Universidad de Oviedo
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ICTEA
Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias

CERN 10 years HIGGS boson discovery

Higgs to fermion decays

J. Cuevas
U. Oviedo (Spain)

12th International Workshop on the CKM Unitarity Triangle
September 18 to 22, 2023
Santiago de Compostela, Spain.

ATLAS Higgs results: papers, conference notes

CMS Higgs results: papers, preliminary results

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GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

EUROPEAN UNION European Regional Development Fund

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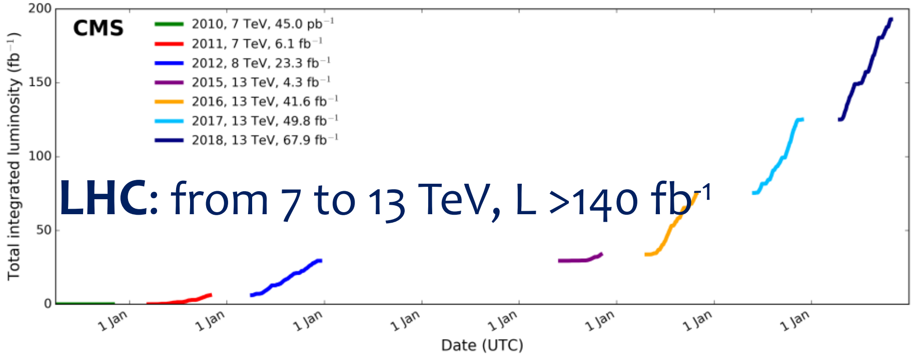
The long road of the Higgs boson: a worldwide effort

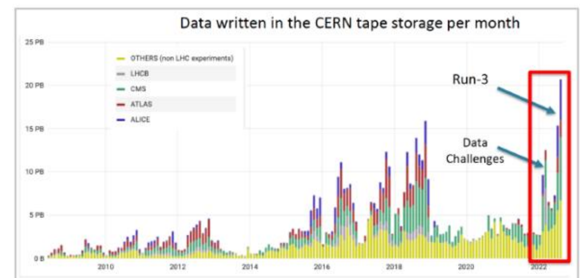


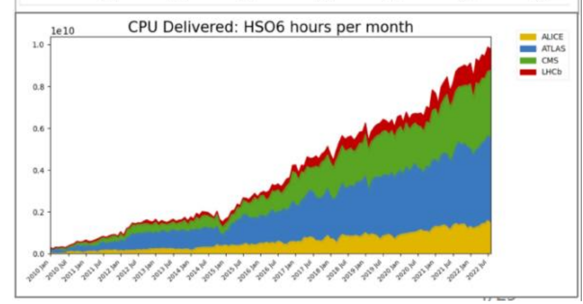
LHC: from 7 to 13 TeV, L >140 fb^{-1}

Run2 wrt Run1, Lumi ×10 more

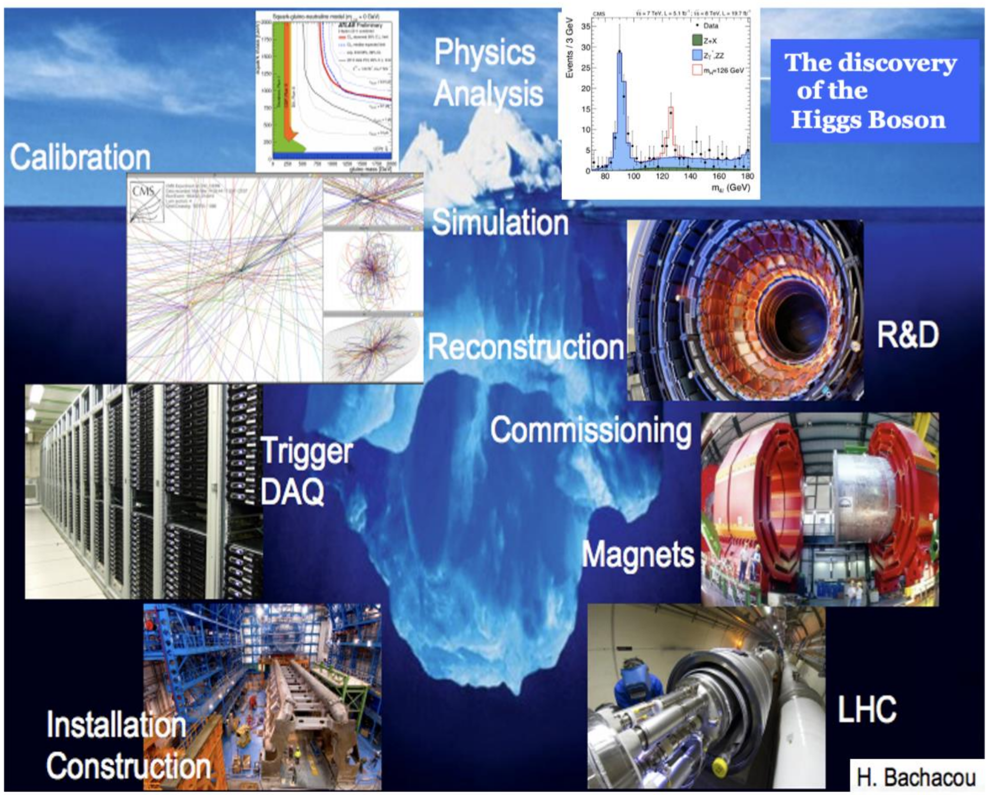
σ ×2–4 larger, **Higgs ×30 more**

The WLCG

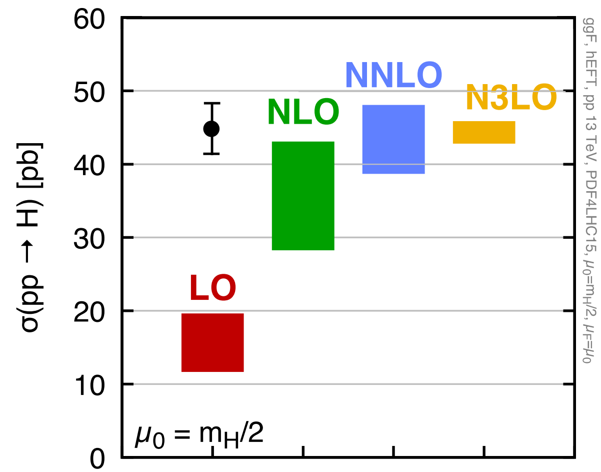




Superb detector performance



The LHCHXSWG



Introduction and Outline

- The discovery of the Higgs boson in 2012 by ATLAS and CMS fulfilled one of the main aims of the LHC:
  - **Identifying a mass generation mechanism for the SM**
- It has given us access to a new sector of the SM with new lines of enquiry to follow:
  - **Yukawa couplings, a new type of interaction to investigate**
  - Gauge–scalar boson interactions
  - The parameters of the Higgs potential, and its self coupling
- No direct observation of new physics at the LHC after the Higgs boson discovery
- **Precision measurements of the Higgs are increasingly important and in various aspects drive the future of HEP**
- Properties of the new scalar particle at LHC **in this talk**:
  - Standard Model Higgs Boson Cross Sections and Branching Fractions, STXS, differential measurements, EFT interpretations.
  - **Couplings to fermions and to the top quark**
  - **Couplings to second generation**
  - **See also Maria Moreno´s talk on Higgs CP:** https://indico.cern.ch/event/1184945/timetable/?view=standard#14-single-top-measurements-inc

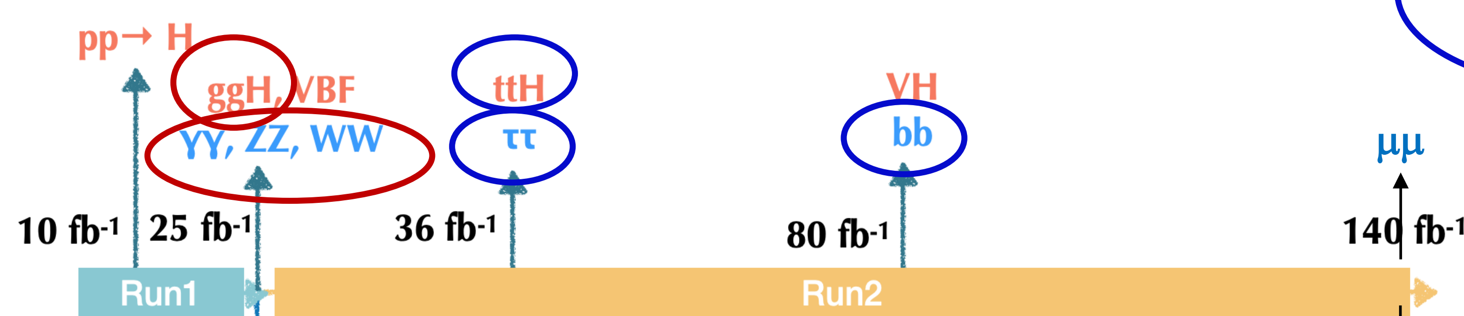
From the 4 of July 2012 to the end of Run2

~ 5% precision per exp.

Higgs story at the LHC

Main production: ggH, VBF, VH, ttH
Main decay: γγ, ZZ, WW, ττ, bb

~10% precision per exp.



width
fiducial xsec
STXS

STXS stage0,1

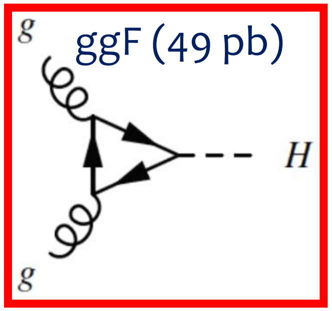
width, lifetime, fiducial xsec

mass, Spin CP, anomalous couplings

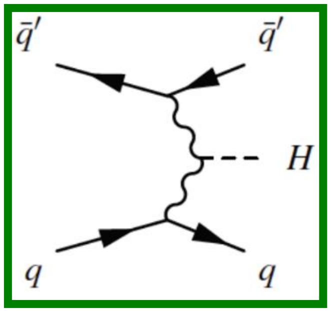
More precision on Higgs properties
New Combined Fits with all data
Observation of H→ττ
Direct observation of ttH production
Observation of H→bb
Evidence for H→$\mu\mu$ (second generation fermions)
Detailed CP analysis eg in H→VV & H→ττ
Differential distributions/STXS event classification…

Zγ
Dalitz llγ

SM Higgs Production and decay at the LHC

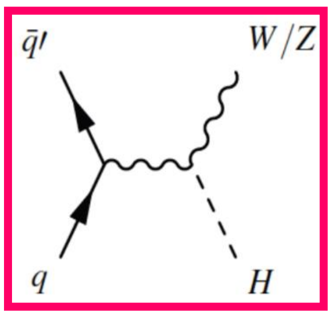


Gluon Fusion
(WH 1.4 pb, ZH 0.9 pb)

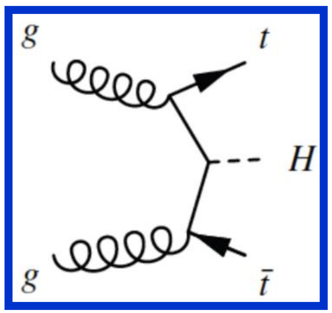


VBF 3.8 pb

Vector-Boson Fusion

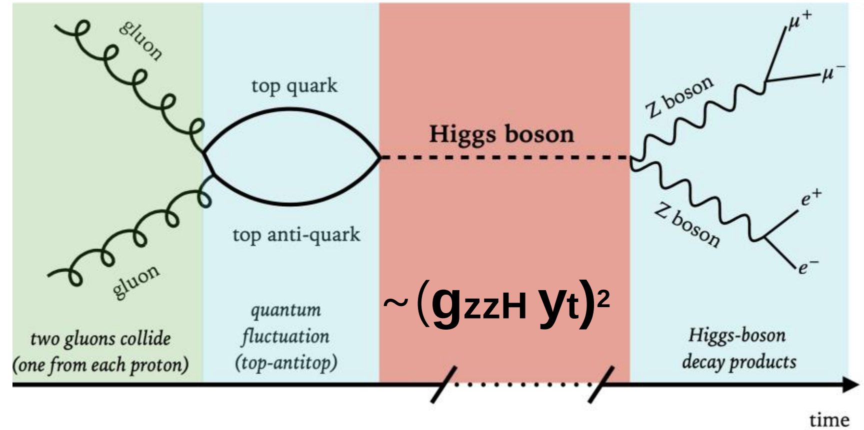


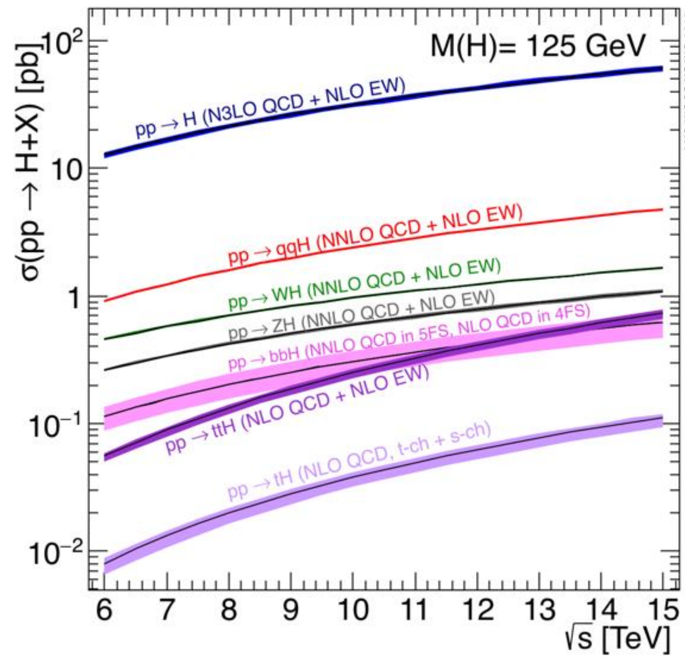
Higgs-strahlung



ttH (0.5 pb)

Top Fusion ($t\bar{t}H$)





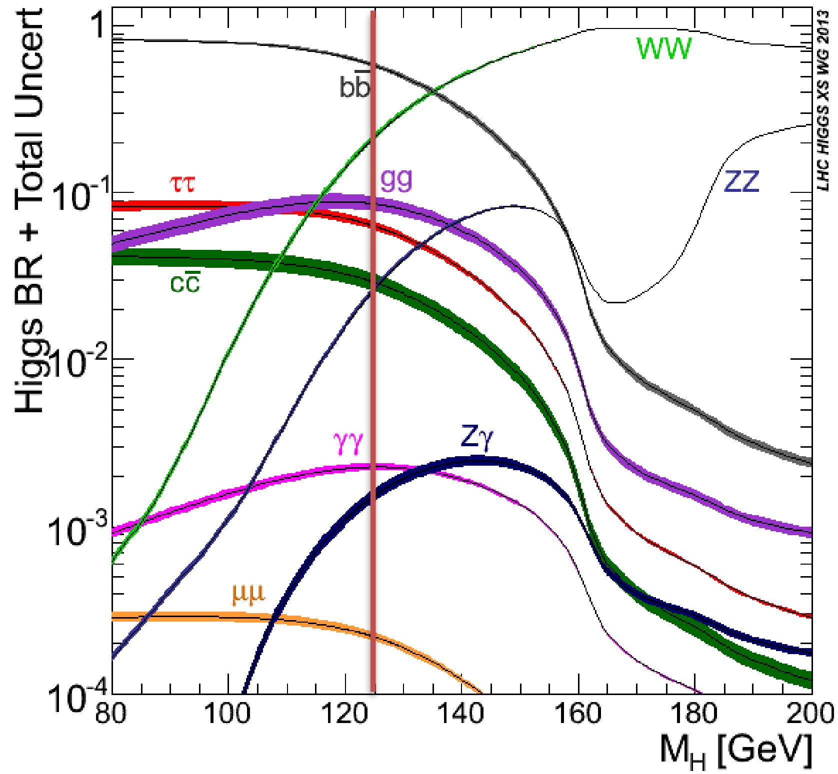
LHC in 2012 at (the old) record luminosity (7×10^{33} $cm^{-2}s^{-1}$) and energy (8 TeV) was producing SM Higgs bosons (M_H = 125 GeV) at a rate **~750/hr**

Decay of the Higgs Boson

Need **multi-purpose detectors** like ATLAS and CMS to find the Higgs boson and measure its properties at the LHC!

Had the Higgs boson been 50 GeV heavier, it would have been impossible to detect more than just two channels ZZ and WW

Had the Higgs been just 10 GeV lighter, the decays to WW and ZZ would have been impossible so far…



Only region in m_H where:

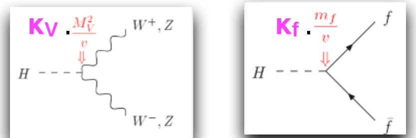
- very good combination of signal-strength for the whole set of decay channels below the top-antitop threshold
- Cross sections are large
- **Fermion decays (bb+ττ) are accessible**
- Natural width is negligible

The portrait of the Higgs boson

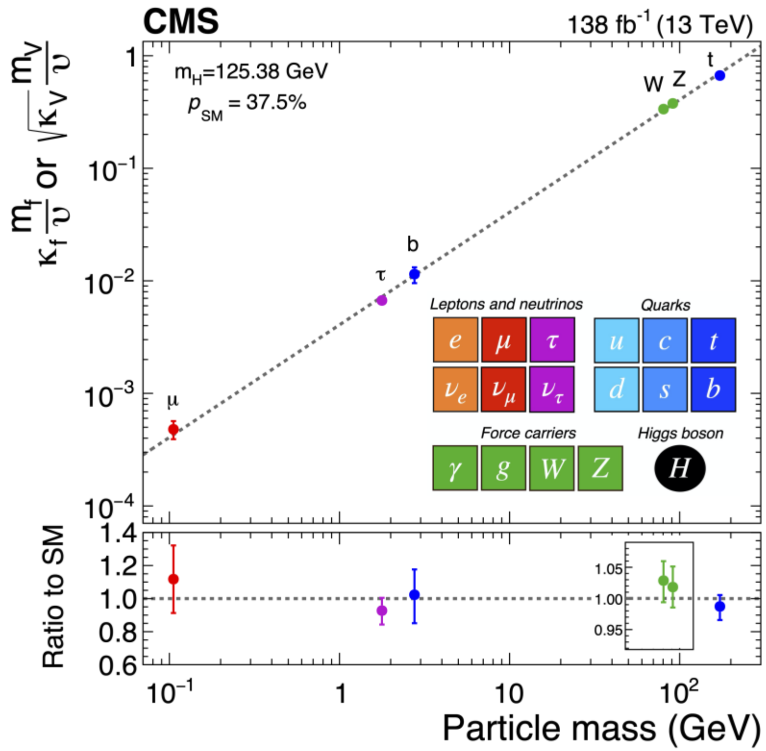
ATLAS:
Nature 607 (2022) 52

CMS:
Nature 607 (2022) 60

Coupling modifier interpretation



$$\sigma(i \rightarrow H \rightarrow f) = \sigma_i B_f = \frac{\sigma_i(\boldsymbol{\kappa})\Gamma_f(\boldsymbol{\kappa})}{\Gamma_H(\boldsymbol{\kappa}, B_{\text{inv.}}, B_{\text{u.}})}$$



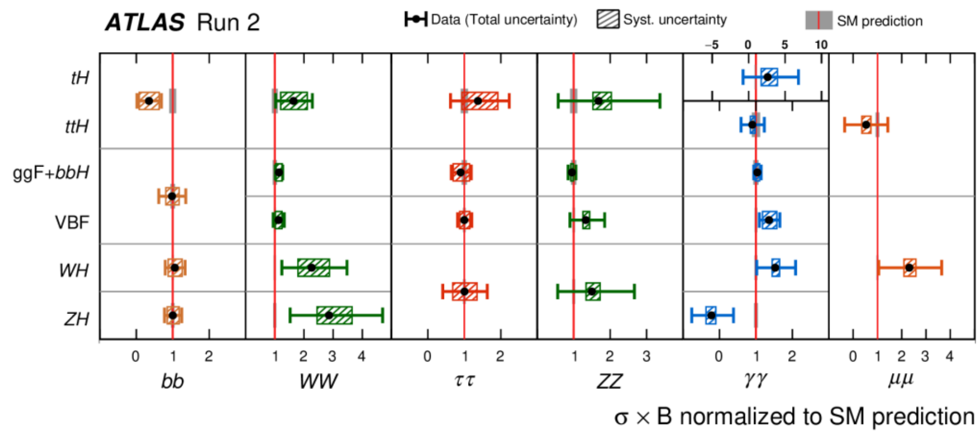
The Higgs couples with the particle mass

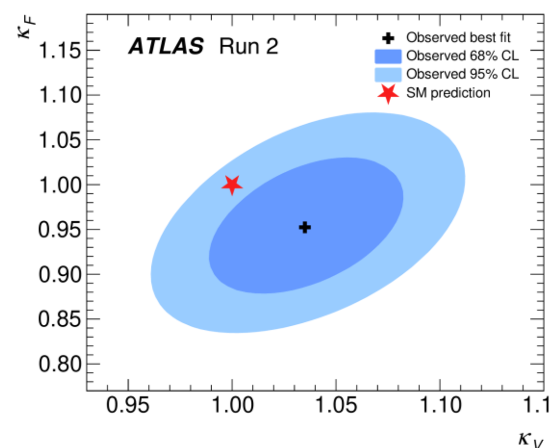
SM test over many orders of magnitude

Total cross-section / Standard Model prediction

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$

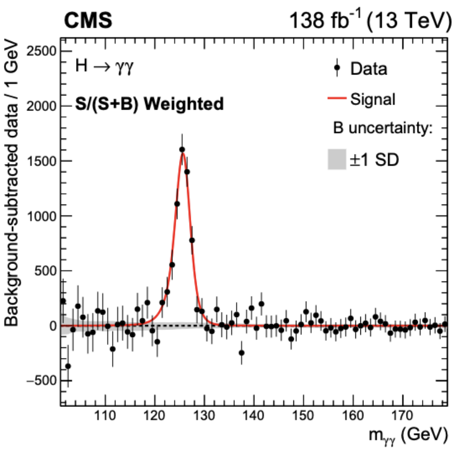
Ratio of observed rate to predicted SM event rate for different combinations of Higgs boson production and decay processes.

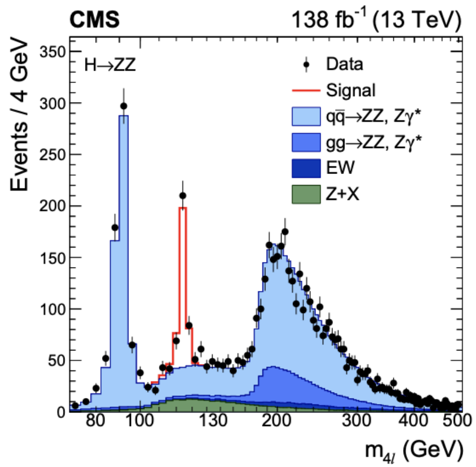


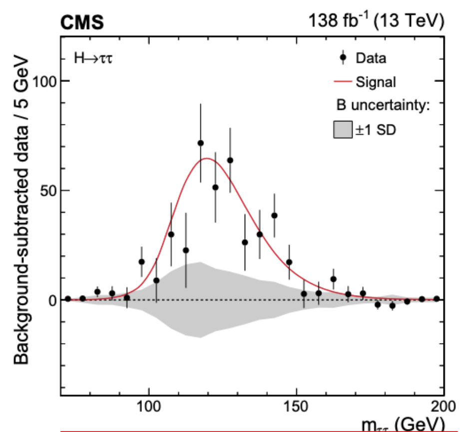


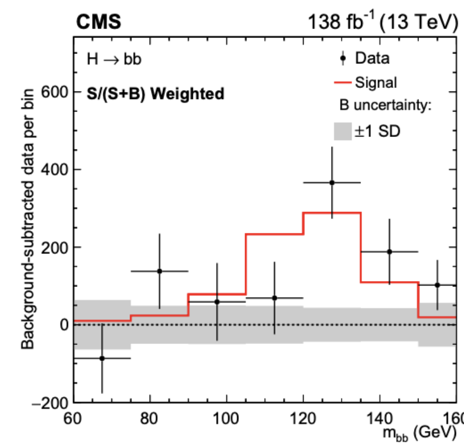
Bosonic channels   Fermionic channels

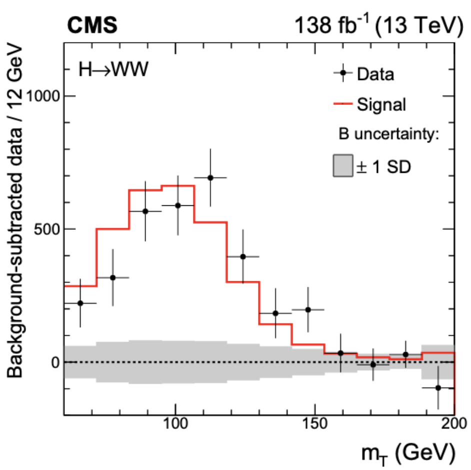
- The discovery channels: $\gamma\gamma$, ZZ (high sensitivity, high resolution),WW, (high sensitivity, low resolution) dominated Run 1 results., precision in Run 2.
- H -> bb (low sensitivity, low resolution) observed during Run 2.

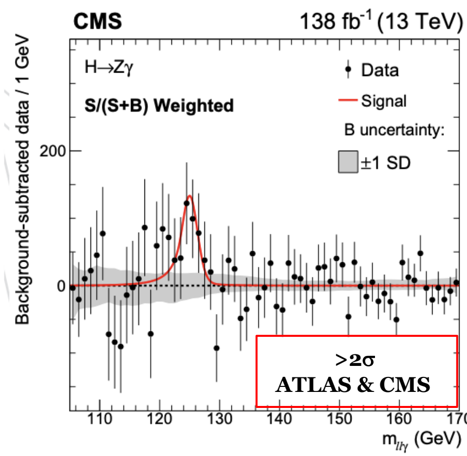




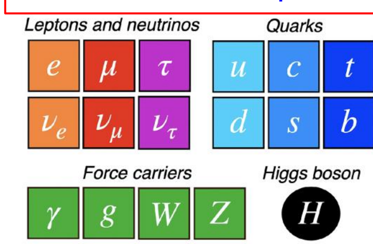


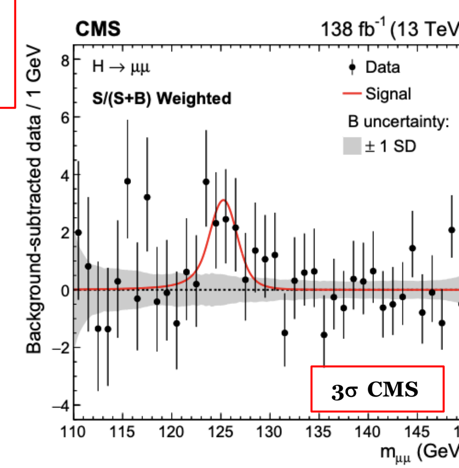






These are the CMS Run-2 legacy results!
Full run-2 data sample



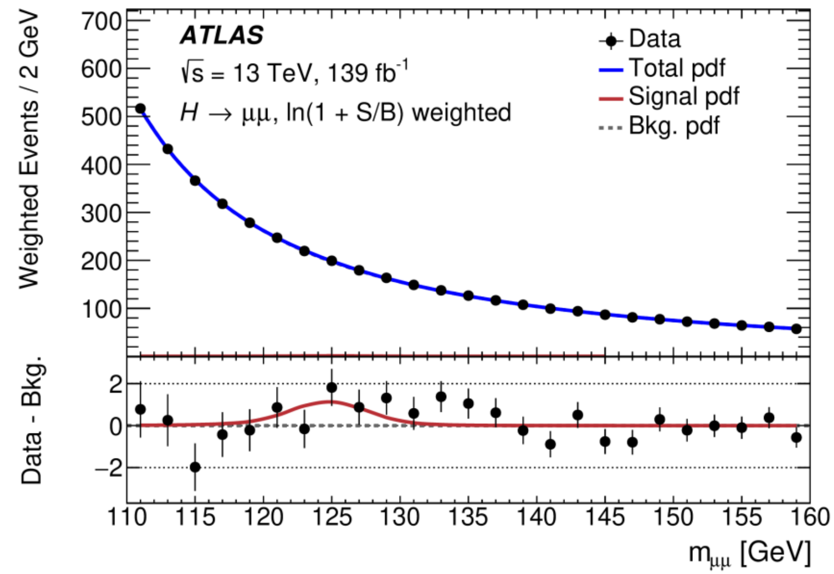


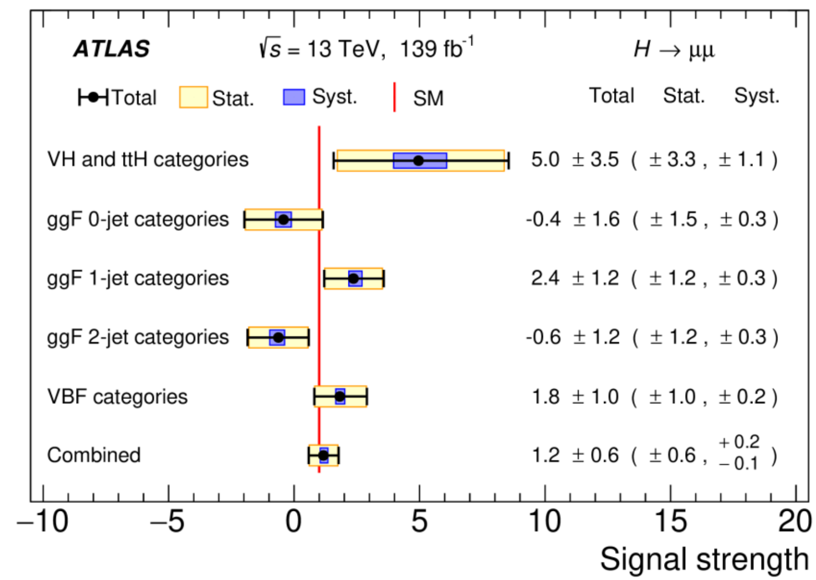
Nature 607, 60-68 (2022)

ATLAS: Couplings to 2nd generation: $H \rightarrow \mu\mu$

PLB 812 (2021) 135980

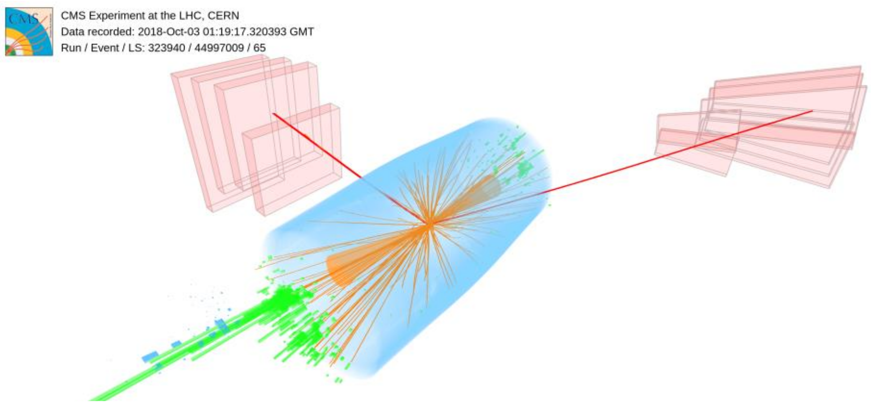
- **$BR_{SM}(H \rightarrow \mu\mu) = 2.17 \times 10^{-4}$**, and large irreducible DY $\rightarrow \mu\mu$ background
  - S/B ~ 0.2% for inclusive events at 125 GeV
- **To increase sensitivity:**
  - MVA categorization to select events at high S/B, e.g. from VBF
  - New FSR recovery to improve $\sigma(m_{\mu\mu})$
  - Rejection of jets from pileup
- **Signal extraction from $m_{\mu\mu}$ fit**
  - background parametrization: inclusive "core" pdf + per-category empirical transfer function (with less free parameters)

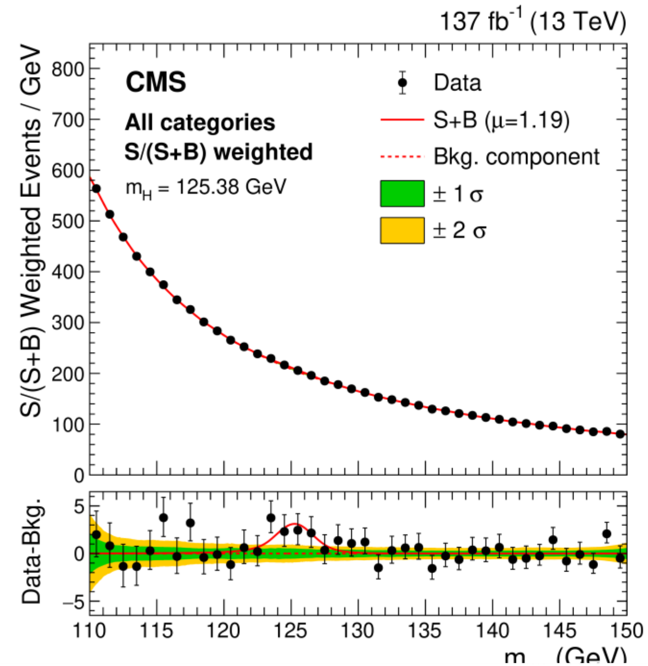




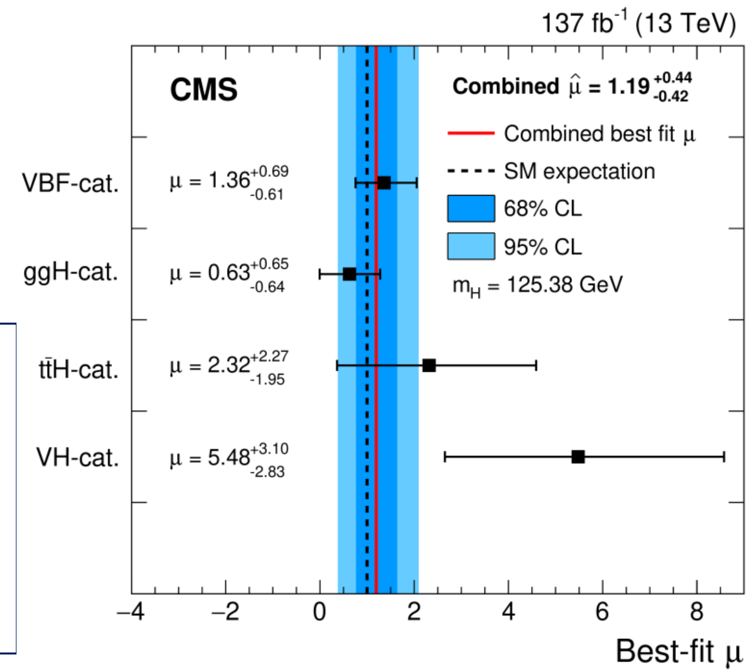
Signal strength: $\mu = 1.2 \pm 0.6$
Significance: 2.0 obs. (1.7 exp.) σ
Observed BR limit at 95% CL < 4.7×10^{-4}

CMS: H⟶ μμ JHEP 01 (2021) 148





- **Yukawa couplings between H and muons**
  - **Trigger: Single Muon**
- **Multiple categories targeting different Higgs production modes**
- **Main channels: ggH and VBF productions**



- **Signal strength: $\mu = 1.19^{+0.44}_{-0.42}$**
- **$0.85 < k\mu < 1.29$**
- **First evidence of H decay to muons (3.0 std dev)**

ATLAS: H → ττ

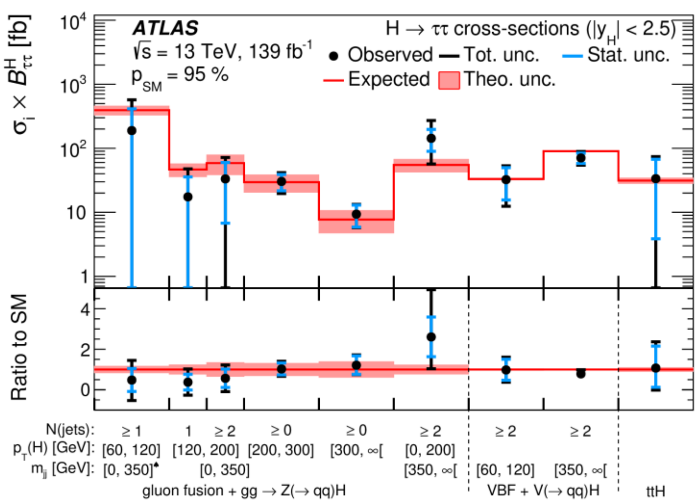
Direct measurement of coupling to the 3rd gen leptons.

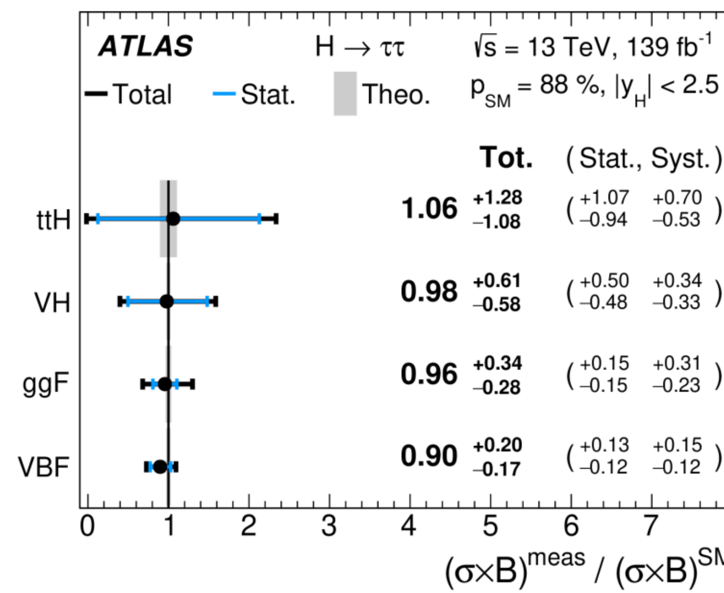
ATLAS: [J. High Energ. Phys. 2022, 175 (2022).]

- Three decay channels considered: $\tau_{had}\tau_{had}, \tau_{had}\tau_{e,\mu}, \tau_e\tau_\mu$
- Targets various production modes, with good sensitivity to VBF in high mass and ggF
- Z→ ττ (leading bkg) normalization determined from Z→*ll* data samples using the "Embedding" technique
- Signal extracted from fit to **Missing mass calculator** (MMC) mass in bins of BDT.

Main sources of uncertainties: **Signal theory, Jets, MET**

Inclusive H → ττ cross-section measured with 13% precision, and 9 STXS bins were measured





CMS: $H \to \tau\tau$

CMS: [Eur. Phys. J. C 83 (2023) 562]

VH analysis

Final states based on the vector boson decay mode

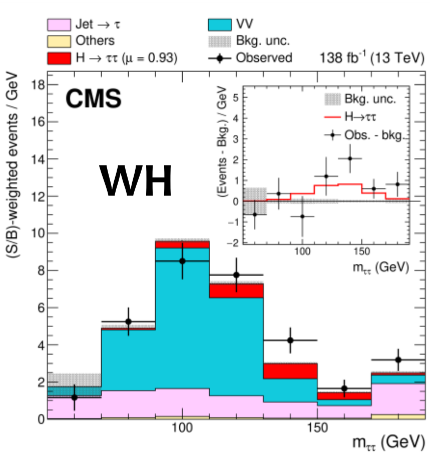
- 1 lepton ($W \to e\nu, W \to \mu\nu$)
- 2 leptons ($Z \to ee, ZZ \to \mu\mu$)

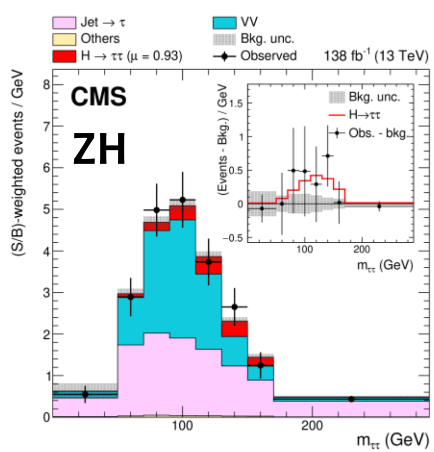
and three final states of

$H \to \tau\tau$: $\tau_{had}\tau_{had}, \tau_{had}\tau_{e}, \tau_{had}\tau_{\mu}$

Dominant background: $W(\ell\nu)Z(\tau\tau)$ for WH and $ZZ \to 4\ell$ for ZH

2D distributions with $m_{\tau\tau}$ and p_T of vector boson



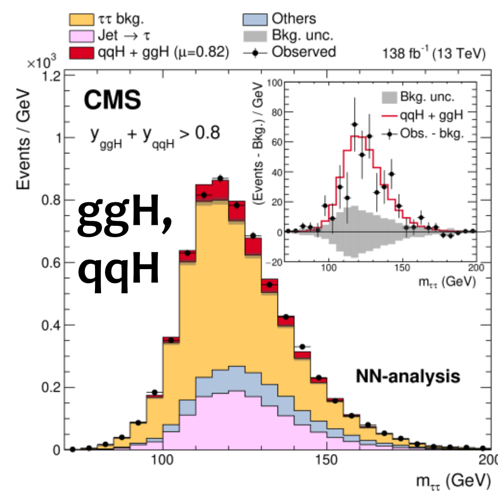


qqH, ggH analysis

Final states: **$\tau_e\tau_\mu, \tau_{had}\tau_e, \tau_{had}\tau_\mu, \tau_{had}\tau_{had}$**

Neural network multi classification with 15 signal classes and 5 background processes

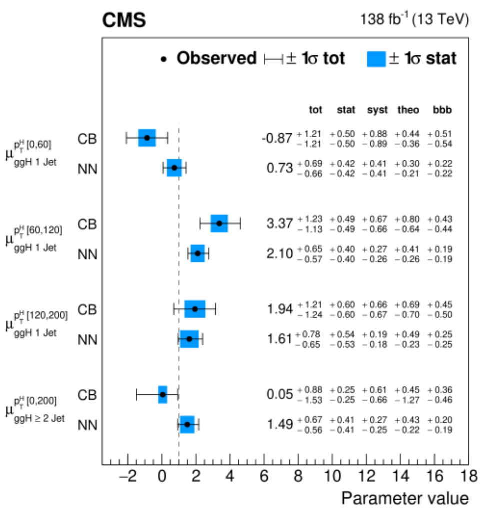
Dominant backgrounds: Z+jets, W+jets, tt, and QCD multijet

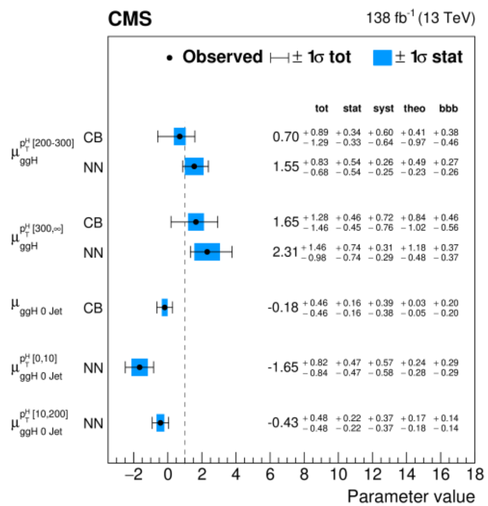


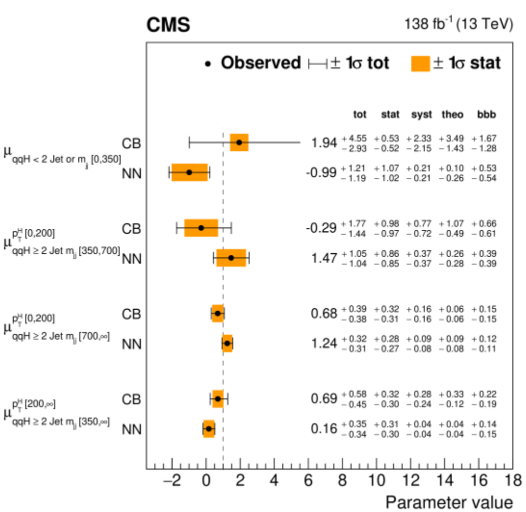
Inclusive signal strength: $\boldsymbol{\mu_{incl} = 0.82_{-0.10}^{+0.11}}$ compatible with SM expectation within 2σ

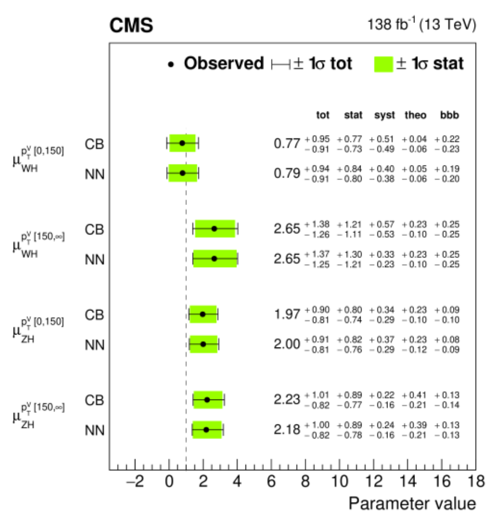
CMS: H → ττ STXS and couplings

STXS measurement performed in a total of 16 STXS bins, Signal compatible with SM expectation







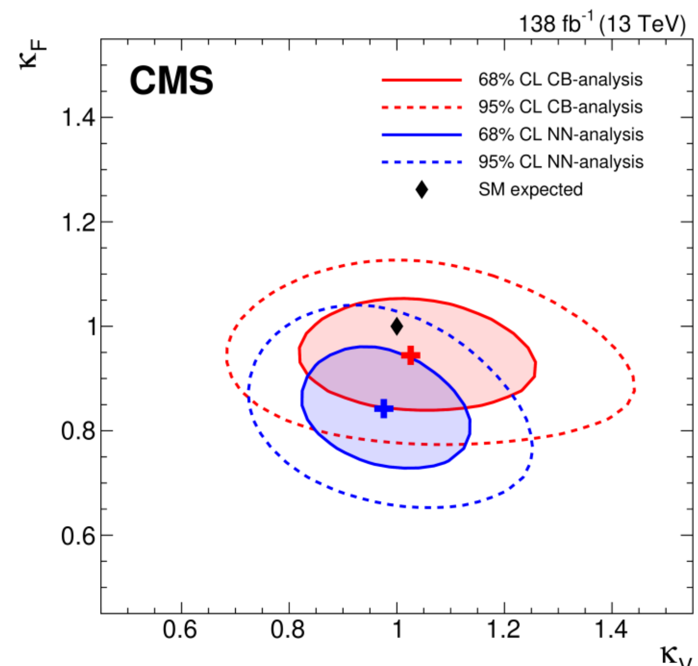


Higgs coupling to fermions (κ_F) and vector bosons (κ_V)

$H \rightarrow WW$ treated as signal

$\boldsymbol{\kappa_V}$ close to one, $\boldsymbol{\kappa_F}$ 15% lower than SM expectation

2D fit result is consistent with signal strengths shown in the left.



CMS: Boosted $H \rightarrow \tau\tau$

CMS PAS HIG-21-017 (new)

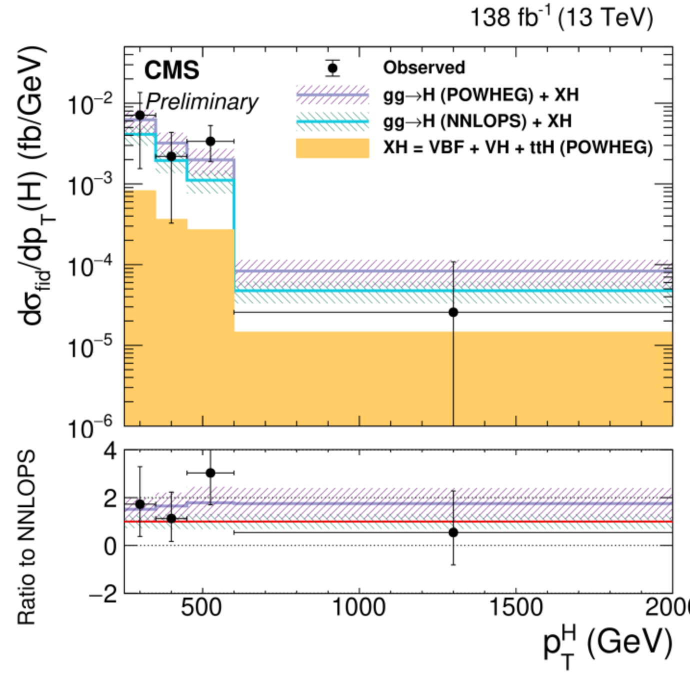
- Highly Lorentz-boosted Higgs boson (**p^{H}_{T} > 250 GeV**) to **a pair of collimated τ leptons**

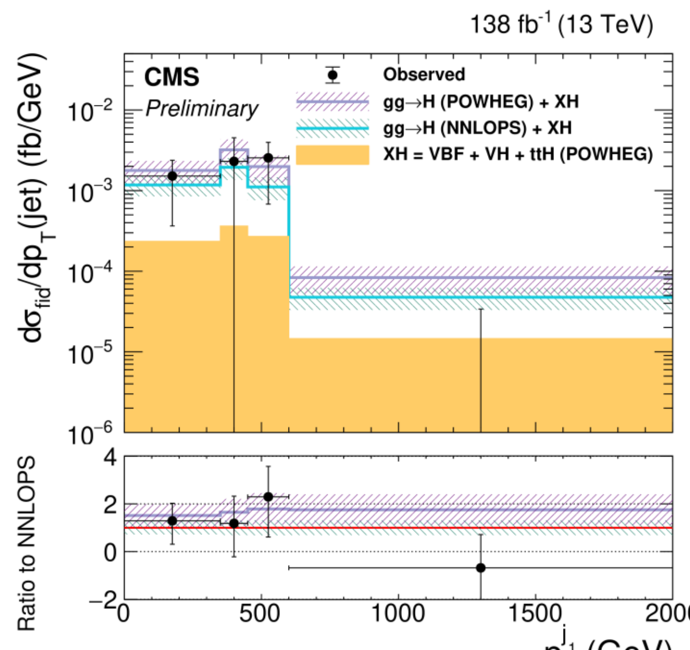
- A dedicated boosted **τ_{had}** reconstruction algorithm and a multi-class NN with three output nodes : signal, $Z \rightarrow \tau\tau$ and fake backgrounds $\rightarrow$ A binned maximum likelihood fit between three NN outputs

- **Background estimations:** irreducible $Z \rightarrow \tau\tau$, fake backgrounds estimated from data other backgrounds estimated by MC simulations

- Observed (expected) significance **3.5σ (2.2σ)**
- Main systematics : fake backgrounds, tau ID, QCD scale uncertainty

- Best fit value of inclusive fiducial cross section is **$1.96^{+0.86}_{-0.69}$ pb**, consistent with the SM: **1.20 pb**



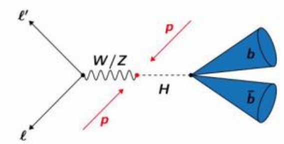


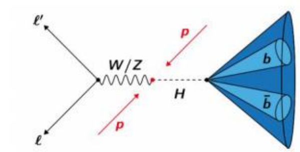
ATLAS: VH, H→bb

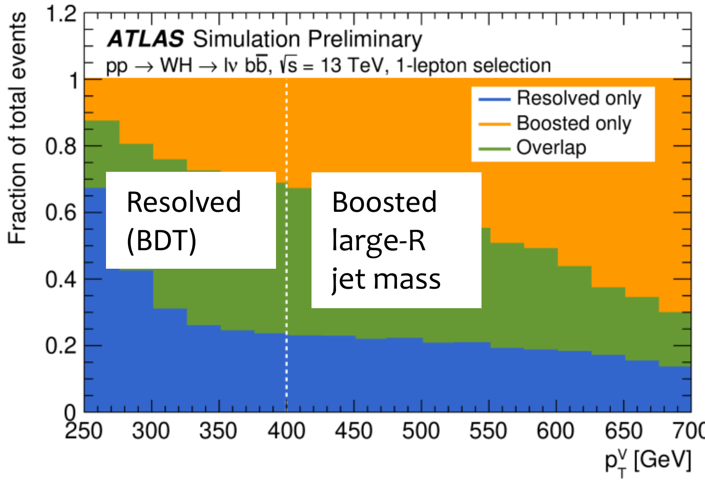
CMS results in CMS-PAS-HIG-20-001
Inclusive signal strength:
$\mu=0.58_{-0.18}^{+0.19}$
observed significance of 3.3σ(exp. 5.2σ)

VH, H→bb extensively studied using full Run 2 dataset

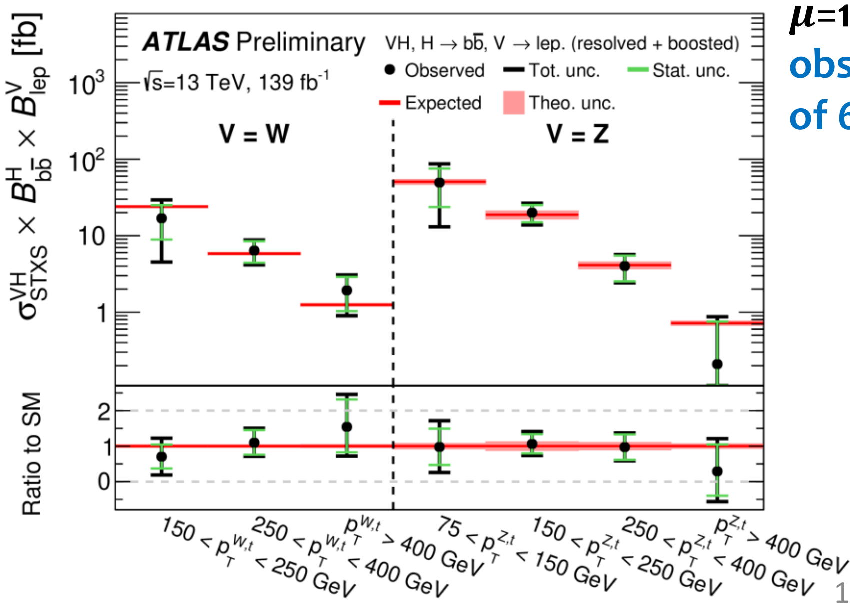
Resolved: EPJC 81 (2021) 178, Boosted PLB 816 (2021)



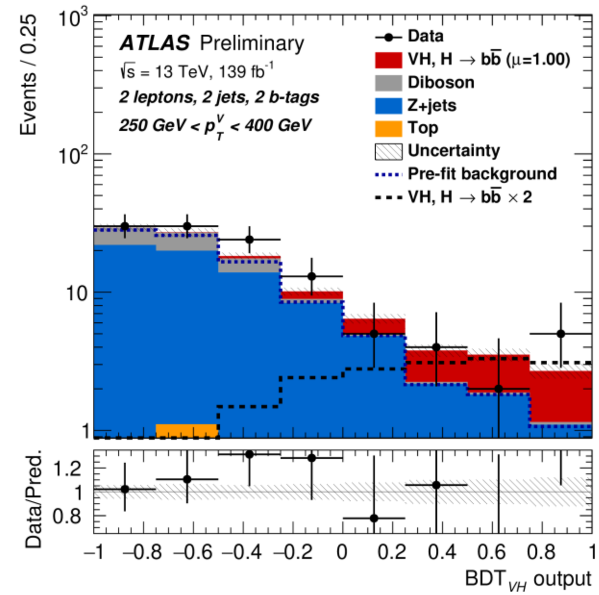




- Combination of the two analyses: ATLAS CONF 2021 051
- Combined using $p_T{}^V$>400 GeV events for boosted only
- Uncertainties dominated by b tagging, jet, signal and V+jets modelling.
- STXS measurement in combined analysis with 7 bins.

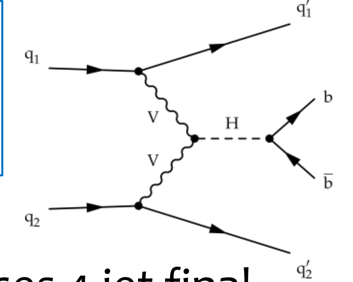


$\mu=1.00_{-0.17}^{+0.18}$
observed significance of 6.4σ(exp. 6.3σ)



CMS: VBF, H→bb

ATLAS results in Eur. Phys. J. C. 81 (2021) 537
$\mu_{Hbb}=0.95_{-0.31}^{+0.31}(stat)_{-0.17}^{+0.2}(syst)$
observed significance of 2.7σ (exp. 2.9 σ)

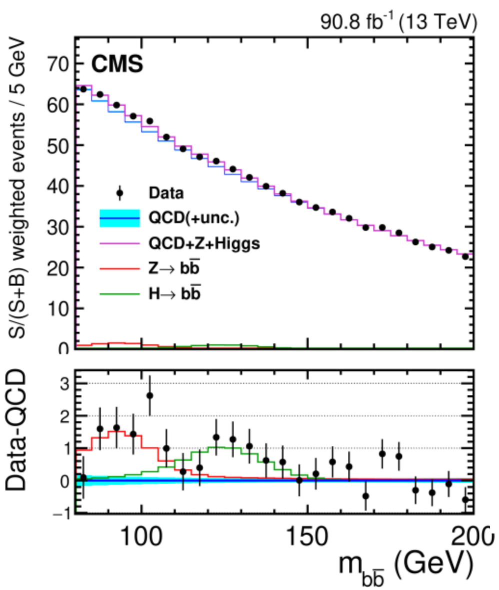


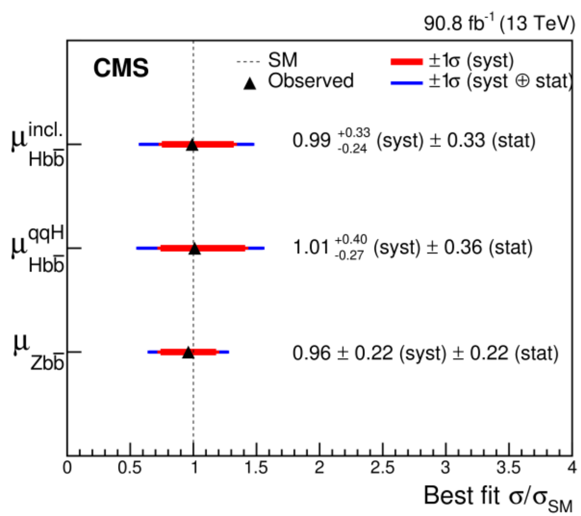
2308.01253 **VBF production of Higgs boson followed by H→bb** decay produces 4 jet final state, 2 jets in central region (from H→bb) and 2 in forward and backward directions relative to beam line with large rapidity separation (VBF jets)

Dominant background:

- QCD multijet: Estimated by fit to data in the side bands of the m_{bb} distribution
- Z+Jets: Estimated from simulation

BDT used to separate signal from background in 18 categories, 5 per year for VBF, 2 per year for ggH and 2 per year for Z+Jets, Signal is extracted from the m_{bb} distribution





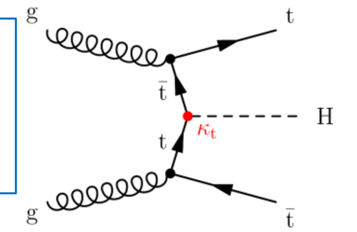
(ggH constrained to SM pred.):
$\boldsymbol{\mu_{Hbb}^{qqH}=1.01_{-0.27}^{+0.40}(syst)\pm0.36(stat)}$
Obs. significance of 2.4σ (exp. 2.7σ)

Inclusive signal strength (qqH+ggH):
$\boldsymbol{\mu_{Hbb}^{incl.}=0.99_{-0.24}^{+0.33}(syst)\pm0.33(stat)}$
Obs. significance of 2.6σ (exp. 2.9σ)

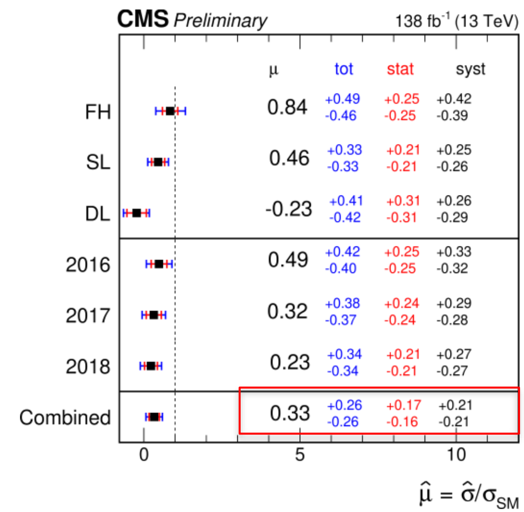
CMS: ttH, H→bb

NEW

Latest **ATLAS** results in 2303.05974
Probing the CP nature of the top-Higgs Yukawa coupling.

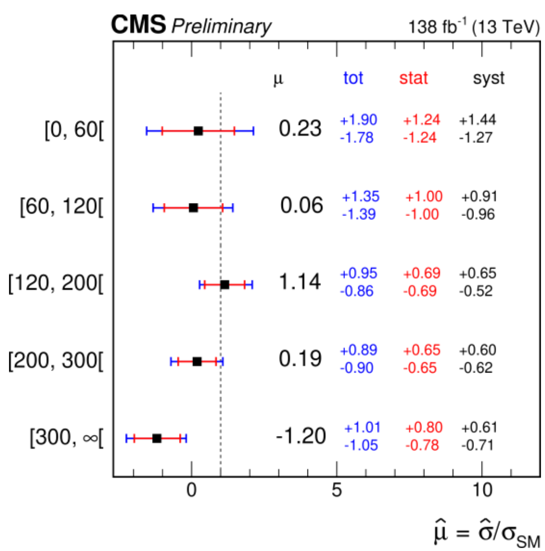


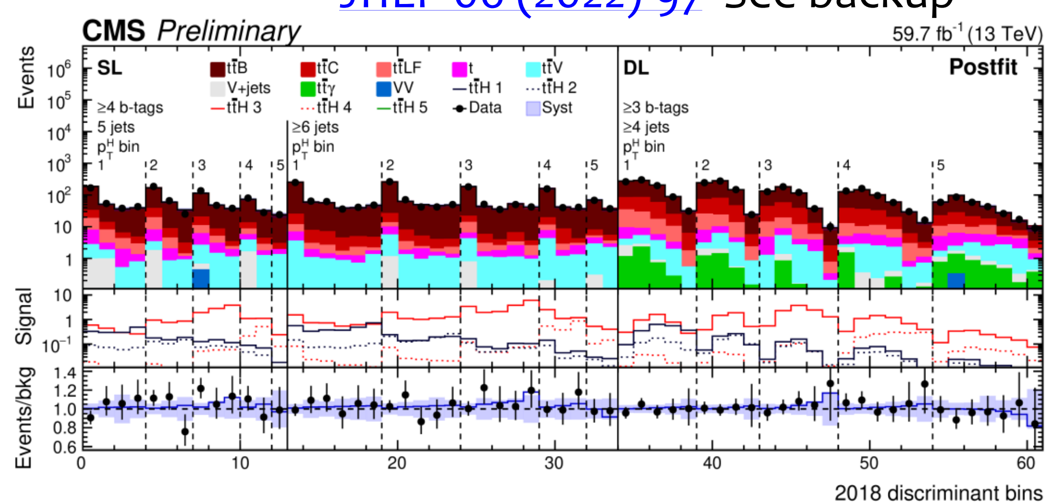
- **CMS-PAS-HIG-19-011 ttH and tH with H→bb in three final states 0,1 or 2 leptons**
- High p_T b jets and depending on channel jets, isolated electrons , muons or missing transverse momentum
- Dominant background: QCD multijet (0ℓ channel) and tt + jets.
- Normalization of ttB and ttC with constrained by fit to data
- ANN used to separate S from B, binary (0ℓ) or multi classification (1ℓ, 2ℓ)
- **Obs. significance of 1.3σ (exp. 4.1σ). Compatibility of ttH signal strength to SM expectation above 2σ.**



ATLAS: μ= 0.35$^{+0.36}_{-0.34}$

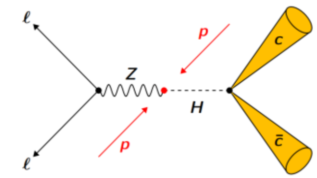
JHEP 06 (2022) 97 See backup





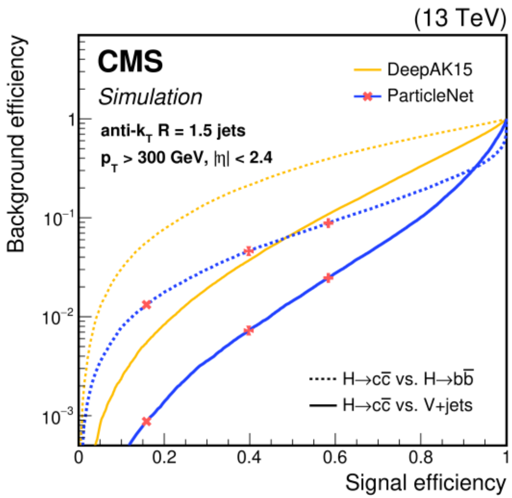
CMS:Higgs coupling to charm quark

(Phys. Rev. Lett. 131 (2023) 061801), (Phys. Rev. Lett. 131 (2023) 041801)



Inclusive H → cc decay search with 138 fb^{-1}:

- **Yukawa couplings between H and charm quark**
- B(H → cc) = 2.9 x 10^{-2} ($^{+5\%}_{-2\%}$)
- Trigger: MET or single/double iso lepton
- Multijet backgrounds and need to perform **charm-jet tagging**
- Main channel considered: *pp* → VH → *ℓℓcc*
- "Resolved-jet" and "Merged-jet" (single large-*R* jet) topologies

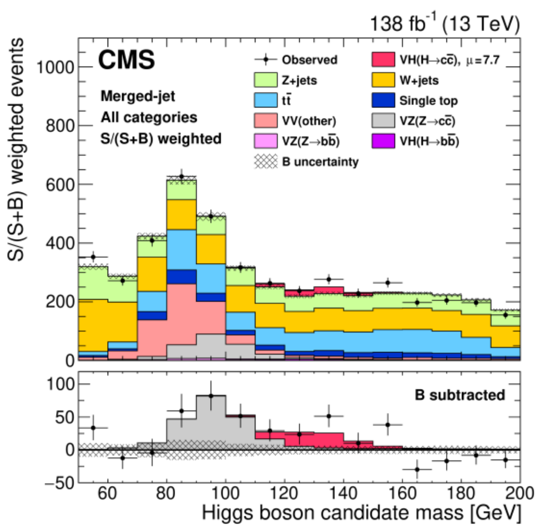


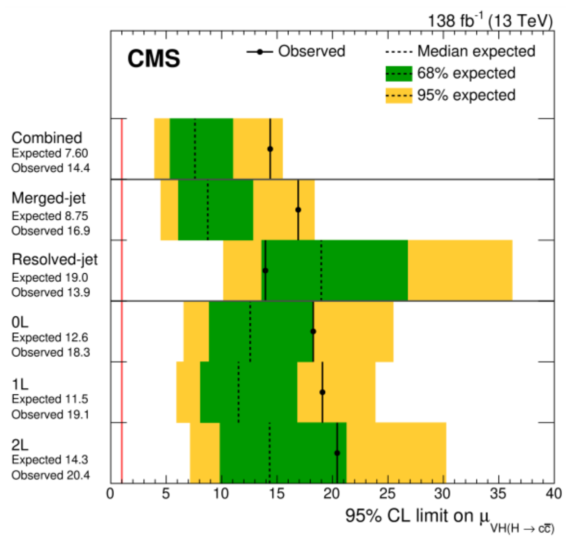
Upper limits on B set at 95% CL:

$\mu_{VH(H\to cc)}$ = 14 (7.6 $^{+3.4}_{-2.3}$) the SM prediction

1.1 < |k_c| < 5.5 (|k_c| < 3.4)

Most stringent constraint on k_c to date





Validation of analysis strategy:

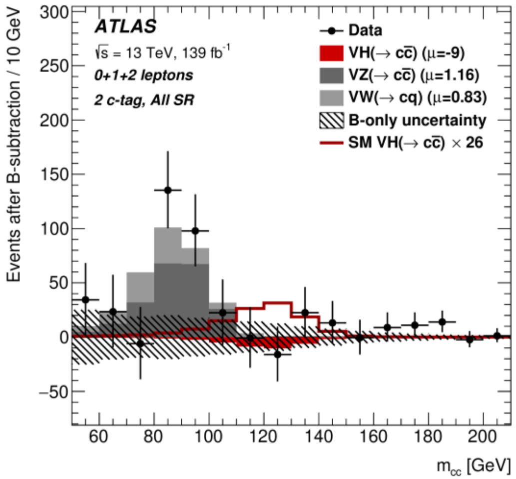
Search for the analogous SM process VZ(Z → cc)

Best fit: **$\mu_{VZ(Z\to cc)}$ = 1.01 $^{+0.23}_{-0.21}$**

5.7 std dev of observed significance

ATLAS:Higgs coupling to charm quark

(Eur. Phys. J. C 82 (2022) 717)



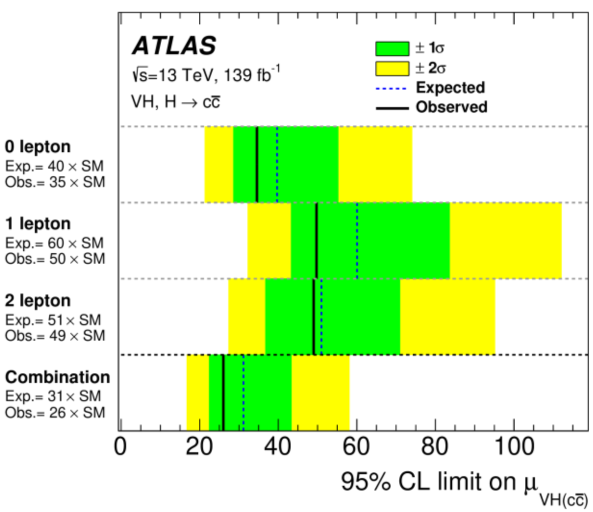
Inclusive H → cc decay search with 139 fb^{-1}:

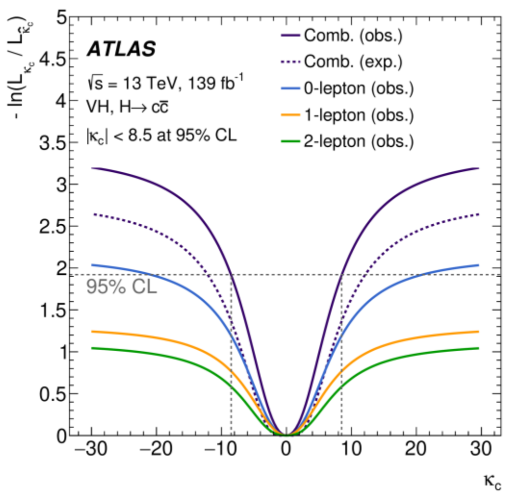
- $pp \rightarrow VH \rightarrow \ell\ell cc$, or $\ell\nu cc$ or $\nu\nu cc$, **charm-jet tagging**
- Control regions to constrain the ttbar and W/Z+jets backgrounds.
- Constraints on $\boldsymbol{k_c}$ when all the other Higgs couplings are SM like is set to $\boldsymbol{k_c}$ **< 8.5 at 95 %CL**

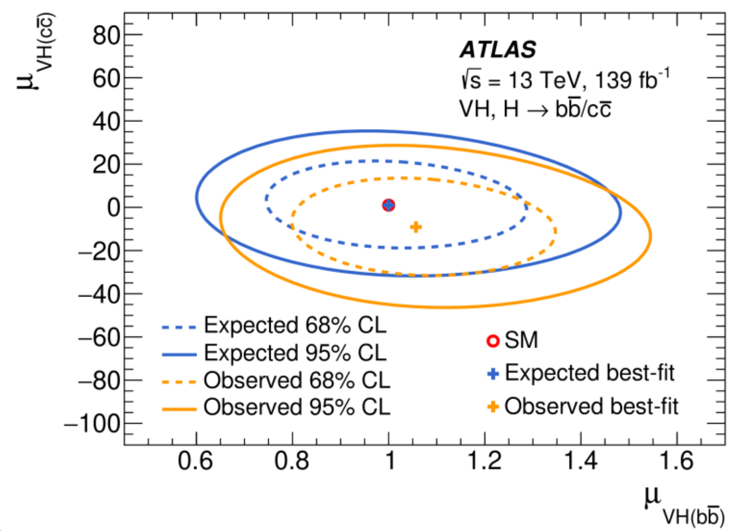
μ(VH, H→*cc*) < 26(31) obs(exp) at 95% CL

Average efficiency of 27% to tag c-jets in simulated $t\bar{t}$ events, and b- and light-jet misidentification rates of 8% and 1.6%

Combination of VHbb and VHcc analyses thanks to the orthogonality of tagging selection





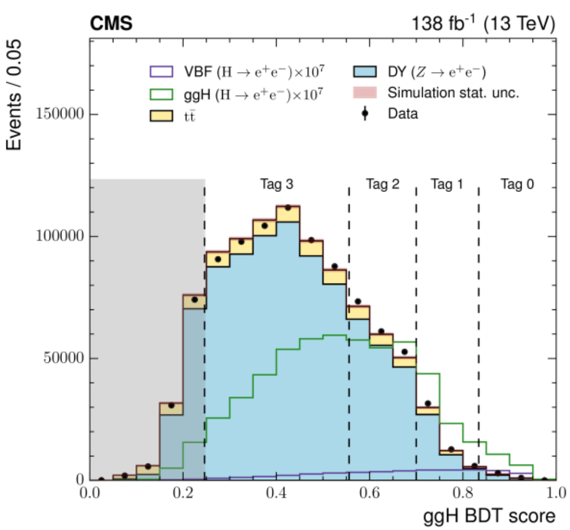


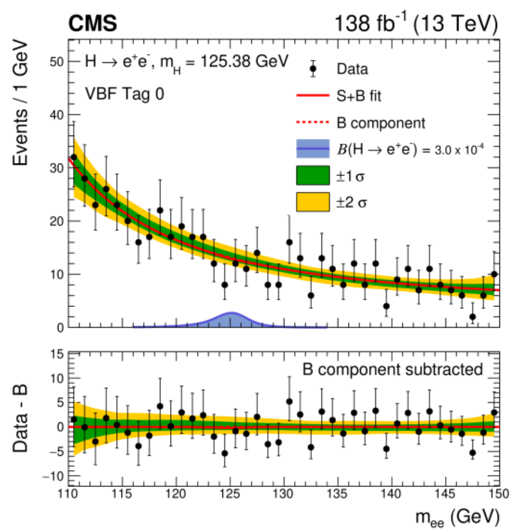
CMS: Searches for H ⟶ ee

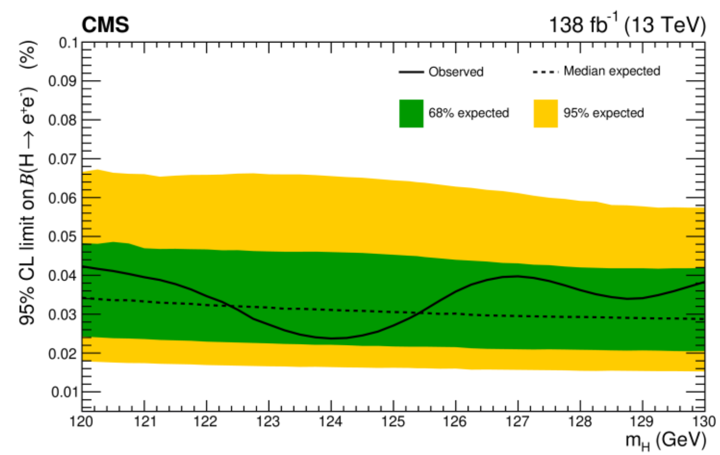
2208.00265 accepted PLB

- Br(H⟶ e^+e^-) = 5 × 10^{-9} in the SM
- Impossible to access at LHC or HL-LHC
  - Look for BSM effects that enhance the branching fraction
- Search for ggF and VBF production modes,
- BDT based analysis categorised according to the BDT score, validated in a Z⟶ e+e- enriched region.
- UL on **Br(H⟶ e^+e^-) = 3.0 × 10^{-4}** (3.0 ×10^{-4}expected) at 95% CL

ATLAS, result is comparable:
Br(H⟶ e^+e^-) < 3.6×10^{-4} @95% CL
Phys. Lett. B 801 (2020) 135148







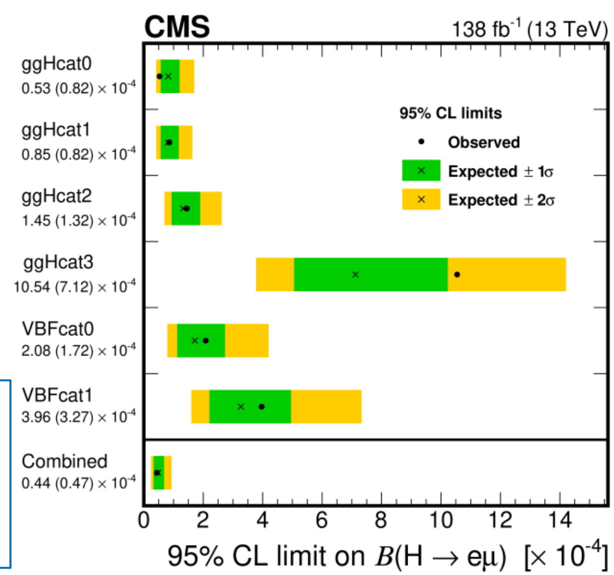
CMS: Searches for lepton-flavor violating Higgs decays

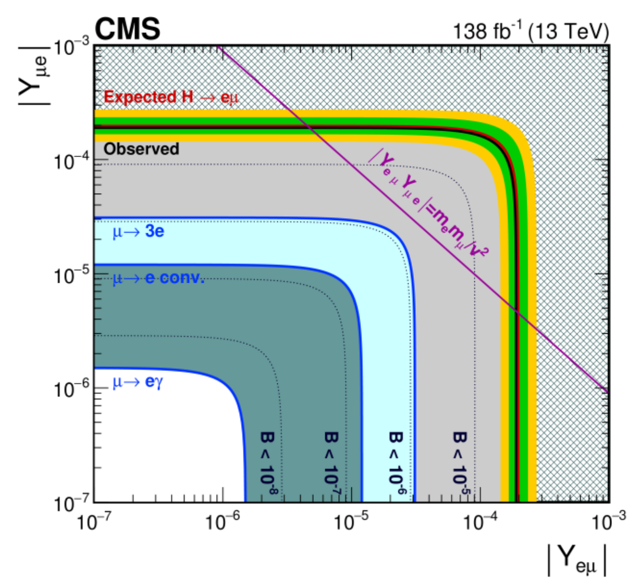
2305.18106 (accepted by Phys. Rev. D) *(2023 result)*

- In the SM, the H boson decays to lepton pairs of the same flavor
- In BSM models, e.g. in certain 2HDM variants, Yukawa couplings which do not conserve lepton-flavor are posible
  - flavor-violating decays of H boson at 125 GeV
  - new bosons at other masses appearing in such final states
- **Search for H $\to$ eμ in gluon-fusion and VBF**
  - Choose mass window beyond the peak from ttbar production $\to$ smoothly falling background
  - Categorization with signal/background discriminating BDT $\to$ in total 6 categories

No excess observed for
H $\to$ eμ at m=125 GeV
B(H $\to$ eμ) < 4.4 (4.7) x 10^{-5}
obs.(exp.) at 95% CL
Most stringent direct limit so far

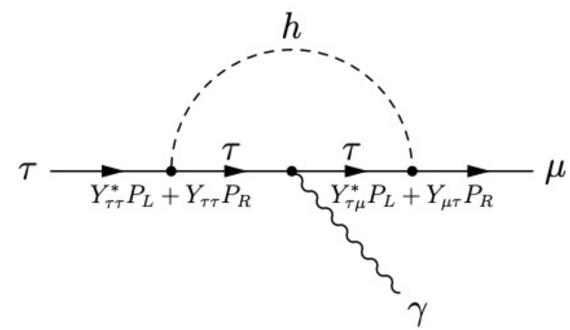
ATLAS result:
B(H→eμ) 6.2×10^{-5} (5.8×10^{-5}).
Phys. Lett. B 801 (2020) 135148



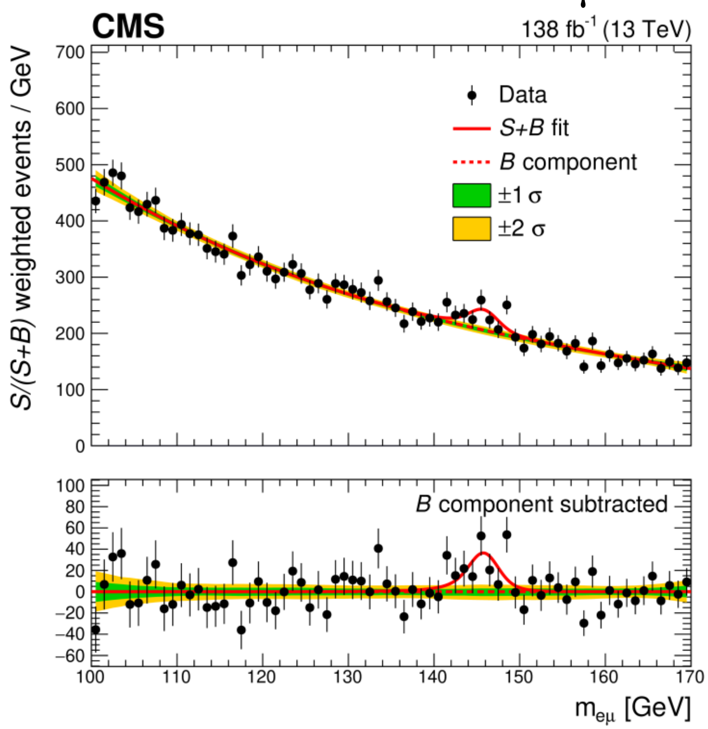


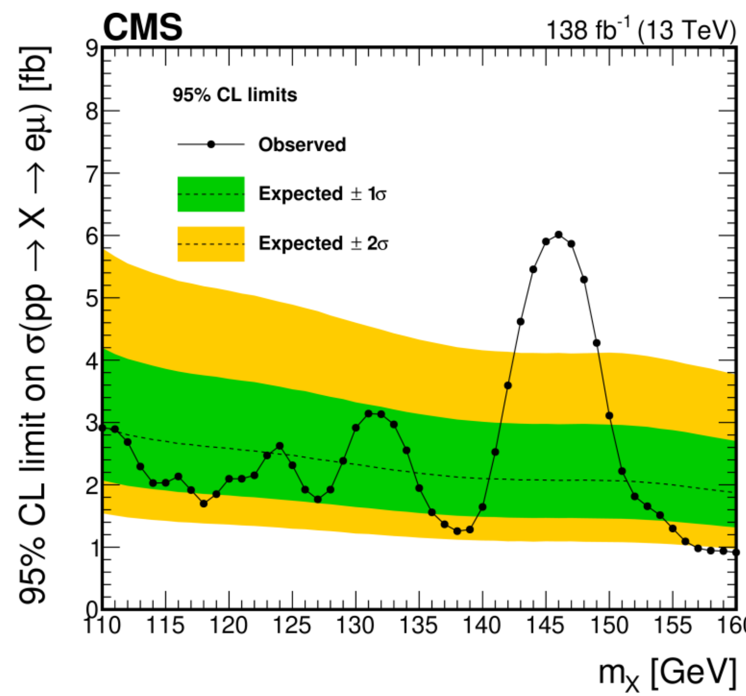
CMS: Searches for lepton-flavor violating Higgs decays, H_{125} (or additional X) → eμ

2305.18106 (accepted by Phys. Rev. D) (2023 res



- At a larger mass of ~146 GeV, a mild excess is seen
- significance 3.8 σ local (2.8 σ global) → need more data to conclude
- first result of a direct X→eμ search with $M_X < 2m_W$





ATLAS did not scan different mass points
Phys. Lett. B 801 (2020) 135148

ATLAS: LFV Higgs $H \to \mu\tau$, $H \to e\tau$

JHEP 07 (2023) 166

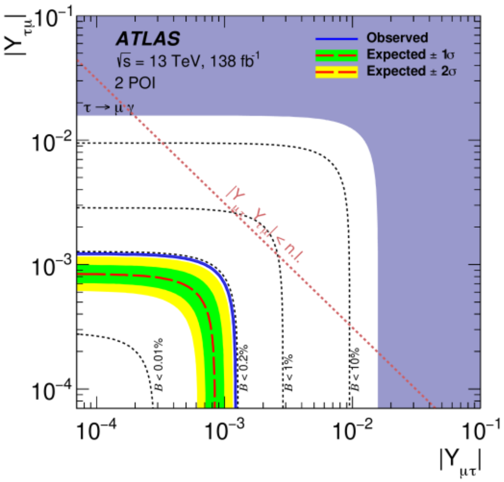
Searching for Higgs Decays to different flavor leptons: constraints on Br($H \to \mu\tau$), Br($H \to e\tau$), precise probe into off-diagonal yukawa couplings.

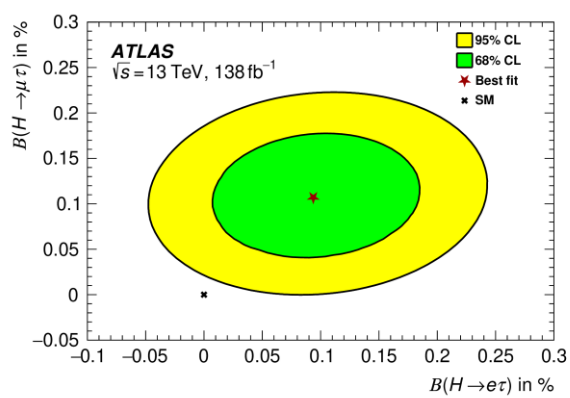
Two analyses targeting leptonic τ decays (different background estimation) and one for hadronic τ decays

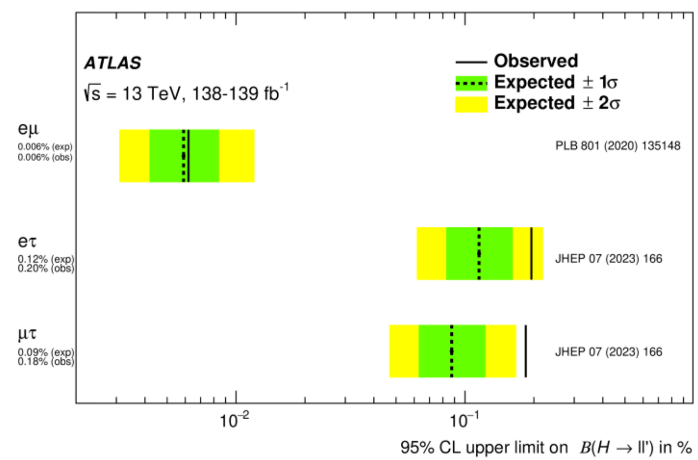
Gluon fusion, vector boson fusion (VBF), vector boson associated production.

Loose preselection, further cut-based categorization into VBF and Non VBF regions.

Control regions dependent on the analysis to extract normalization of main backgrounds, and MVA used to enhance sensitivity. Final discriminants for fit built from MVA outputs.







From the simultaneous fit of the two signals, obs. (exp.) **ULs at 95% CL** on the BRs are: $\mathcal{B}(H \to e\tau) < 0.20\%$ (0.11%). $\mathcal{B}(H \to \mu\tau) < 0.18\%$ (0.09%) **Compatibility with SM within 2.1 σ**

CMS: $B(H \to \mu\tau) < 0.15$ (0.15)% and $B(H \to e\tau) < 0.22$ (0.16)% at 95% CL. PRD 104 (2021) 032013

Summary

- The Higgs boson particle was discovered in 2012
  - Properties of H boson measured with unparalleled precision by ATLAS + CMS
  - Approaching the ultimate precision from Run 2
  - Currently all property measurements are a formidable confirmation of electroweak symmetry breaking as predicted in the SM
  - An enormous effort by a community: reaching from the theorists, the accelerator physicists, computing experts, detector builders and the analyzers ...
- It couples to bosons, to leptons and to quarks of the 3rd generation
  - **Just seen first evidence that it also couples to the 2nd generation**
    - $H \rightarrow cc$: most stringent limits on κ_c to date
    - $H \rightarrow \mu\mu$: 3.0 std dev evidence of the decay
  - Some mild excesses observed by CMS in the search for H_{125} (or additional X) $\rightarrow e\mu$ whose nature needs to be clarified with further data and additional analyses
- **Precision measurements of the Higgs are increasingly important and, in many aspects, drive the future of HEP**

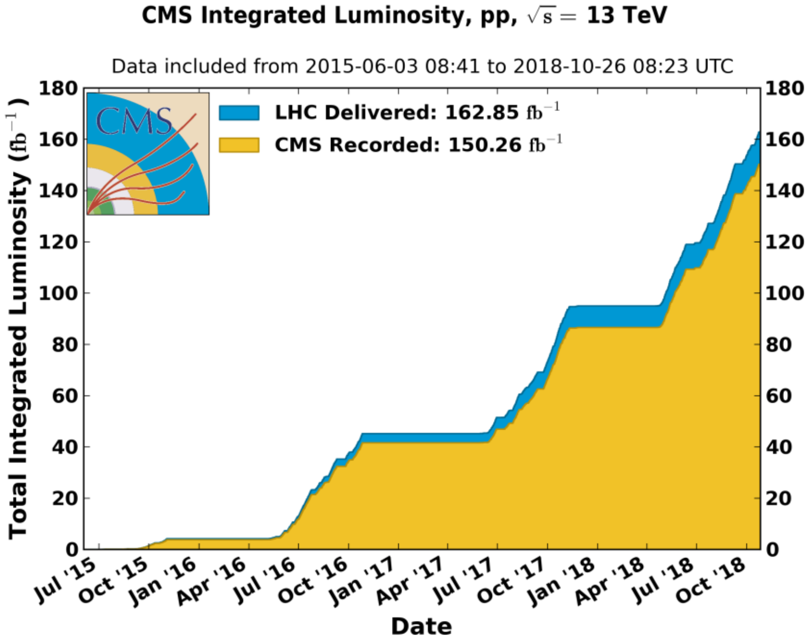
Backup slides

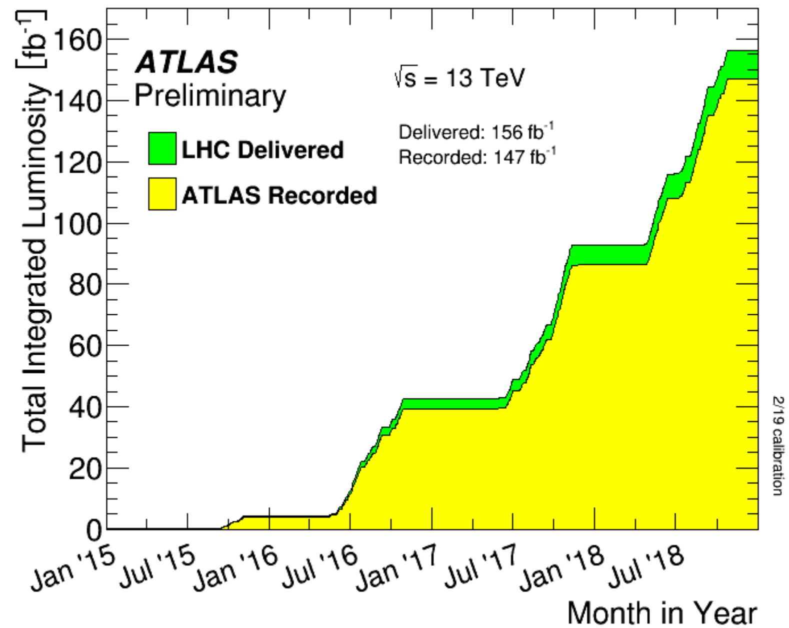
The experimental conditions at the LHC

- **The LHC is a discovery machine: the ultimate goal is to experimentally find the answers to the open questions about fundamental particles and interactions.**

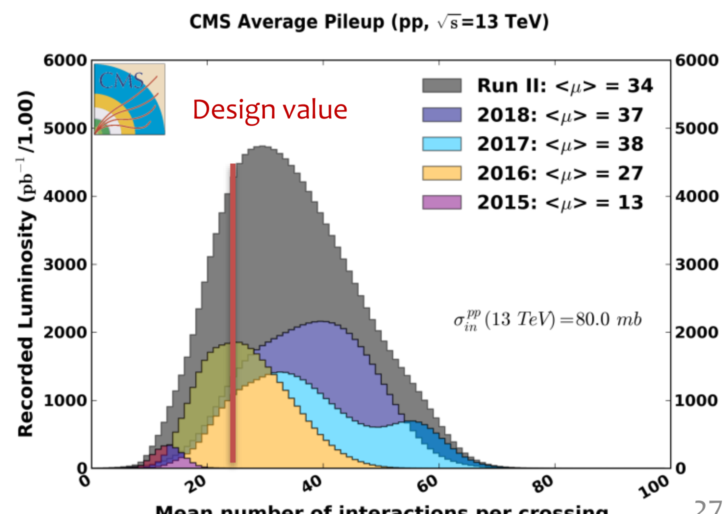
- The big challenge at the LHC is the huge range of cross sections that needs to be understood:
  - Huge cross section for "uninteresting" processes
  - Large cross sections for previously known processes
  - Medium cross section for not so-well studied processes
  - Low cross section for discovery processes
- It should be noted that all challenges at LHC are produced exactly for this reason:
  - Large backgrounds: interesting physics swamped by known processes.
  - Large Pile-Up: to be able to produce some small number of very interesting events, need to produce so many of un-interesing ones that they even happen in the same crossing!
  - Large available energy implies the chance to produce a lot of soft or medium-pT stuff affecting the reconstruction

LHC data taking at 13 TeV:



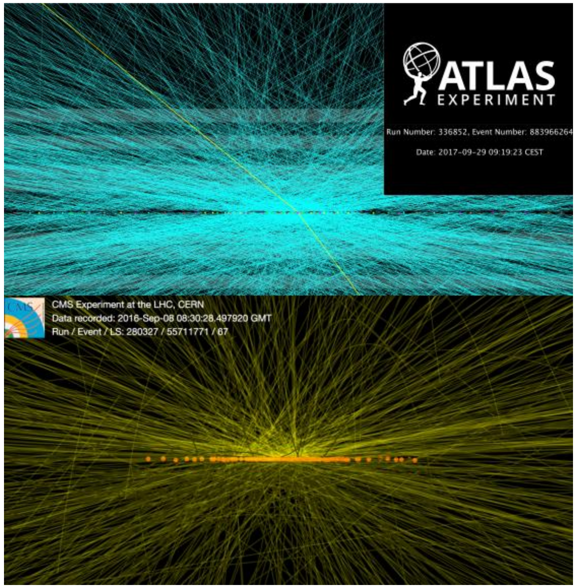


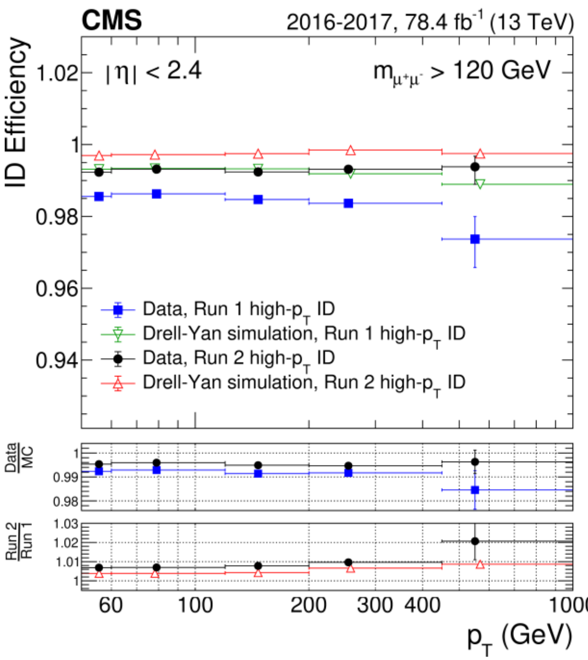
- The LHC had an excellent Run 2, delivering ≈ **160 fb^{-1}** to both experiments! (29 fb^{-1} in Run 1)
- Both experiments recorded data with superb overall Run 2 data taking efficiency: **ATLAS 95.6%, CMS 93.4%,**
  - achieved despite challenging pile-up conditions with **$<\mu>$ 35**: i.e. on average 35 simultaneous p – p collisions per bunch crossing!

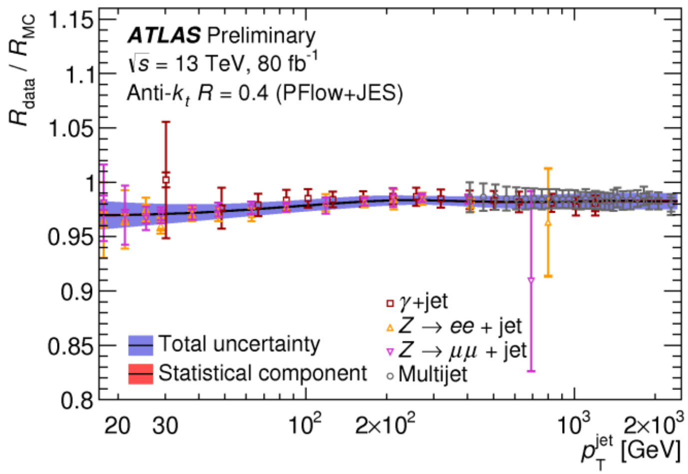


ATLAS and CMS, reconstruction and calibration

- Both experiments have excellent reconstruction and calibration performance, even in the harsh pileup conditions of Run 2
- Continuous improvements seen in the calibrations, understandings of efficiencies, systematic uncertainties etc. over a wide p_T range
  - A better understanding of the detectors along with data-driven and machine learning techniques mean that object calibrations and efficiencies are often now better even in the harsher environment of Run 2







- These datasets give both experiments broad physics programme potential
- **High-precision SM measurements, including Higgs properties**
- Detection of extremely rare processes
- Exploration of new kinematic regimes for potential new physics signals!

General Comments on SM Higgs searches and measurements

Blind analysis methods are used in ~all Higgs searches at ATLAS/CMS.

We searched **explicitly** for the SM Higgs boson: most analyses use unique properties of the SM Higgs boson to optimize their search sensitivity relative to known SM backgrounds.

This means that analyses are **model dependent** (i.e., the SM!) to varying degrees, and the significance of an observed excess is within the context of a search for the SM Higgs boson.

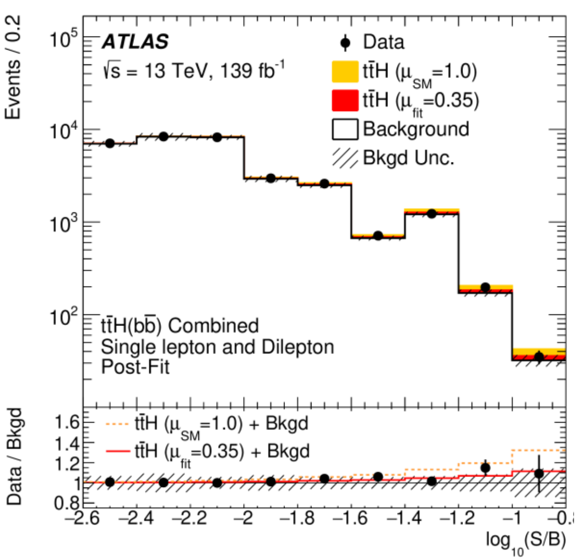
Due to *historical* agreement , we quote 'signal strength' (μ) relative to SM:

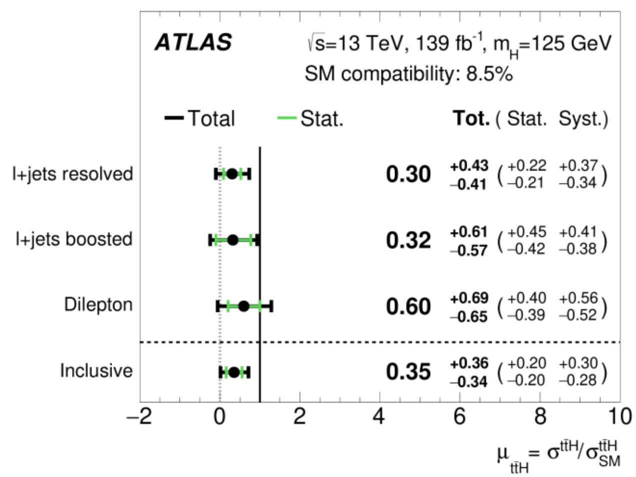
$$\mu \equiv \sigma \times \mathrm{BF} / \sigma_{\mathrm{SM}} \times \mathrm{BF}_{\mathrm{SM}}$$

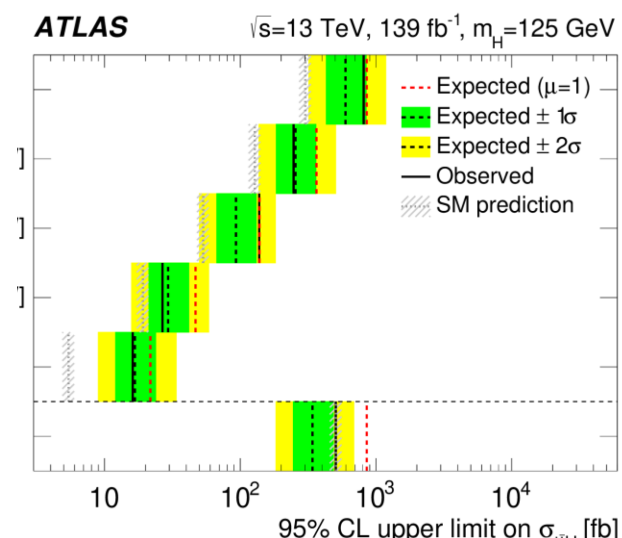
The product of production and decay couplings is what can be measured, then, **the LHC experiments study a multitude of Higgs production and decay modes**, with complementary sensitivities

ATLAS ttH→ bb JHEP 06 (2022) 97

- Background modeling, which is particularly challenging, and fitting, developing new techniques to discriminate between signal and background.
- $\mu = 0.35^{+0.36}_{-0.34}$







Beyond SM, A/H→ττ

- Beyond SM A/H→ττ publishing a first search well surpassing the Run 1 limits in this channel in PRL with just 3.2 fb^{-1} of Run 2 data.
- This is a search continued during the whole Run 2: Phys. Rev. Lett. 125 (2020) 051801