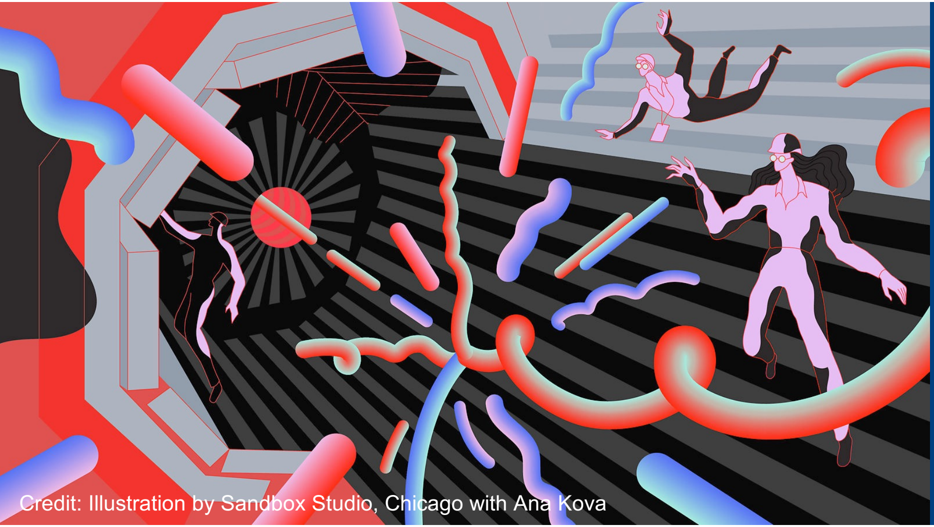
TAE 2023 – International Workshop on High Energy Physics
Benasque (Spain), 3-16 September 2023


Credit: Illustration by Sandbox Studio, Chicago with Ana Kova

Higgs Physics
(Lecture 2)

Aurelio Juste (ICREA/IFAE)

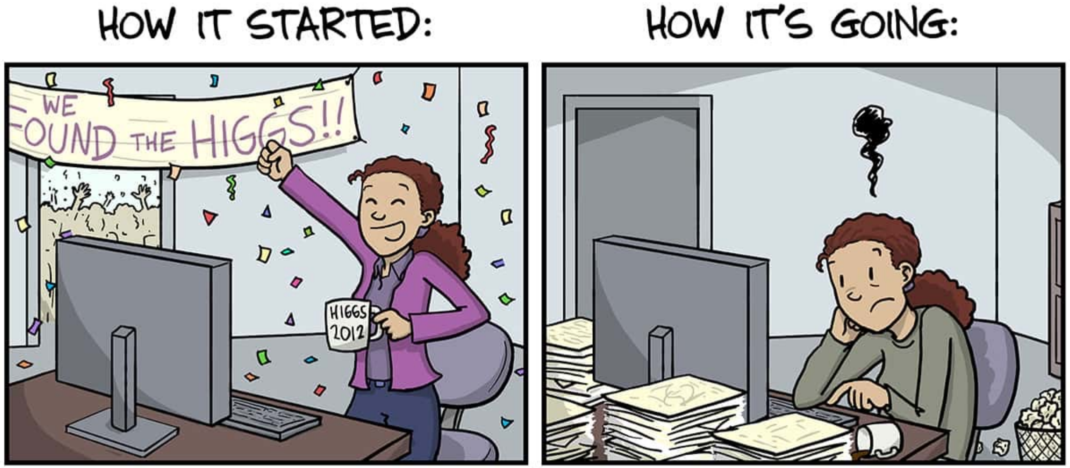
ICREA

IFAE Institut de Física d'Altes Energies
BIST Barcelona Institute of Science and Technology

Outline

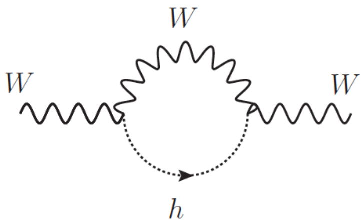
Lecture 1: Stalking the Higgs boson
- Preliminaries on Higgs physics
- Pre-LHC searches
- The discovery

Lecture 2: Studying the Higgs boson
- Overview of Run 1 studies
- Summary of recent Run 2 results
- Future prospects



Much more to Higgs physics than the LHC!

Indirect precision EW



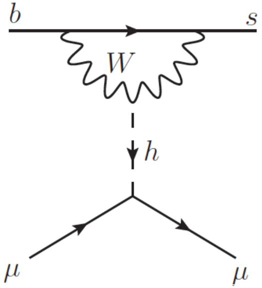
Direct Search Programs

- LEP
- TeVatron
- SLC
- Etc…

H^0

LHC

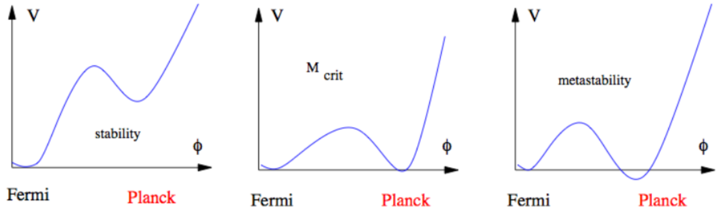
Indirect Flavor



(Higgs penguin)

Indirect cosmology

- Vacuum stability
- Higgs Inflation
- Etc…

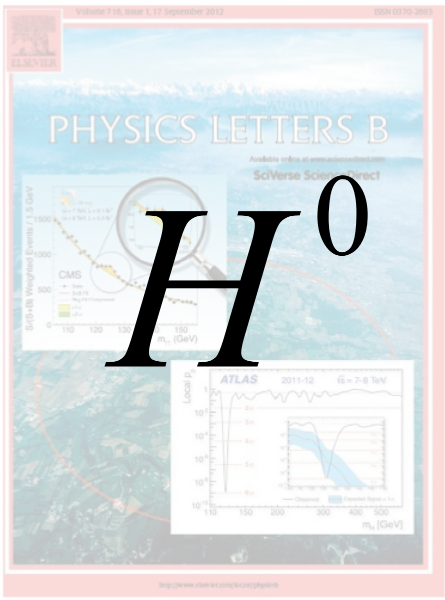


Explosion of the Higgs landscape

Precision measurements
- Mass and width
- Quantum numbers (spin, CP)
- Coupling properties
- Differential cross sections
- Off-shell couplings and width
- Interferometry

Is the SM minimal?
- 2HDM searches
- MSSM, NMSSM searches
- Doubly-charged Higgs bosons

Since the discovery of the Higgs boson, an entire new field has emerged



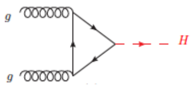
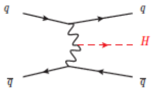
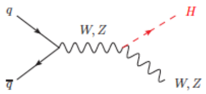
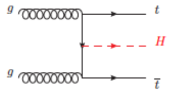
Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (VH^0, H^0H^0)

Rare / BSM decays
- $H^0 \rightarrow \mu\mu$
- $H^0 \rightarrow Z\gamma$
- $H^0 \rightarrow J/\psi\gamma$, $\Upsilon(ns)\gamma$
- LFV $H^0 \rightarrow \mu\tau$, $e\tau$, $e\mu$
- $H^0 \rightarrow aa$

…and more!
- FCNC $t \rightarrow H^0q$ decays
- Di-Higgs production
- Trilinear coupling
- … etc

Overview of main Higgs analyses

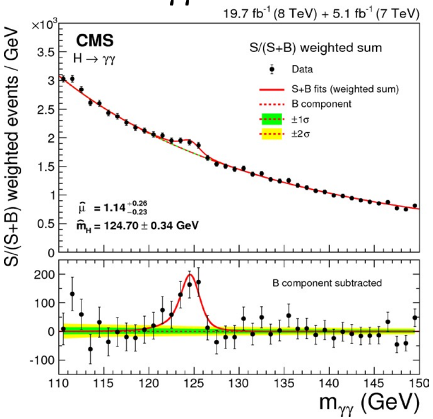
Production modes

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓			
ττ	✓			
bb				
Zγ	✓			
μμ	✓			
Invisible	✓ (mo			

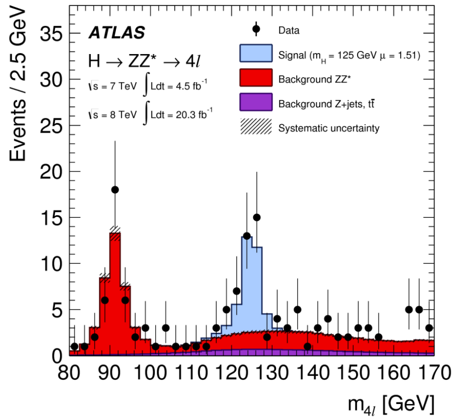
Decay modes

Discovery channels

γγ



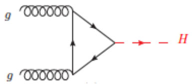
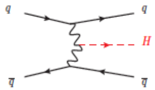
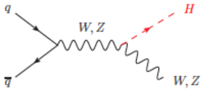
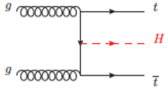
ZZ* → 4l



Overview of main Higgs analyses

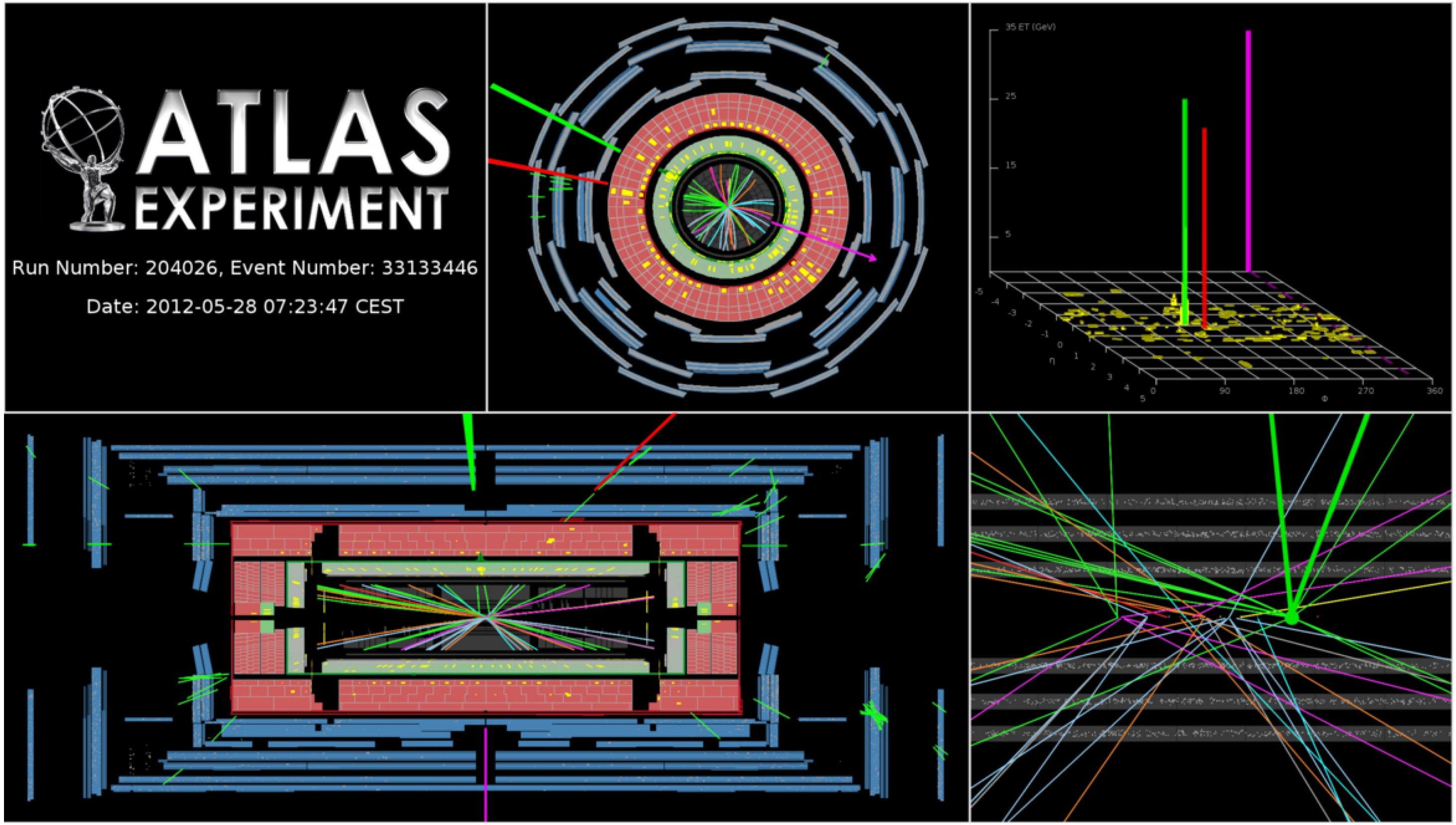
Production modes

Decay modes

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ	✓			
bb		✓	✓	✓
Zγ	✓	✓		
μμ	✓	✓		
Invisible	✓ (monojet)	✓	✓	

A different kind of discovery channel…

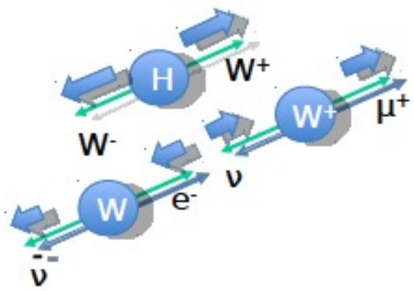
$H \rightarrow WW^{*} \rightarrow l\nu l\nu$

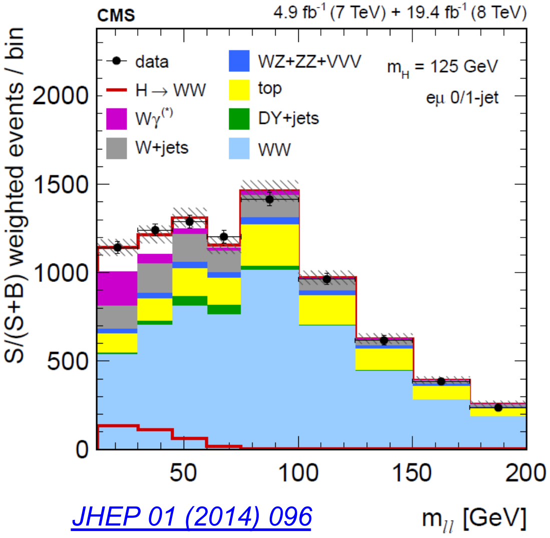


Requires exquisite background understanding!

H→WW*→lνlν

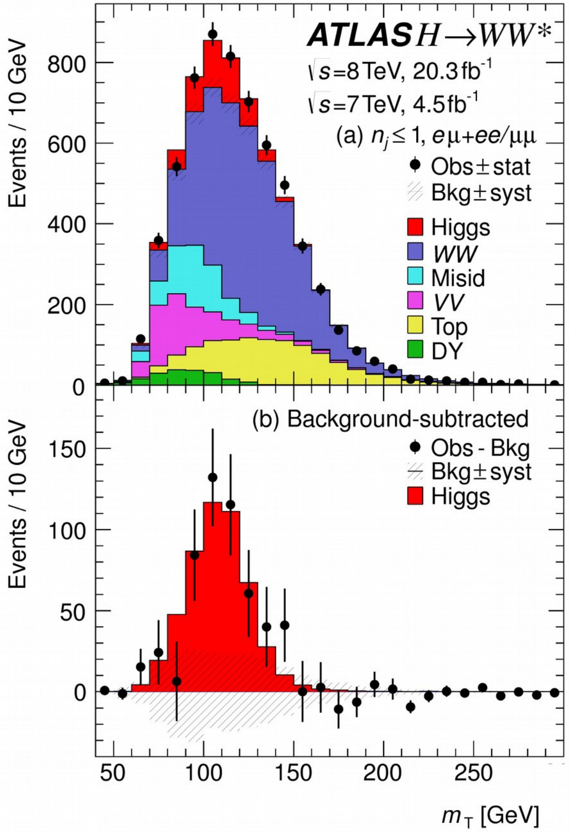
- High-sensitivity channel for $130<m_H<200$ GeV.
- Clean dilepton plus E_T^{miss} signature but low S/B.
- Main backgrounds: Z+jets, WW, W+jet/γ, tt.
  ➔ normalization in data control regions.
- No direct reconstruction of Higgs mass possible (neutrinos)
  ➔ use transverse mass variable.
- Exploit spin correlation between W bosons:
  spin 0 ➔ small angular separation between leptons.





JHEP 01 (2014) 096

PRD 92 (2015) 012006

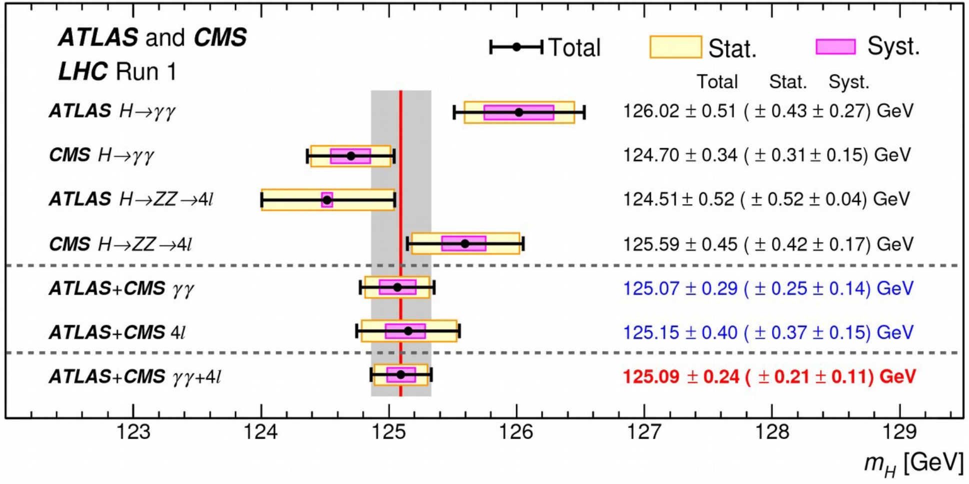


Higgs mass

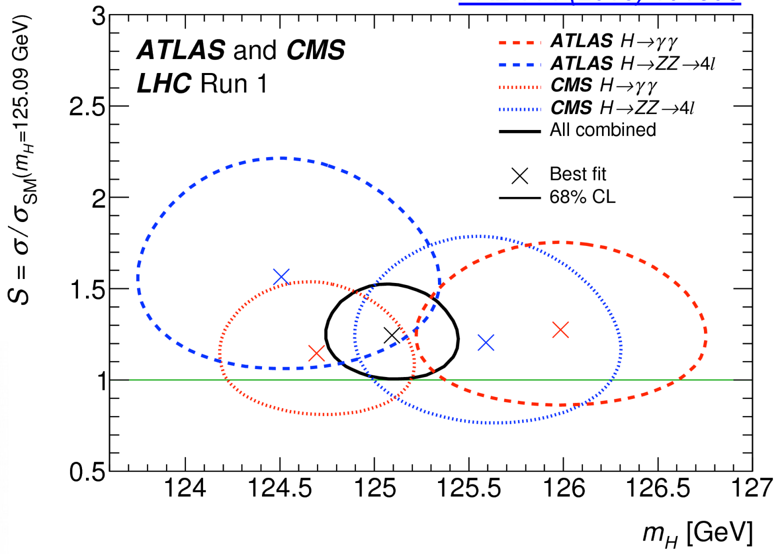
- Measurement of the Higgs boson mass performed in the two channels with the best mass resolution: H→γγ and H→ZZ*→4l using final Run 1 calibrations.
- Signal yield left free to avoid biasing mass measurement.

$m_H = 125.09 \pm 0.24$ GeV

2 per-mille accuracy!



PRL 114 (2015) 191803



- Compatibility of the four measurements ~10%.
- Measurement dominated by the statistical uncertainty.
- Main systematic uncertainty related to photon and lepton energy scales.

Spin and CP

- **Goal**: verify scalar and CP-even nature ($J^{CP}=0^+$) of the new boson.
  - Spin is a property of the particle. Possibilities:
    J=0 and J=2 allowed
    J=1 forbidden by Landau-Yang theorem (since $H\rightarrow\gamma\gamma$ is observed)
  - CP is a property of the interaction
    ➔ here will discuss about CP tests in the HVV interaction. Additional tests required to test the CP properties of the interactions with fermions

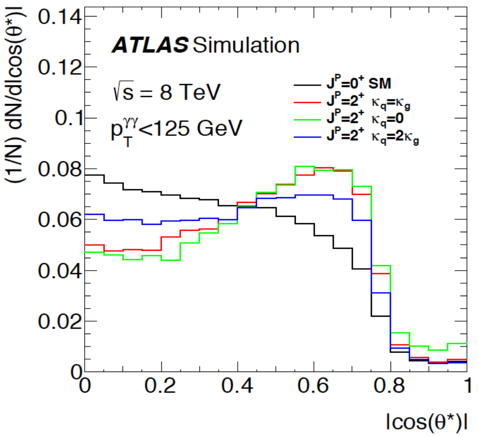
- Many options to probe J^{CP} from angular (or threshold behavior) distributions:
  - From the associated production modes (VH, VBF or gg→H+jets)
  - From the production angle cosθ* distribution
  - From the decay angles and the spin correlation when applicable

- Basic idea:
  - Measure compatibility with the 0^+ hypothesis.
  - Try to exclude alternative hypotheses (in favor of the 0^+ hypothesis) simulated using an effective Lagrangian including higher order couplings.

Spin and CP

- Use H→γγ, ZZ* and WW* analyses re-optimized for J^{CP} tests. Different kinematic distributions used.

H→γγ: mostly sensitive to spin. Uses $p_T(\gamma\gamma)$ and photon decay angle in γγ rest frame.



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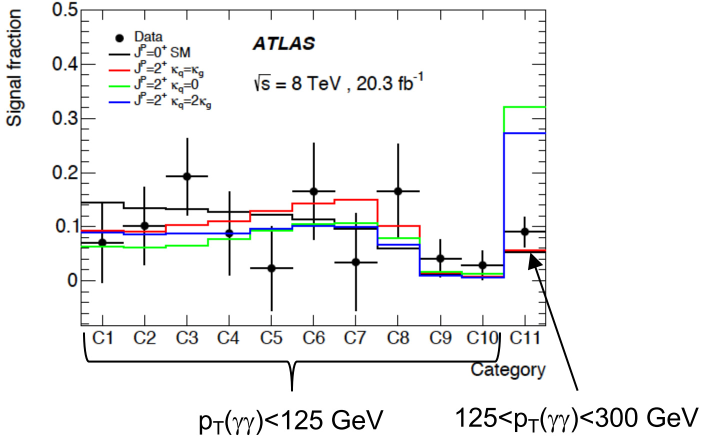
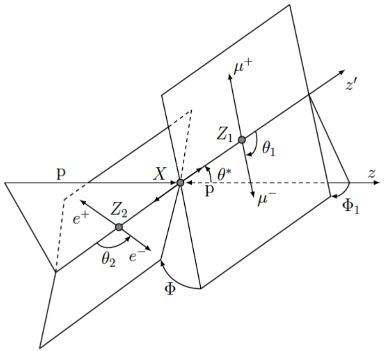
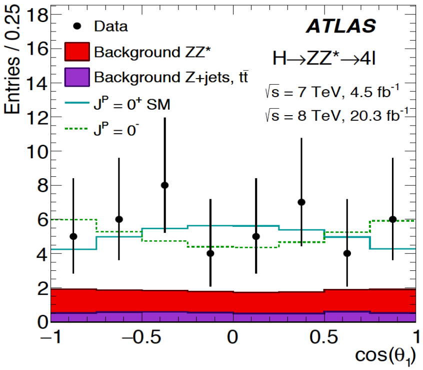


H→ZZ*→4l: mostly sensitive to parity. Uses the distribution of 5 production and decay angles combined in a BDT or Matrix Element (MELA) discriminants

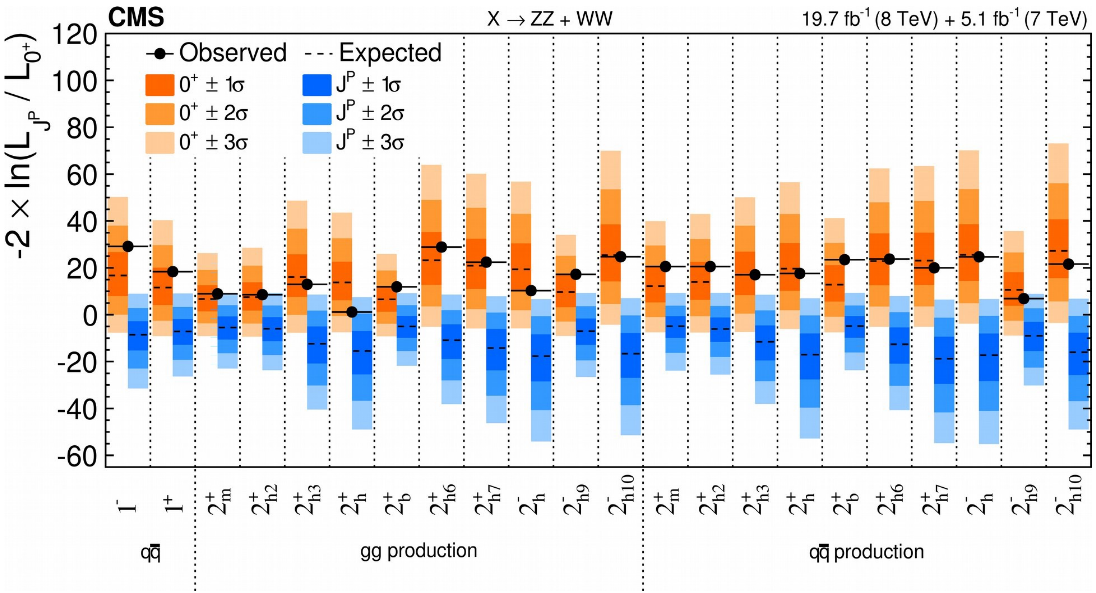




Spin and CP

- Alternative spin hypotheses are disfavored by >3σ combining H→γγ, H→ZZ*, and H→WW* analyses.
- Tensor structure of the HVV interaction has been tested using H→ZZ*, H→WW*, H→Zγ, and H→γγ analyses, including CP-odd contributions.

PRD 92 (2015) 012004



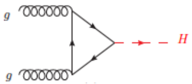
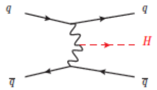
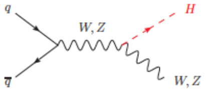
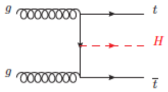
$$L(HVV) \sim a_1 \frac{m_Z^2}{2} H Z^\mu Z_\mu - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 H Z_\mu \Box Z^\mu - \frac{1}{2} a_2 H Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 H Z^{\mu\nu} \tilde{Z}_{\mu\nu} + a_1^{WW} m_W^2 H W^{+\mu} W_\mu^- - \frac{1}{(\Lambda_1^{WW})^2} m_W^2 \times H(\kappa_1^{WW} W_\mu^- \Box W^{+\mu} + \kappa_2^{WW} W_\mu^+ \Box W^{-\mu}) - a_2^{WW} H W^{+\mu\nu} W_{\mu\nu}^- - a_3^{WW} H W^{+\mu\nu} \tilde{W}_{\mu\nu}^- + \frac{\kappa_2^{Z\gamma}}{(\Lambda_1^{Z\gamma})^2} m_Z^2 H Z_\mu \partial_\nu F^{\mu\nu} - a_2^{Z\gamma} H F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} H F^{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma} H F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} H F^{\mu\nu} \tilde{F}_{\mu\nu},$$

Results consitent with a SM-like Higgs boson, within the precision of the tests

Overview of main Higgs analyses

Production modes

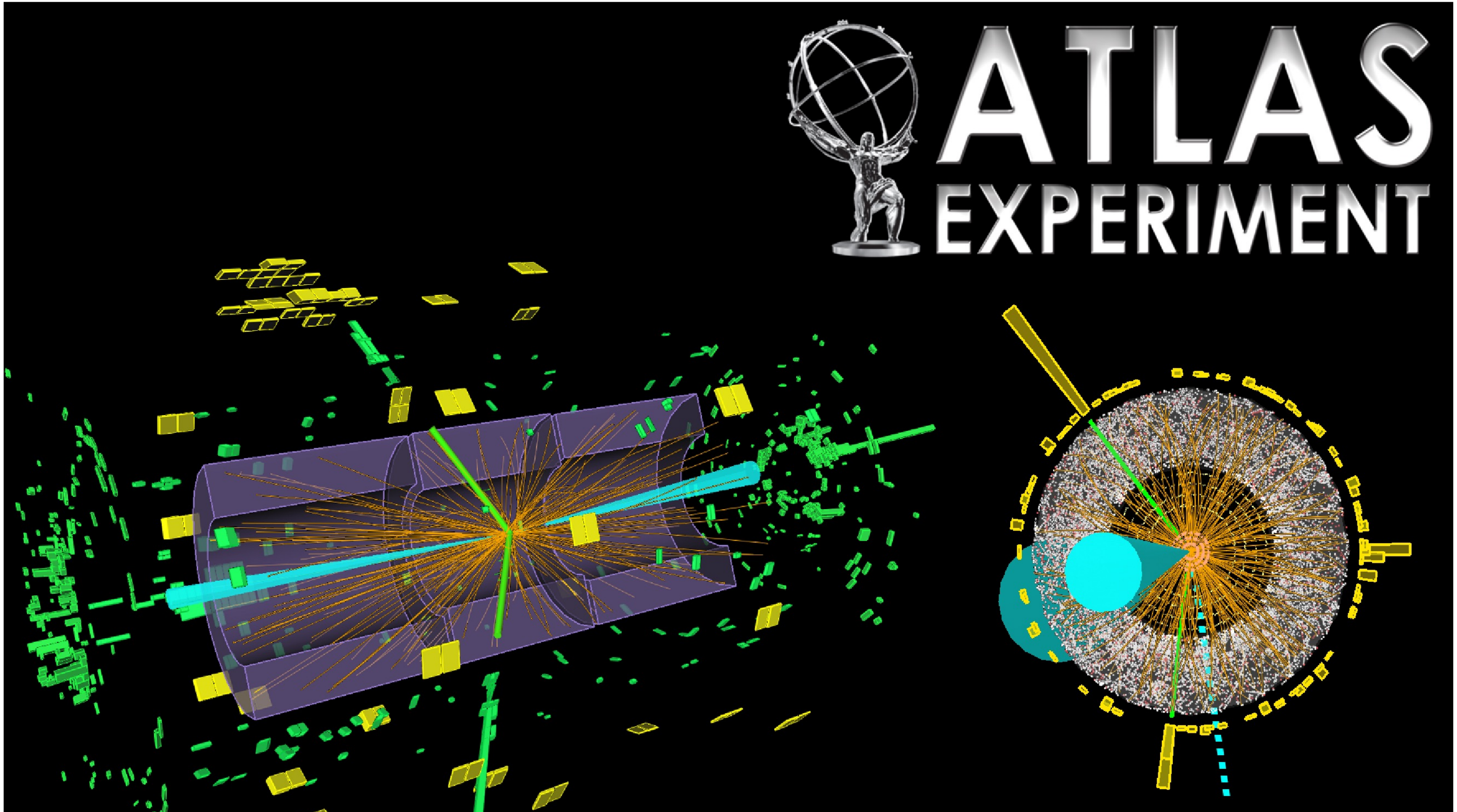
Decay modes

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lνlν)	✓	✓	✓	✓
ττ	✓	✓	✓	✓
bb		✓	✓	✓
Zγ	✓	✓		
μμ	✓	✓		
Invisible	✓ (monojet)	✓	✓	

The rest of the channels are crucial to establish the nature of the particle

And more!

Higgs couplings to fermions: H→$\tau^+\tau^-$



H→$\tau_{had}\tau_{had}$ candidate in VBF channel (m_{MMC} = 131 GeV)

Higgs couplings to fermions: $H \rightarrow \tau^+\tau^-$

- The most sensitive of the fermionic decay modes.
- Events categorized depending on the tau decay modes (leptonic, hadronic) and the jet multiplicity to enhance the sensitivity to VBF and gluon fusion production of highly-boosted Higgs bosons.
- Main background is $Z \rightarrow \tau\tau$, modeled from $Z \rightarrow \mu\mu$ data replacing muons by simulated tau decays ("τ embedding").

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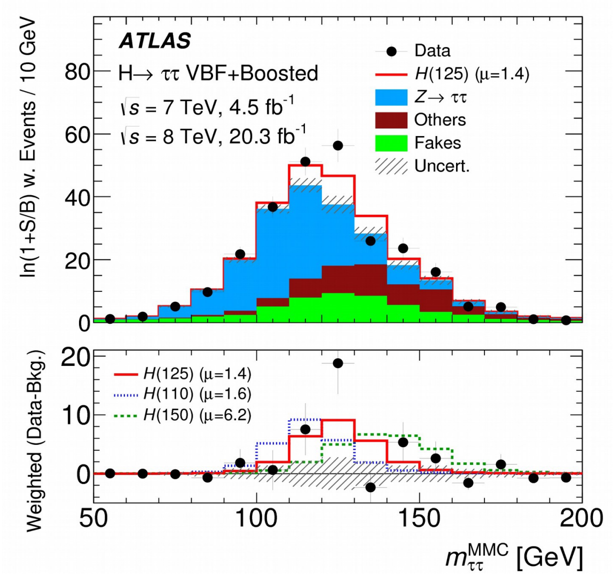

Obs (exp) significance: 4.5σ (3.4σ)

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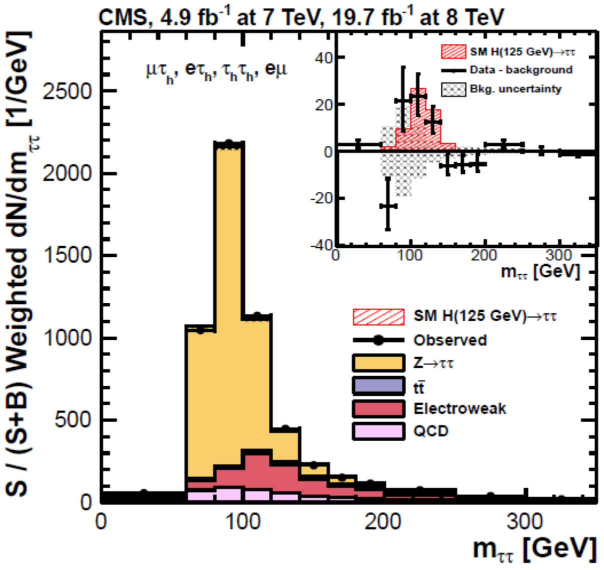
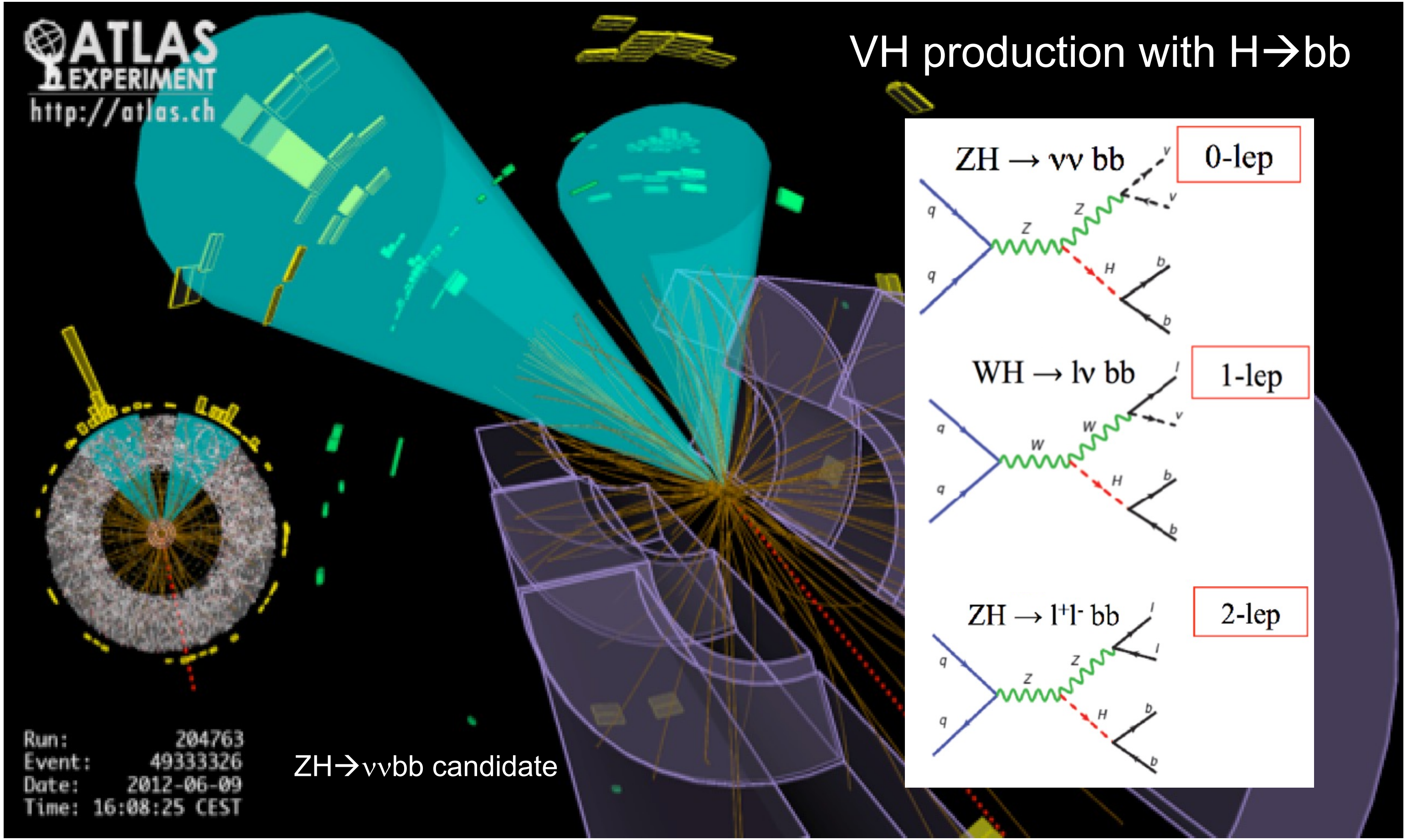


Obs (exp) significance: 3.2σ (3.7σ)

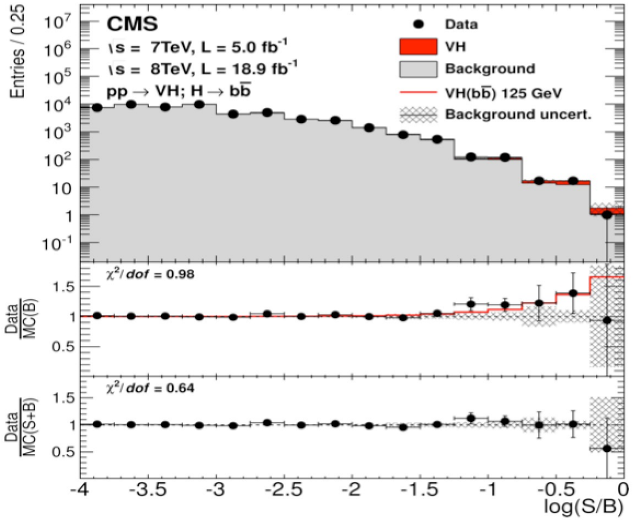
Higgs couplings to fermions: H→bb



Higgs couplings to fermions: H→bb

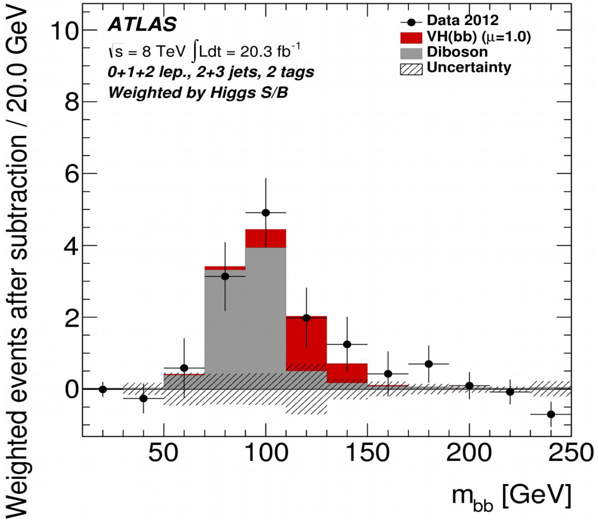
- Most abundant decay mode: BR(H→bb)~58%.
- Exploit three leptonic W/Z decay modes in VH associated production
  ➔ categorize events by lepton multiplicity (0-lepton, 1-lepton, 2-lepton).
- Broad di-b-jet resonance over large background from W+heavy-flavor and tt production.
- Multivariate analyses to increase sensitivity. Use VZ(Z→bb) to validate search strategy.

PRD 89 (2014) 012003



Obs (exp) significance: 2.1σ (2.1σ)

JHEP 01 (2015) 069

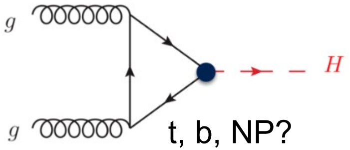


Obs (exp) significance: 1.4σ (2.6σ)

Higgs couplings to fermions: H→bb

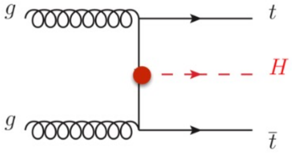
- Associated ttH production allows direct measurement of the top-Higgs Yukawa coupling.

Indirect



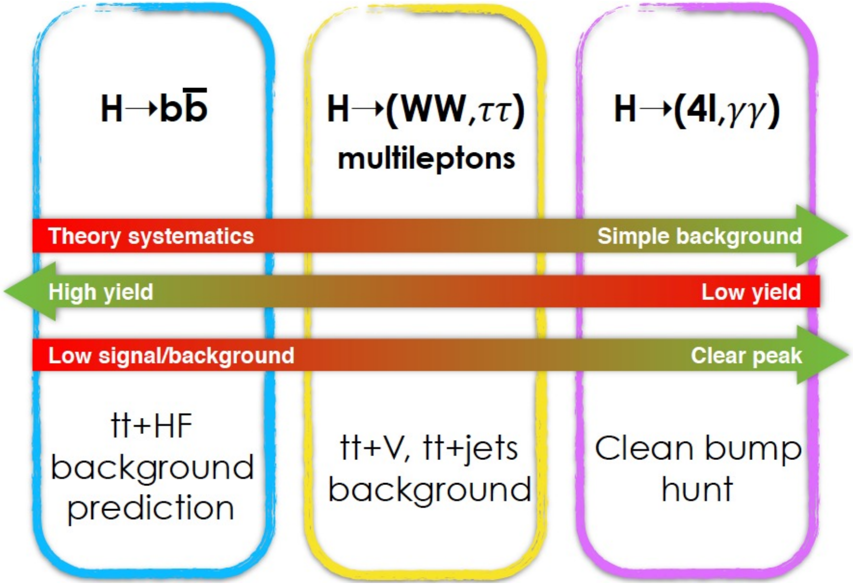
vs

Direct



$$\sigma_{t\bar{t}H} \propto \lambda_t^2$$

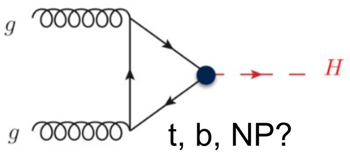
- Very rich experimental signature, depending on the decay of the top quarks and the Higgs boson.
- Analyses characterized by large number of categories and control regions.



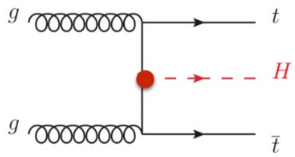
Higgs couplings to fermions: H→bb

- Associated ttH production allows direct measurement of the top-Higgs Yukawa coupling.

Indirect vs **Direct**



vs



$$\sigma_{t\bar{t}H} \propto \lambda_t^2$$

- Very rich experimental signature, depending on the decay of the top quarks and the Higgs boson.

- Analyses characterized by large number of categories and control regions.

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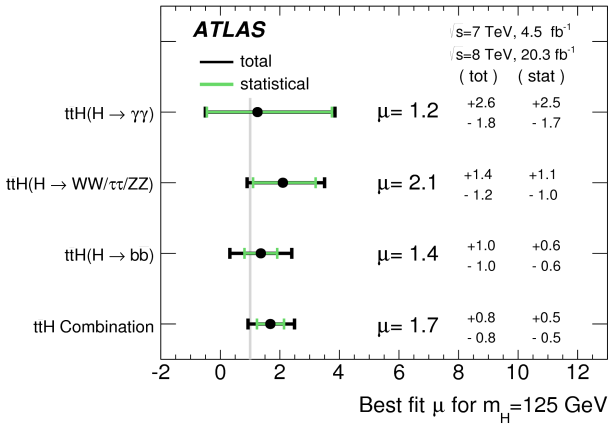
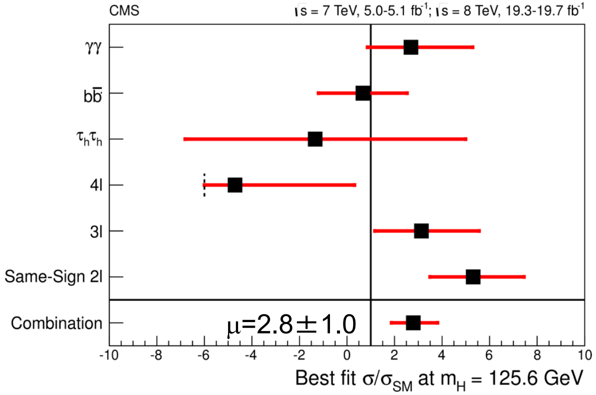


Obs (exp) significance: 2.5σ (1.5σ)

JHEP 09 (2014) 087



Obs (exp) significance: 3.4σ (1.2σ)

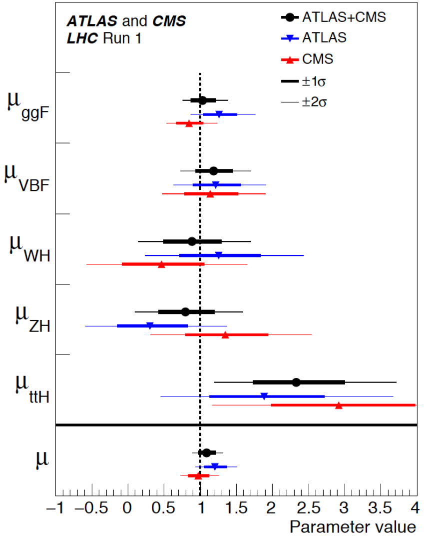
Probing Higgs couplings

- At the LHC only products of cross section times branching ratios are measured.
  - There is no model-independent way to determine the cross section and the branching ratio separately.
  - Several production and decay mechanisms contribute to signal rates per channel ➔ interpretation is difficult.

$$n_s^c = \underline{\mu}\left(\sum_{i\in\{processes\}} \underline{\mu^i}\sigma_{SM}^i \times A^{ic} \times \varepsilon^{ic}\right) \times \underline{\mu^f} Br^f \times L^c$$

$\sigma_{meas}/\sigma_{SM}$ per production mode

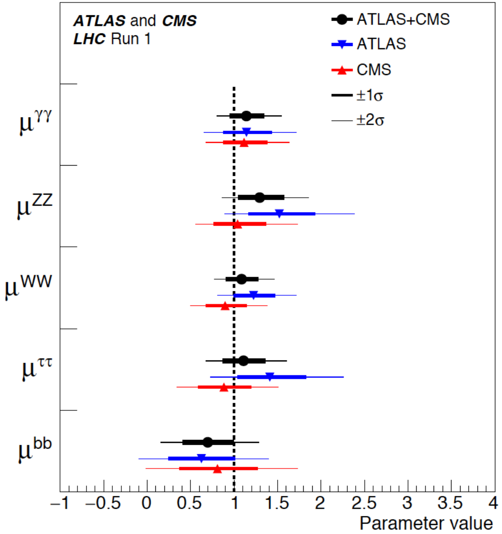
(assuming SM decay)



Significance $[\sigma]$	
VBF	5.4 (4.7)
WH	2.4 (2.7)
ZH	2.3 (2.9)
VH	3.5 (4.2)
ttH	4.4 (2.0)
Expected in parentheses	

BR_{meas}/BR_{SM} per decay mode

(assuming SM production)



Significance $[\sigma]$	
$H \to \gamma\gamma$	> 5
$H \to ZZ$	> 5
$H \to WW$	> 5
$H \to \tau\tau$	5.5 (5.0)
$H \to bb$	2.6 (3.7)
Expected in parentheses	

Probing Higgs couplings

- A better option: measure deviations of couplings from the SM prediction using an effective Lagrangian (arXiv:1209.0040).

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$+ \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu}\right) H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$

- MOTIVATION: **Precision Higgs coupling measurements can provide an indirect probe for NP.**

  - SUSY (tanβ=5): $\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$
  - Composite Higgs: $\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$
  - Top partners: $\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2$

Expected deviations in general small. Need precise measurements!

The “kappa framework”

- Basic assumptions:
  - there is only one underlying state with m_H=125.09 GeV,
  - it has negligible width,
  - it is a CP-even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched).

- Under these assumptions all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings.

  Examples:

$$\sigma(gg \to H)BR(H \to WW) = \sigma_{SM}(gg \to H)BR_{SM}(H \to WW)\frac{\kappa_g^2\kappa_W^2}{\kappa_H^2}$$

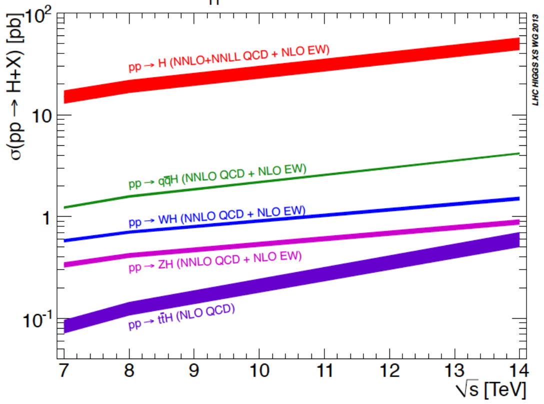
$$\sigma(WH)BR(H \to bb) = \sigma_{SM}(WH)BR_{SM}(H \to bb)\frac{\kappa_W^2\kappa_b^2}{\kappa_H^2}$$

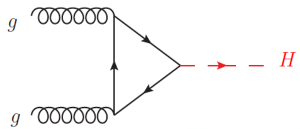
where $\kappa_H^2 = \frac{\sum_i \kappa_i^2 \Gamma_{i,SM}}{\sum_i \Gamma_{i,SM}}$

Parameterizing Higgs production cross-sections

Higgs Production Modes

κ for m_H = 125.5 GeV





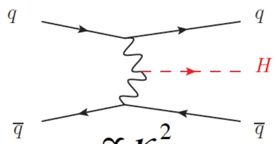
Gluon fusion process

NNnLO ~O(10%)

~0.5 M events produced

$$\propto \kappa_g^2 = 1.06\kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$$

(when assuming no colored BSM in the loop)



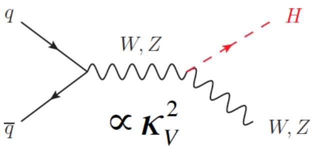
Vector Boson Fusion

NLO TH uncertainty ~O(5%)

Two forward jets and a large rapidity gap

~40 k events produced

$$\propto \kappa_V^2$$

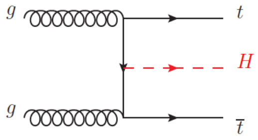


W and Z Associated Production

NNLO TH uncertainty ~O(5%)

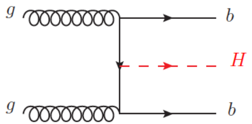
~20 k events produced

$$\propto \kappa_V^2$$



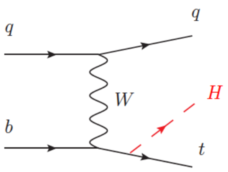
$$\propto \kappa_t^2$$

Top Assoc. Prod. ~3 k evts produced

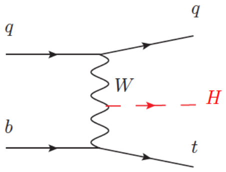


$$\propto \kappa_b^2$$

B-quark Assoc. Prod. ~5 k evts produced



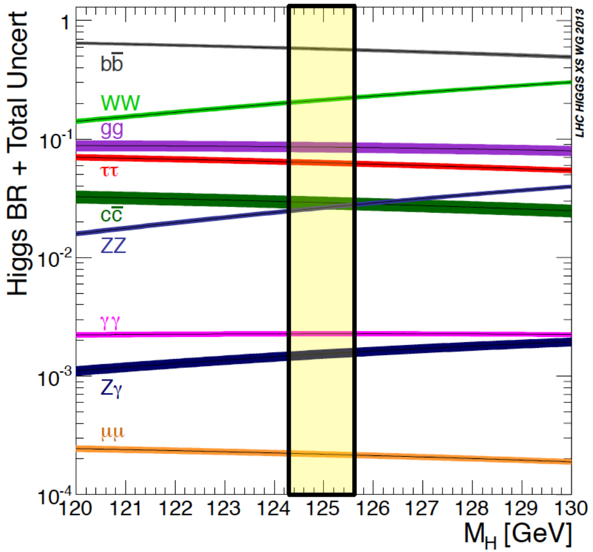
tH

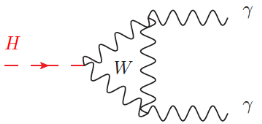


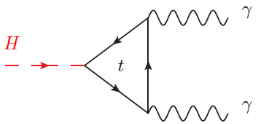
$$\propto 3.3\kappa_W^2 - 5.1\kappa_t\kappa_W + 2.8\kappa_t^2$$

Parameterizing Higgs branching ratios

- Dominant: bb (57%) $\propto \kappa_b^2 / \kappa_H^2$
- WW channel (22%) $\propto \kappa_W^2 / \kappa_H^2$
- ττ channel (6.3%) $\propto \kappa_\tau^2 / \kappa_H^2$
- ZZ channel (3%) $\propto \kappa_Z^2 / \kappa_H^2$
- cc channel (3%) $\propto \kappa_c^2 / \kappa_H^2$
  Extremely difficult
- The γγ channel (0.2%) $\propto \kappa_\gamma^2 / \kappa_H^2$







$$\kappa_\gamma^2 \propto 1.6\kappa_W^2 - 0.7\kappa_t\kappa_W + 0.1\kappa_t^2$$

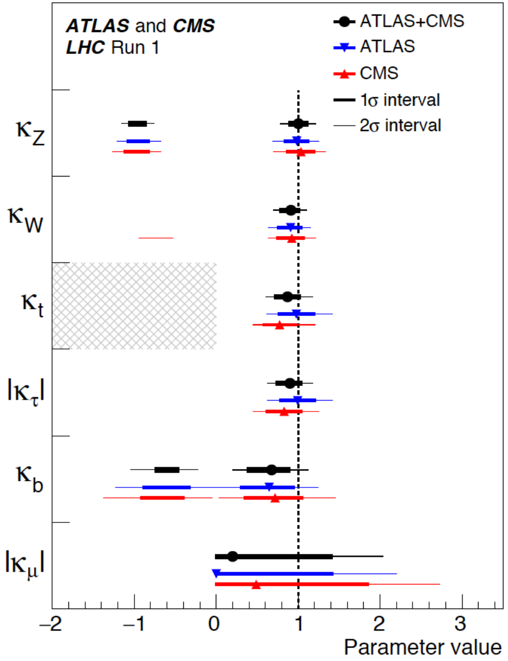
(when assuming no BSM charged in the loop)

- The Zγ (0.2%) $\propto \kappa_{Z\gamma}^2 = 1.12\kappa_W^2 - 0.15\kappa_t\kappa_W + 0.03\kappa_t^2$
- The μμ channel (0.02%) $\propto \kappa_\mu^2 / \kappa_H^2$

Standard Model fit

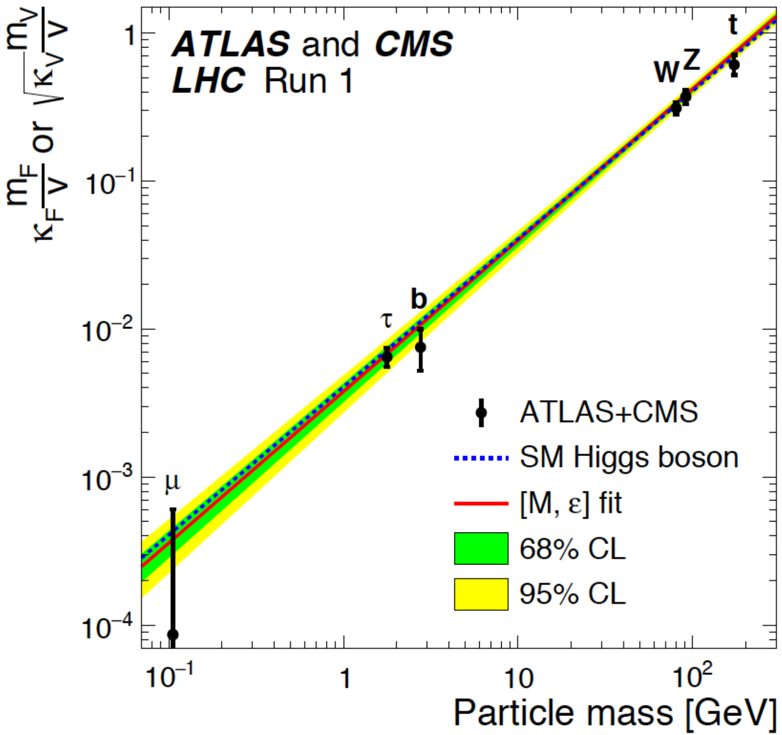
- Resolve all loops.
- One coupling parameters per SM particle.
- No beyond-SM decays.

$\kappa_Z, \kappa_W, \kappa_t,$
$\kappa_b, \kappa_\tau, \kappa_\mu$



Compatibility with the SM: 74%

JHEP 08 (2016) 045



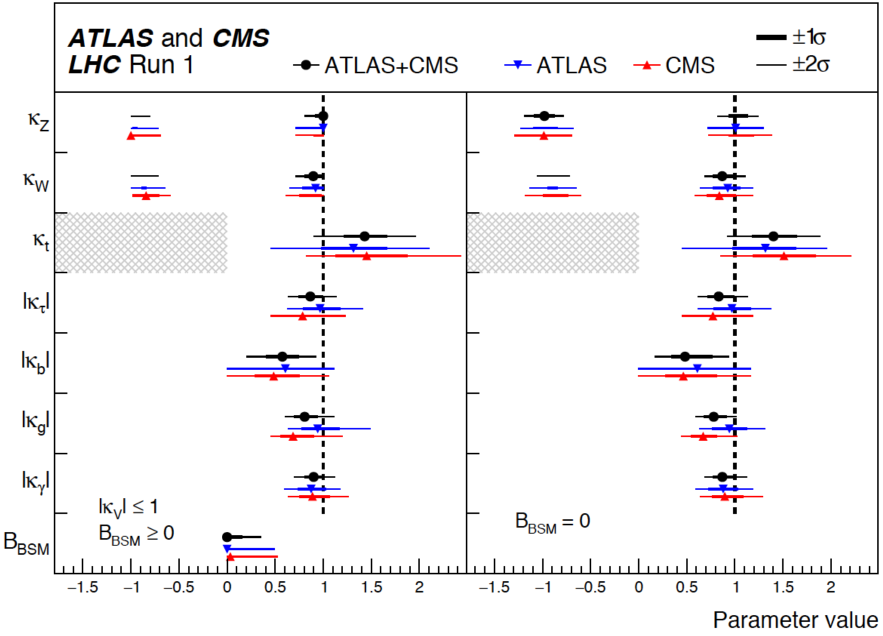
Beyond Standard Model fit

- Allow deviations in all tree-level couplings.
- Allow independent deviations in loop couplings.
- Allow beyond-Standard-Model decays.
- Impose weak constraint $\kappa_V \leq 1$.

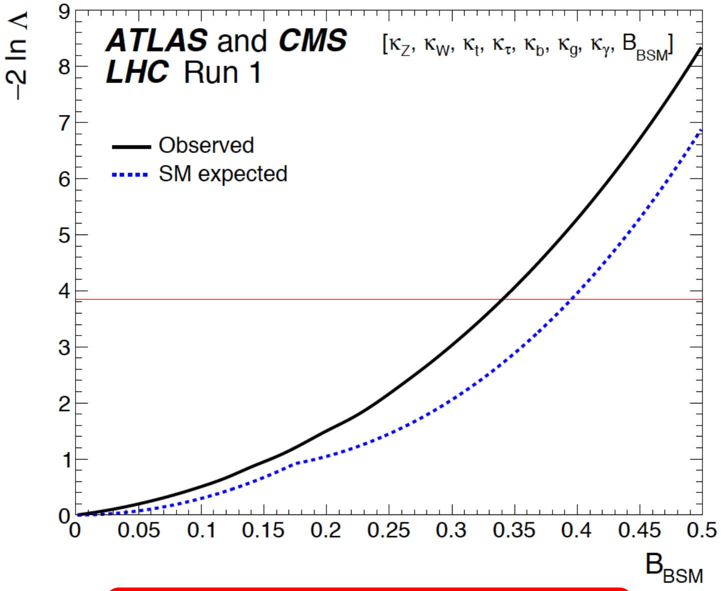
$\kappa_Z, \kappa_W, \kappa_t, \kappa_b,$
$\kappa_\tau, \kappa_g, \kappa_\gamma, BR_{BSM}$

$$\Gamma_H = \Gamma_H^{SM} \times \frac{\kappa_H^2}{1-BR_{BSM}}, \quad BR(H \to xx) = BR_{SM}(H \to xx) \times (1 - BR_{BSM}) \cdot \frac{\kappa_x^2}{\kappa_H^2}$$

JHEP 08 (2016) 045

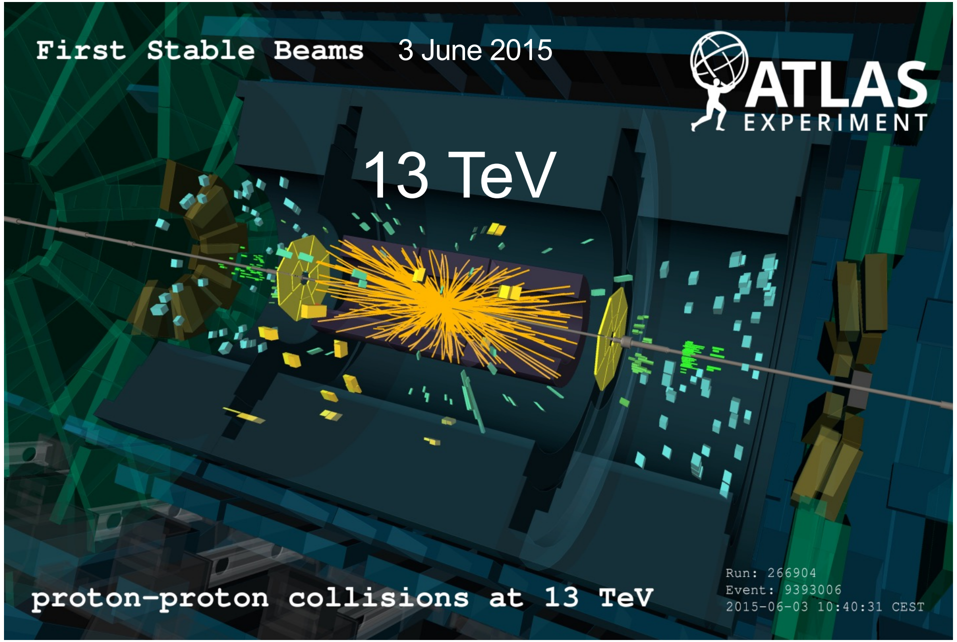


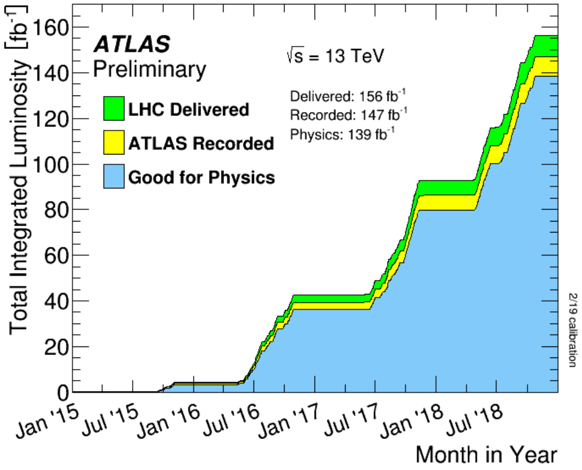
Compatibility with the SM: 11%

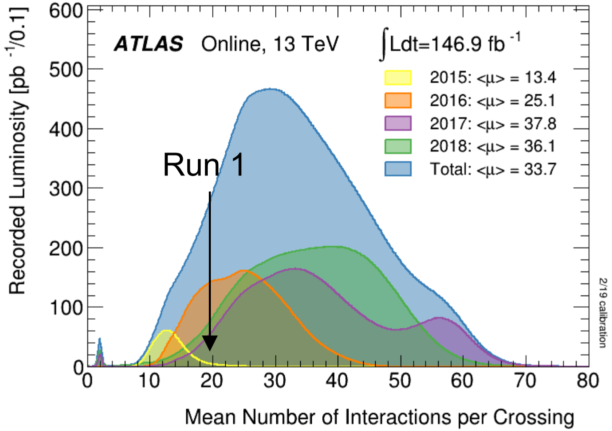


Obs (exp) limit: $BR_{BSM} < 0.34$ (0.39)

The LHC Run 2







Extremely successful Run 2 during 2015-2018:

- pp collisions at $\sqrt{s}$=13 TeV
  ➔ x2.3 higher Higgs production cross-section than at $\sqrt{s}$=8 TeV
- Integrated luminosity: 139 fb^{-1} (vs 25 fb^{-1} in Run 1)
  - Peak instantaneous luminosity of 2×10^{34} $cm^{-2}s^{-1}$ (a x2 higher than the detector was designed for) ➔ Higher pile-up!

Run 2 milestones in Higgs physics

Precision
Cross-sections
Couplings
Mass

Discovery
Couplings to fermions

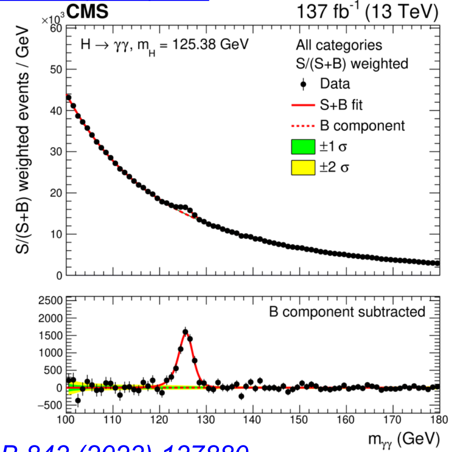
Other scalars
Charged/neutral
Heavy/light

Known unknowns
Rare decays
Self-couplings

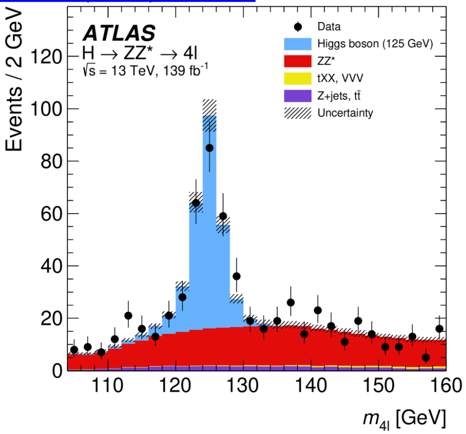
Unknown unknowns
BSM couplings
BSM decays

H→γγ and H→ZZ*→4l: inclusive cross-sections

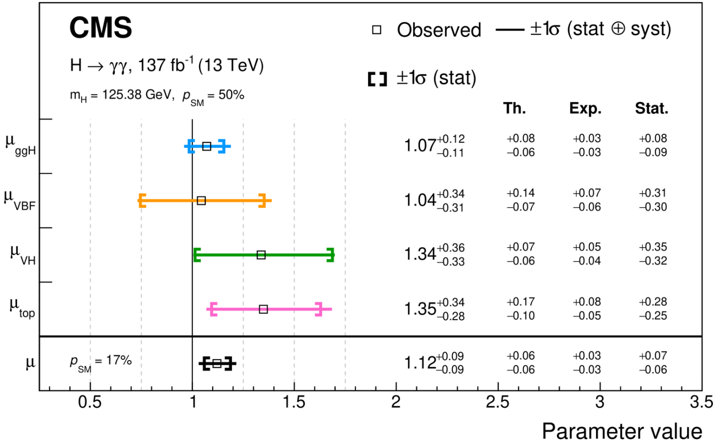
JHEP 07 (2021) 027



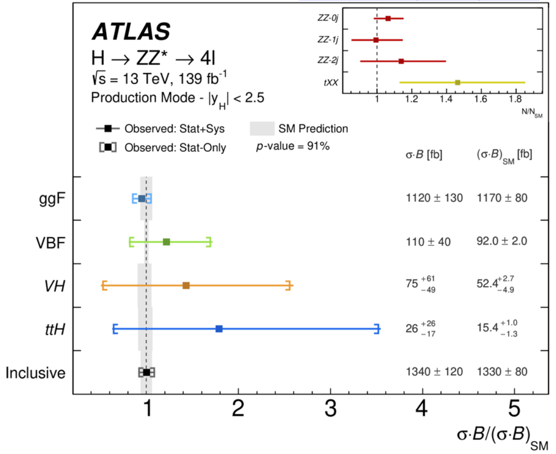
PLB 843 (2023) 137880



JHEP 07 (2021) 027



EPJC 80 (2020) 957

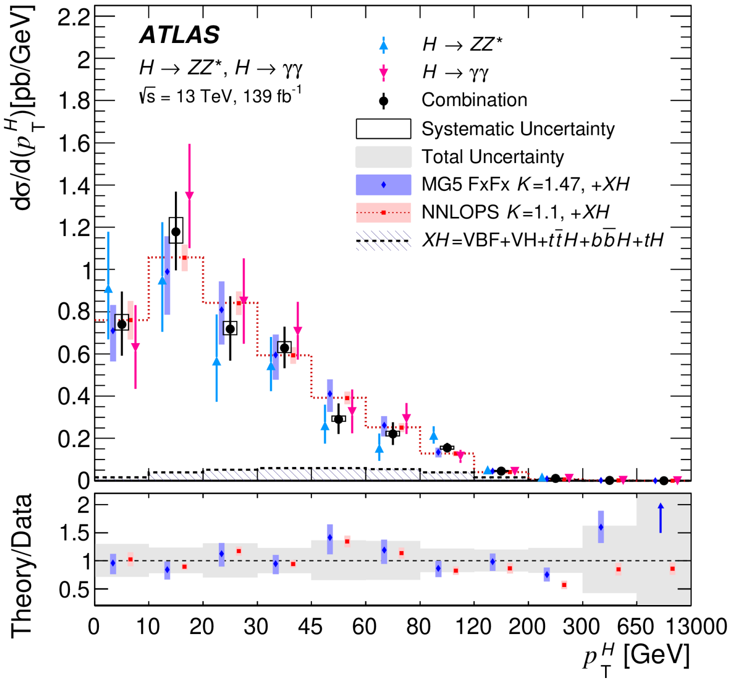


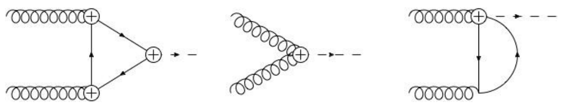
- Significantly improved precision compared to Run 1 (almost x3 better).
- Starting to approach SM theory uncertainty (~6%)
- Much higher statistics allows to perform differential measurements.

H→γγ and H→ZZ*→4l: differential cross-sections

- Comprehensive program of differential cross-section measurements. E.g. CMS: arXiv:2305.07532
- Significantly improved precision in differential cross section distributions, particularly in the tails.
- $d\sigma/dp_{T,H}$ sensitive to perturbative QCD calculations but also allows probing in a model-independent way the ggH vertex!

JHEP 05 (2023) 028

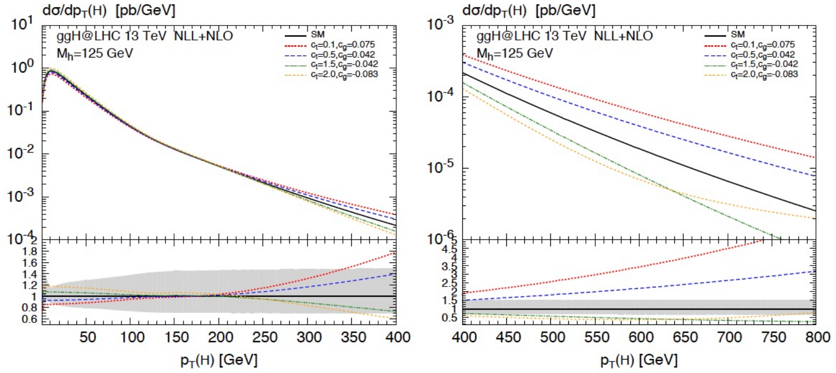




$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

$$\frac{c_1}{\Lambda^2}\mathcal{O}_1 \to \frac{\alpha_S}{\pi v} c_g h G^a_{\mu\nu} G^{a,\mu\nu},$$
$$\frac{c_2}{\Lambda^2}\mathcal{O}_2 \to \frac{m_t}{v} c_t h \bar{t} t,$$
$$\frac{c_3}{\Lambda^2}\mathcal{O}_3 \to \frac{m_b}{v} c_b h \bar{b} b,$$
$$\frac{c_4}{\Lambda^2}\mathcal{O}_4 \to c_{tg}\frac{g_S m_t}{2v^3}(v+h)G^a_{\mu\nu}(\bar{t}_L \sigma^{\mu\nu} T^a t_R + h.c).$$

arXiv:1612.00283



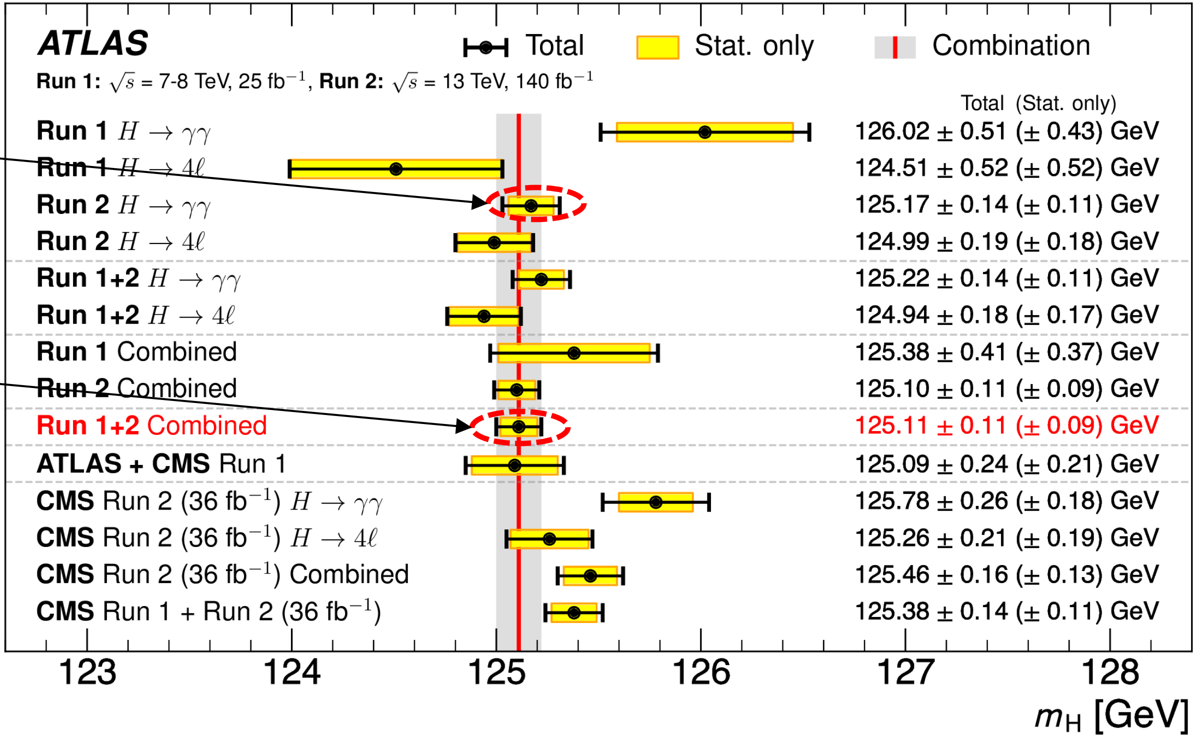
Higgs mass

- Individual measurements by the experiments already better than ATLAS+CMS Run 1 combination!

arXiv:2308.04775

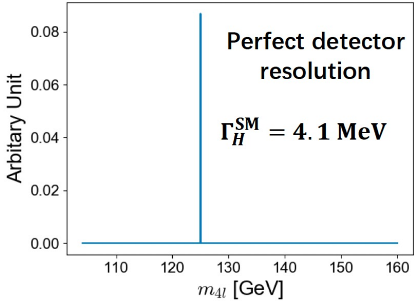
Most precise single measurement (x3.8 decrease in syst. unc., mainly from photon energy scale)

Most precise measurement (still dominated by stat. unc.)

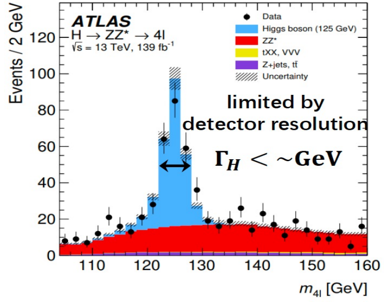


Higgs width

- Γ_H(SM)=4.1 MeV (~3 orders of magnitude smaller than $\Gamma_{W,Z}$!)
- A precise and model-independent determination at the LHC through rate measurements is not possible, since what is measured is σ x BR.
  ➔ Much better prospects at an e^+e^- collider.
- Existing direct bounds are quite weak:
  - $\Gamma_H > 3.6 \times 10^{-9}$ MeV (from lifetime in H→ZZ$^{(*)}$→4l)
  - $\Gamma_H < 1.7$ GeV (from width of invariant mass distribution in H→ZZ$^{(*)}$→4l)
- Other possibilities:
  - Constraints from invisible (and exotic) decays
  - Interferometry in $\gamma\gamma$: interference with background shifts mass by ~30 MeV. ➔ Use p_T dependence of shift: exp limit $\Gamma_H < 200$ MeV (3 ab^{-1}).
  - Coupling measurements (with some assumptions)

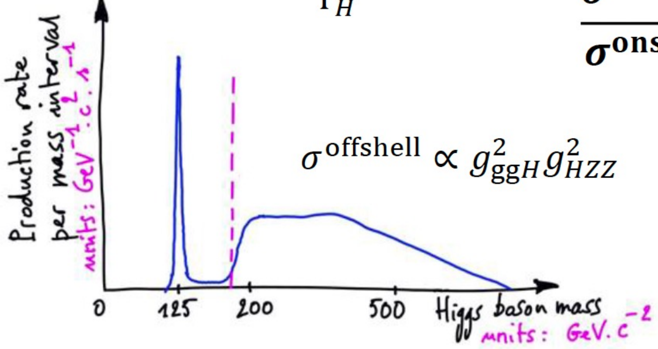


VS



$$\sigma^{\text{onshell}} \propto \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}$$

$$\frac{\sigma^{\text{offshell}}}{\sigma^{\text{onshell}}} \propto \Gamma_H$$



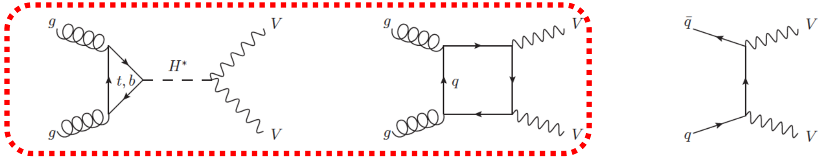
$$\sigma^{\text{offshell}} \propto g_{ggH}^2 g_{HZZ}^2$$

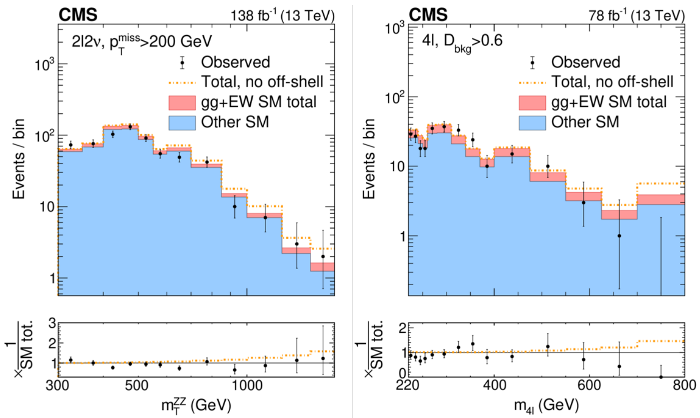
Indirect Higgs width measurement

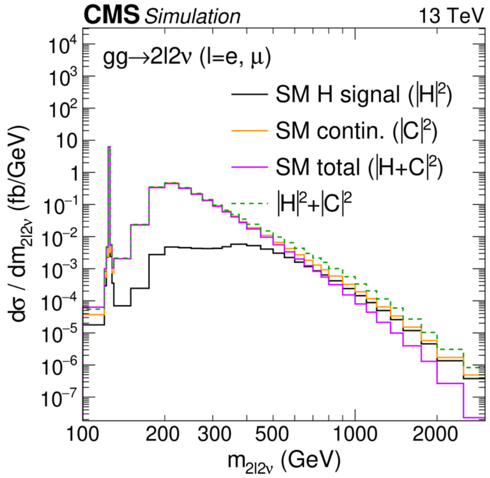
[NP 18 (2022) 1329]

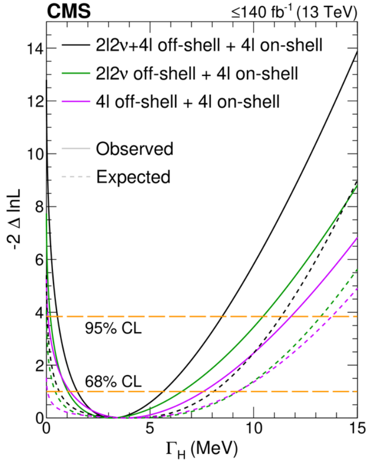
- Measure Higgs signal strength in the far off-shell region in H→VV decays (V=W,Z).
- Need to take into account interference effects with the gg→ZZ background, which can be significant.

Negative interference!









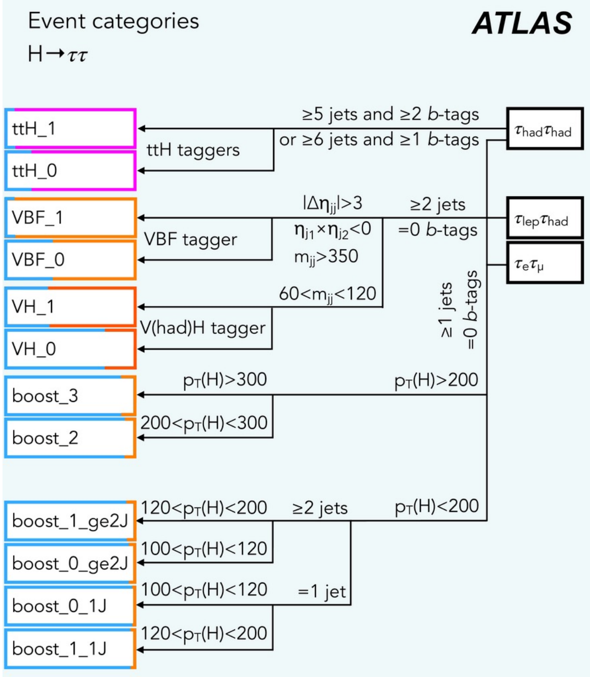
- Consider H→ZZ*→4l and llνν decays.
- Both experiments established evidence for off-shell Higgs production.

- Assuming $\mu_{\text{on-shell}} = \mu_{\text{off-shell}}$:
  - ATLAS: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV [arXiv:2304.01532]
  - CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV [NP 18 (2022) 1329]

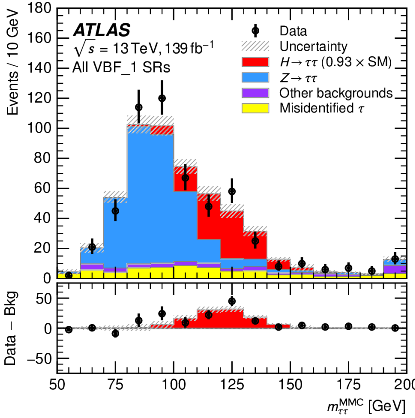
Impressive but they still leave plenty of room for New Physics!

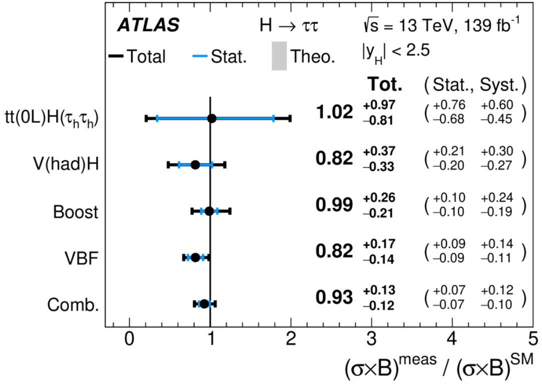
H→ττ

- Observed with a fraction of Run 2 data.
- Very sophisticated analyses targeting different production modes in different kinematic regimes. E.g.

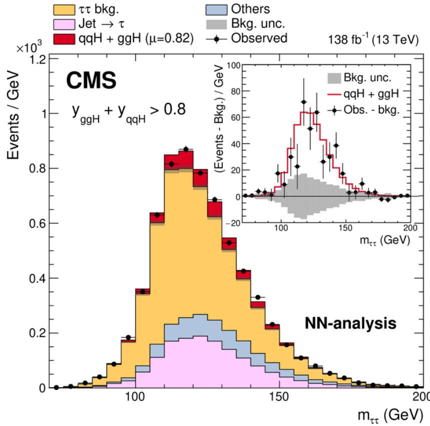


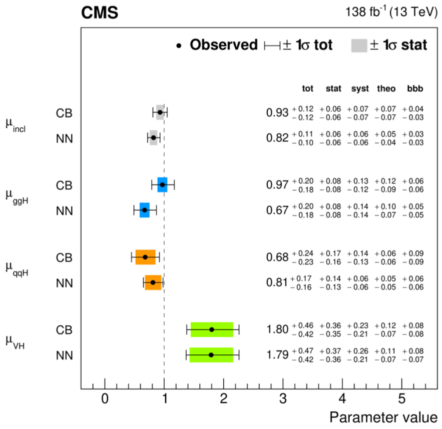
[JHEP 08 (2022) 175](#)





[EPJC 83 (2023) 562](#)

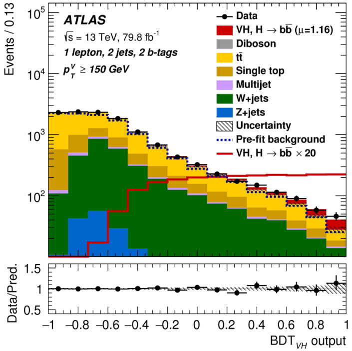


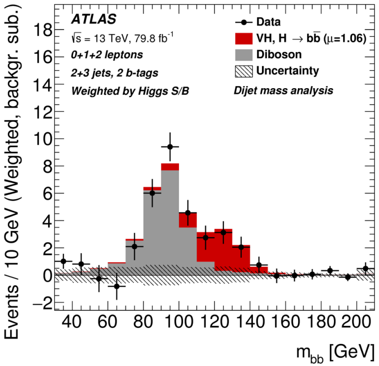


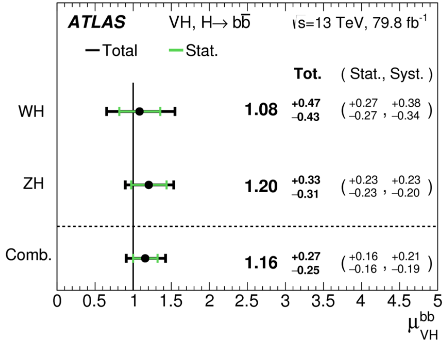
H→bb

- VH production observed with a fraction of Run 2 data.
- Also targeting gg→H and VBF production modes
  ➔ additional measurements in extreme kinematic regimes.

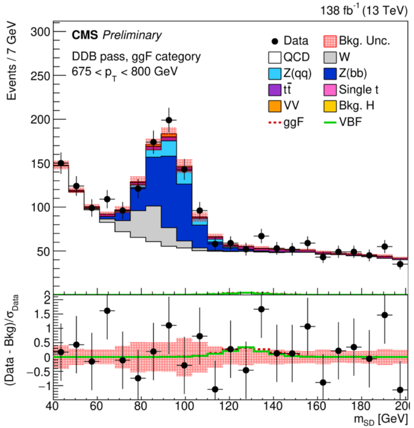
PLB 786 (2018) 59

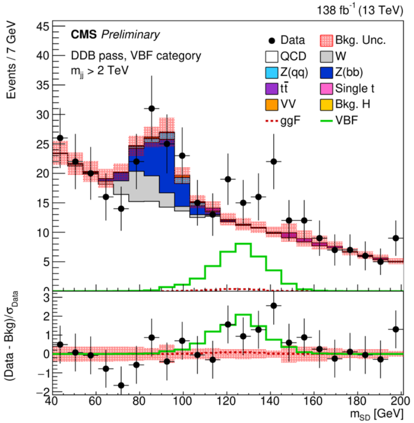


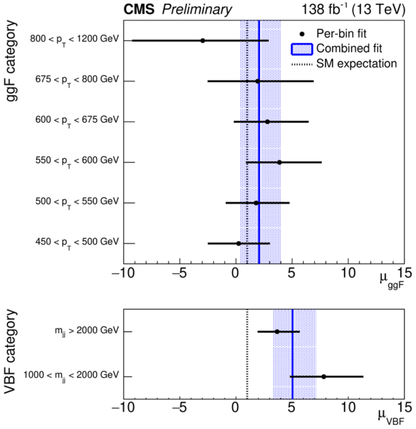




CMS-PAS-HIG-21-020

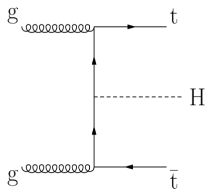


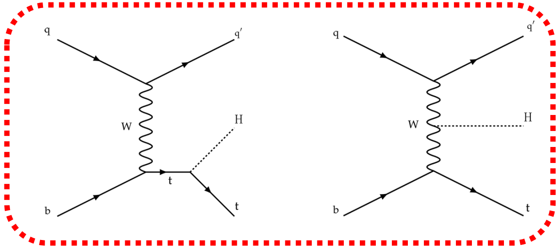




Probing ttH and tH production

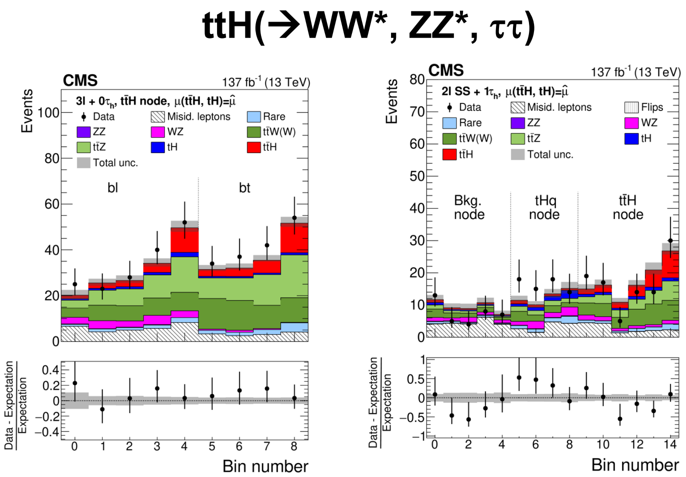
Negative interference in SM!

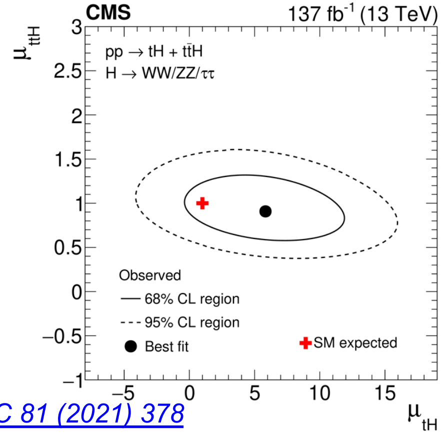




- Increasingly more sophisticated analyses bring significant improvements in sensitivity.
- Observation separately in multilepton and γγ final states.

ttH(→WW*, ZZ*, ττ)

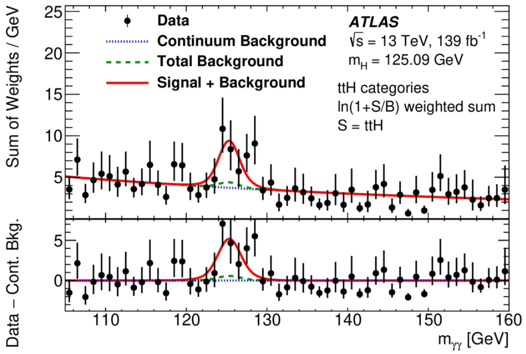


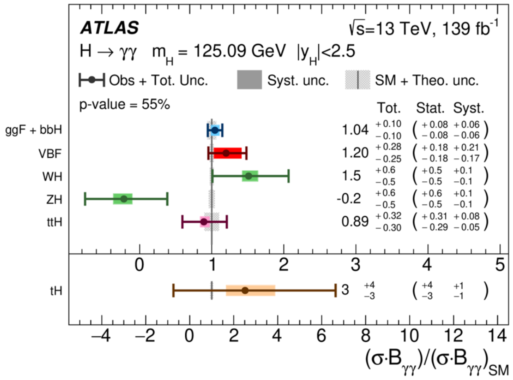


EPJC 81 (2021) 378

ttH(→γγ)

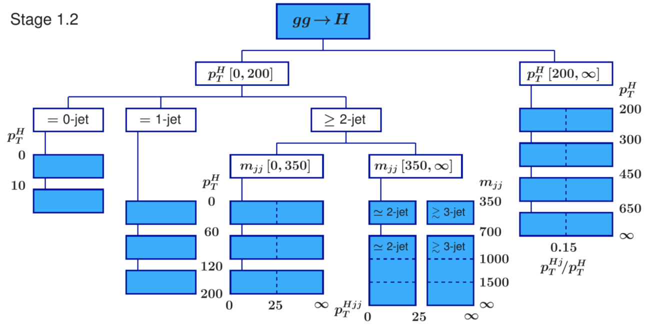
JHEP 07 (2023) 088

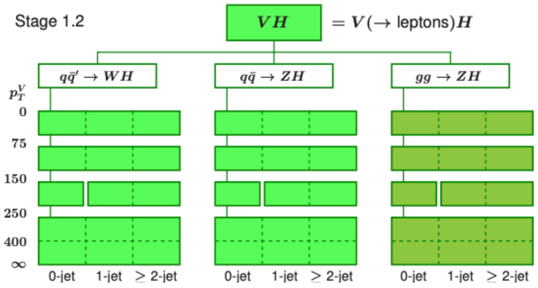


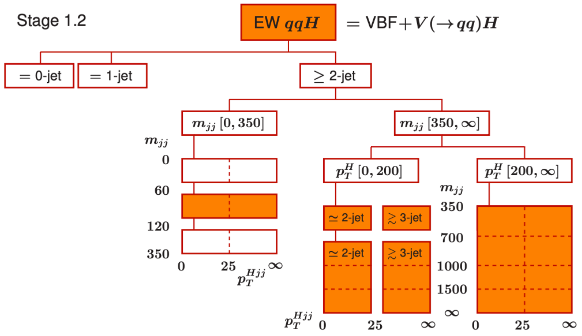


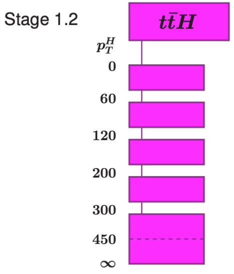
Simplified template cross-sections (STXS)

- Measure production modes separately, categorising each into bins of key (truth) quantities ($p_{T,H}$, N_{jets}, m_{jj}).
- Chosen as most sensitive variables for theory predictions / signal sensitivity / new physics.
- Framework provided in different stages (e.g. stage 0, stage 1, stage 1.2) with varying degrees of granularity.
- Decay mode agnostic: well-suited for combinations.









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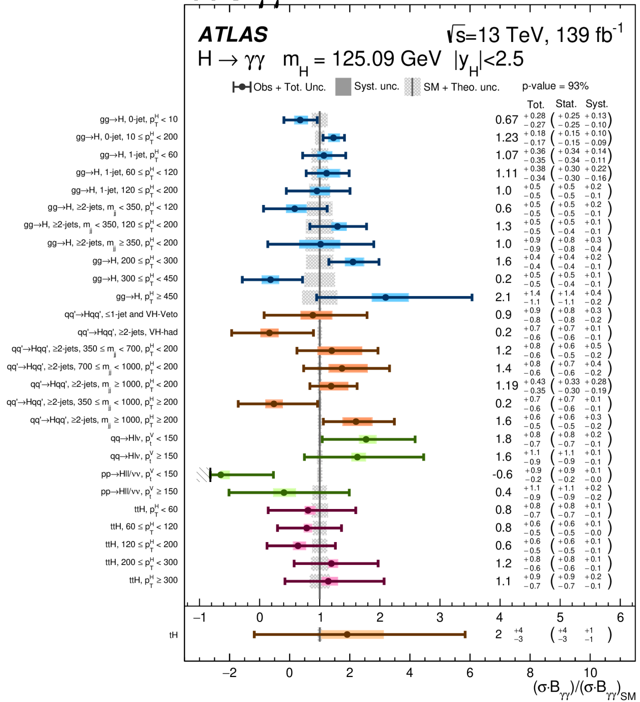
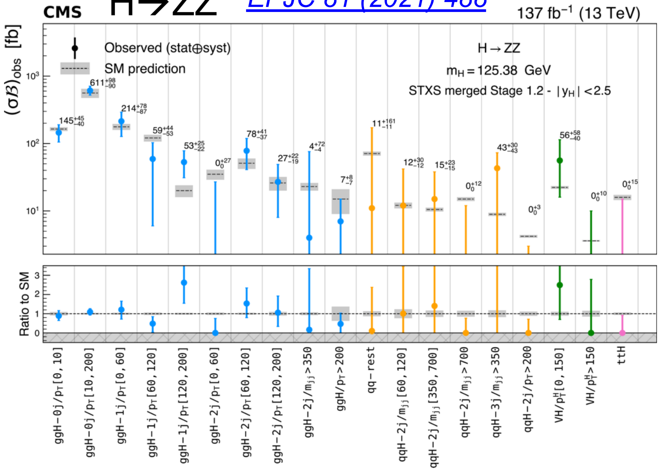
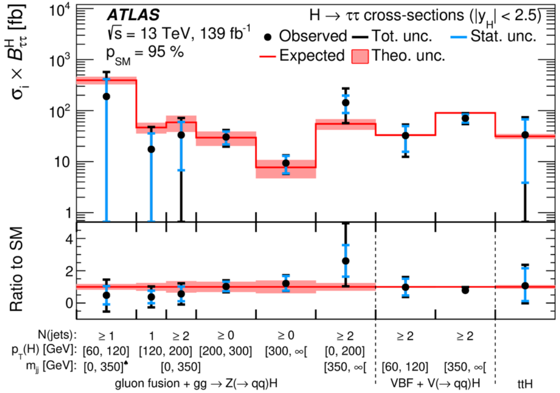
$H \to \gamma\gamma$ JHEP 07 (2023) 088



$H \to ZZ$ EPJC 81 (2021) 488

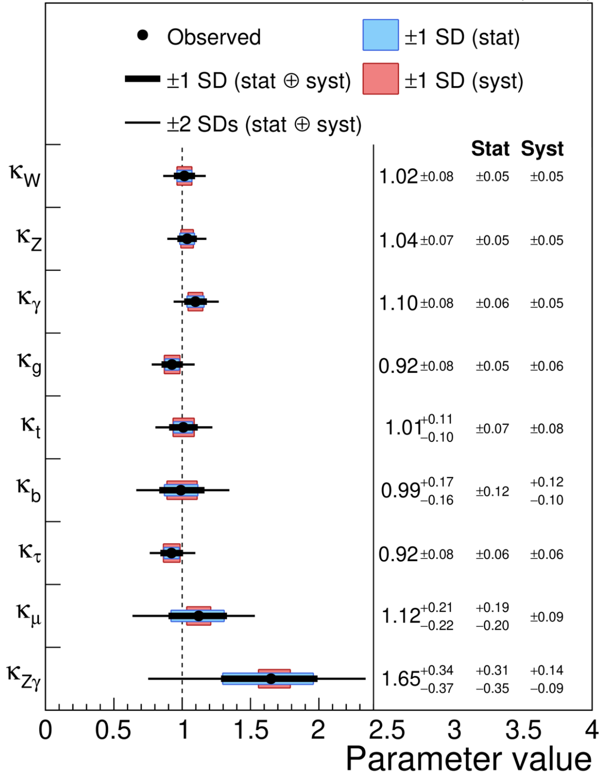


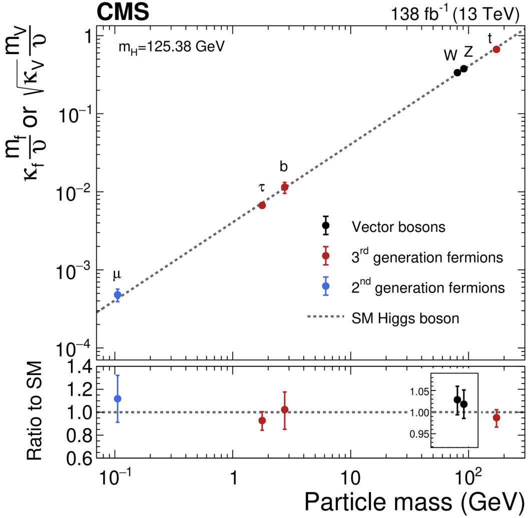
$H \to \tau\tau$ JHEP 08 (2022) 175



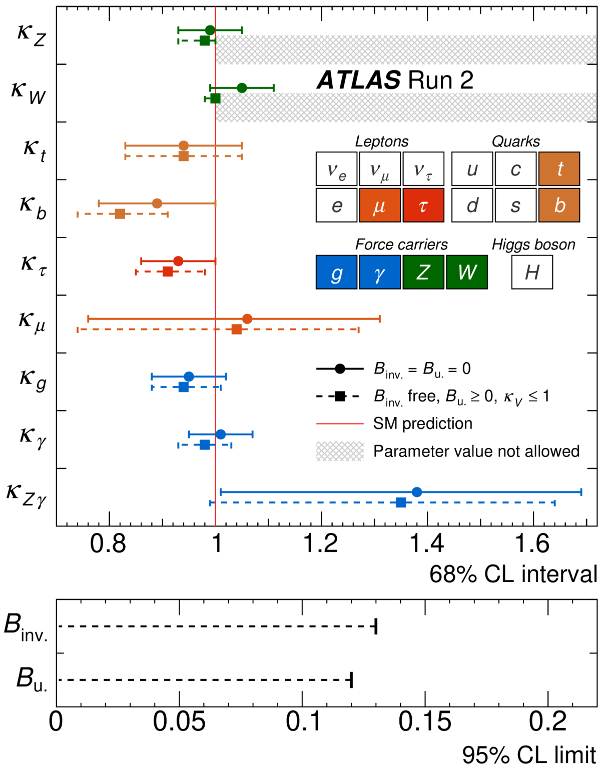
Higgs couplings

[Nature 607 (2022) 60](#)





[Nature 607 (2022) 52](#)



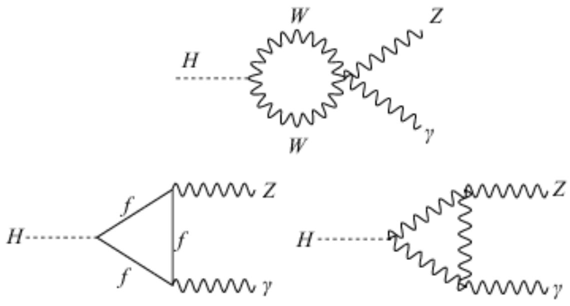
Excellent agreement with the SM

Also EFT interpretations
See [ATLAS-CONF-2023-052](#)

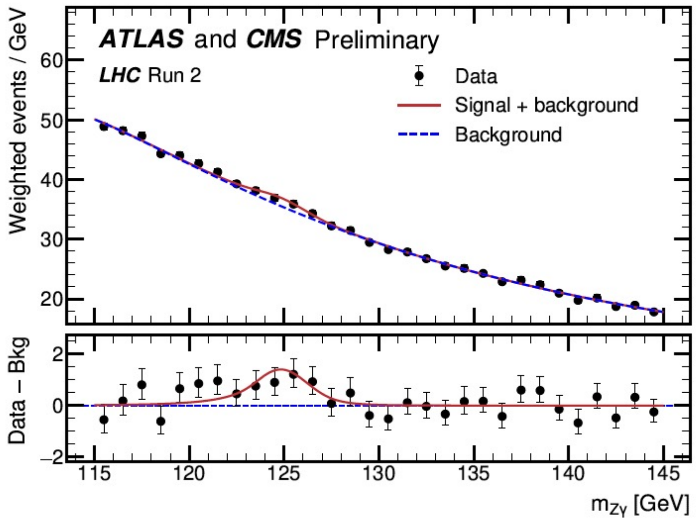
Rare decays

H→Zγ

- BR~0.2% (similar to H→γγ). Sensitive to New Physics in the loop.
- First evidence for H→Zγ with ATLAS and CMS combination.

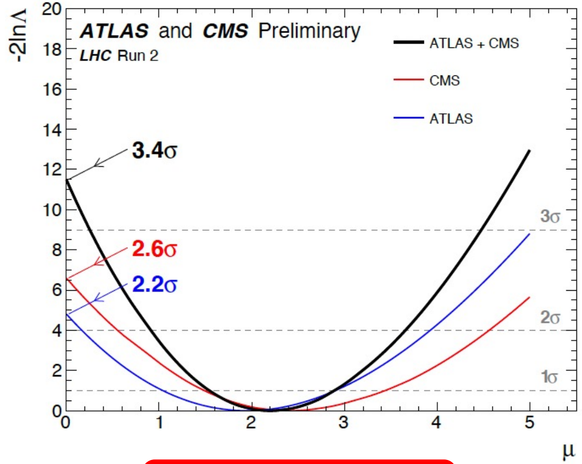


ATLAS-CONF-2023-025



Obs (exp) significance: 3.4σ (1.6σ)

Evidence for H→Zγ



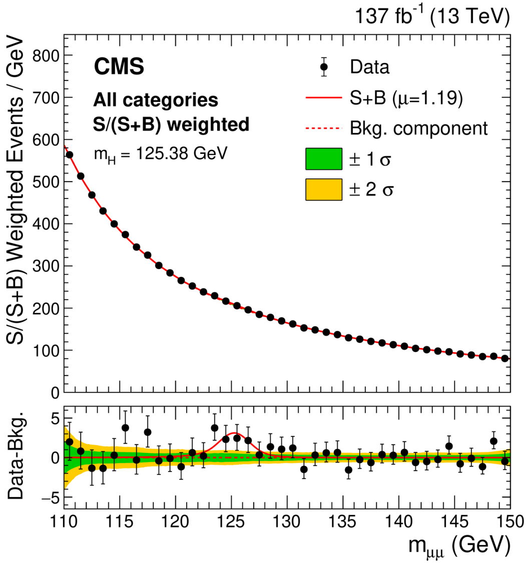
$$\mu = 2.2 \pm 0.7$$

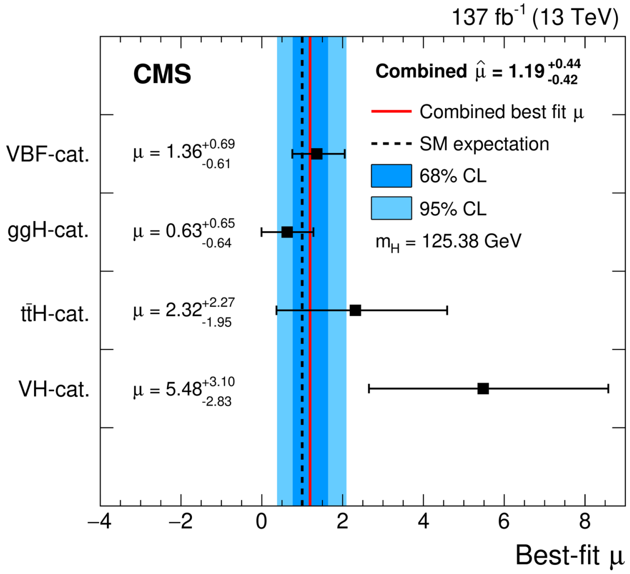
Compatibility with the SM: 1.9σ

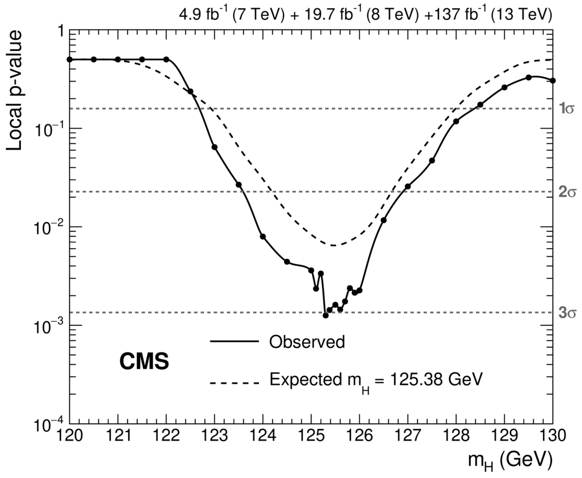
H→μμ

- BR~0.02% (x10 rarer than H→γγ!).
- Very sophisticated analysis with different MVA-based categories.

JHEP 01 (2021) 148







$\mu = 1.2 \pm 0.4$

Obs (exp) significance: 3.0σ (2.5σ)

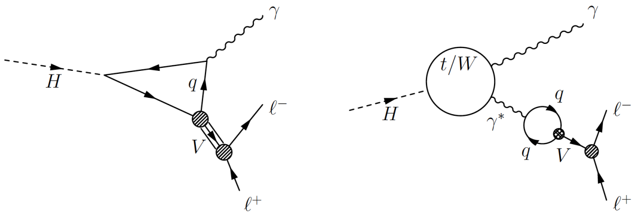
Evidence for H→μμ

H→meson+γ

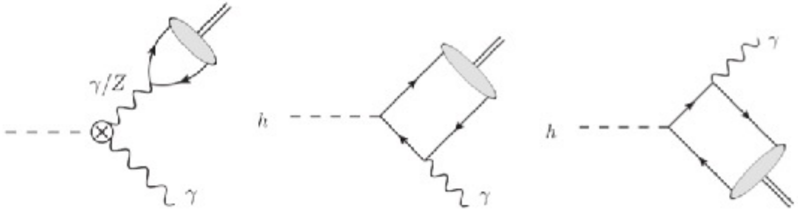
- Couplings to 1st and 2nd generation quarks extremely challenging.
- H→cc may still be probed in a similar way as H→bb (needs excellent c-tagging). Other, lighter quarks, hopeless.

One possibility:

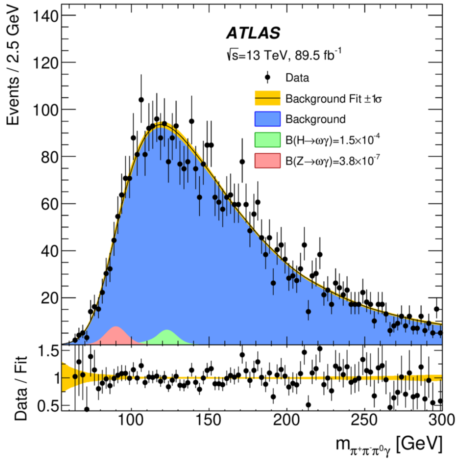
- **H→J/ψγ :** coupling to charm

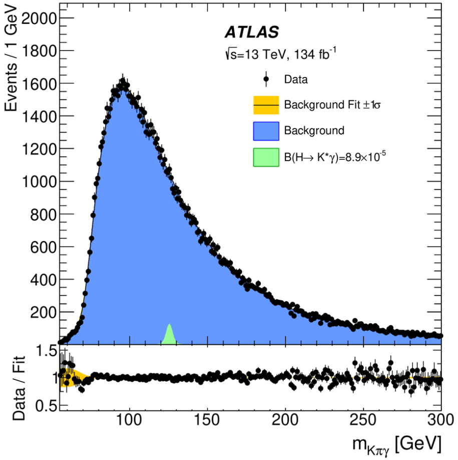


- **H→ϕγ :** coupling to s quarks
- **H→ργ & H→ωγ :** coupling to u/d quarks
- **H→K*γ :** flavor-violating coupling to u and d quarks



arXiv:2301.09938





BR(H→ωγ)<1.5x10^{-4} (<100xSM)

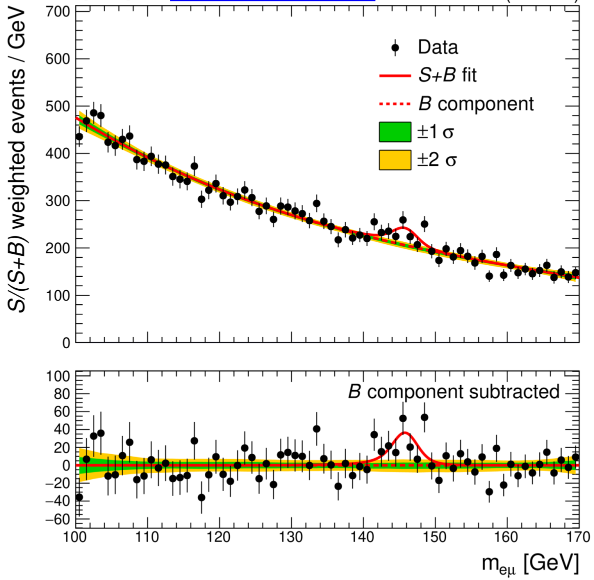
BR(H→ωγ)<8.9x10^{-5}

LFV Higgs decays: H→eμ, eτ, μτ

- Extremely suppressed in the SM. An observation would indicate New Physics.

H→eμ

arXiv:2305.18106



Obs. (exp.) limit: BR<4.4 (4.7) × 10^{-5}

3.8σ (2.8σ) excess at 146 GeV
(not confirmed by ATLAS)

H→eτ, μτ

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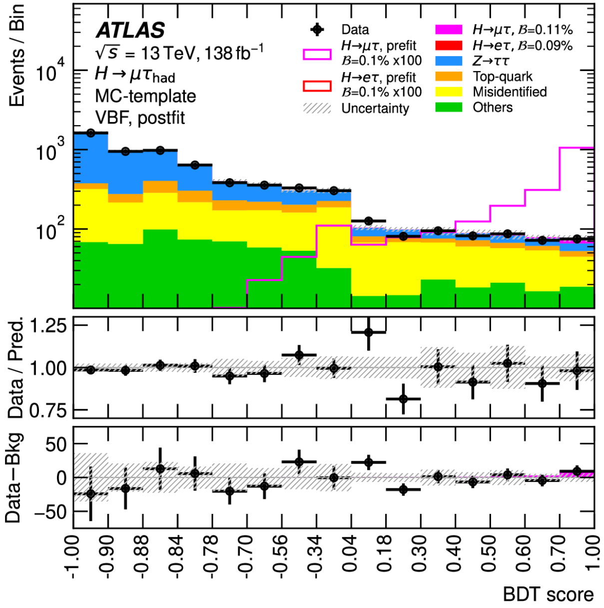
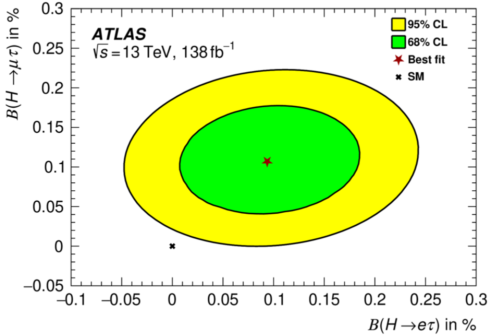


eτ: Obs. (exp.) limit: BR<0.20% (0.12%)
μτ: Obs. (exp.) limit: BR<0.18% (0.09%)

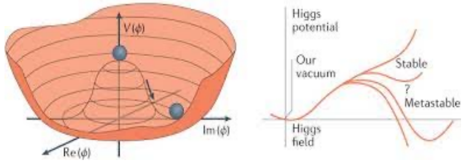


Compatibility with the SM: 2.1σ

Probing the Higgs potential

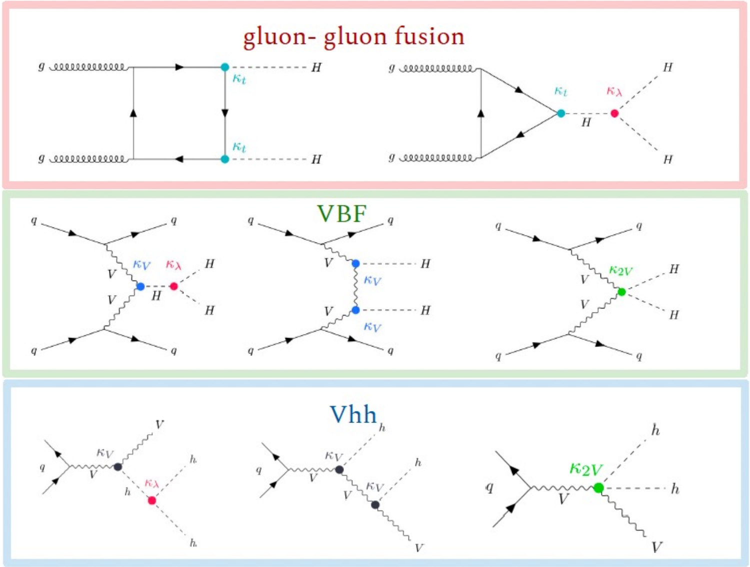
Double-Higgs production

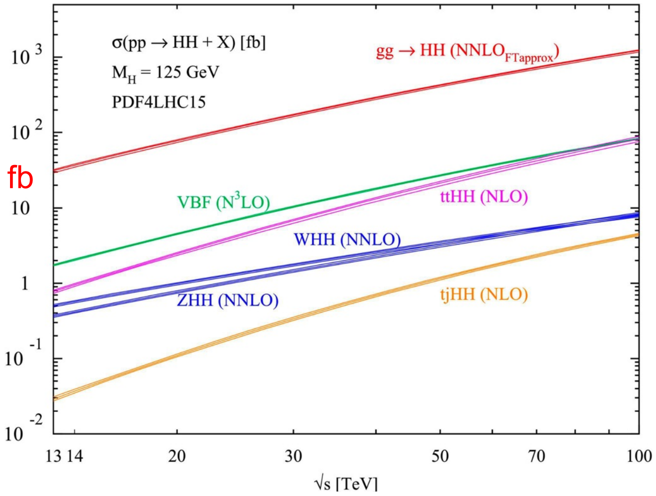
- Determination of the scalar potential ➔ self interaction!
  λ_4: currently hopeless at any planed experiment
  λ_3: in principle possible via double-Higgs production, but very challenging because of negative interference among diagrams (particularly ggF)



$$\mathcal{L} \supset -\frac{m_h^2}{2}h^2 - \lambda_3^{SM} v h^3 - \lambda_4^{SM} h^4,$$

$$\lambda_3^{SM} = \frac{m_h^2}{2v^2}, \qquad \lambda_4^{SM} = \frac{m_h^2}{8v^2},$$

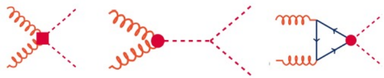




σ_{HH}~33 fb

x10^3 smaller than σ_H !!

Also sensive to BSM contributions:

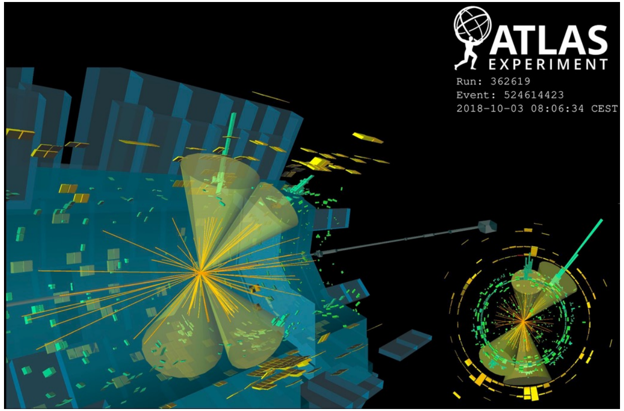


Double-Higgs production

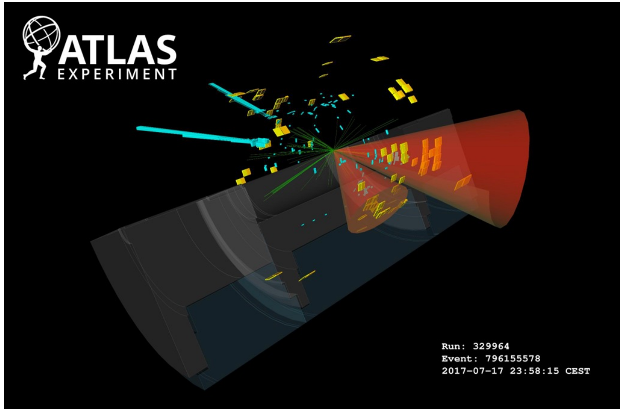
- No single golden channel. Exploit all channels with at least one H→bb. Also some channels giving multilepton final states.
- Main channels:
  - **HH→bbbb**: highest BR, large background
  - **HH→bbγγ**: small BR, small background
  - **HH→bbττ**: balance of both
- Different production modes (non- resonant: ggF, VBF, VH; resonant production) exploited.
- Very sophisticated analyses.

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

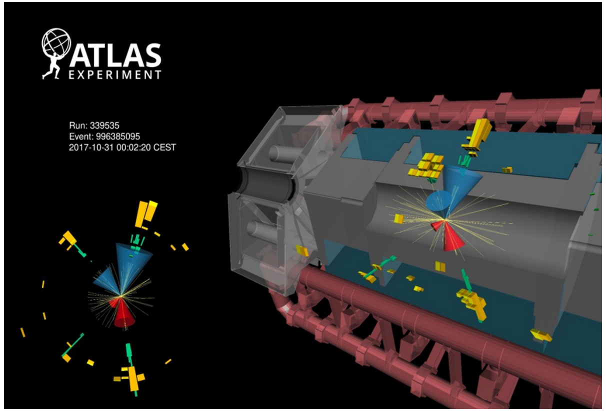
HH→bbbb



HH→bbγγ



HH→bbττ



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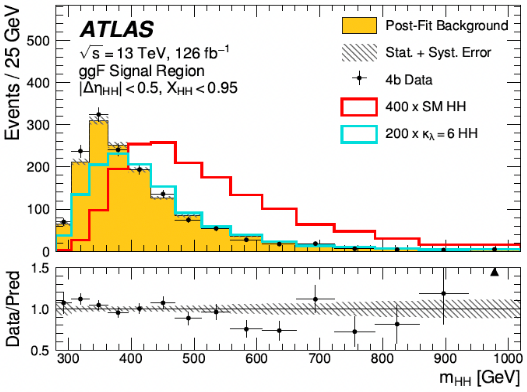
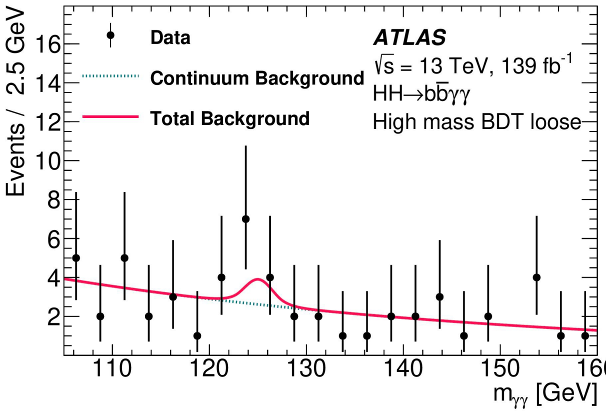
HH→bbbb

arXiv:2301.03212



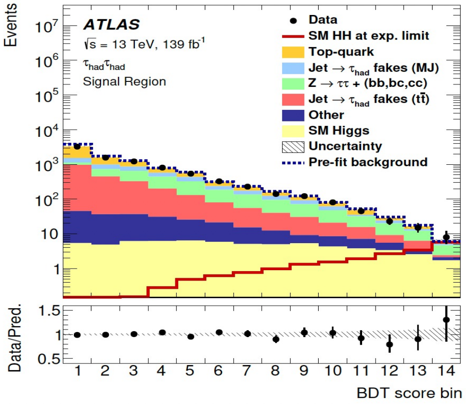
HH→bbγγ

PRD 106 (2022) 052001

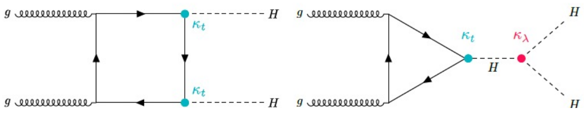


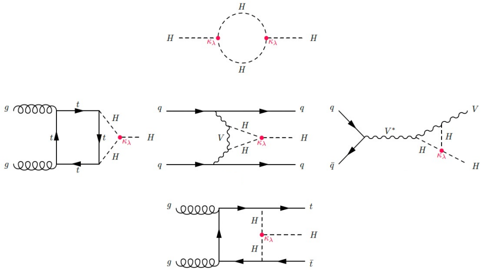
HH→bbττ

JHEP 07 (2023) 040

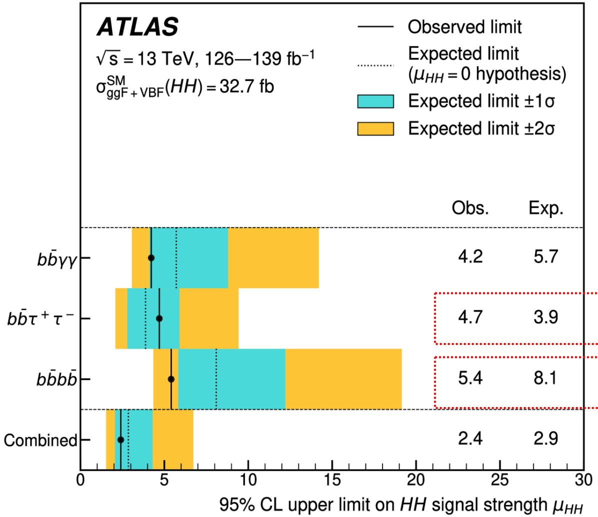


Double-Higgs production

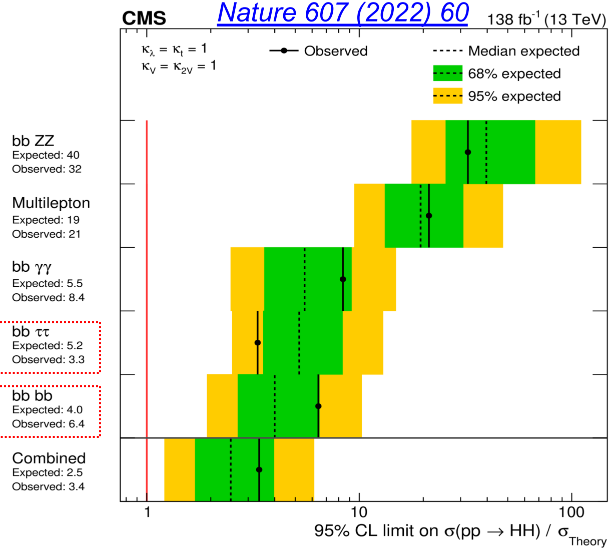




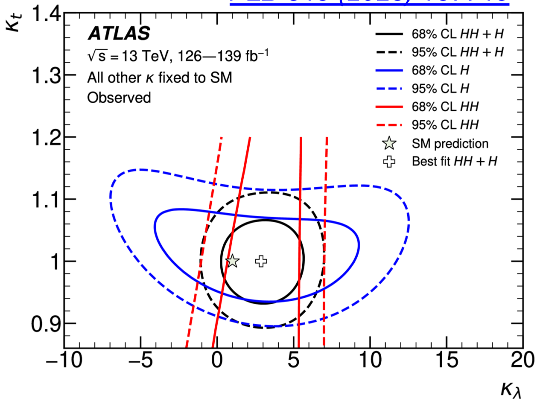
PLB 843 (2023) 137745



Nature 607 (2022) 60



PLB 843 (2023) 137745



- Impressive progress on di-Higgs search program during Run 2.
- Latest combinations per experiment reaching 3xSM expected sensitivity, but still room for improvement!

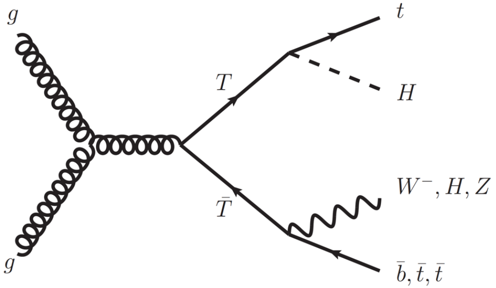
- Include precise single-Higgs measurements for more model-independent interpretation.

Higgs as a tool for discovery

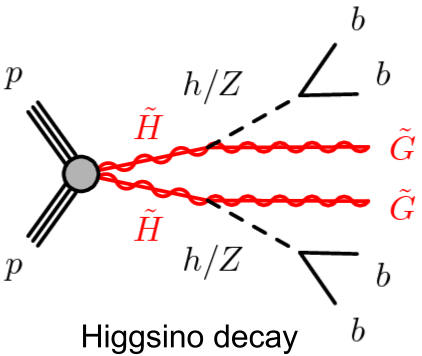
Probing NP through the Higgs boson

- In many NP scenarios the Higgs boson couples preferentially to new particles:
  - $m_X > m_h$: the Higgs boson may appear in decays of X or is produced in association with X.
  - $m_X < m_h$: Higgs boson may decay into X.

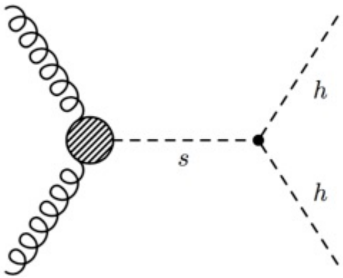
Some examples:



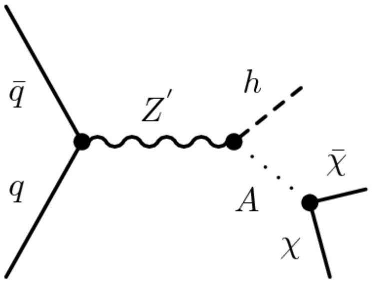
Vector-like quark decay



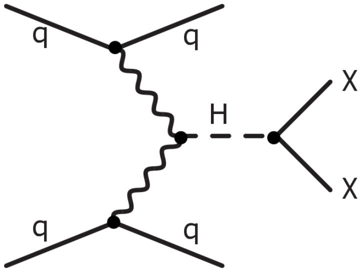
Higgsino decay



Di-higgs resonances



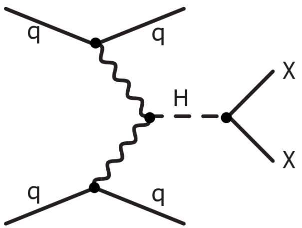
Mono-Higgs production

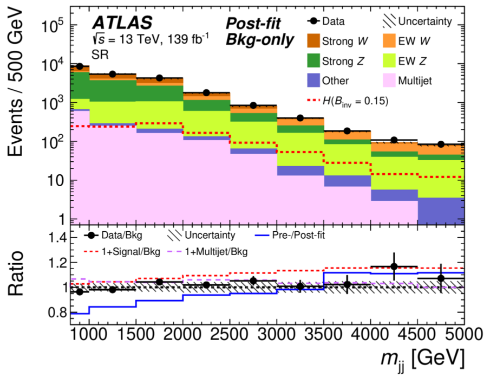


Invisible Higgs decays

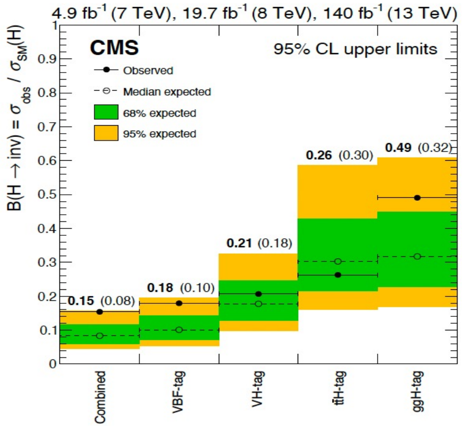
Invisible Higgs decays

- SM prediction: BR(H→ZZ→νννν)~0.1%
- Most sensitive searches use VBF production.
  - Main selection on m_{jj}, $\Delta\eta_{jj}$, and large E_T^{miss}.
  - Challenging backgrounds from V+jets production.
- Derive upper limit on BR(H→inv), under the assumption of SM production cross section.
- Different SM Higgs production modes combined.
- Result also interpreted in the context of a Higgs-portal model of dark matter interactions.



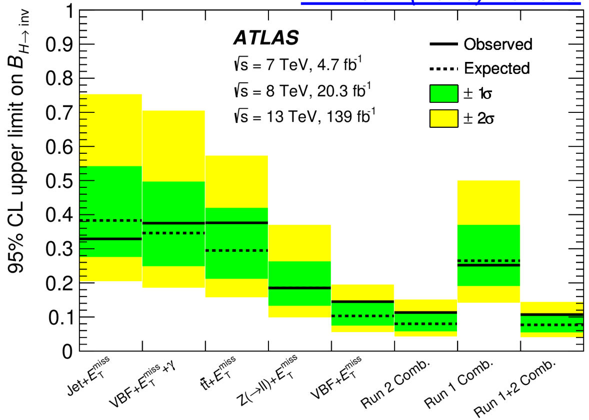


arXiv:2303.01214

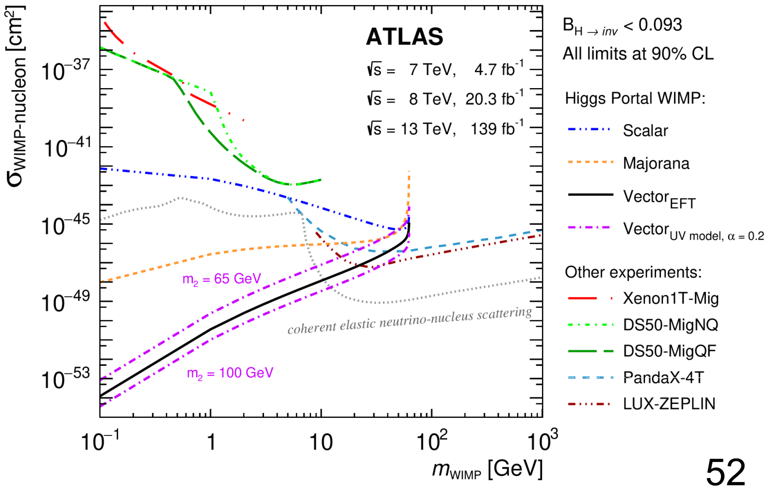


Obs. (exp.) limit: BR<18% (8%)

PLB 842 (2023) 137963



Obs. (exp.) limit: BR<10.7% (7.7%)



Is the Higgs sector minimal?

Extended Higgs sectors

Many possibilities beyond the SM!

- **EWS** (EW singlet): add a Higgs singlet real scalar field to the SM
  ➔ 2 neutral physical states (h and H).

- **2HDM** (Two Higgs Doublet Model): add 2nd Higgs doublet to the SM
  ➔ 5 physical states: 2 neutral CP-even (h and H), 1 neutral CP-odd (A), 2 charged ($H^{\pm}$).
  6 free parameters in minimal model:
  m_h, m_H, m_A, $m_{H\pm}$, $\tan\beta = v_1/v_2$ (ratio of doublet vacuum expectation values), α (mixing angle between CP-even states)

  MSSM (Minimal Supersymmetric SM): extended Higgs sector is a particular case of a 2HDM type II.

Type	Description	up-type quarks couple to	down-type quarks couple to	charged leptons couple to	remarks
Type I	Fermiophobic	Φ_2	Φ_2	Φ_2	charged fermions only couple to second doublet
Type II	MSSM-like	Φ_2	Φ_1	Φ_1	up- and down-type quarks couple to separate doublets
X	Lepton-specific	Φ_2	Φ_2	Φ_1	
Y	Flipped	Φ_2	Φ_1	Φ_2	
Type III		Φ_1, Φ_2	Φ_1, Φ_2	Φ_1, Φ_2	Flavor-changing neutral currents at tree level

By convention, Φ_2 is the doublet to which up-type quarks couple.

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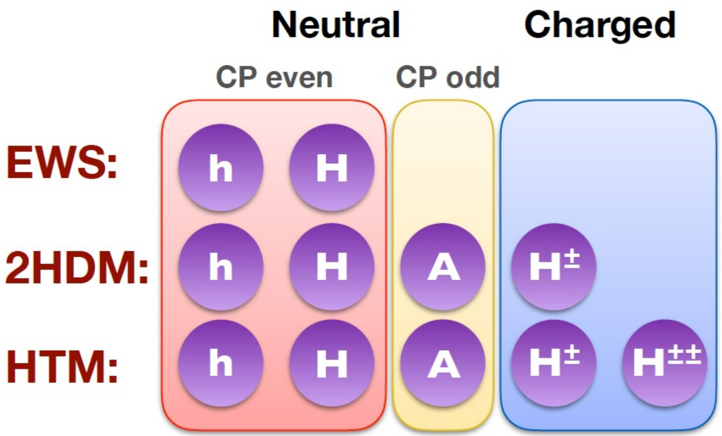
  MSSM (Minimal Supersymmetric SM): extended Higgs sector is a particular case of a 2HDM type II.

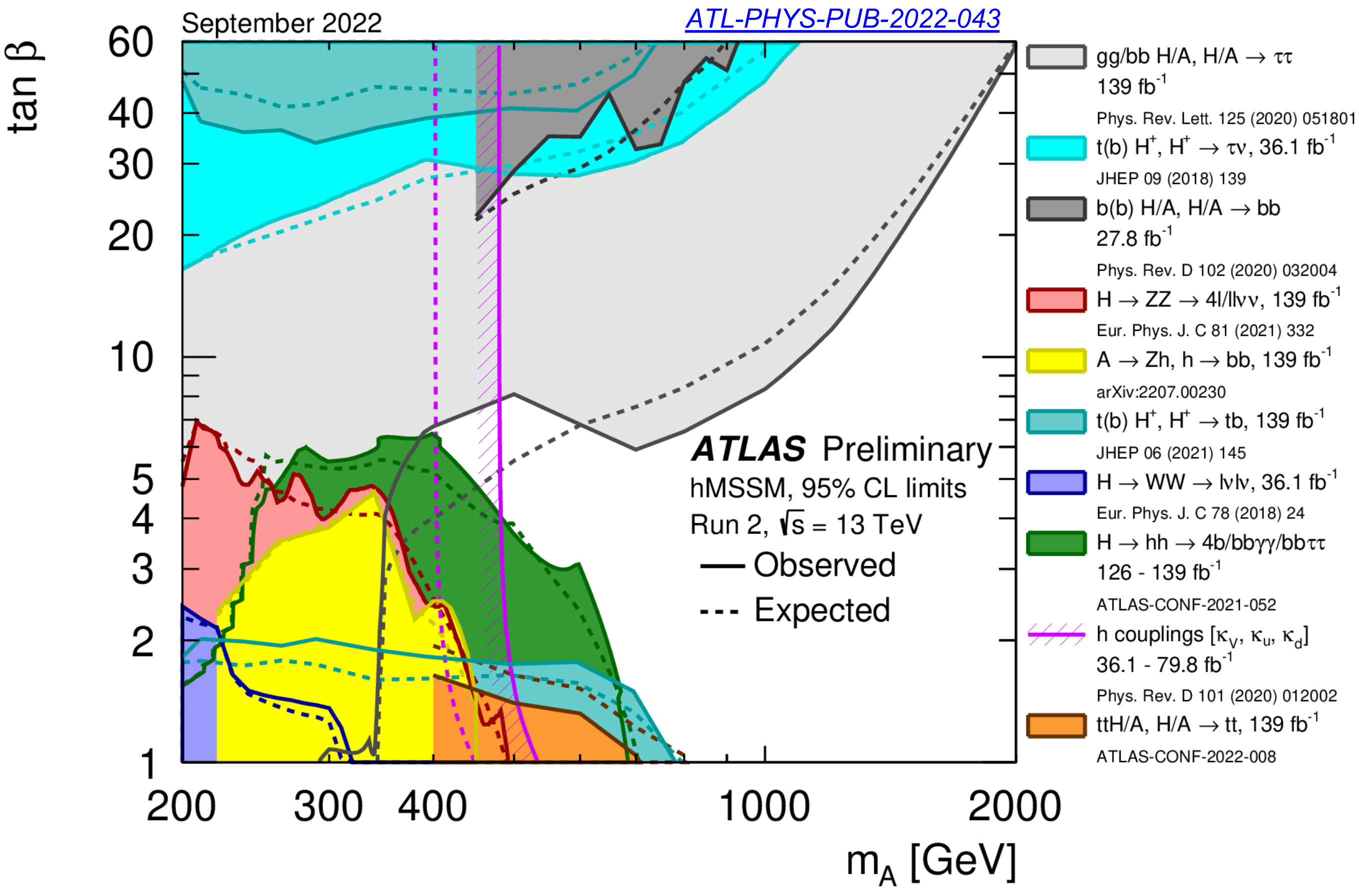
- **NMSSM** (next-to-MSSM): add Higgs singlet to MSSM.
  ➔ 7 physical states: CP-even H_1, H_2, H_3,
  CP-odd A, $H^{\pm}$.

- **HTM** (Higgs Triplet Model): add Higgs triplet to SM in order to generate Majorana mass terms for neutrinos
  ➔ 7 physical states: h, H, A, $H^{\pm}$, and $H^{\pm\pm}$.

- …



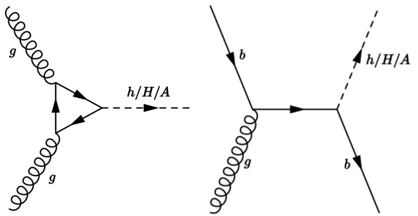
Heavy Higgs searches: a broad program



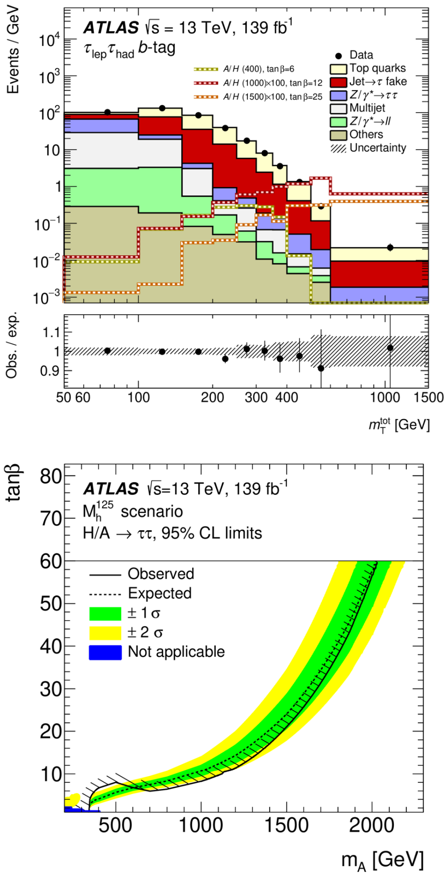
Heavy neutral Higgs: fermionic decays

In Type II 2HDM:

- **High tanβ**: main search mode is H/A(b)→tt(b) (also H/A(b)→bb(b) but lower sensitivity)
- **Low tanβ**: main search mode is H/A→tt
  - Challenging due to strong interference between gg→H/A signal and gg→tt bkg that creates peak-dip structure.



PRL 125 (2020) 051801



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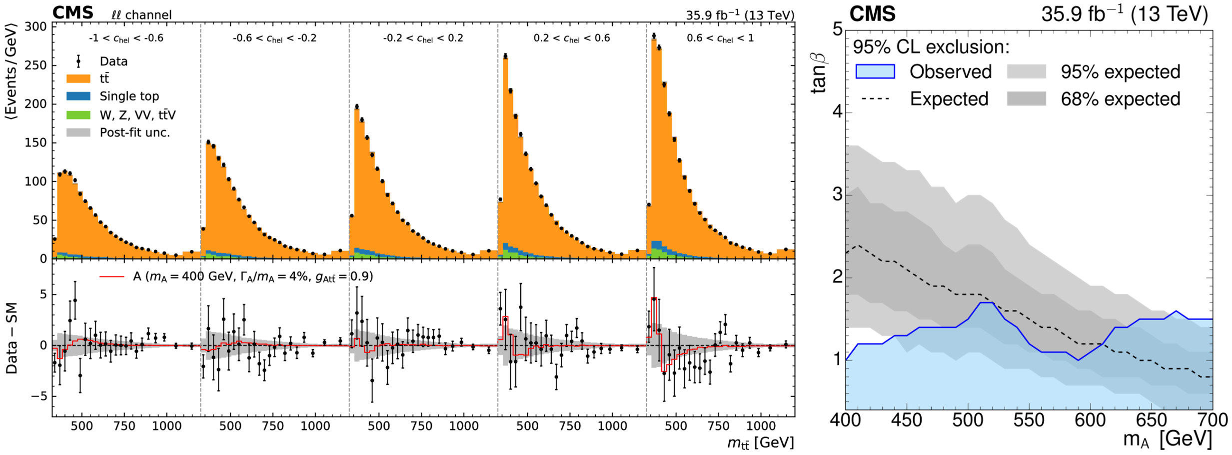
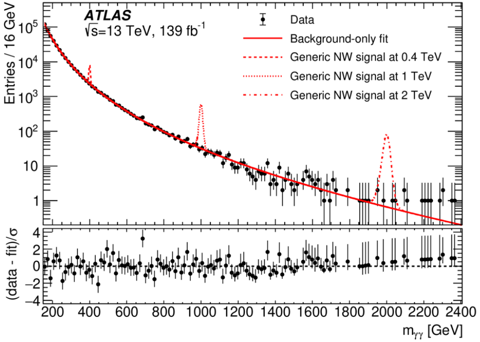


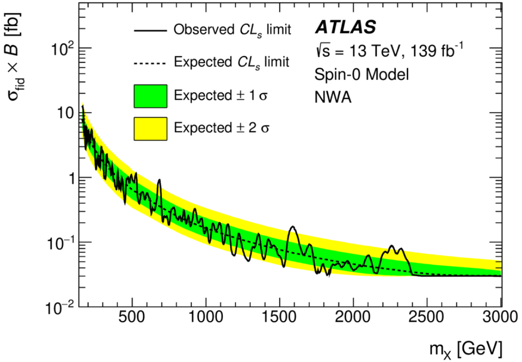
Heavy neutral Higgs: bosonic decays

- Many searches in many channels (γγ, WW, ZZ, Zγ, Zh, hh) considering gg/bb→H/A and/or VBF.

gg→H/A→γγ

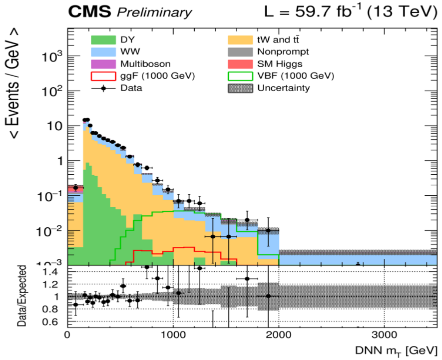
PLB 822 (2021) 136651

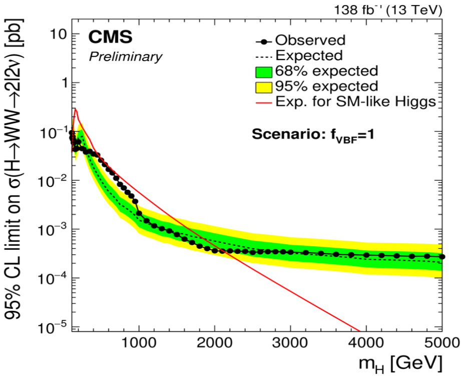




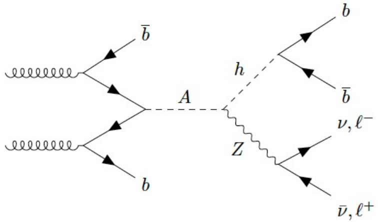
VBF H→WW(→lνlν)

CMS-PAS-HIG-20-016

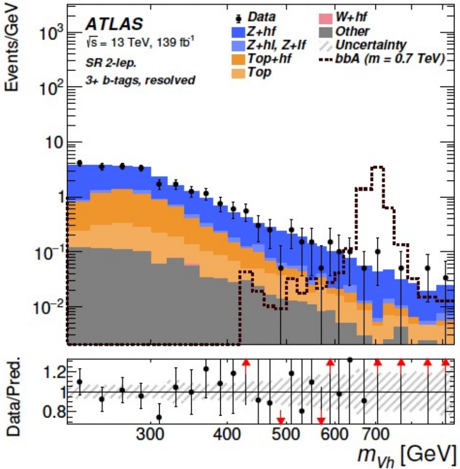




bb→A→Zh(→llbb)

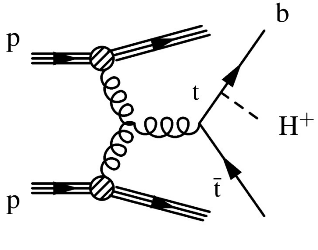


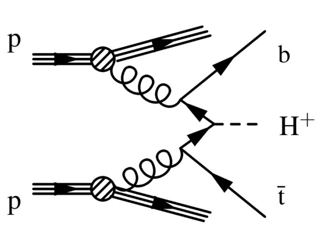
JHEP 06 (2023) 016

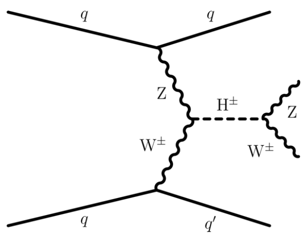


Charged Higgs

- Production modes:
  - $m_{H\pm} < m_t - m_b$: $tt \rightarrow WbH^{\pm}b$
  - $m_{H\pm} > m_t - m_b$: associated $tbH^{\pm}$
  - Also possible via VBF
- Decay modes:
  - High $\tan\beta$: $H^{\pm} \rightarrow \tau\nu$
  - Low $\tan\beta$: $H^{\pm} \rightarrow tb$
  - Also possible: $H^{\pm} \rightarrow Wh$, WZ

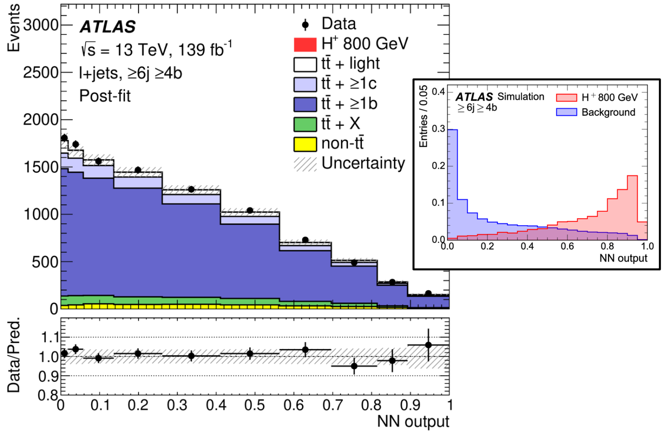






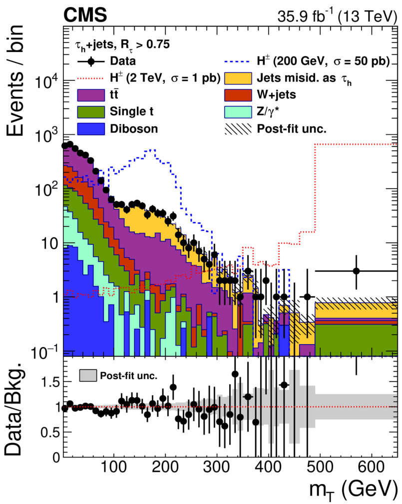
$tbH^{\pm}(\rightarrow tb)$

JHEP 06 (2021) 145



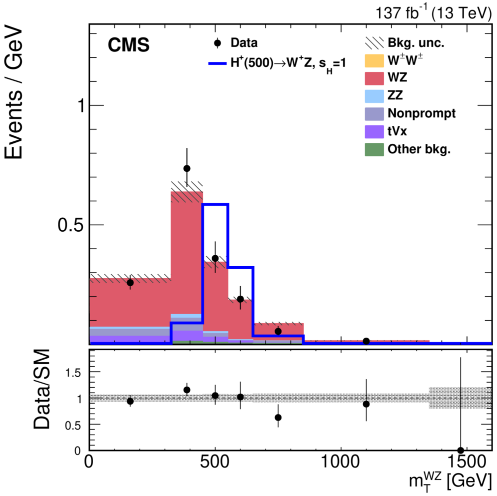
$tbH^{\pm}(\rightarrow\tau\nu)$

JHEP 07 (2019) 142



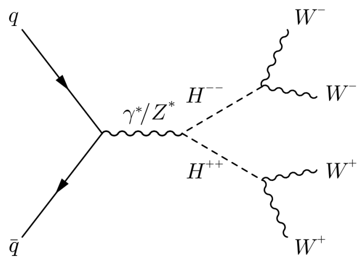
VBF $H^{\pm} \rightarrow WZ$

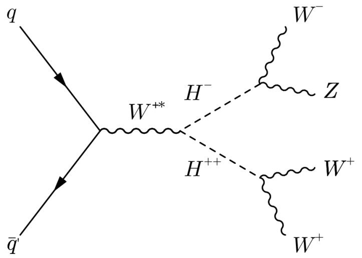
EPJC 81 (2021) 723

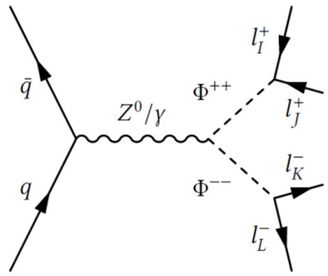


Doubly charged Higgs

- Production via the EW interaction.
- Decay modes: $l^{\pm}l^{\pm}$, $W^{\pm}W^{\pm}$.
- Exploit multilepton final states: 2lSS, 3l, 4l.







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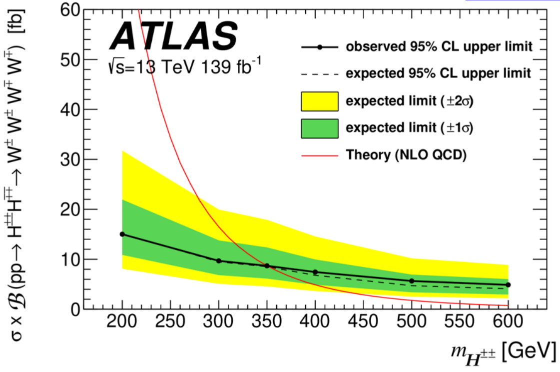
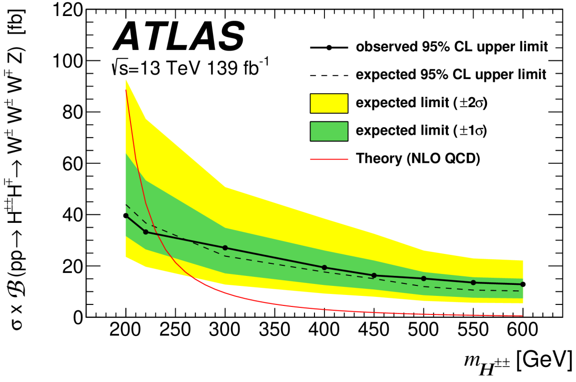
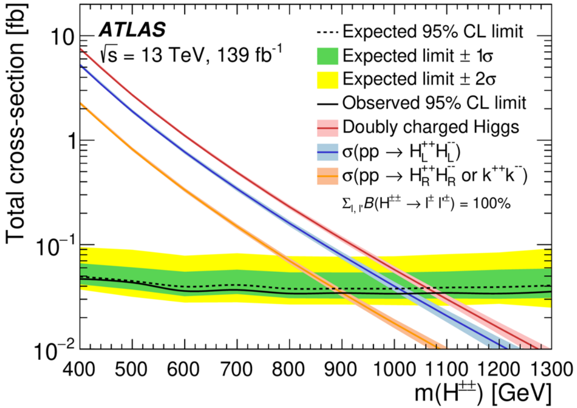
JHEP 06 (2021) 146

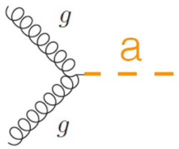


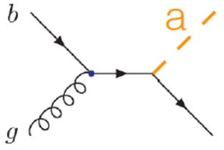




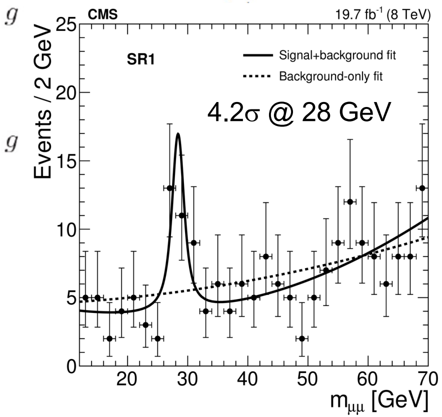
Light scalars

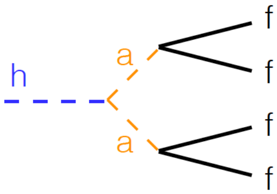
- Production modes for light CP-odd scalars (e.g. from NMSSM):
  - Direct production: gg→a, bba, tta
  - In Higgs decays: h→aa
    - Decay modes are model dependent.

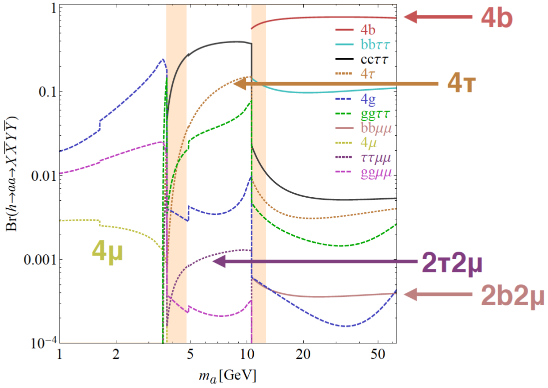




[JHEP 11 (2018) 161]







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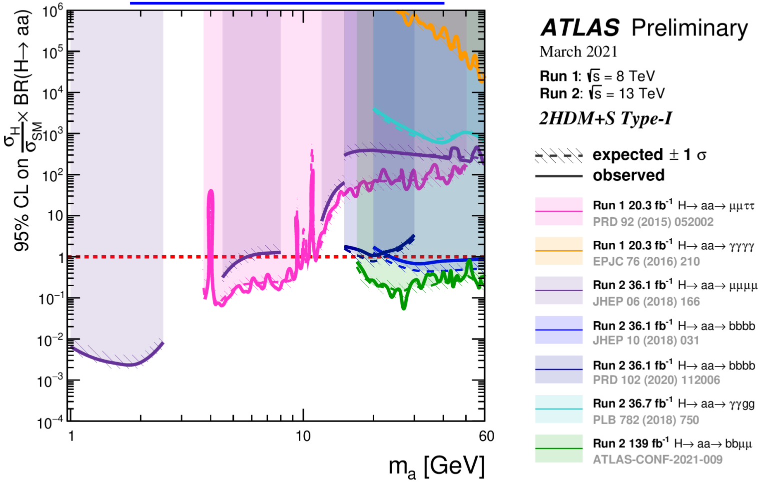
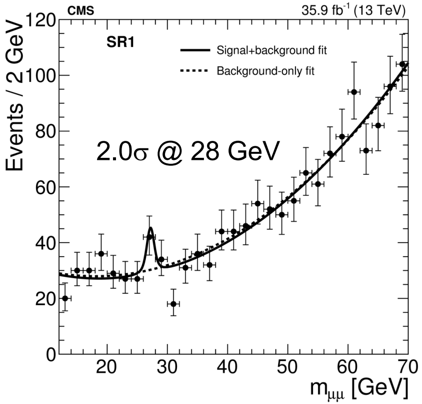
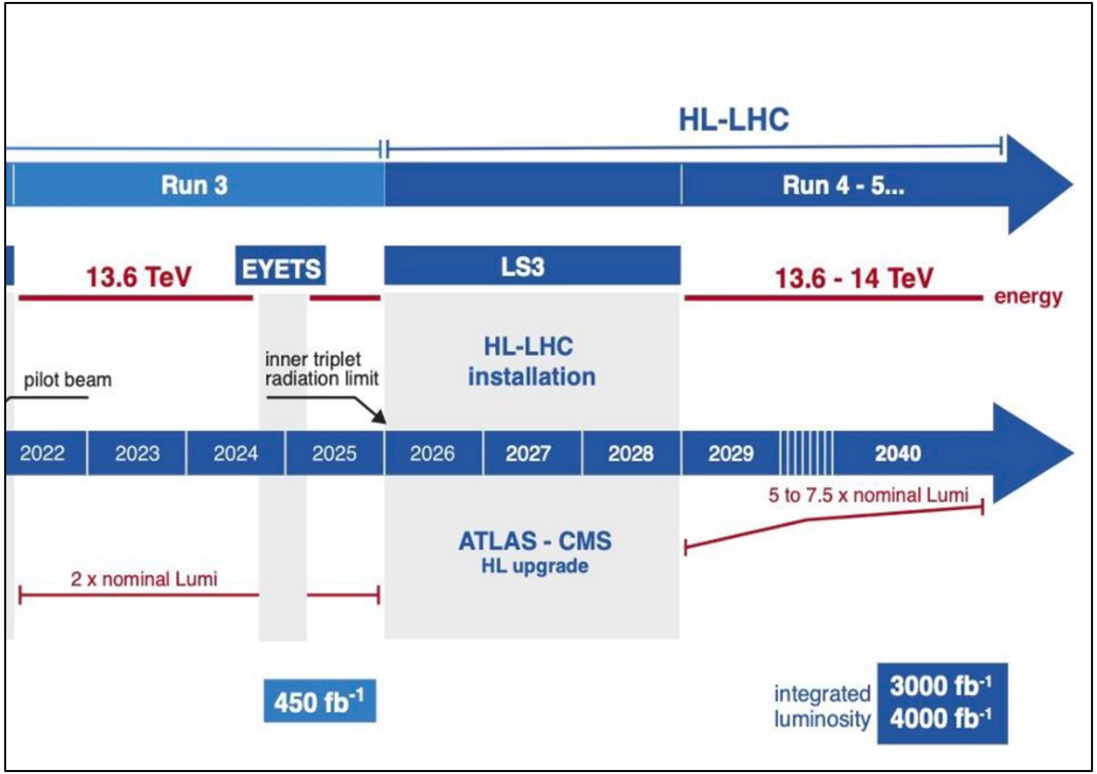


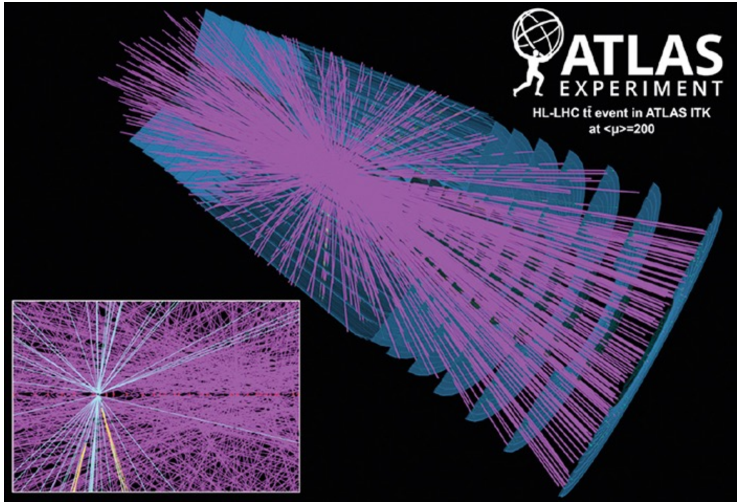


Future prospects

Beyond LHC Run 2



Significant detector upgrades being planned to cope with high pileup at HL-LHC

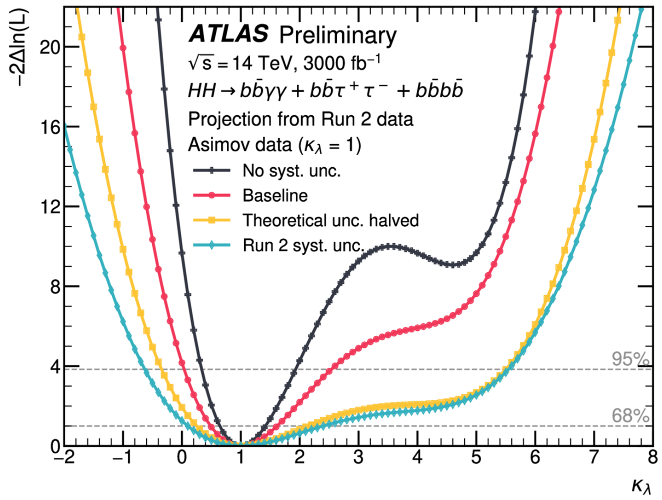


tt event with 200 pileup interactions overlaid in ATLAS Phase-II tracker

Beyond LHC Run 2

- The high available statistics will allow an unprecedented level of scrutiny of the Higgs sector.
  - Precise Higgs coupling measurements.
  - Observation of rare decay modes.
  - Evidence for SM di-Higgs production.
  - Improved searches for BSM Higgs.
  - Studies of vector-boson scattering.

ATL-PHYS-PUB-2022-053



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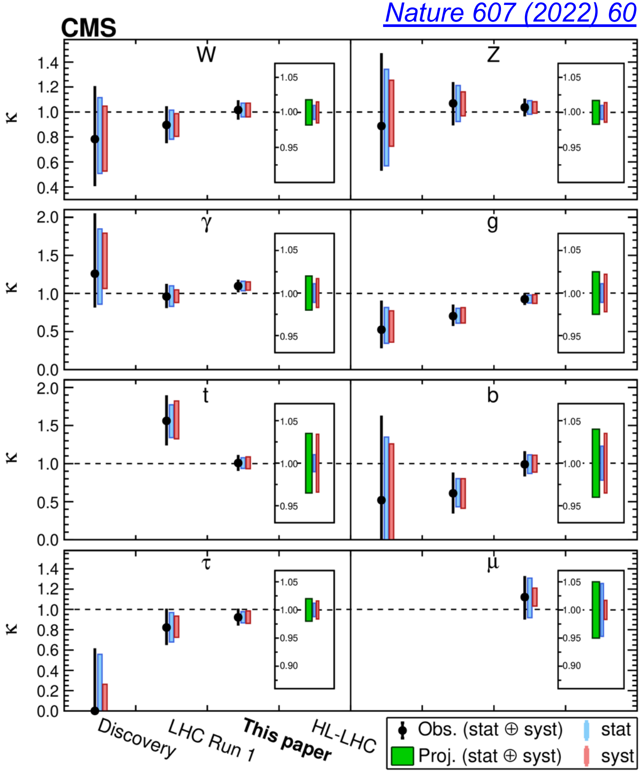

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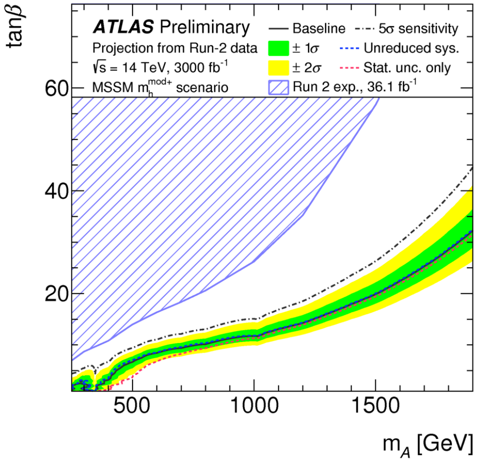

Conclusions

- Since the discovery of the Higgs boson, and entire new field of research has emerged.

- The LHC Run 1 program allowed outlining the experimental profile of the Higgs boson:
  - Mass measured to 0.2% accuracy.
  - Evidence of CP-even scalar nature.
  - Observation of coupling to W, Z and taus.
  - Evidence for non-universal couplings.
  - First studies on Higgs production.
  - First constraints on Higgs width and rare/BSM decay modes.

  Greatly benefited from strong experiment-theory connection.

- A deep exploration of the Higgs sector is a top priority of the LHC Run 2 and beyond.

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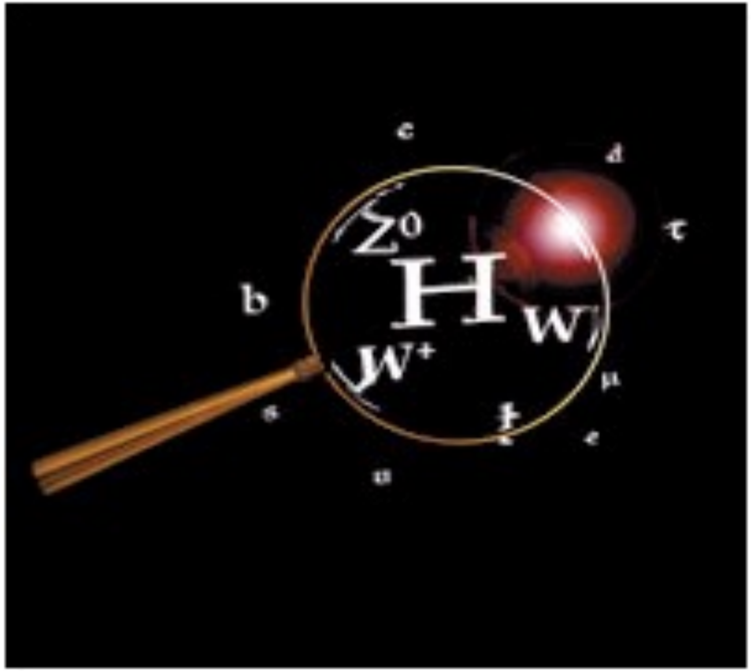

Backup