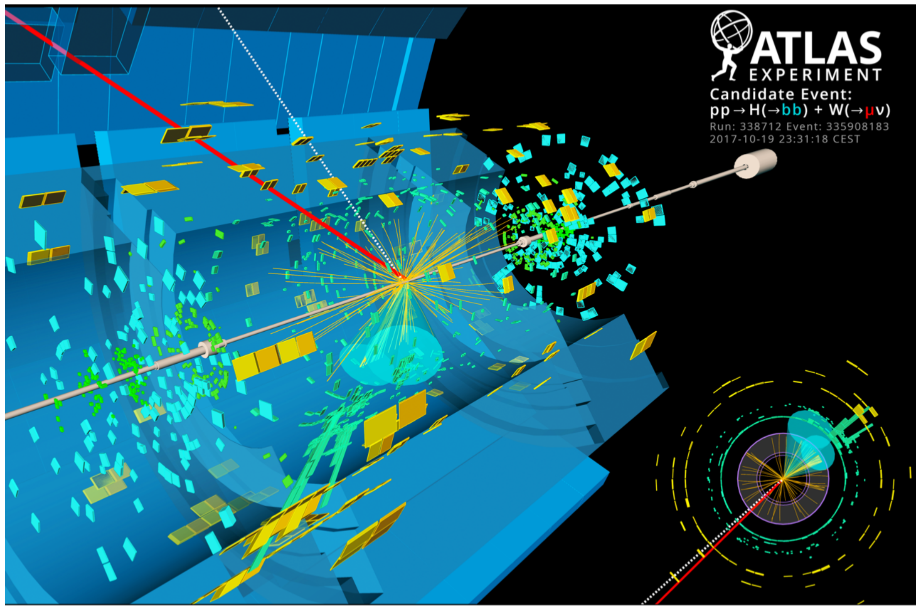
The Higgs Boson
- A decade after the discovery -



Karl Jakobs
University of Freiburg

Humboldt-Kolleg, Kitzbühel
27th June 2022

4 July 2012

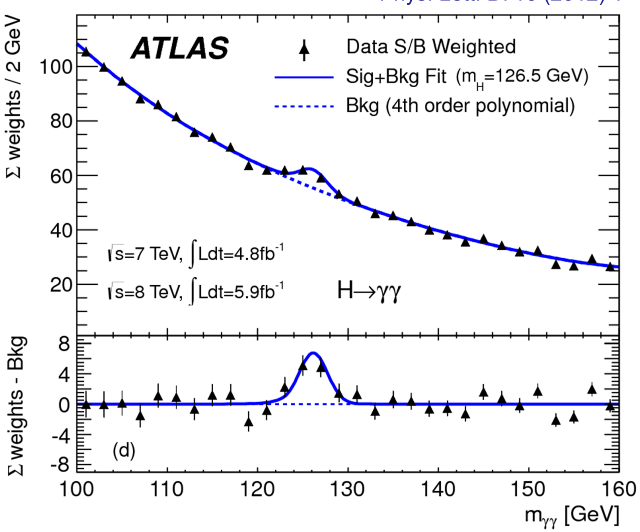
Nobel-Preis für Physik 2013: François Englert und Peter Higgs

" … for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of sub-atomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider."

Higgs boson discovery

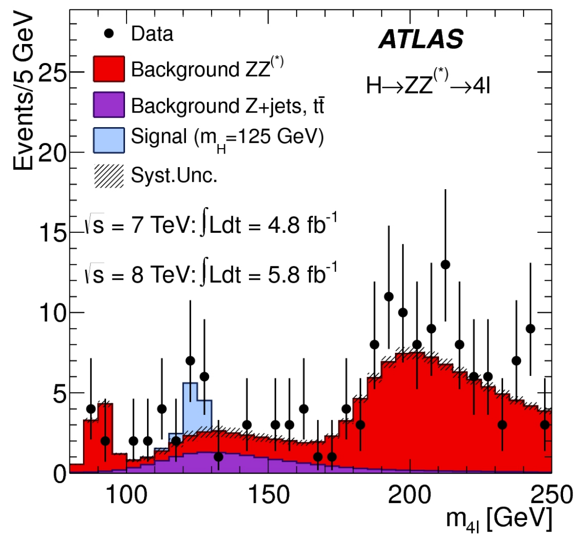
H → γγ

Phys. Lett. B716 (2012) 1

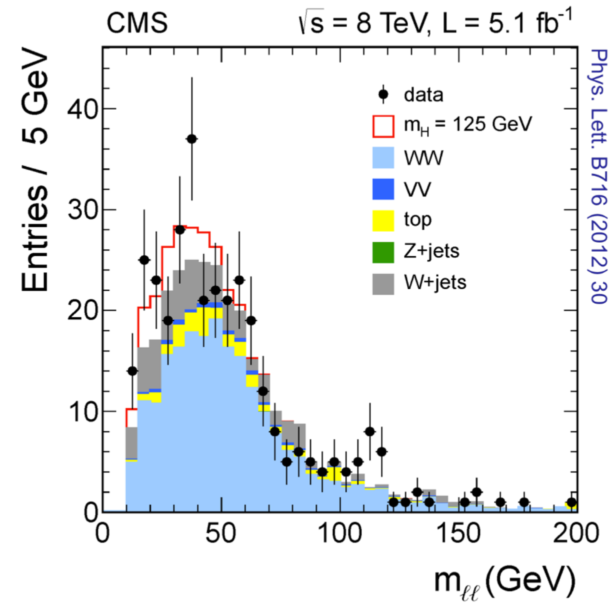


H → ZZ* → ℓℓ ℓℓ

Phys. Lett. B716 (2012) 1



H → WW* → ℓν ℓν

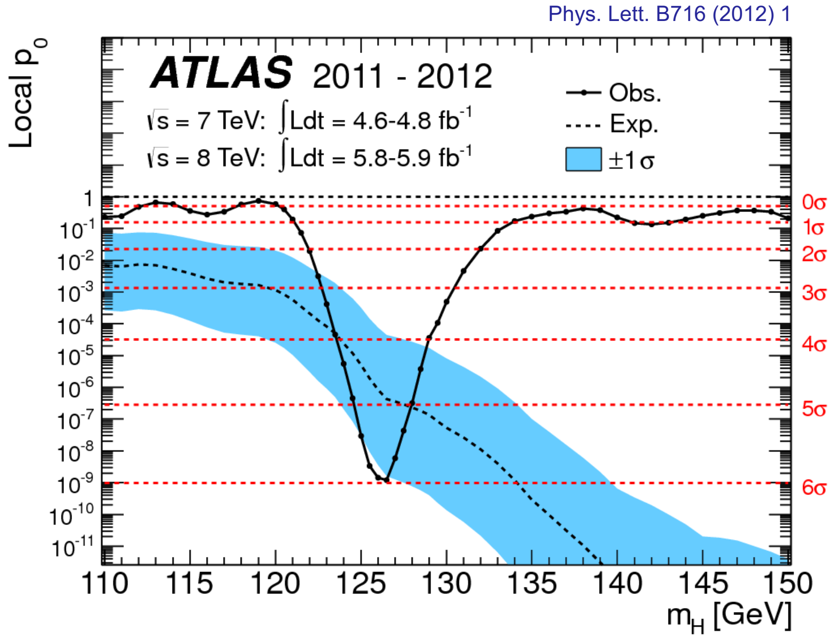


- Higgs boson discovery in the bosonic decay channels

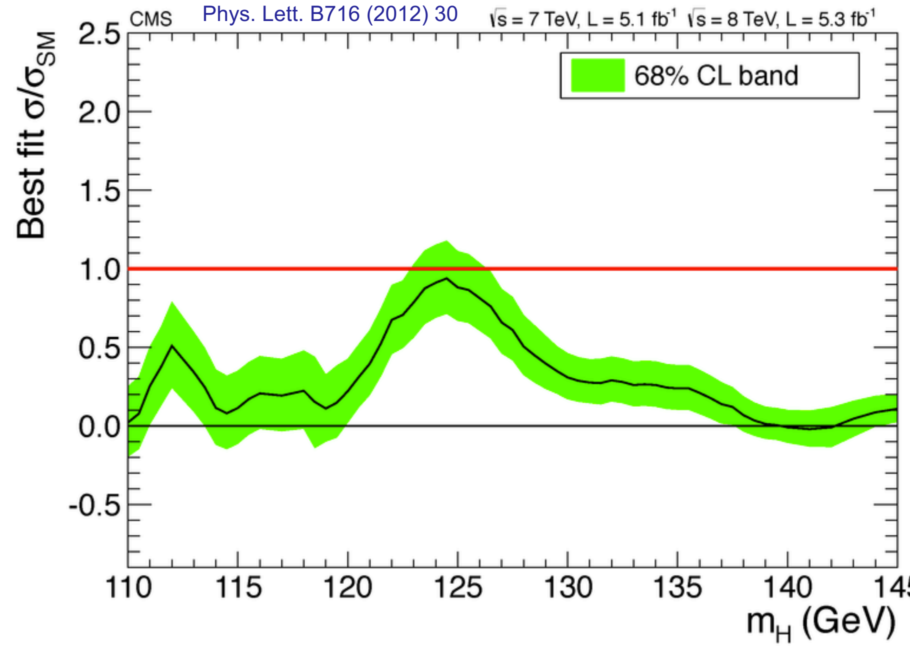
  (based on final states with leptons, photons and missing transverse energy)

http://www.scholarpedia.org/article/The_Higgs_Boson_discovery

Discovery via combination of the three bosonic channels:



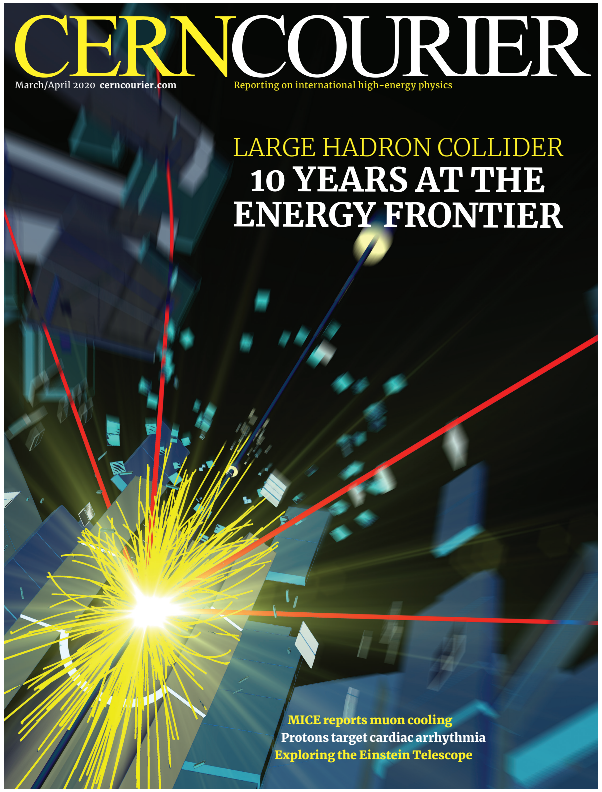
The observed local p-value as a function of m_H (solid line) and the expectation with its $\pm 1\sigma$ band assuming the presence of a Standard Model Higgs boson at that mass (dashed line).



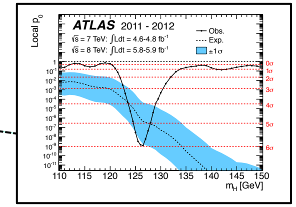
Best-fit signal strength $\mu = \sigma/\sigma_{SM}$ as a function of m_H. Around the fitted signal strength the $\pm 1\sigma$ uncertainty band is shown.

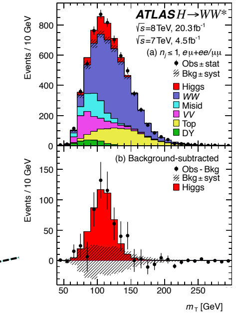
http://www.scholarpedia.org/article/The_Higgs_Boson_discovery

“The Higgs turns 10”

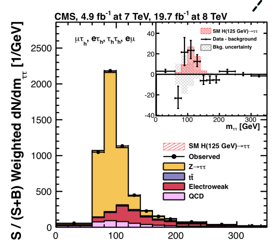


2012

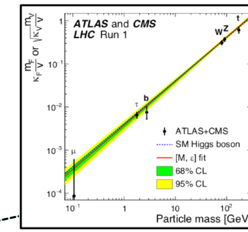


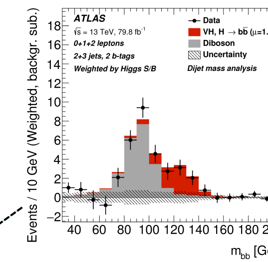


2014

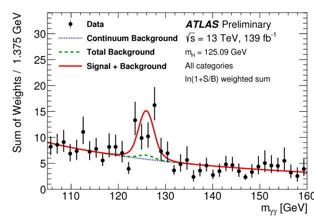


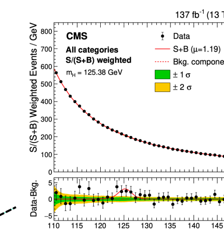
2016



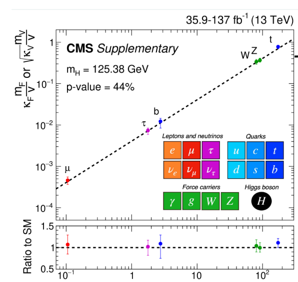


2018

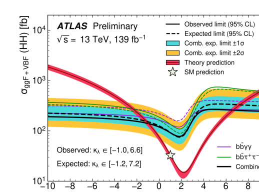




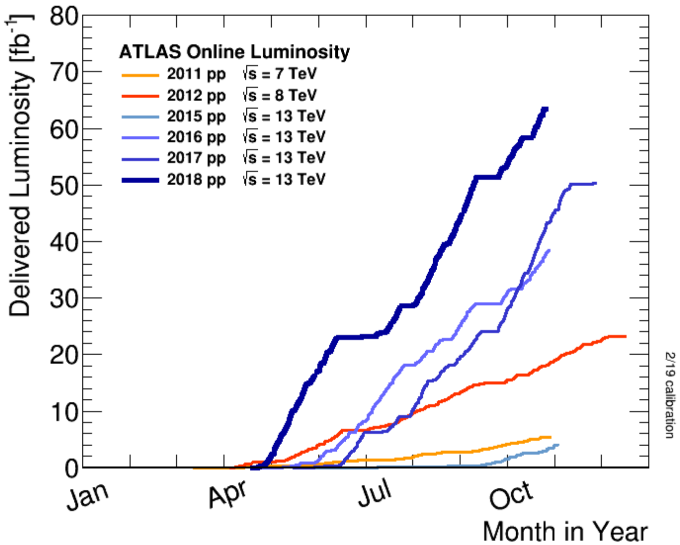
2020

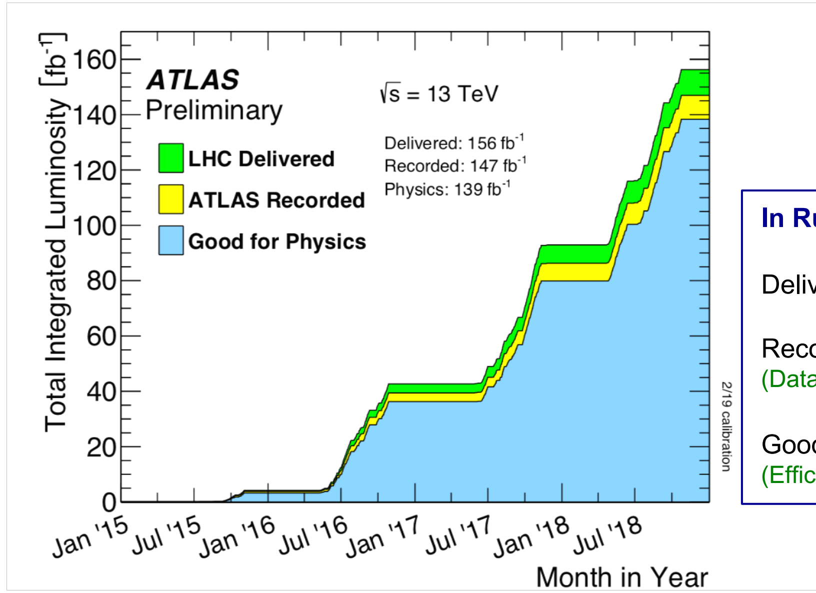


2022



Data Taking at the LHC





In Run 2 (2015 – 2018):

Delivered: 156 fb^{-1}

Recorded: 147 fb^{-1}
(Data taking efficiency 94.2%)

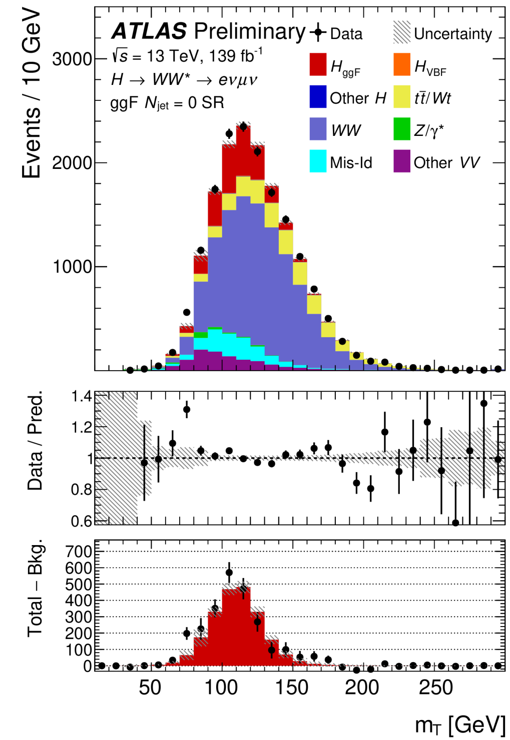
Good for Physics: 139 fb^{-1}
(Efficiency 94.6%, → high data quality)

- The LHC operation have produced sensational performance, well beyond our expectations
- The combination of the performance of the LHC machine, the detectors and the GRID computing have proven to be a terrific success story

Progress over the past 10 years (Run 2)

H → WW* → ℓν ℓν

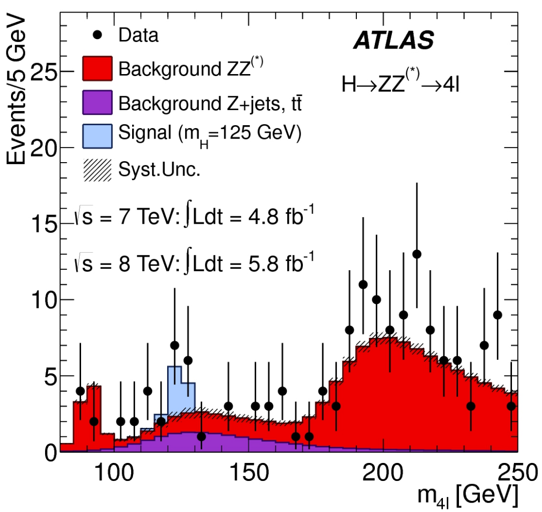
ATLAS-CONF-2021-014



Run 2

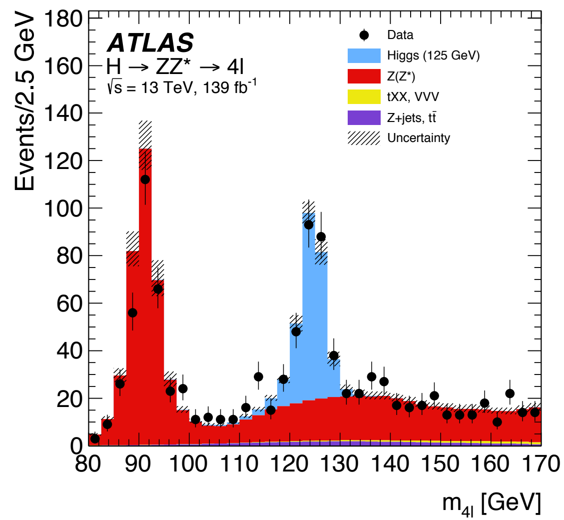
H → ZZ* → ℓℓ ℓℓ

Phys. Lett. B716 (2012) 1



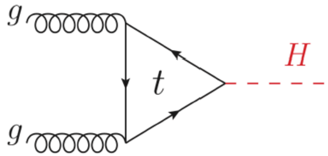
Run 1

Eur. Phys. J. C 80 (2020) 942



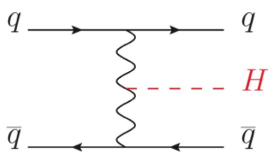
Run 2

Higgs boson production



Gluon fusion process

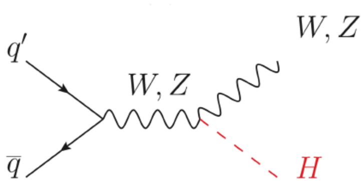
~8 M events produced



Vector Boson Fusion

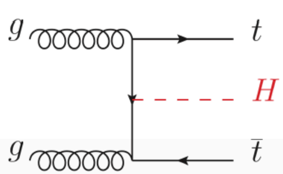
Two forward jets and a large rapidity gap

~600 k events produced



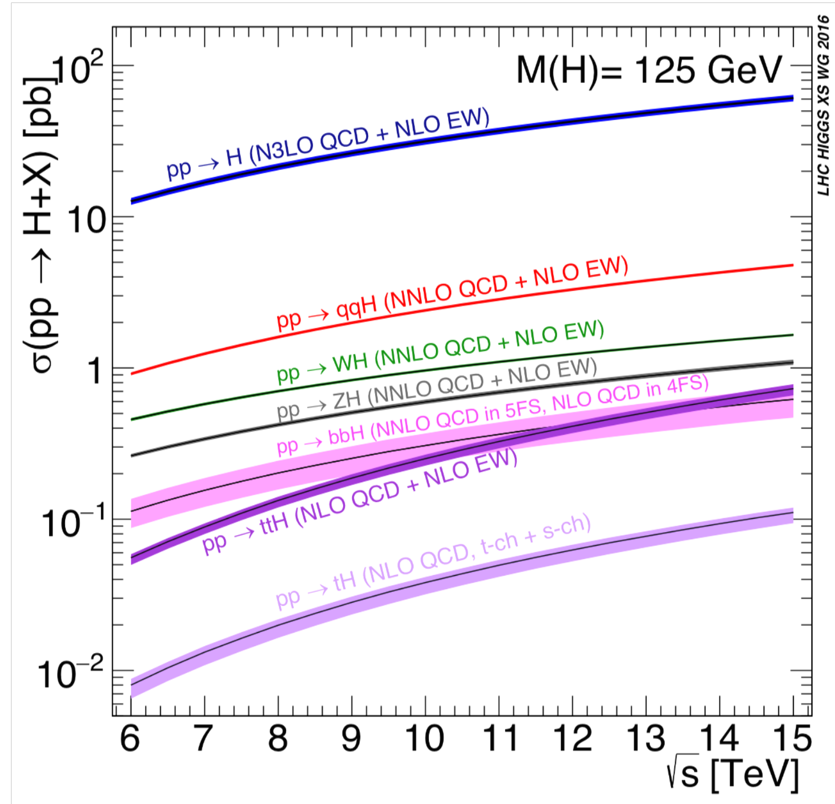
W and Z Associated Production

~400 k events produced



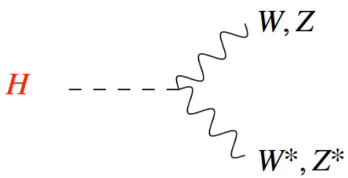
Top Assoc. Prod.

~80 k evts produced



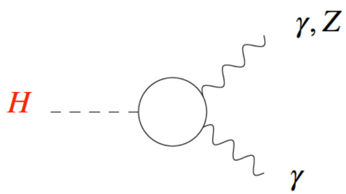
Huge progress also on the theory side;
NNLO (and beyond) is “state of the art”

Higgs boson decays



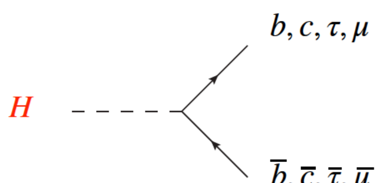
$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$



$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$

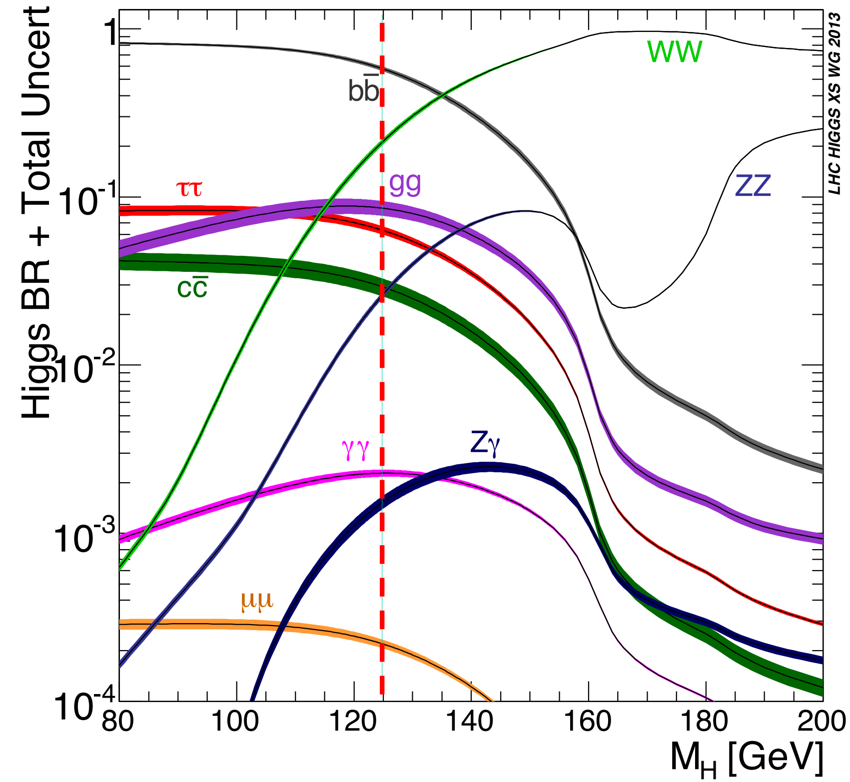


$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

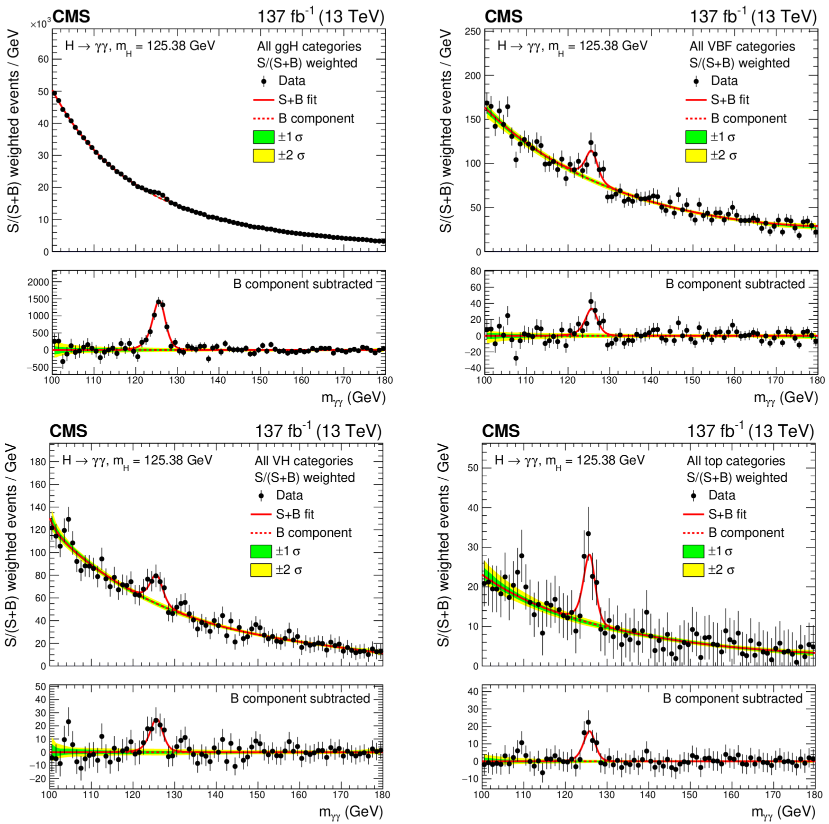
$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

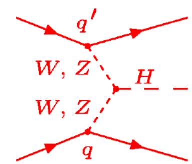


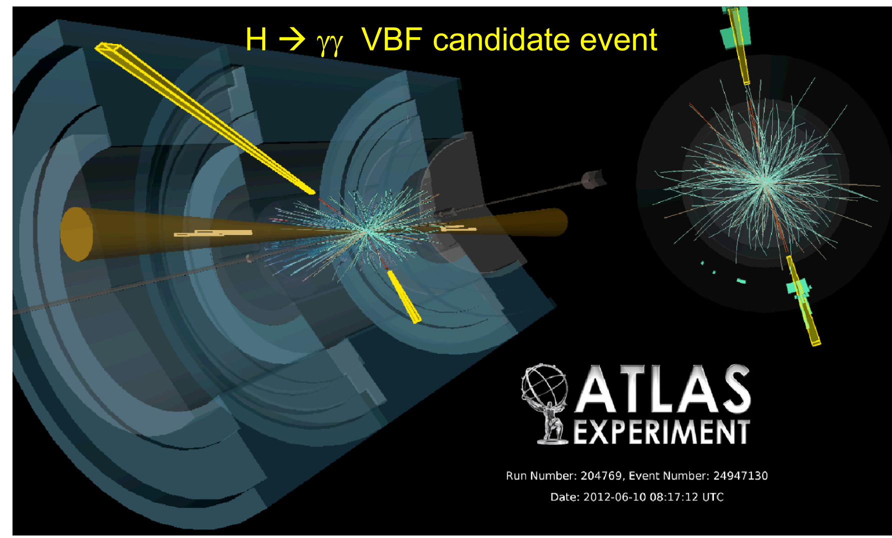
A rich spectrum of decays available for $m_H = 125$ GeV

Sensitivity to various production modes



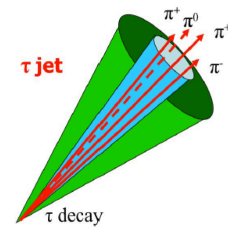
JHEP 07 (2021) 027



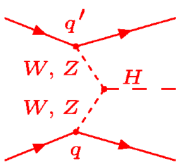


Higgs signals demonstrated in various production channels; example: H → $\gamma\gamma$

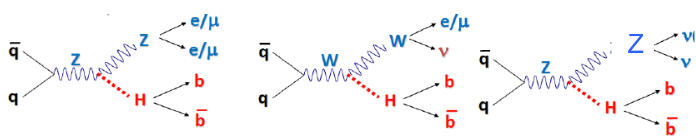
Couplings to quarks and leptons?



- Search for **H → ττ** and **H → bb** decays;
- Challenging signatures due to jets (bb decays) or significant fraction of hadronic tau decays
- Vector boson fusion mode essential for **H → ττ** decays



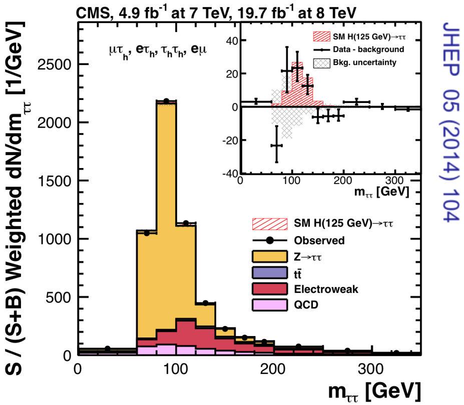
- Associated production WH, ZH modes have to be used for **H → bb** decays; Large backgrounds from Vbb production!



- Exploitation of **multivariate analyses, vector boson fusion topologies,** and **high p_T(H) phase space regions** (boosted Higgs boson)

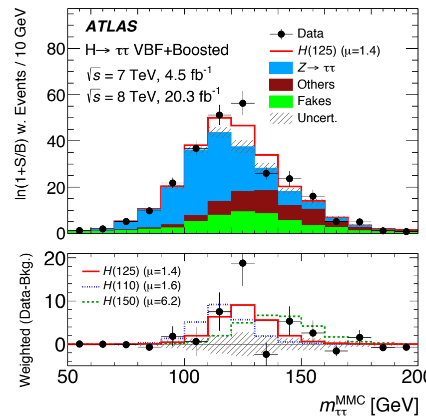
Observation of H → ττ decays

- First evidence in Run-1 data; one of the most important LHC result in 2014



JHEP 05 (2014) 104

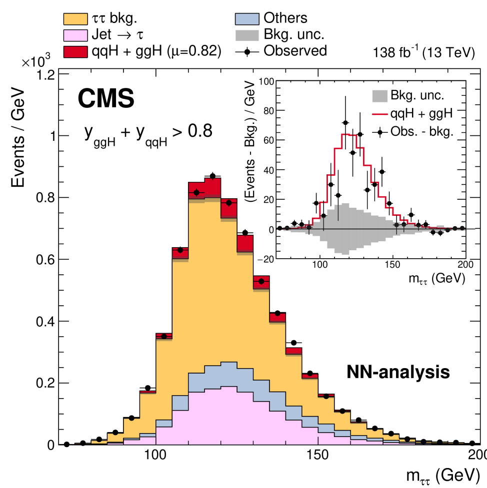
JHEP 04 (2015) 117



4.3σ

$m_{\tau\tau}$ distribution, events weighted by ln (1+S/B)

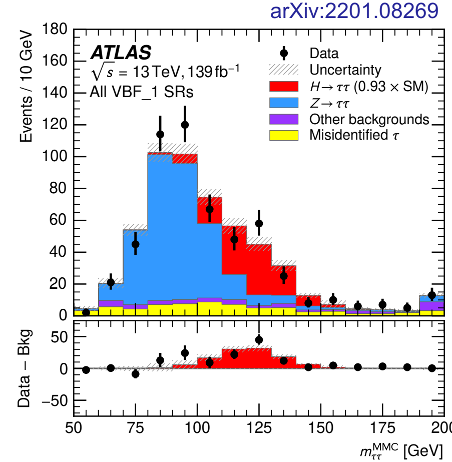
- Clear observation in Run 2



arXiv:2204.12957

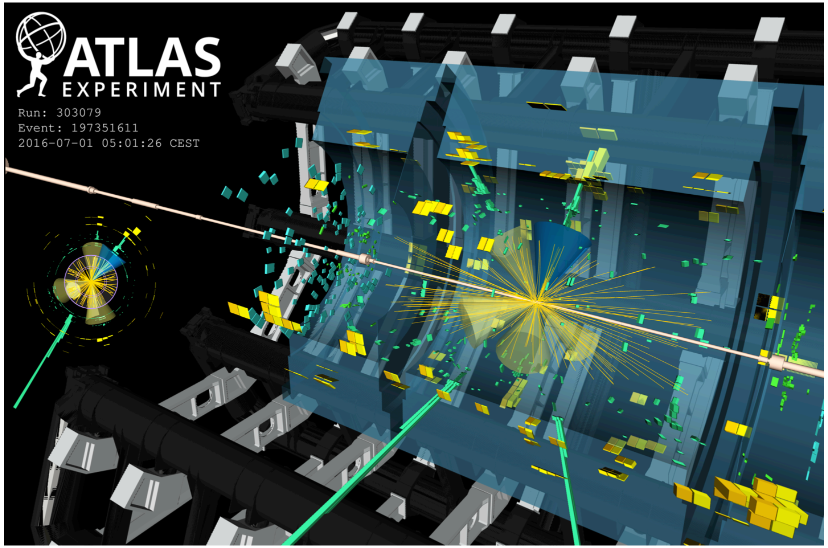
Observed and expected $m_{\tau\tau}$ distribution of the analysed data in all ττ final states for the NN-analysis.

arXiv:2201.08269



Distribution of the reconstructed di-τ invariant mass ($m^{MMC}_{\tau\tau}$) for all events in the VBF category

Physics Highlights 2018

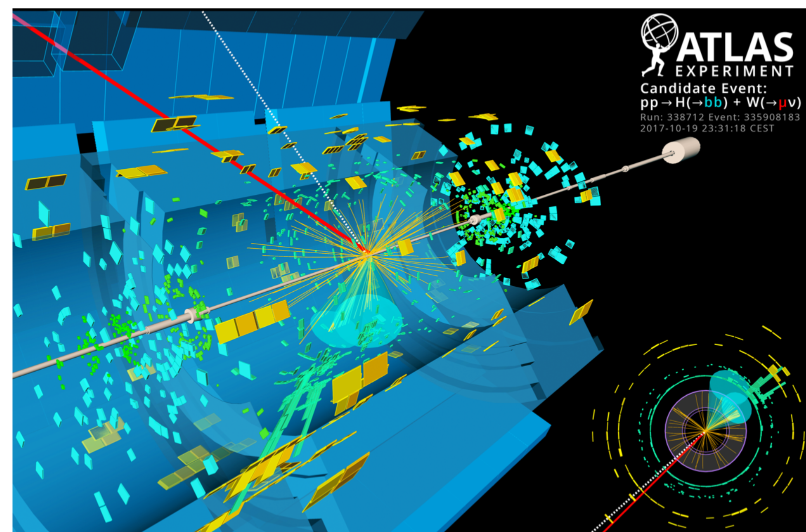


Observation of ttH production
LHCP Conference, Bologna, 4th June 2018

Phys. Lett. B784 (2018) 173

Observation of H→ bb decays and VH production
ICHEP Seoul, 9th July 2018

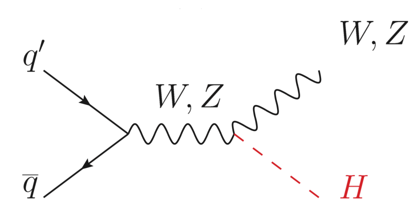
Phys. Lett. B786 (2018) 59



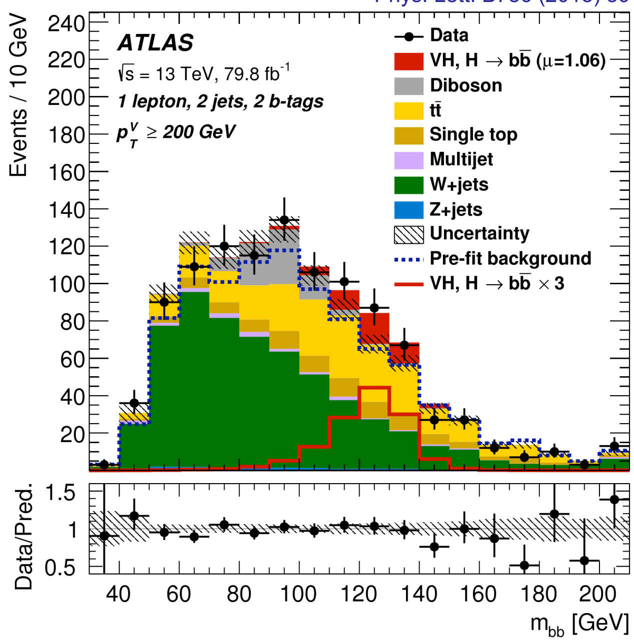
Based on partial Run-2 dataset
(2015 – 2017), 80 fb^{-1}

Observation of H → bb decays

- H→bb mode dominates Higgs decays (BR~58%)
- Exploit VH, H→bb (V=W/Z)
  - Combination of Z and W final states characterised by lepton multiplicity (Z→ ℓℓ, W→ ℓν, and Z→νν)

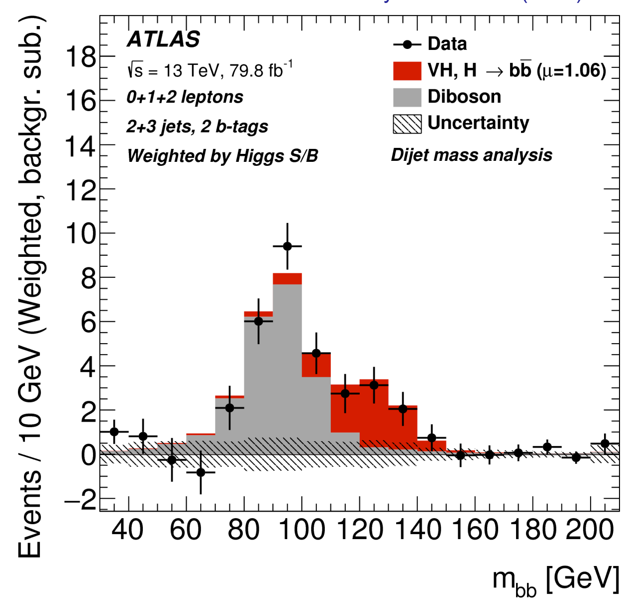


Phys. Lett. B786 (2018) 59



Distribution of m_{bb}
(1-lept. channel, signal region)

Phys. Lett. B786 (2018) 59



Distribution of m_{bb} (after subtraction of non-resonant background)

Observation of ttH production

Analysis	Integrated luminosity [fb^{-1}]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	4.1 σ	3.7 σ
$H \to$ multilepton	36.1	4.1 σ	2.8 σ
$H \to b\bar{b}$	36.1	1.4 σ	1.6 σ
$H \to ZZ^* \to 4\ell$	79.8	0 σ	1.2 σ
Combined (13 TeV)	36.1−79.8	5.8 σ	4.9 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1−79.8	6.3 σ	5.1 σ

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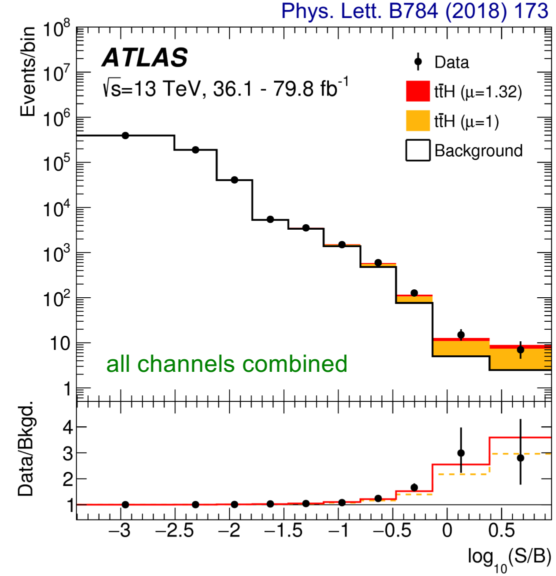

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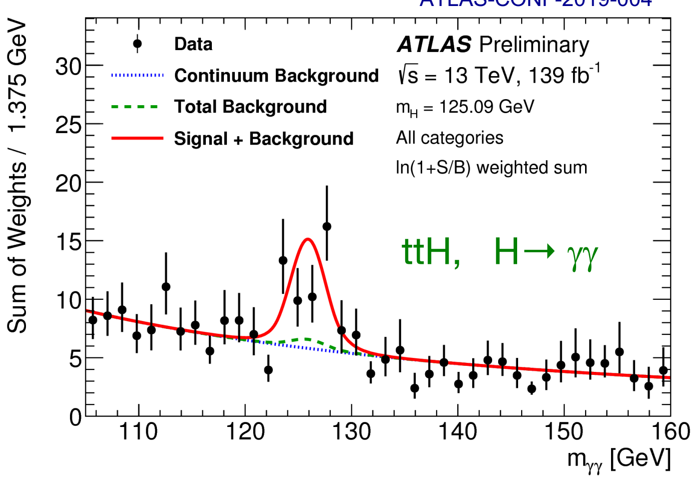
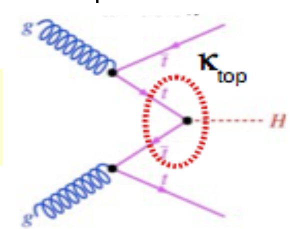


ttH production

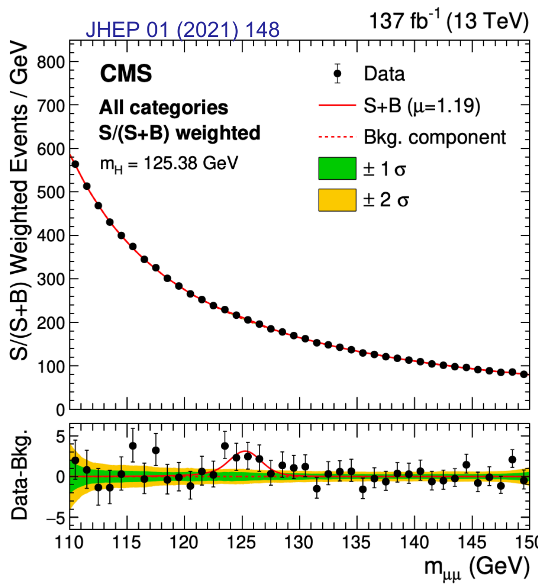


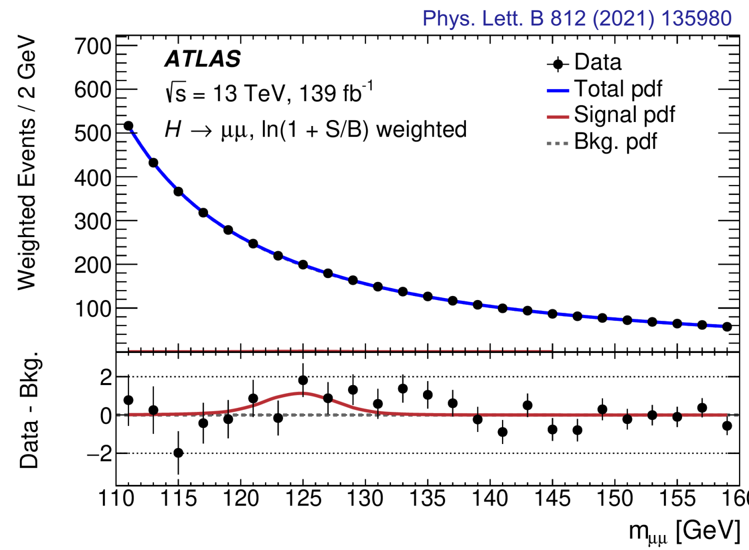
Direct observation of top-Higgs coupling

Yukawa couplings of the 2nd generation?

H → μμ

- Very challenging! ~2000 events produced on top of a huge background
- Gain in sensitivity through separation of production modes (ggF, VBF, VH, ttH)
- Neural network and BDT discriminants in all categories, sidebands as control regions





Signal strength: $\mu = \sigma_{obs} / \sigma_{SM} = 1.19 \pm 0.43$ $\mu = 1.2 \pm 0.6$

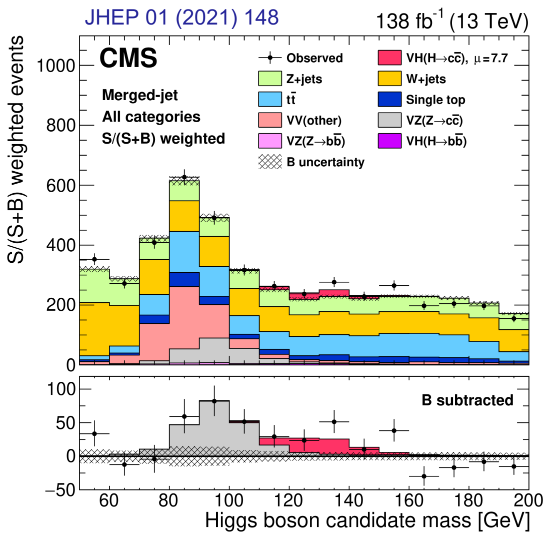
Significance: **3.0σ** (2.5σ expected) **2.0σ** (1.7σ expected)

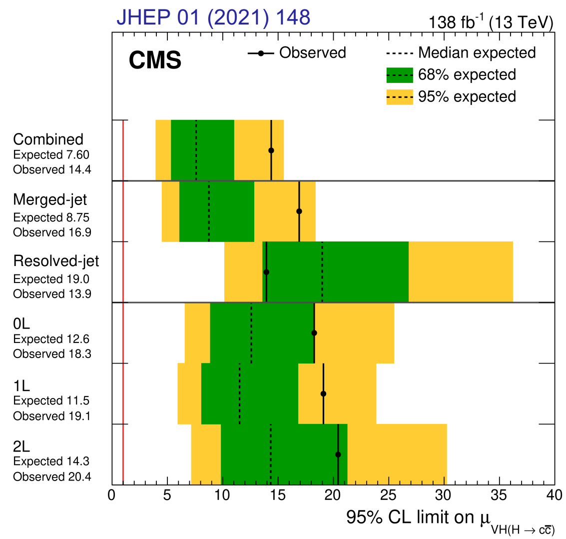
Run 3 and beyond essential to increase sensitivity

Yukawa couplings of the 2nd generation?

H → cc?

- Even much more challenging! Search for associated production, with a leptonically decaying W/Z
- Novel charm jet identification and analysis methods using machine learning techniques
- Analysis is validated by searching for Z → cc in VZ events (first observation, 5.7σ)





(strong contribution from "boosted" analysis, limit from combination)

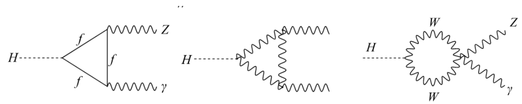
Limit on signal strength: CMS: $\mu = \sigma_{obs} / \sigma_{SM} < 14$ (expected 7.6)

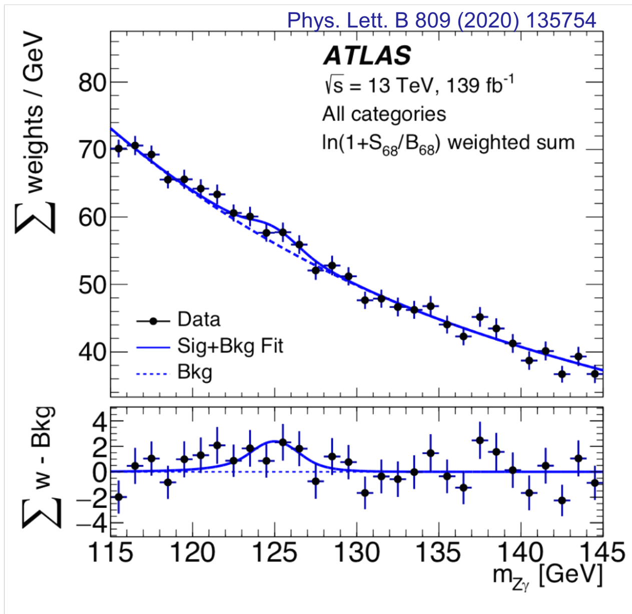
ATLAS: $\mu = \sigma_{obs} / \sigma_{SM} < 26$ (expected 31) [arXiv:2201.11428]

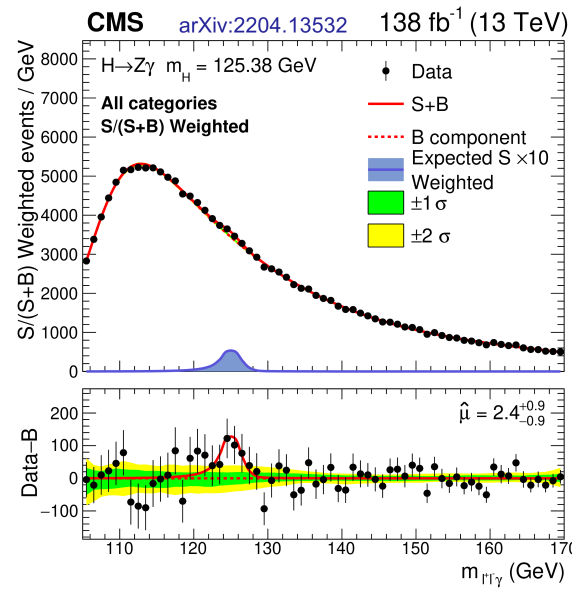
Run 3 and beyond essential to increase sensitivity

Rare Higgs Boson decays?

$H \rightarrow Z\gamma$







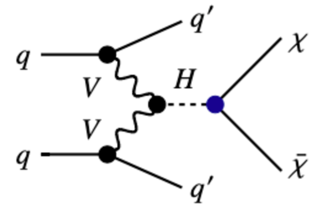
Background-only hypothesis: p-value of 1.3% (2.2σ) (2.7σ)

Best fit signal strength: $\mu_{Z\gamma}$ = 2.0 ± 0.9 (stat) $^{+0.4}_{-0.3}$ (syst) $\mu_{Z\gamma}$ = 2.4 ± 0.9

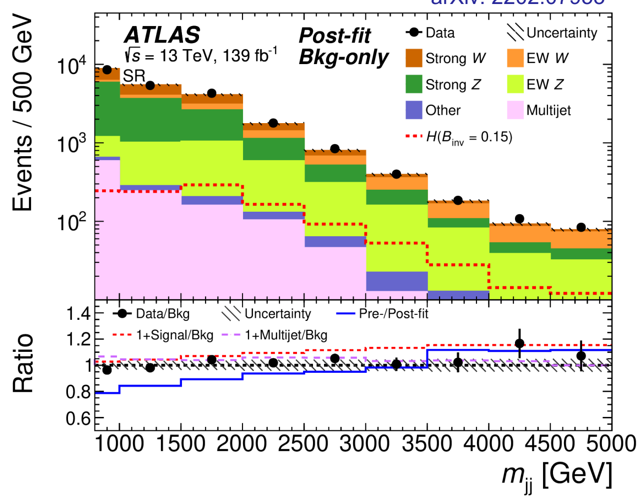
Run 3 and beyond essential to increase sensitivity

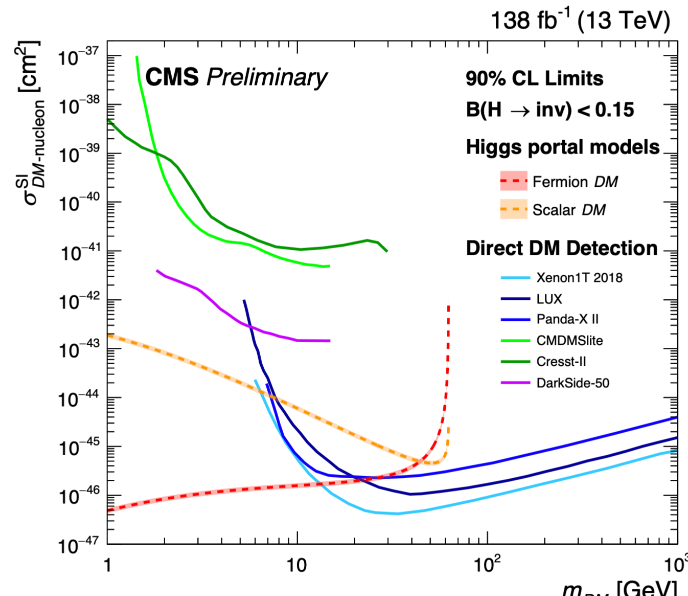
Invisible Higgs boson decays?

qqH → qq inv. (VBF)



arXiv: 2202.07953



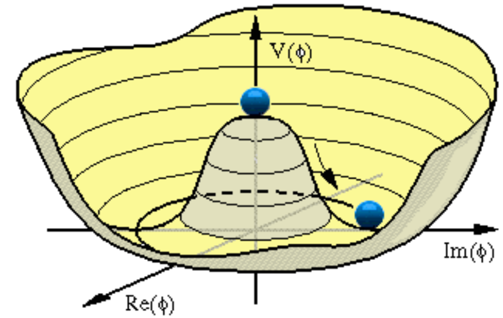


Nice complementarity to direct searches

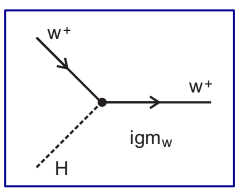
Dark Matter interpretation (Higgs portal models)

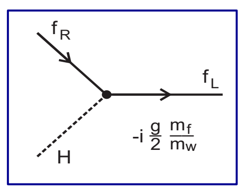
Limit on BR (H → inv.):	ATLAS:	< 0.145	(95% CL)
	CMS:	< 0.17	(95% CL)

Higgs Boson Parameters



- Mass ("input parameter")
- Width
- Production rates
- Couplings to bosons and fermions



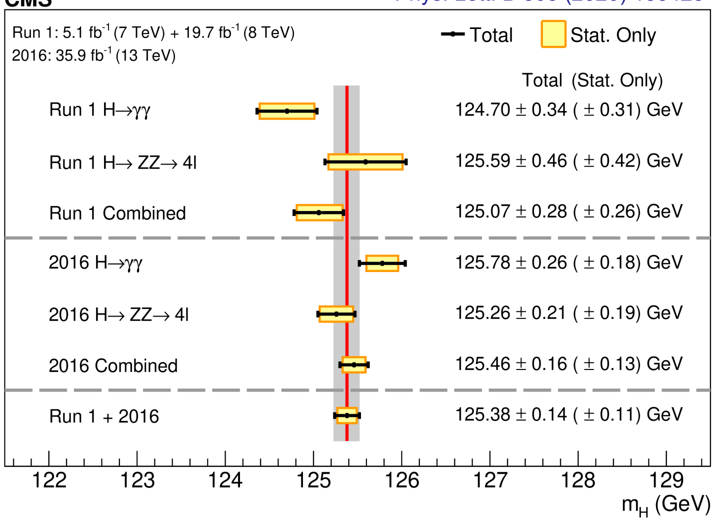


- Higgs boson self coupling?

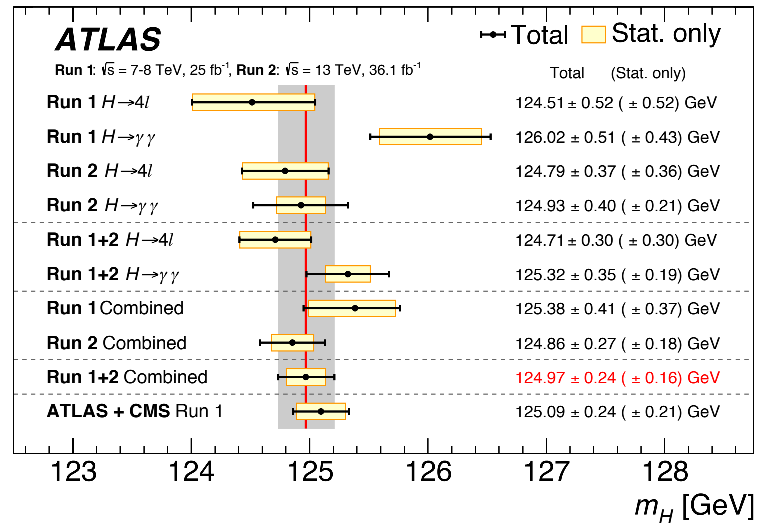
Higgs boson mass

- The two high resolution channels H → ZZ*→ 4ℓ and H → γγ are best suited (reconstructed mass peak, good mass resolution)
- Good control of the lepton and photon energy scales, calibration via Z → ℓℓ and J/ψ and ϒ signals;

Phys. Lett. B 805 (2020) 135425



Phys. Lett. B 784 (2018) 345



ATLAS: m_H = 124.97 ± 0.24 GeV (± 0.16 stat.)

CMS: m_H = 125.38 ± 0.14 GeV (± 0.11 stat.)

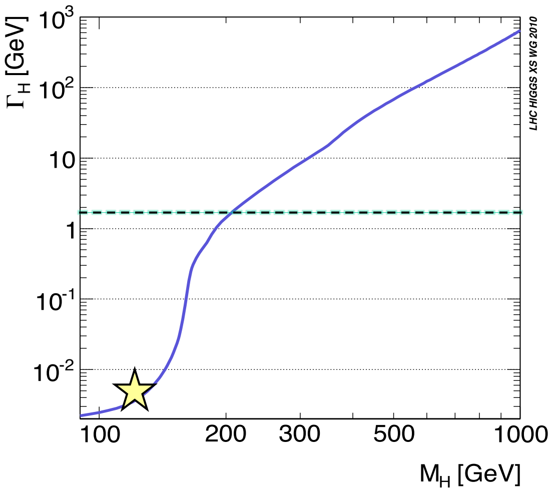
Precision still limited by **statistical uncertainty**!

On the longer term, 4-lepton channel will become dominant (systematic uncertainty today: ± 0.05 GeV)

Higgs boson width

- The Standard Model Higgs boson width is expected to be small: $\Gamma_H \sim 4$ MeV
- Experimental mass resolution in H → γγ and H → ZZ*→4ℓ channel ~1 - 2 GeV

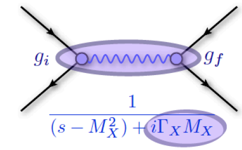
→ only upper limits can be extracted from the observed mass peaks



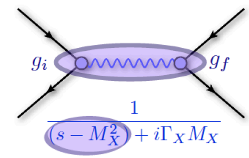
Γ_H < 1.1 GeV (95% CL limit)

(from H → ZZ*→ 4ℓ line shape)

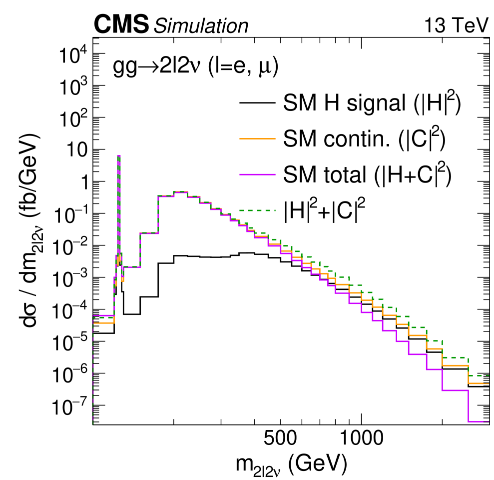
- Indirect measurement via "off-shell" cross section measurement



$$\sigma^{on}_{i\to X\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_X}$$



$$\sigma^{off}_{i\to X\to f} \sim g_i^2 g_f^2$$



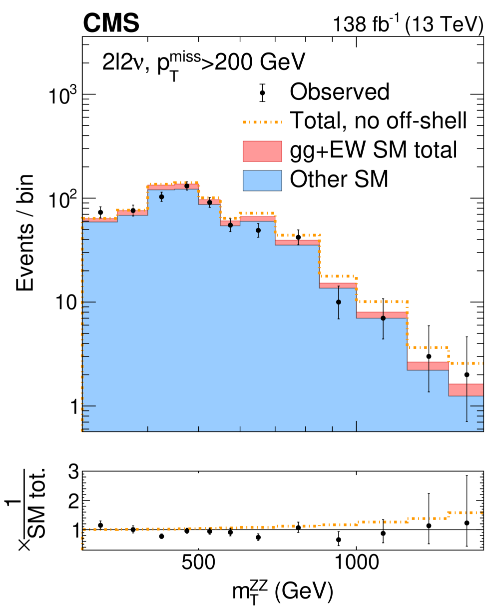
Example: H → ZZ → 2ℓ 2ν

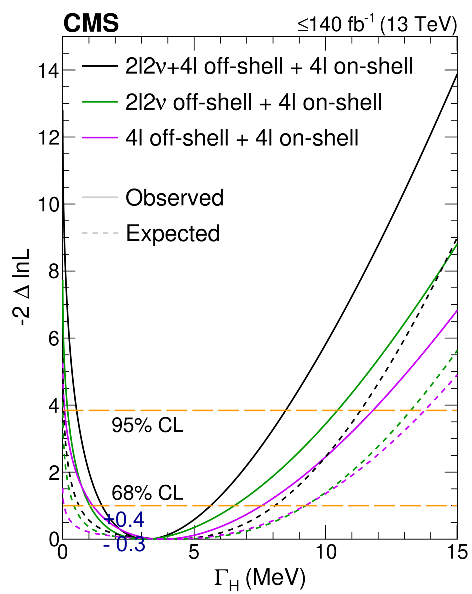
Destructive interference of Higgs and continuum background contributions

JHEP 11 (2017) 047

Indirect measurement of the Higgs boson width from "off-shell cross sections"

- Different sensitivity of on-shell and off-shell cross-sections on the Higgs boson width
- However, model dependent: assumes that on-shell and off-shell couplings are the same
- Dependence on K-factors for signal and backgrounds (gg → VV)





arXiv:2202.06923

CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

- Evidence for off-shell Higgs boson production at 3.6σ
- *A remarkable result; Run 3 and beyond essential to increase sensitivity*

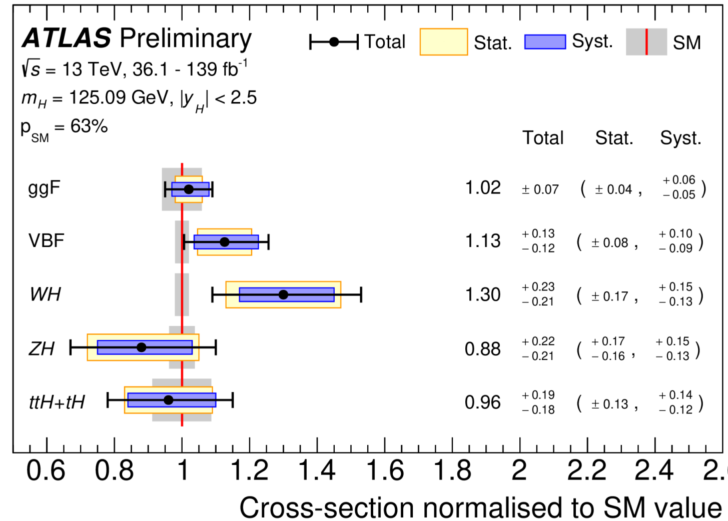
Combined measurements of Higgs boson production and decays

Channels included in the combination:

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139
	$t\bar{t}H$	36.1
$H \to WW^*$	ggF, VBF	139
	$t\bar{t}H$	36.1
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139
	$t\bar{t}H$	36.1
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H$	139
$H \to \mu\mu$	ggF, VBF, $VH, t\bar{t}H$	139
$H \to Z\gamma$	ggF, VBF, $VH, t\bar{t}H$	139
$H \to inv$	VBF	139

(i) Production Cross Sections
(assume SM branching ratios)

ATLAS-CONF-2021-053

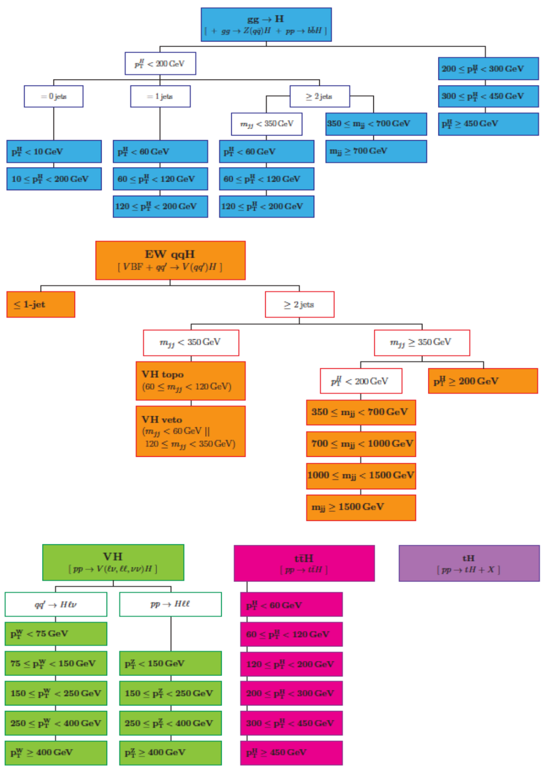


All major production processes observed
(significance > 5σ)

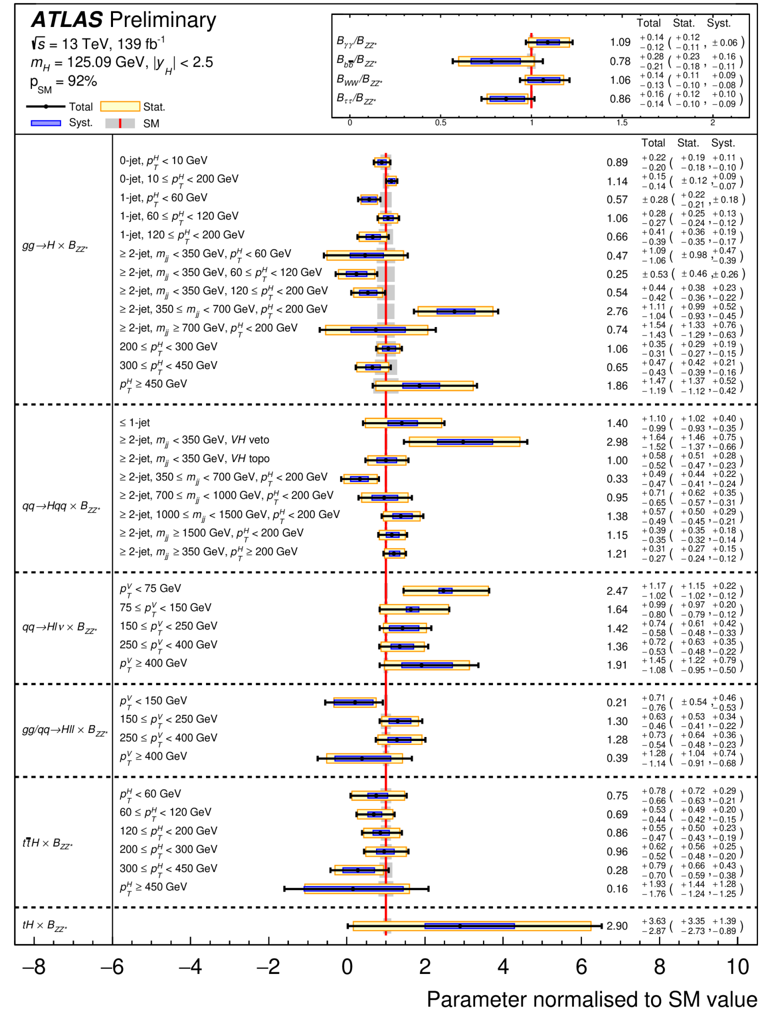
(ii) Measurements of **simplified template cross-sections (STXS)**

- *Partition phase space into a set of non-overlapping regions*
- *Defined in terms of kinematics of the Higgs boson, associated jets, W and Z bosons*

  → Match experimental selections, avoid large theory uncertainties, sensitive to deviations from SM



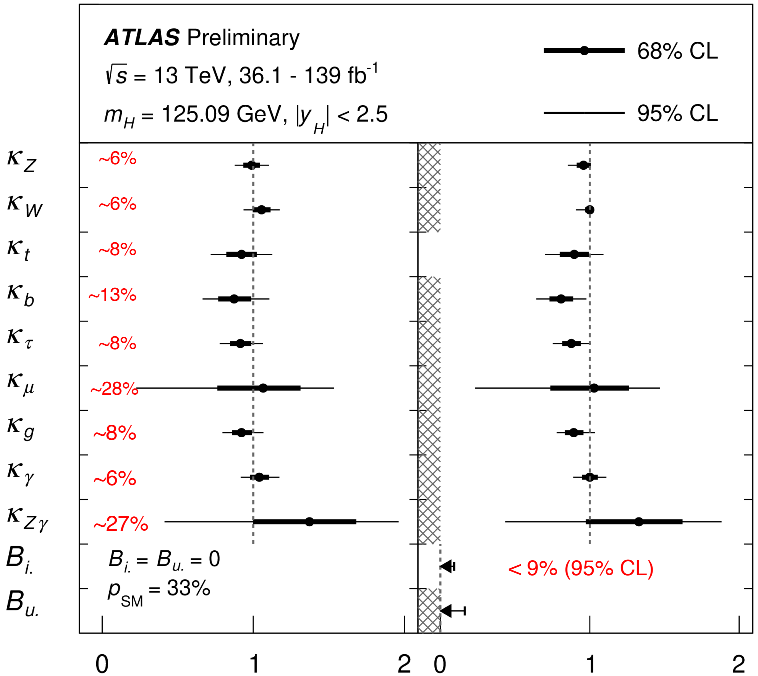
ATLAS-CONF-2021-053



(iv) Interpretation in the κ framework

- *Introduce* ***coupling scale factors κ*** *for each particle, including effective photon and gluon couplings*

ATLAS-CONF-2021-053



No BSM contributions ($B_{inv} = B_{undet} = 0$)

B_{inv} and B_{undet} added as free parameters with constraints $\kappa_W \le 1$ and $\kappa_Z \le 1$

Cross section times branching fraction of an individual channel σ(i → H → f) contributing to a measured signal yield:

$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H}$$

Definition of coupling strength modifier: $\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}}$ or $\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$

Scale factor of Higgs boson width: $\kappa_H^2(\boldsymbol{\kappa}, B_{i.}, B_{u.}) = \frac{\sum_j B_j^{SM} \kappa_j^2}{(1 - B_{i.} - B_{u.})}$

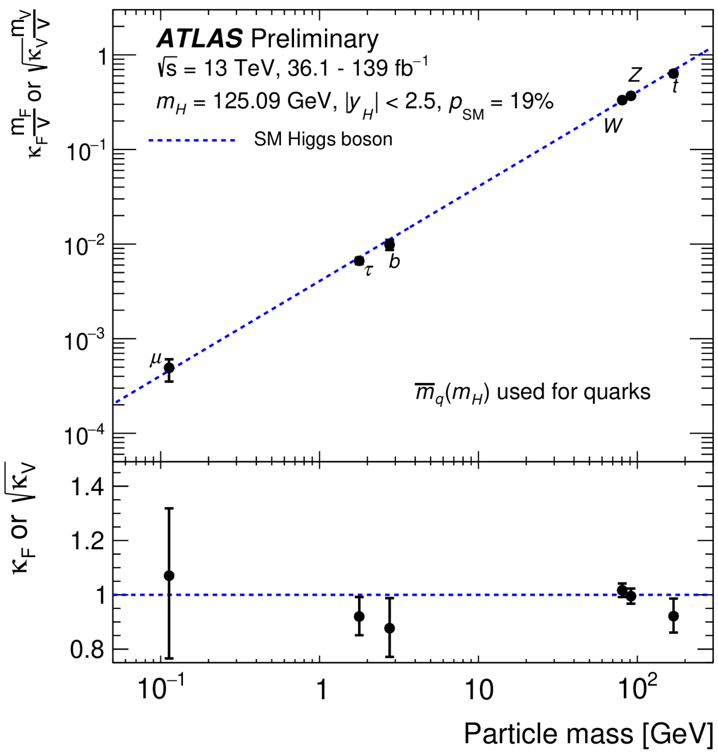
Branching ratio of Higgs into invisible particles constrained to < 9% (95% CL) (<11% expected)

(VBF H → invisible, global fit)

Coupling strength versus particle mass

(assuming no new particles in loops and decays)

ATLAS-CONF-2021-053



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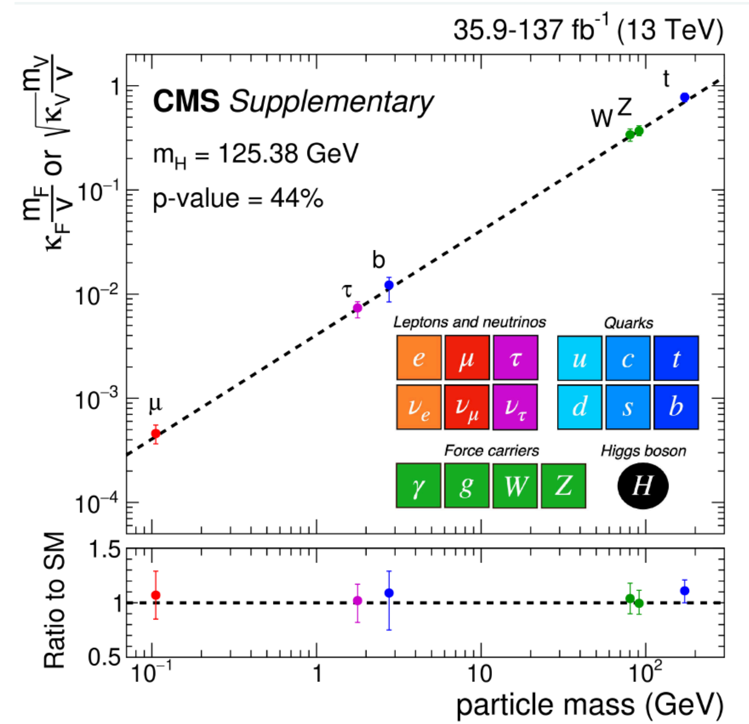
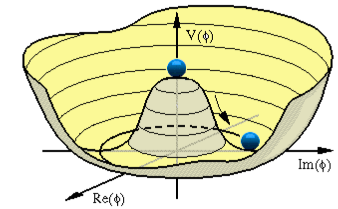


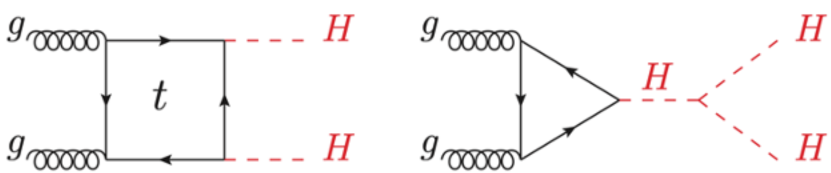
Excellent agreement with SM predictions; Coupling scaling ~mass over three orders of magnitude

Higgs boson self coupling



- The missing piece!
  A key milestone for the High-Luminosity phase of the LHC (HL-LHC)

- Requires the measurement of di-Higgs boson production

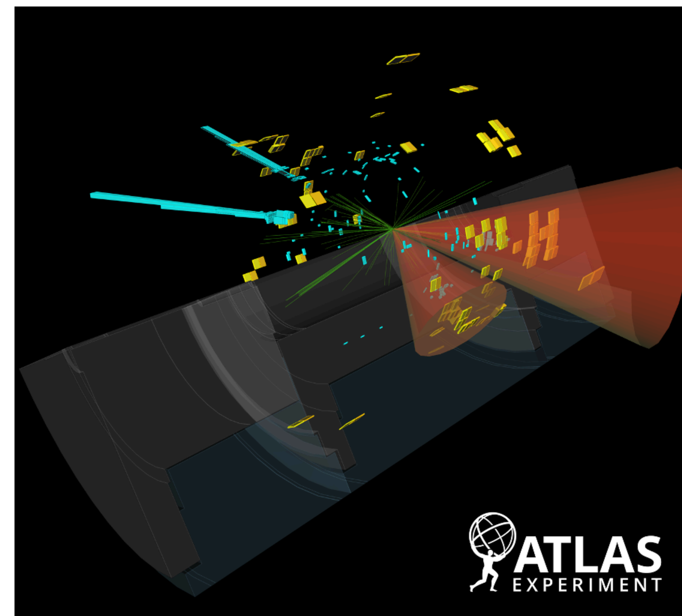


- Very small cross sections!
  - 1000 times smaller than for Higgs production
  - In addition, for self-coupling measurement, large di-Higgs continuum background!

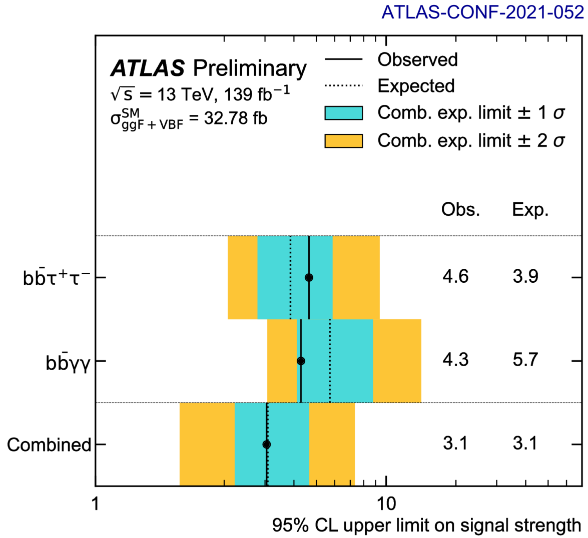
- Multiple channels investigated;

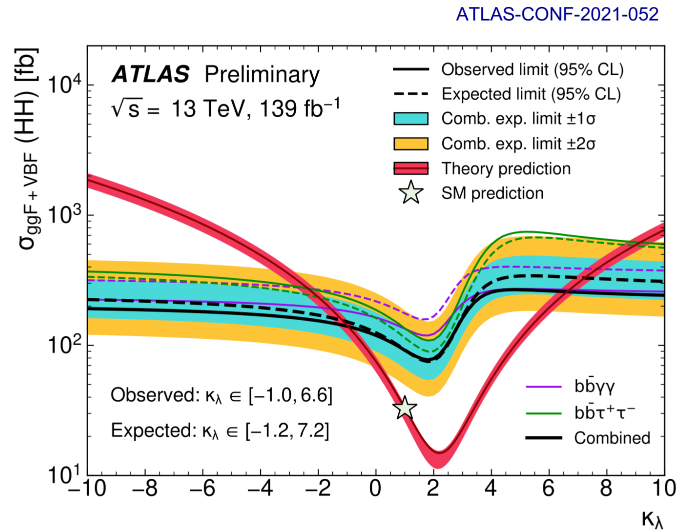
Promising: HH → bb $\gamma\gamma$, bb $\tau\tau$, …

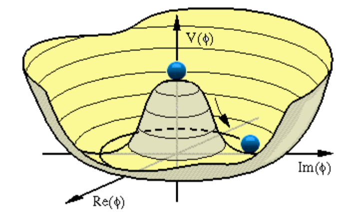
… already interesting constraints obtained with present data!



Higgs boson self coupling

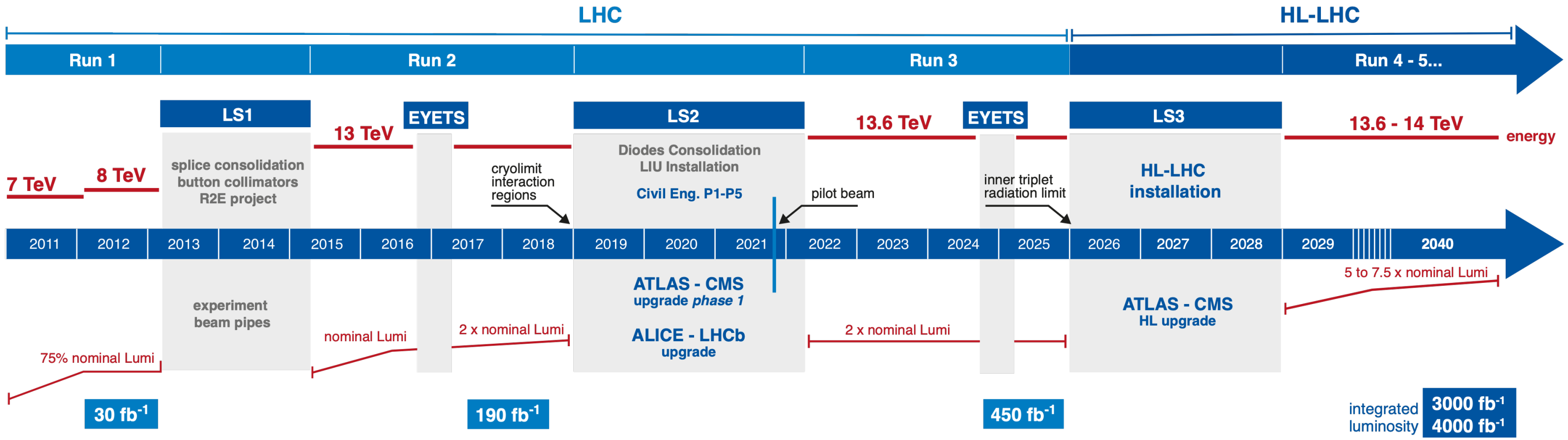






- ATLAS combination of the current best constraints from bb $\tau\tau$ and bb $\gamma\gamma$
- Observed constraint on trilinear coupling: $-1.0 < \kappa_\lambda < 6.6$ (95% C.L.) (expected: $-1.2 < \kappa_\lambda < 7.2$)
- Major and exciting challenge for Run 3 (i.e. now), and for the HL-LHC
  (more data, more channels to be combined, two experiments, …)

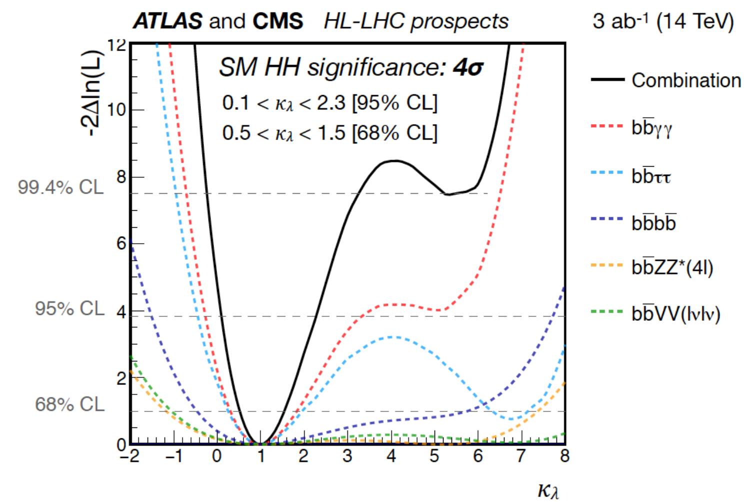
Future prospects



- **Run 3** ahead of us: → at least double the available integrated luminosity

  Improved measurements:
  - Differential cross sections, EFT interpretations, …
  - Higgs boson parameters (address CP admixtures, …)
  - Rare decays (H → $\mu\mu$, Zγ, cc, ...)
  - Tighter constraints on self-coupling

- **HL-LHC**: → increase of int. luminosity by factor of ~ 20 (compared to today)
  - Reach sensitivity to Higgs boson self coupling
  - Higgs boson as portal to new physics



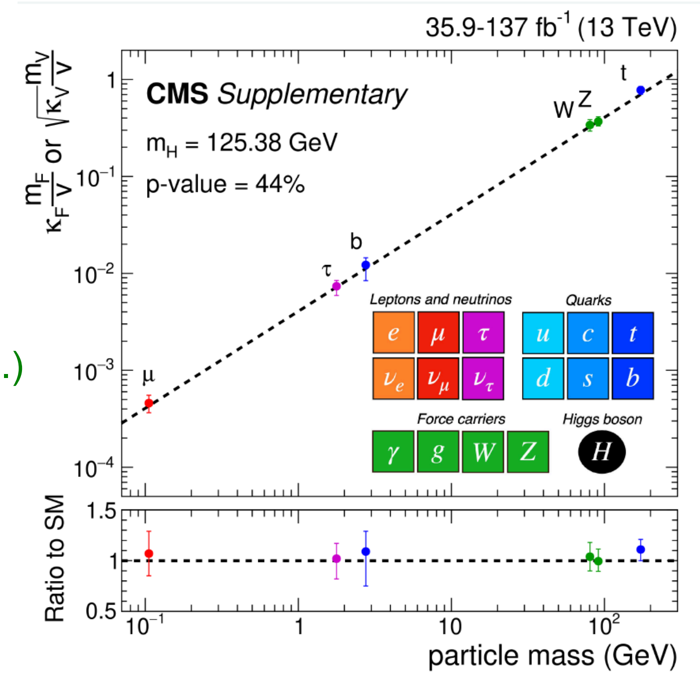
Conclusions

- The analyses of the complete LHC Run 1 and Run 2 dataset by the ATLAS and CMS experiments have established the observed particle as "the Standard Model Higgs Boson"
  (properties in excellent agreement with the predictions from the SM)

  The large data sets have allowed for:

  - very precise measurements of production and decay properties;
    Era of Higgs boson precision measurements started

  - Started to explore rare and challenging decays (μμ, Zγ, cc, ..)



- Many measurements still statistically limited
  → significant improvements expected in Run 3 and beyond

  → The Higgs particle might be the portal to new physics

- Exciting times ahead of us to exploit the full physics potential of the (HL)-LHC