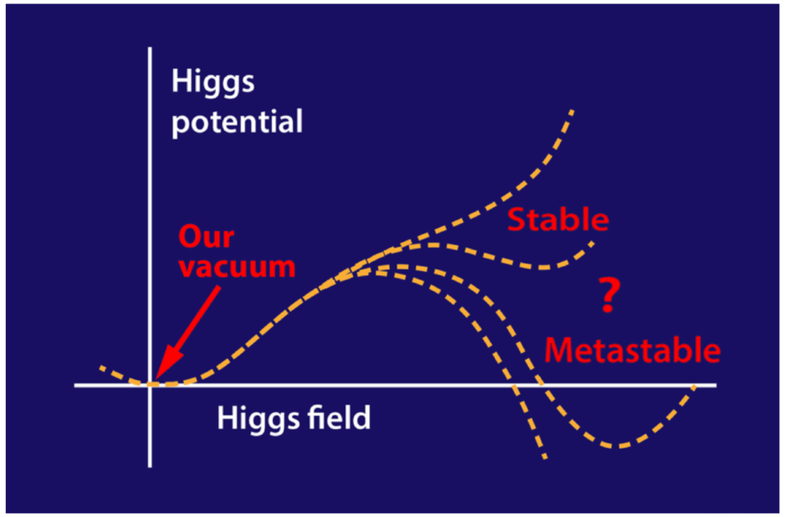
Phys. Rev. Lett. 133 (2024) 101801

ATLAS Higgs self-coupling results

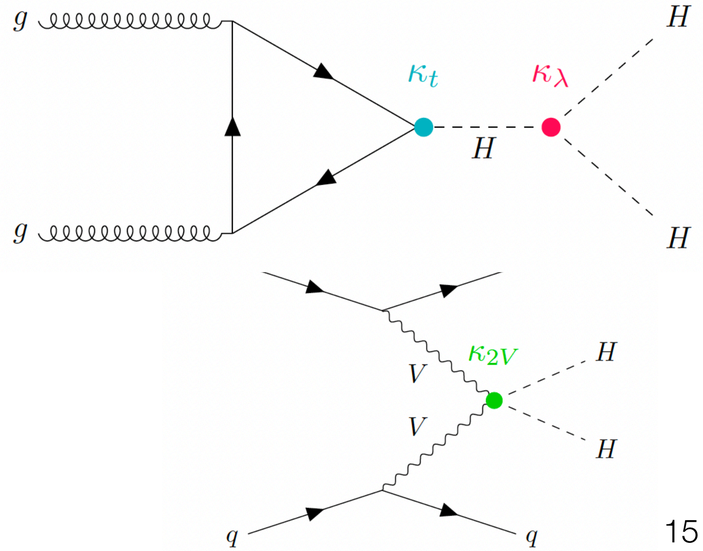
- Higgs self-interaction can be measured via HH production
  - 10^3 times more rare than single Higgs processes
  - Allows us to probe the shape of the Higgs potential
- Many different channels analyzed
- Sensitivity better than 3x the SM







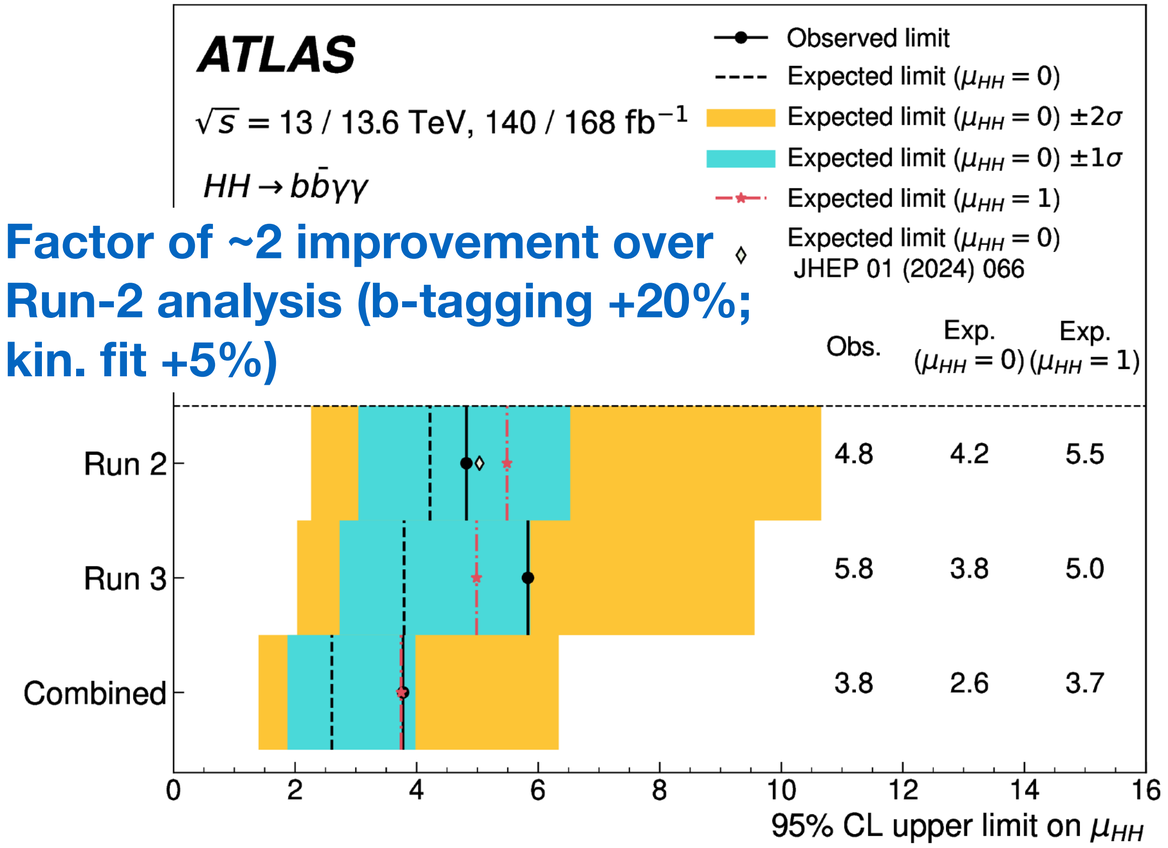
https://physics.aps.org/articles/v8/108



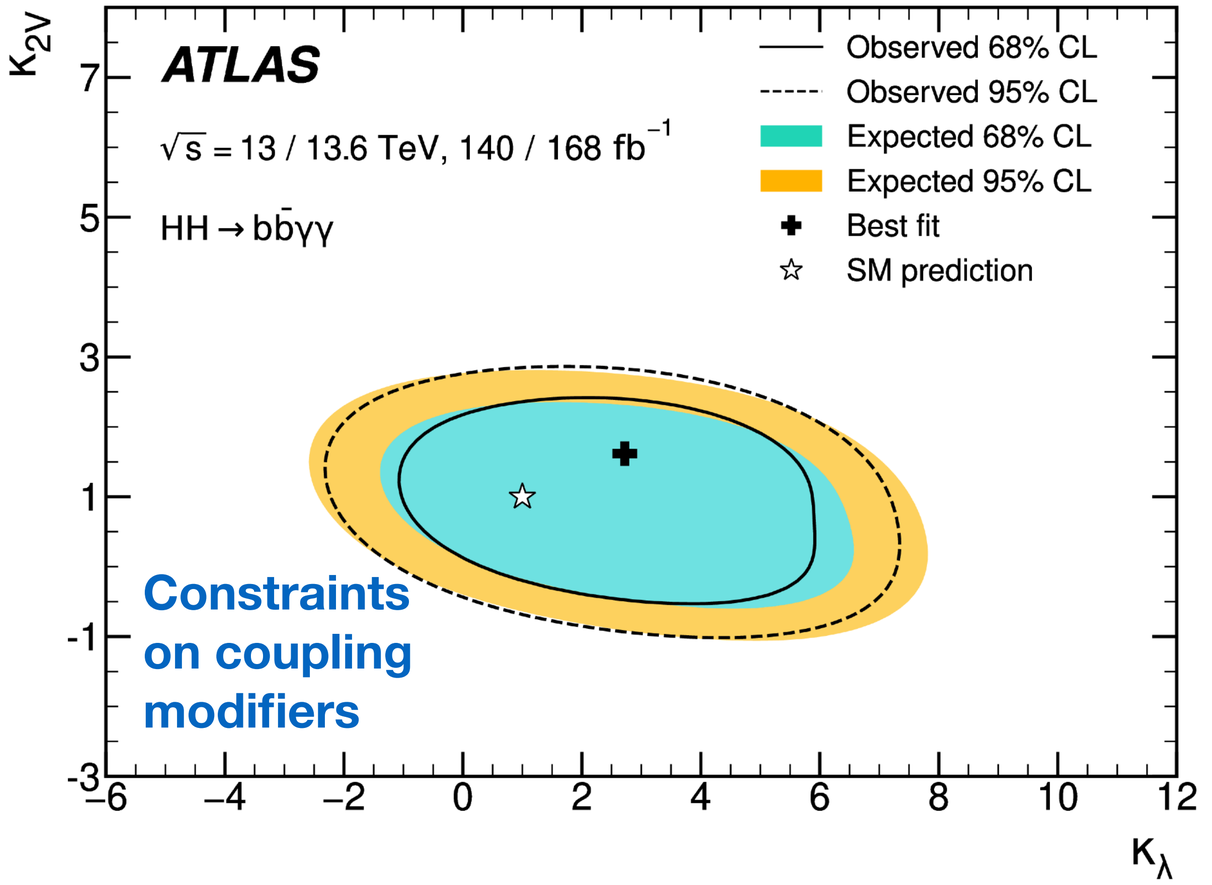
arXiv:2507.03495

Latest on ATLAS Di-Higgs searches

- Recent result for one of the “golden” decay channels of the Higgs pairs: HH → bbγγ
- Based on over 300 fb^{-1} of pp collision data, reaching an expected sensitivity comparable to that of the full Run-2 combination across all Higgs boson pair production channels.



Factor of ~2 improvement over Run-2 analysis (b-tagging +20%; kin. fit +5%)



Constraints on coupling modifiers

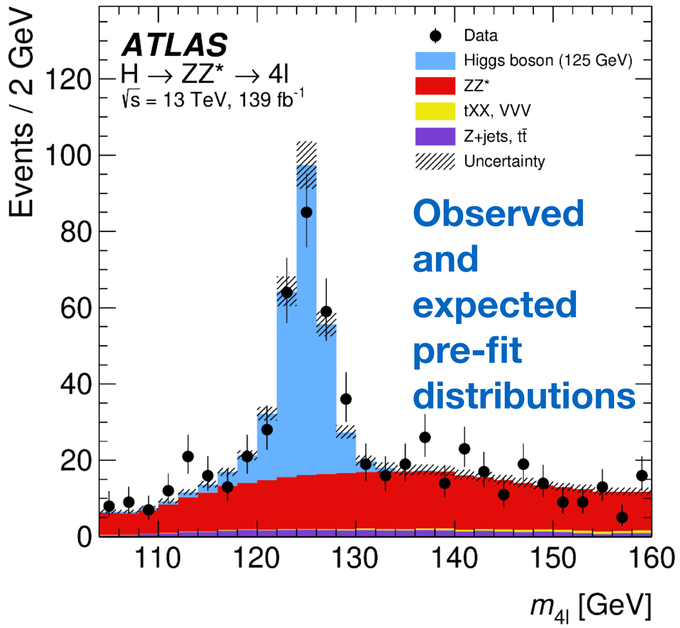
Phys. Lett. B 843 (2023) 137880

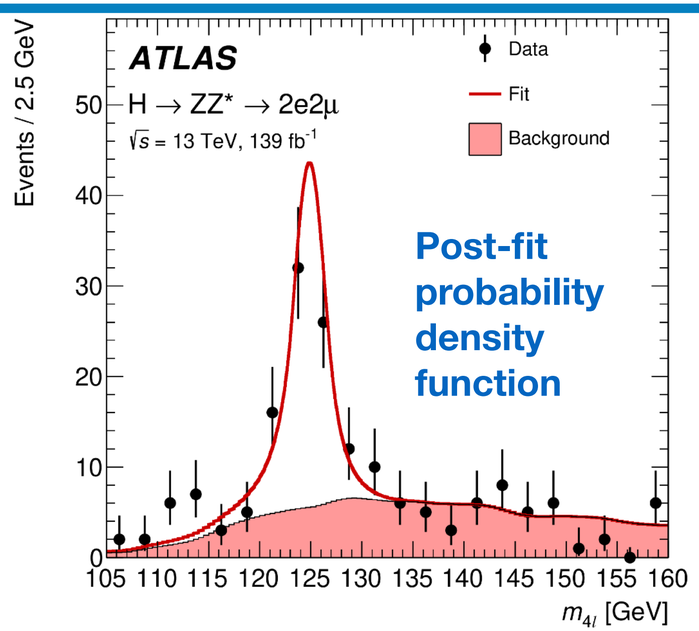
Higgs Boson Mass Measurements

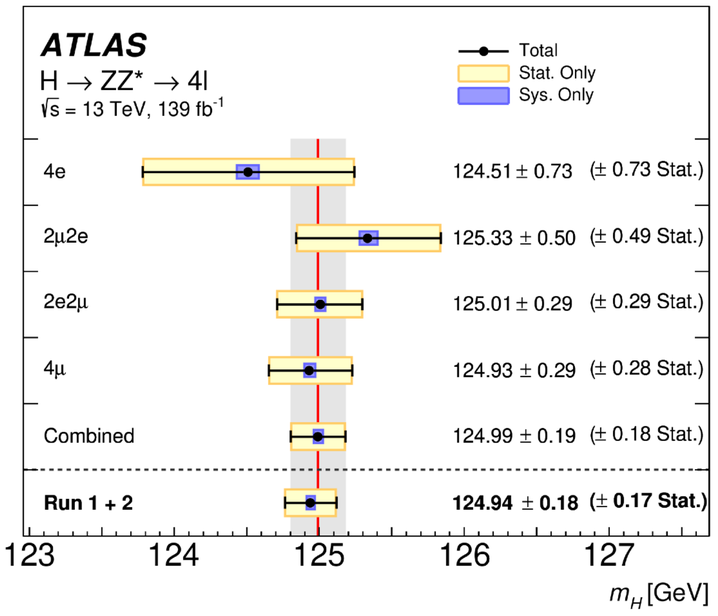
- No update yet beyond the Run-2 legacy ATLAS analysis for H → ZZ* → 4ℓ (ℓ = e or μ):
  - Profits from an increased data sample (full Run-2 dataset of 139 fb^{-1}), includes a new high-precision muon momentum calibration,
  - exploits a neural-network-based classifier for the signal versus background discrimination (improves measurement precision by ~2%) and the inclusion of the event-by-event invariant mass resolution in the analytical model used to fit the data (reducing the total expected uncertainty on m_H by ~1%).

Full Run-2 result: $m_H = 124.99 \pm 0.18\,(\text{stat.}) \pm 0.04\,(\text{syst.}) = 124.99 \pm 0.19\,\text{GeV}$

Run-1 + Run-2 result: $m_H = 124.94 \pm 0.17\,(\text{stat.}) \pm 0.03\,(\text{syst.}) = 124.94 \pm 0.18\,\text{GeV}$







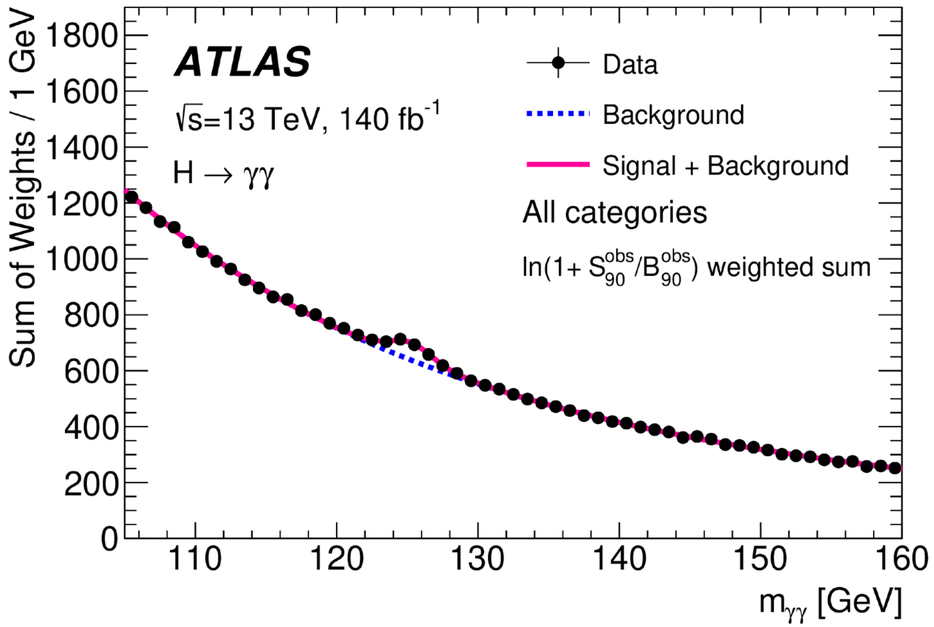
Phys. Lett. B 847 (2023) 138315

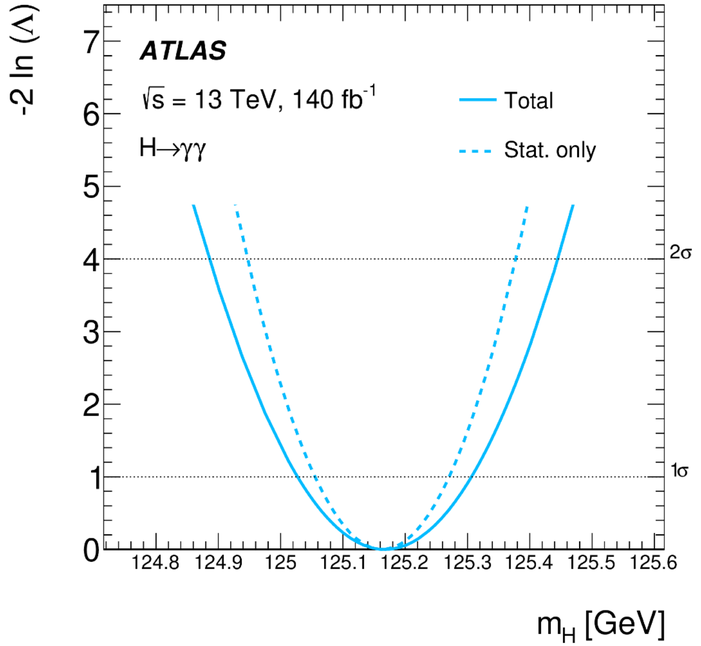
Higgs Boson Mass Measurements

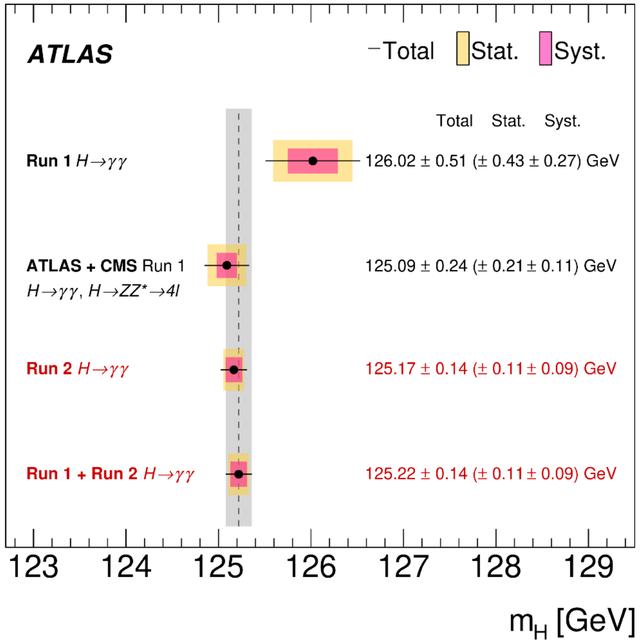
- Run-2 legacy mass measurement analysis in the Higgs to γγ channels benefits from:
  - An increased data sample (full Run-2 dataset of 140 fb^{-1}), and a new photon reconstruction algorithm with better energy resolution,
  - an improved estimation of the photon energy scale with reduced uncertainties—total systematic uncertainty now down to 90 MeV as compared to an earlier result with 340 MeV (Phys. Lett. B 784 (2018) 345)

Full Run-2 result: $m_H = 125.17 \pm 0.11\,(\text{stat.}) \pm 0.09\,(\text{syst.}) = 125.17 \pm 0.14\,\text{GeV}$

Run-1 + Run-2 result: $m_H = 125.22 \pm 0.11\,(\text{stat.}) \pm 0.09\,(\text{syst.}) = 125.22 \pm 0.14\,\text{GeV}$







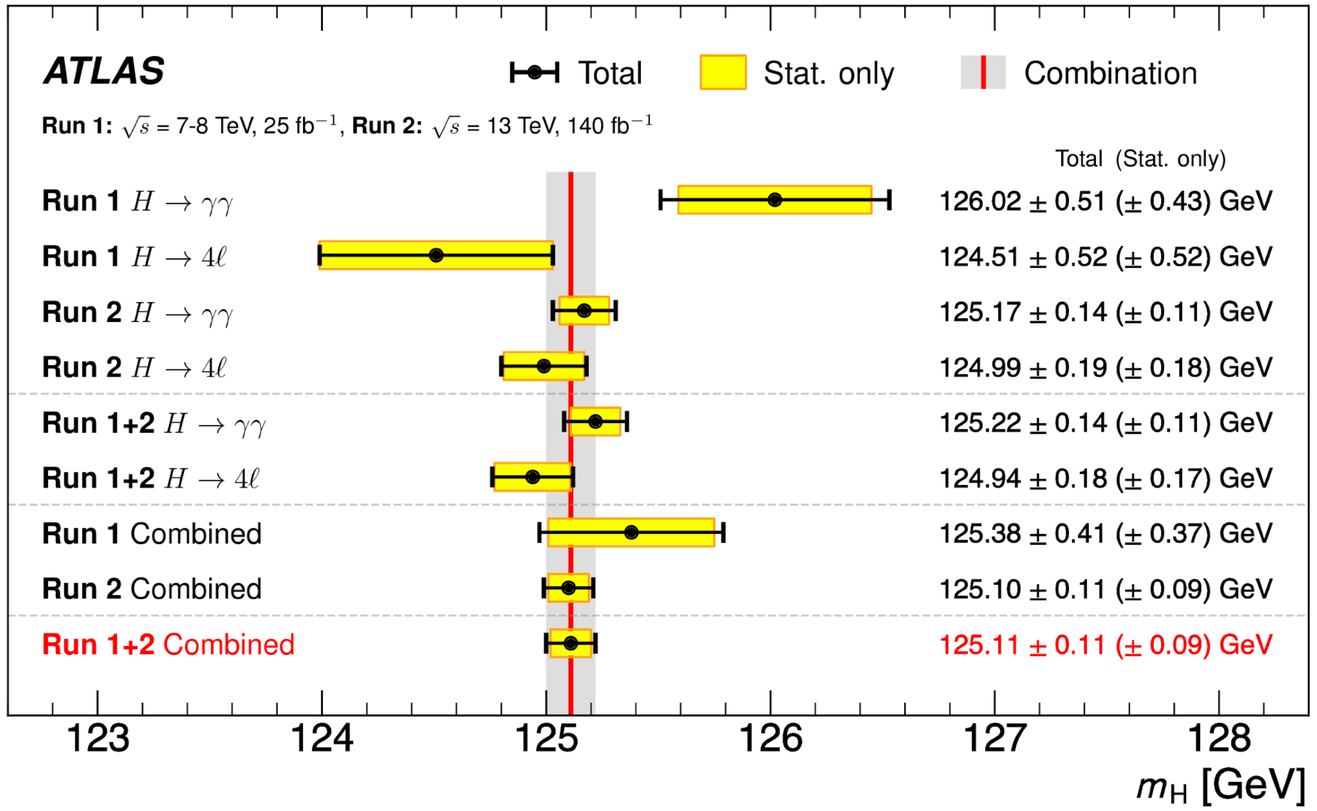
Phys. Rev. Lett. 131 (2023) 251802

Higgs Boson Mass Combination

- Measurement combines the latest results in the H → ZZ* → 4ℓ and H → γγ decay channels
- Result based on 140 fb^{-1} of pp collision data collected at a center of mass energy of 13 TeV during Run-2

Full Run-2 result: $m_H = 125.10 \pm 0.09\,(\text{stat.}) \pm 0.07\,(\text{syst.}) = 125.10 \pm 0.11\,\text{GeV}$

Run-1 + Run-2 result: $m_H = 125.11 \pm 0.09\,(\text{stat.}) \pm 0.06\,(\text{syst.}) = 125.11 \pm 0.11\,\text{GeV}$



Extremely precise measurement of the Higgs boson mass, with an uncertainty of only 110 MeV!

arXiv:2506.19395

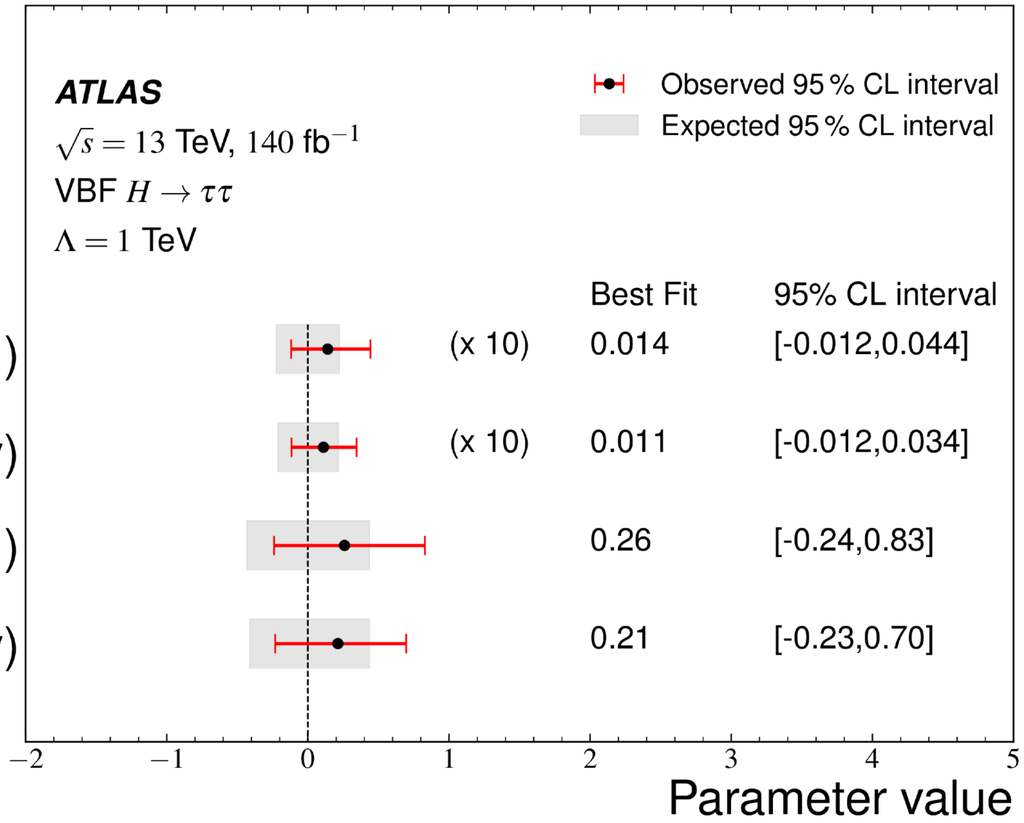
CP properties of Higgs boson interactions in VBF with τ leptons

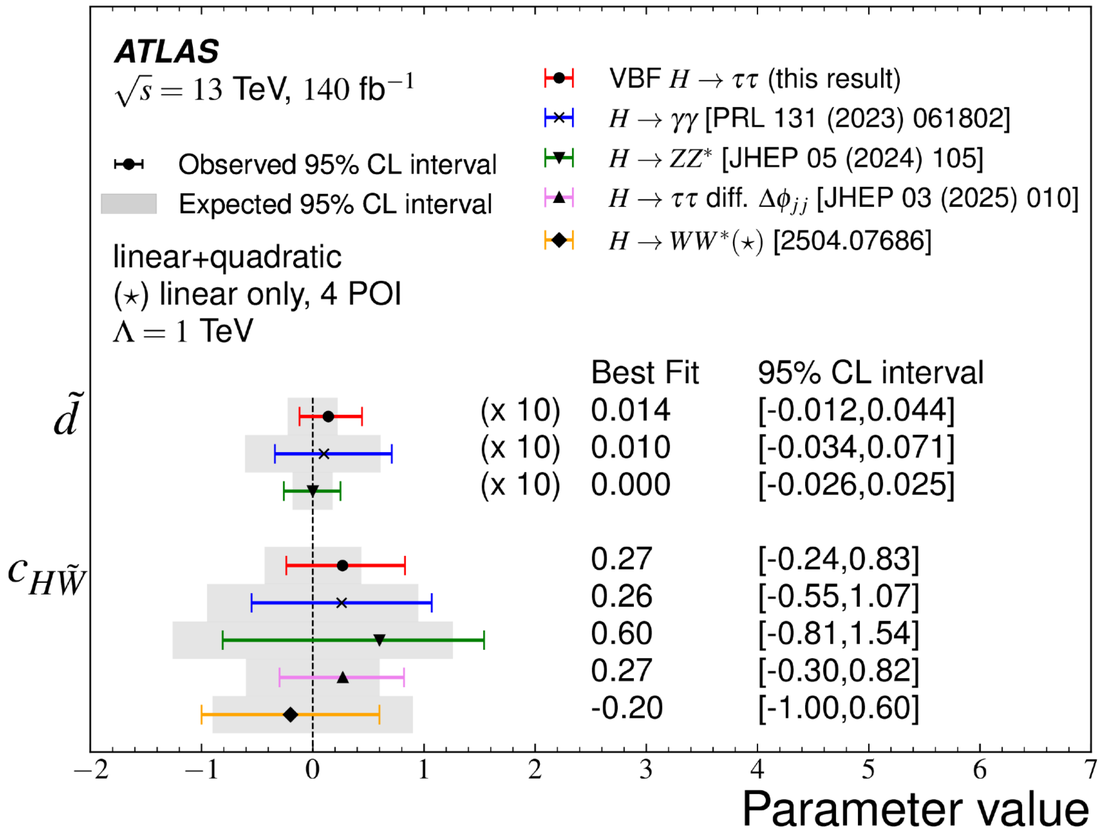
- CP properties of the Higgs boson are studied in the vector-boson fusion production mode (Run-2 dataset)
- Results obtained using the Optimal Observable (OO). CP-violating interactions between the Higgs boson and electroweak gauge bosons are considered in the effective field theory framework
- No deviations relative to the Standard Model are observed, and limits are set

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

$\tilde{d}$ is interaction strength in the HISZ basis

$C_{H\tilde{W}}$ is in the Warsaw basis

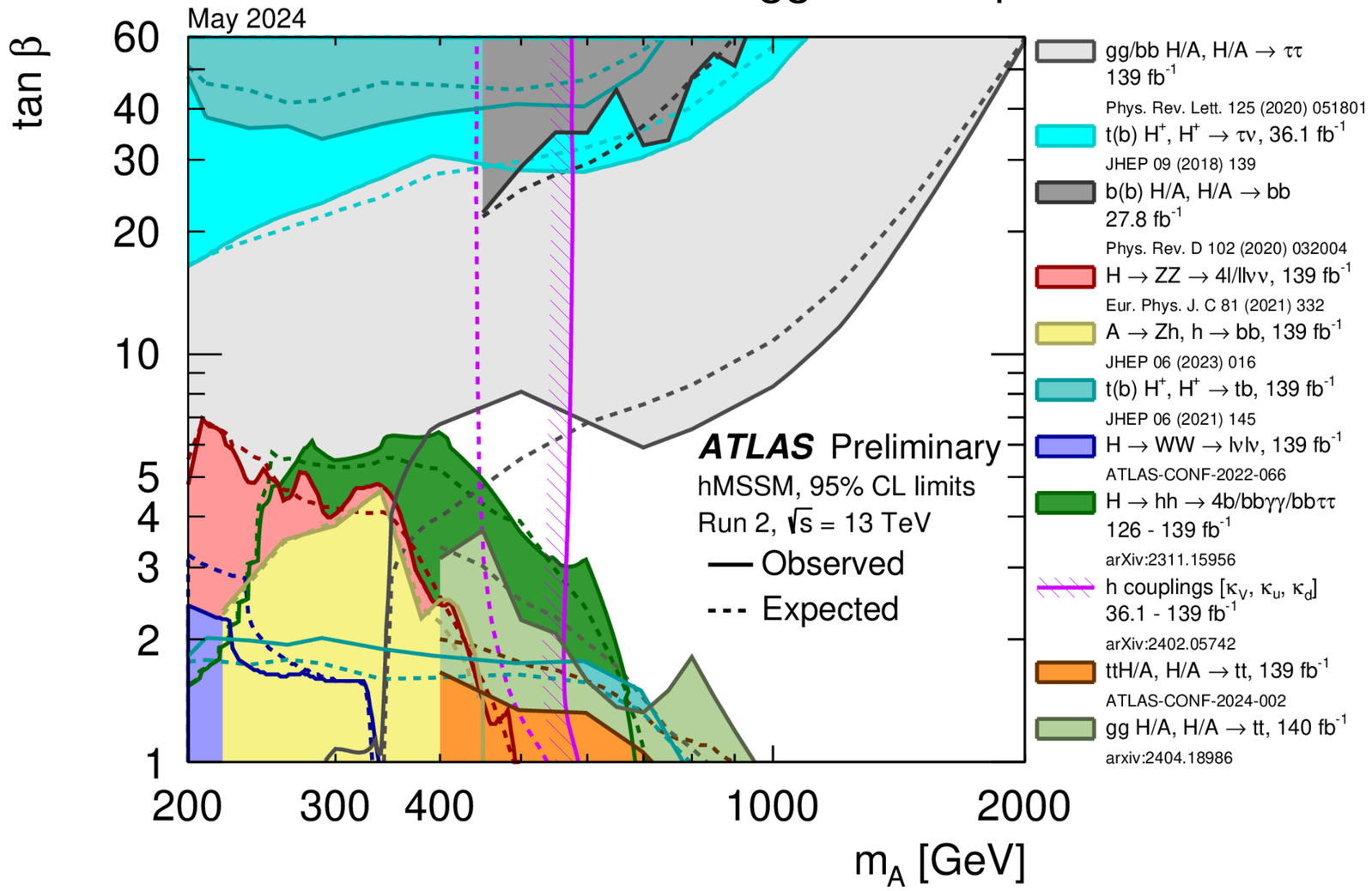




Searches for New Scalars… ‘dragons’

ATLAS BSM Higgs search results

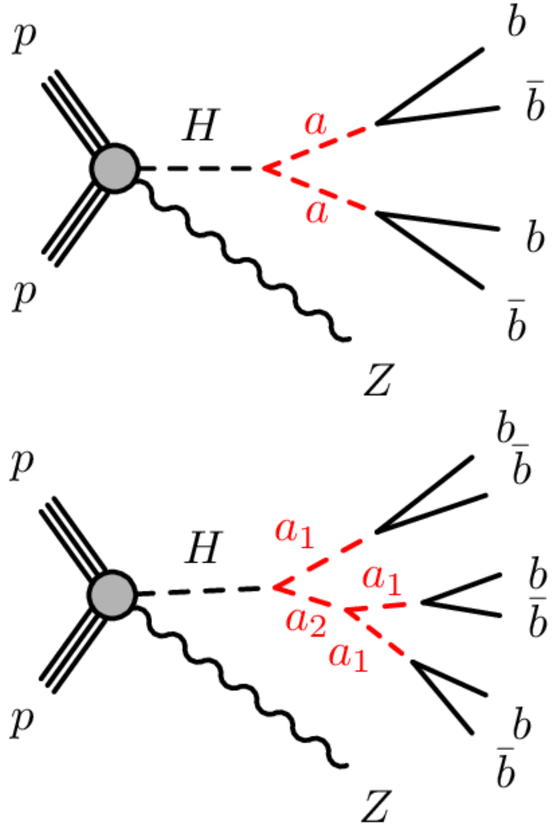
- Regions of the m_A-tanβ plane excluded (95% CL) in the hMSSM via direct searches for heavy Higgs bosons and fits to the measured rates of observed Higgs boson production and decays

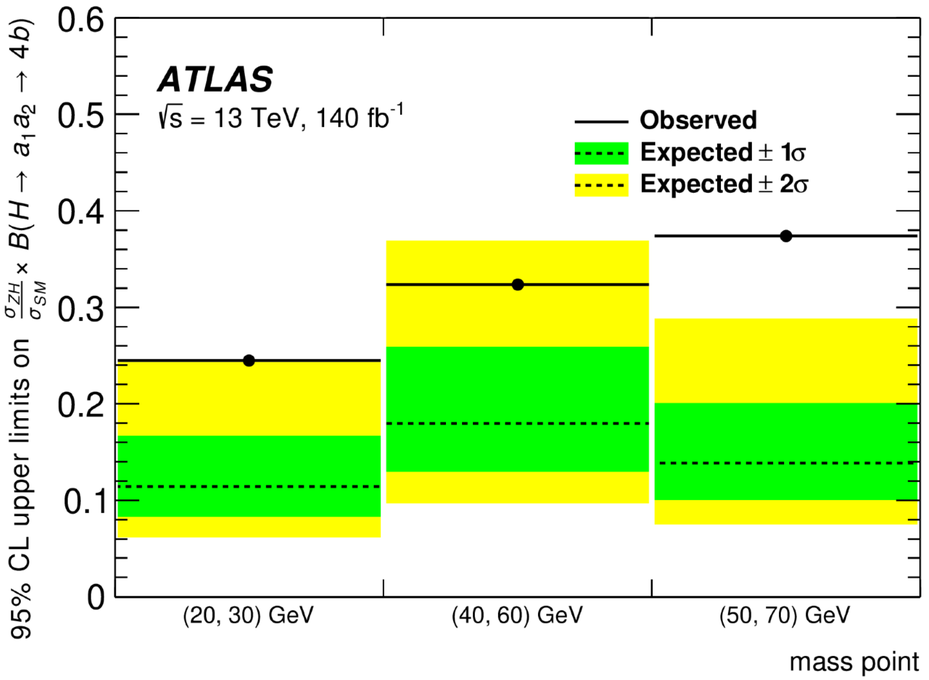


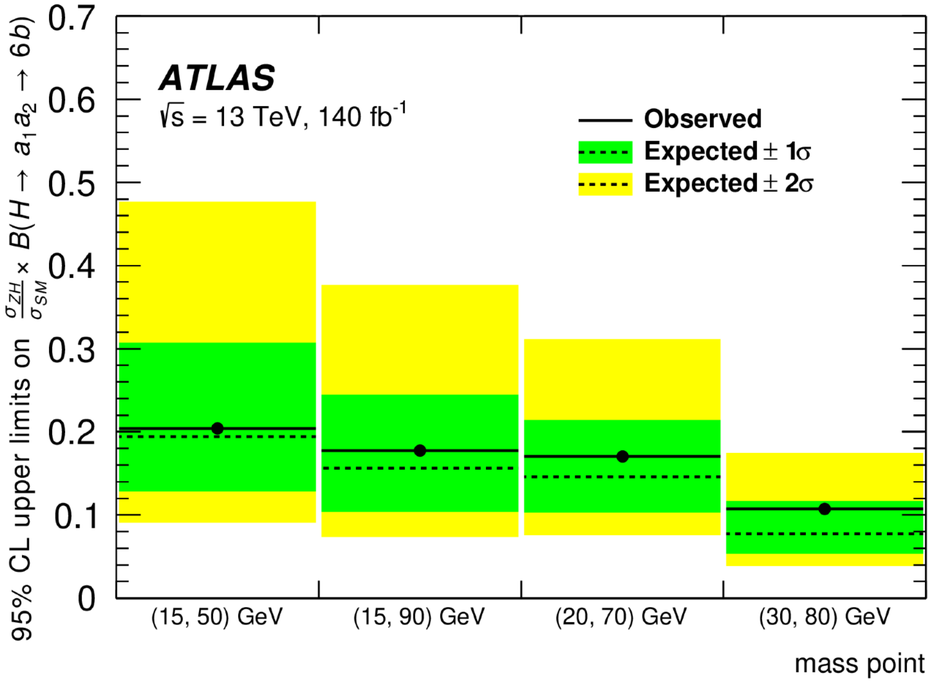
arXiv:2507.01165

ATLAS searches for additional scalars

- Search for exotic decays of the Higgs boson into new scalar or pseudoscalar (a) particles that decay into b-quarks (consider the 4b and 6b final states)
- Uses 140 fb^{-1} of pp collision data recorded during Run-2
- No significant excess above the Standard Model prediction is observed



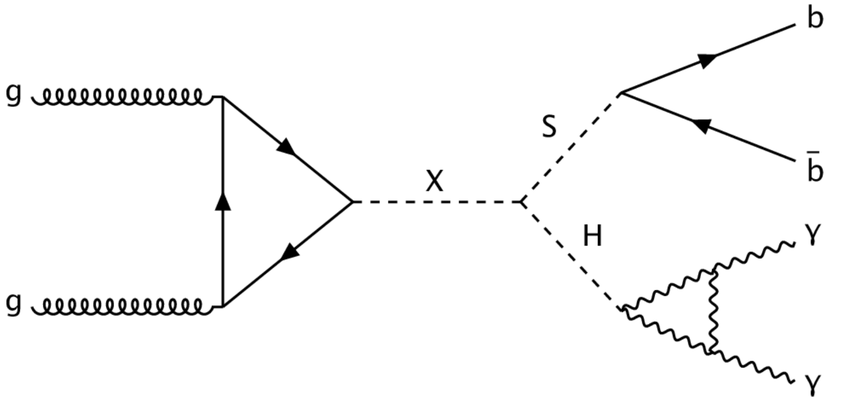


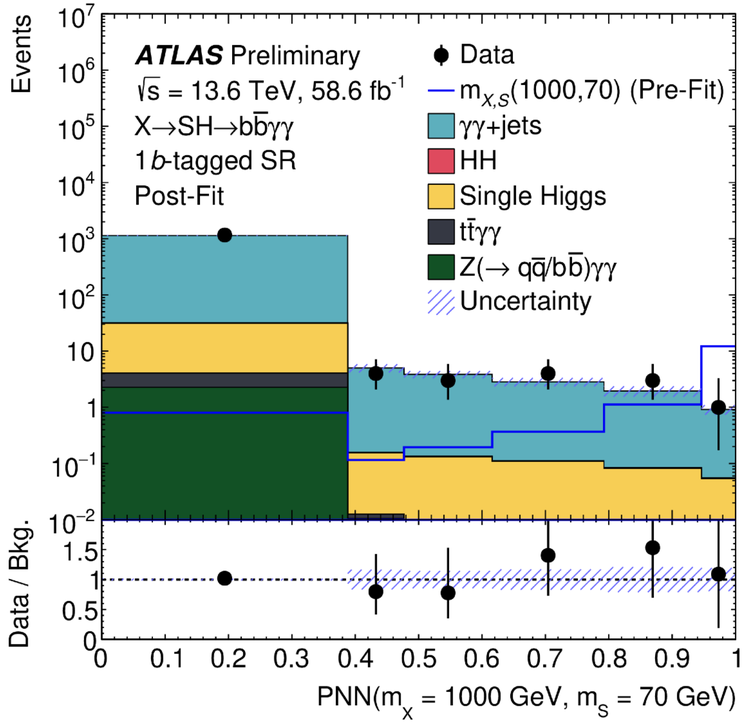


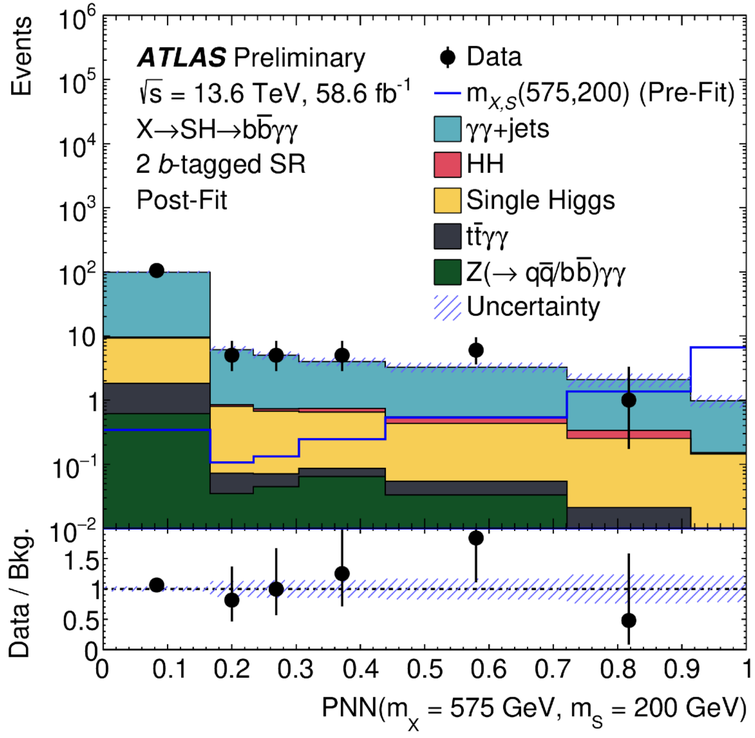
largest local (global) sig. is 3.28 (2.57)

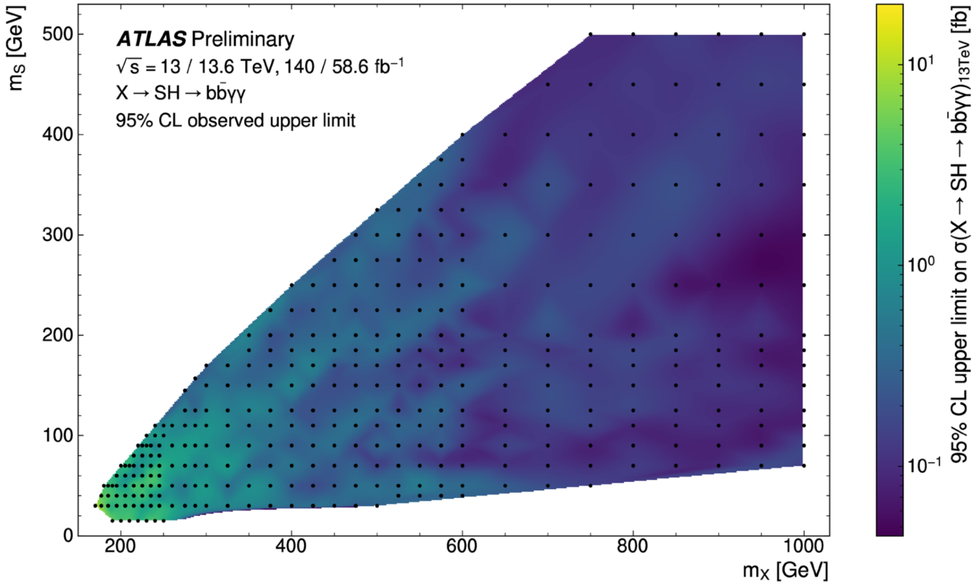
Search for resonance decaying to a new scalar and Higgs

- Search for resonant production of a heavy scalar X decaying into a Higgs and a lighter scalar S in the S→bb and H→γγ final state
- Analysis uses 140 fb^{-1} and 58.6 fb^{-1} of pp collision data at centre-of-mass energies of 13 TeV and 13.6 TeV
- No significant excess over the SM background prediction is observed and limits at 95% CL limits are set on the cross-section









Summary

- ATLAS measurements of Higgs boson properties have been presented; some analyses now including Run-3 data

- Results from the full Run-2 dataset, using the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ decay channels, are combined with the Higgs boson mass measurements performed on Run-1 data. The combined result is:

  - An extremely precise measurement of the Higgs boson mass, reaching a 0.87 per mille accuracy on this fundamental quantity.

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

- The Higgs boson width is measured to be:

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

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- CP properties of the Higgs have been studied in various channels and found to be consistent with the Standard Model
  - A pure CP-odd contribution is excluded for H-tau and H-top interactions
  - There is still room for a CP mixture

- Analysis of Run-3 data is on-going, and we're excited to learn even more about the Higgs boson and its properties

- Of course the search for any additional scalars continues…

Back-up

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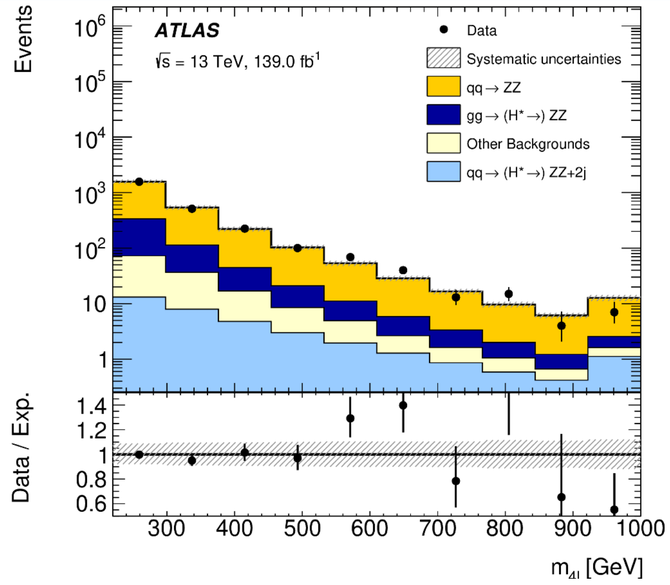
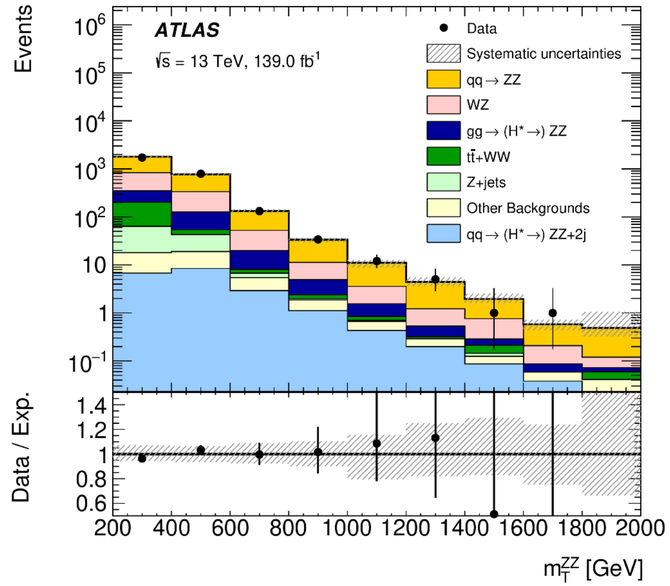
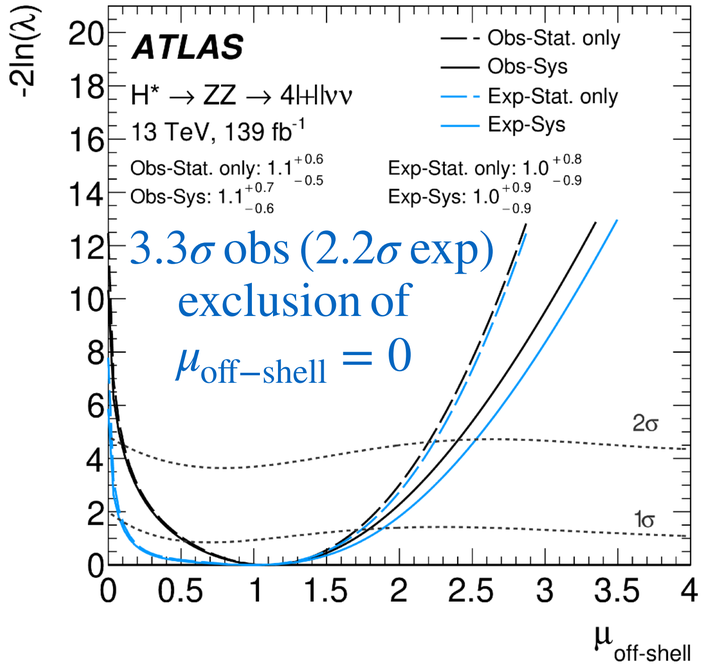
Determination of the Higgs Boson Width



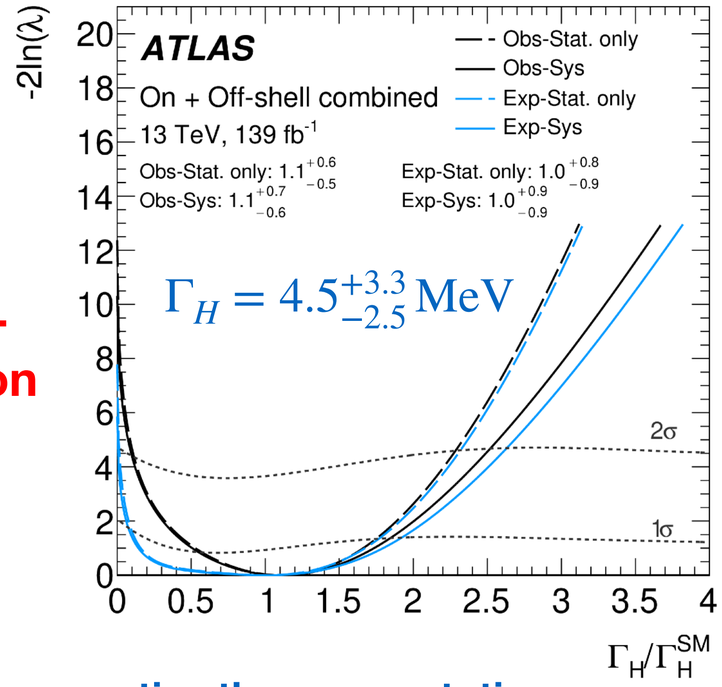


- Predicted Higgs width of 4.1 MeV is much smaller than the detector resolution
- This 4ℓ and $2\ell\,2\nu$ ZZ combination exploits the independence of off-shell cross section on Γ_H and relies on identical on-shell and off-shell Higgs couplings to determine Γ_H from measurements of $\mu_{\text{off-shell}}$ and $\mu_{\text{on-shell}}$

$$\sigma^{\text{on-shell}}_{gg\to H\to VV} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{gg\to H\to VV} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m^2_{ZZ}}$$



Evidence for off-shell Higgs boson production!



NB: Neyman likelihood profiles shown; ~5-10% more conservative than asymptotic

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Measuring CP properties of Higgs boson interactions with τ leptons

- Analysis tests the CP properties of the tau Yukawa coupling, where contributions can be present at tree level
- The CP-mixing angle ϕ_τ is reflected in tau decay kinematics

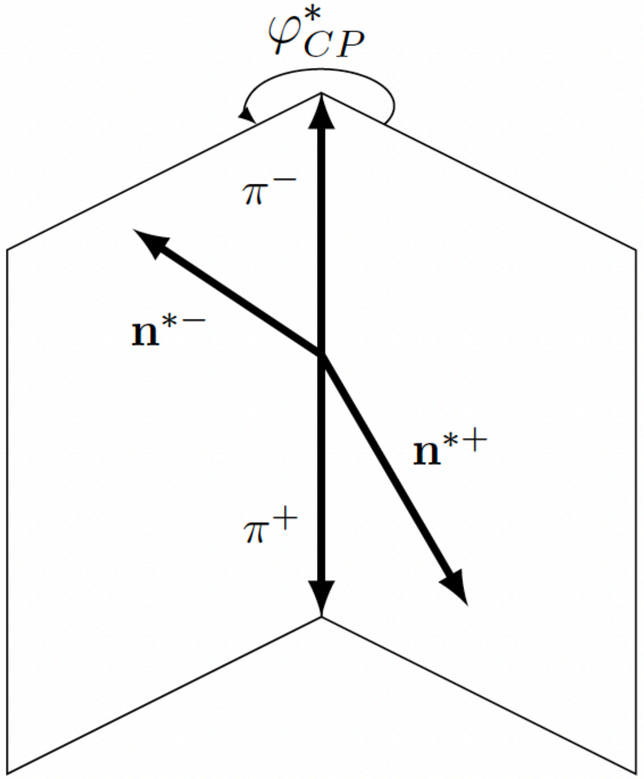
First ATLAS analysis to use tau decay classification!

- Rejection of the CP-odd hypothesis at 3.4σ (2.1σ expected)

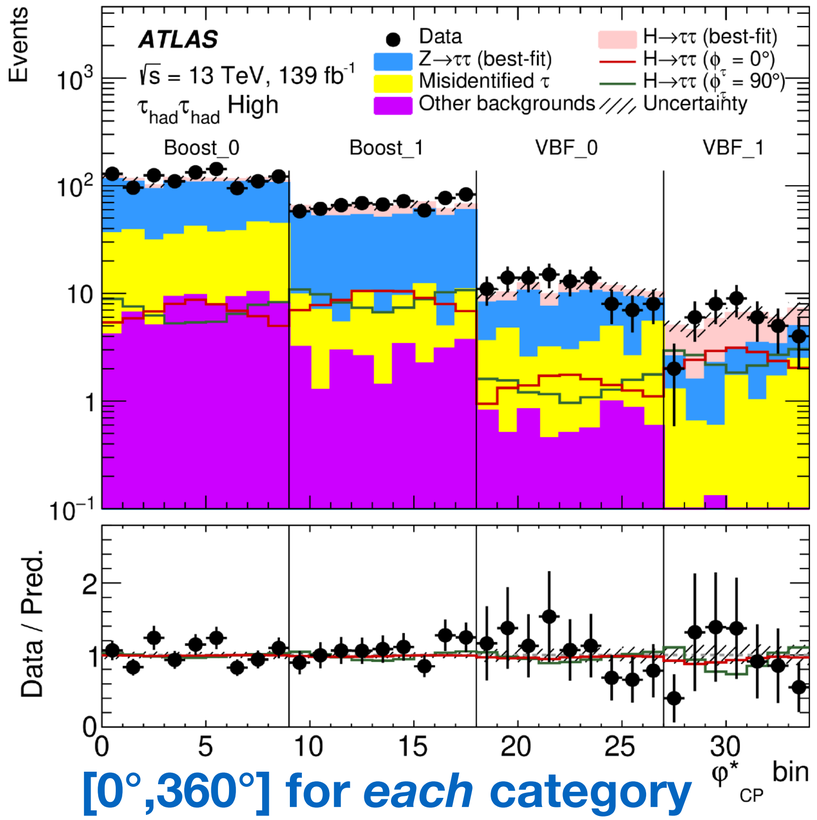
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

CP-even **CP-odd**

SM case: $\phi_\tau = 0$



$H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$



[0°,360°] for *each* category