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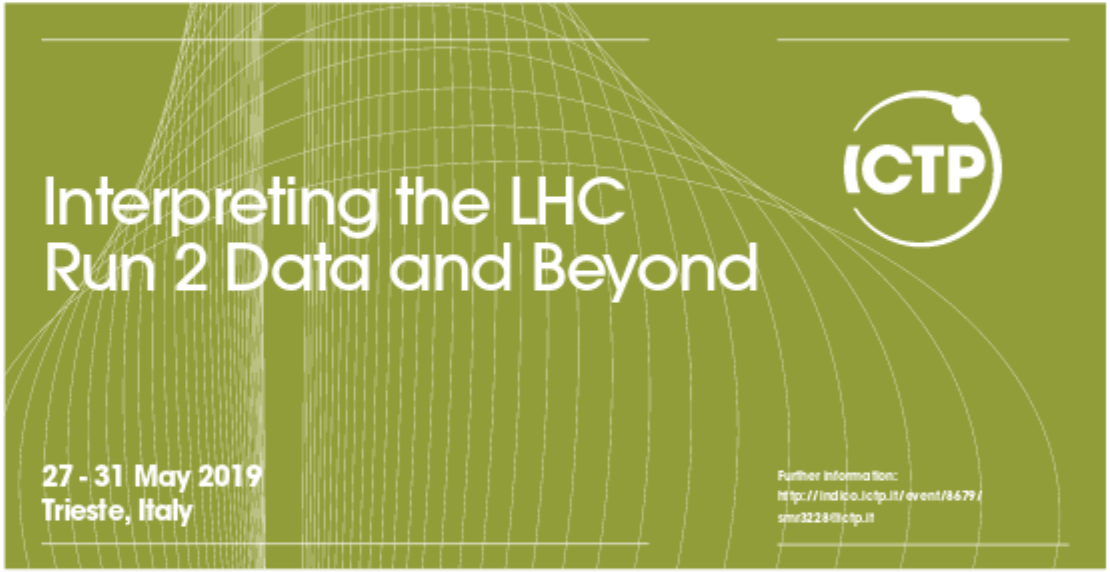


SM and BSM Higgs physics in CMS

J. Cuevas
U. Oviedo (Spain)

Interpreting the LHC Run 2 data and Beyond,

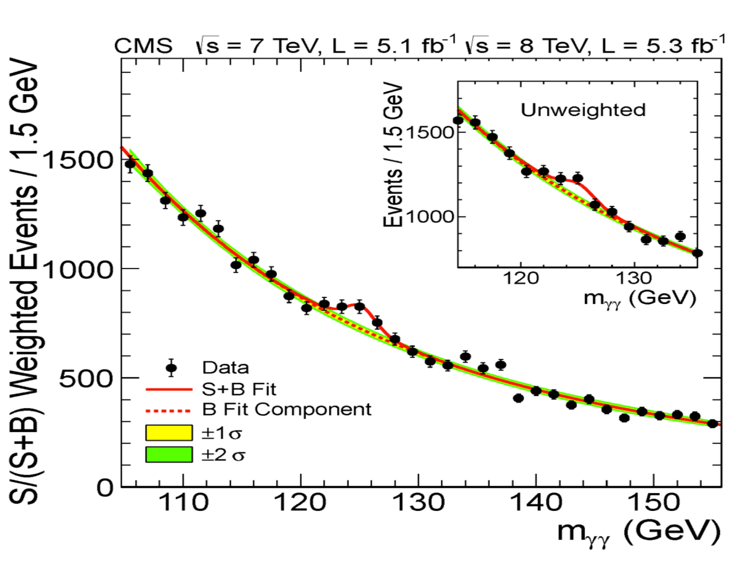
27-31 May 2019, ICTP Trieste, Trieste (Italy)

Introduction and Outline

- **SM Higgs Boson discovered in 2012**
- **No direct observation of new physics at the LHC after the Higgs boson discovery**
- **Precision measurements of the Higgs are increasingly important and in many aspects drive the future of HEP**
- Standard Model Higgs Boson Cross Sections and Branching Fractions at the LHC
- Mass, spin, width
- Couplings to fermions observed
- Couplings to the top quark observed
- 'Simplified Template' and differential cross section measurements
- Recent highlights
- Searches in extended models (BSM Higgs)

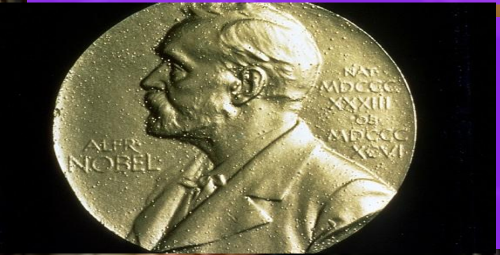
July 4 2012, ….A Higgs Boson

Phys. Lett. B 716 (2012)



"This result constitutes evidence for the existence of a new massive state that decays into two photons."

"Clear evidence for the production of a neutral boson …is presented."



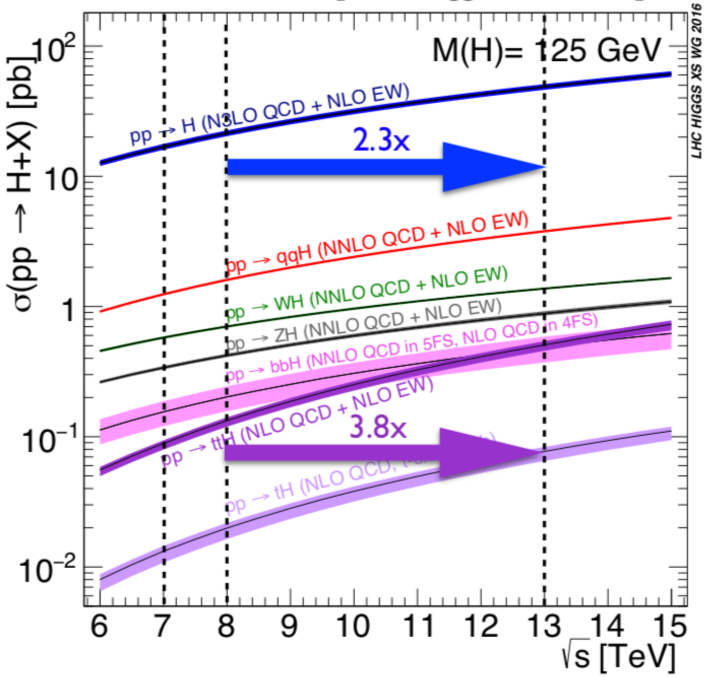
Goal for Runs 1-3 of the LHC and beyond:

Measure its mass and other properties including couplings

Is it alone?

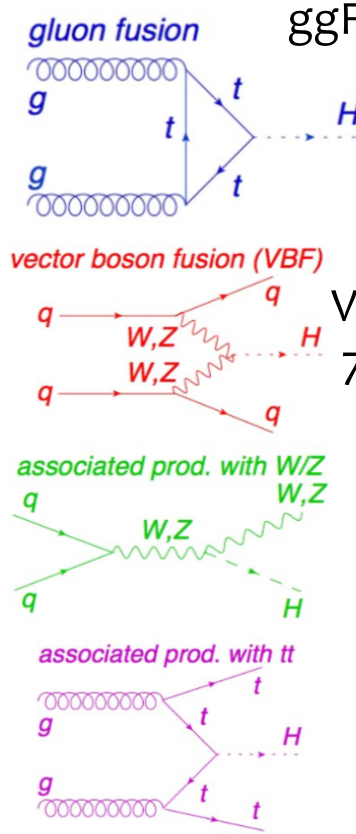
Standard Model Cross Sections and Branching Fractions

[LHC Higgs X-sec WG]



- Significant increase in production rate due to higher center-of-mass energy from LHC Run-1 to Run-2!

Production modes

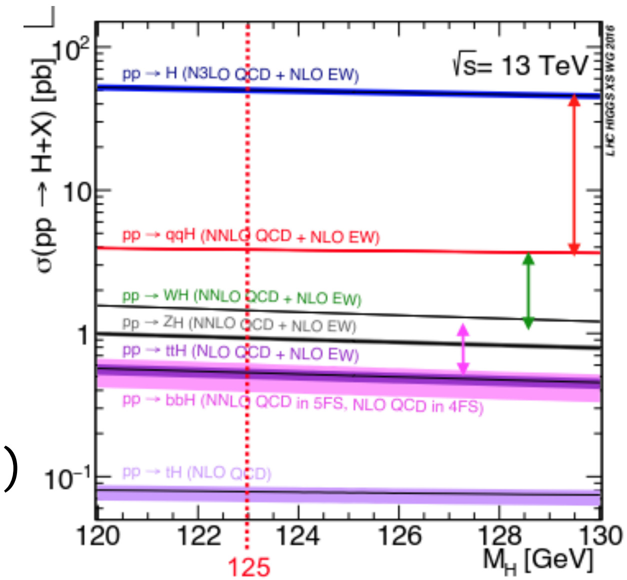


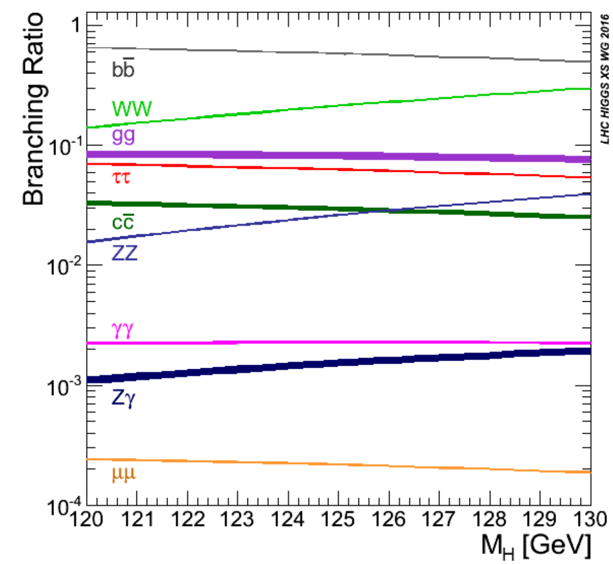
ggF: 87%

VBF (qqH) 7%

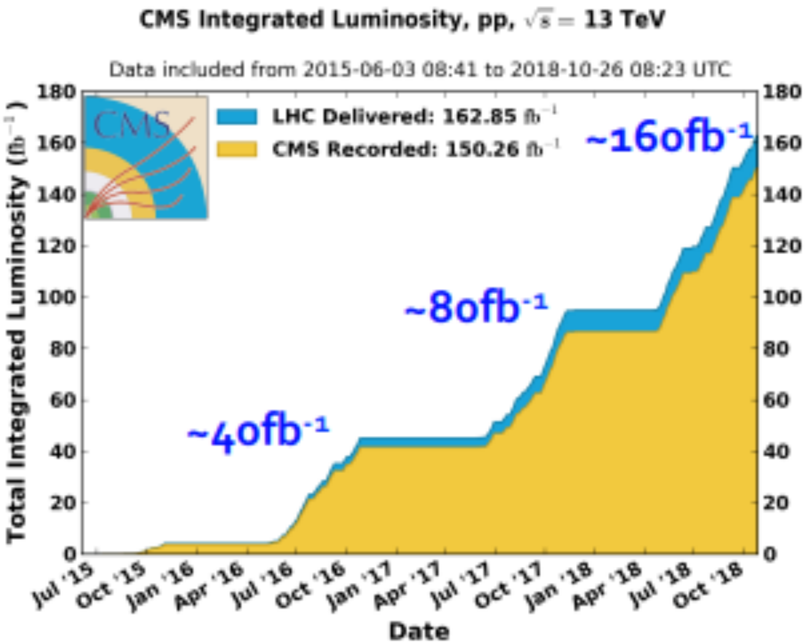
WH: 3%
ZH: 2%

ttH: 1%





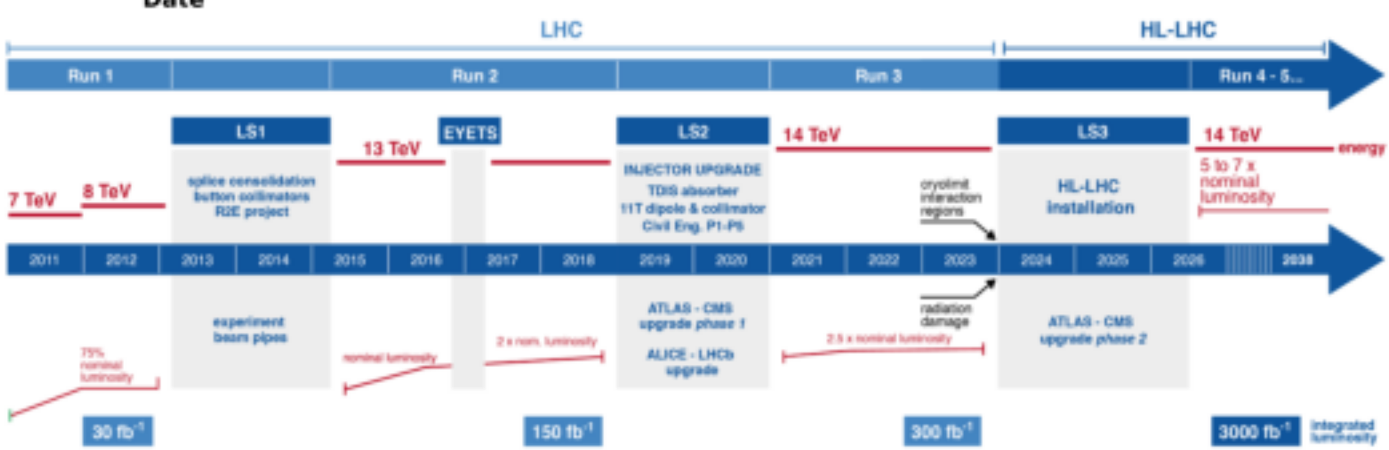
LHC data taking at 13 TeV:



Run-II provides a great opportunity to revisit Run-I Higgs Legacy results

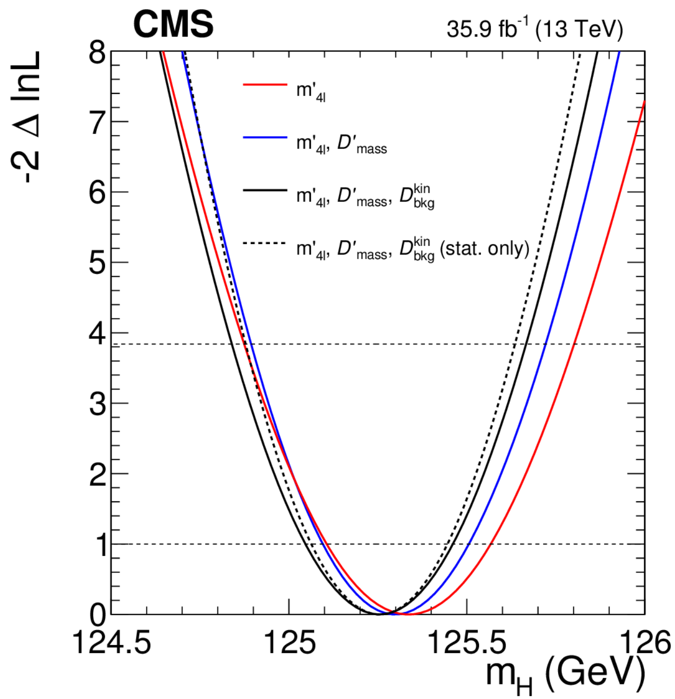
- **Observation -> measurements!**
- **From SM to BSM?**

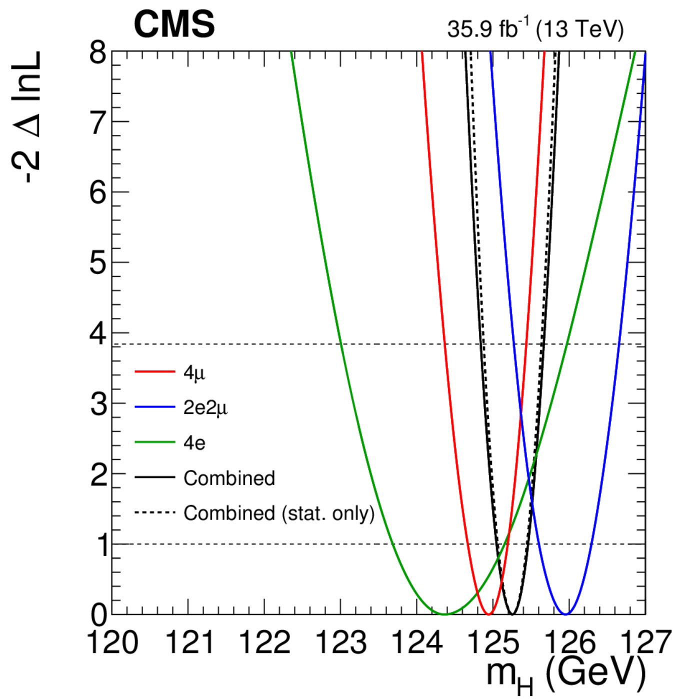
Still O(100 fb^{-1})being analysed before releasing full run II results.



Higgs Mass:

[JHEP 11 (2017) 047](#) $H \to ZZ^* \to 4\ell$





$m_H = 125.09 \pm 0.21$ GeV

$m_H = 125.26 \pm 0.21$ GeV
[$\pm$ 0.20 (stat.) $\pm$ 0.08 (syst.)]

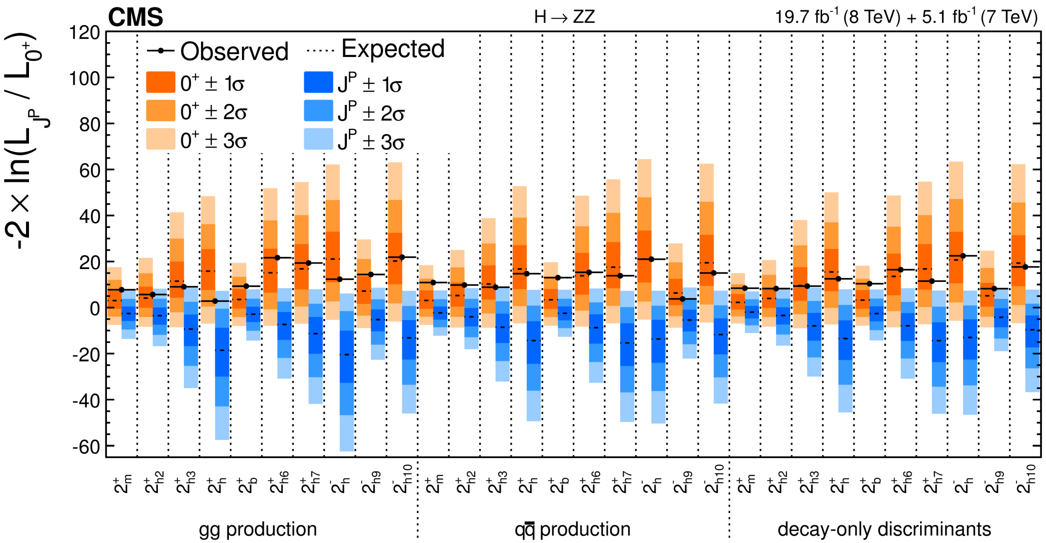
Compare to Run 1 ATLAS + CMS combined:
m_H = 125.09 ± 0.21 (stat) ± 0.11 (scale)
± 0.02 (other) ± 0.01 (theory) GeV
-> Single experiments now better, still statistics-dominated

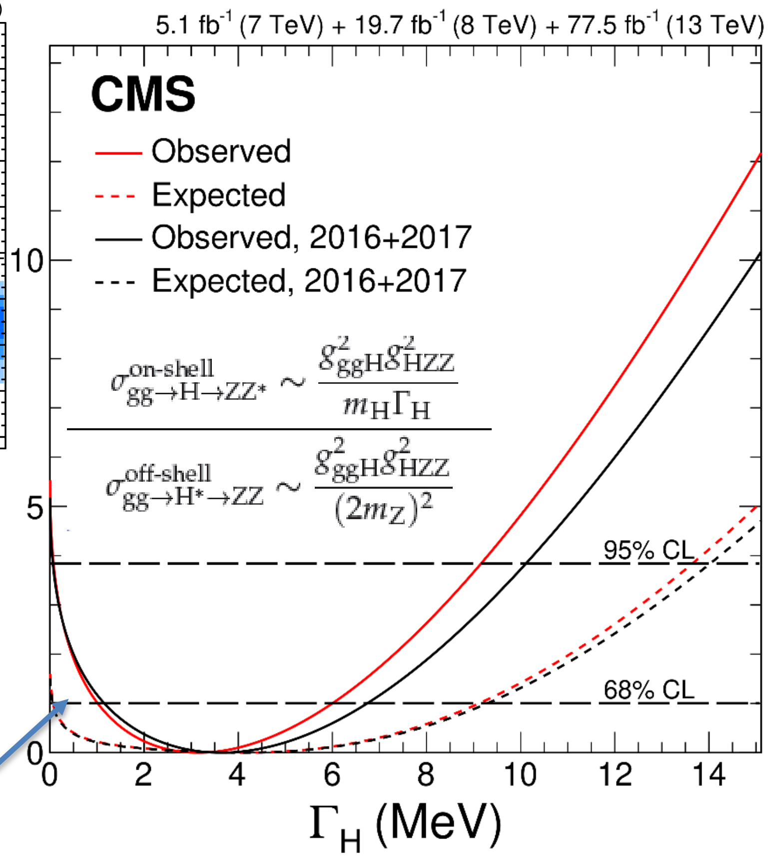
m_H is known to a precision of 2 per mille!

Spin and width:

arXiv:1901.00174, accepted by PRD

Width: Exploit coupling ratio between off- and on-shell production





Run 1 results:
compatible with Spin-0 and CP-even, CP-even/odd mix not ruled out

Starting to also place a lower bound on Γ

Γ < 9.16 MeV (13.7 exp.) @ 95% C.L.
Run1 + Run2, $H \to ZZ^* \to 4\ell$

The «κ» framework:

Couplings, κ

Parameters scale cross sections and partial widths relative to SM

$$\kappa_j^2 = \sigma_j / \sigma_j^{\rm SM} \qquad \kappa_j^2 = \Gamma_j / \Gamma_j^{\rm SM}$$

$$\sigma_i \cdot {\rm BR}^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_{\rm H}},$$

Total width determined as

$$\Gamma_{\rm H} = \frac{\kappa_H^2 \cdot \Gamma_H^{\rm SM}}{1 - {\rm BR}_{\rm BSM}}$$

Where

$$\kappa_H^2 = \sum_j {\rm BR}^j_{\rm SM} \kappa_j^2$$

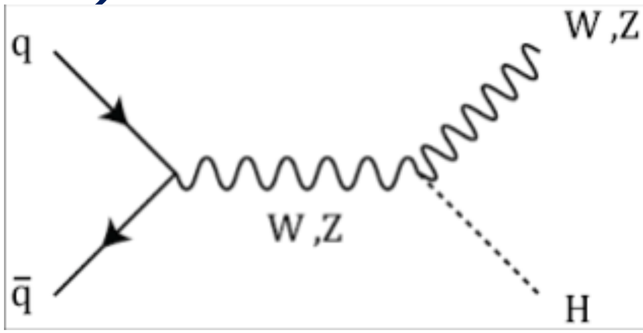
– Relationship between signal strengths μ and coupling modifiers κ :
  - $\sigma_i = \kappa_i^2 * \sigma_i(SM)$, $\Gamma_f = \kappa_f^2 * \Gamma_f(SM)$ ->

    $\mu^f_i = \kappa_i^2 * \kappa_f^2 / (\Gamma_H / \Gamma_H(SM))$
- Effective coupling modifiers κ_g , κ_γ for loops (describing ggF production and H->γγ decay)
- Coupling modifier ratios $\lambda_{ij}=\kappa_i/\kappa_j$
- All measurements assume the combined mass measurement exact value: m_H = 125.09 GeV
- Production processes: ggF, VBF, WH, ZH, ttH
- Decay channels: H->ZZ,WW,γγ,ττ,bb,μμ
- Parameter estimation via profile lh ratio test statistic Λ and estimator q=-2lnΛ assumed X^2

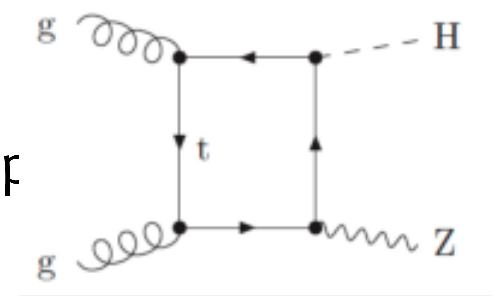
Higgs boson associated production
(observation of the bb decay mode)

Higgs-Strahlung (associated production)

– 4% of Higgs production mechanism
– NLO QCD corrections can be obtained from those to Drell-Yan: +30% (also NNLO QCD)
– Full EW corrections known: they decrease the cross section by 5-10%



- For ZH at NNLO further diagrams from gg initial state
- Important at the LHC (+2-6% effect up to +14% at high-p

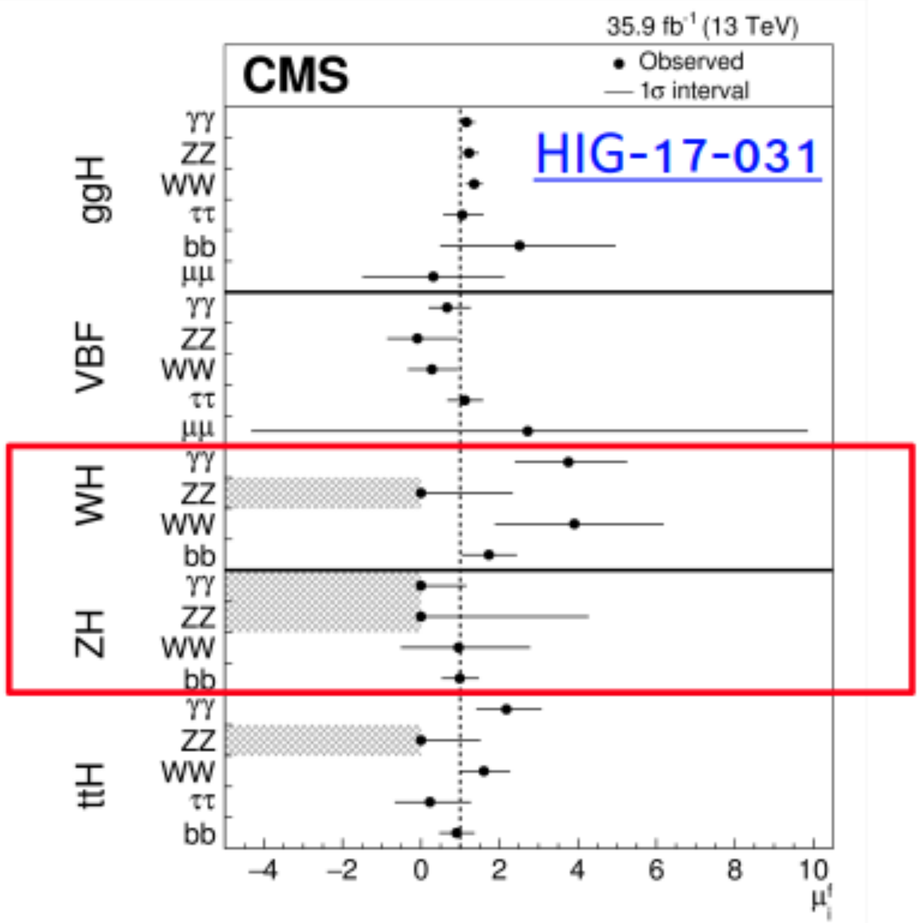


Experimental advantages:

- Vector boson (V) decay leptonically: -> Benefit from lepton triggers
- V-Boost: Further reduce background requiring high vector-p_T

VH production mode

- Combined measurements of Higgs production cross-sections in the ZZ, $\gamma\gamma$, WW, bb, ττ, and μμ decay modes



In general, consistent with SM predictions

➢ Integrated luminosity of 36 fb^{-1}

H->bb, physics case and the VH role

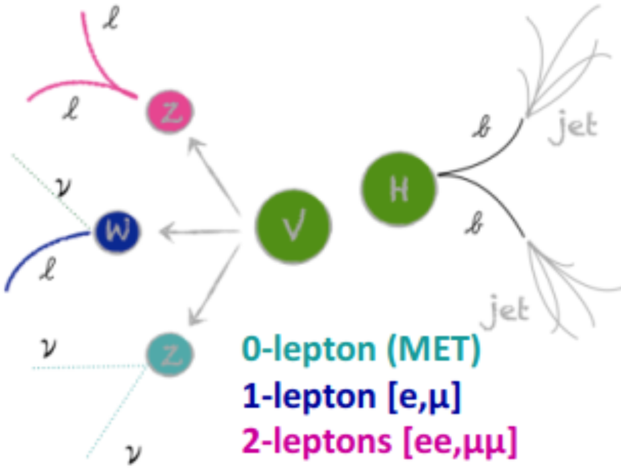
- Unique final state to measure coupling with down-type quarks
- H->bb has the largest BR (58%) for mH=125 GeV
- Drives the uncertainty on the total Higgs boson width
  - Limits the sensitivity to BSM contributions
- Only recently observed by CMS (and ATLAS)

• High BR • Low mass resolution • Low S/B	→	• Highly efficient b-jets identification • Improved resolution on m(bb) • Full event information to increase S/B

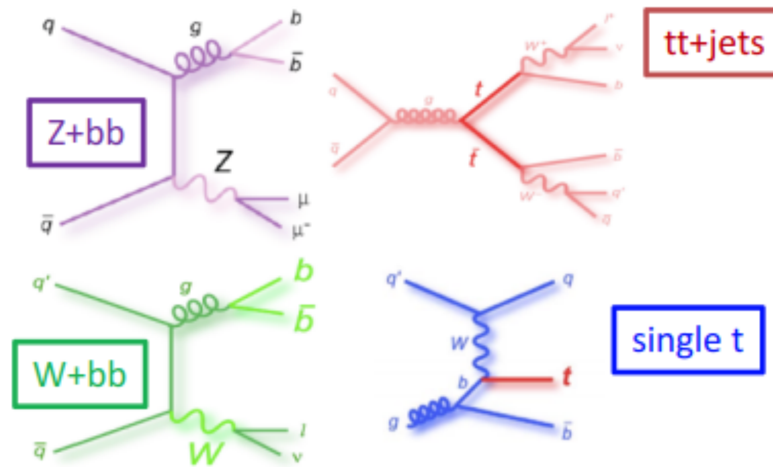
- VH production plays a crucial role
- W/Z decays leptonically
- W/Z produced generally back-to-back vs Higgs
- Possible to exploit the W/Z transverse boost
  - **Provides the most sensitive channel for H->bb**

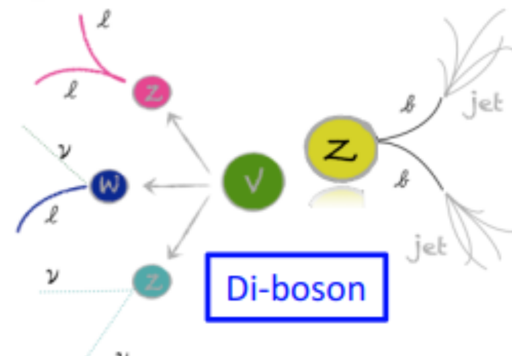
VH(H->bb) Analysis Strategy

SIGNAL PROCESSES



IRREDUCIBLE BACKGROUNDS





- **3 channels** with 0, 1, and 2 leptons and 2 b-tagged jets
  - Target **Z(vv)H(bb)**, **W(lv)H(bb)** and **Z(ll)H(bb)**
- **Signal region designed to increase S/B**
  - **Large boost** for vector boson
  - **Multivariate analysis**
  - Exploiting the most discriminating variables ($m_{b\bar{b}}$, $\Delta R_{b\bar{b}}$, b-tag)
- **Control regions to validate backgrounds and constrain normalizations**
- **Signal extraction:** binned maximum likelihood fit of final MVA/mass distribution

Event selection (and categorization)

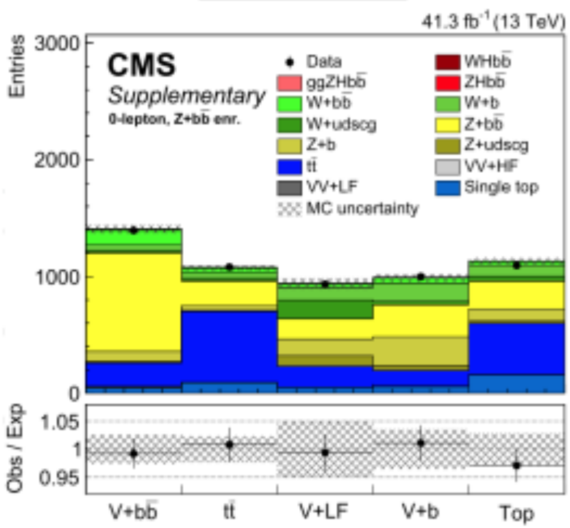
Phys. Rev. Lett. 121 (2018) 121801

- **Selections** (jets, leptons, b-tagging) **optimized separately by channel**
  - 4 analysis categories:
    - 0-lepton: **p_T(Z) > 170 GeV**
    - 1-lepton: **p_T(W) > 150 GeV**
    - 2-lepton High-Vp_T: **p_T(Z) > 150 GeV**
    - 2-lepton Low-Vp_T: **50 GeV < p_T(Z) < 150 GeV**

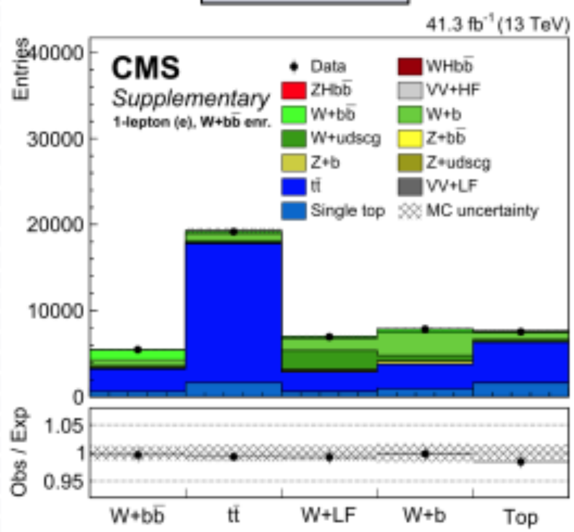
- **Control regions** designed to map closely each signal region
  - Inverted selections to **enhance purity in targeted backgrounds:**

  tt, V+light flavor, and V+heavy flavor

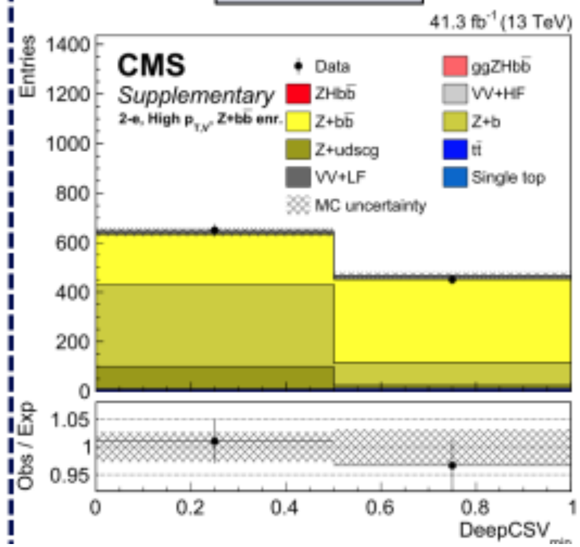
0-Lepton



1-Lepton



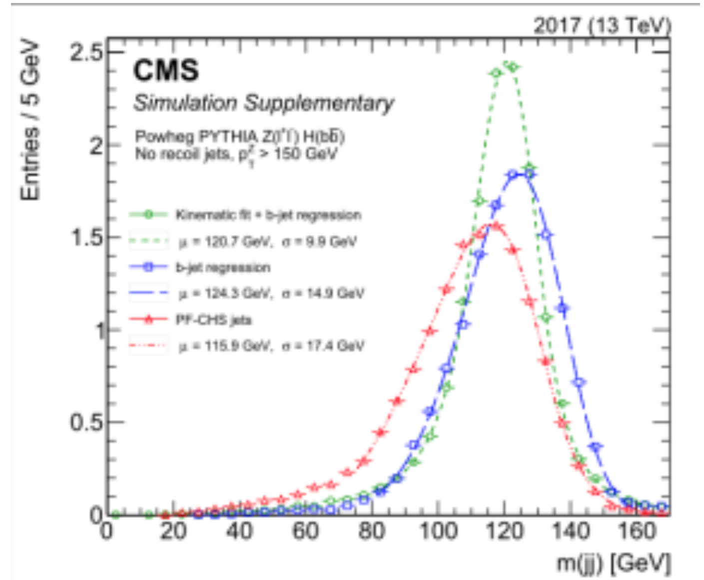
2-Lepton



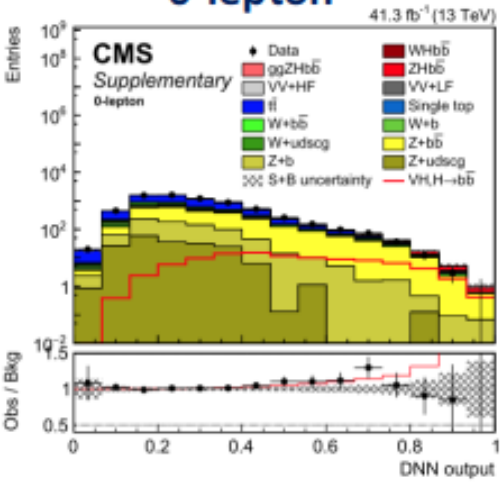
Mass resolution and signal extraction

- Better b-jet identification vs 2016
  - Improved b-tagger (2017)
  - new pixel detector (2017)
- b-jet energy regression + FSR
- Kinematic fit in 2-lepton channel

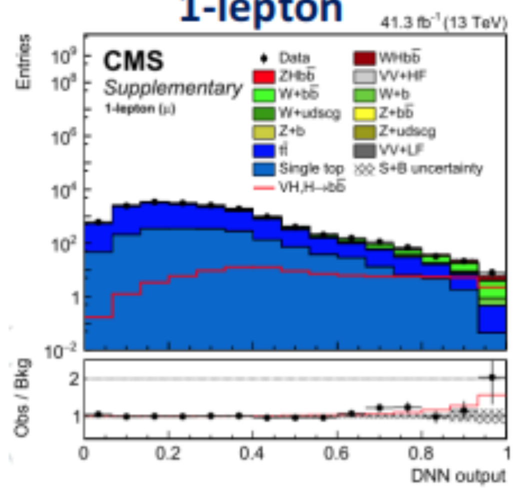
- Signal extraction:
- Use of (DNN) to discriminate sig. from bkg. in SR + various bkg in CRs



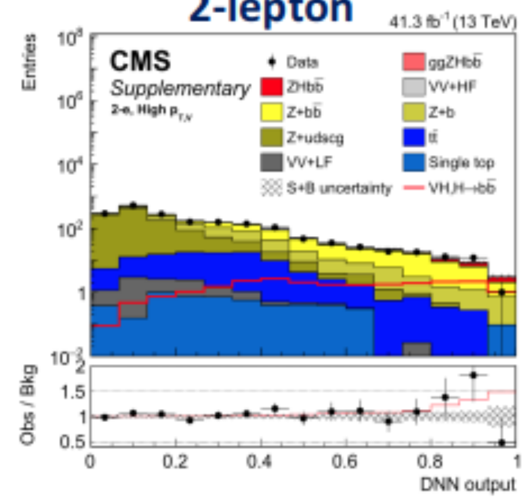
0-lepton



1-lepton



2-lepton



Combination of VH(H->bb) measurements

	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23

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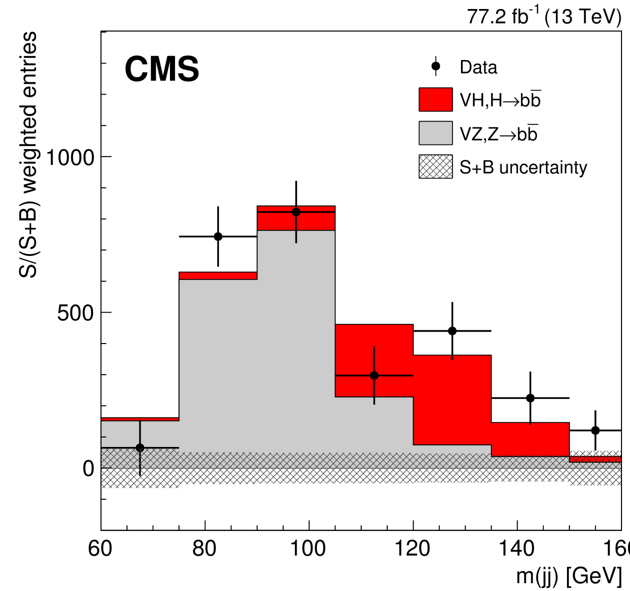
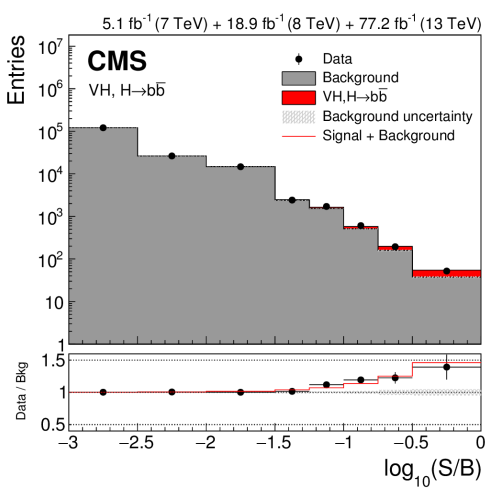
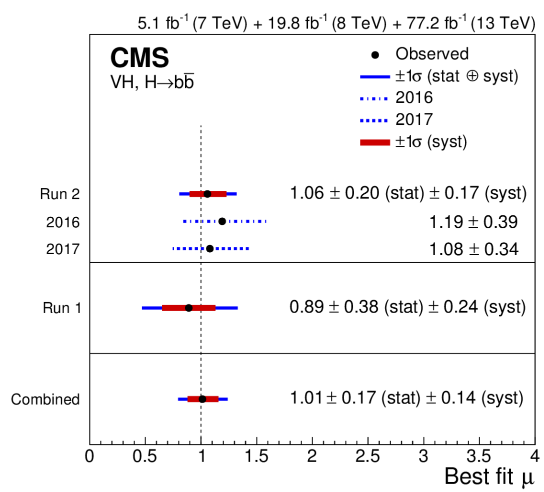




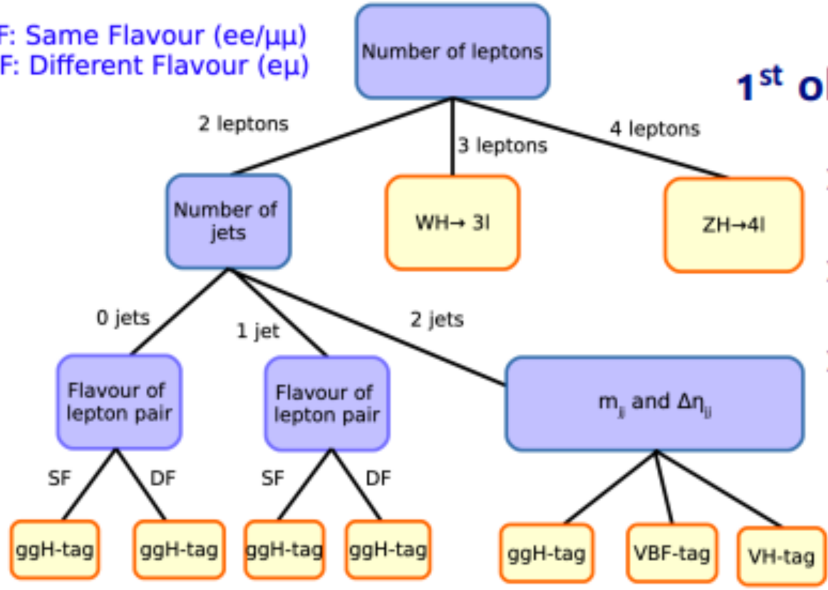


Significance:	**Measured signal strength:**
5.5σ expected	**μ = 1.04 ± 0.20**
5.6σ observed	

- **CMS achieved a >5σ observation of the H->bb decay combining several channels, dominated by VH(bb).**
- **SM assumption on Yukawa coupling to b's is confirmed within uncertainty (20%)**
- **All 3rd generation fermion couplings are now observed.**

Measurement of VH(H->WW)

SF: Same Flavour (ee/μμ)
DF: Different Flavour (eμ)

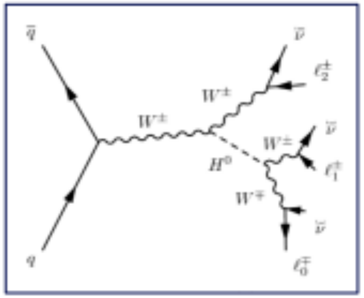


[10.1016/j.physletb.2018.12.073](https://doi.org/10.1016/j.physletb.2018.12.073)

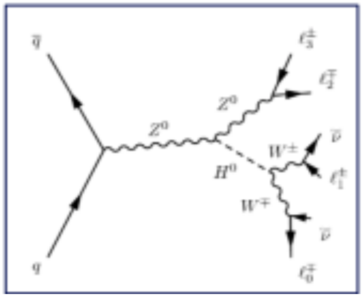
1st observation of the H→WW process in CMS

- Higgs production via ggH, VBF and **VH**
- Analysis based on the **2016** data (**35.9** fb^{-1})
- Categorization in Nr.-leptons and Nr.-jets

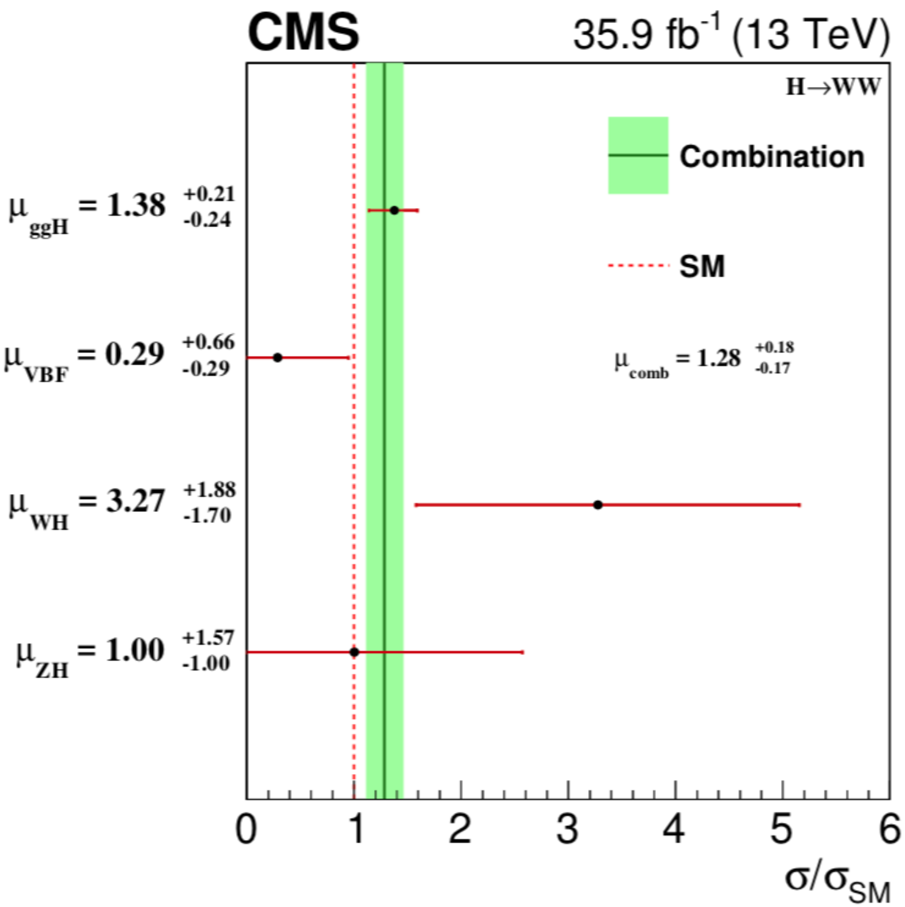
- **WH→3 leptons**
  - WZ and Zγ normalizations estimated from data with CR
  - Shape analsysis



- **ZH→4 leptons**
  - Categorization in the flavor of leptons from the Higgs
  - ZZ bkg normalization taken from data with CR.
  - Cut&Count analysis



Measurement of VH(H->WW)

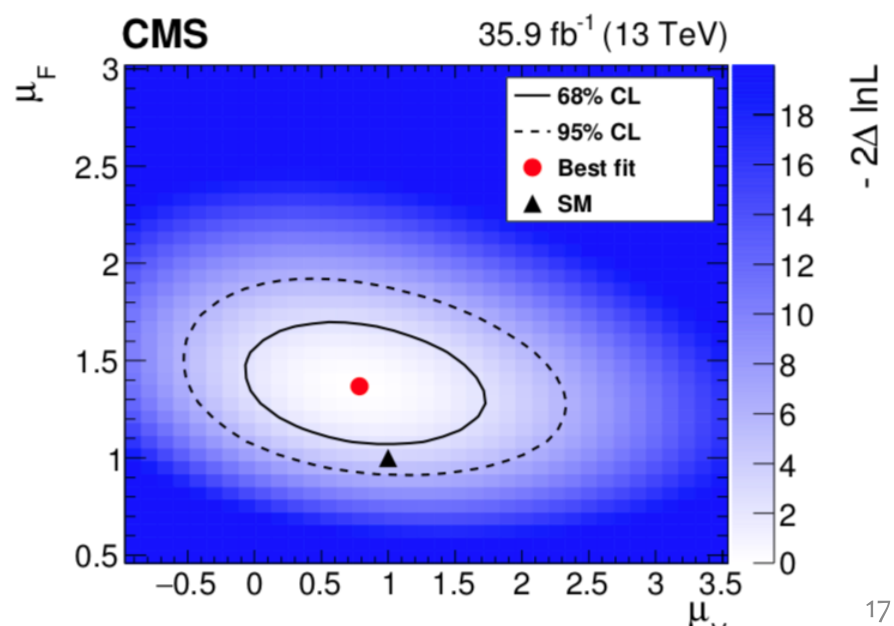


CMS combining all categories:

$\mu_{WH} = 3.27^{+1.88}_{-1.70}$

$\mu_{ZH} = 1.0^{+1.57}_{-1.0}$

Simultaneous fits are performed to probe the Higgs boson couplings to fermions and vector bosons



The VH production mode contributed to the first CMS observation of the H->WW* decay mode.

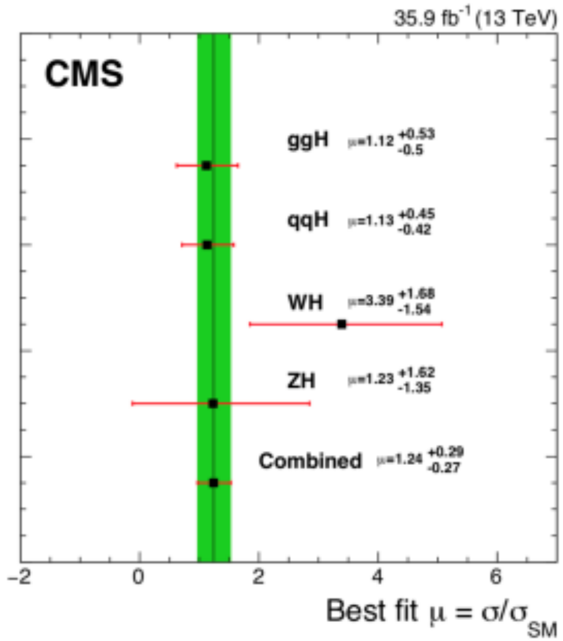
Measurement of VH(H->$\tau\tau$)

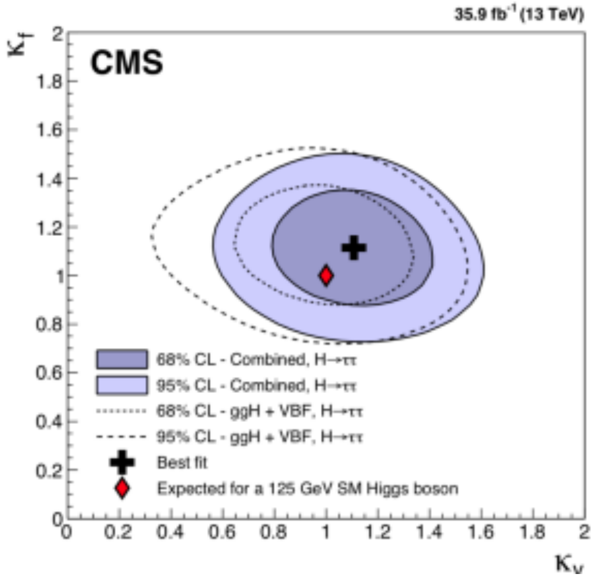
The H→$\tau\tau$ decay is the second most sensitive channel to establish VH production

- WH semi-leptonic: W($e\upsilon$)H($\mu\tau_h$), W($\mu\upsilon$)H($\mu\tau_h$)
- WH hadronic: W($e\upsilon$)H($\tau_h\tau_h$), W($\mu\upsilon$)H($\tau_h\tau_h$)
- With Z(ee)+H($\tau_e\tau_\mu$), H($\tau_e\tau_h$), H($\tau_\mu\tau_h$), H($\tau_h\tau$)
- With Z($\mu\mu$)+H($\tau_e\tau_\mu$), H($\tau_e\tau_h$), H($\tau_\mu\tau_h$), H($\tau_h\tau_h$)

Main Background:

- Irreducible: WZ, ZZ estimated from MC
- tt+jets, Z+jets, estimated with fake rate method





VH signal strength: CMS-HIG-18-007

$$\mu = 2.54^{+1.35}_{-1.26}\ (obs.)$$

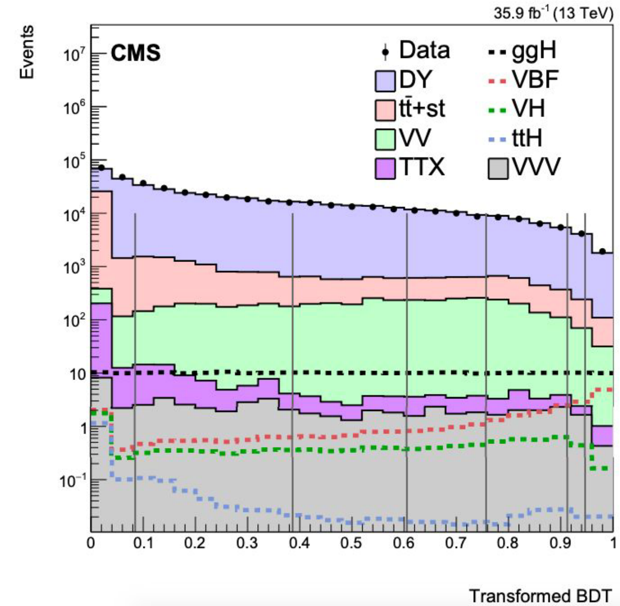
$$\mu = 1.00^{+1.08}_{-0.97}\ (exp.)$$

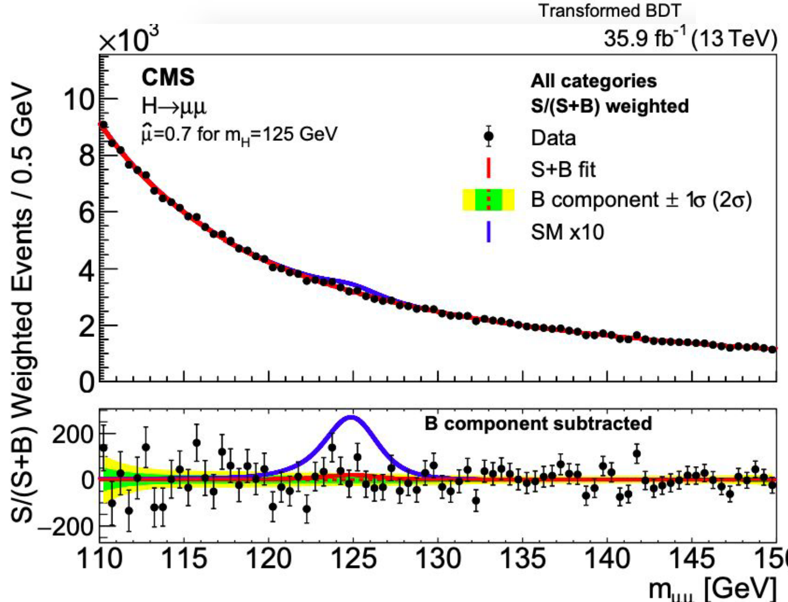
VH production mode represents a unique bench test to probe the coupling of the Higgs boson to leptons (VH($\tau\tau$))

Higgs->μμ analysis strategy and results

Phys. Rev. Lett. 122, 021801

- **Higgs boson decay to muons most sensitive channel to investigate couplings to 2nd generation fermions.**
  - very rare process, but high di-muon mass resolution makes channel accessible
- Signal would appear as narrow resonance over smoothly falling background (primarily Drell-Yan and leptonic top decays.)
- Separate signal from background using BDT.
  - Define 15 signal regions based on BDT score and η^{μ}
- Use analytic functions to describe signal and background distributions





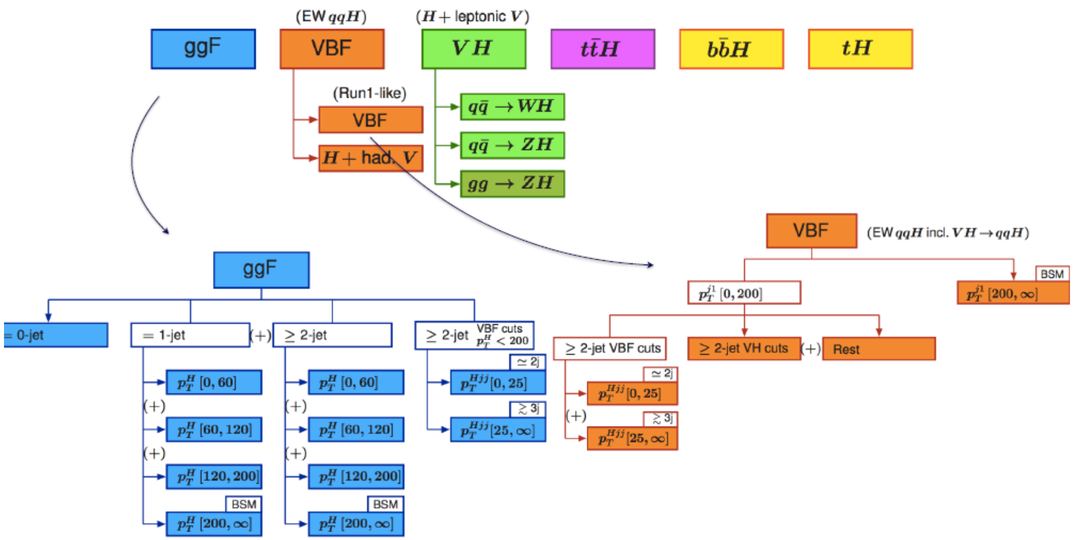
- 95% CL observed (background-only expected) upper limit on $\sigma x \mathcal{B}$ is:

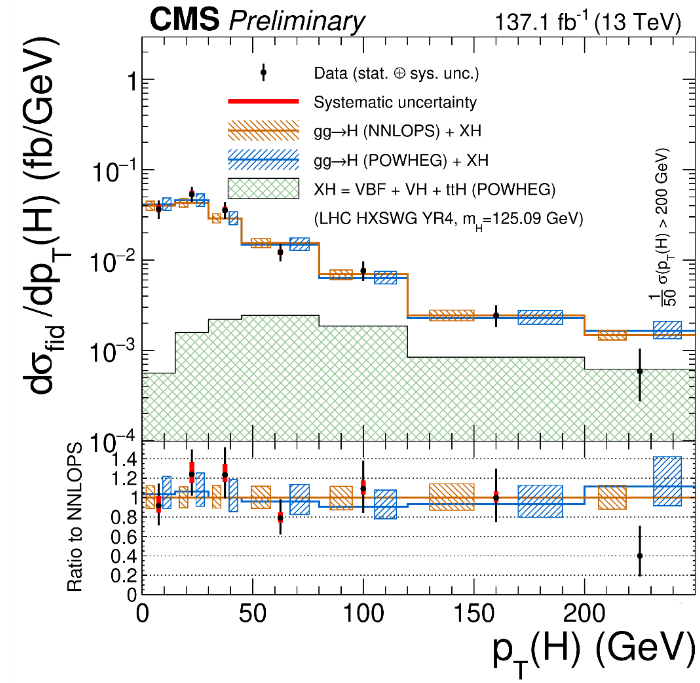
  2.9 (2.2) x SM

(Combination with data recorded at 7 and 8 TeV)

H → μμ in reach with full Run II and Run III data.

Current focus in Higgs boson measurements : ‘Simplified Template’ (STXS) and differential cross sections





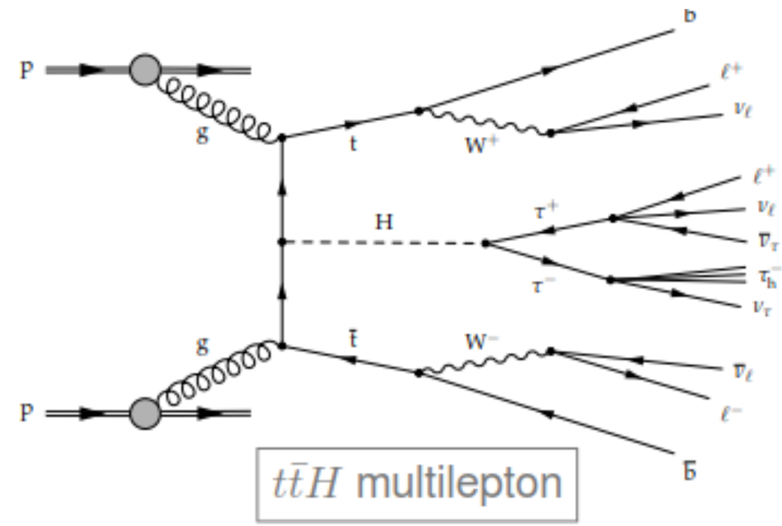
- Measure cross sections for the different production modes, split more finely into kinematic regions
- Results less model-dependent, more adapted for kinematically-dependent interpretations (EFT…)

CMS-PAS-HIG-19-001

- Also continue to target traditional differential cross section measurements

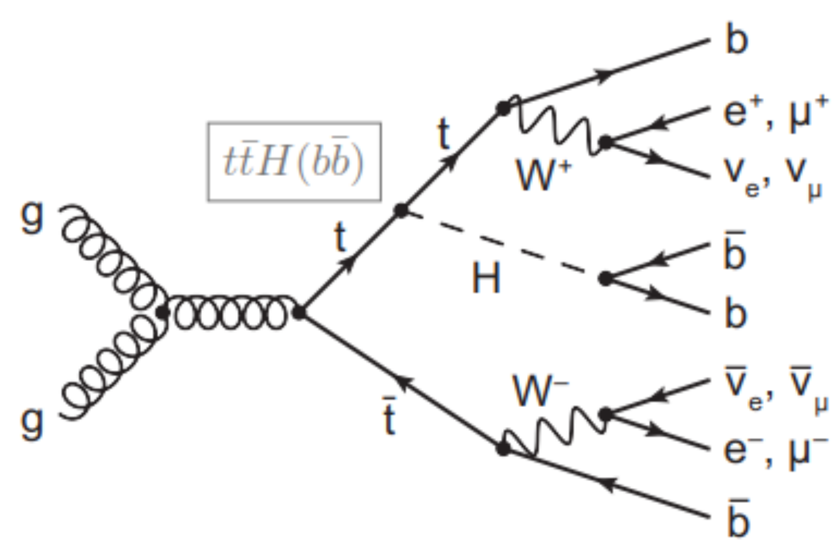
ttH analysis channels:

- $t\bar{t}H$ multilepton:
  - targets $H \rightarrow WW^*, ZZ^*, \tau^+\tau^-$
  - 2 same-sign or $\geqslant 3$ charged leptons, including hadronic τ decays



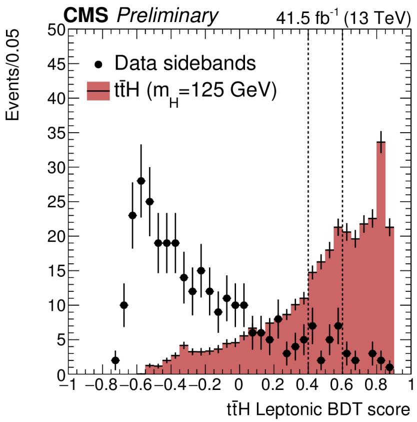
- $t\bar{t}H$ with $H \rightarrow b\bar{b}$ decays:
  - 0, 1 or 2 leptons + jets (with up to 4 b-jets)

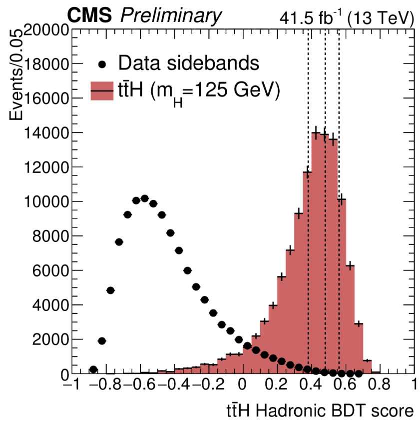
- $t\bar{t}H$ with $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$ decays:
  - high purity, but lowest signal yields
  - excess in inv-mass of Higgs candidate

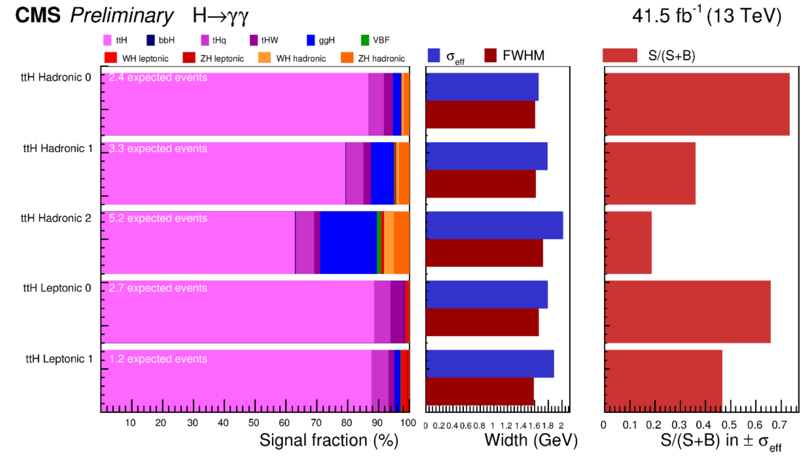


Recent results: ttH, H-> γγ

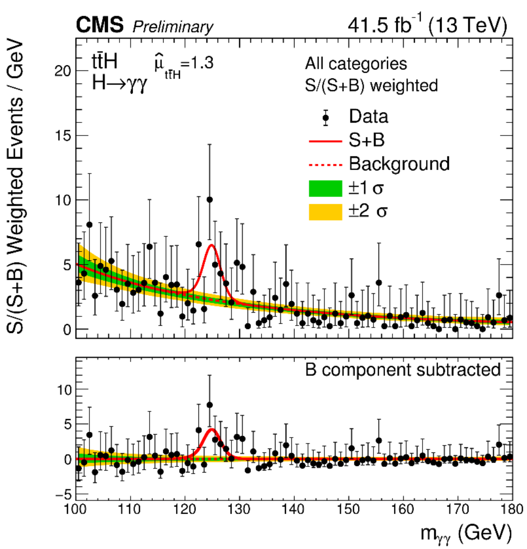
CMS-PAS-HIG-18-018

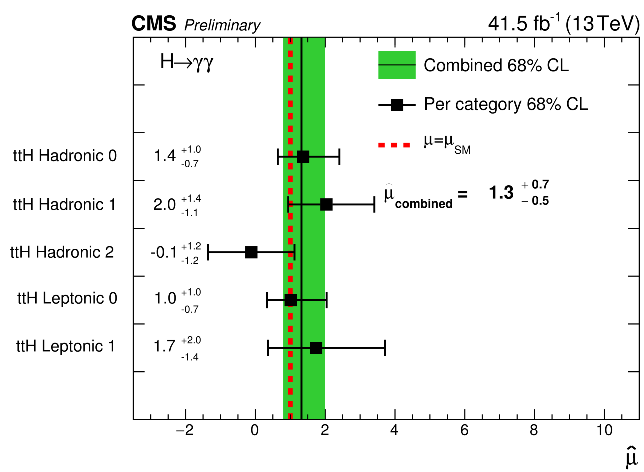


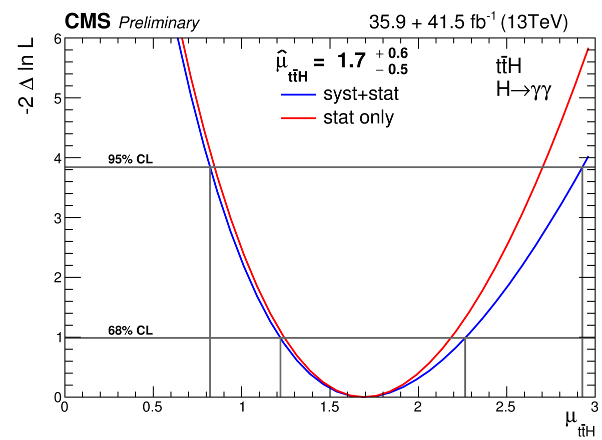




- **BDT used in all classes**



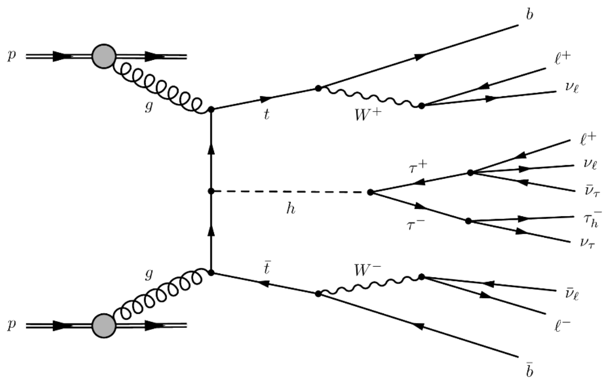




2016-2017 combined μ

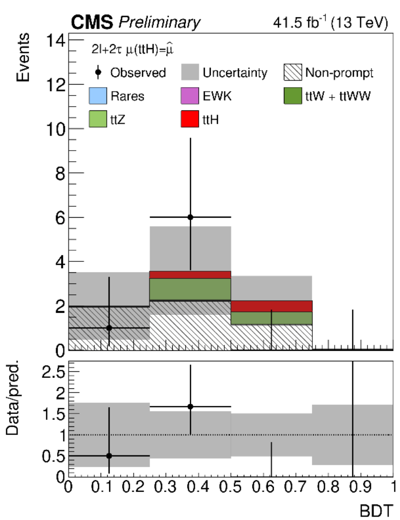
Recent results: ttH, multilepton (τ_h) final states

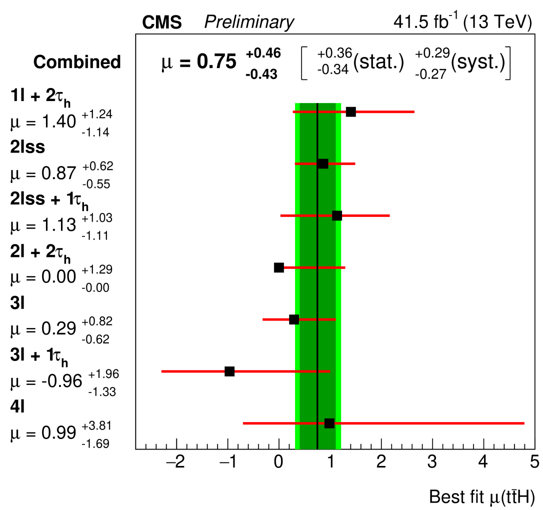
CMS-PAS-HIG-18-019



- 7 event classes including **1 new: $2\ell + 2\tau_h$**
- Classification:
- Main systematic uncertainty from fake background yield estimate
- Observed (expected) combined (2016+2017) signa rate : 0.96+0.34−0.31 (1.00+0.30−0.27) times SM

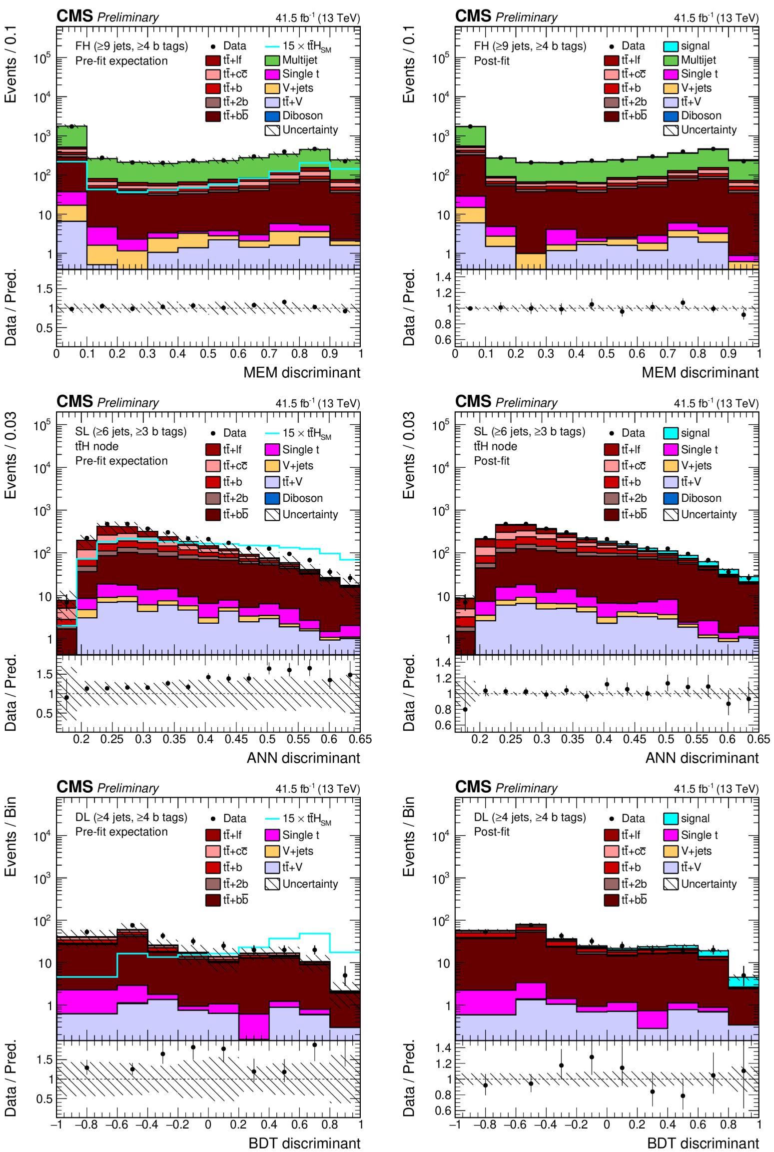
->**observed (expected) significance : 3.2σ (4.0σ)**



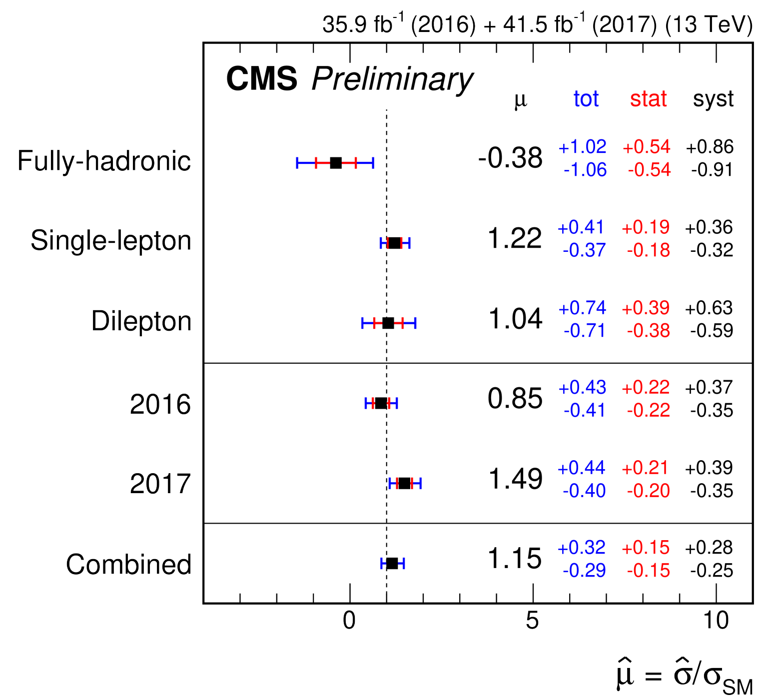


	Observed limit	Expected limit ($\mu = 0$)	Expected limit ($\mu = 1$)
$1\ell + 2\tau_h$	3.8	$2.4^{+1.3}_{-0.8}$	3.3
$2\ell ss$	2.0	$1.1^{+0.5}_{-0.3}$	1.9
$2\ell ss + 1\tau_h$	3.1	$2.1^{+1.0}_{-0.7}$	2.8
$2\ell + 2\tau_h$	5.2	$5.8^{+3.4}_{-2.0}$	6.8
3ℓ	1.7	$1.2^{+0.6}_{-0.4}$	2.1
$3\ell + 1\tau_h$	3.8	$4.6^{+2.7}_{-1.6}$	5.1
4ℓ	8.1	$6.2^{+3.6}_{-2.1}$	6.4
Combined	1.6	$0.8^{+0.3}_{-0.2}$	1.7
Combined with 2016 analysis	1.6	$0.6^{+0.2}_{-0.2}$	1.5

Recent results: ttH, **bb** final states CMS-PAS-HIG-18-030



- Events are selected based on **the number of leptons in the event, and categorised according to the number of jets.**
- **Multivariate analysis** techniques are employed to further categorise the events and discriminate between signal and background.
- A combined fit of multivariate discriminant distributions in all categories is used.



Combined with 2016 data, an **observed (expected) significance** of **3.9 (3.5)** s. d. above the background-only hypothesis is obtained.

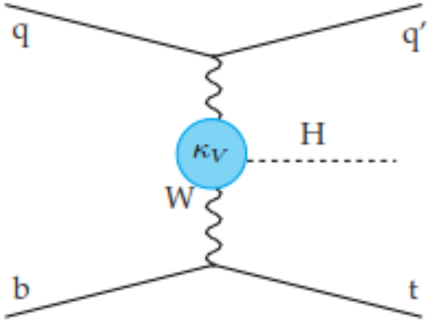
tH production

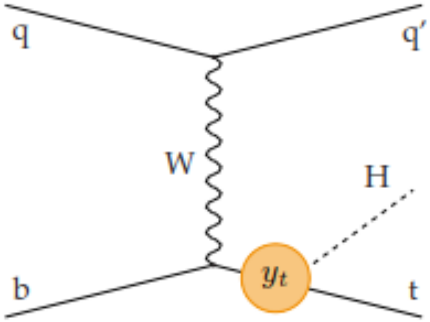
- tH production: tHq and tHW
  - depends on Higgs couplings to both top and gauge bosons
  - interf. effects make it sensitive to relative sign of y_t and g_{HVV}. For $\kappa_V = 1$:

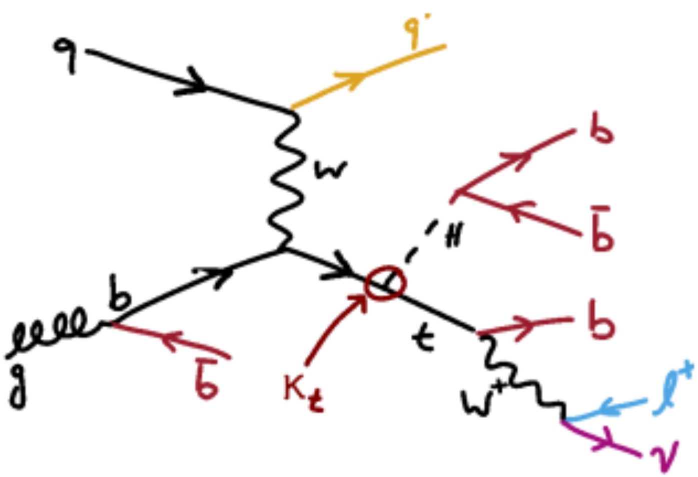
SM ($y_t = +1$) : low xsec (~ 0.1 pb) due to destructive interf.

ITC ($y_t = -1$) : xsec $\times 10$ higher wrt SM

- **CMS** has performed dedicated searches for tH production in multilepton and $H \to b\bar{b}$ channels using 2016 data
  - analysis methods (obj-reco, bkg model) similar to the corresponding $t\bar{t}H$ analyses



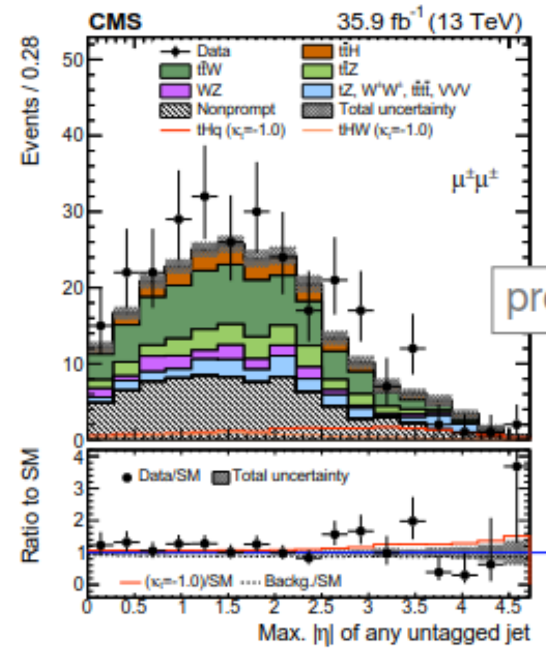




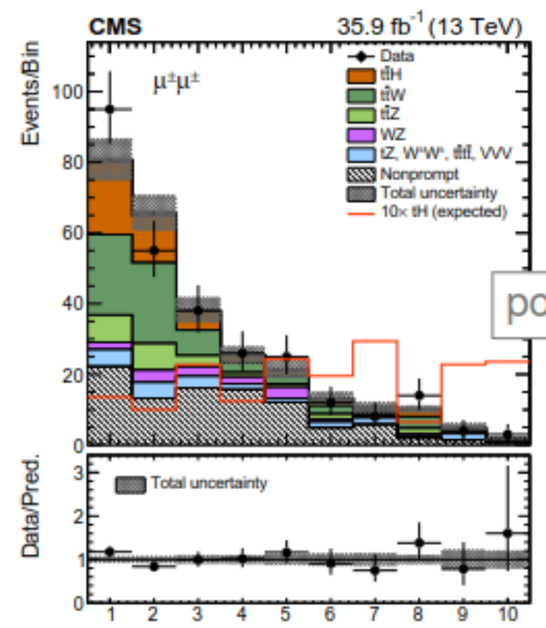
tH multilepton

HIG-18-009, HIG-17-005

- 3 channels: $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$ and 3ℓ
  - 1 b-jet + 1 forward jet in final state
- Signal yield:
  - tH SM (ITC) $\sim 1\%(10\%)$ wrt SM bkg
- final discriminant in each SR:
  1D dist. based on 2 BDT outputs
  [tHq vs $t\bar{t}V$], and [tHq vs $t\bar{t}$], inputs:
  - forward jet activity
  - jet and b-jet multiplicities
  - leptons' kinematics
- bkg model and dominant systematics
  very similar to $t\bar{t}H$ multilepton



pre-fit



post-fit

tH combination:

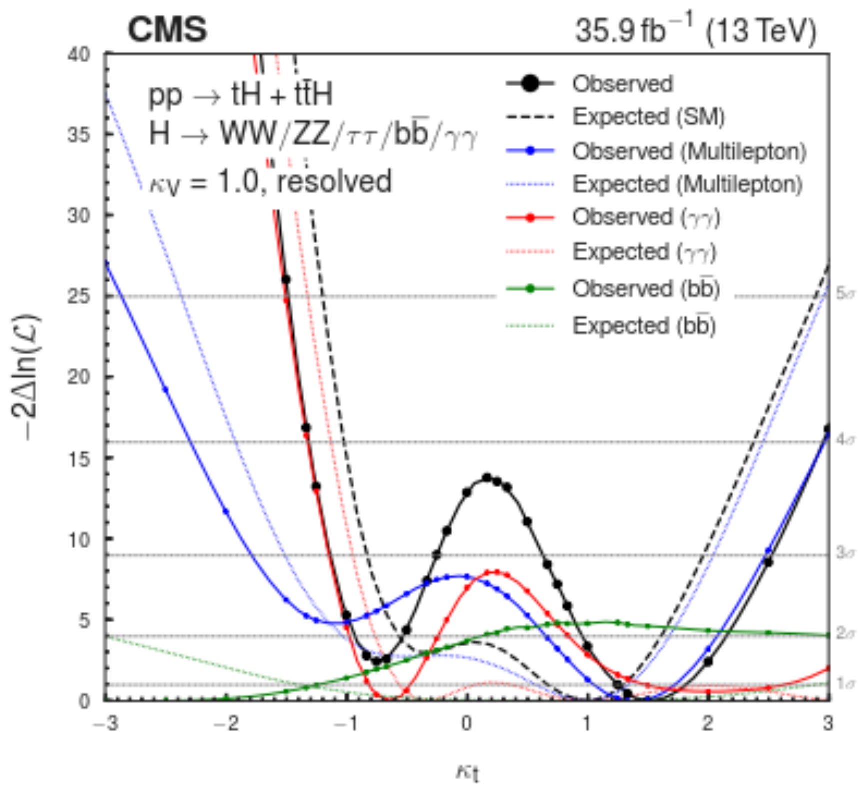
HIG-18-009

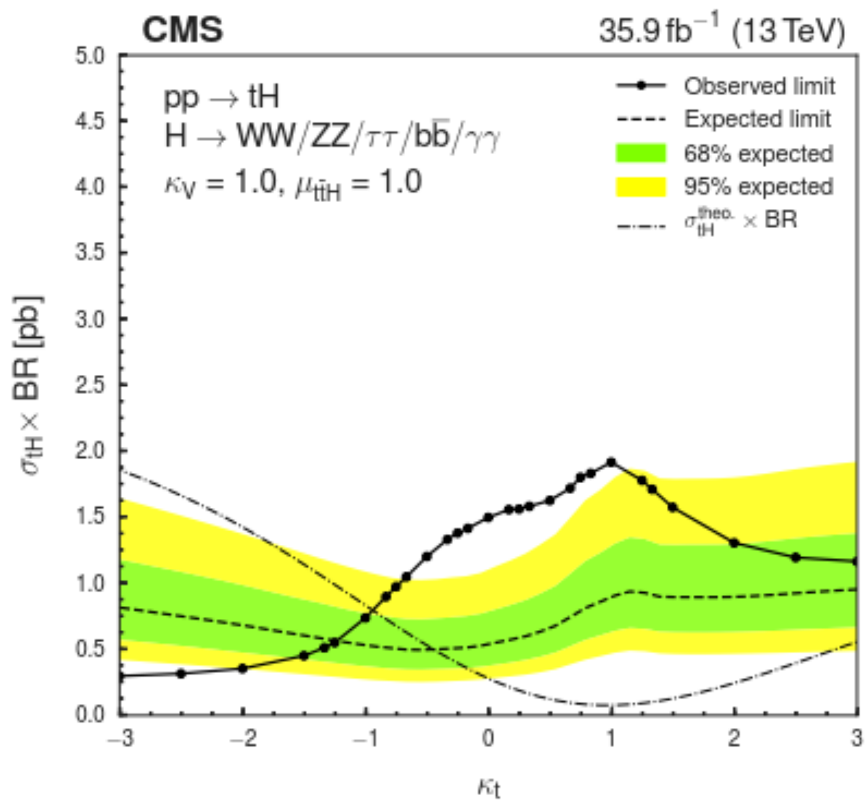
Likelihood scan with respect to κ_t ($\kappa_V = +1$):

- positive κ_t favored over negative value by 1.5σ
- y_t values outside of $[-0.9, -0.5]$ and $[1.0, 2.1]$ excluded at 95% CL

95% CL UL on $\sigma_{tH} \times$ BR ($\kappa_V = +1$):

- $t\bar{t}H$ yield fixed to SM (κ_t-dep.)
- Obs (Exp) UL for $y_t = +1$: $25(12) \times$ SM





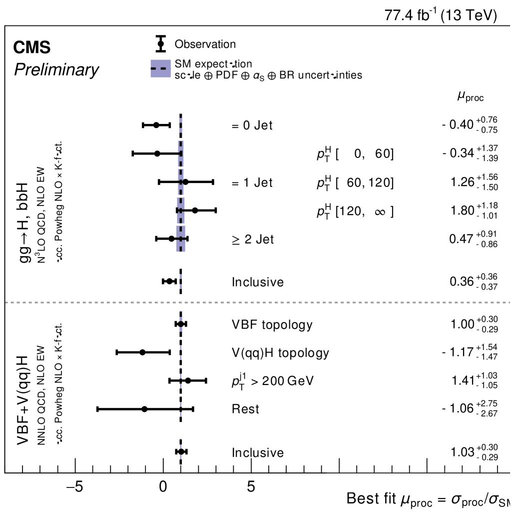
Recent results: H→ττ

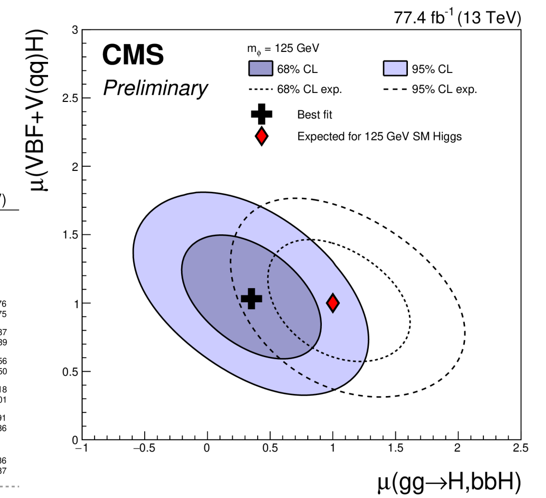
CMS-PAS-HIG-18-032

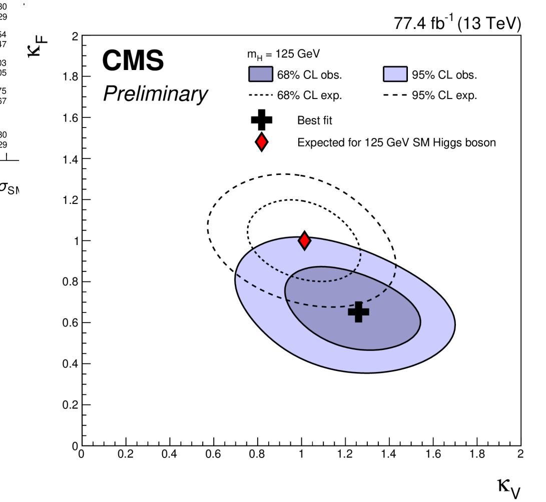
- Probes eμ, eτ$_h$, μτ$_h$ and τ$_h$τ$_h$ final states with 2016/17 data
- Signal extracted with fit to neural network output dist'n

Variable	eμ	eτ$_h$	μτ$_h$	τ$_h$τ$_h$
$m_{\tau\tau}^{SV}$	✓✓	✓✓	✓✓	✓✓
$m_{T\tau\tau}^{SV}$	✓✓	−−	−−	−−
$p_{T\tau\tau}^{SV}$	✓✓	−−	−−	−−
m_{vis}	✓−	✓−	✓−	✓✓
p_T^{vis}	✓✓	✓✓	✓−	✓−
$p_T^{\tau_1}$	−−	−−	✓−	✓✓
$p_T^{\tau_2}$	✓−	✓✓	✓✓	✓−
$\Delta R^{e\mu}$	✓✓	−−	−−	−−
$p_T(jet_1)$	✓✓	✓✓	✓✓	✓−
$\eta\ (jet_1)$	✓−	−−	−−	−−
$p_T(jet_2)$	✓✓	✓✓	✓✓	✓✓
$\eta\ (jet_2)$	✓−	−−	−−	−−
m_{jj}	✓✓	✓✓	✓✓	✓✓
$\Delta\eta_{jj}$	✓✓	✓✓	✓✓	✓✓

Variable	eμ	eτ$_h$	μτ$_h$	τ$_h$τ$_h$
p_T^{jj}	✓✓	✓✓	✓✓	✓✓
$p_T(b\ jet_1)$	−−	✓✓	✓✓	✓✓
$p_T(b\ jet_2)$	−−	✓✓	✓✓	✓✓
p_T^{miss}	−✓	✓✓	✓−	✓−
D_ζ	✓✓	−−	−−	−−
m_T^e	−−	✓✓	−−	−−
m_T^μ	✓✓	−−	✓✓	−−
$m_T^{e+\mu}$	✓−	−−	−−	−−
$\max(m_T^\mu, m_T^e)$	✓✓	−−	−−	−−
$m_T^{\tau_h}$	−−	✓✓	✓−	✓✓
$p_T^{\tau\tau+miss}$	✓✓	✓✓	✓✓	✓✓
$p_T^{\tau\tau jj+miss}$	−✓	−−	−−	−−
$N_{b\ jet}$	−−	✓✓	✓✓	✓✓
N_{jet}	✓✓	✓✓	✓✓	−✓







- Inclusive and per-process μ and σ, σ also in STXS bins

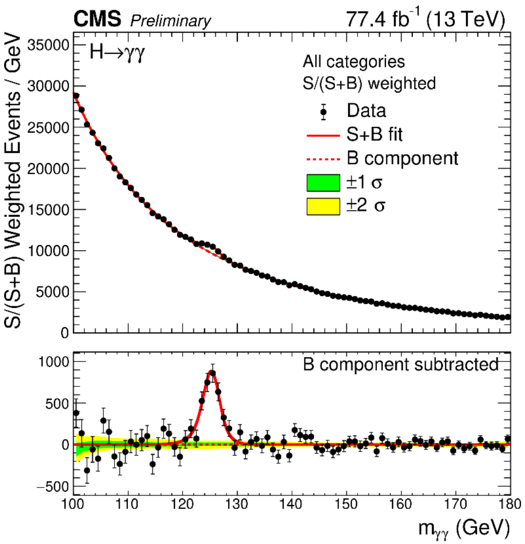
Processes (X)	μ_X	$\sigma_X\mathcal{B}(H\to\tau\tau)$ (pb) Expected	Observed
Inclusive	0.75 ± 0.14 (stat) ± 0.10 (syst)	3.40 ± 0.20 (theo)	2.56 ± 0.48 (stat) ± 0.34 (syst)
$gg \to H, bbH$	0.36 ± 0.26 (stat) ± 0.25 (syst)	3.07 ± 0.19 (theo)	1.11 ± 0.81 (stat) ± 0.78 (syst)
VBF+V(qq)H	1.03 ± 0.26 (stat) ± 0.14 (syst)	0.33 ± 0.01 (theo)	0.34 ± 0.08 (stat) ± 0.09 (syst)

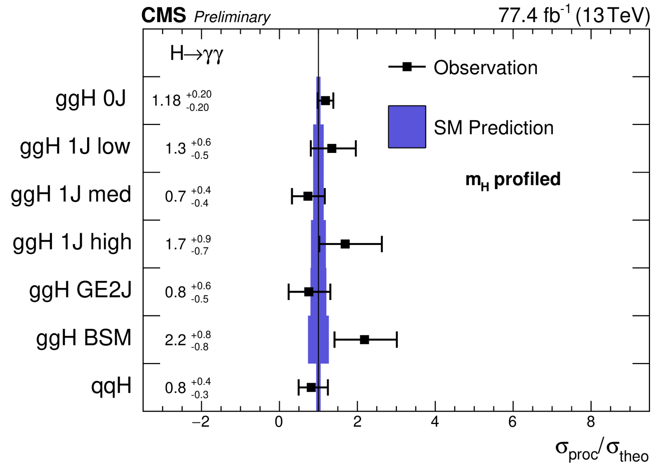
STXS allows the combination of fully optimised analysis techniques with a clean and interpretable framework

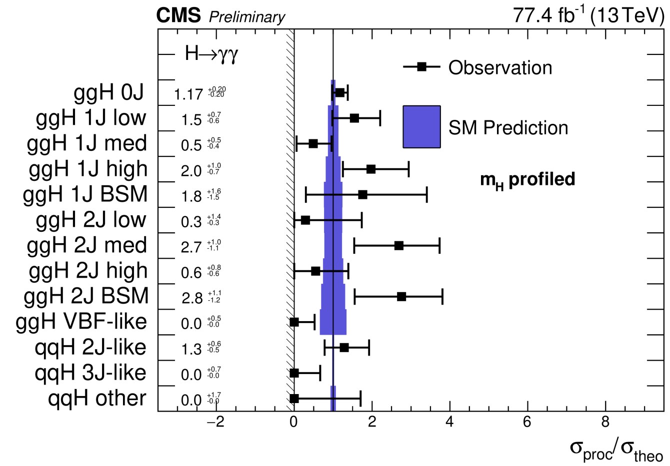
- μ of quark- vs gluon-initiated processes, κ_F vs κ_V

Recent results: H->γγ STXS

CMS-PAS-HIG-18-029







- 2016/17 data combined permits cross section measurements in STXS 'stage 1' with some bins merged: 7- and 13-bin variants
- All measurements in agreement with SM predictions

Recent Results: H->ZZ*->4ℓ **Full Run 2**

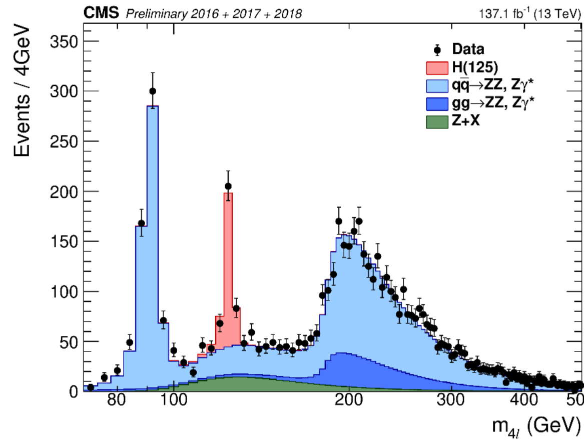
CMS-PAS-HIG-19-001

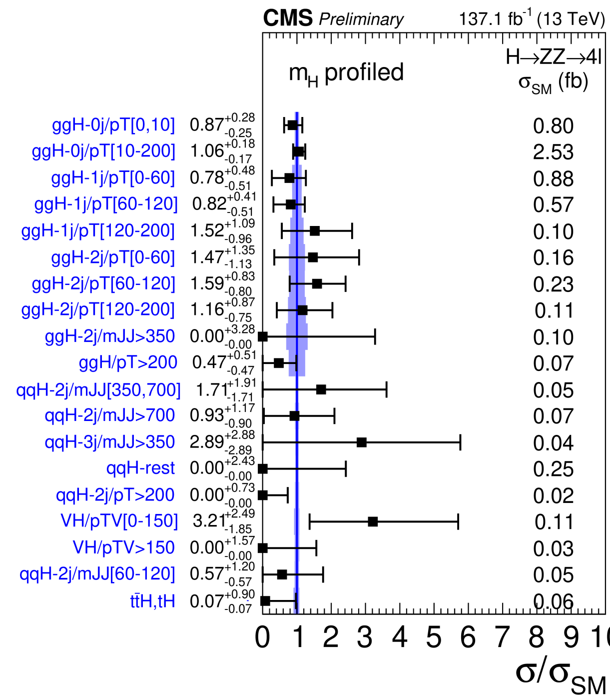
- Fiducial cross section $\sqrt{s}$= 13 TeV agrees with SM predictions:

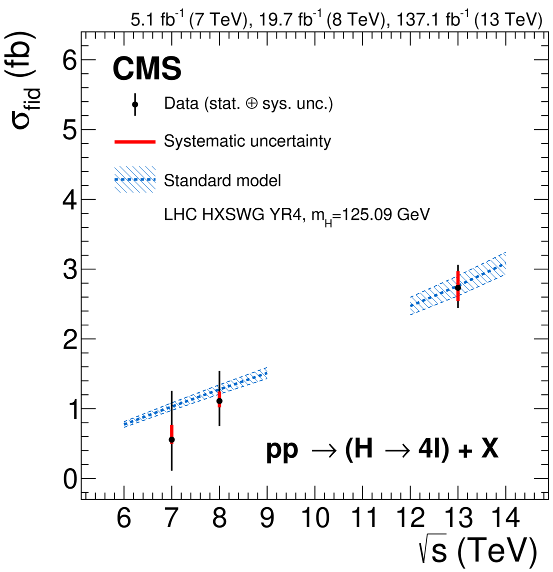
$$\sigma_{fid} = 2.73^{+0.23}_{-0.22}(\text{stat.})^{+0.24}_{-0.19}(\text{syst.})\ \text{fb}$$

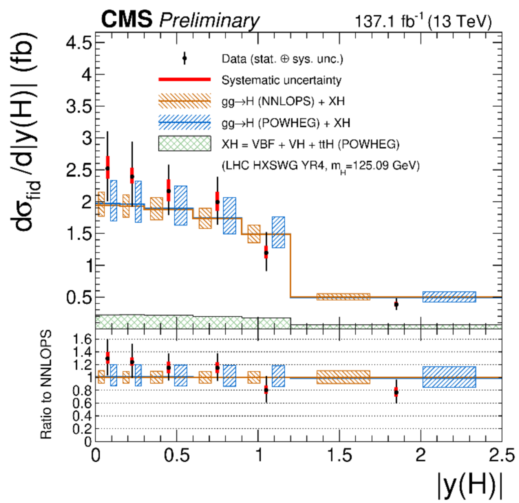
$$\sigma_{SM} = 2.76 \pm 0.14\ \text{fb}$$

- As well as at the other 2 $\sqrt{s}$





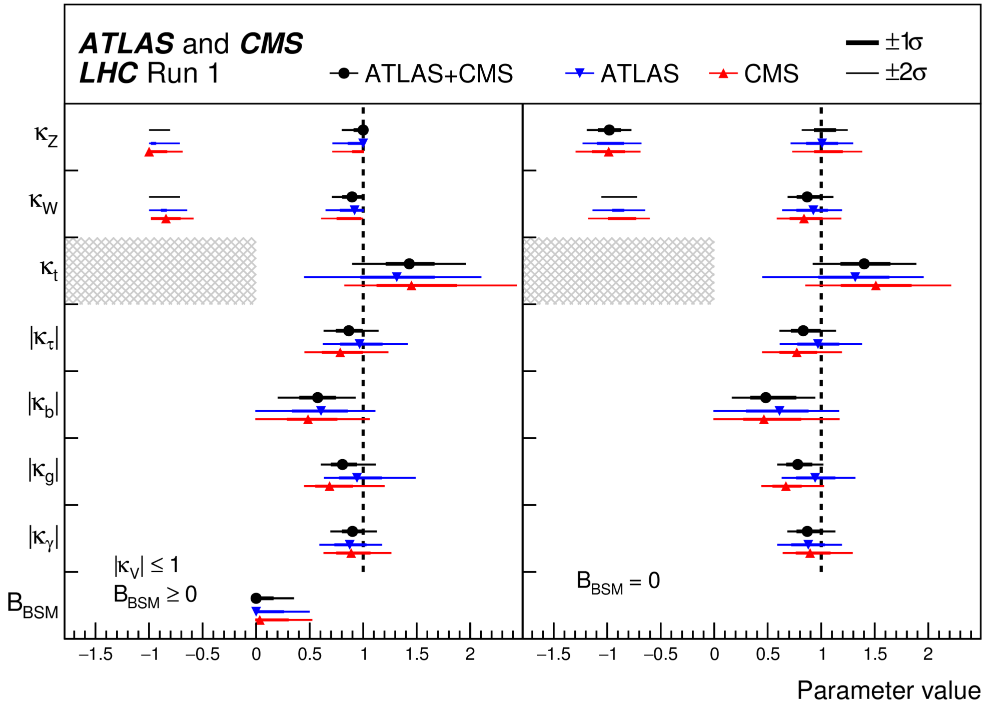


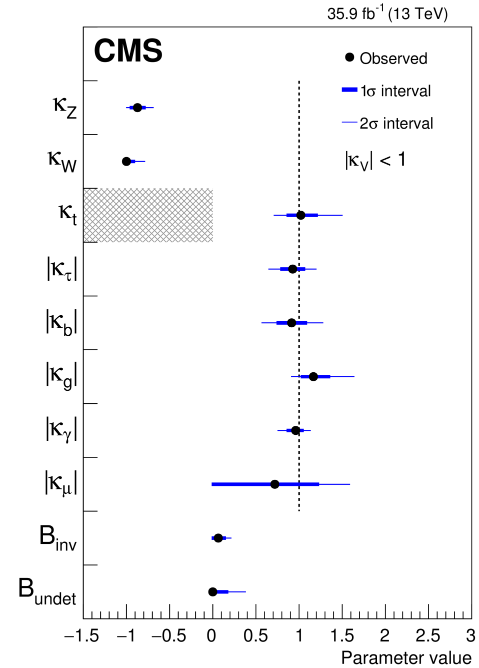


- Cross-section measurements in many STXS bins ('Stage 1.1') and differential measurements in several variables possible, all compatible with SM predictions

Generic Parametrization

HIG-17-031 arXiv:1809.10733, accepted by Eur.Phys J.C



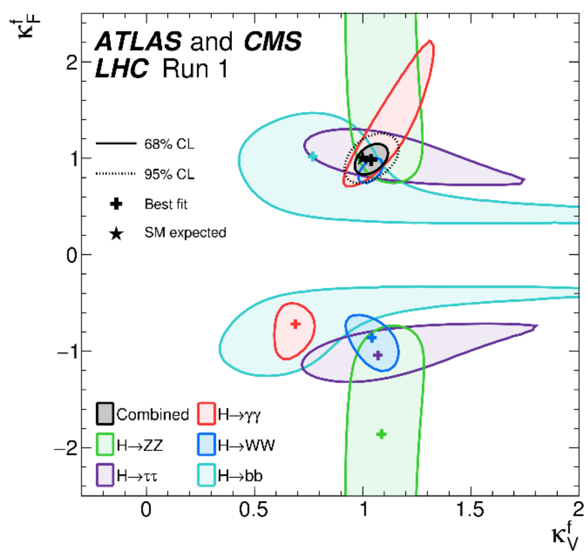


- Allow BSM loop contributions + either BSM contributions to Γ_H ($\kappa_V \leq 1$) or not (BR_{BSM} =0)

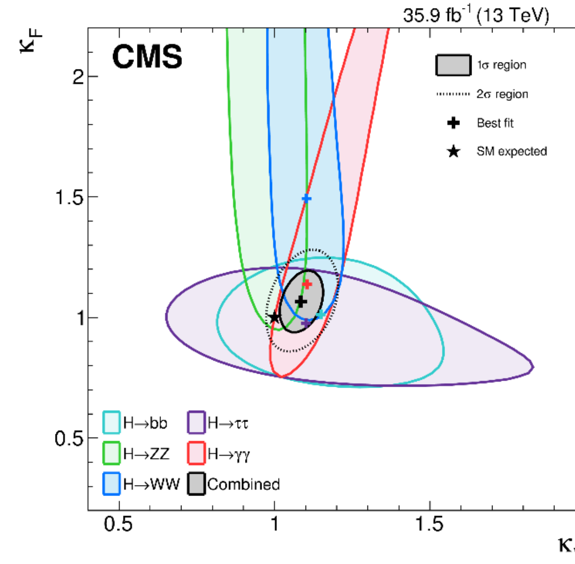
- ATLAS+CMS Run 1: BR_{BSM} < 0.34 @95%CL
- CMS 2016: B_{inv}<0.22, B_{undet}<0.38

κ framework constrained scenarios

- Assume no BSM loop contributions and BR_{BSM} =0: Coupling modifiers to fermions vs. to vector bosons

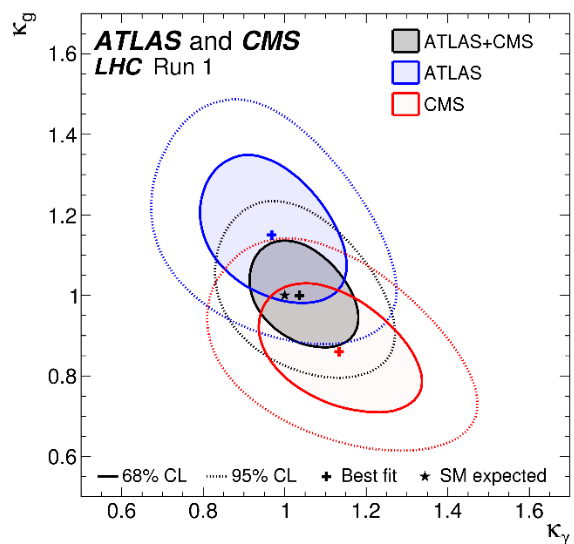


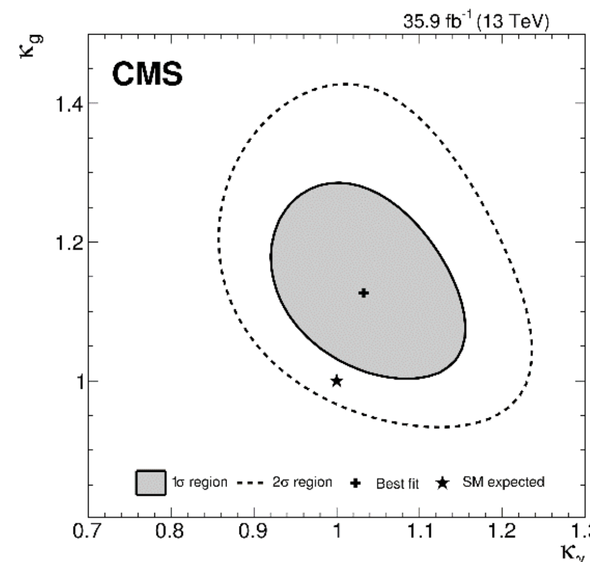
J. High Energy Phys. 08 (2016) 045



arXiv:1809.10733, accepted by Eur.Phys J.C

- Assume BSM contributions from loops only (BR_{BSM} =0), other κ fixed to SM values: Effective coupling modifiers κ_g , κ_γ for loops describing ggF production and H→γγ decay

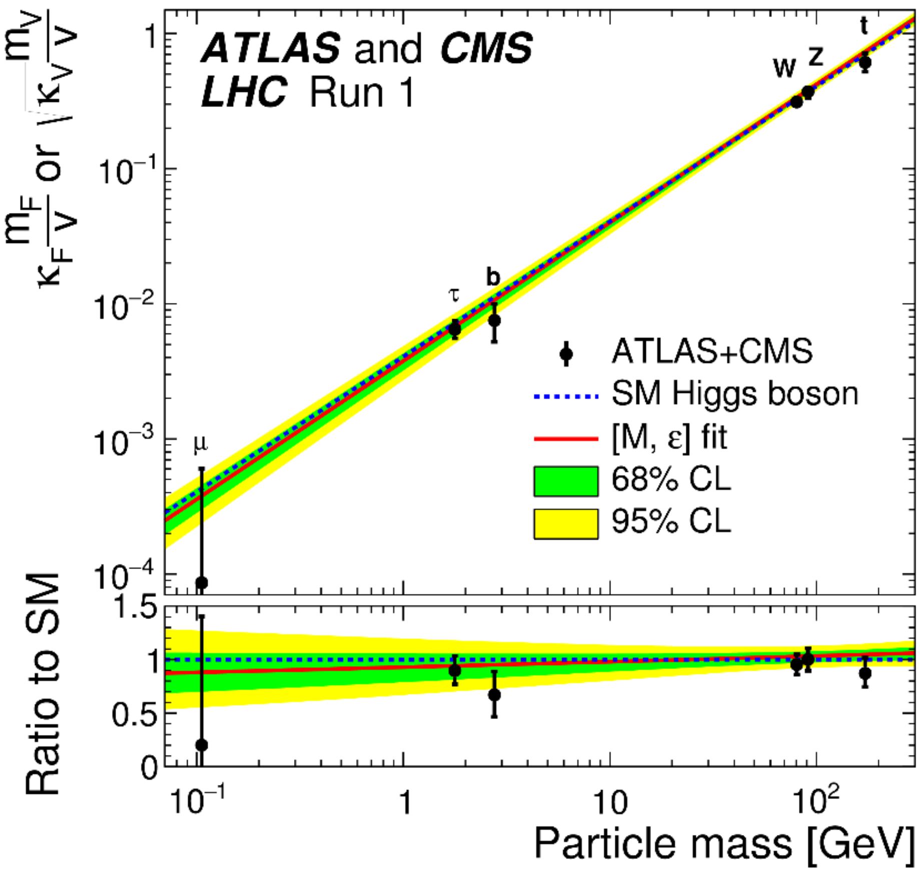


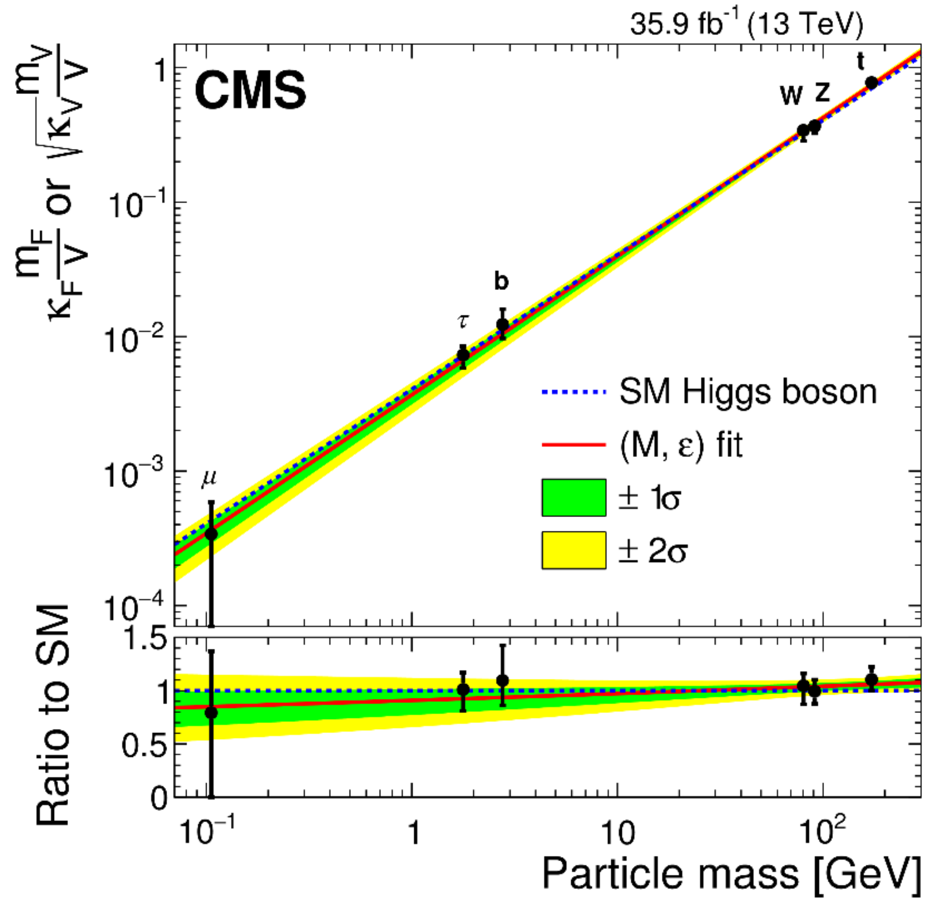


Mass-scaled κ vs. Mass

J. High Energy Phys. 08 (2016) 045

arXiv:1809.10733, accepted by Eur.Phys J.C

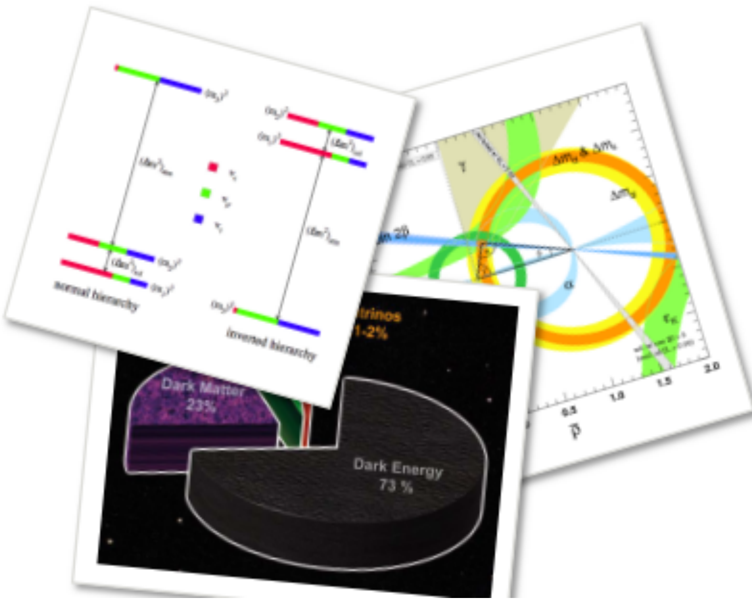




– Assume no BSM loop contributions and $BR_{BSM}=0$

Rare and BSM decays

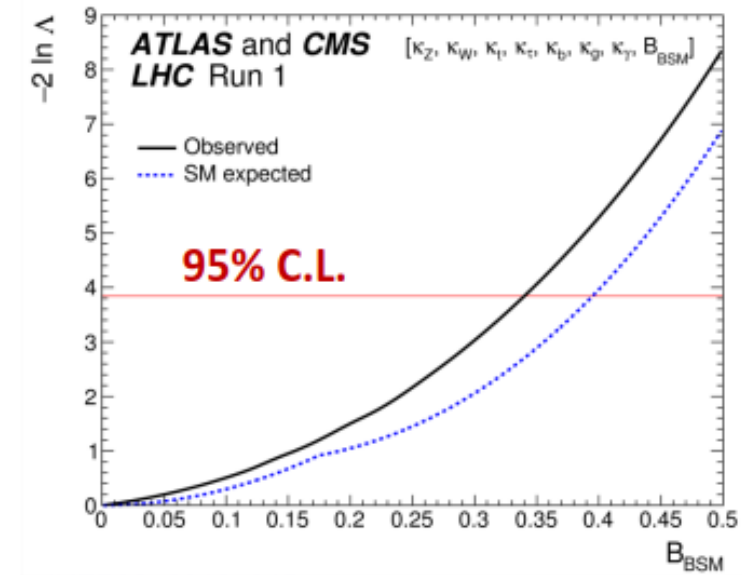
- **The discovery of a new boson consistent with the Standard Model (SM) Higgs boson has completed the SM theory**
- Nevertheless, this theory cannot address several crucial issues
- Direct evidence from observation:
  - existence of neutrino masses
  - existence of dark matter and dark energ
  - matter-antimatter asymmetry
- Conceptual problems in the SM:
  - the large number of free parameters
  - the "hierarchy problem“
  - the coupling unification



Strong indications that the SM is only a low-energy expression of a more global theory

Exotic Decays of the Higgs Boson

- The SM Higgs boson has a very narrow width (~4 MeV): current limits still allow for **additional contributions from BSM decays**
- Constraints on new physics are still relatively loose (Run 1 limit $\mathcal{B}(H \to BSM) < 34\%$)
- Possibilities to **detect BSM physics** in the scalar sector:
  - **Direct evidence** through observation of BSM decays of the Higgs boson
  - **Indirect evidence** through observation of deviations in the couplings of the H boson



JHEP08 (2016) 045

Search for BSM Physics in Higgs Decays

- Search for Higgs boson decays to SM particles:
  - Very rare decays predicted by the SM
    - An excess on these channels would be an indication of BSM physics
  - **Decays not allowed in the SM**
    - Lepton flavor violating Higgs decays

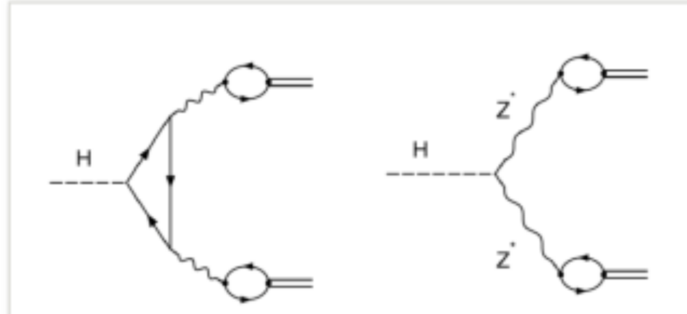
- Search for Higgs boson decays to non-SM particles:
  - **Invisible** Higgs boson decays, with H produced via
  - ggF, VBF, VH or ttH ($H \to$ invisible)
  - Higgs boson decays to light pseudoscalars/scalars

  ($H \to aa$), decaying to SM particles

(Recent) results reported here CMS-HIG-18-025, CMS-EXO-19-007, CMS-HIG-17-023, CMS-HIG-18-008, CMS-HIG-18-006

Rare Decay: H → J/ψJ/ψ - YY

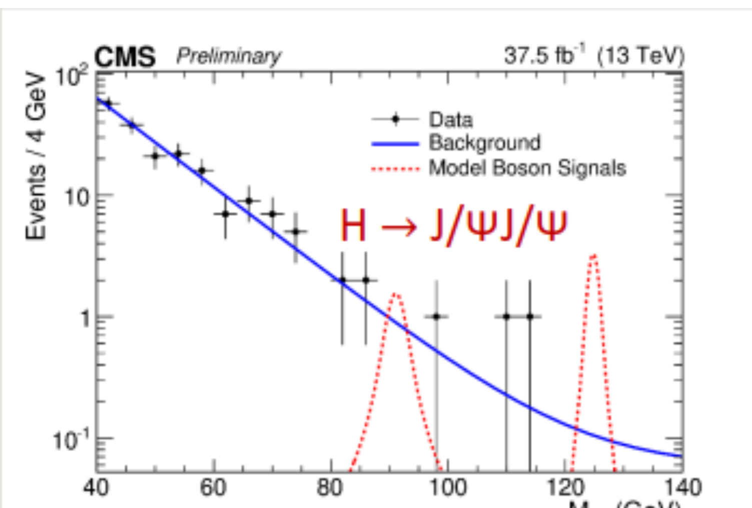
- Almost background-free
  - sensitivity scales with luminosity
- 4-muon final state: **very clean signature with narrow intermediate resonant states**
- • Dedicated triggers: 2μ ($m_{J/\psi}$), 3μ (m_{Υ})



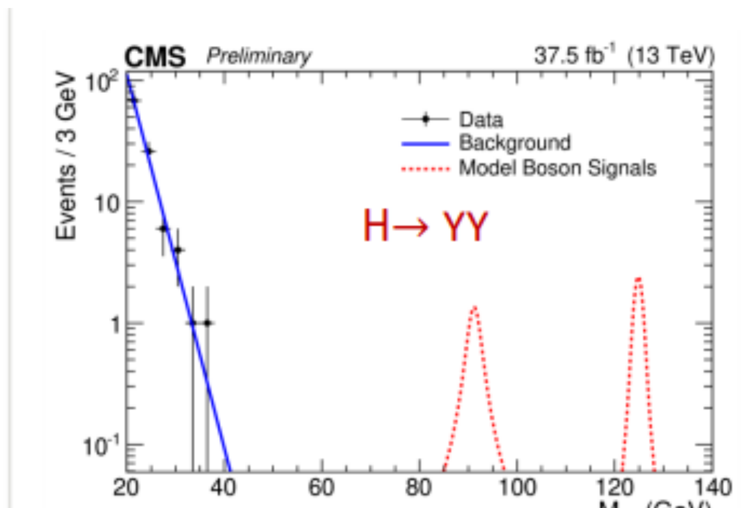
CMS-HIG-18-025

CHANNEL	BR (SM)
H → ΥΥ	$\sim 2 \times 10^{-9}$
H → J/ψ J/ψ	$\sim 1.5 \times 10^{-10}$

Exclusion Limits at 95%	observed	expected
$\mathcal{B}(H \to J/\psi J/\psi) \times 10^3$	1.8	$1.8^{+0.2}_{-0.1}$
$\mathcal{B}(H \to \Upsilon\Upsilon) \times 10^3$	1.4	1.4 ± 0.1



CMS-HIG-18-025

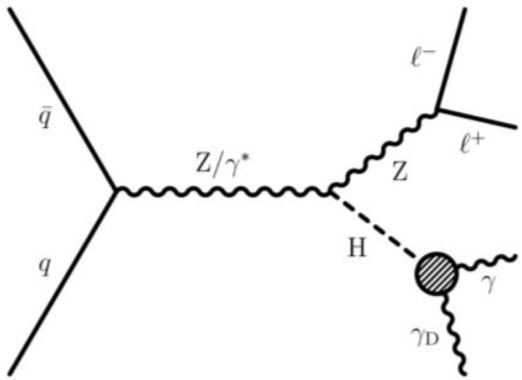


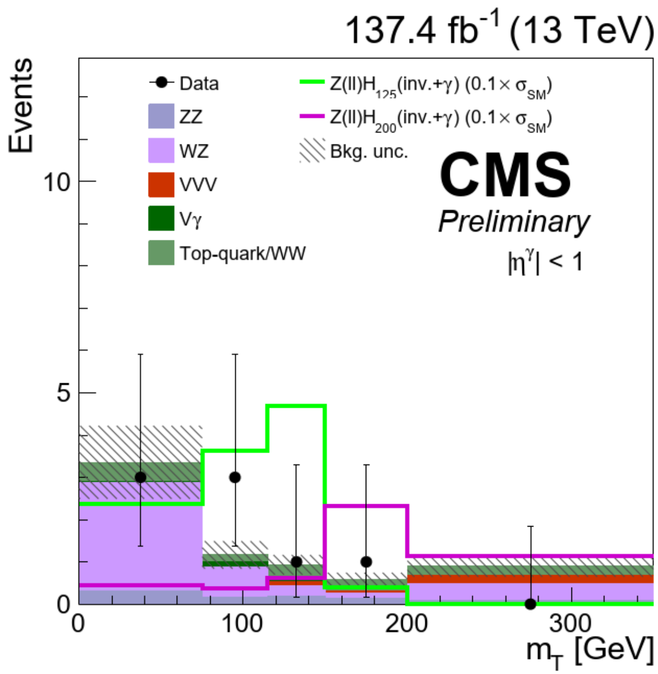
CMS-HIG-18-025

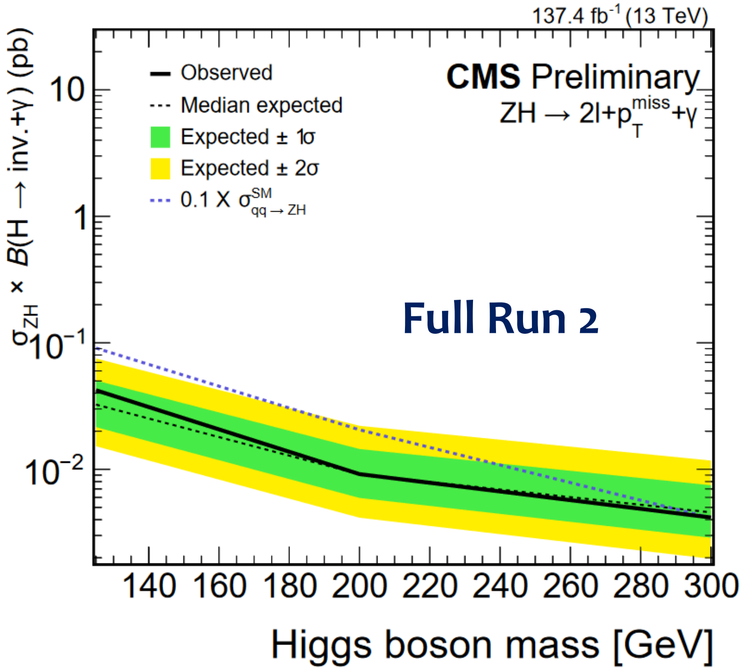
Search for Dark Photons in ZH Decays

- Massless dark photon that couples to Higgs boson
  - γ_D is a dark photon, which is undetected (large p_T^{miss})
- Two opposite-sign same-flavor leptons and a photon
- Background from data-based method and simulation
- $\boldsymbol{m_T}$ (transverse mass of p_T^{miss} and photon system) and $|\boldsymbol{\eta^\gamma}|$ used in the fit

CMS-EXO-19-007

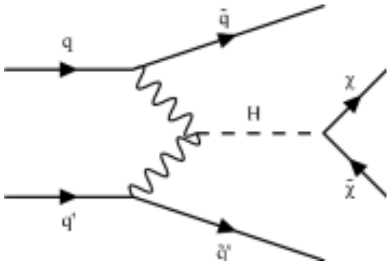




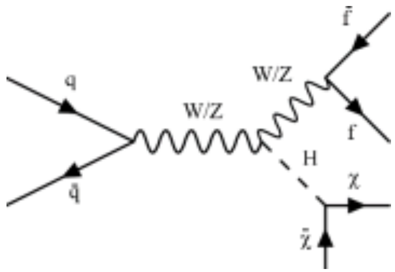


Higgs To Invisible Searches

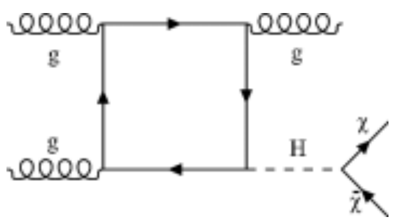
- In the SM, H → invisible only via H → ZZ* → 4ν with BR of 0.1%
  - Rate for invisible decays significantly enhanced in several BSM scenarios
  - The 125 GeV boson could be a portal between a dark sector and the SM sector
  - All the main Higgs production modes can be used to probe its coupling with "invisible" particles
  - All searches characterized by large p_T^{miss} (DM particles escape detection)
  - The Higgs boson recoils against a visible system used to distinguish between production modes



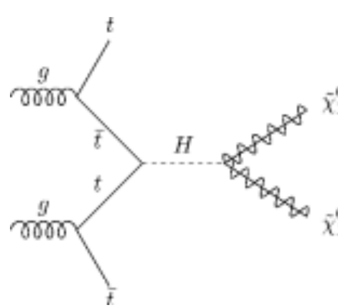
VBF



VH (V→ ℓℓ, *qq'*)



ggH + jet



ttH

Higgs To Invisible Searches

- **VBF topology**: characteristic final states with two jets with large $\Delta\eta_{jj}$ and m_{jj}
  - Allows for suppression of SM backgrounds: most sensitive production mode
  - Main backgrounds: W+jets, Z+jets
- Background estimated from high-purity 1 or 2 lepton CRs
- Improved sensitivity by fitting the shape of the m_{jj} distribution

Observed (expected) limit @ 95% CL [36 fb-1]:
$\mathcal{B}$(H→inv) < 0.33 (0.25)

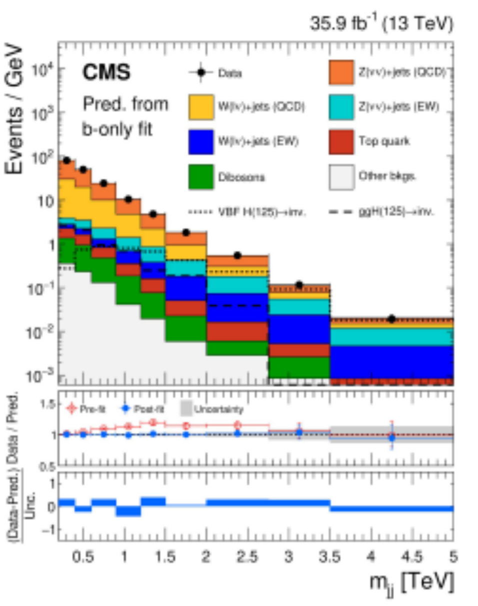
Higgs → Invisible [Z→ℓℓ]

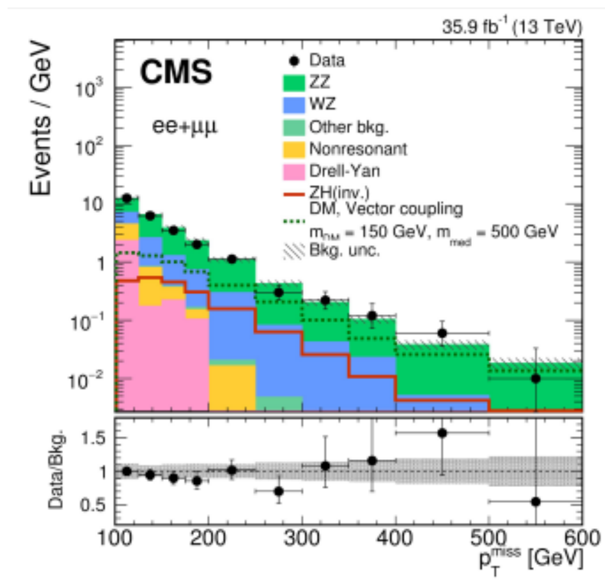
Signature: 2 opposite-sign, same-flavor electrons or muons + pTmiss

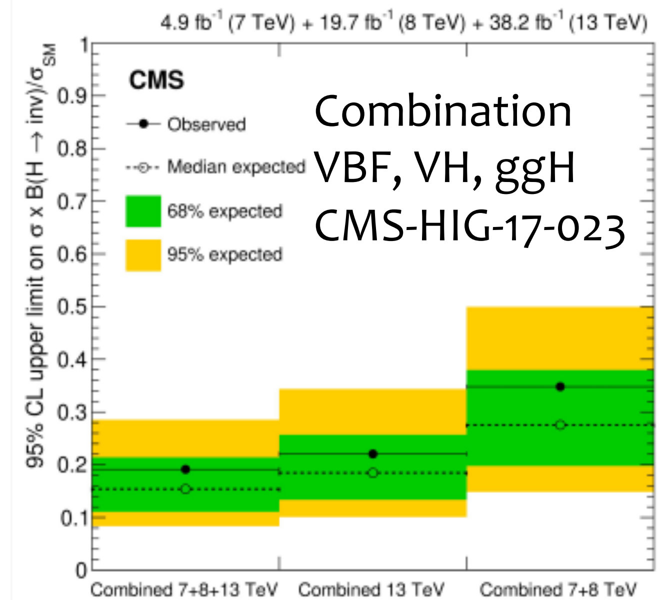
Main backgrounds: Z(ℓℓ)Z(νν), Z(ℓℓ)W(ℓν)

- Require dilepton system be back-to-back wrt p_T^{miss} 12-variable BDT

Observed (expected) limit @ 95% CL [36 fb-1]:
$\mathcal{B}$(H→inv) < 0.40 (0.42)





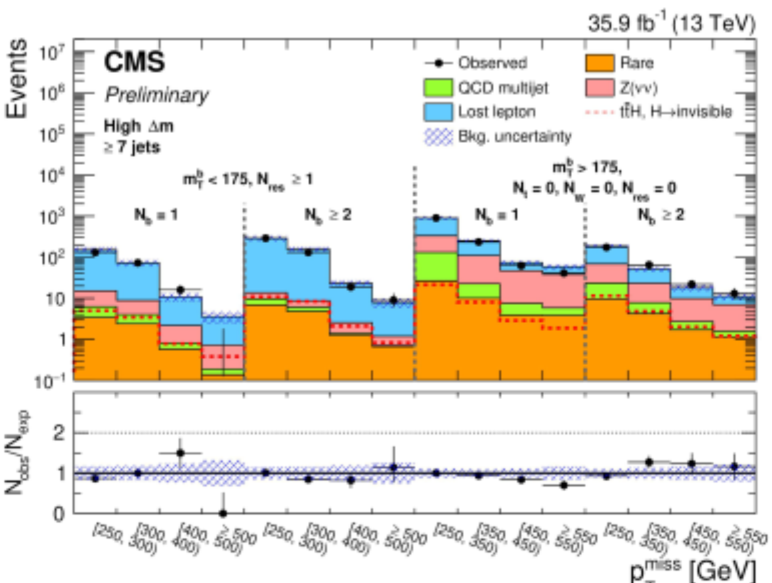


Observed (expected) limit @ 95% CL:
Run 1 + Run 2: $\mathcal{B}$(H→inv) < 0.19 (0.15)

H → Invisible [ttH], and H→Exotic [LFV]

Reinterpretation of results from 0/1/2ℓ stop searches (0/1/2ℓ + jets + pTmiss + b-tag)
No modification to signal regions and background predictions
No re-optimization for ttH signals
Multiple signal bins to cover large parameter space
Major backgrounds constrained/validated in control regions

CMS-HIG-18-008

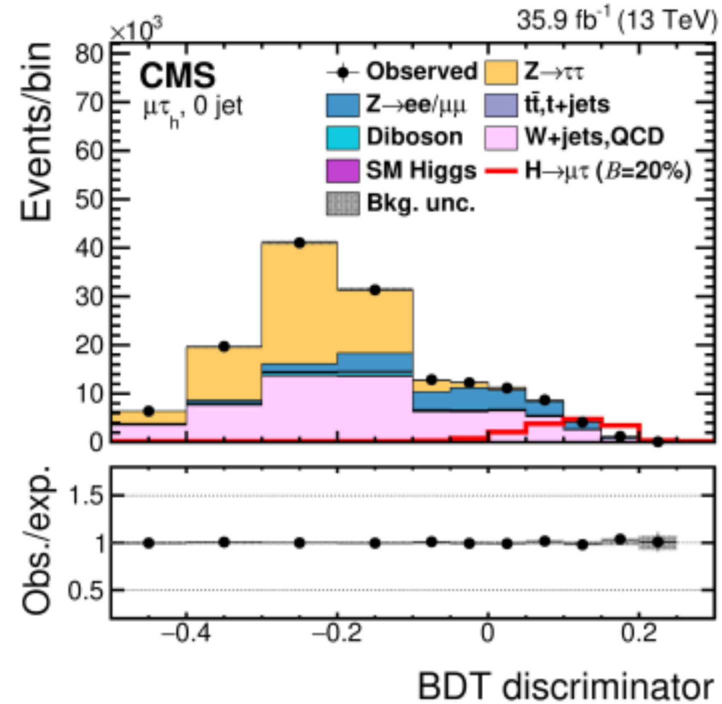


Observed (expected) limit @ 95% CL [36 fb-1]:
$\mathcal{B}$(H→inv) < 0.46 (0.48)

CMS-HIG-17-001

H → e+τ / μ+τ
- Multiple τ-decay channels
- BDT fits to improve sensitivity

Observed (expected) limit @ 95% CL [36 fb-1]:
$\mathcal{B}$(H → μτ) < 0.25 (0.25) %
$\mathcal{B}$(H → eτ) < 0.61 (0.37) %



Exotic Decays in 2HDMs

- Two-Higgs-doublet models are simple extensions of the SM introducing two doublets of scalar fields (ϕ1 and ϕ2) in the SM Lagrangian
- After symmetry breaking, five physical states are left (h, H, A and H± bosons)
- Four types, according to different patterns of quark and lepton couplings

Further extension 2HDM+S: possible search for H $\rightarrow$ $\boldsymbol{aa}$ (a pseudoscalar)
Exotic decays still consistent with all the LHC measurements so far

$a \rightarrow bb$

- ✓ **Large BR**
- ✗ Hard to trigger
- ✗ Low identification efficiency
- ✗ High p_T thresholds
- ✗ Large jet-backgrounds

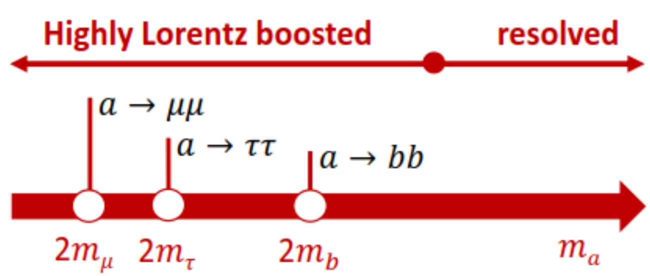
$a \rightarrow \tau\tau$

- ✓ **Large BR**
- ✓ Possible to **trigger** on leptonic τ decays
- ✗ Low τ_h identification efficiency, with high p_T thresholds (> 20 GeV)

With SM-like couplings:
$\mathcal{B}(a \rightarrow bb) \sim$
$9\,\mathcal{B}(a \rightarrow \tau\tau) \sim$
$1700\,\mathcal{B}(a \rightarrow \mu\mu)$

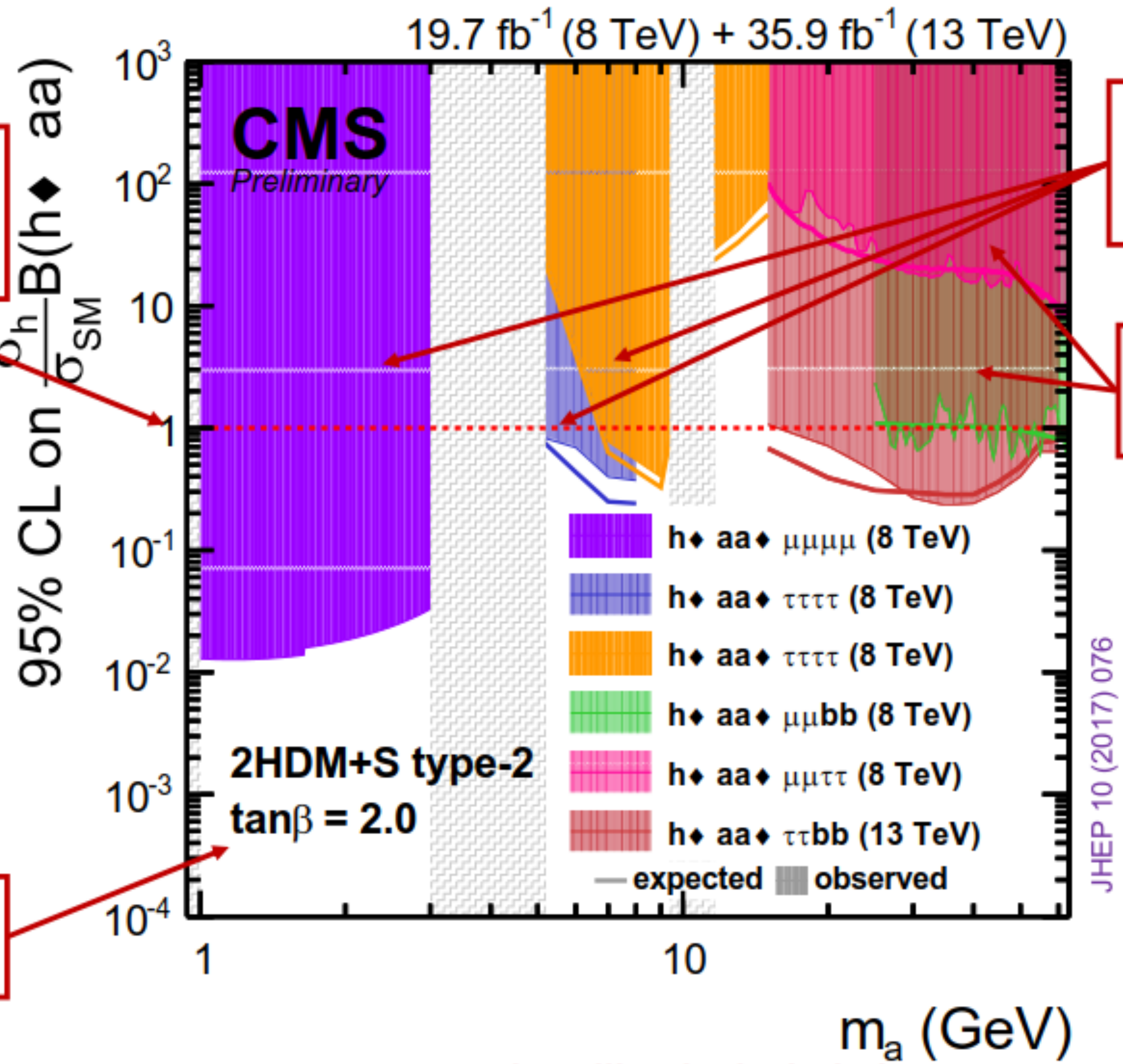
$a \rightarrow \mu\mu$

- ✓ Excellent **mass resolution**
- ✓ Easy to trigger
- ✓ Easy identification, with low p_T
- ✓ Open for any m_a>2m_μ
- ✗ Low BR



Higgs Exotic Decays

Sensitivity to $\mathcal{B}(h \rightarrow aa) = 1$ if $\sigma_h = \sigma_{SM}$



Boosted reconstruction techniques

Well separated decay products

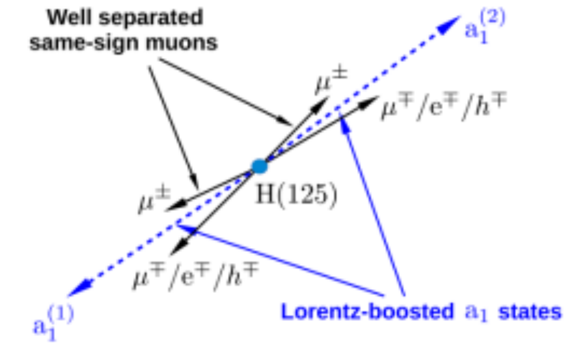
Model dependency

No significant deviations from SM predictions yet observed

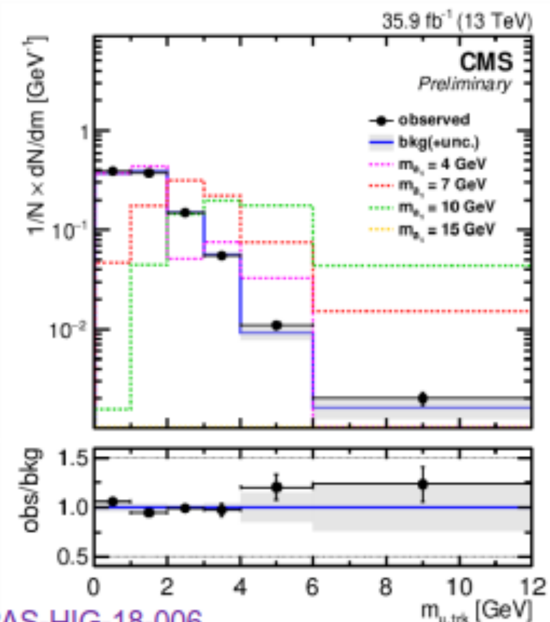
Many Run II results still to be included

Exotic Decays: $H \rightarrow aa \rightarrow 2\mu 2\tau/4\tau$

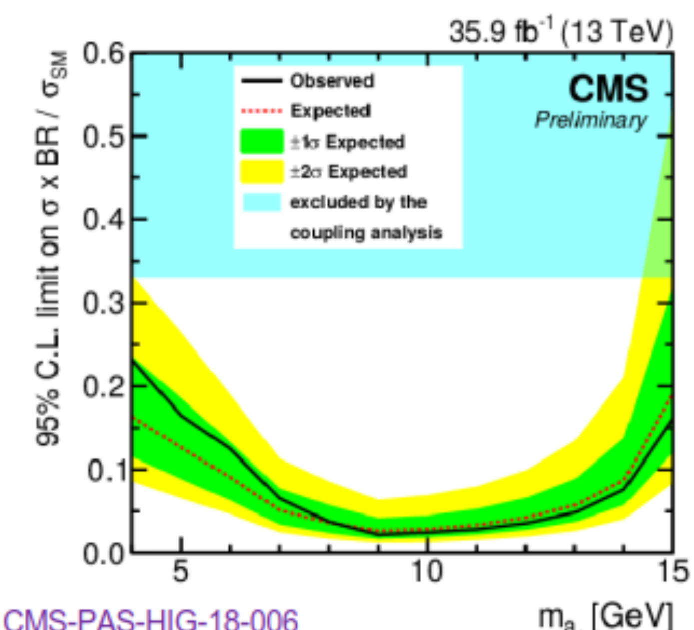
- **Highly boosted *a*** boson, non-isolated muons
- 4 GeV < m_a < 15 GeV
- Selection: SS μ pair + two 1-prong τ decays (OS wrt nearest μ)
- **Main background**: QCD multijet events
- **2D search** in ($m_{\mu1,\ trk1}$, $m_{\mu2,\ trk2}$) plane
- **Reduced sensitivity** as **topology** becomes **resolved**
- **Improves** Run 1 CMS limits by up to a **factor 10**



CMS-PAS-HIG-18-006



CMS-PAS-HIG-18-006



CMS-PAS-HIG-18-006

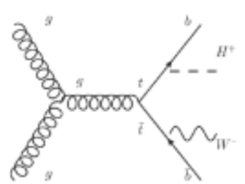
Searches for charged Higgs

7/8 TeV		13 TeV	
Final State	Ref	Final State	Ref
$H^{\pm} \to \tau\nu$,tb	JHEP 11 (2015) 018	$H^{\pm} \to \tau\nu$	arXiv:1903.04560 (JHEP)
$H^{\pm} \to cb$	JHEP 11 (2018) 115	$H^{\pm} \to tb$ lep	CMS-PAS-HIG-18-004
$H^{\pm} \to cs$	JHEP 12 (2015) 1	$H^{\pm} \to tb$ had	CMS-PAS-HIG-18-015
		$H^{\pm} \to Wa$	CMS-PAS-HIG-18-020
$H^{\pm\pm}$ multileptons	EPJC 72 (2012) 2189	$H^{\pm\pm}$ multileptons	CMS-PAS-HIG-16-036
		VBF $H^{\pm} \to$WZ	PRL 119 (2017) 141802
		$H^{\pm\pm} \to W^{\pm}W^{\pm}$	PRL 120 (2018) 081801

New results with 2016 13 TeV data including intermediate mass range.
"Standard" decays very constrained now in MSSM-like models.
New benchmarks: opening decays to $\chi_i^{\pm}\chi^0_j$, Wh, WA.

Low mass

Low mass

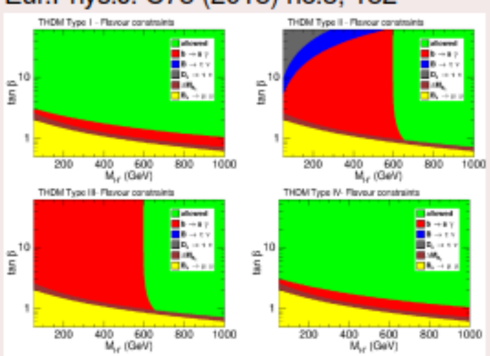


σ(pp → tt) * BR (t → bH⁺) * BR (t → bW)

NNLO
PRL 110 (2013)

NLO: Phys. Rev. D76 (2007), hep-ph/9301237
NNLO: eg. hep-ph/9806244

Eur.Phys.J. C78 (2018) no.3, 182

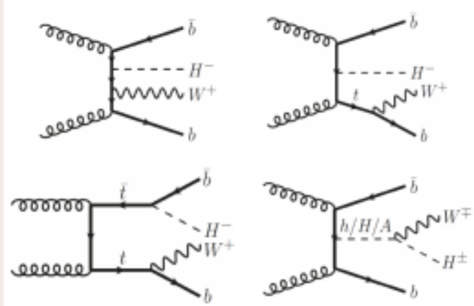


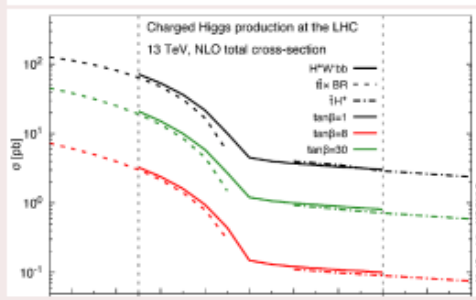
Intermediate mass

Phys.Lett. B772 (2017) 87

Intermediate mass

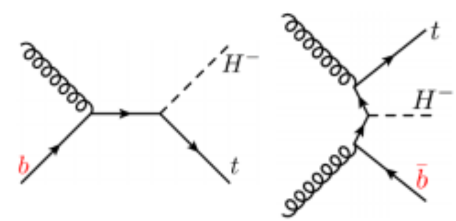
NLO pp → H⁺W⁻bb





High mass

High mass



Tools: 4FS: MG5_aMCatNLO, 5FS: Prospino

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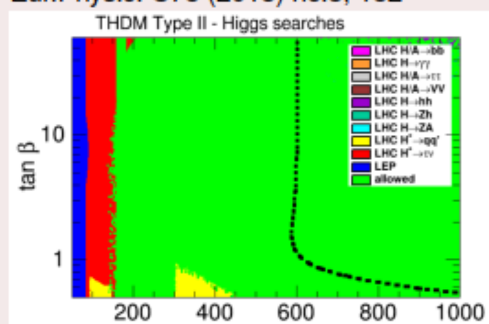
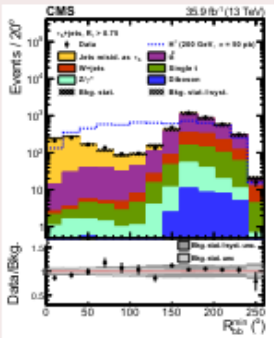
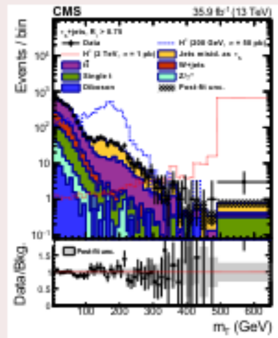


$H^\pm \to \tau\nu$ and $H^\pm \to tb$ leptonic, and combination

$H^\pm \to \tau\nu$ — arXiv:1903.04560

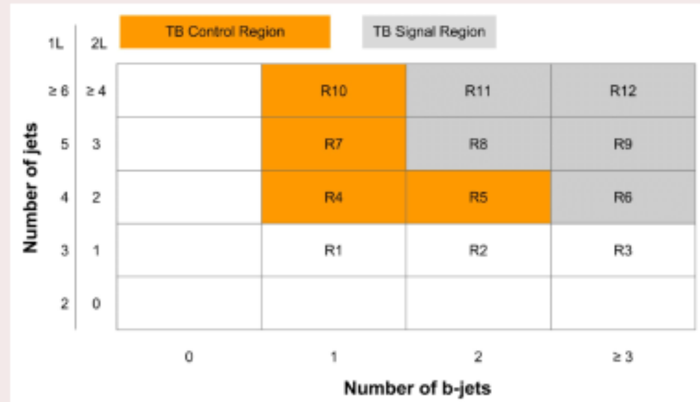
- combination of 36 categories in all hadronic (τ_h+jets) and leptonic ($\ell + \tau_h$, $\ell + no\tau_h$) FS.

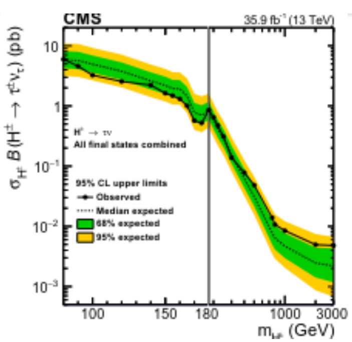


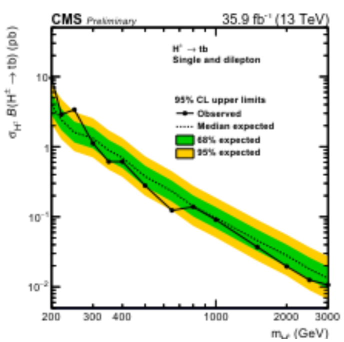


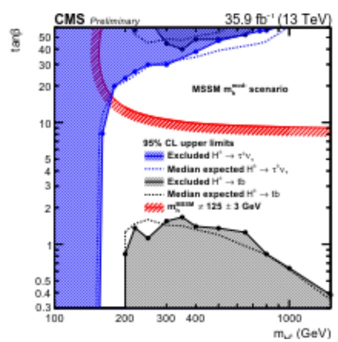
$H^\pm \to tb$ (lep) — CMS-PAS-HIG-18-004

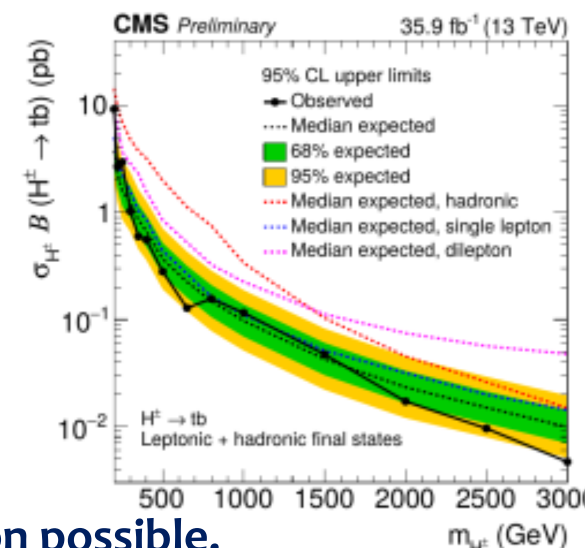
- combination of ℓ+jets and $\ell\ell$+jets.







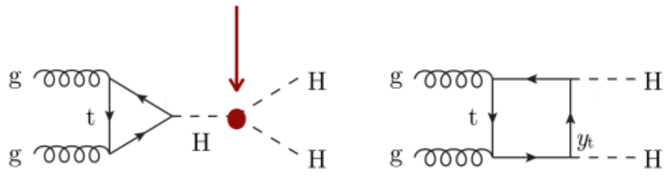




In all hadronic channel: no neutrinos = full mass reconstruction possible.
Best sensitivity still from single lepton channel.
All hadronic channel contributes most at high $H^\pm$ mass.

Double Higgs production

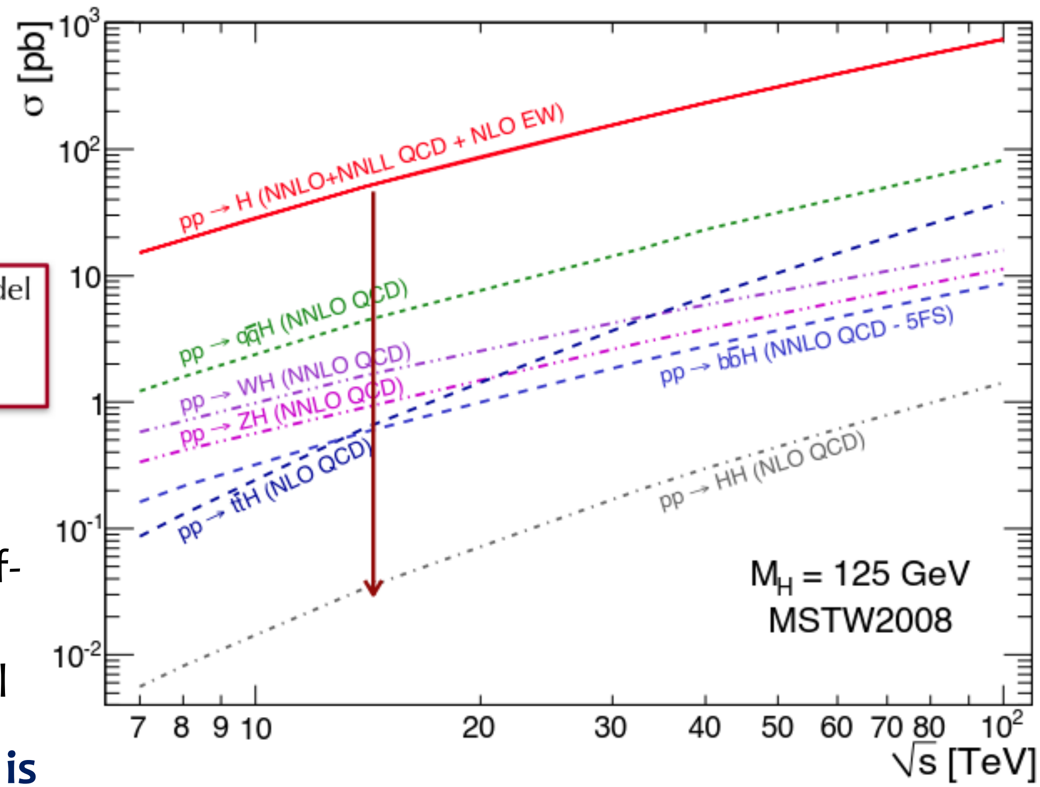
$$\lambda = \frac{m_H^2}{2v^2} = 0.13$$



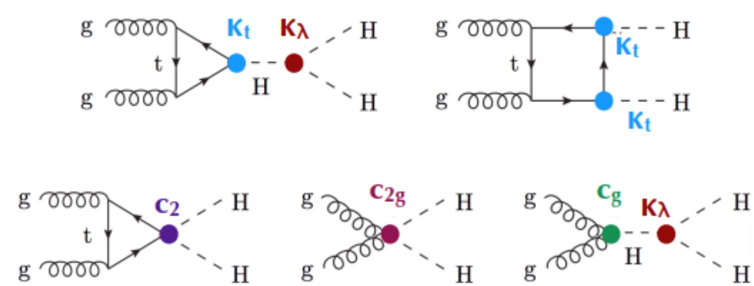
HH has **extremely small cross section** in the Standard Model
10^3x smaller than the single Higgs boson production
31.05 fb at 13 TeV ($NNLO_{FTapprox}$)

HH production allows to probe the self-coupling
The measurement of the Higgs boson self-coupling is a fundamental test of the SM
It probes the shape of the Higgs potential

20%(or better) precision on self-coupling is needed to probe BSM modifications

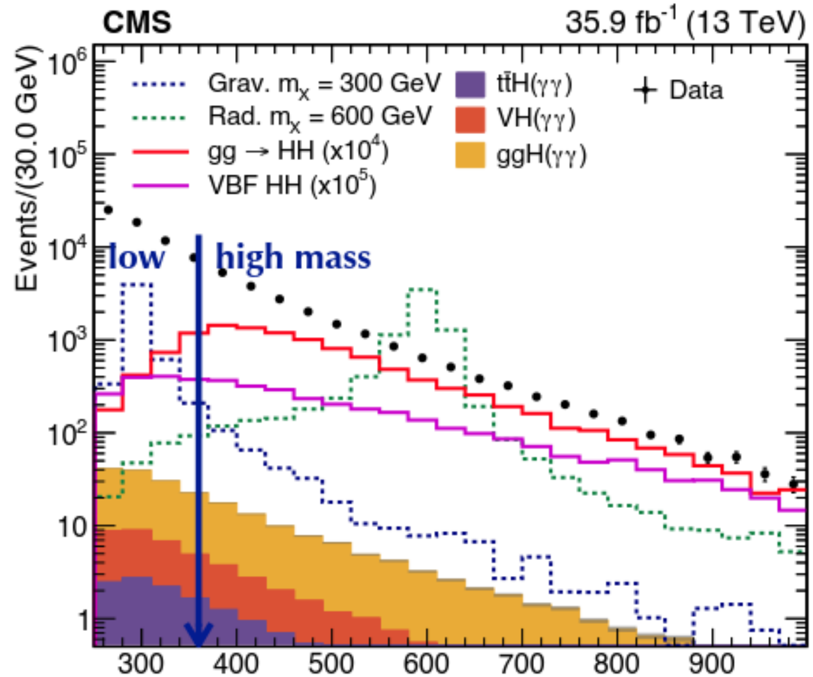


Anomalous Higgs boson couplings has strong effect on cross-section and m(hh) shape
EFT approach parametrizes new physics modifications to $\kappa_\lambda = \lambda/\lambda_{SM}$ and $\kappa_t = y_t/y_{t,SM}$ and new contact interactions c2 , c2g , cg



Double Higgs production

- **H(bb̄)** is a key element in the exploration of HH at the LHC highest BR good b-jets identification performance: 70% efficiency at 0.3-1% q/g mistag probability
- **H(γγ)** clean final state excellent mass resolution, ~1%
- **H(γγ)H(bb̄)** Phys. Lett. B 788 (2018) 7:
  - Photon selection similar to H(γγ) measurements
  - mγγ and m(bb̄) compatible with the Higgs boson mass
  - Mx and BDT (includes angular correlations) classifier used to categorize events
- Main backgrounds are:
  - γγ+jets (prompt or jets misidentified as photon)
  - SM single Higgs
- Likelihood fits simultaneous to m(bb̄) and m(γγ)



$$M_X = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - m_H) - (m_{\gamma\gamma} - m_H)$$

Most sensitive channel to SM HH for CMS and low mass HH resonances

24 x SM observed 95% CL on SM HH cross section (19 x SM) expected

Summary

- The Higgs boson represents a unique particle in Nature
  - Its characterisation is essential to explore the scalar sector of the SM
- A broad program of Higgs boson study is ongoing with the ATLAS and CMS experiments
- The Run 2 dataset offers unprecedented possibilities of study: from observations to precision measurements
  - increasingly precise and granular measurements as more data are available

- **Run 2 Higgs Physics Milestones Already Reached: Third Generation (Charged) Completed**

- A broad and exciting program of Higgs boson physics is ahead of us, from updated properties and couplings measurements with the Run 2 dataset to the HL-LHC precision measurements

Perspectives

arXiv:1902.00134

- Most Run 2 full-statistics results are still to come (~140fb^{-1})
- Perspectives for Run 3 (2021-2023): Hope for >150fb^{-1} at $\sqrt{s}$= **14 TeV**
- HL-LHC: Starts 2026, expect 3ab^{-1}, hope for ~2-4% precision for most couplings