Higgs boson production and Decays

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on behalf of CMS and ATLAS Collaborations

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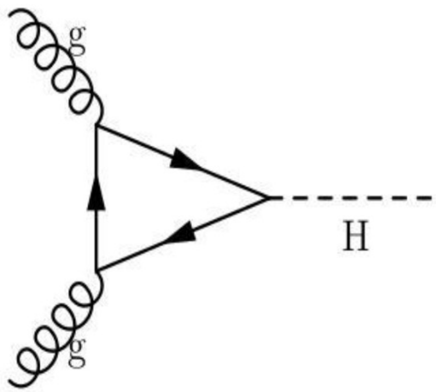
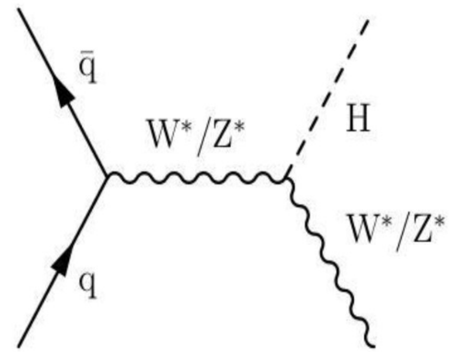
Higgs Production Mechanism at the LHC

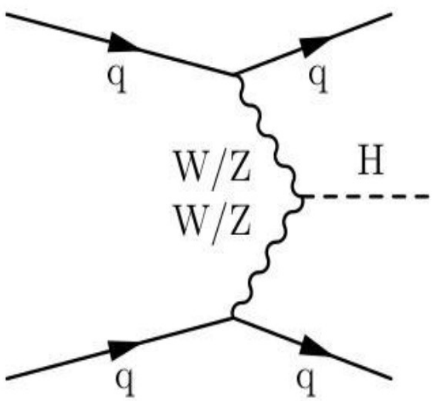
Cross-section values at 13 TeV from LHC Higgs WG



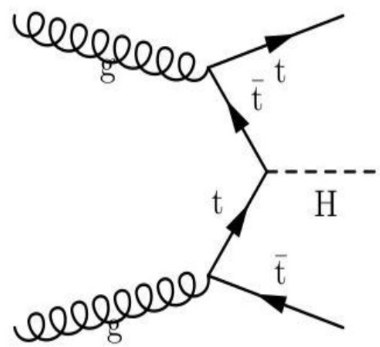
gluon-gluon fusion
48.6 pb



production in association with a vector boson
2.3 pb



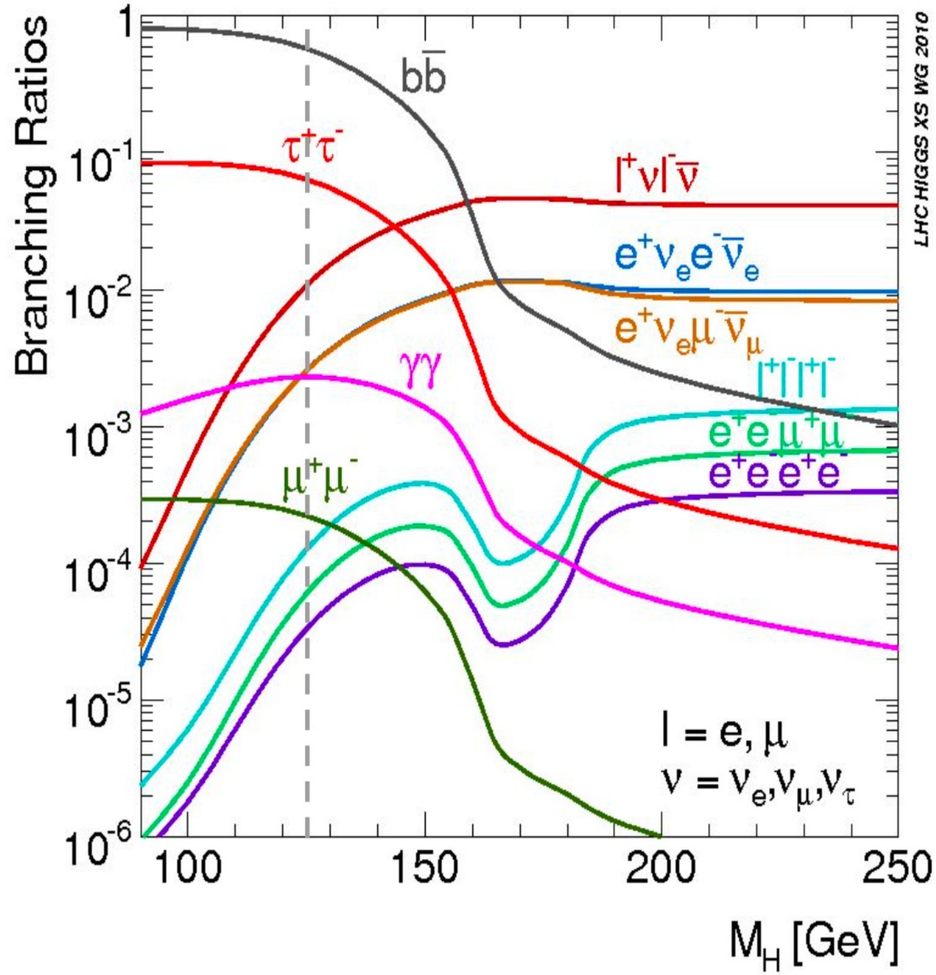
vector boson fusion
3.8 pb



production in association with a top quark pair
0.5 pb

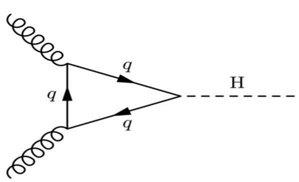
Higgs Decay Channels

- Branching fraction fixed by the Higgs mass from LHC Higgs working groups
- Golden channels:
  - H → ZZ (2.6%)
  - H → $\gamma\gamma$ (0.23%)
- Other di-boson or third-generation decay channels:
  - H → WW (21.5%)
  - H → $\tau\tau$ (6.3%)
  - H → bb (57.7 %)
- More Challenging decay channels:
  - H → **μμ** (0.02%)
  - H → CC (2.9%)
  - H → Z$\boldsymbol{\gamma}$ (0.15%)
  - H → $\boldsymbol{\gamma\gamma^*}$ (0.01%)



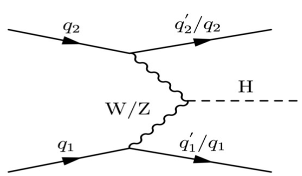
Simplified Template Cross Section (STXS)

- One pathway to further study the Higgs is to perform cross section measurements within multiple phase space regions
- Two complementary approaches are being explored
  - Simplified template cross sections
  - Differential cross sections
- ATLAS, CMS and the theory community have been working together in the LHC Higgs Working Group setup a common framework for Higgs boson measurements in Run2
- STXS targets phase space regions within production modes, using Standard Model kinematics as a template.
  - Categorize each production mode in bins of key (truth) quantities
  - Reduce theory systematics, but more model-dependent.
  - No decay information available in STXS (for the moment).



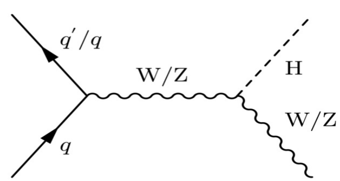
(a) Gluon Fusion

pTH
Njet
Mjj, pT(H+jj)



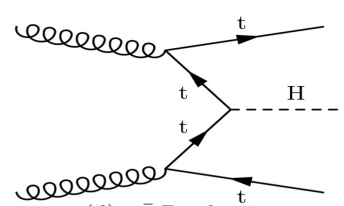
(b) Vector Boson Fusion

pTH
Njet
Mjj, pT(H+jj) (if Njets>1)



(c) Higgsstrahlung

pTV



(d) $t\bar{t}$ Production

pTH

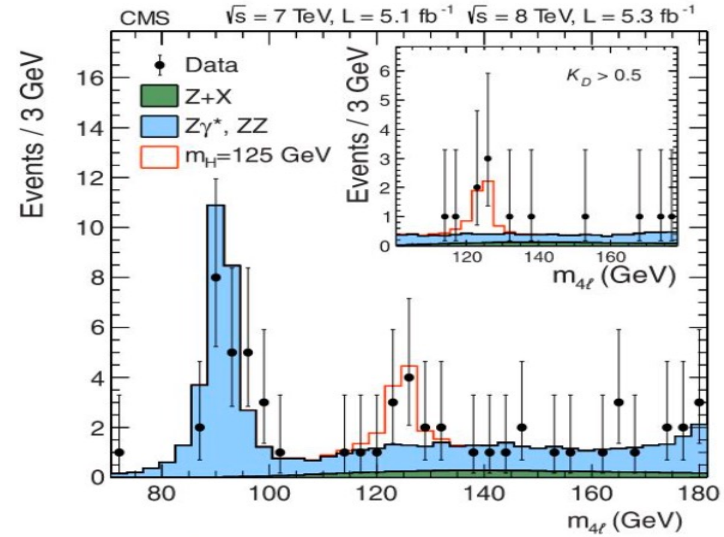
Current status of Higgs boson

About 7.7 millions Higgs bosons produced during Run 2 by each experiment

Enough data for precision measurements and rare decays

- Main production modes and decay channels studied in detail
  - Decays to bosons and third generations
  - Fiducial, differential and STXS
  - Challenging phase spaces
- Starting the inspection of second – generation fermions
  - Evidence for **H →μμ** and searches for **H →**CC
- And other rare decays
  - H →$\gamma\gamma^*$ or **H →** $Z\gamma$
- Double Higgs production
  - Key to study self – coupling and the structure of the scalar Higgs field potential

Phys. Lett. B 716 (2012) 30



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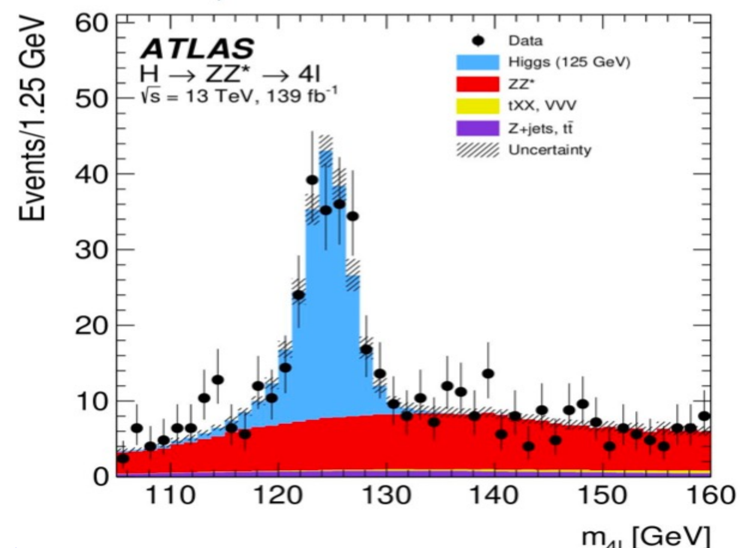
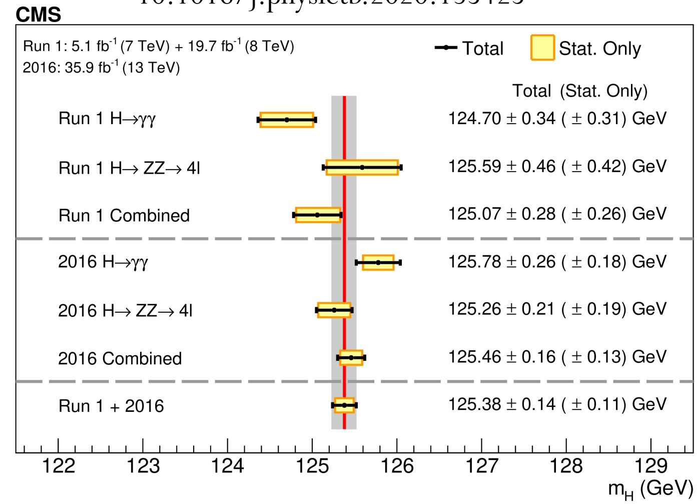


Higgs Mass Measurements

Only free parameter, fixes all other properties

- Measured using golden channel
- provides best resolution, exploits key momentum and energy calibration

10.1016/j.physletb.2020.135425

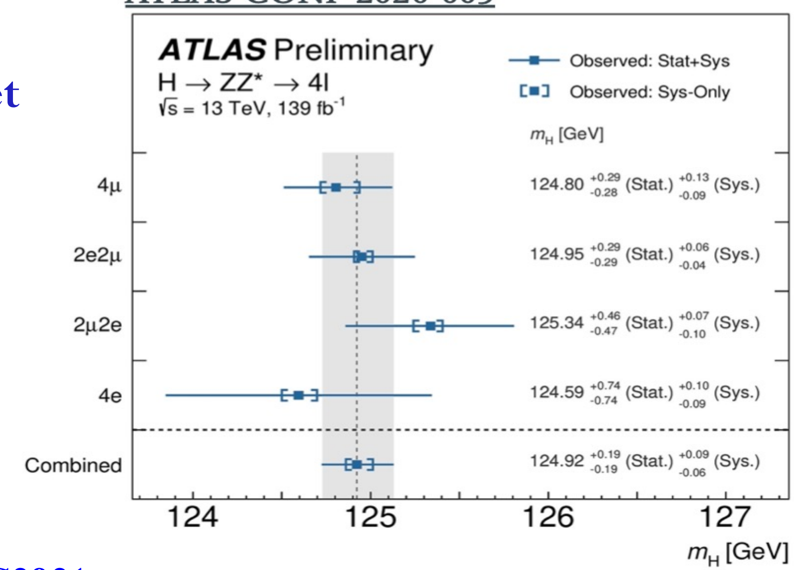


CMS: Combination of H → ZZ and H → $\gamma\gamma$ using Run1 and 2016 data

$$125.38 \pm 0.14\ \text{GeV}$$

- **Systematic uncertainty is ~ 0.1 %**

ATLAS-CONF-2020-005



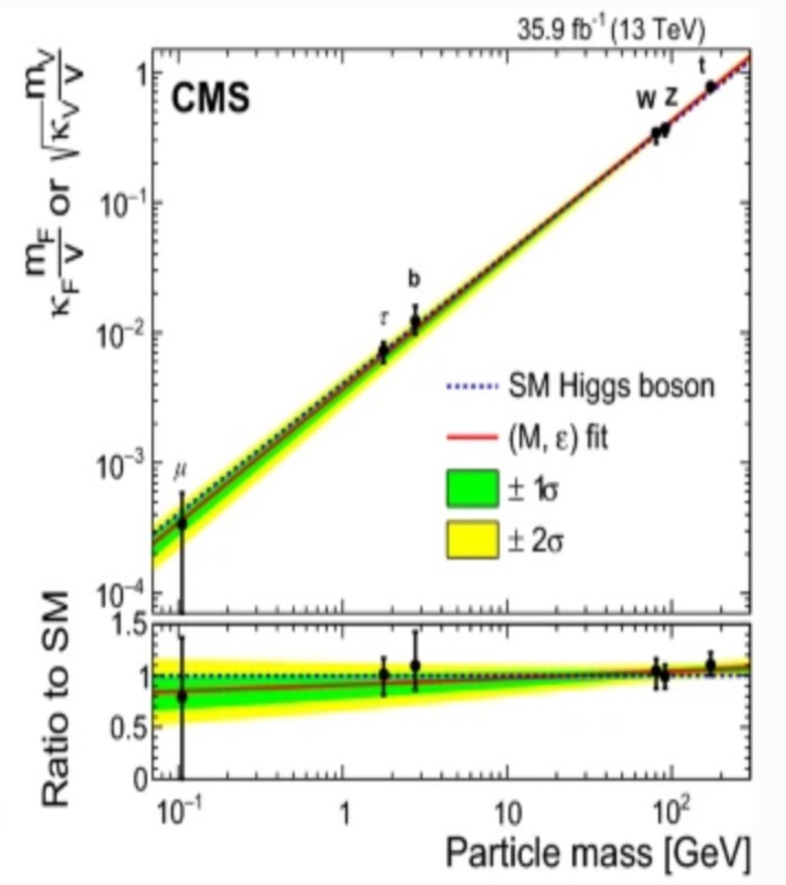
ATLAS: H → ZZ->4l result using full RUN2 dataset

- **Improved techniques: per-event error reconstruction and Z mass constraint**

$$124.92 \pm 0.19\ (\text{stat.})^{+0.09}_{-0.06}\ (\text{syst.})$$

Both measurements are limited by statistics

Fit for couplings modifiers



Eur. Phys. J. C 79 (2019) 421

Event rate for $ii \to H \to ff$: $\sigma_i \mathcal{B}^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H(\vec{\kappa})}$

Fit for six Higgs coupling modifiers: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu$

Assuming:

- no "new physics" in loop-driven couplings ($H \to \gamma\gamma$, gg→ H)
- no BSM decays (invisible, not observed)
- couplings to the 1st/2nd–gen. quarks and electrons are SM-like (i.e., small and hence having a negligible effect on the fit)

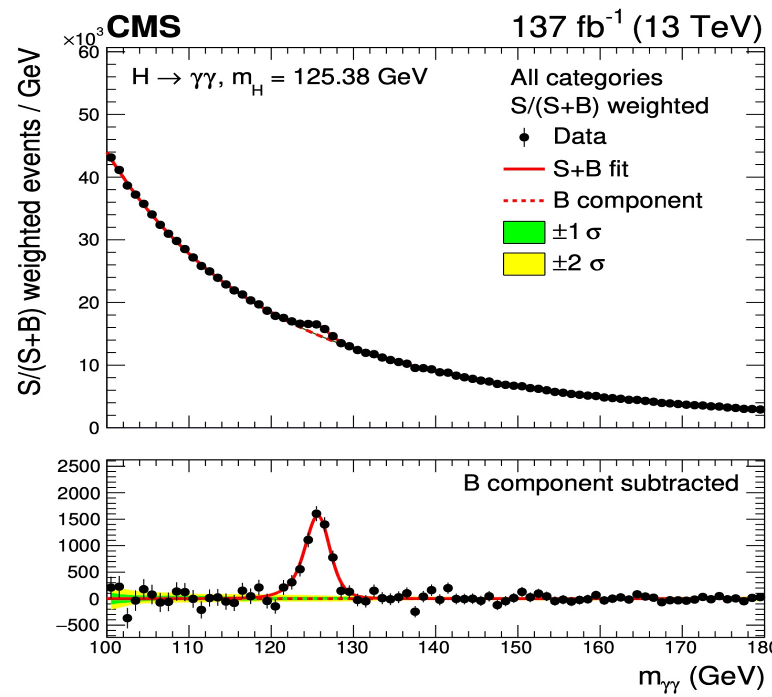
Impressive agreement with SM **over three orders of magnitude of couplings !** (note: ±5% for ttH coupling)

$H \rightarrow \gamma\gamma$ Measurements

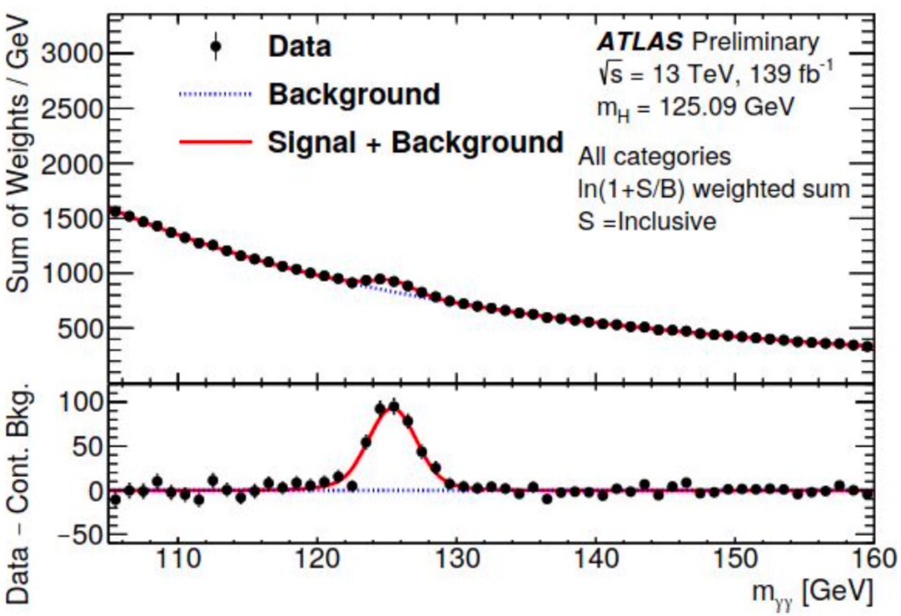
Large backgrounds due to non-resonant photon pairs but estimated through fit to data

Both ATLAS and CMS measured inclusive and STXS

JHEP07 (2021) 027



ATLAS-CONF-2020-026

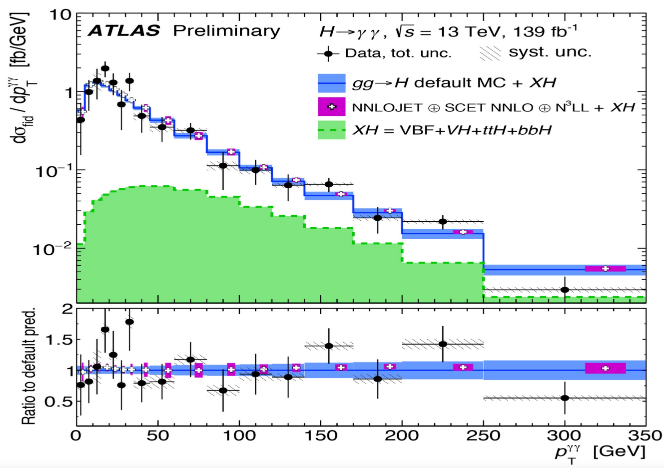


Inclusive cross-section measurements are:

- ATLAS:
  - $(\sigma \times B_{\gamma\gamma})_{obs} = 127 \pm 10$ fb $(\sigma \times B_{\gamma\gamma}{}^{SM} = 116 \pm 5$ fb)
- CMS:
  - $\mu = \sigma/\sigma_{SM} = 1.12^{+0.07}_{-0.06}(\text{stat.}) \pm 0.03(\text{syst.}) \pm 0.06\ (\text{theo.})$

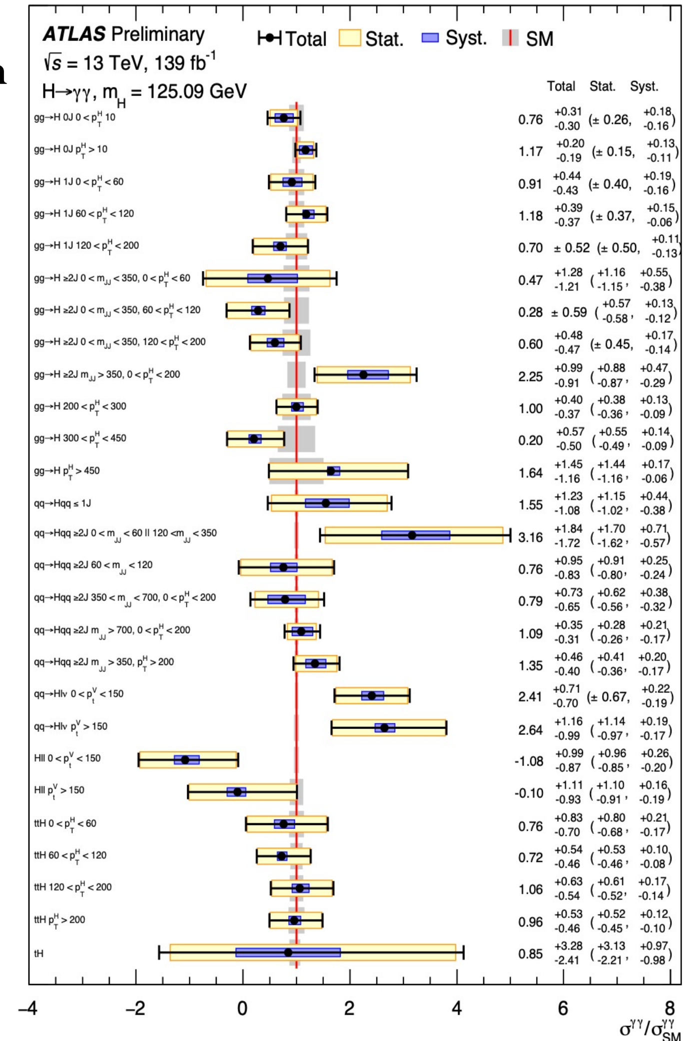
H $\rightarrow \gamma\gamma$ Measurements conti..

ATLAS-CONF-2019-029

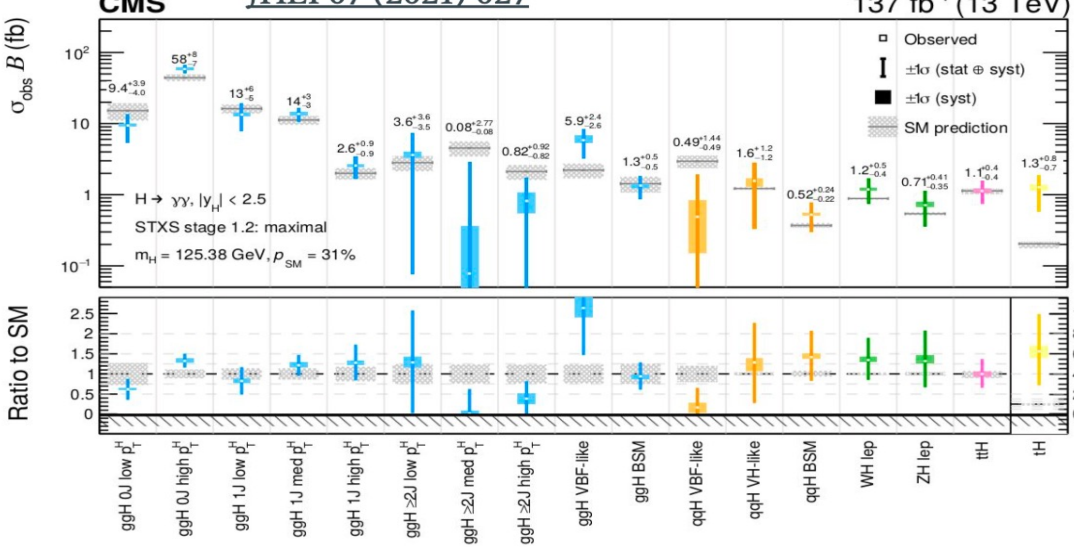


- STXS results for different production mechanism
- ggH, VBF, VH, ttH and tH
- Consistent with Standard Model

ATLAS-CONF-2020-026



JHEP07 (2021) 027

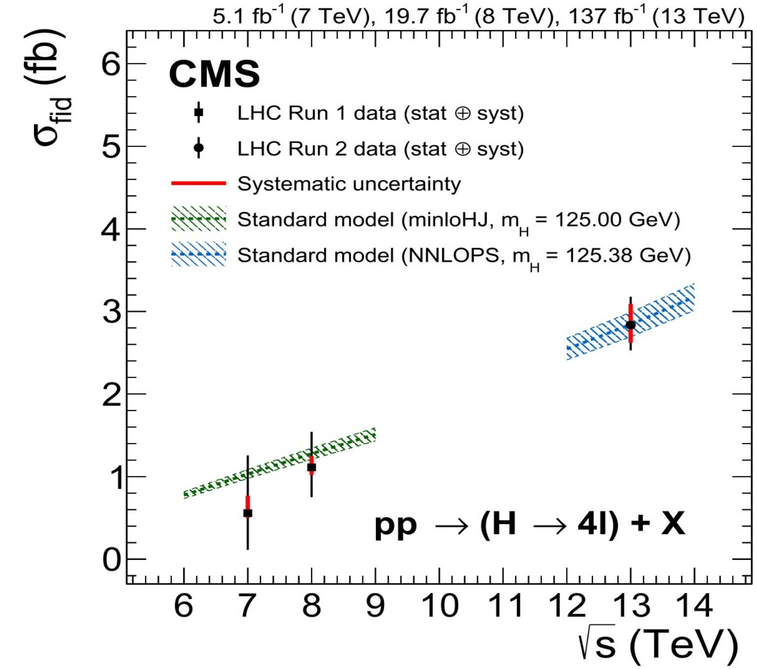


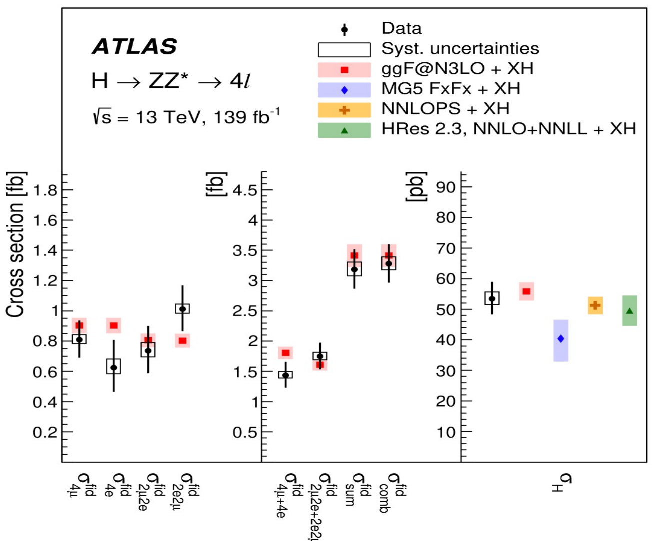
Measurement of H → ZZ

Final states with two lepton (e/μ) pairs with opposite sign

- Cross-section is measured in a fiducial volume that closely matches reconstruction level selection
  - Reduce model dependance
  - differential cross-sections are measured with respect to H_{PT} , rapidity and angular variables are sensitive to the structure of the Higgs boson interaction, QCD correction, BSM etc..

Eur. Phys. J. C 81, 488 (2021)





Phys. J. C 80 (2020) 942

Fiducial cross-section results:

CMS:

- $\sigma_{fid} = 2.84 \,^{+0.23}_{-0.22}\,(\text{stat})\,^{+0.26}_{-0.21}\,(\text{syst})$ fb $(\sigma^{SM}_{fid} = 2.84 \pm 0.15$ fb$)$

ATLAS:

- $\sigma_{fid} = 3.28 \pm 0.32$ fb $(\sigma^{SM}_{fid} = 3.41 \pm 0.18$ fb$)$

Measurement of H → ZZ

- differential fiducial cross sections can be used to probe possible effects of physics beyond the SM

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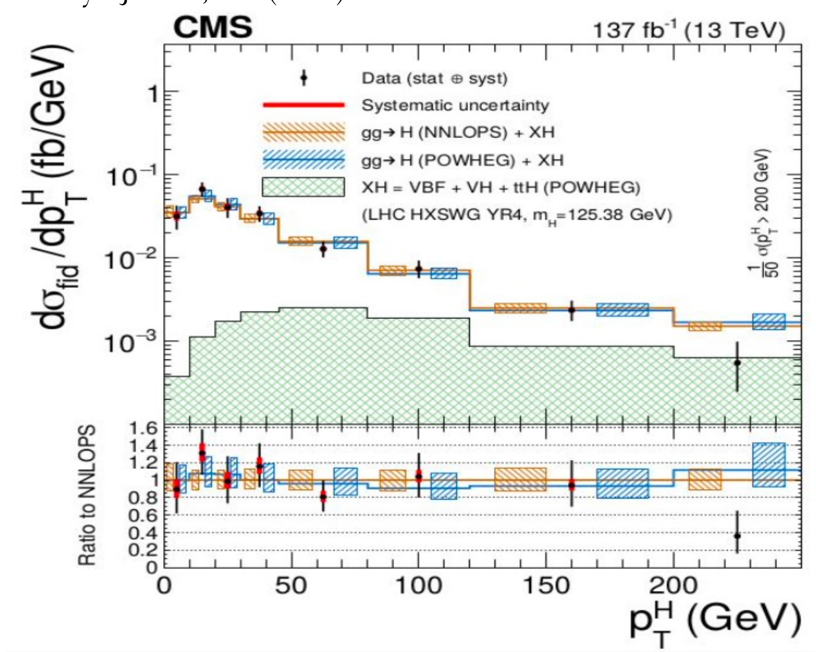

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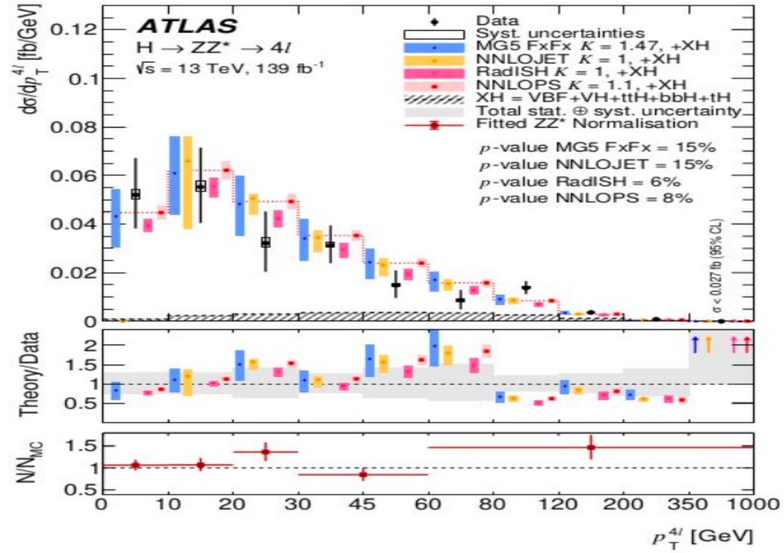
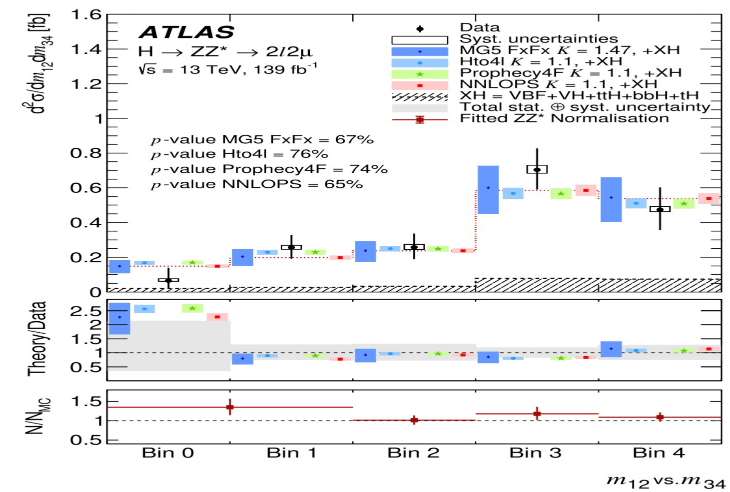
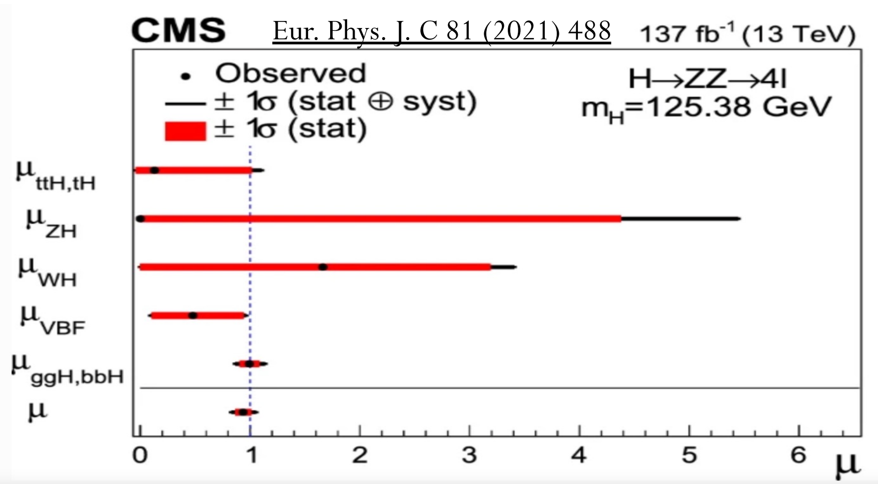


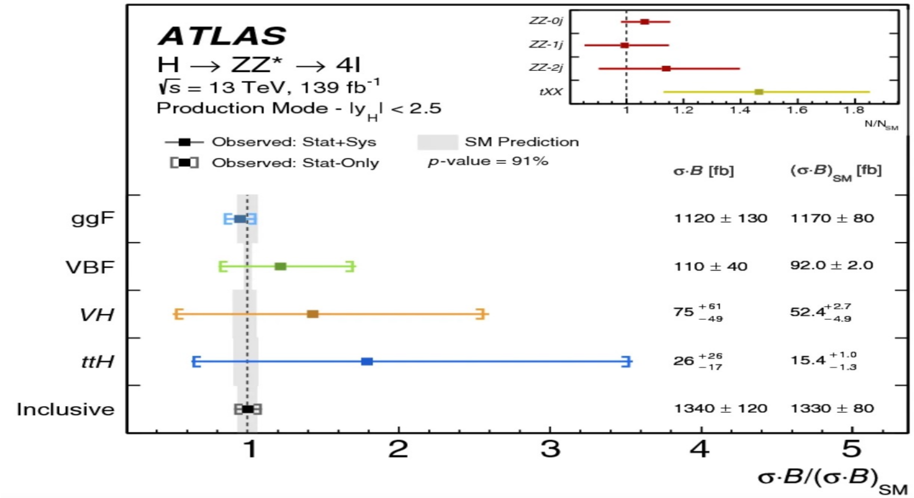


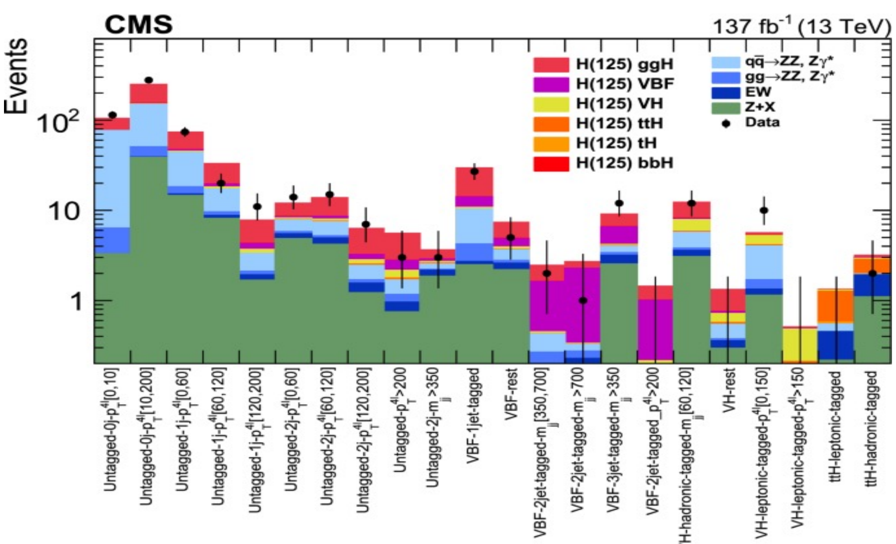
- Double differential cross section is used to probe several BSM scenarios within the framework of pseudo-observables

Measurement of H ➜ ZZ conti..

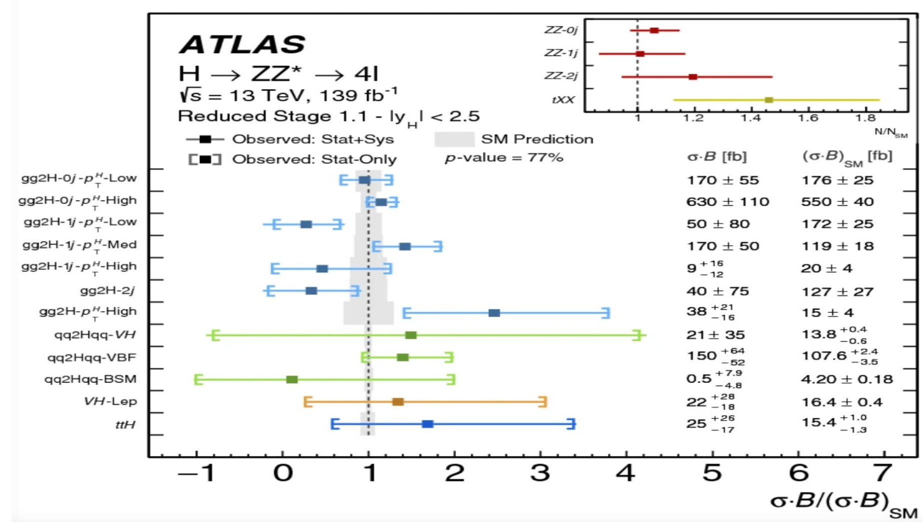
Measurement of different production mechanics in mutually exclusive regions







Eur. Phys. J. C 80 (2020)957

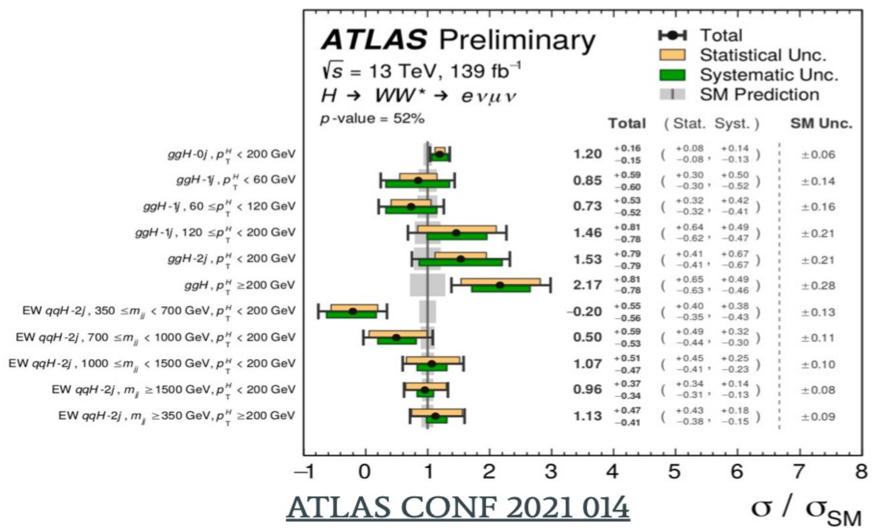


H → WW measurements

Neutrinos in the final state spoils mass resolution but very clean due to lepton in final states

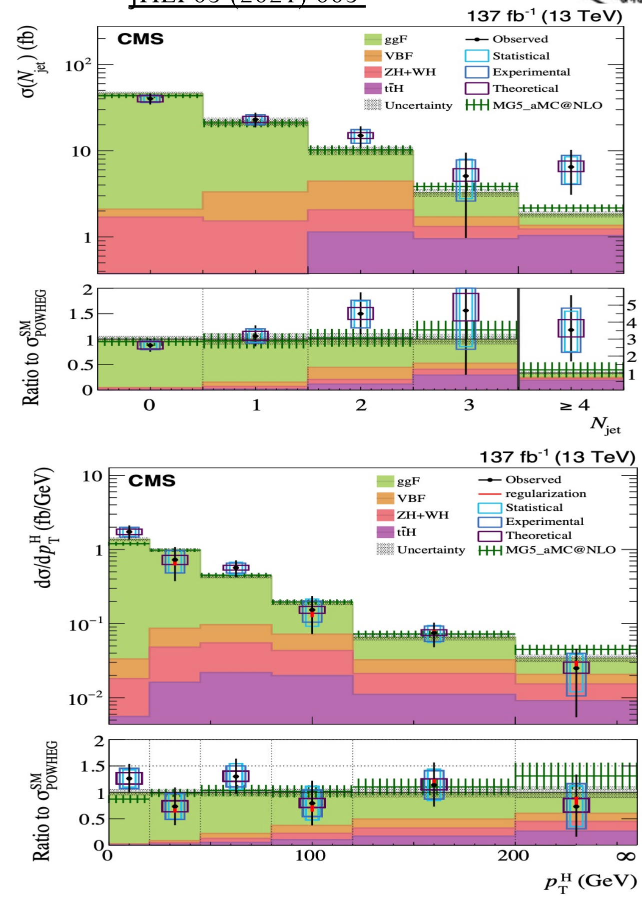
ATLAS:

- ggH and VBF total cross-sections measurements
  - ggH: $\sigma_{obs} = 12.4 \pm 1.5$ pb ($\sigma_{SM} = 10.4 \pm 0.6$ pb)
  - VBF: $\sigma_{obs} = 0.79^{+0.19}_{-0.16}$ pb ($\sigma_{SM} = 0.81 \pm 0.02$ pb)
- STXS in 11 categories



ATLAS CONF 2021 014

JHEP03 (2021) 003



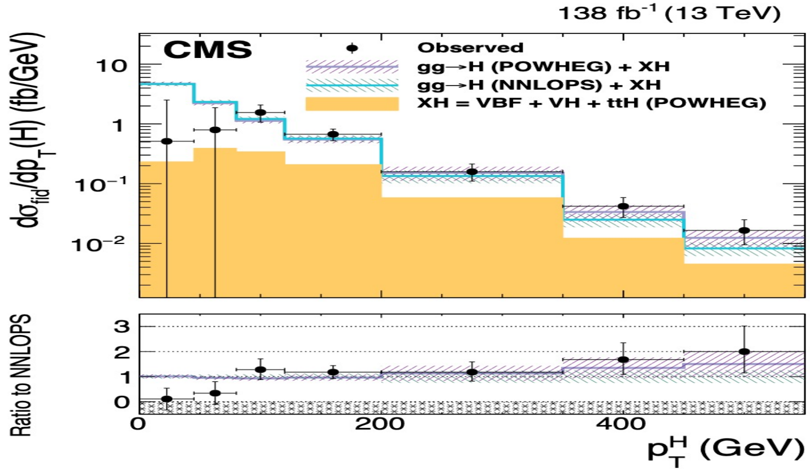
CMS:

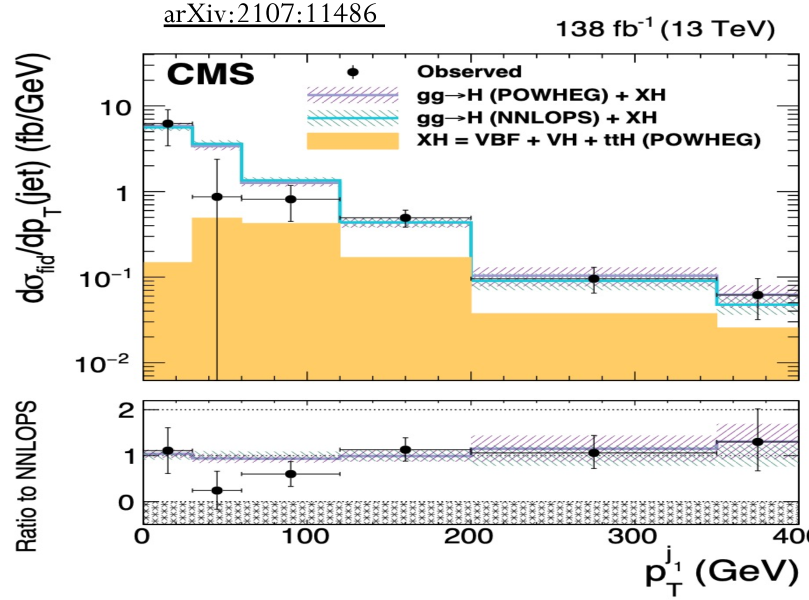
- integrated fiducial cross section
  - $\sigma_{fid} = 86.5 \pm 9.5$ fb ($\sigma_{fid}^{SM} = 82.5 \pm 4.2$ fb)

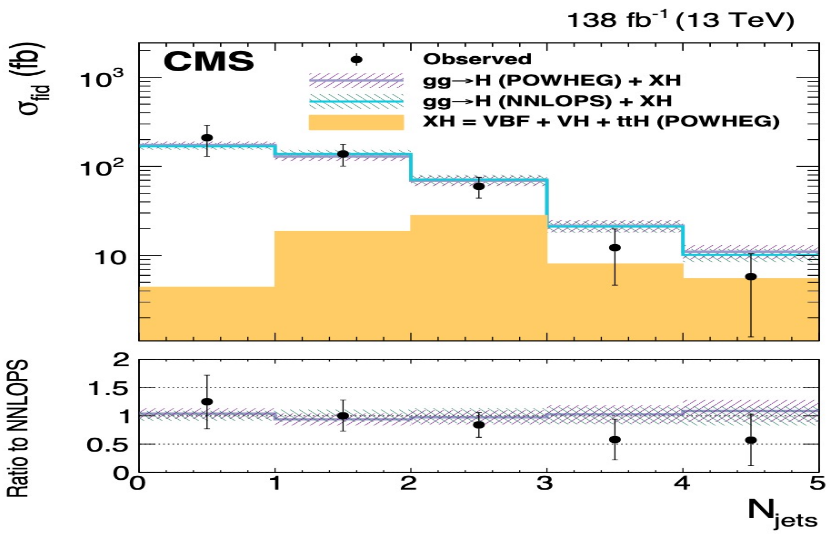
H → ττ

- Final states with at least one hadronically-decaying τ lepton

arXiv:2107:11486







Measured in Higgs P_T , leading Jet P_T and No. of Jets

inclusive fiducial cross-section

- $\sigma_{fid} = 426 \pm 102$ fb ($\sigma_{fid}^{SM} = 408 \pm 27$ fb)

H → ττ

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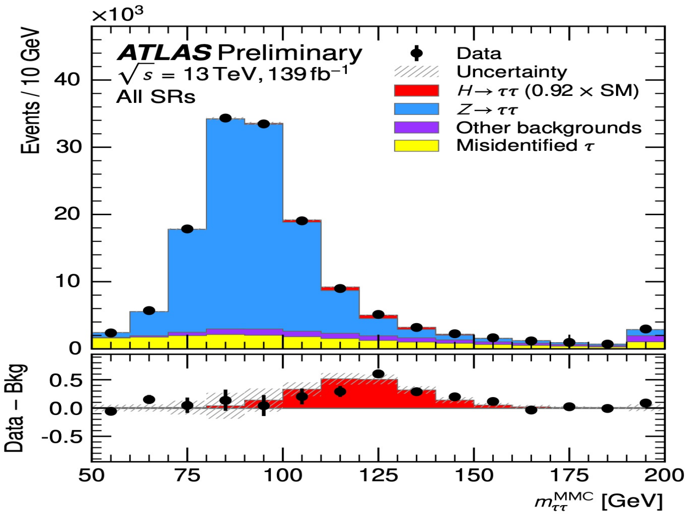
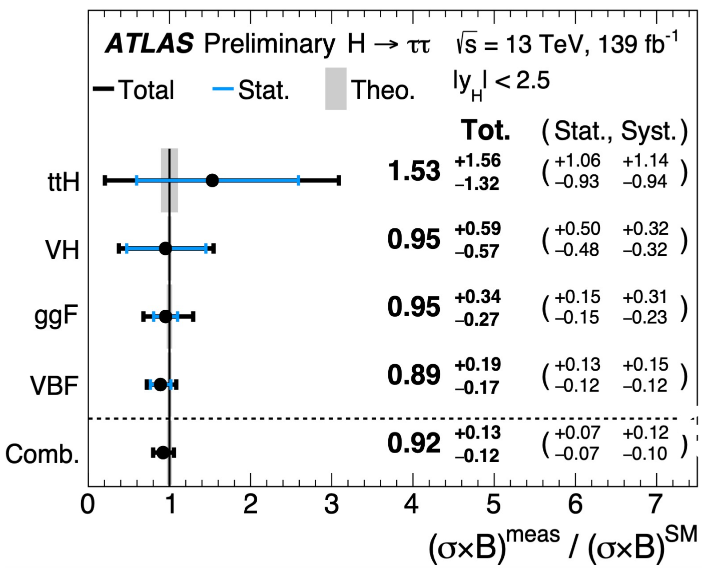
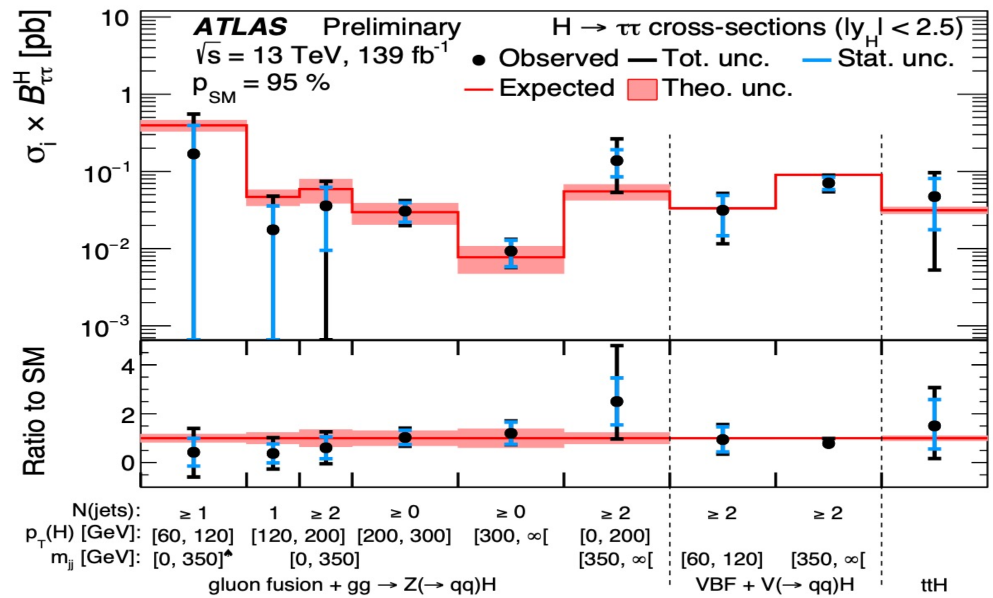






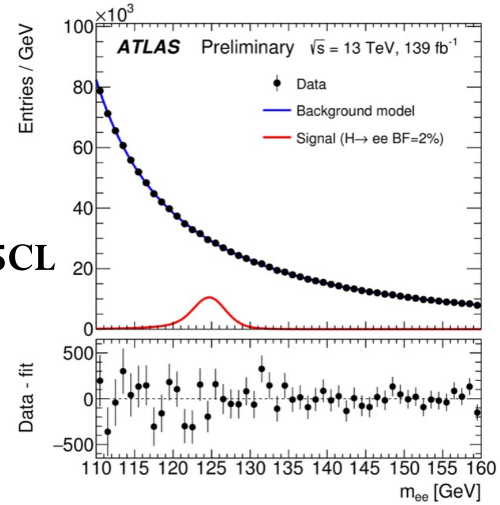
inclusive cross-section for $|y_H| < 2.5$:

$$\sigma_{obs} = 2.89 \pm 0.21\,(\text{stat.})\,^{+0.37}_{-0.32}\,(\text{syst.})\text{ pb } (\sigma_{SM} = 3.14 \pm 0.08\text{ pb})$$

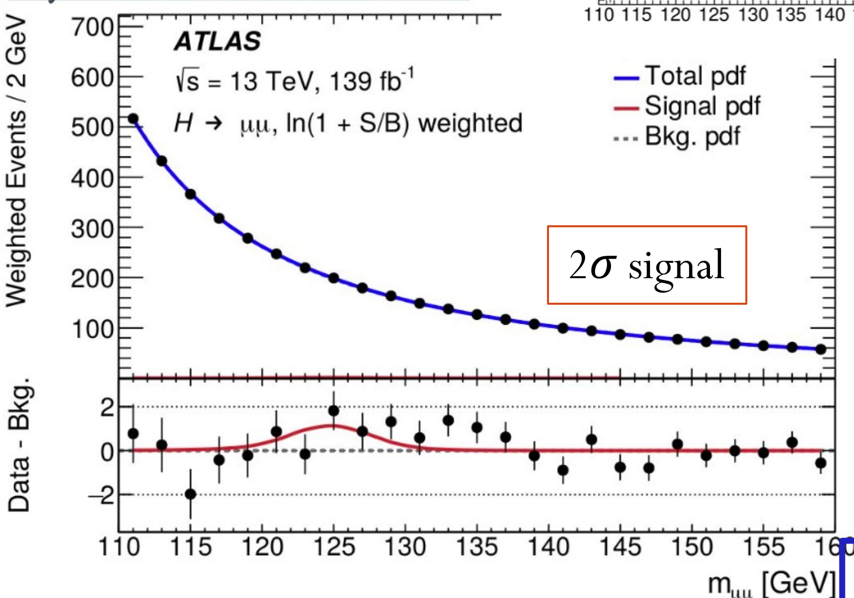
H ➔μμ/ee

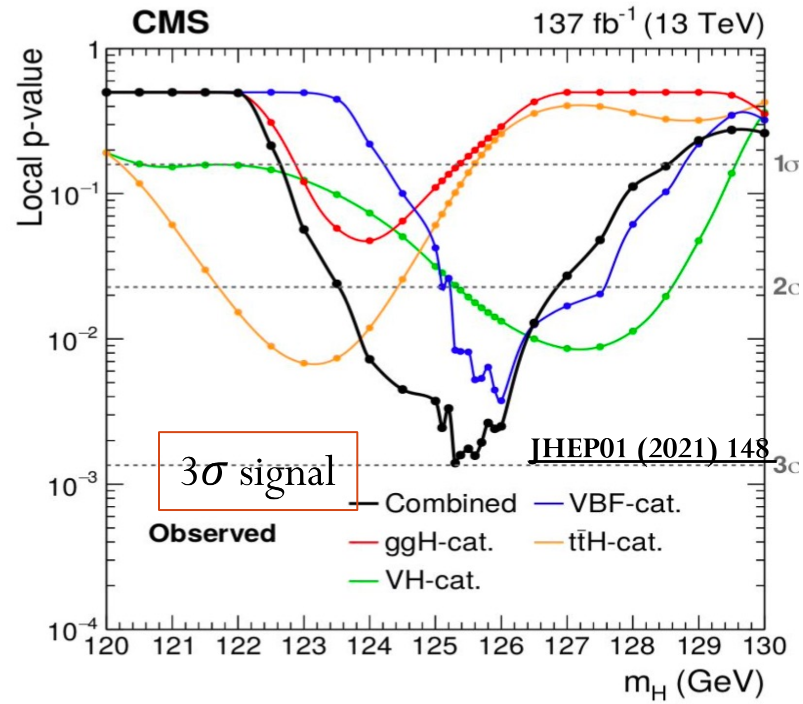
- Probing Higgs coupling to second generation lepton, Fit to mass of di-muon.
  - ATLAS: Events split in exclusive categories based on MVA discriminants.

BR(ee): 0.036%@95CL



Phys. Lett. B 812 (2021) 135980

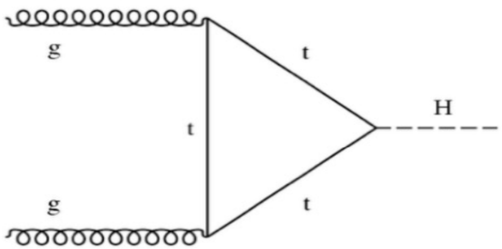


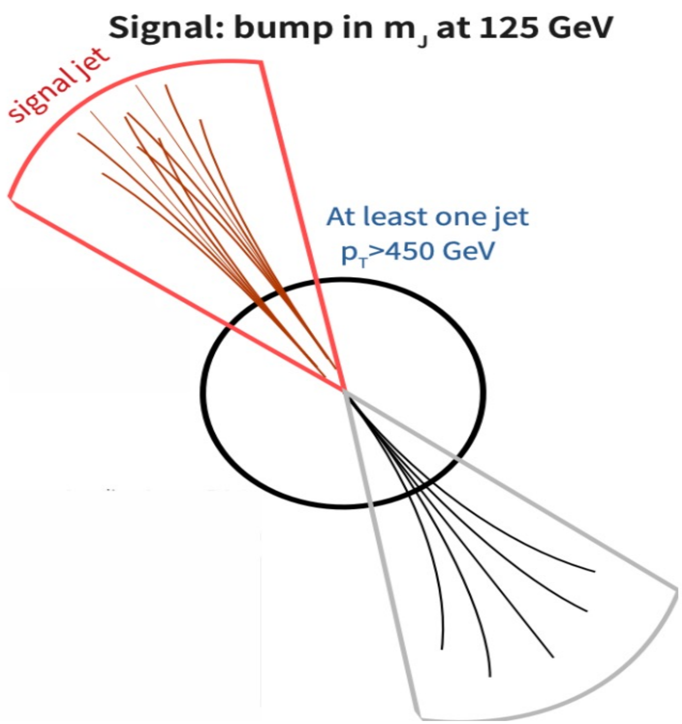


- CMS uses template-based approach for VBF for better significance using DNN

Need more data for observation for this decay

ggH(H ➔bb)



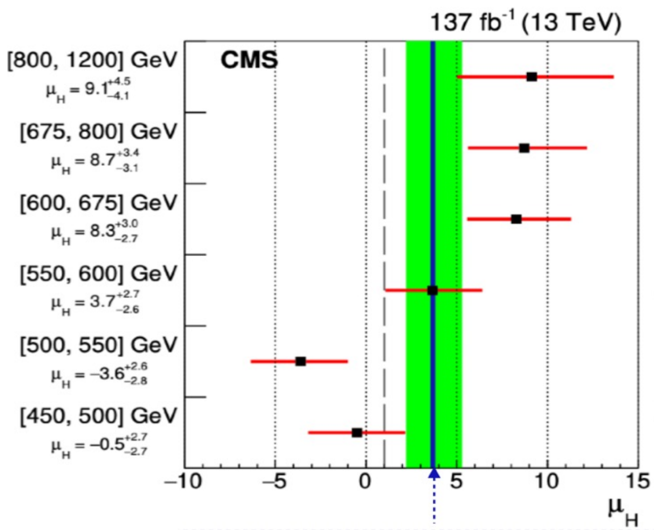


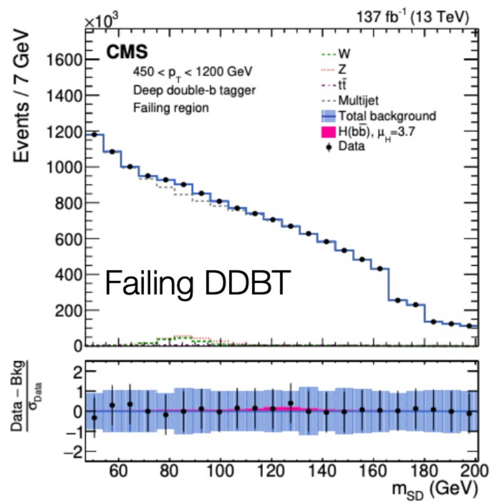
- ggH(H ➔bb) production is the dominant but large background
- Look at boosted selection
- Measurement focuses on
- Inclusive
- pT differential measurement (STSX)
- fiducial measurement (pT,truth>450 GeV)

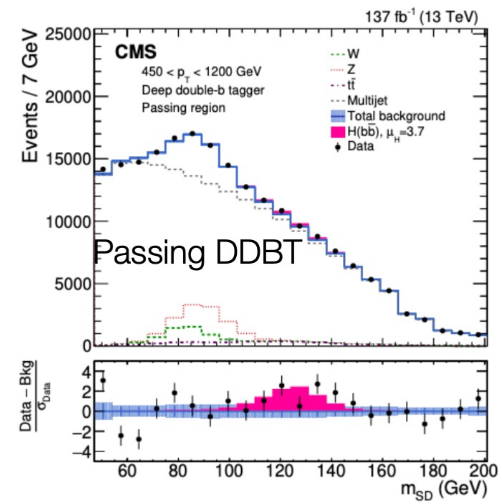
$H \rightarrow bb$

[JHEP12 (2020) 085](#)

- Highly boosted two b-jets in the final state. Merged both to one large radius jet
- New DeepDoubleBTag (DDBT) algorithm (1.6x signal efficiency)
- QCD bkg. estimated using CR, populated with events failing DDBT selection.
- Transferred to signal region
- Higgs p_T (H_{pT}) > 450 GeV







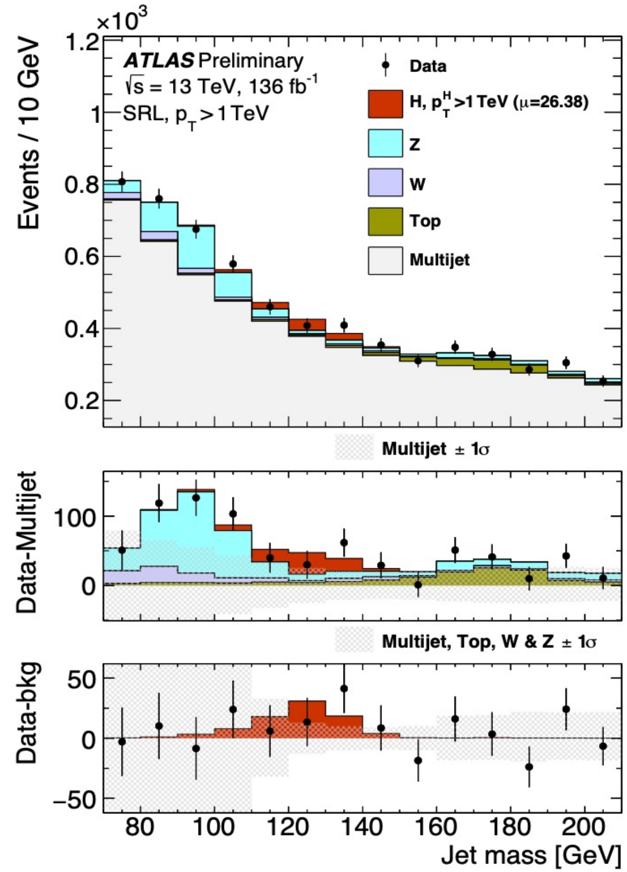
- Higgs candidate mass is fitted for signal extraction
- Other processes are fixed to SM prediction:
- Analysis has been validated using $Z \rightarrow bb$

- For differential measurement STXS bins are used; 2.6 local significance PT(H) > 650 GeV

$$\mu_H = 3.7 \pm 1.2\,(\text{stat})^{+0.8}_{-0.7}\,(\text{syst})^{+0.8}_{-0.5}\,(\text{theo}) = 3.7^{+1.6}_{-1.5}$$

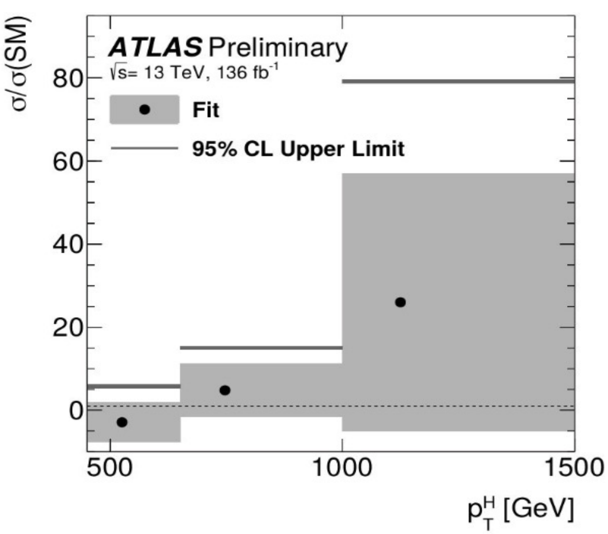
H → bb

- Fit QCD with smooth function
- extensively validated in 0-btag region
- W/Z + jets
  - Shape from simulation
  - Fully floating during fit (standard candle)
  - Mostly Z+jets after b-tagging



- ttbar:
  - Shape from simulation
  - CRttbar for normalization

ATLAS-CONF-2021-010



Fiducial

p_T^H/Jet p_T	μ_H Exp.	μ_H Obs.	μ_Z Exp.	μ_Z Obs.	$\mu_{t\bar{t}}$ Exp.	$\mu_{t\bar{t}}$ Obs.
> 450 GeV	1.0 ± 3.3	0.7 ± 3.3	1.00 ± 0.18	1.27 ± 0.22	1.00 ± 0.07	0.81 ± 0.06
> 1 TeV	1.0 ± 29.0	26 ± 31	1.0 ± 1.6	2.4 ± 1.7	1.0 ± 0.3	0.51 ± 0.19

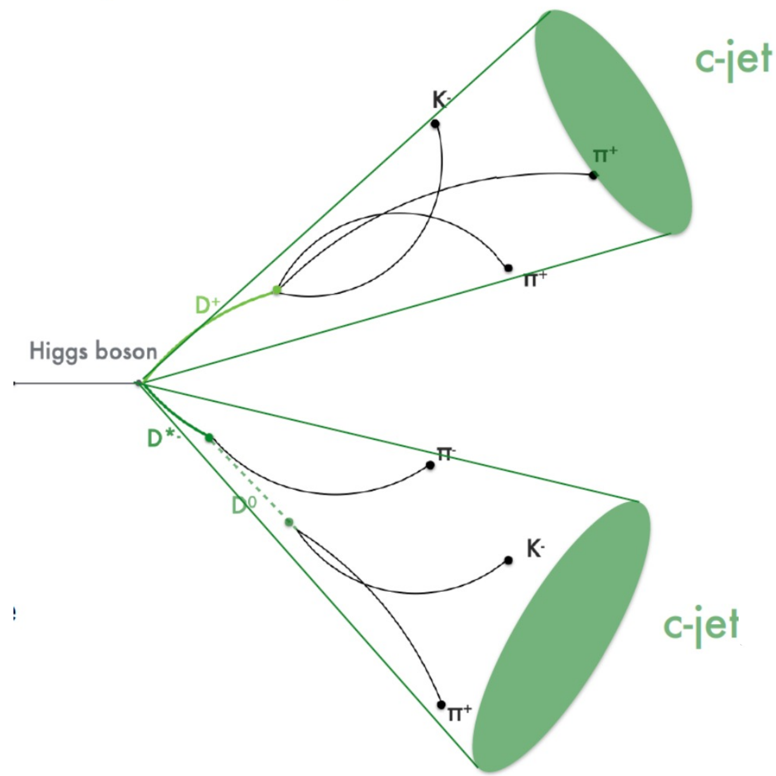
- σ_{obs} (p_T(Higgs) > 450 GeV) = 13 ± 57 (stat) ± 22 (syst) ± 3 (theo) fb

Higgs couplings to 2nd gen quarks

- Test of Yukawa interactions with 2nd generation fermions: evidence for leptons only
- Search for **H →cc** in associated production
- Dedicated charm tagging

Higgs coupling to Charm quarks

earch for H→cc: VH production mode
- 0-lepton: Z(→νν) H(→cc)
- 1-lepton: W(l±ν)H(→cc), l=e,μ
- 2-lepton: Z(l+l-)H(→cc), l=e,μ

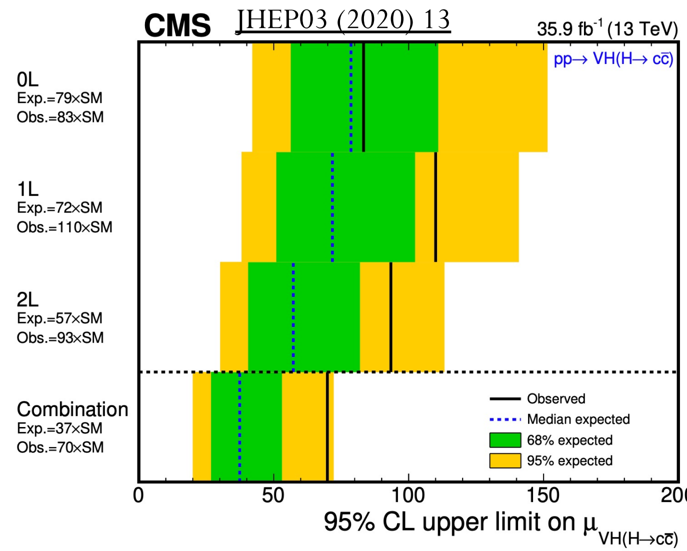


H ➔cc

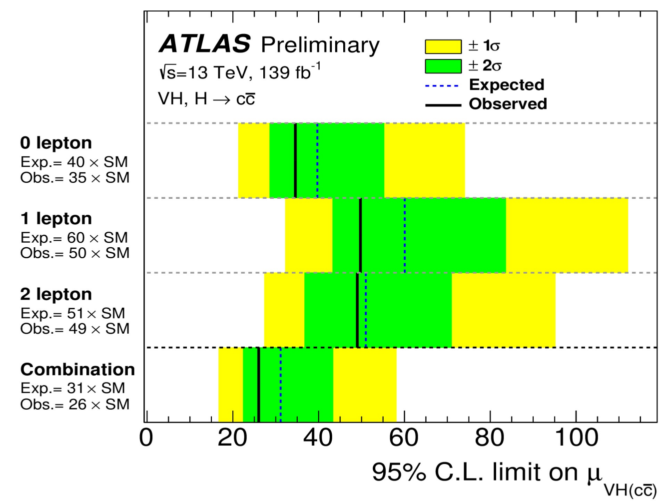
- Use of multivariable analysis techniques to identify jets produced by c quarks
- Targeting VH associate production to suppress backgrounds
  - ZH ➔ννcc, WH ➔lνcc and ZH ➔llcc
  - At least one c tagged jet
- Analysis strategy validated in VW(cq) and ZW(cc) channels

Good agreement with SM

- Diboson fit results: validation of the analysis
  - VZ(cc): **2.6σ observed** (2.2 expected)
  - VW(cq): **3.8σ observed** (4.6 expected)
  - First measurement of VZ(cc) and VW(cq) using c-tagging!



ATLAS-CONF-2021-021

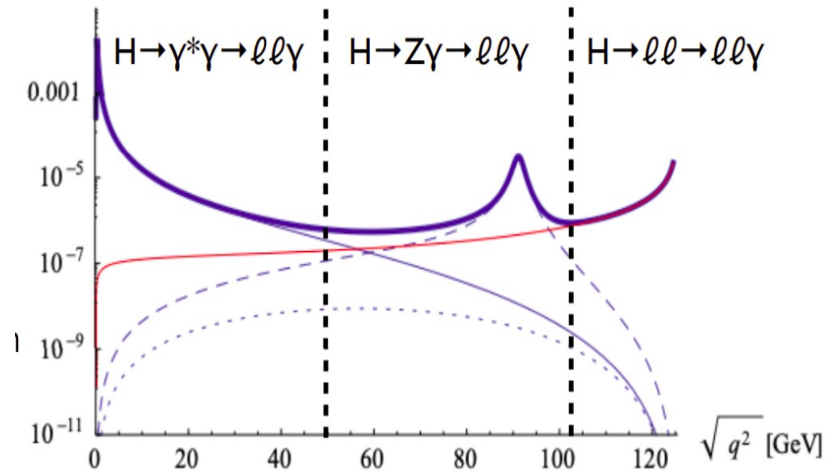


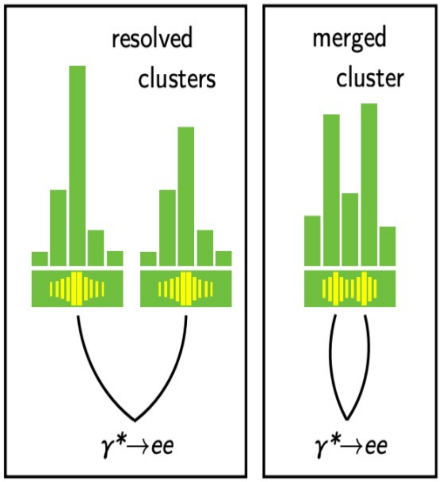
Upper limits:

- ATLAS: 26 (31^{+12}_{-8}) SM at 95% CL (full Run 2 data)
- CMS: 70 (37^{+16}_{-11}) SM at 95% CL (2016 data only)

H → $\gamma^*(ll)\gamma$

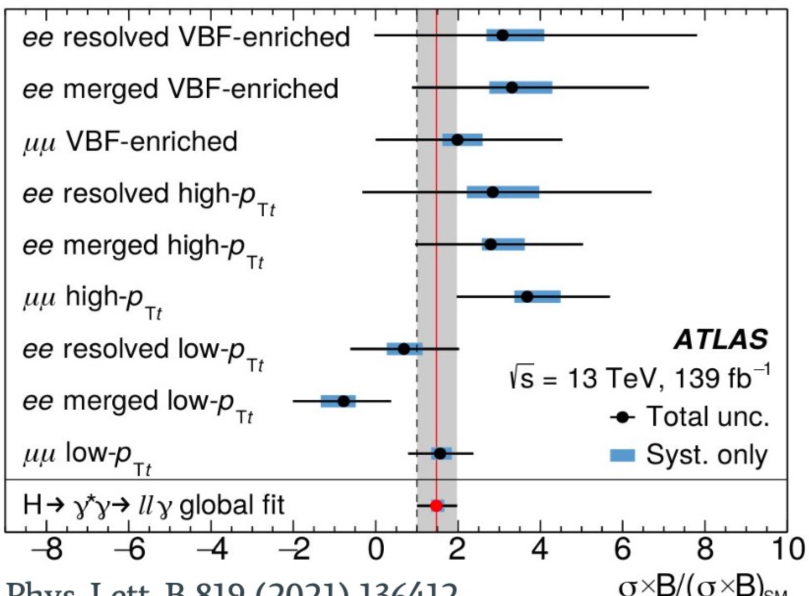
- The Higgs boson can decay to a lepton pair and a photon in three main ways:
  - the leptons can be produced via an intermediate Z boson (H→Zγ→llγ)
  - or a virtual photon (H→γ*γ→llγ), or two leptons (H→ll) with one lepton radiating a final-state photon.
- Target the decay mediated by the virtual photon.
  - focus on events where the dilepton mass (mll) is less than 30 GeV,
  - Due to the low mass of the dilepton pair they are often very collimated
- Limited spatial resolution of the detector
  - Merged electron + Photon / 2 electrons + Photon
  - Not an issue for muons



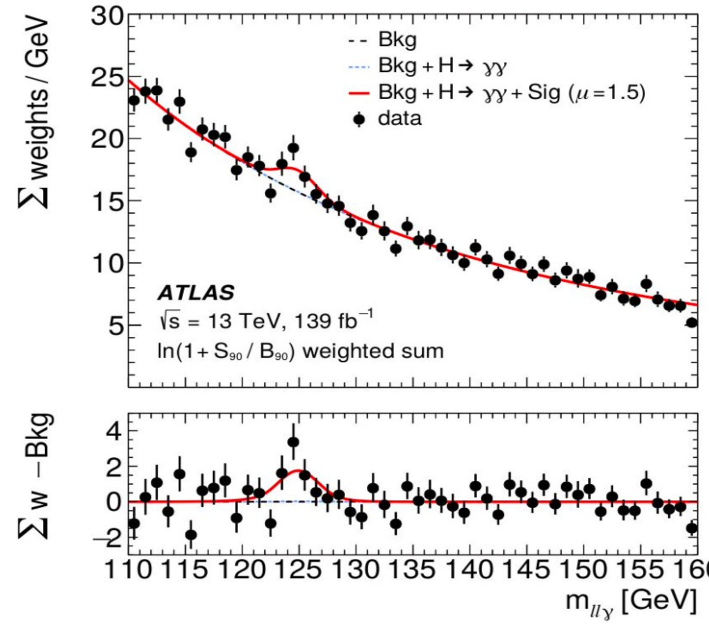


$H \rightarrow ll\gamma$

- Fit to $ll\gamma$ invariant mass with a well-behaved combinatorial background
- dedicated trigger for close by electron
- Select low-m_{ll} events (< 30 GeV)



Phys. Lett. B 819 (2021) 136412



ATLAS full Run 2 results:

- Evidence for $H \rightarrow ll\gamma$
  - 3.2 σ obs (2.1 σ exp)
- Results also for $H \rightarrow Z\gamma$
  - $m_{ll} \sim m_Z$
  - 2.2 σ obs (1.2 σ exp)

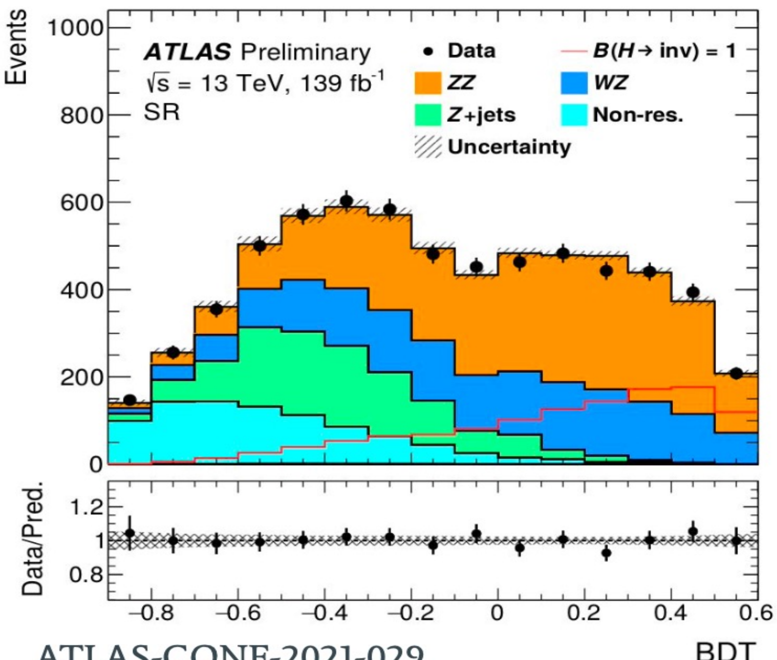
CMS results (2016 data only): JHEP 11 (2018) 152

Higgs decays to invisibles particles

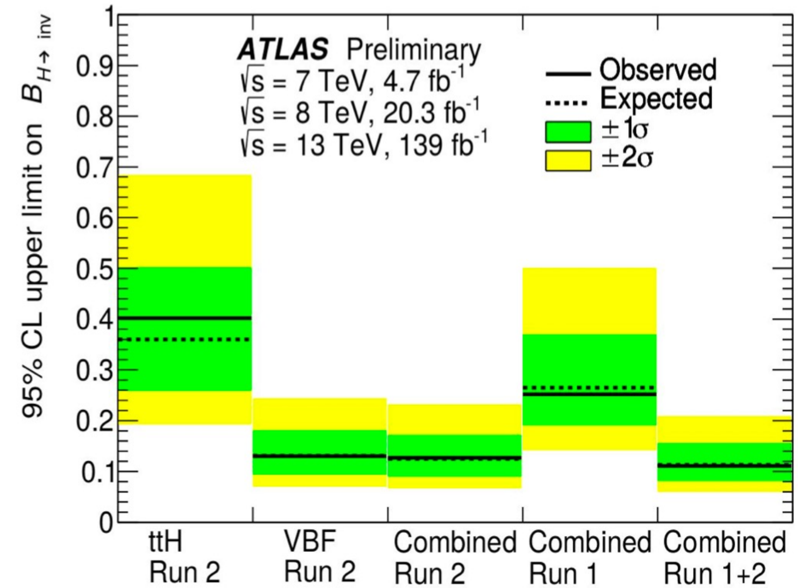
- Reinterpretation in terms of Higgs couplings with Dark Matter or Higgs exotic decays

Latest results:

- ZH ➔ ll + E_T miss
- Fit to BDT discriminant



ATLAS-CONF-2021-029



Results:

- ZH: B(H → inv) < 18% obs (18% exp) at 95% CL
- combination of previous ATLAS analyses (VBF and ttH): B(H → inv) < 11% obs. (11% exp.) at 95% CL

CMS results (2016 data only): Phys. Lett. B 793 (2019) 520

Charged Lepton Flavor Violation in decays:

$H \to \mu\tau, H \to e\tau, H \to e\mu$

[JHEP 03 (2020) 103]

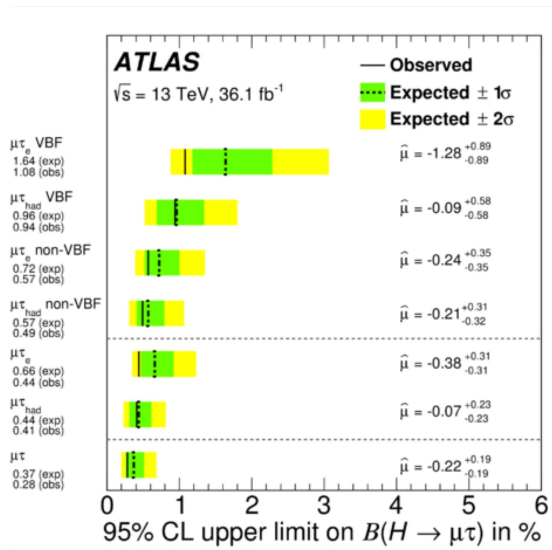
Channels used:

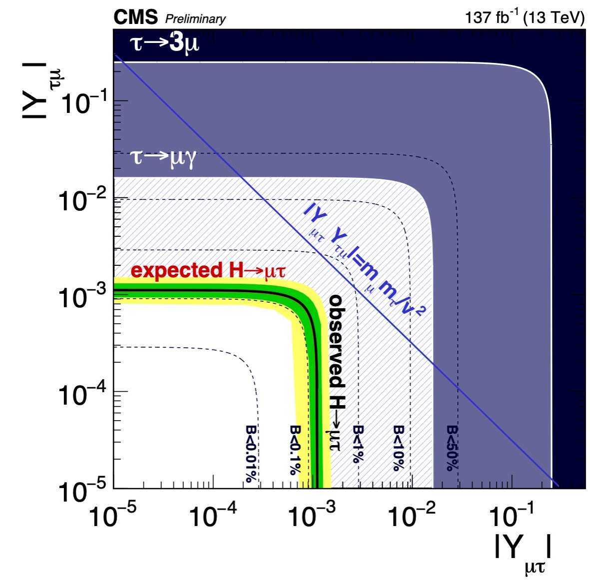
- $\mu\tau_h, \mu\tau_e$
- $e\tau_h, e\tau_\mu$

Very similar to the "nominal" $H \to \tau\tau$ analysis, except that μ and e

- *are prompt*
- *tend to have larger momenta*

BDT is used to separate signal from non-Higgs bkg and $H \to \tau\tau$





B(H → $\mu\tau$) < 0.15% (CMS) B(H → $\mu\tau$) < 0.28% (ATLAS)
H → eμ) < 0.006% (ATLAS)
B(H → $e\tau$) < 0.22% (CMS)
B(H → $e\tau$) < 0.47% (ATLAS)

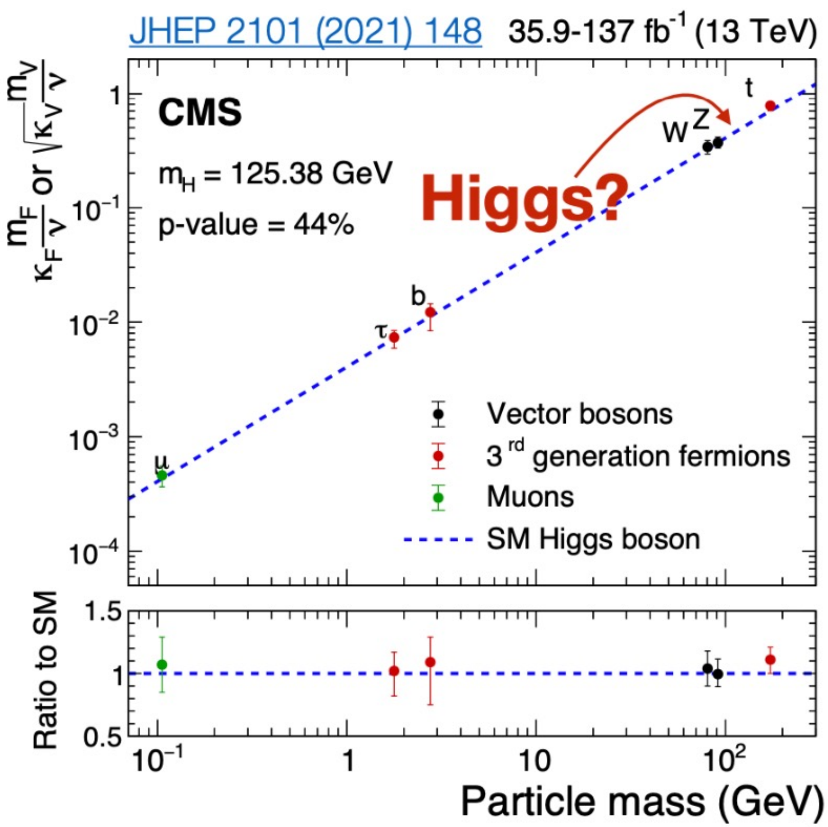
ATLAS-CONF-2019-037 and Phys. Lett. B 800 (2020) 135069

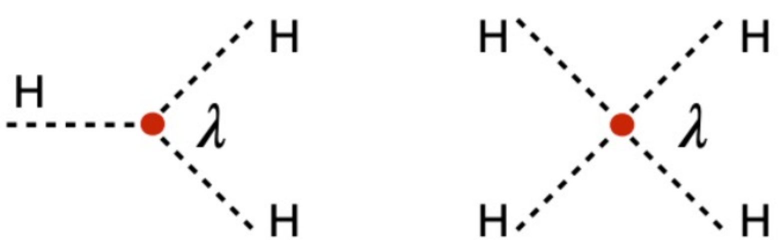
most sensitive final state in $H \to \mu\tau$ search, $\mu\tau_h$ + 2-jet VBF tag

Limits on off-diagonal Yukawa couplings $Y_{\mu\tau}$

The Higgs boson and its self-coupling

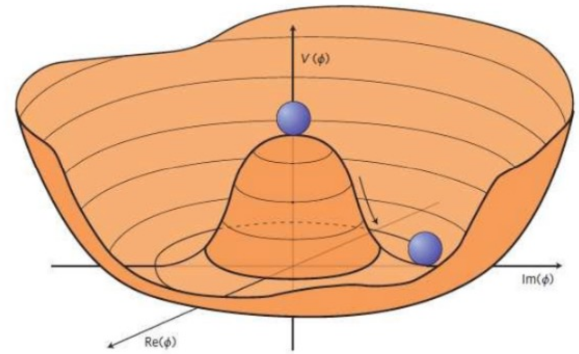
- Higgs boson mass measurement getting very precise
- Interaction with fermions and vector boson well established by now…
- Time to measure the Higgs boson self-coupling experimentally



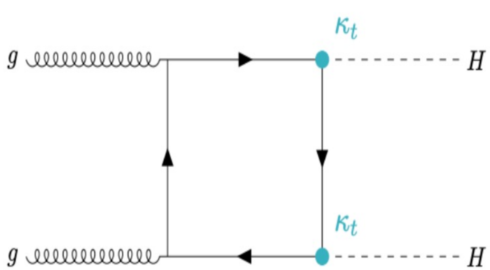


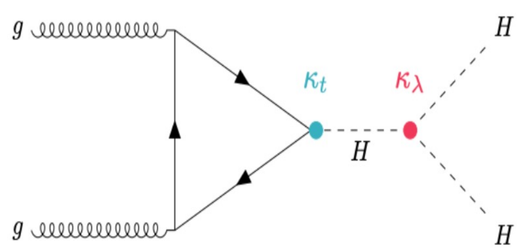
Searches for di-Higgs production

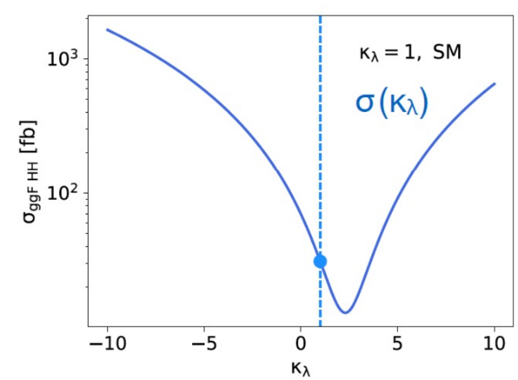
- Measuring production will gives us access to the triple Higgs coupling (self coupling) λ_3, which gives information of the shape of the Higgs potential:
- $V(H) = 1/2\, m^2_H H^2 + \lambda_3 v H^3 + 1/4\, \lambda_4 v H^4 + O(H^5)$
- shape of the Higgs potential linked to a wide range of open questions in particle physics ==> characterizing it is a major goal of HL-LHC



- The leading production mode is gluon gluon fusion (ggF):
- The coupling modifier κ_λ controls the strength of the Higgs self coupling with respect to SM: $\kappa_\lambda = \lambda_3/\lambda_3SM$ (any change will enhance cross-section significantly)
- Destructive interference between the two diagrams results in a very small SM cross section of σ^{HH}_{ggF}=31.05 fb at 13 TeV.



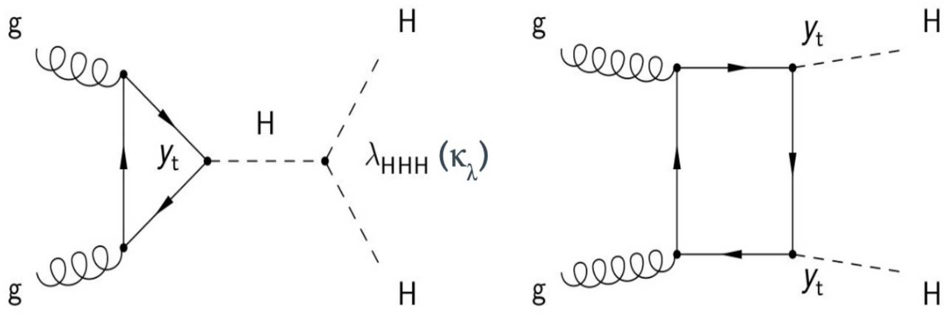




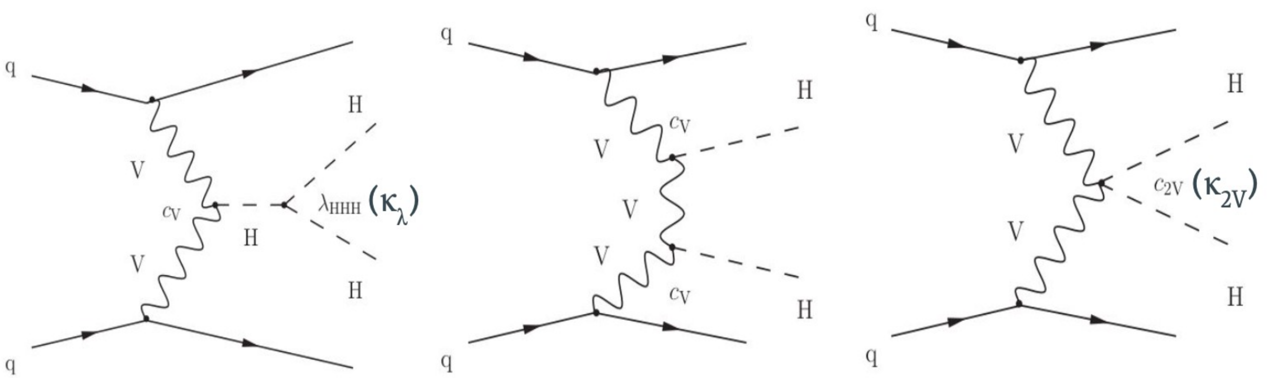
Double-Higgs search

Possibility to directly inspect the Higgs coupling and shape of the potential

- Cross-section values at 13 TeV



gluon-gluon fusion
31.1 fb

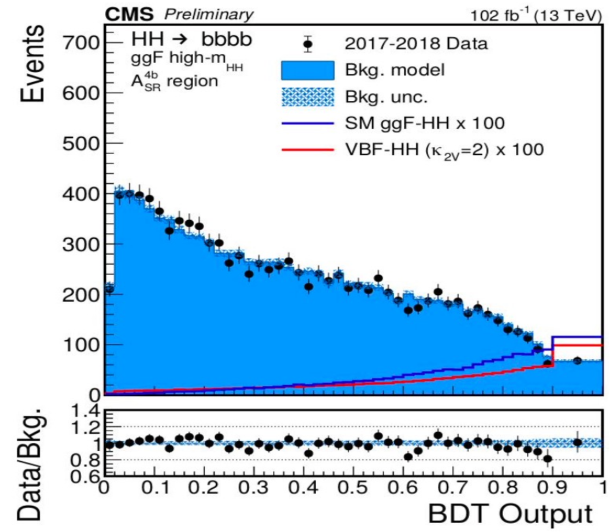


vector-boson fusion
1.726 fb

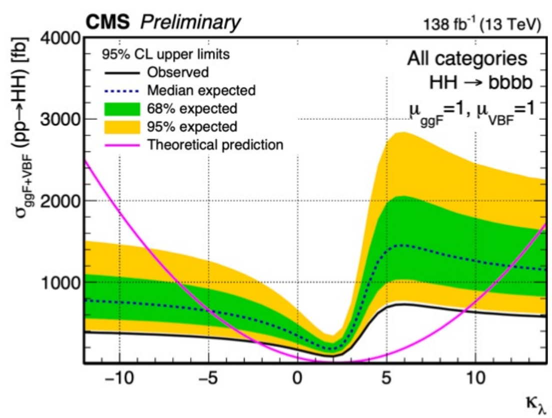
HH→ bbbb

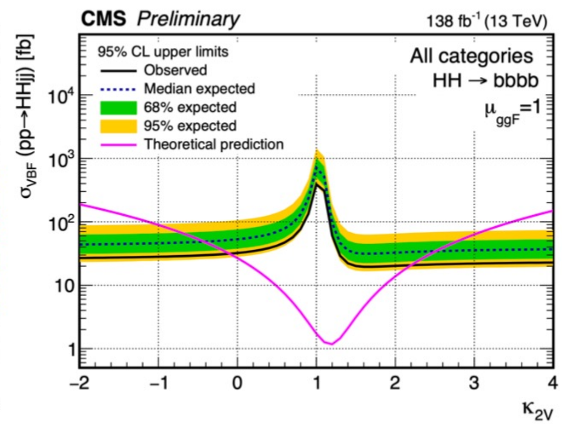
- HH candidates reconstructed from 4 jets and $\chi = (m_{H1} - 125)^2 + (m_{H2} - 120)^2$ is used to divide events in SR and CR
- VBF candidates are selected by requiring 2 additional non b- jets and a VBF-vs-ggF BDT is used to reduce mis- classification of ggF events.
- VBF-vs-ggF BDT or a dedicated ggF BDT are used to enhance sensitivity to both SM and BSM scenarios, resulting in a total of 4 SRs.
- The large multi-jet background is estimated from data and a maximum likelihood binned fit is simultaneously performed in all SRs.

CMS PAS HIG-20-005



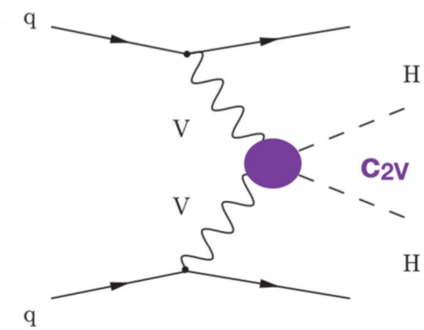
- $\sigma(pp \rightarrow HH \rightarrow 4b) < 3.6\ (7.3) \times$ SM obs (exp)
- $-2.3 < \kappa_\lambda < 9.4\ (-5.0 < \kappa_\lambda < 12.0)$
- $-0.1 < \kappa_{2V} < 2.2\ (-0.4 < \kappa_{2V} < 2.5)$





HH→ bbbb

- New production mode : VBF HH
- Sensitive to c_{2V} coupling unique to HH
- Distinct VBF signature: two high p_T jets with large rapidity gap and invariant mass
- 4 b jets final state : M(bb) energy resolution improved by 25% with BDT energy regression
- Main challenge - multijet background, estimated from data events with lower b-jet multiplicity
- Fit m4b to extract presence of signal



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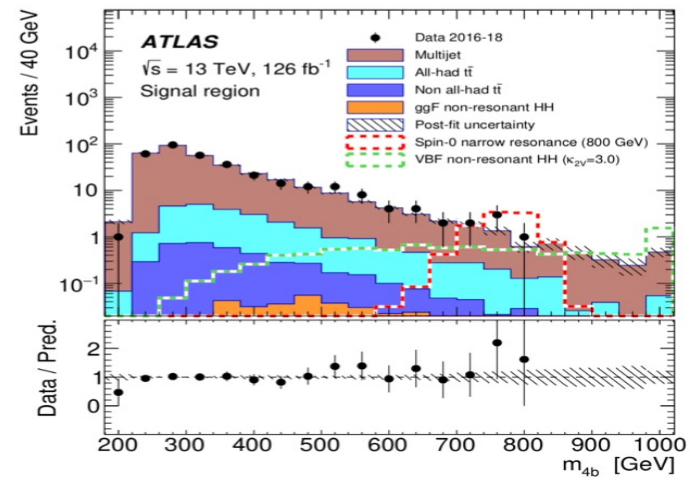
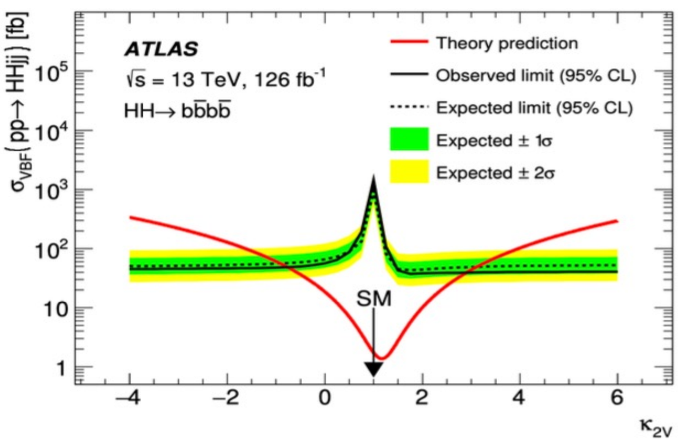




Observed (expected) :

$\sigma^{VBF}/\sigma^{VBF}{}_{SM} < 840(550)$ at 95%CL

$-0.43\ (-0.55) < c_{2V} < 2.56\ (2.72)$

HH → bbbb (boosted)

Targets non-resonant VBF HH production to measure κ_{2V}

Boosted topology:

- each $H \rightarrow bb$ candidate reconstructed as a large-radius jet
- multivariate classifier based on graph convolutional networks and mass regression to identify signal events

Leading top and QCD backgrounds estimated in control regions

Results:

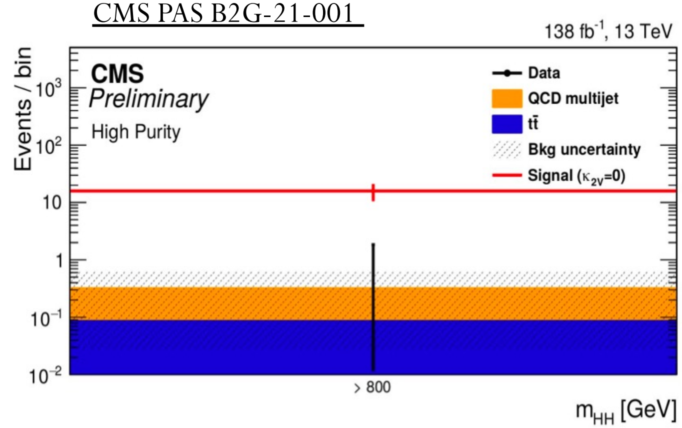
- $0.6 < \kappa_{2V} < 1.4$ (obs and exp) at 95% CL

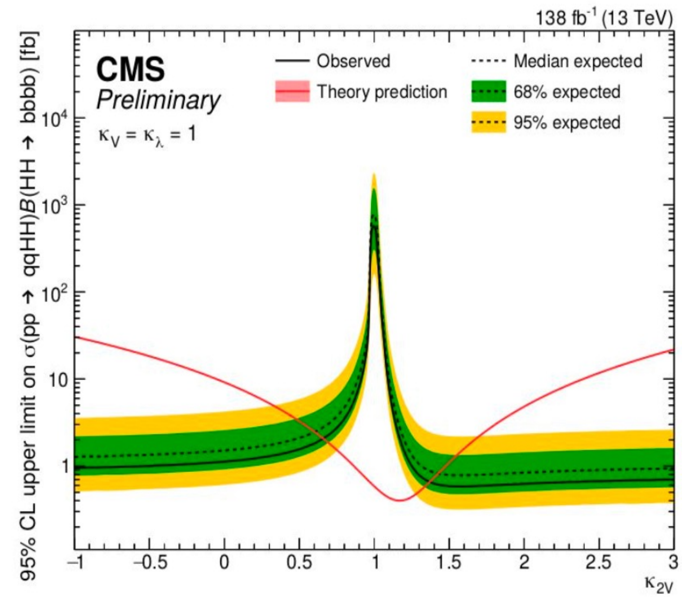
Assuming $k_t = k_v = 1$, $k_{vv}=0$ is excluded at a CL higher than 99.99 %

$K_{vv}=0$ is shown in red

Very sensitive to search!

CMS PAS B2G-21-001

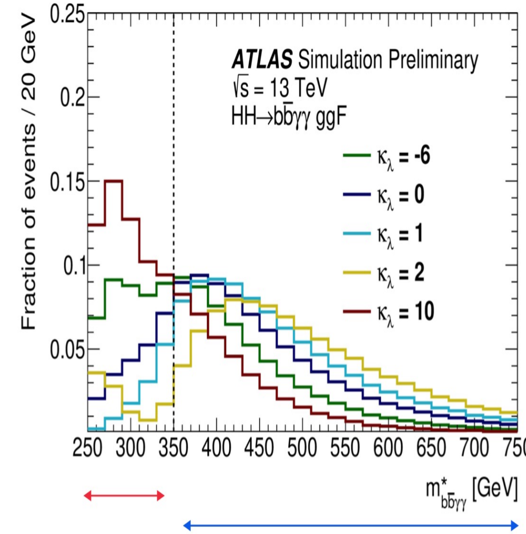




HH → bbγγ

- Two different BDTs are used for events with high/low Mx masses to discriminate $\kappa_\lambda = 1$ or $\kappa_\lambda = 10$ against background. A total of 4 regions are defined from cuts on the score of the BDTs.
- The analysis is optimised for ggF HH ==> VBF events are also considered as signal.
- The SB are fit to estimate the non-resonant background with data.

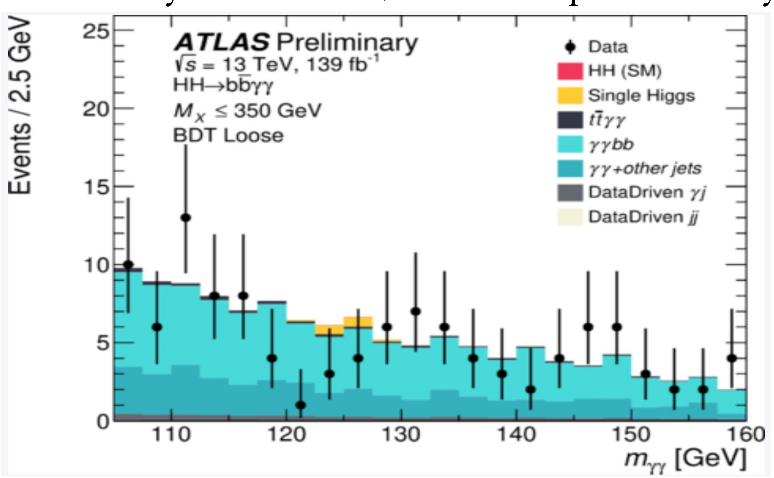
ATLAS-CONF-2021-016

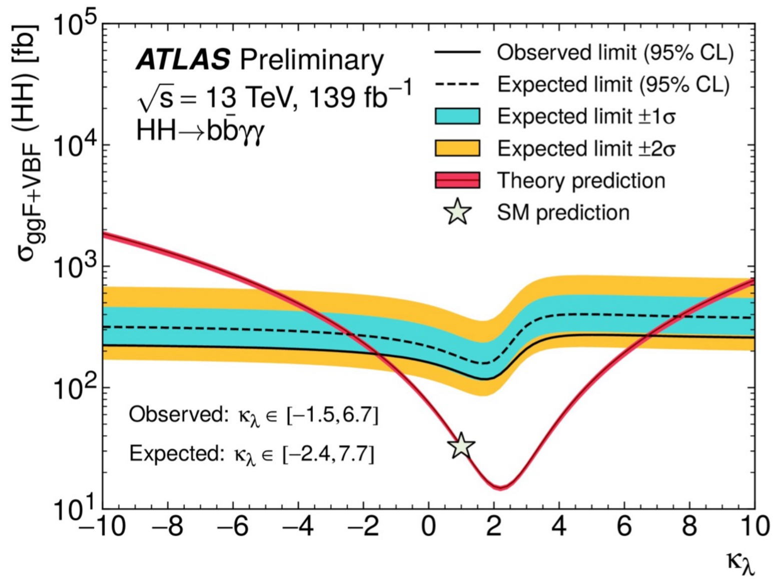


Results:**4.1 (5.5) x SM σHH**

5x improvement wrt previous result, ~3x due to analysis techniques driven by mHH categorization & MVA as well as b-jet corrections

Statistically dominated, few % impact from systematics





HH → bbγγ

- A ggF and VBF BDT are used to discriminate the HH signals against background + a DNN is also used to further discriminate against ttH
- M(bb) energy resolution improved by 25% with DNN-based b jet energy regression
- A 2D fit to mγγ and mjj side bands is performed in
- all regions to estimate the non-resonant backgrounds with data.

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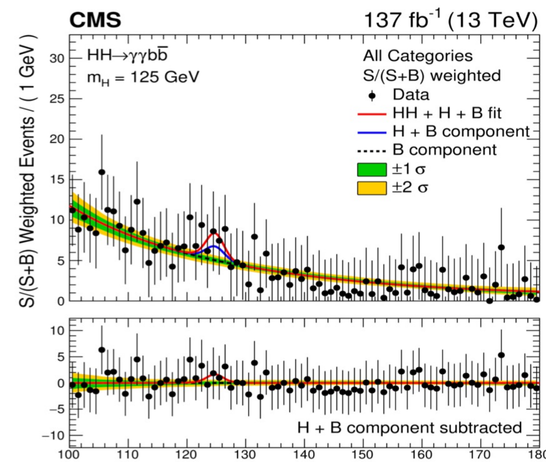
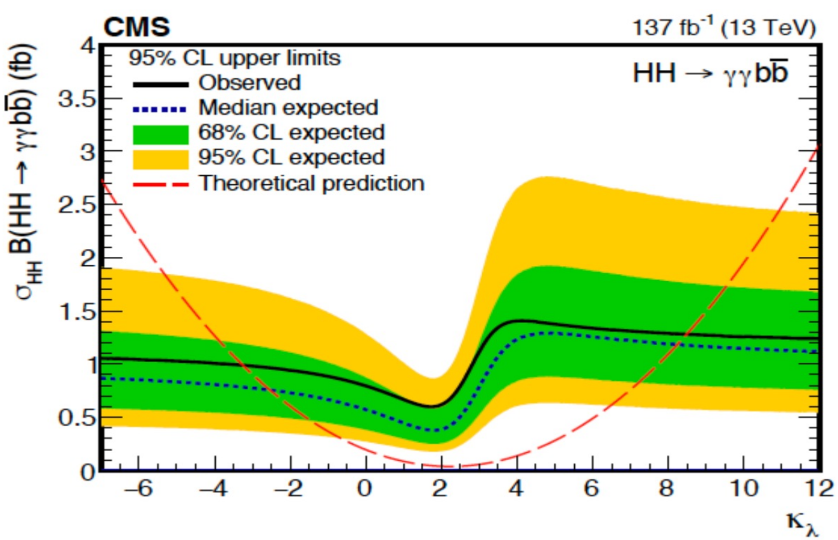
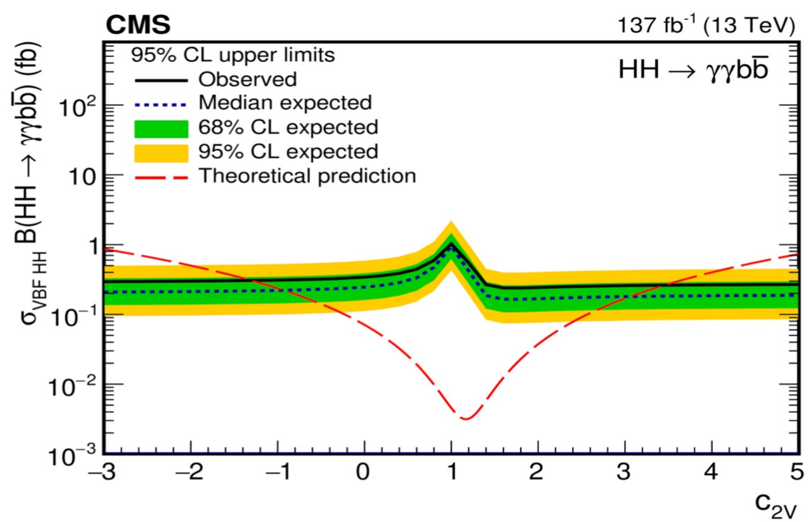






σ_{HH} (ggF+VBF)/σ_{HH} SM (ggF+VBF) < 7.7 (5.2) at 95% CL
$-3.3(-2.5) < \kappa_\lambda < 8.5\ (8.2)$

σ_{HH} (VBF)/σ_{HH} SM (VBF) < 225 (208) at 95% CL
$-1.3(-0.9) < c_{2V} < 3.5\ (3.0)$

HH → bb$\tau\tau$

Compromise between BR and background contamination

Search is optimised for maximum sensitivity to cross-section measurement

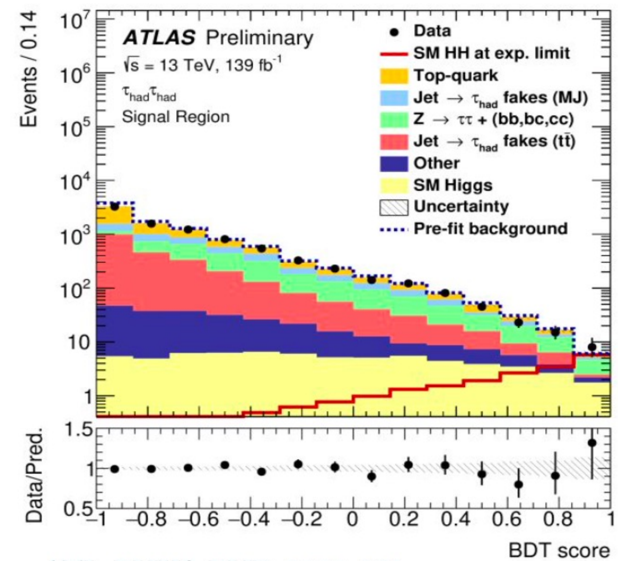
At least one τ_{had} in each event

Signal extracted from fits to multivariate discriminants

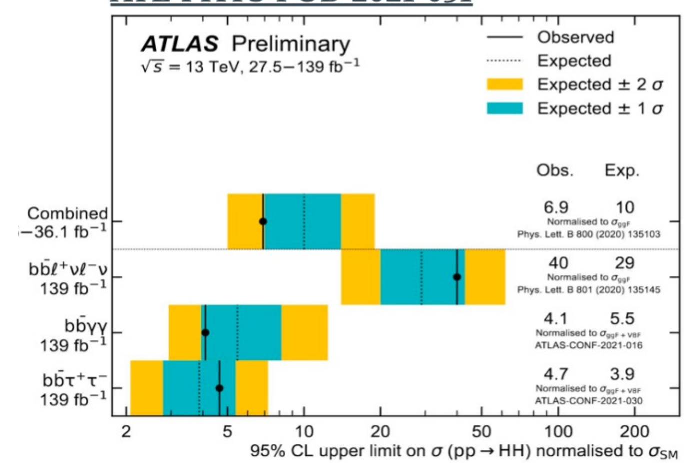
Results:

- $\sigma(HH \rightarrow bb\tau\tau) < 4.7\ (3.9) \times$ SM obs (exp) at 95% CL

CMS results (2016 data only): Phys. Lett. B 778 (2018) 101



ATL-PHYS-PUB-2021-031



Conclusions

- Recent Higgs results from ATLAS and CMS using full Run2 data
- Golden channels, vector bosons, and third generation fermions established
- Effort to explore decays to second generation fermions and rare final states
- Inclusive, fiducial, and Differential STXS measurements
- Limits on HH measurements are more stringent and already close to SM expectation
- The forthcoming Run3 will help improving current measurement and prepare for the high luminosity phase