Recent Higgs measurements

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on behalf of the ATLAS and CMS Collaborations

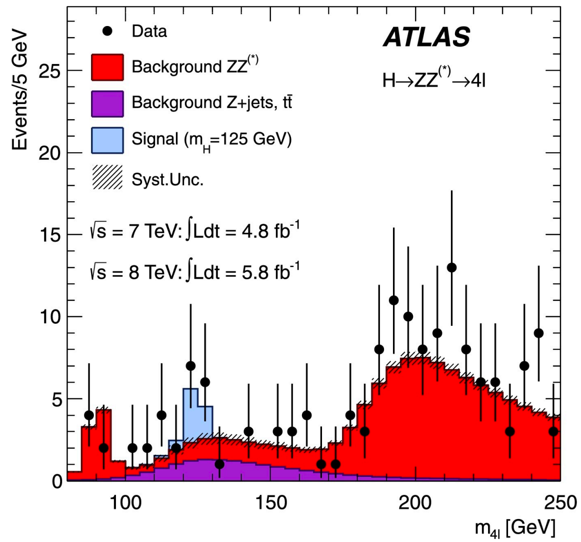
BF2021

4th November 2021

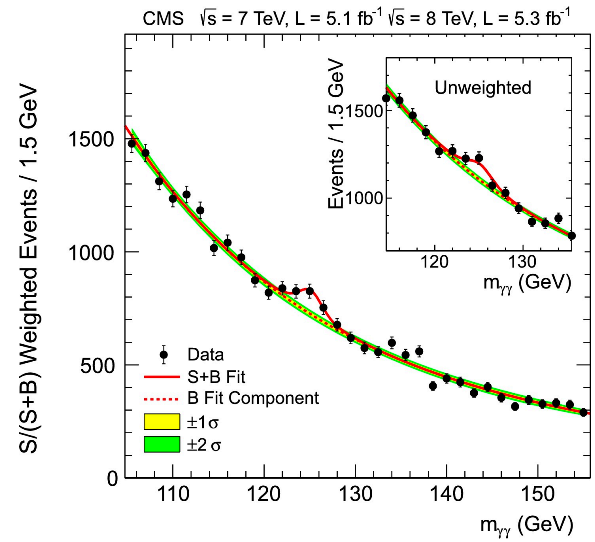
Higgs status

- **Higgs boson** discovered in 2012.
- Using <u>Run 1 data</u>:
  - **Spin 0** particle;
  - **Mass** known at **0.2% level**;
  - **Couplings** consistent with SM predictions.
- Using <u>Run 2 data</u>:
  - **Observation** of all the **main production processes**;
  - **Observation** of **decays to bosons** and **third-generation fermions**;
  - **Improvement** of m_H **precision** and **CP** measurements;
  - **Off-shell production** measurements.
- Now shift focus from *discovery era* to *precision era*
  - Precision unfolded differential measurements;
  - **Combined measurements** → Simplified Template Cross-Section (STXS) framework.

[Phys. Lett. B 716 (2012) 1-29]

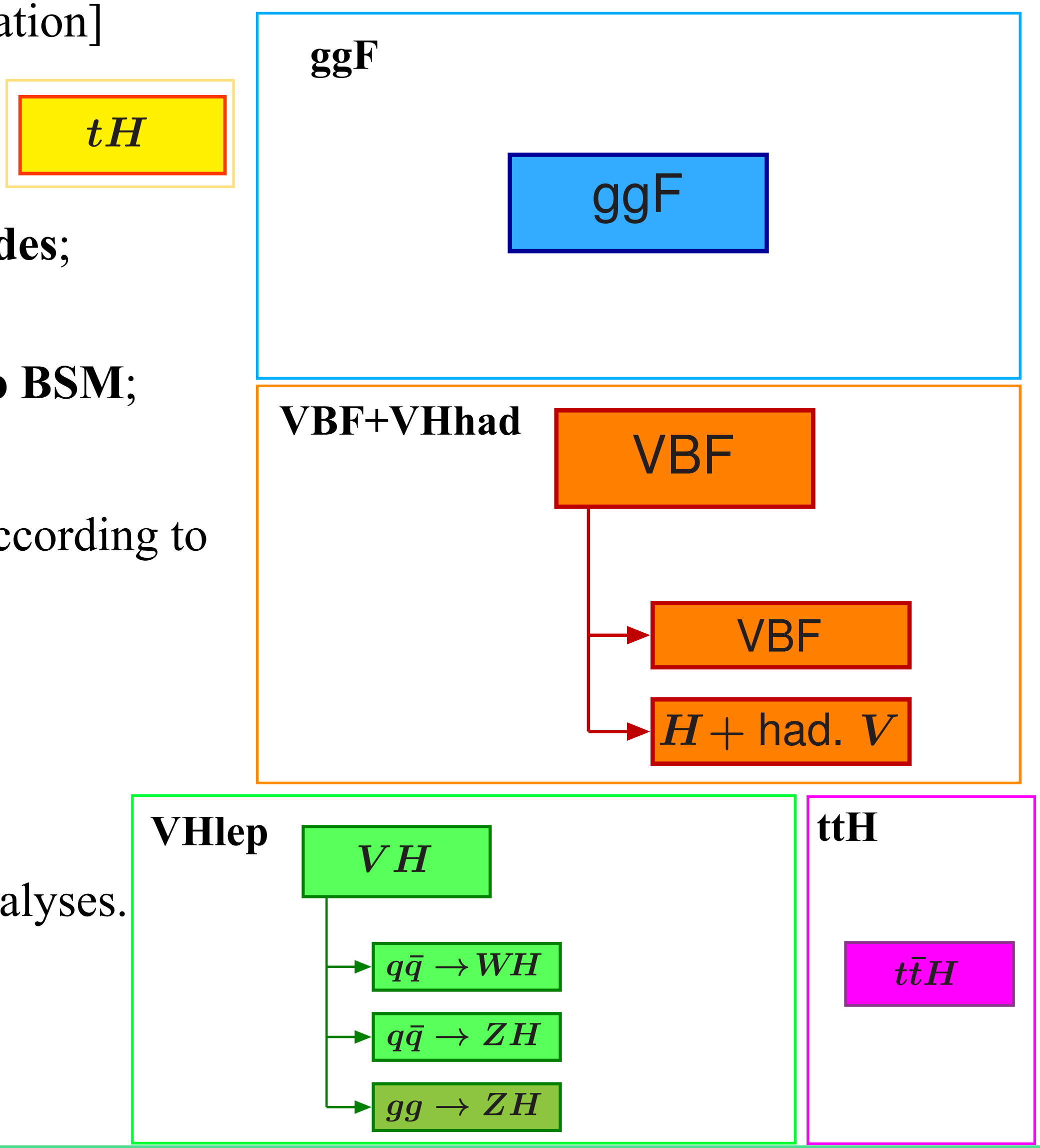


[Phys. Lett. B 716 (2012) 30]



STXS framework

- Framework for **subdividing Higgs Boson measurements into orthogonal regions** - *STXS bins* [defined using generator level information]
  - **$(\sigma \times B)$ measurement** for each bin
- STXS bins chosen such that they:
  - are **defined by Higgs production modes**;
  - **reduce theory uncertainties**
  - **isolate regions** potentially **sensitive to BSM**;
- STXS stage 1.2 Higgs boson signal split according to
  - production modes,
  - number of jets
  - p_T^H / p_T^V;
  - invariant mass of the leading jets m_{jj}.
- **Advantage**: easy to combined different analyses.



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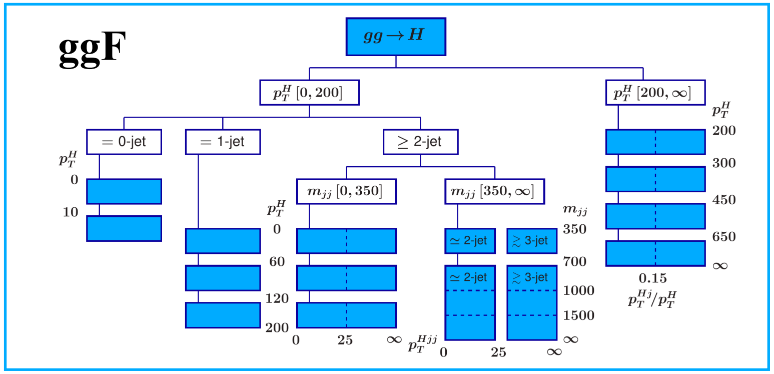

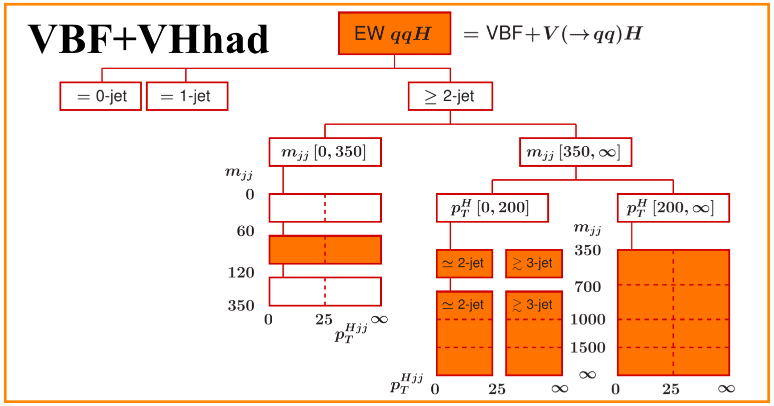

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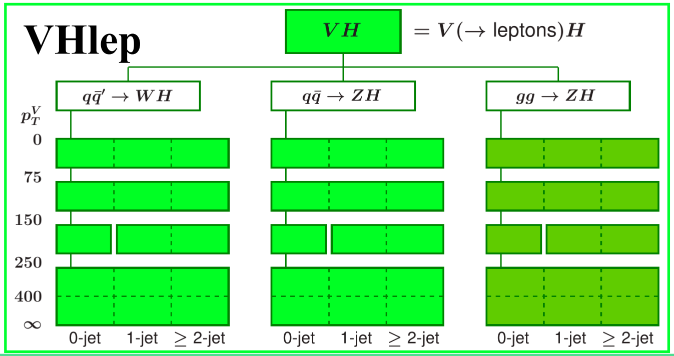
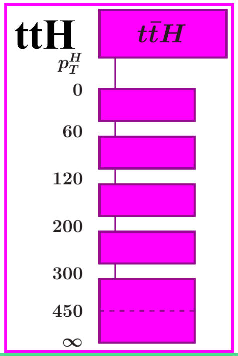




Outline

In this talk I am focusing on results released in the past one year:

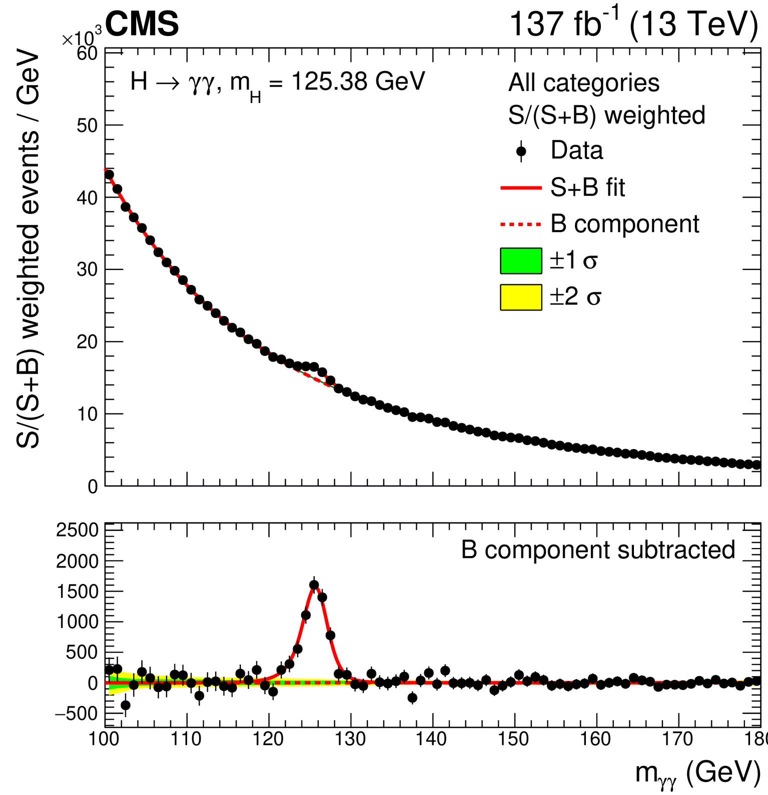
- $H \to \gamma\gamma$ analysis (CMS)
- $H \to ZZ \to 4\ell$ analysis + off-shell production (CMS);
- $H \to \tau\tau$ analysis (ATLAS);
- $H \to b\bar{b}$ analysis (ATLAS);
- $H \to \mu\mu$ analysis (ATLAS, CMS);
- $H \to Z\gamma$ analysis (ATLAS, CMS);
- Combined Higgs boson measurements (ATLAS).

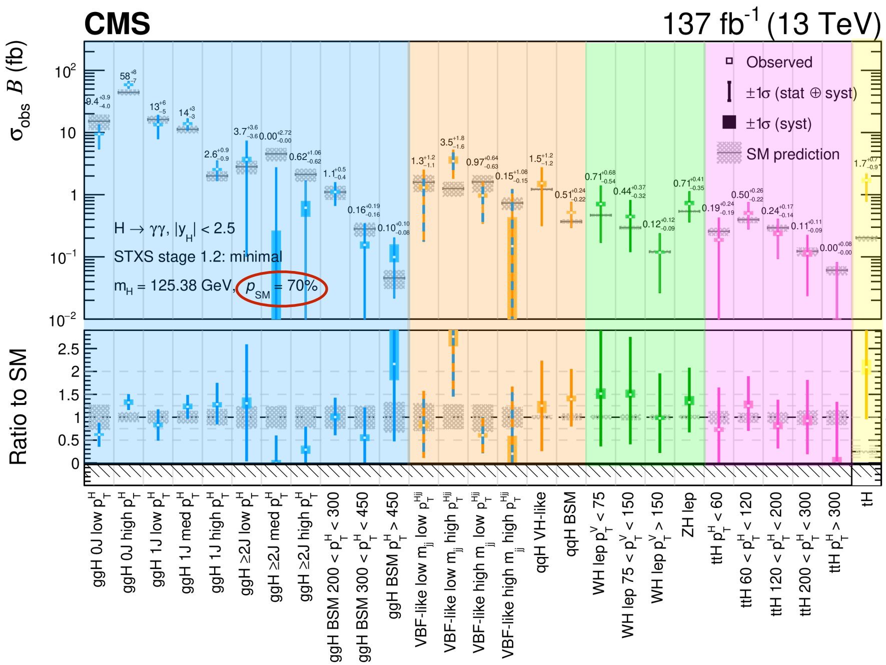
$H \rightarrow \gamma\gamma$ analysis

[JHEP 2017 (2021) 027]

- Analysis **targets all Higgs production modes**: ggF, VBF, VH, ttH, **tH**
- **Clean final state** topology with two photons
- Simultaneous **binned maximum likelihood fit** to $m_{\gamma\gamma}$ distributions

$$\mu = 1.12^{+0.06}_{-0.06}(\text{theo})^{+0.03}_{-0.03}(\text{syst})^{+0.07}_{-0.06}(\text{stat})$$





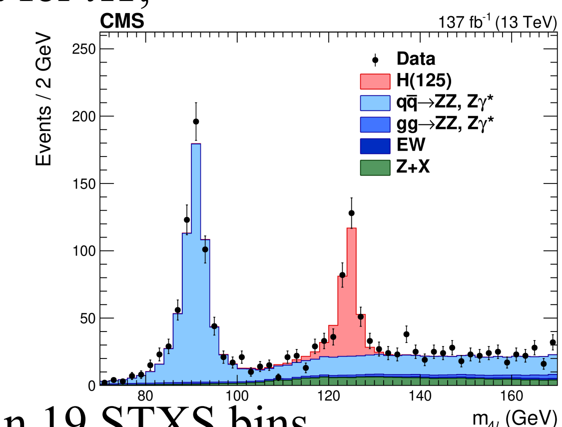
- **STXS measurements** in 27 STXS bins ["minimal merging scenario"]
  - **Most granular XS measurement** performed in a single Higgs decay
  - **First measurement** of ***ttH* in bins of $p_T(H)$**;
  - **Large uncertainty** on **tH bin**

ATLAS analysis: [link]

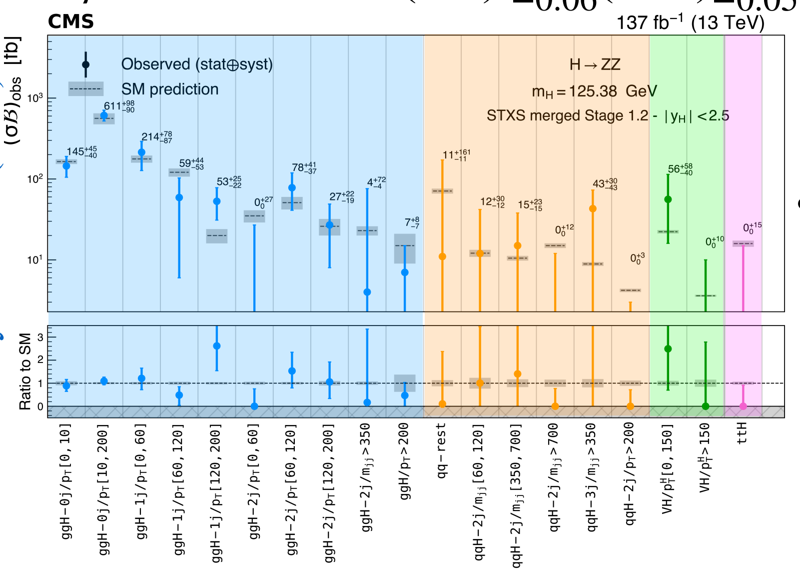
$H \to ZZ \to 4\ell$ and off-shell Higgs production

- Events with **same flavor**, **opposite sign lepton pairs** form the Higgs candidate
    - **Clear signature** → targets **all the production modes** except for tH;
- **Dominant irreducible background**: ZZ^*
- **Unbinned likelihood fit**

$$\mu = 0.94 \pm 0.07\ (\text{stat})\ {}^{+0.07}_{-0.06}(\text{theo})^{+0.06}_{-0.05}(\text{exp})$$

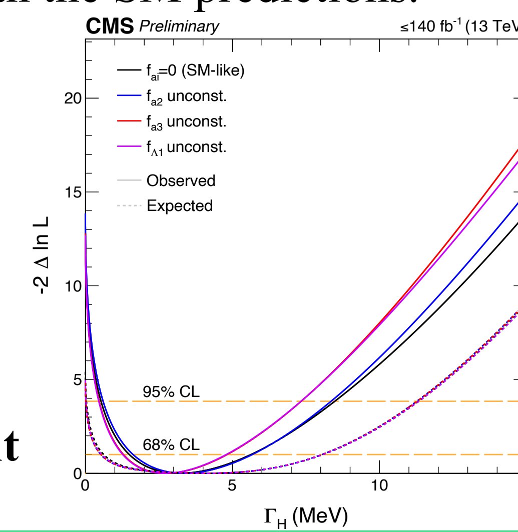


Eur. Phys. J. C 81 (2021) 488



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

- <u>STXS measurements in 19 STXS bins</u>.
    - **Statistically limited channel**
    - Results consistent with the SM predictions.



CMS-PAS-HIG-21-013

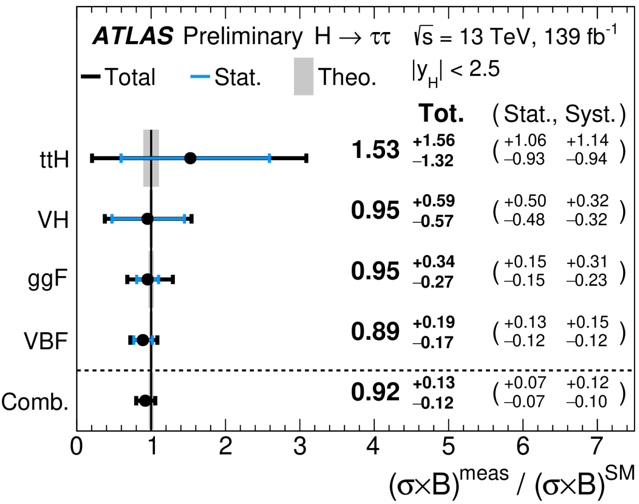
- On-shell analysis combined with off-shell $H \to ZZ \to 2\ell 2\nu$
  ⇒ **first evidence of off-shell Higgs production** (**3.6** σ)
- Comparison of on-shell and off-shell rates yields constrain on Higgs width $\Gamma_H =$ **3.2** ${}^{+2.4}_{-1.7}$ **MeV ←Most precise** Γ_H **measurement**

ATLAS analysis: link

$H \to \tau\tau$ analysis

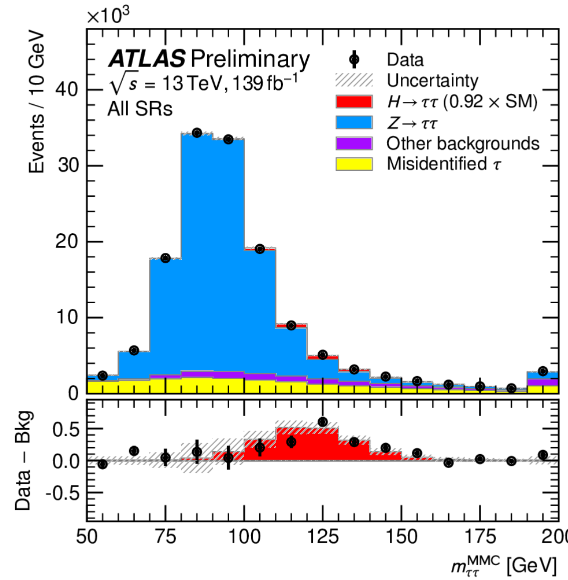
[ATLAS-CONF-2021-044](https://atlas.web.cern.ch)

- Analysis **targets** all production modes
- Events classification: $\tau_h\tau_h, \tau_{lep}\tau_h, \tau_e\tau_\mu$.
- **Binned maximum-likelihood fit to $m_{\tau\tau}$**



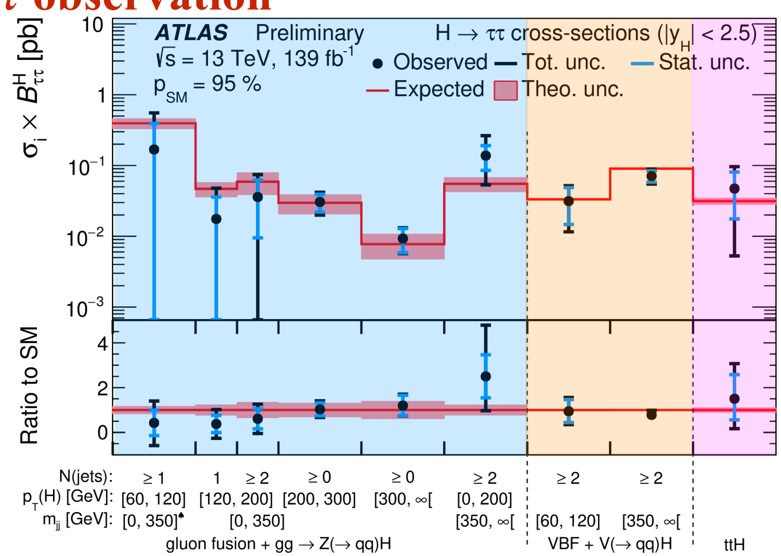
→ **3.9σ**

→ **5.3σ First VBF H→$\tau\tau$ observation**



$Z\to\tau\tau$ is dominant **irreducible bkg**
$\Rightarrow$ $Z\to\tau\tau$ **CRs** used to extract the normalisation

- STXS measurement in 9 STXS bins:
  - **Good agreement with SM prediction;**
  - ggF with 200 GeV < p_T^H < 300 GeV and p_T^H >300 GeV have best precision (O(40%)).



CMS analysis: [link](https://cms.cern.ch)

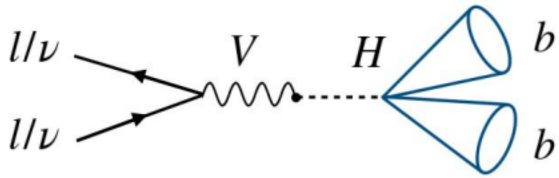
$VH, H \to b\bar{b}$ combination

ATLAS-CONF-2021-051

- $H \to b\bar{b}$ **dominant decay, triggered by leptonic decays of vector boson**
- $VH(b\bar{b})$ final states studied by two analyses and significant **overlap** (~25%) between the two analyses

Resolved analysis

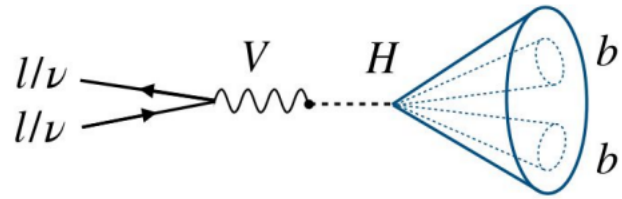
Eur. Phys. J. C 81 (2021) 178



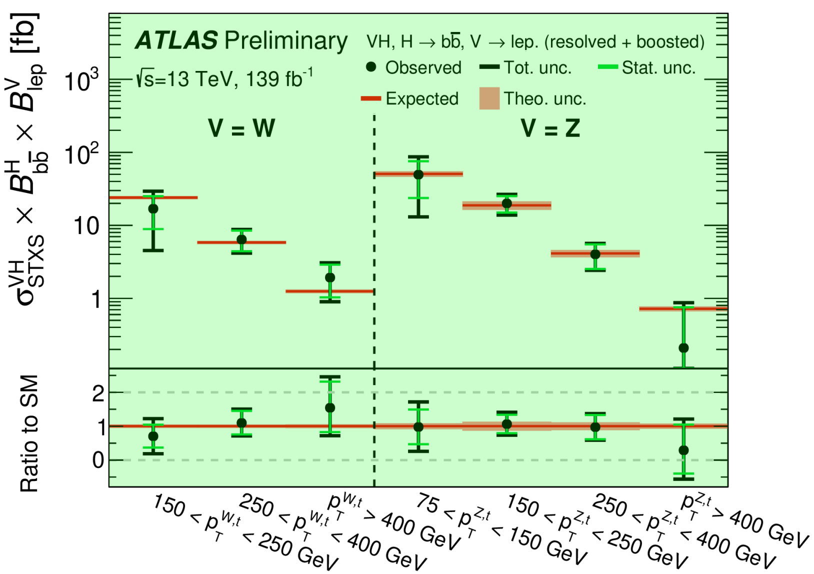
O(30%) measurement of STXS bins

Boosted analysis

Phys. Lett. B 816 (2021) 13204



Probes high-p_T^V regime



- In the combination **drop resolved events with p_T^V>400 GeV** and **use boosted only in p_T^V > 400GeV**
- STXS measurements in 7 STXS bins
  - bins with p_T^V>400 GeV are statistically limited
  - **Good agreement with SM predictions**.

$H \rightarrow \mu\mu$ analysis

- Analysis **targets all the production modes**;
- Final state with **two muons** → good signal resolution but small branching ratio (~$2.2\text{x}10^{-4}$)
- Large **irreducible bkg** from $Z \rightarrow \mu\mu$
- **Simultaneous binned-likelihood fit**
- CMS results:

$$\mu = 1.19\ ^{+0.41}_{-0.40}(\text{stat})^{+0.17}_{-0.16}(\text{syst})$$

→ Observed (expected) significance 3 (2.5) σ - **Evidence!**

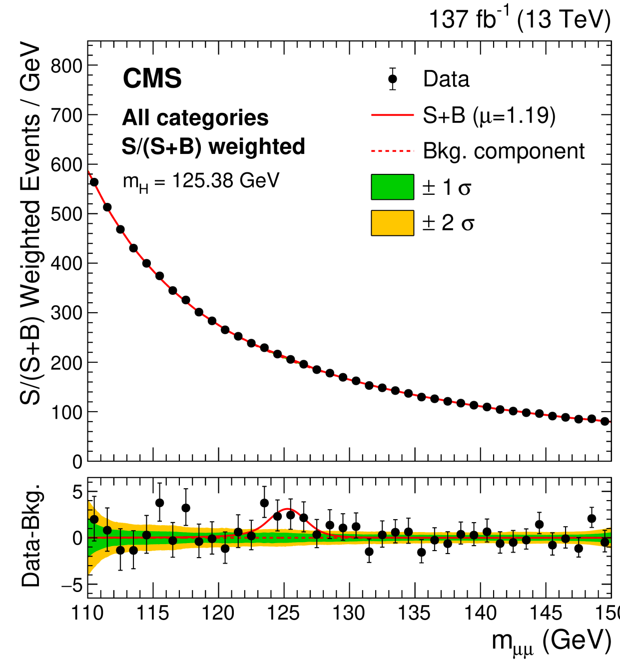
→ upper limits on BR of **1.9×SM** @ 95% CL

- ATLAS results:

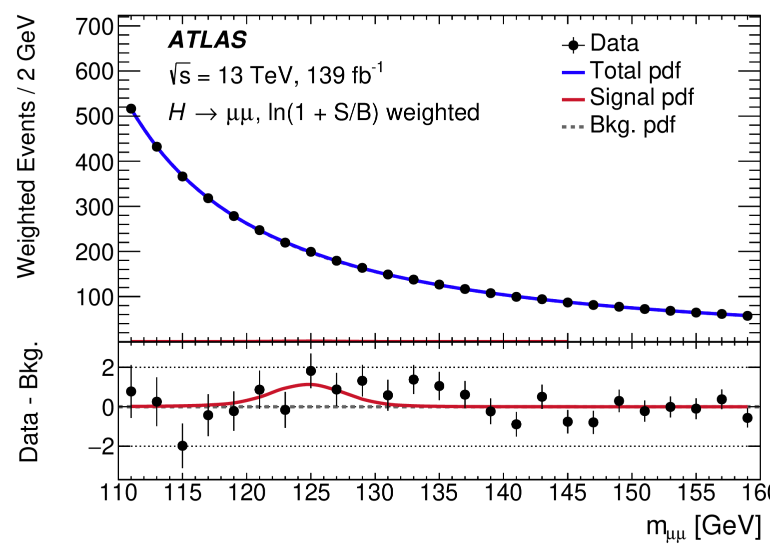
$$\mu = 1.2 \pm 0.6(\text{stat})^{+0.2}_{-0.1}(\text{syst})$$

→ Observed (expected) significance 2.0σ (1.7σ)

→ upper limits on BR of 2.2×SM @ 95% CL



JHEP 01 (2021) 148



Phys. Lett. B 812 (2021) 135980

$H \rightarrow Z\gamma$ analysis

- Analysis **targets all the production modes**;
- $BR(H \rightarrow Z\gamma) = 1.54 \times 10^{-3}$
- Final state with **one photon** and **two same flavor opposite charge leptons** ($\ell = e, \mu$).
- **Binned-maximum likelihood fit** to all $m_{Z\gamma}$ distribution
- CMS results:

  $\mu = 2.4\,^{+0.8}_{-0.9}\,(\text{stat})^{+0.3}_{-0.2}(\text{syst})$

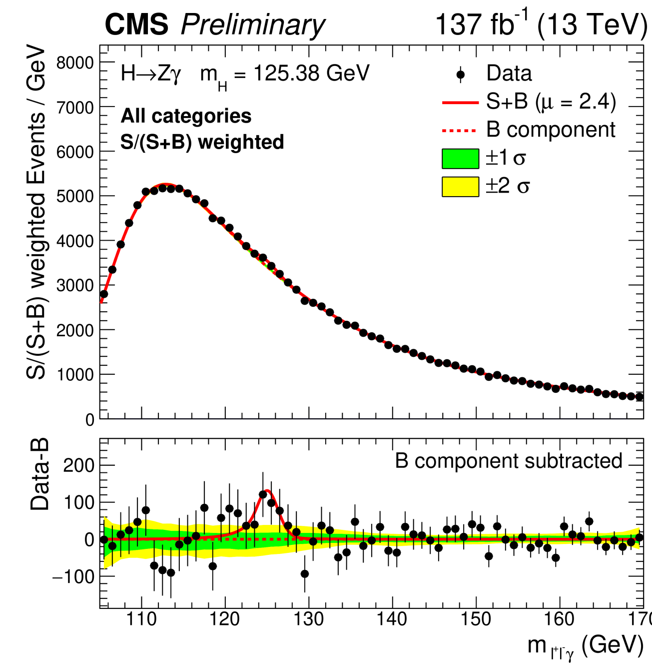
  Observed (expected) significance of 2.7 (1.2) σ

  → upper limits on $(\sigma \times B)$ of 4.1 x SM @ 95% CL
- ATLAS results:

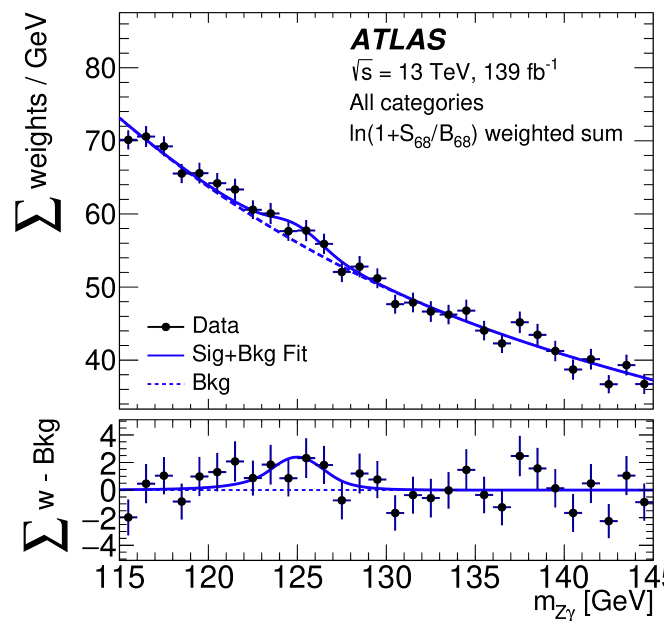
  $\mu = 2.0 \pm 0.9\,(\text{stat})^{+0.4}_{-0.3}(\text{syst})$

  Observed (expected) significance of 2.2 (1.2) σ

  → upper limits on $(\sigma \times B)$ of **3.6 x SM** @ 95% CL



CMS-PAG-HIG-19-014



Phys. Lett. B 809 (2020) 135754

Combined Higgs boson measurements

Input analyses [ATLAS-CONF-2021-053]

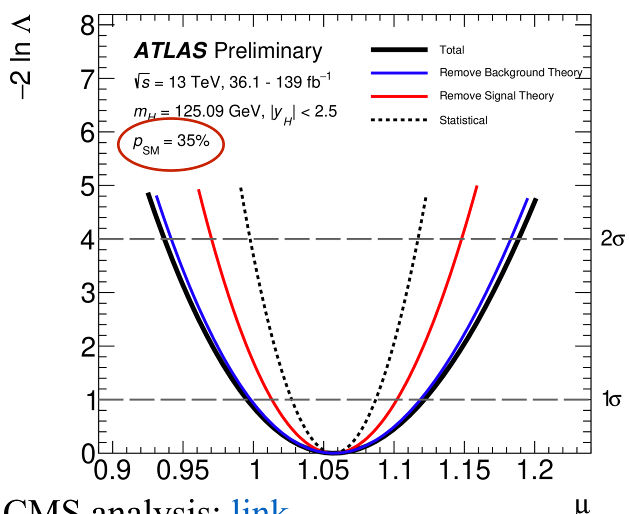
	$\gamma\gamma$	ZZ	WW	$\tau\tau$	bb	$\mu\mu$	$Z\gamma$	inv
ggF	full Run 2	full Run 2	full Run 2	full Run 2		full Run 2	full Run 2	
VBF	full Run 2	full Run 2	full Run 2	full Run 2	full Run 2	full Run 2	full Run 2	full Run 2
VH	full Run 2	full Run 2		full Run 2	full Run 2	full Run 2	full Run 2	
ttH	full Run 2	full Run 2 / partial Run 2	partial Run 2	partial Run 2 / full Run 2	full Run 2	full Run 2	full Run 2	
tH	full Run 2							

full Run 2 (green) — partial Run 2 (yellow)

$t\bar{t}H$(→mult. leptons) analysis uses partial Run 2 dataset (36 fb^{-1})

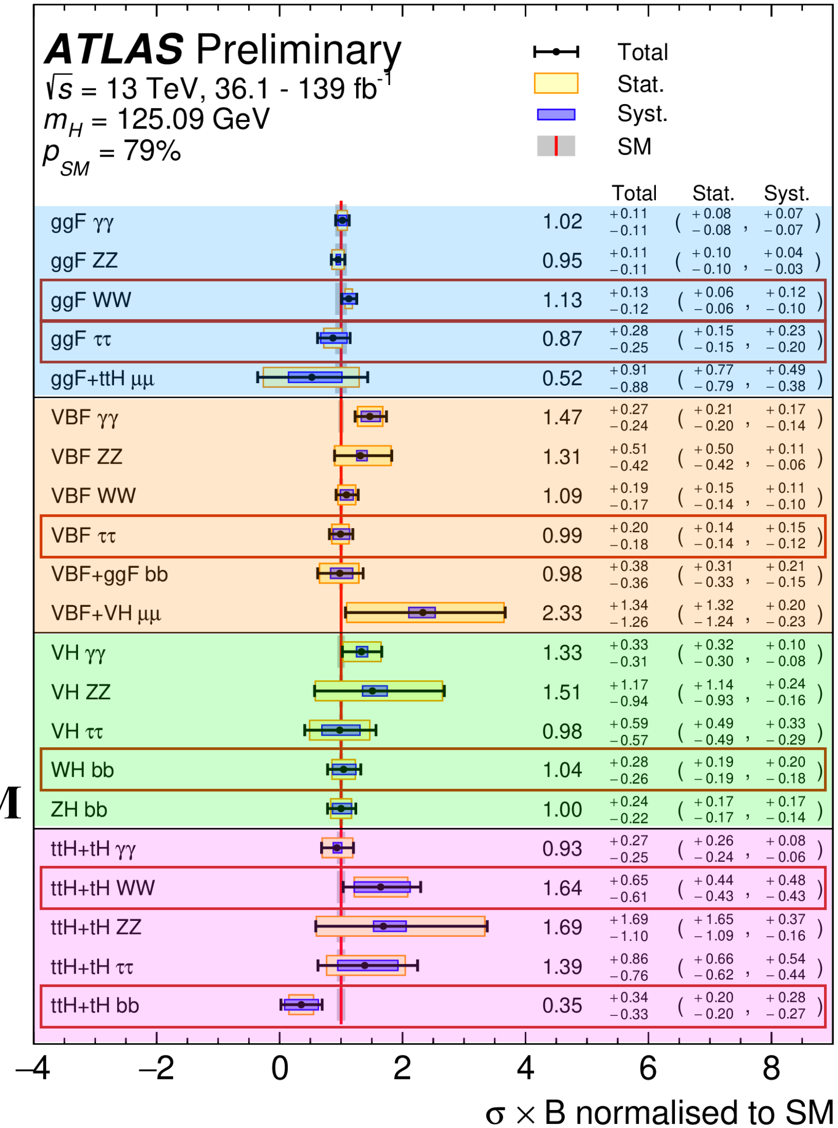
Global signal strength

$$\mu = 1.06 \pm 0.03\ (\text{stat}) \pm 0.03\ (\text{exp}) \pm 0.04\ (\text{sig th}) \pm 0.02\ (\text{bkg th})$$



CMS analysis: link

Very good agreement with SM expectations



Combined Higgs boson measurements: STXS results

ATLAS-CONF-2021-053

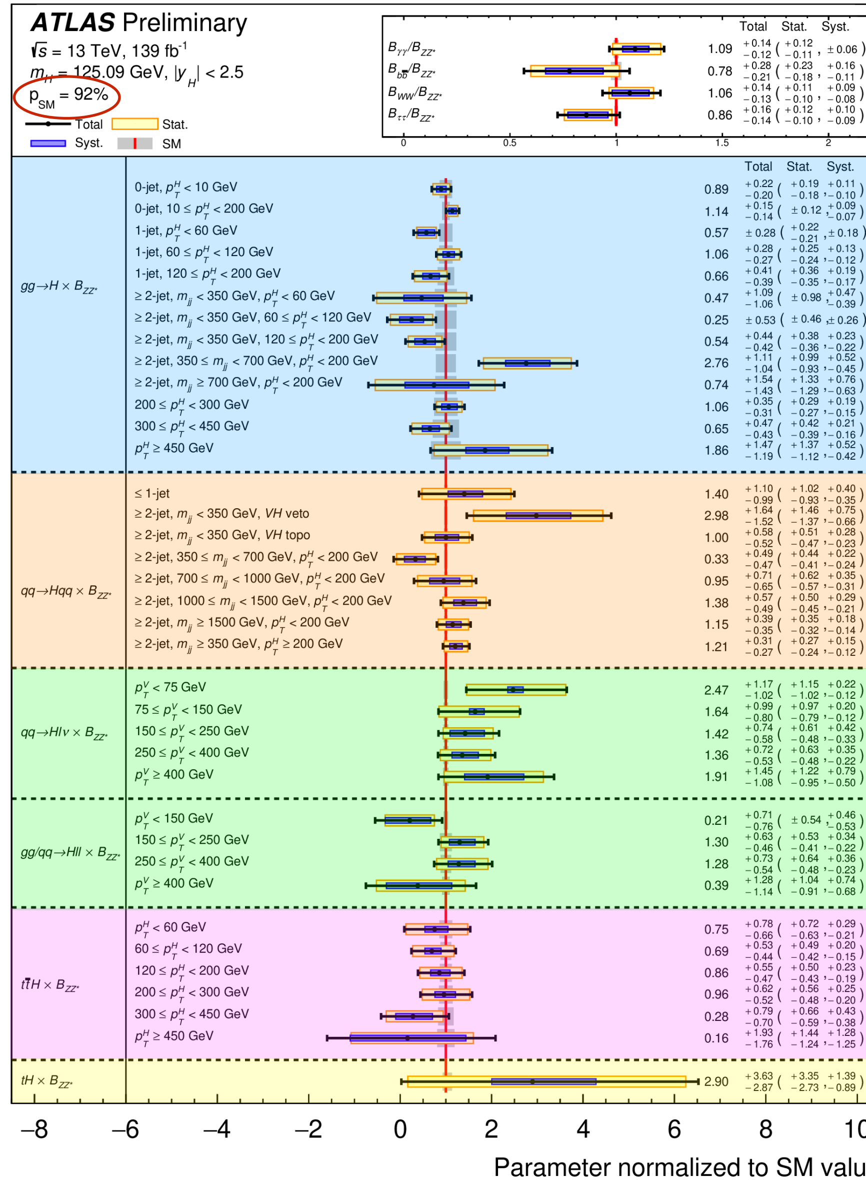
Fit parameters for the STXS measurement:

Decay mode

$$(\sigma \times B)_{if} = (\sigma \times B)_{i,ZZ} \cdot \left(\frac{B_f}{B_{ZZ}}\right)$$

Production mode bin

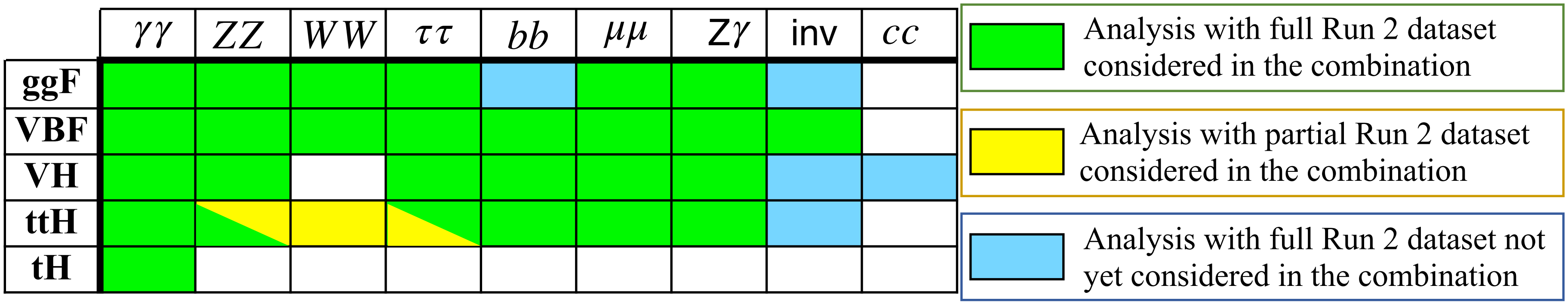
- 37 cross-sections measured simultaneously:
  - Excellent agreement with SM prediction



CMS analysis: link

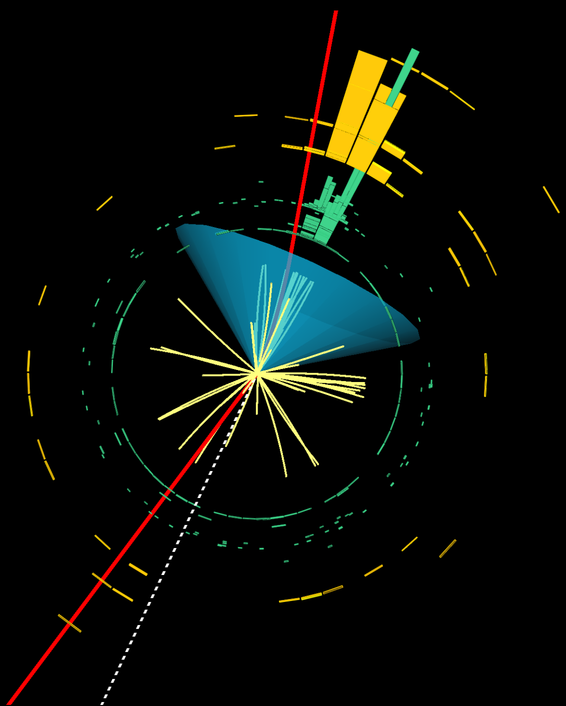
Conclusions

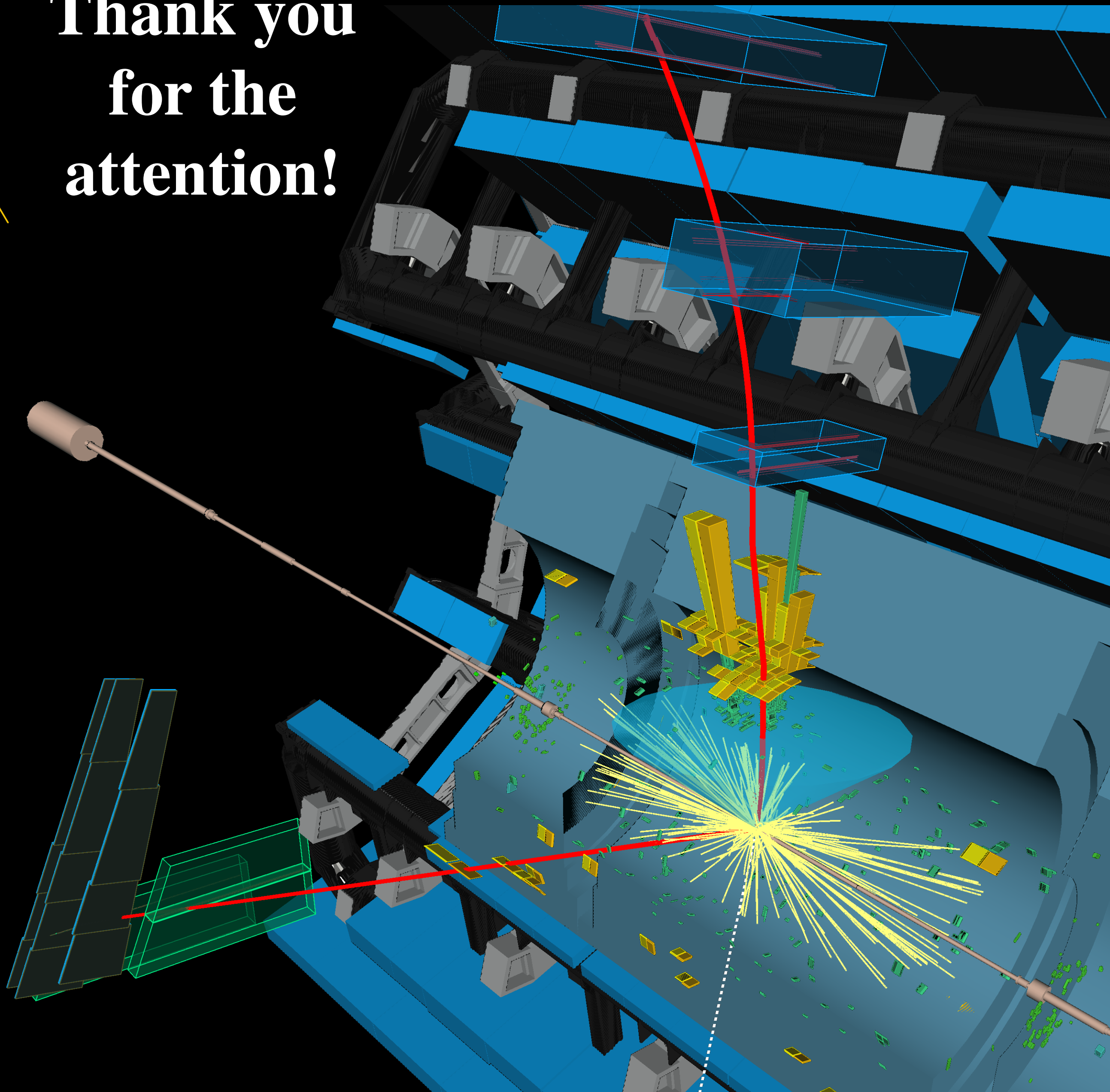
- Using Run 2 dataset, **XS measurements in many channels**;
  - Results are in **good agreement with SM expectations**
- Combination of individual Higgs boson production and decay measurements
  - Almost all the analyses use full Run-2 dataset
  - **Easy combination** of the analyses thanks to the **STXS framework**;
  - Combination provides **unprecedented precision**



- **Stay tuned, more precise results are coming!**

Thank you for the attention!





ATLAS EXPERIMENT

Run: 338349
Event: 616525246
2017-10-16 20:24:46 CEST

Additional material

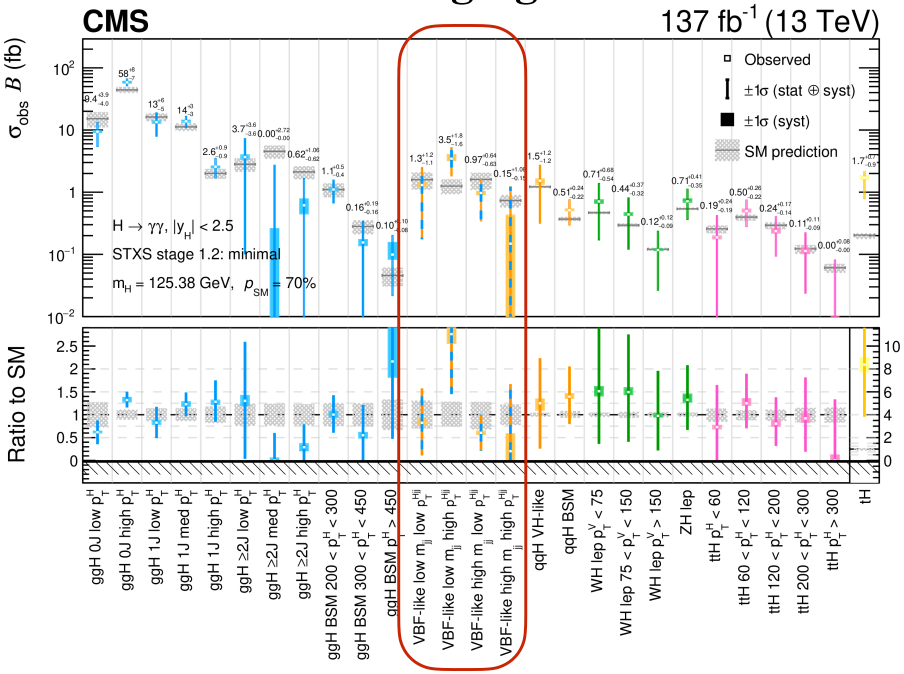
Full list of analysis

- Combination:
  - ATLAS: ATLAS-CONF-2021-053
  - CMS: CMS-PAS-HIG-19-005
- $H \to \gamma\gamma$
  - ATLAS: ATLAS-CONF-2002-026
  - CMS: JHEP 2017 (2021) 027
- $H \to ZZ \to 4\ell$
  - ATLAS: Eur. Phys. J. C 80 (2020) 957
  - CMS (on-shell): Eur. Phys. J. C 81 (2021) 488
  - CMS (off-shell): CMS-PAS-HIG-21-013
- $H \to \tau\tau$:
  - ATLAS: ATLAS-CONF-2021-044
  - CMS: CMS-PAS-HIG-19-010
- $H \to b\bar{b}$
  - ATLAS (resolved): Eur. Phys. J. C 81 (2021) 178
  - ATLAS (boosted): Phys. Lett. B 816 (2021) 13204
  - ATLAS (combination): ATLAS-CONF-2021-051
- $H \to \mu\mu$:
  - ATLAS: JHEP 01 (2021) 148
  - CMS: Phys. Lett. B 812 (2021) 135980
- $H \to Z\gamma$
  - ATLAS: Phys. Lett. B 809 (2020) 135754
  - CMS: CMS-PAG-HIG-19-014

$H \to \gamma\gamma$ analysis (CMS)

JHEP 2017 (2021) 027

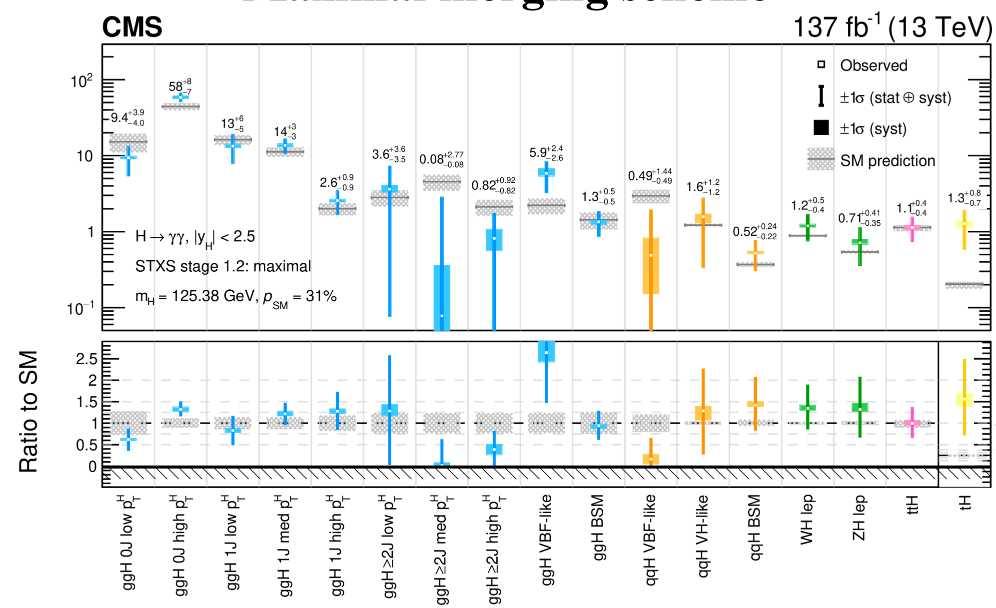
Minimal merging scheme



ggH and qqH STXS bins are merged together

- **Maximal merging scheme**: STXS bins merged until their expected unc is < 150%;
- **Minimal merging scheme**: STXS bins merged ensuring that parameters do not become too anti-correlated (<90%)

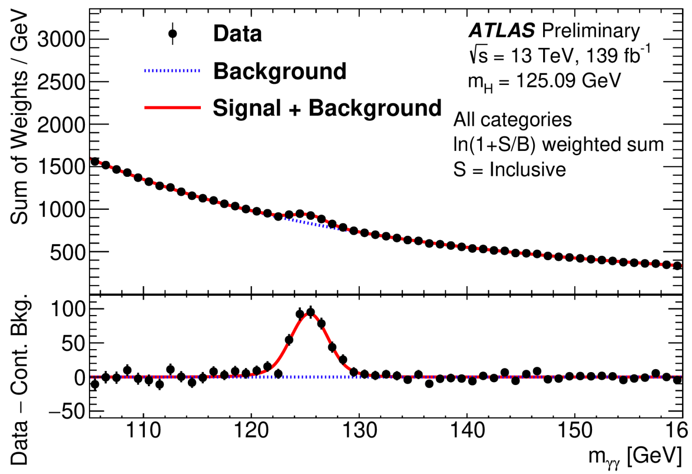
Maximal merging scheme

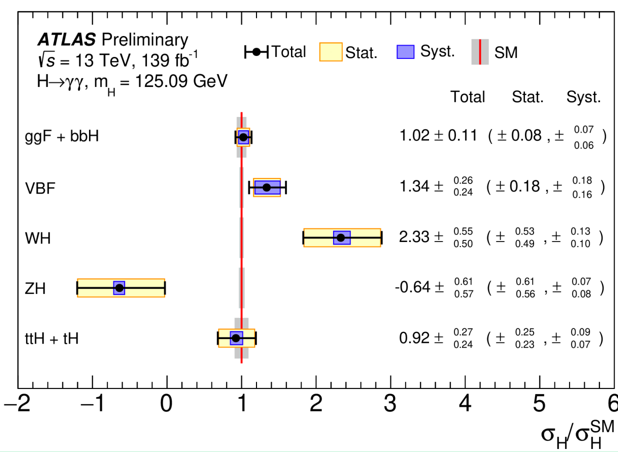


$H \to \gamma\gamma$ analysis (ATLAS)

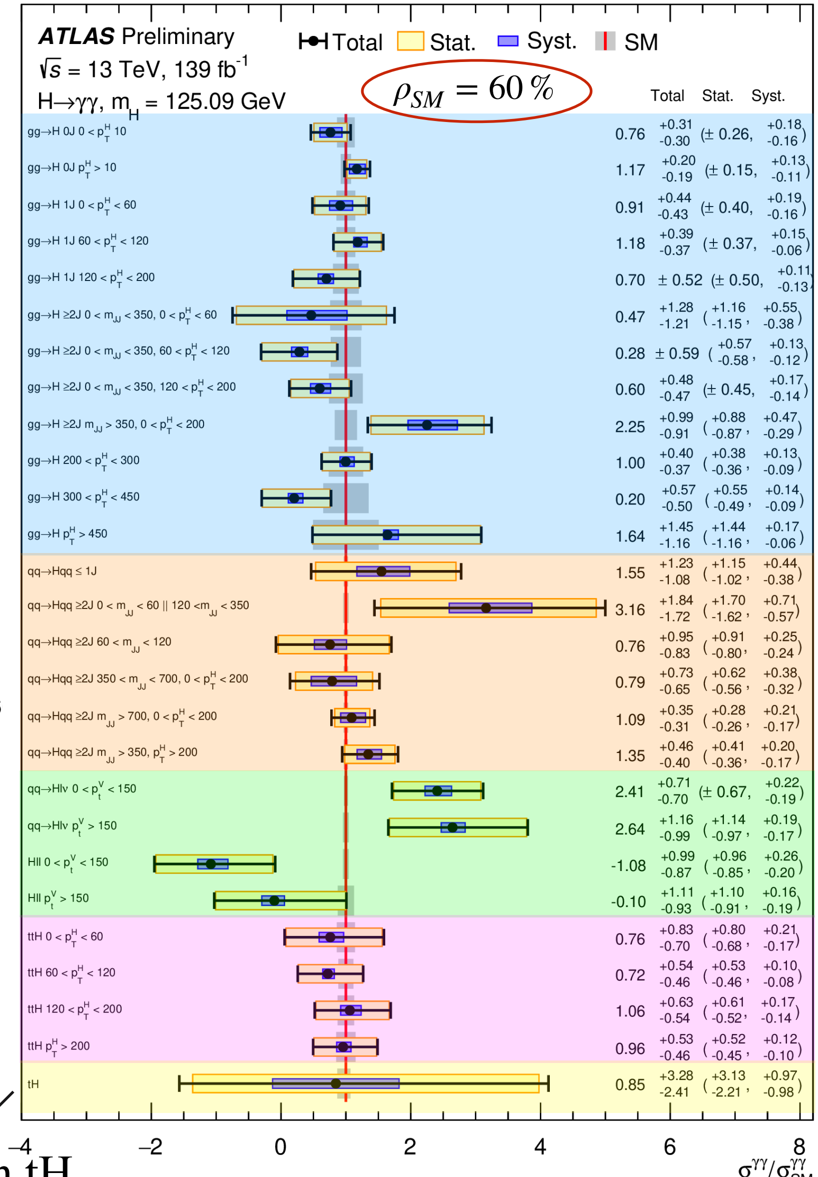
[ATLAS-CONF-2020-026]

- Events with **at least 2 photons**
- MVA techniques to categorize the events and discriminate signal from bkgs.





Strong correlation between WH and ZH (O(40%))



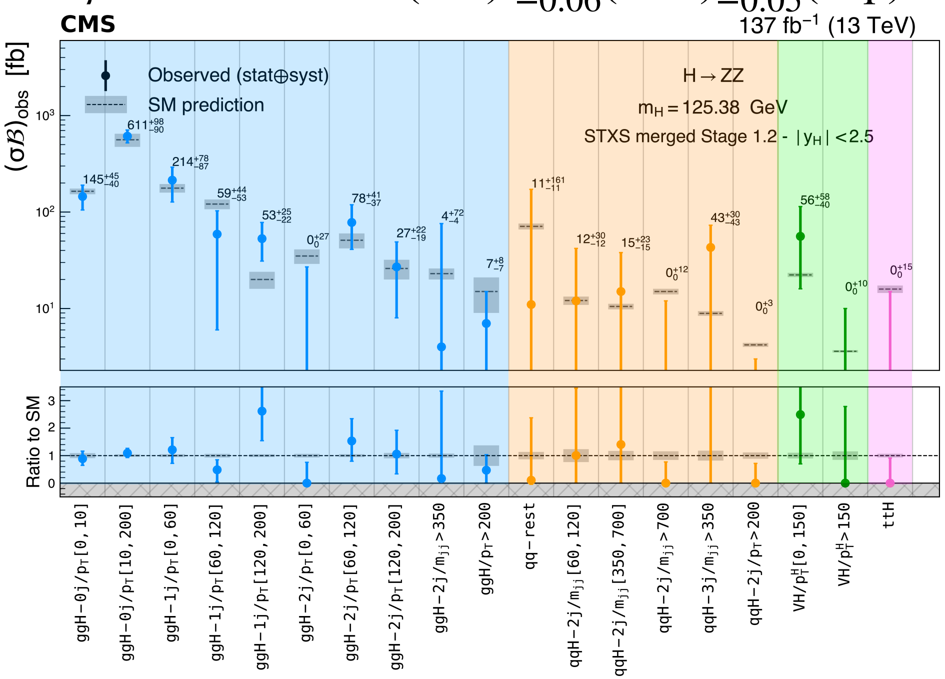
Upper limit on tH

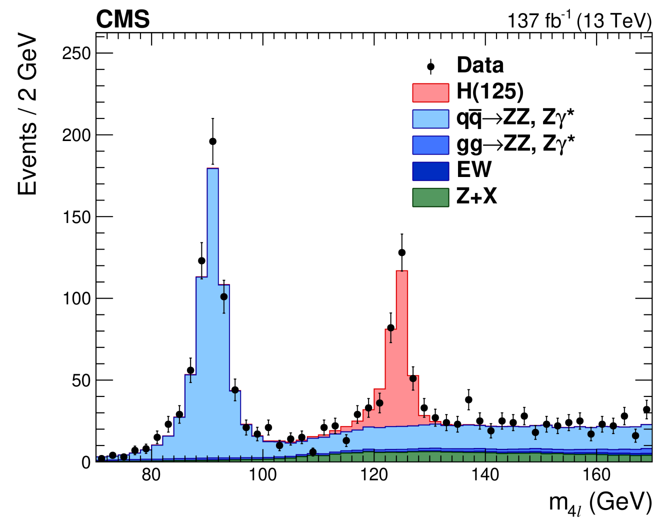
$H \rightarrow ZZ \rightarrow 4l$ (CMS)

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

- Events with **same flavor**, **opposite sign lepton pairs** form the Higgs candidate
  - **Clear signature** → targets **all the production modes** except for *tH*;
- Combined results from *ZZ* decays channels: 4*e*, 4*μ*, 2*e*2*μ*;
- Events categorized according to # jets, # *b*-tagged jets and # additional leptons →**22 event categories**
- **Dominant irreducible background**: *ZZ**
- **Unbinned likelihood fit**

$$\mu = 0.94 \pm 0.07\ (\text{stat})\ {}^{+0.07}_{-0.06}(\text{theo}){}^{+0.06}_{-0.05}(\text{exp})$$





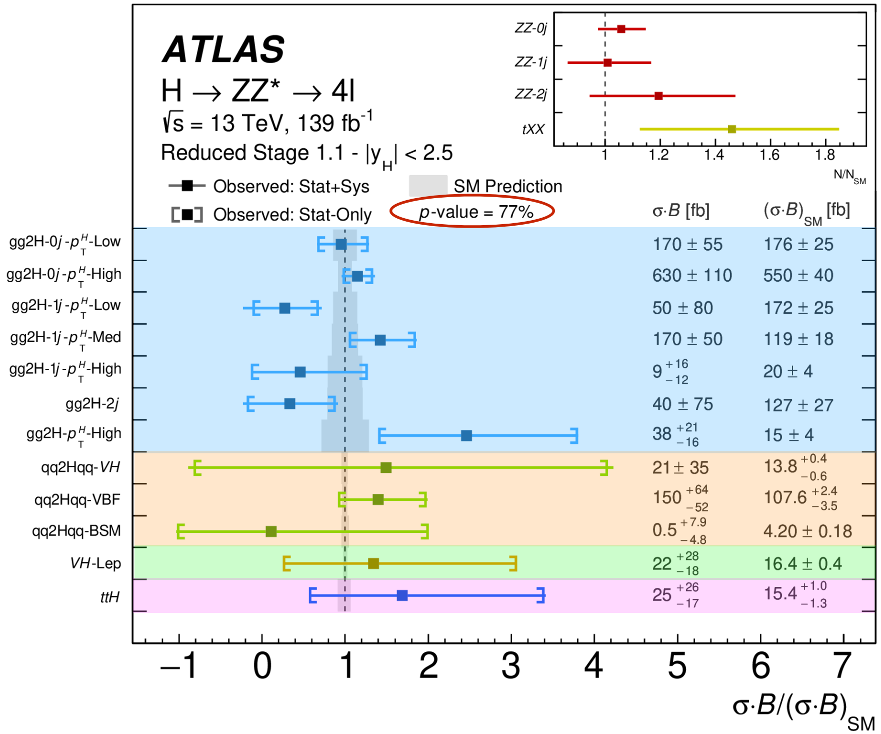
- STXS measurements in 19 STXS bins.
  - **Statistically limited channel** → coarse bins
  - **Results consistent with the SM predictions.**

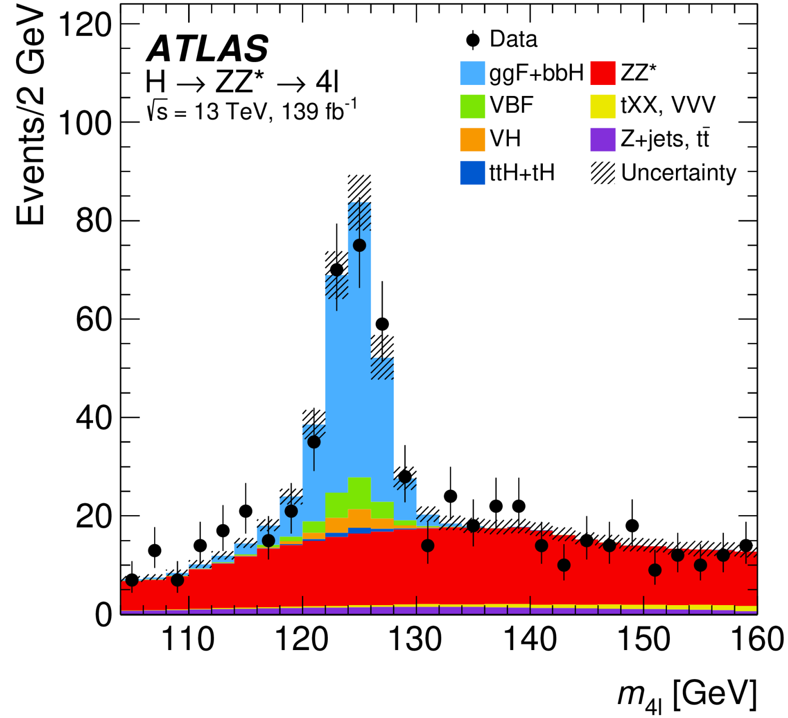
$H \to ZZ \to 4l$ (ATLAS)

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

- Clean signature - fully reconstructed final states - and high S/B
- Events with **same flavor**, **opposite sign lepton** (ℓ=e,μ) **pairs** form the Higgs candidate
- MVA technique to define analysis categories
- Likelihood fit

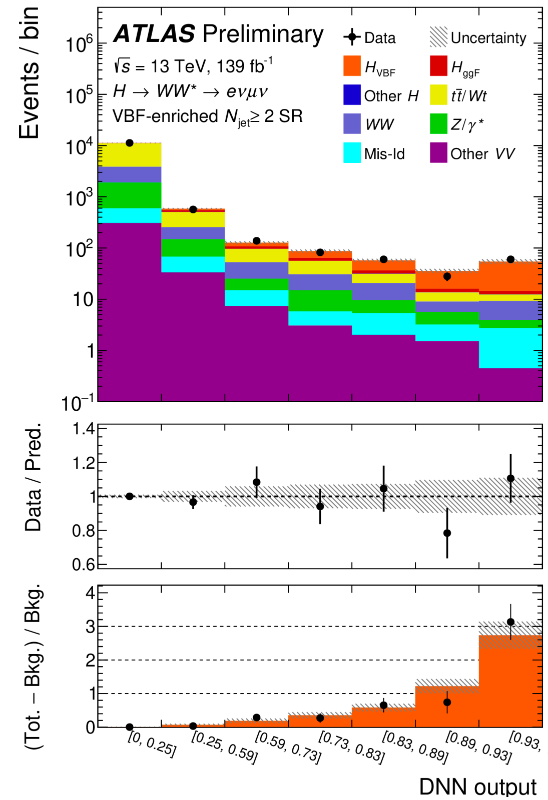
$\mu = 1.01 \pm 0.08(\text{stat}) \pm 0.04(\text{exp}) \pm 0.05(\text{theo})$





$H \rightarrow WW \rightarrow e\nu\mu\nu$ (ATLAS)

ATLAS-CONF-2021-014



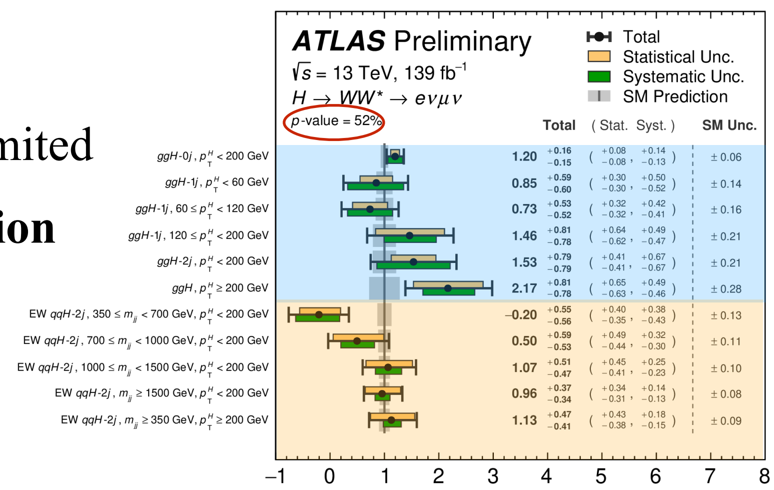
- Analysis targets **VBF** and **ggF production modes**
- Final state with **2 charged leptons** with **different flavor** and **opposite charge**.
- **Control regions (CRs)** to extract normalization of the **dominant bkgs** (WW, $t\bar{t}$/W$\bar{t}$, Z/γ*)
- Profiled likelihood fit to data:

$$\mu_{ggF} = 1.20 \pm 0.05\,(\text{stat})^{+0.09}_{-0.08}(\text{exp systs})^{+0.10}_{-0.08}(\text{sig theo})^{+0.12}_{-0.11}(\text{bkg theo})$$

$$\mu_{VBF} = 0.99\,^{+0.13}_{-0.12}\,(\text{stat})^{+0.07}_{-0.06}(\text{exp systs})^{+0.17}_{-0.12}(\text{sig theo})^{+0.10}_{-0.08}(\text{bkg theo})$$

$\Longrightarrow$ measurements **dominated by systematic sources**

- STXS measurements in 11 STXS bins
  - Most of the STXS bins statistically-limited
  - Results **compatible with SM prediction**



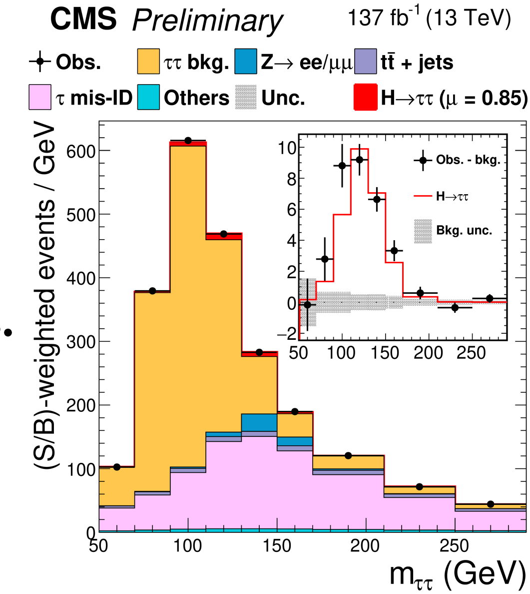
$H \rightarrow \tau\tau$ analysis (CMS)

CMS-PAS-HIG-19-010

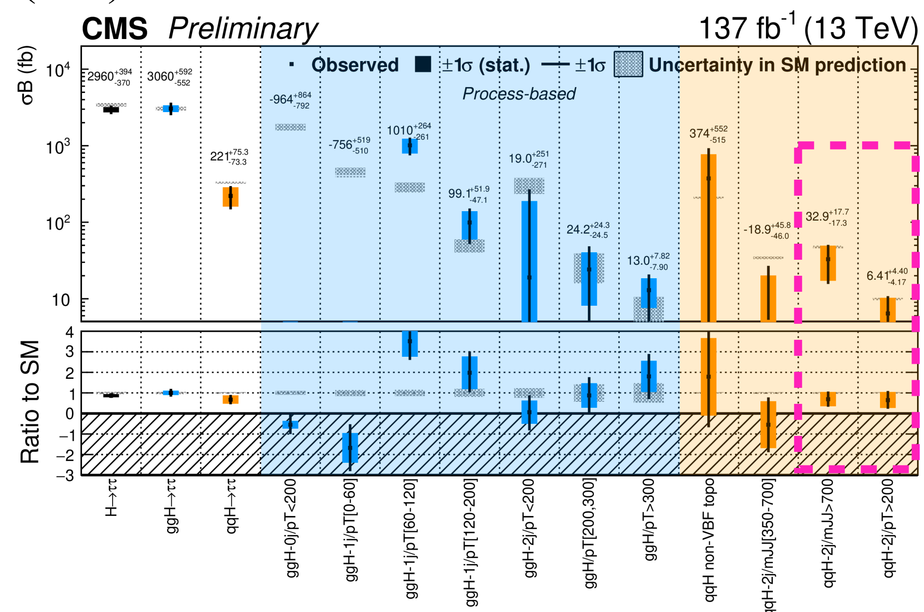
- Analysis **targets** primarily **ggF** and **VBF**
- Events classification: $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$.
- MVA techniques to reconstruct τ_h and reject fakes.
- **Main bkgs** ($Z\rightarrow\tau\tau$, τ mis-ID) estimated with **data-driven techniques.**
- **Binned maximum likelihood fit** to extract the results:

$$\mu_{ggF} = 0.98^{+0.12}_{-0.09}(\text{theo}) \pm 0.09(\text{stat}) \pm 0.12(\text{syst}) \pm 0.06(\text{bbb})$$

$$\mu_{qqH} = 0.67^{+0.06}_{-0.05}(\text{theo})\boxed{^{+0.19}_{-0.18}(\text{stat})}^{+0.09}_{-0.08}(\text{syst}) \pm 0.08(\text{bbb})$$



- STXS measurements in 11 STXS bins.
  - Results **consistent** with the **SM predictions**.
  - **Good sensitivity** to Higgs produced with **high p_T**
  - Results **dominated** by **stat. uncertainty**



$H \to \mu\mu$ analysis (CMS)

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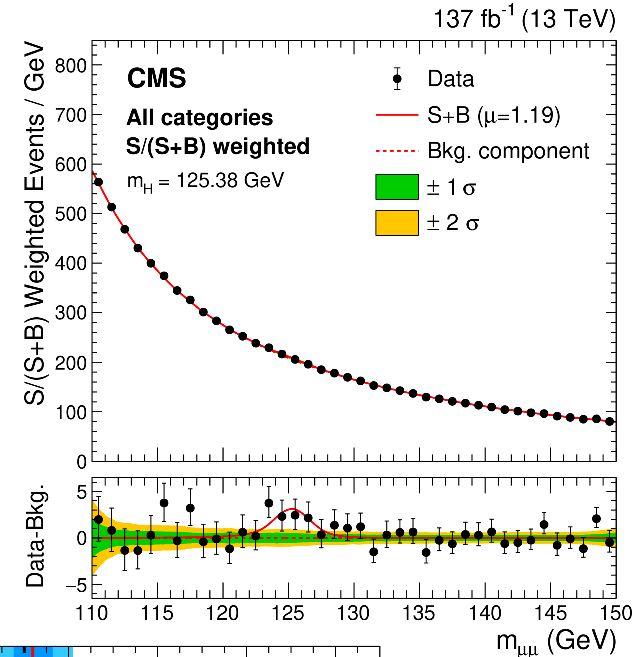
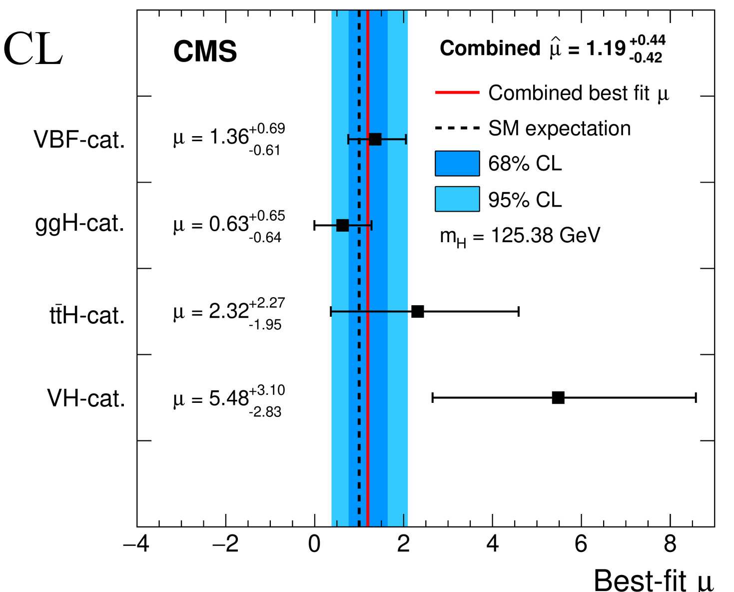


- Analysis **targets all the production modes**;
- Final state with **two muons** → good signal resolution but small branching ratio (~2.2×10^{-4})
- Large **irreducible bkg** from $Z\to\mu\mu$
- **Simultaneous binned-likelihood fit**

$$\mu = 1.19\ ^{+0.41}_{-0.40}(\text{stat})^{+0.17}_{-0.16}(\text{syst})\ [$$

→ Observed (expected) significance 3 (2.5) σ - **Evidence!**

→ Upper limits on BR of 1.9×SM @ 95% CL



$H \rightarrow \mu\mu$ analysis (ATLAS)

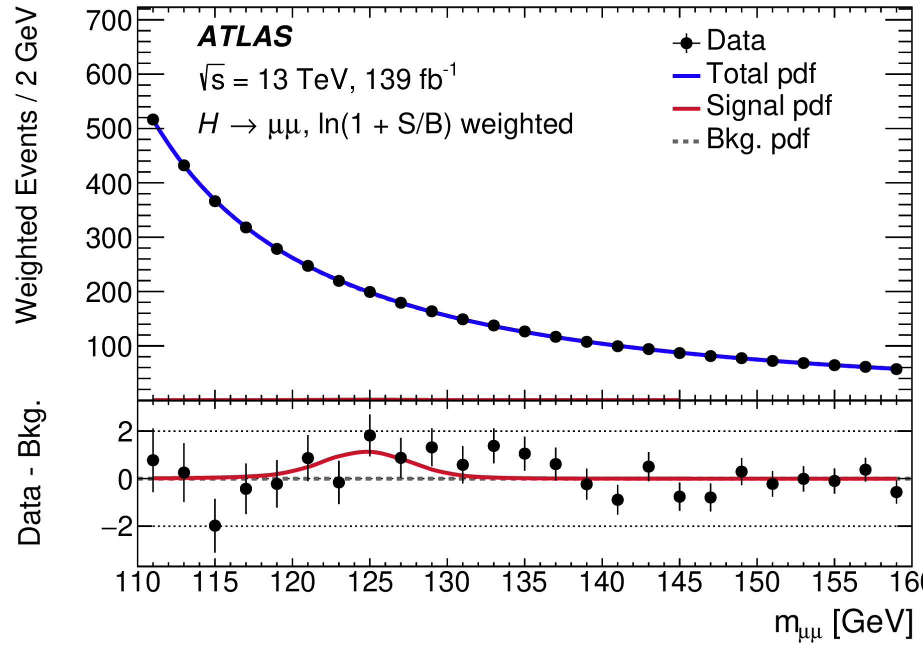
Phys. Lett. B 812 (2021) 135980

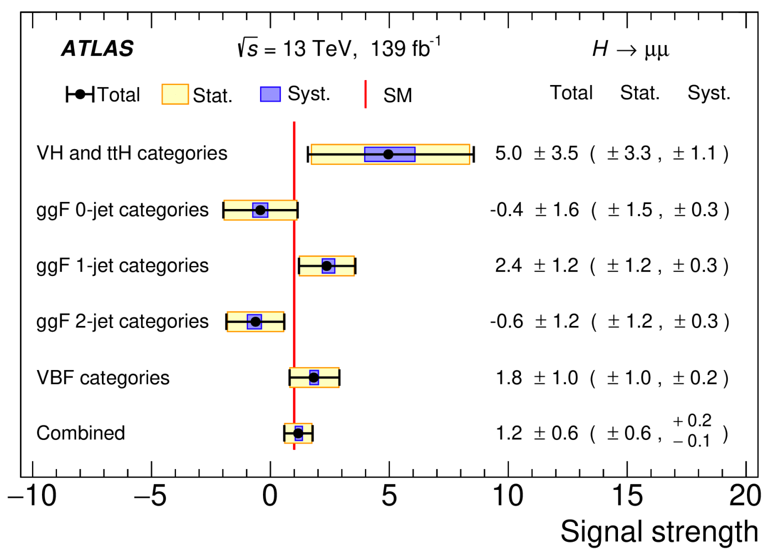
- Analysis **targets all the production modes**;
- Final state with **two muons** → good signal resolution but small branching ratio (~$2.2\text{x}10^{-4}$)
- Large **irreducible bkg** from $Z\rightarrow\mu\mu$
- **Simultaneous binned-likelihood fit** to $m_{\gamma\gamma}$

$$\mu = 1.2 \pm 0.6(\text{stat})^{+0.2}_{-0.1}(\text{syst})$$

→ Observed (expected) significance 2.0σ (1.7σ)

→Upper limits on BR of $4.7\text{x}10^{-4}$





$H \to Z\gamma$ analysis (ATLAS)

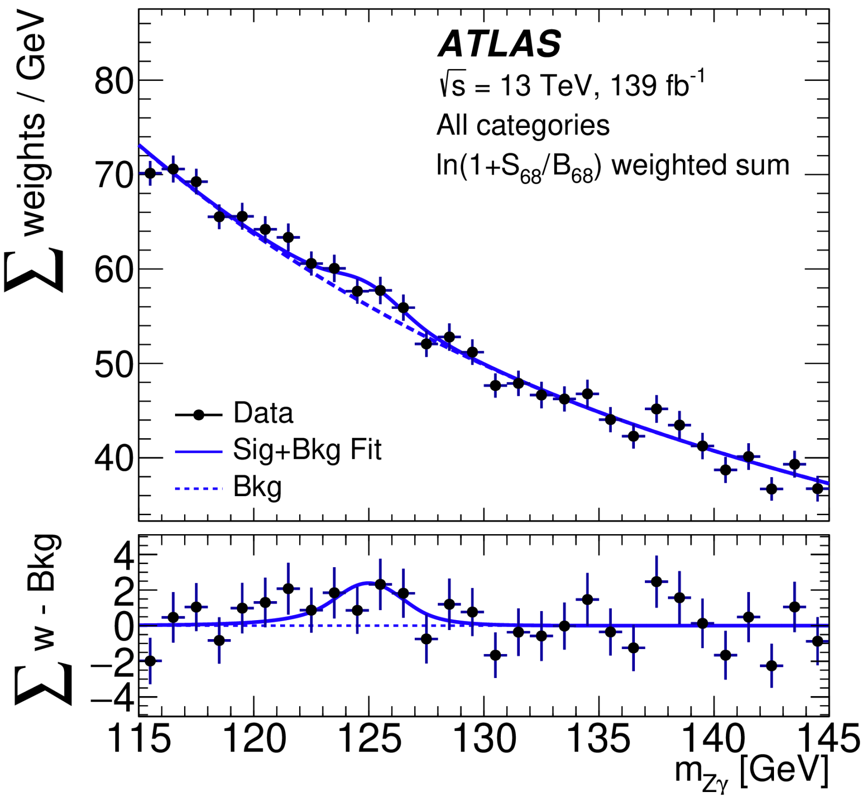
Phys. Lett. B 809 (2020) 135754

- Analysis **targets all the production modes**;
- $BR(H \to Z\gamma) = 1.54 \times 10^{-3}$
- Final state with **one photons** and **two same flavor opposite charge leptons** ($\ell = e,\mu$)
- **MVA techniques to categorise the events**
- **Simultaneous likelihood fit** to all $m_{Z\gamma}$ distributions

$\mu = 2.0 \pm 0.9\ (\text{stat})^{+0.4}_{-0.3}(\text{syst})$

Observed significance of 2.2σ

→ <u>upper limits on $(\sigma \times B)$ of **3.6 x SM**</u>



$H \rightarrow Z\gamma$ analysis (CMS)

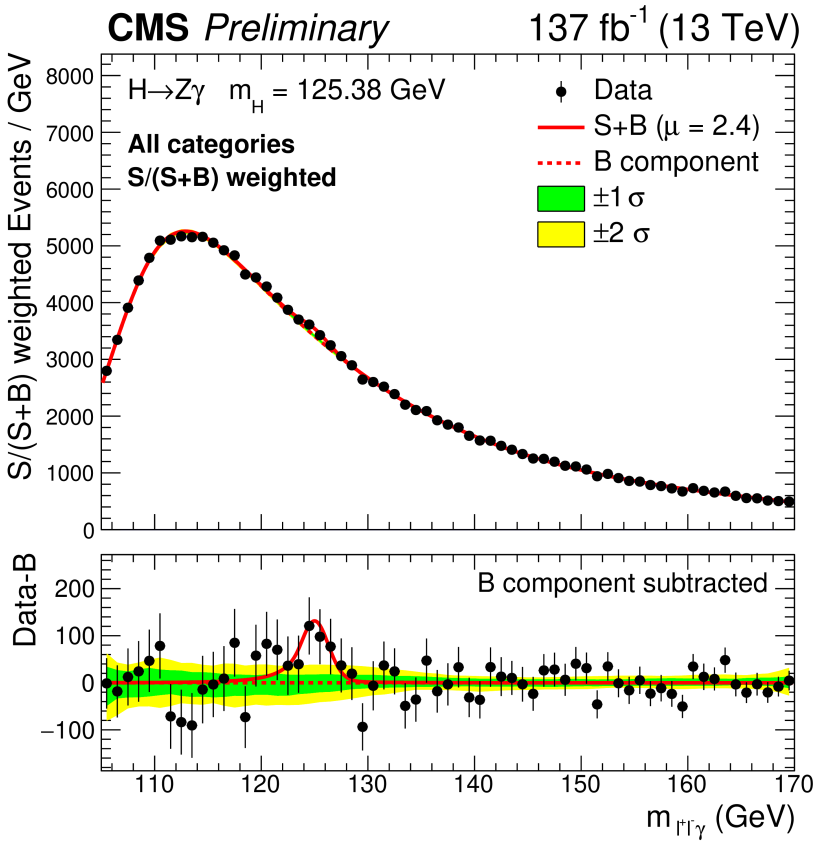
CMS-PAG-HIG-19-014

- Analysis **targets all the production modes**;
- BR($H \rightarrow Z\gamma$) = 1.54×10^{-3}
- Final state with **one photons** and **two same flavor opposite charge leptons** ($\ell = e,\mu$) and $m_{\ell^+\ell^-} > 50$ GeV
- **Binned-maximum likelihood fit** to all $m_{Z\gamma}$ distribution

$\mu = 2.4 \pm {}^{+0.8}_{-0.9}$ (stat)${}^{+0.3}_{-0.2}$(syst)

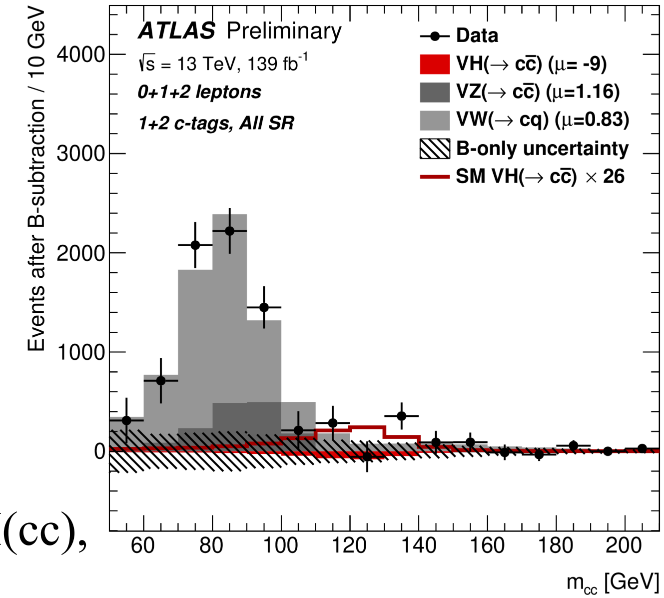
Observed (expected) significance of 2.7 (1.2) σ

→ upper limits on ($\sigma \times B$) of **4.1 x SM** @95% CL



$H \rightarrow cc$ analysis (ATLAS)

ATLAS-CONF-2021-021



- BR($H \rightarrow cc$) = 3%
- Search in **VH production mode**
- Categorization depending on the decay of the vector boson
- Events with at least one c-jet + b-veto
- Final discriminant m_{cc}
- **Simultaneous binned-likelihood fit** to signal strength of VH(cc), VZ(cc) and VW(cq)

$\mu_{VH(cc)}$ = -9 ± 10(stat)$^{+12}_{-11}$(syst) → compatibility with SM: 83%

- Observed VH(cc) limit of **26 x SM** → **best limit on VH(cc) yet!**
- Diboson cross-check measurements:
  - VZ(cc) significance of **2.6σ**
  - VW(cq) significance of **3.8σ**

→ *First measurement of VZ(cc) and VW(cq) using c-tagging!*