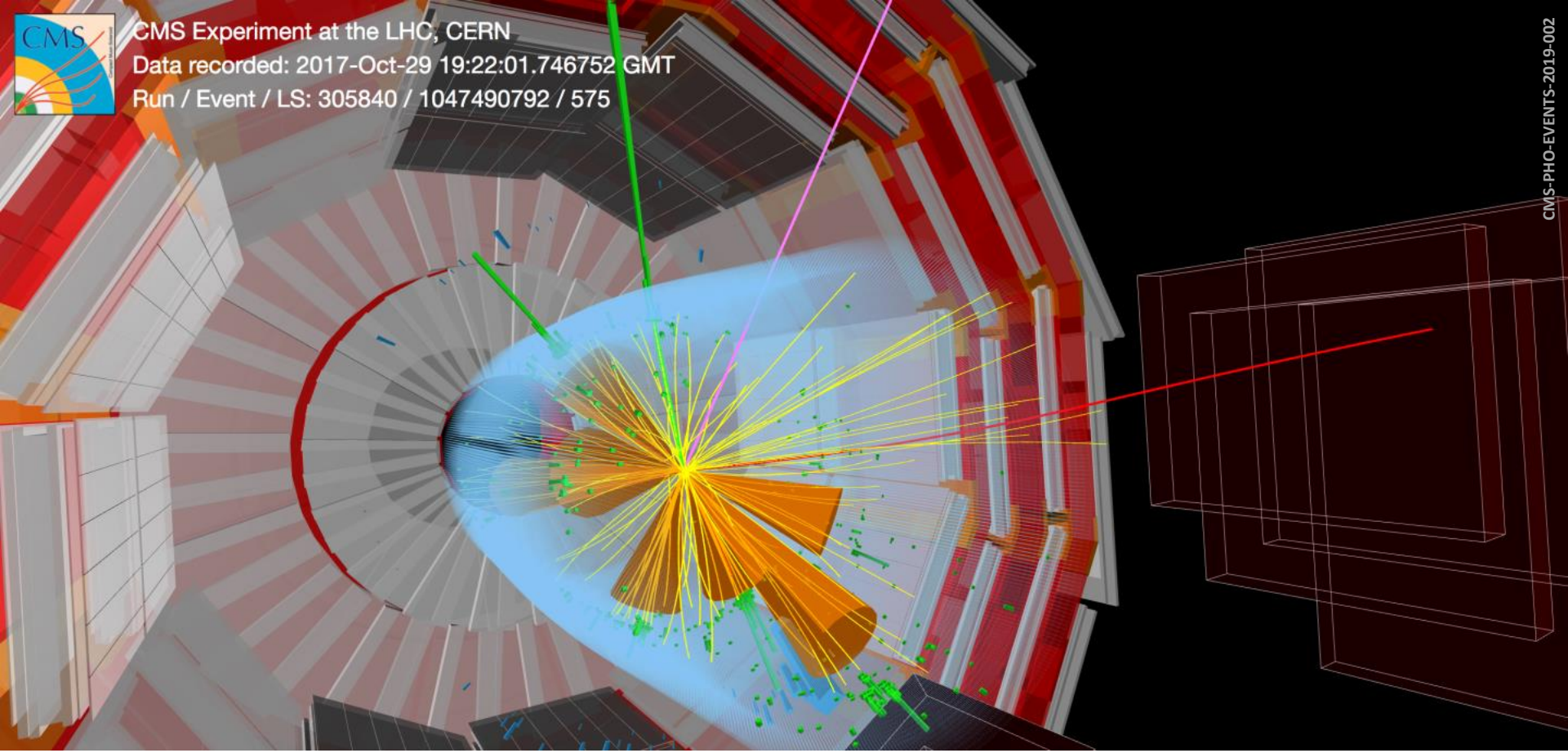


Higgs Physics at CMS

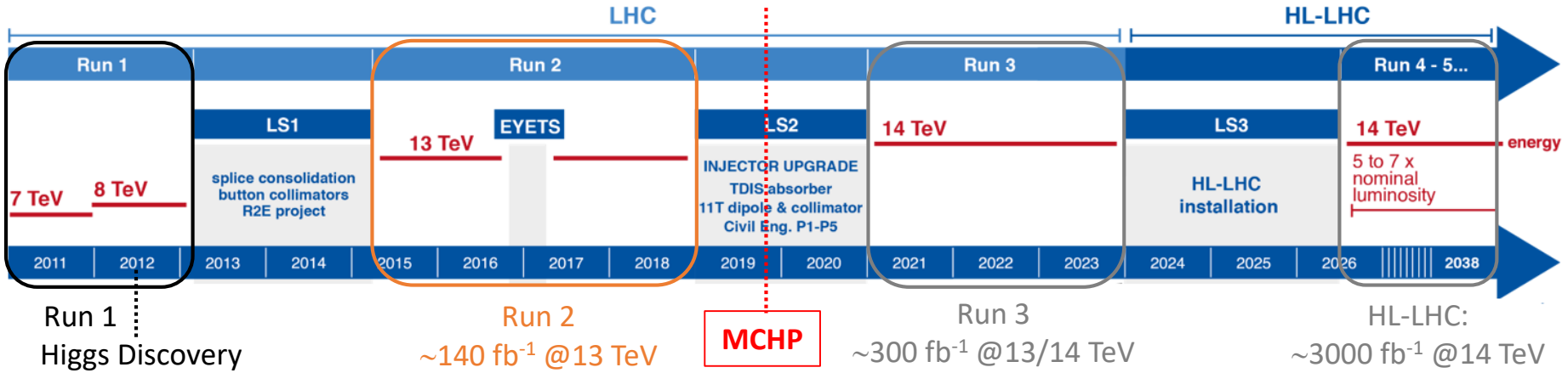
Nicola Amapane (Università di Torino and INFN, Torino, Italy)

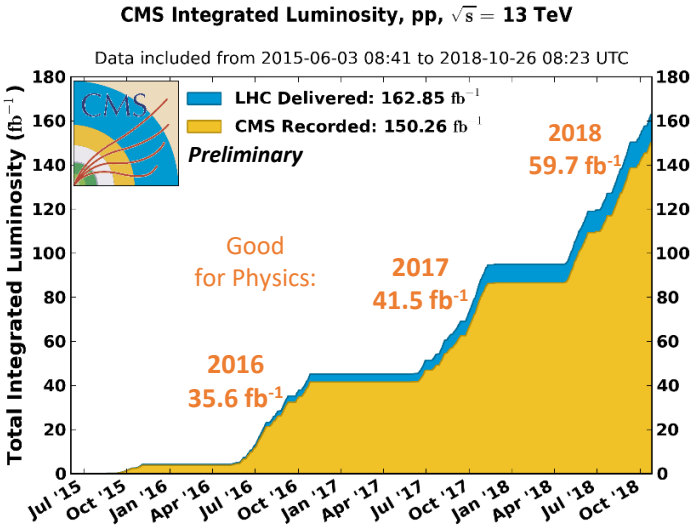
on behalf on the CMS Collaboration

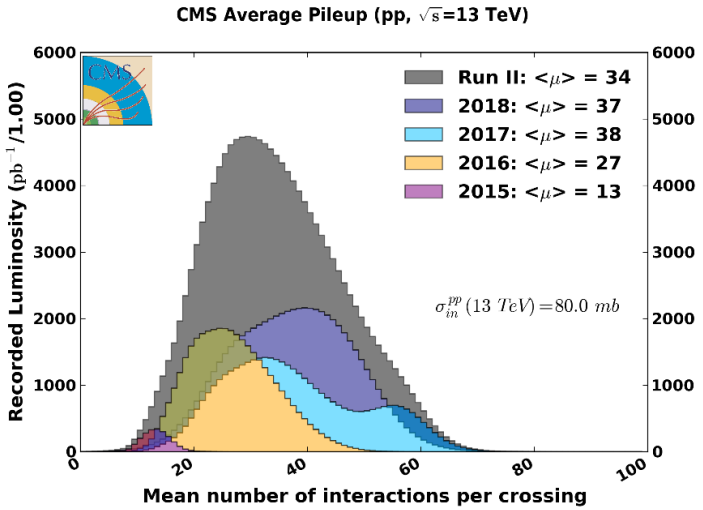
MCHP - Tangier
September 24th, 2019

Istituto Nazionale di Fisica Nucleare

The Higgs Boson timeline at LHC







Excellent data quality from CMS in Run 2

LHC Higgs Physics Menu

1. H properties from ZZ, WW, $\gamma\gamma$
   - Mass and width
   - Couplings
   - Inclusive/Differential Cross Sections
   - Quantum numbers (spin, CP)

2. Coupling to 3rd Generation fermions
   - H-tau interaction in decay (H→$\tau\tau$)
   - H-top interaction (ttH)
   - H-b interaction in decay (H→ bb)

3. Rare decays/production
   - 2nd generation fermions ($\mu\mu$, cc)
   - tHq/tHW
   - Decays to mesons
   - Self-coupling (HH)

4. BSM searches
   - Anomalous couplings
   - Exotic decays
   - Additional scalars, …

Higgs properties: the mass

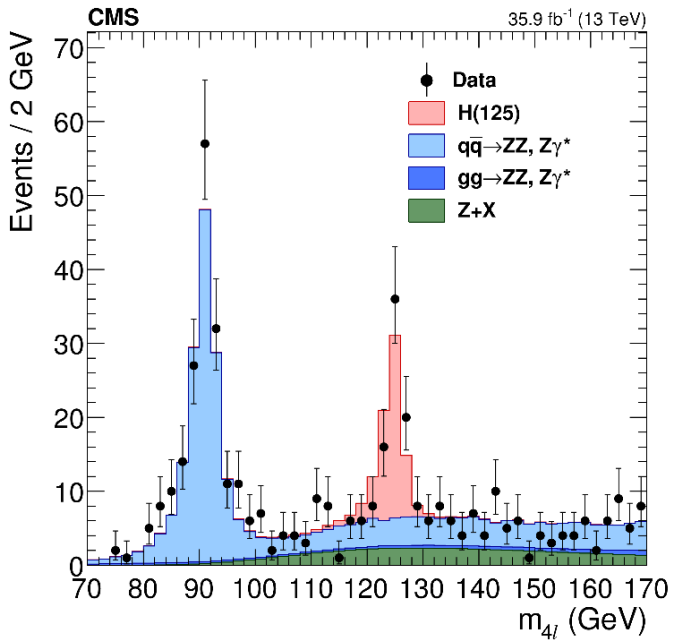
JHEP 11 (2017) 047

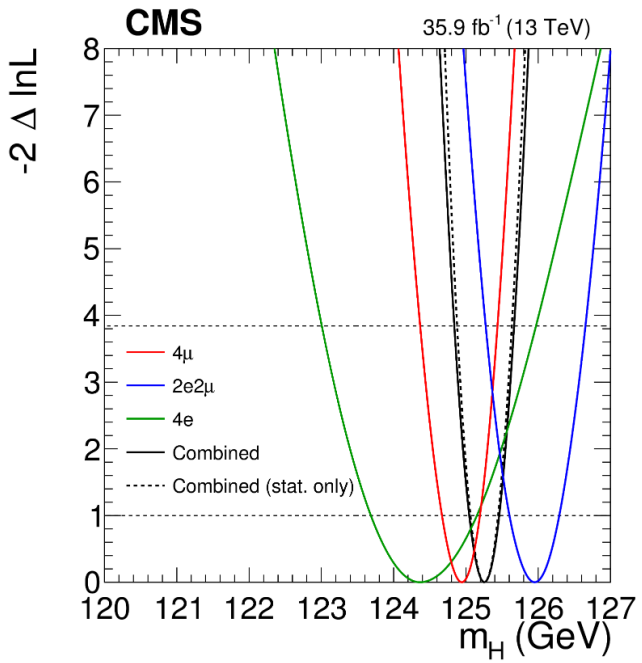
The single parameter that determines all SM couplings and x-sections

- Measured from peaks in high-resolution channels H→ZZ →4ℓ, H→$\gamma\gamma$

Run 1 LHC combination: $m_H = 125.09 \pm 0.21\ (stat) \pm 0.21\ (sys)$ GeV

Most recent CMS result from **H→ZZ →4ℓ** with 2016 data: $m_H = 125.26 \pm 0.20\ (stat) \pm 0.08\ (sys)$ GeV





Still dominated by statistical uncertainties

Higgs properties: the width

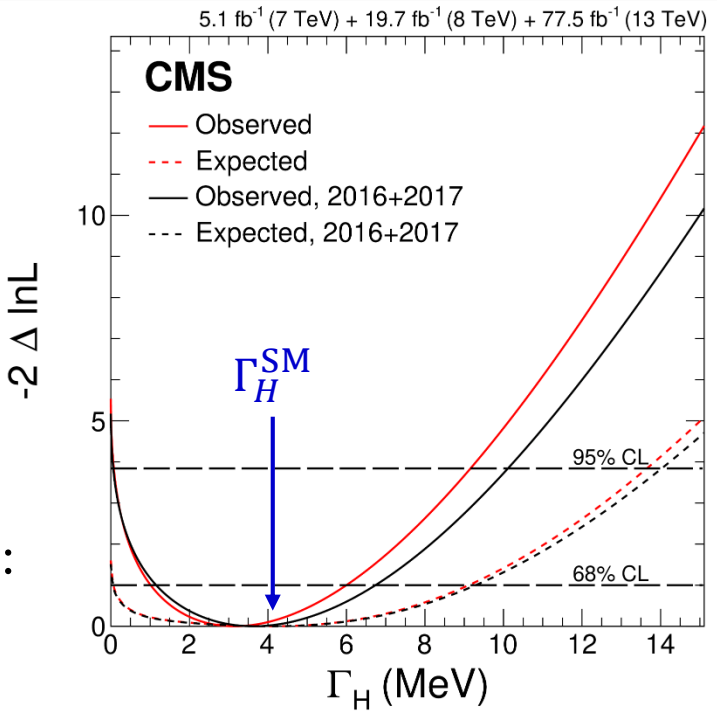
PRD 99 (2019) 112003

- Direct measurements in H→4ℓ, H→$\gamma\gamma$ is spoiled by detector resolution
- **Indirect constraints from** couplings, or from **ratio of on-shell and off-shell production**

Off-shell *H* tail is sizeable (~10% in SM)

$$\sigma^{on-shell}_{gg\to H\to VV} \propto \frac{g_g^2 \cdot g_V^2}{\Gamma_H}, \qquad \sigma^{off-shell}_{gg\to H\to VV} \propto g_g^2 \cdot g_V^2$$

Assuming i**dentical on-shell and off-shell couplings** (no new physics in loops, …), **Γ_H can be extracted from the ratio**



- Most recent CMS result (H→4ℓ, Run I + 2016-17):

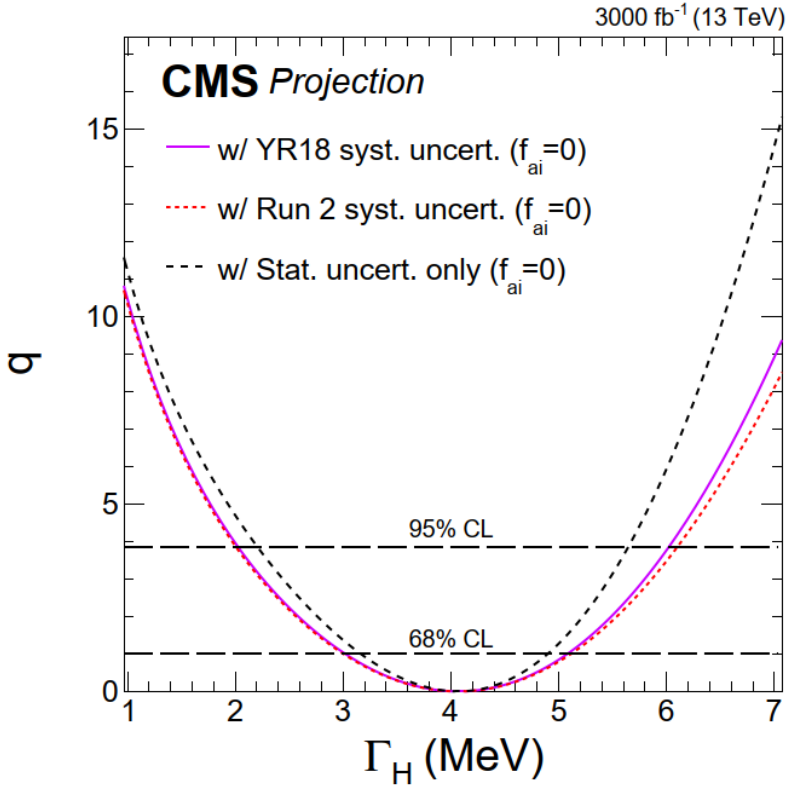
$0.08 < \Gamma_H < 9.16$ MeV @ 95% CL)

The width at HL-LHC

CMS-PAS-FTR-18-011

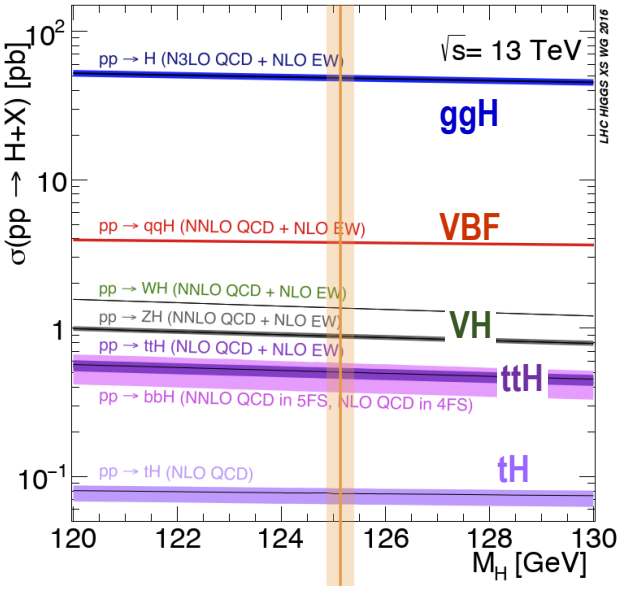
arXiv:1902.00134

- Extrapolation of off-shell analysis to 3000 fb^{-1}
  - Expected precision on Γ_H : **~1 MeV** (CMS only)
  - Conservative assumptions on systematics



Couplings: Production and decay modes

Individual couplings are folded in observable $i \to H \to f$ processes…



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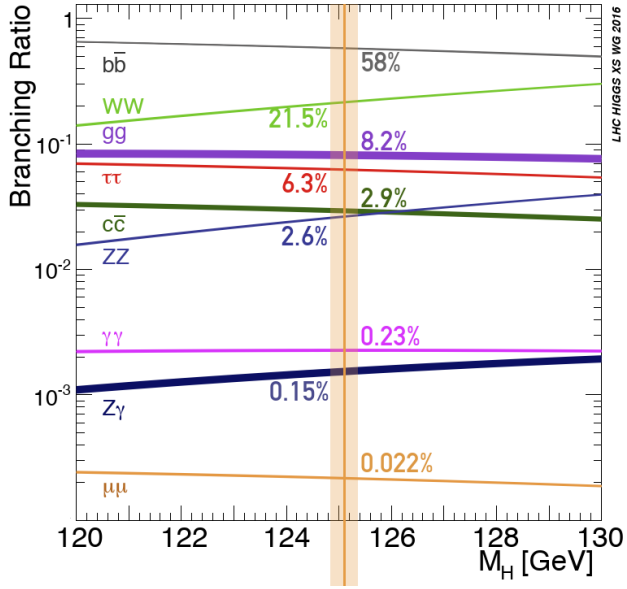


m_H = 125.09 ±0.24 GeV (LHC Run 1 combination)

	ggH	VBF	VH	ttH
$H \to ZZ$	HIG-19-001 (3/19)			
$H \to \gamma\gamma$	HIG-18-029 (3/19)		JHEP 11 (2018) 185	HIG-18-018 (11/18)
$H \to WW$	PLB 791 (2019) 96			HIG-18-019 (11/18)
$H \to \tau\tau$	HIG-18-032 (3/19)		JHEP 06 (2019) 093	
$H \to bb$	PRL 120 (2018) 071802	PRD 92, 032008	PRL 121 (2018) 121801*	HIG-18-030 (5/19)
$H \to \mu\mu$	PRL 122 (2019) 021801			
$H \to cc$			HIG-18-031 (7/19)	
$H \to$ inv	PLB 793 (2019) 520 *			HIG-18-008 (3/19)

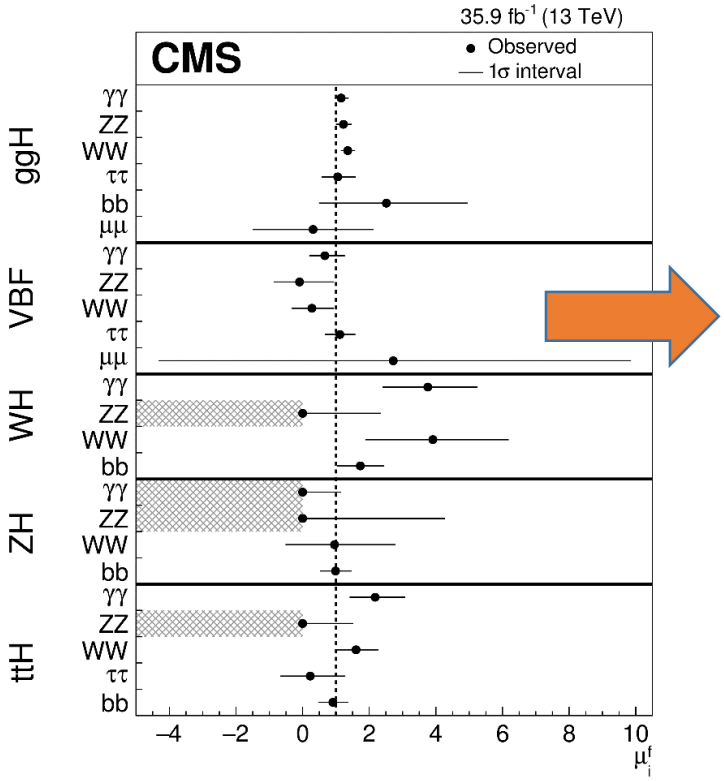
Main Production and decay modes covered by recent CMS results

Data set:
2016
2016+17
Full Run 2
* = incl. combination

Couplings: combination

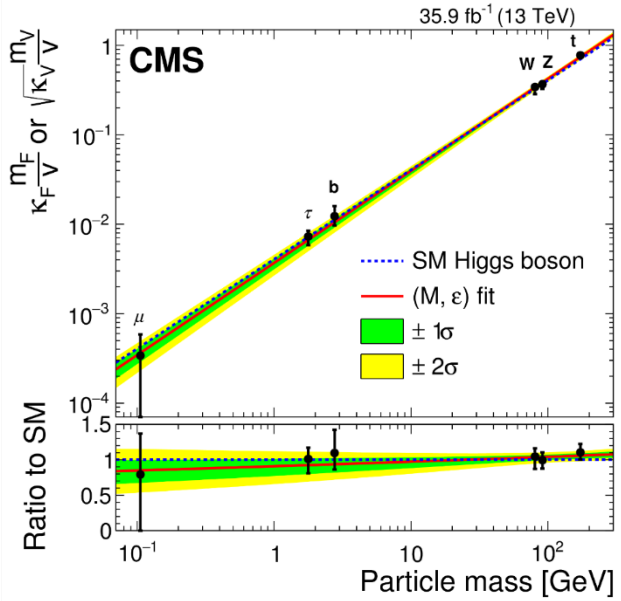
EPJC 79 (2019) 421

CMS combination of
$\gamma\gamma$, ZZ*, WW*, $\tau\tau$, $b\bar{b}$, $\mu\mu$
with 2016 data

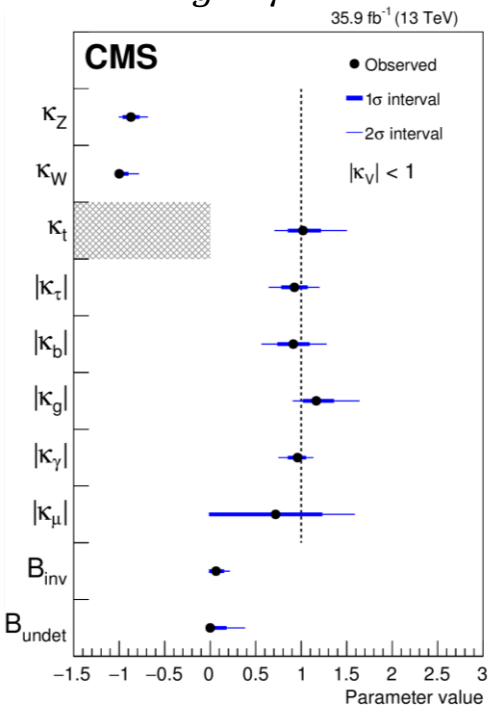


Interpretation in κ- factor formalism

Resolved loops



Effective κ_g, κ_γ couplings



constrain BSM:

$\mathbf{BR_{inv} < 0.22\ @95\%\ CL}$

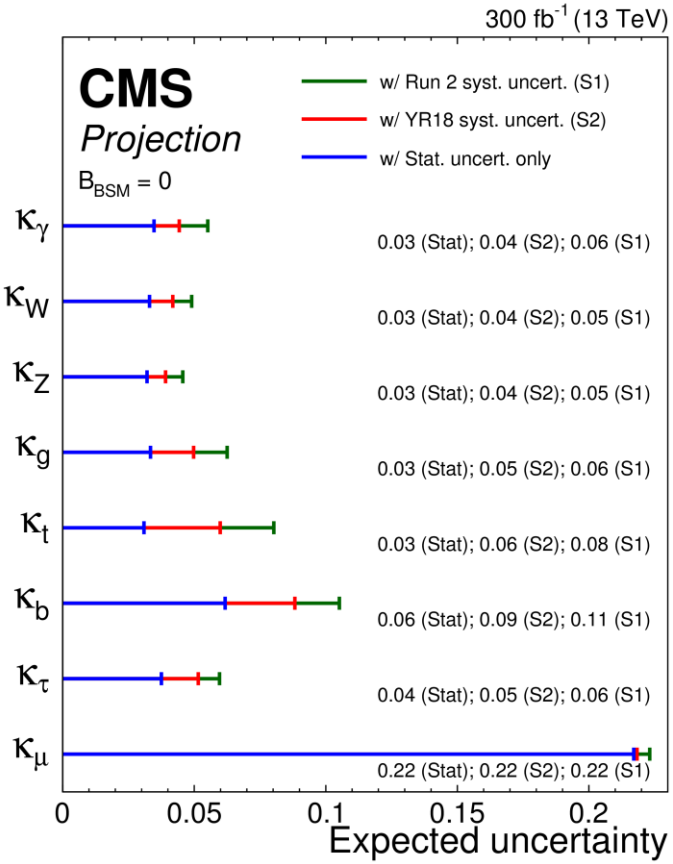
$\mathbf{BR_{undet} < 0.38\ @95\%\ CL}$

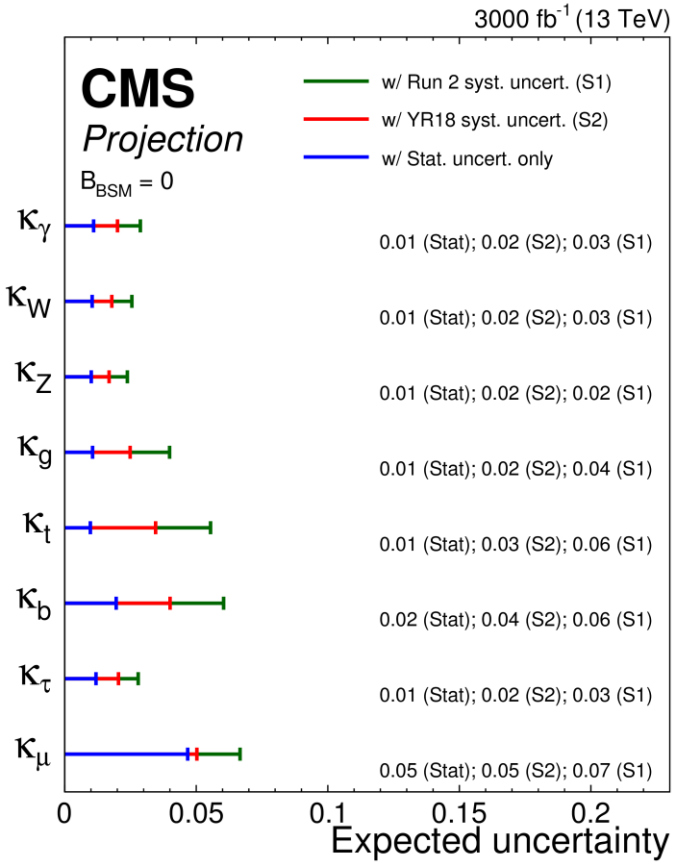
Couplings at Run 3 and HL-LHC

CMS-PAS-FTR-18-011

arXiv:1902.00134

- Extrapolations to 300 and 3000 fb^{-1}
- Couplings constrained to few % by the end of HL-LHC
- Statistical uncertainty no longer dominant by then

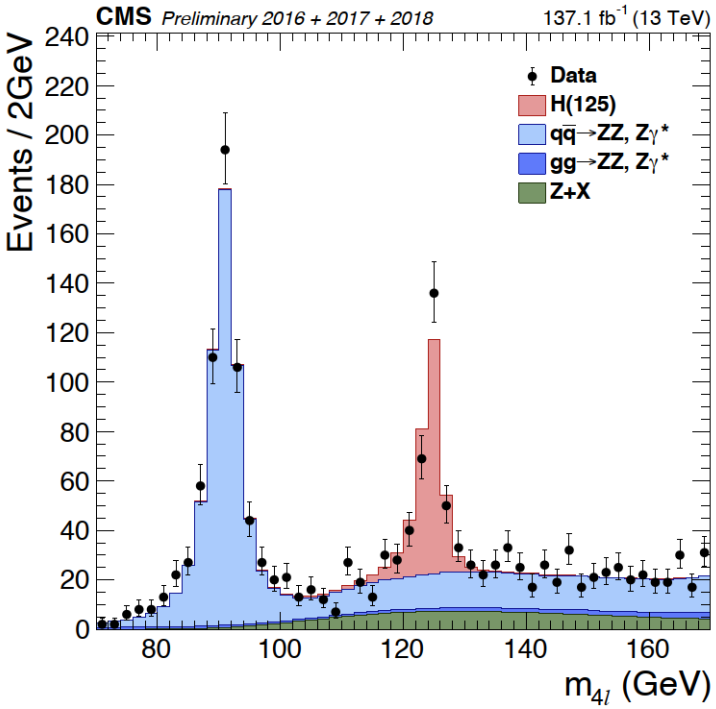




Couplings from H→4ℓ

CMS-PAS-HIG-19-001

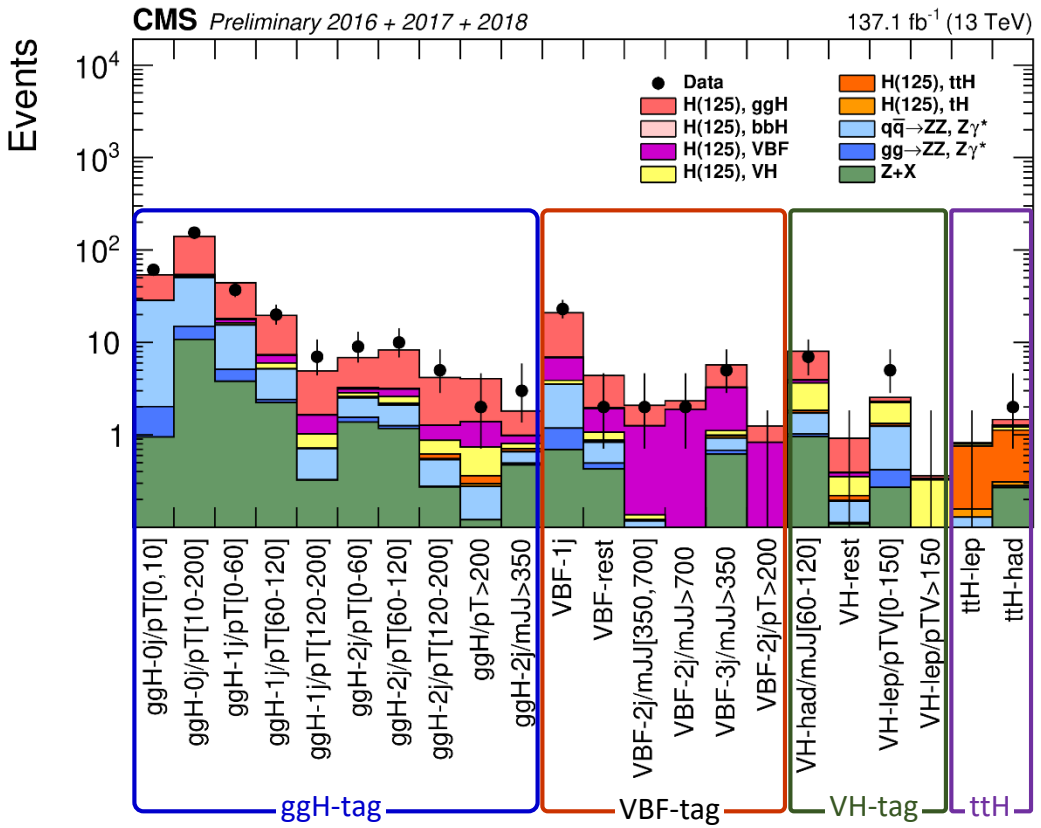
Analysis updated to **full Run 2** dataset



Global signal strength, H→4ℓ:

$$\mu = 0.94^{+0.07}_{-0.07}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$$

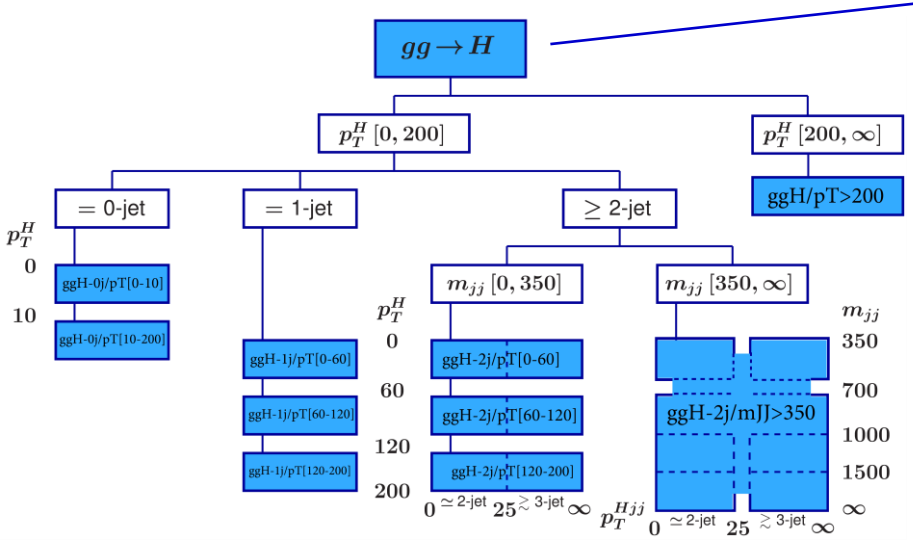
- Categorization to target production modes based on full event topology
- 22 categories to match Stage 1.1 STXS bins



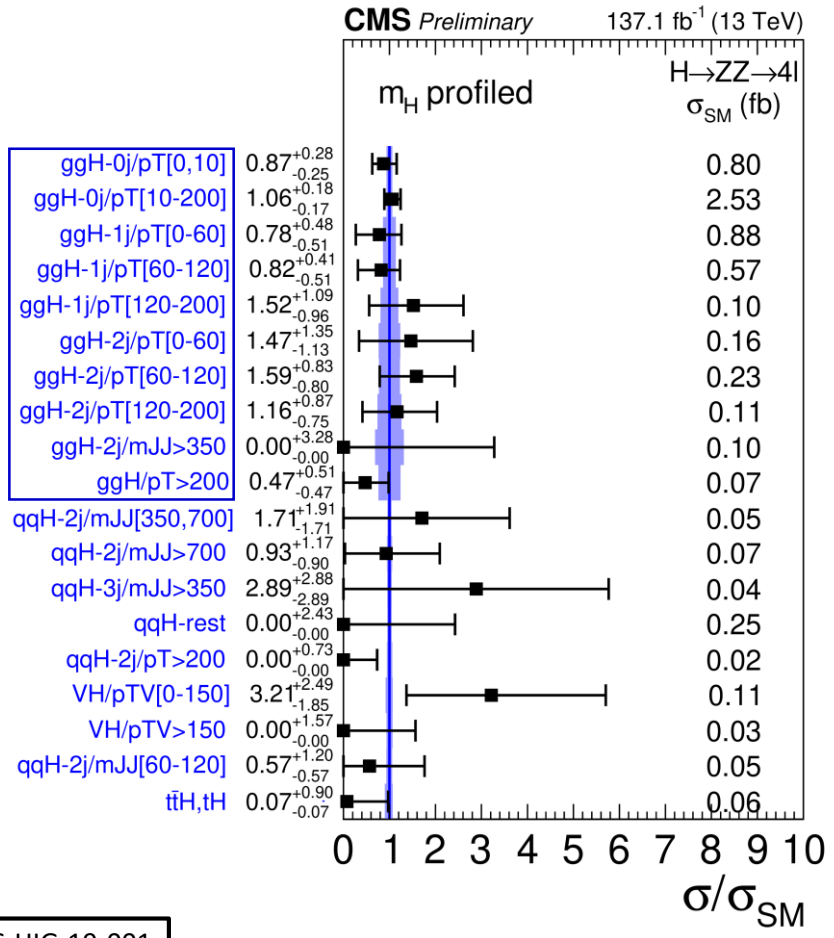
Simplified Template Cross Sections (STXS) in H→4ℓ

Cross sections per production mode, in standardized fiducial phase space regions ("bins")

- Inclusive in decays to allow for combination
- Factorize theory uncertainty on overall yield from exp/th uncertainties in the measurements
- Allow MVA analysis
- Can be re-interpreted easily in terms of μ's, κ's, test of specific BSM models…
- Bins can be merged when lacking experimental
  - Eg "stage 0": bins = production modes



Example: ggH Stage 1.1 bins

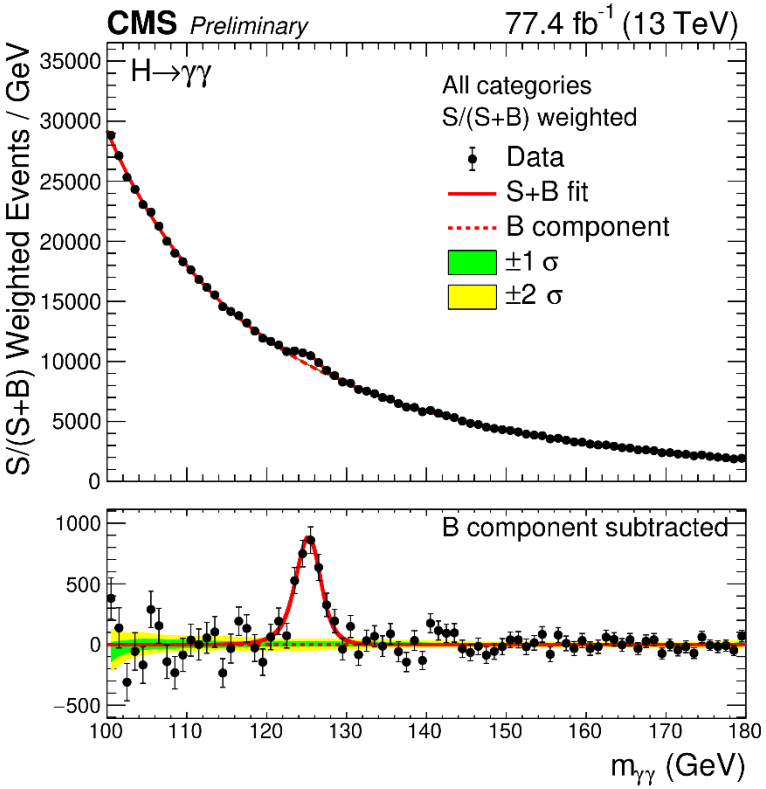


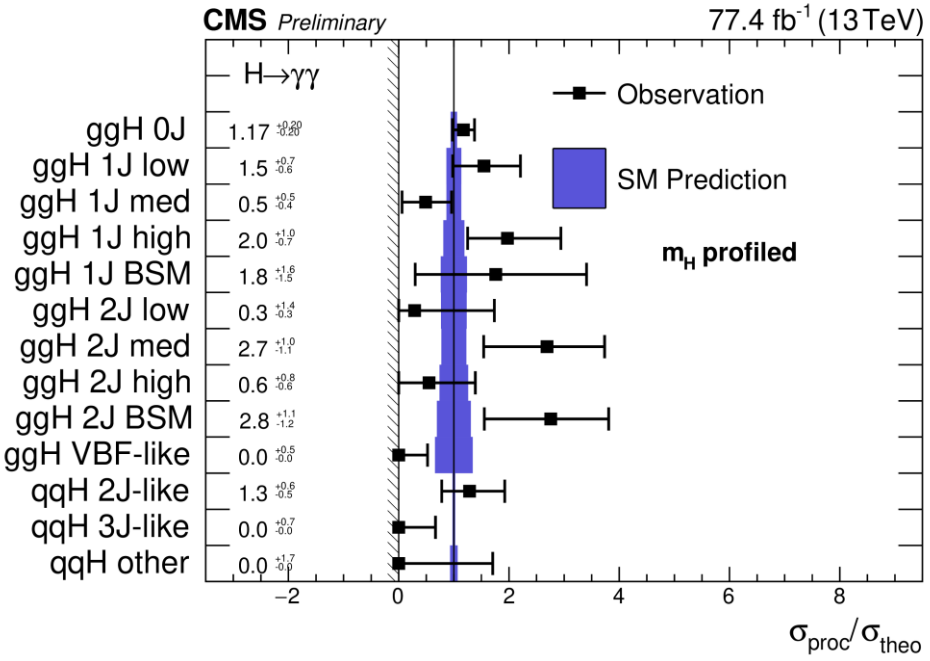
CMS-PAS-HIG-19-001

STXS results from H→γγ

CMS-PAS-HIG-18-029

- Analysis updated to 2016-2017 dataset
- STXS Stage 1 bins for ggH, VBF

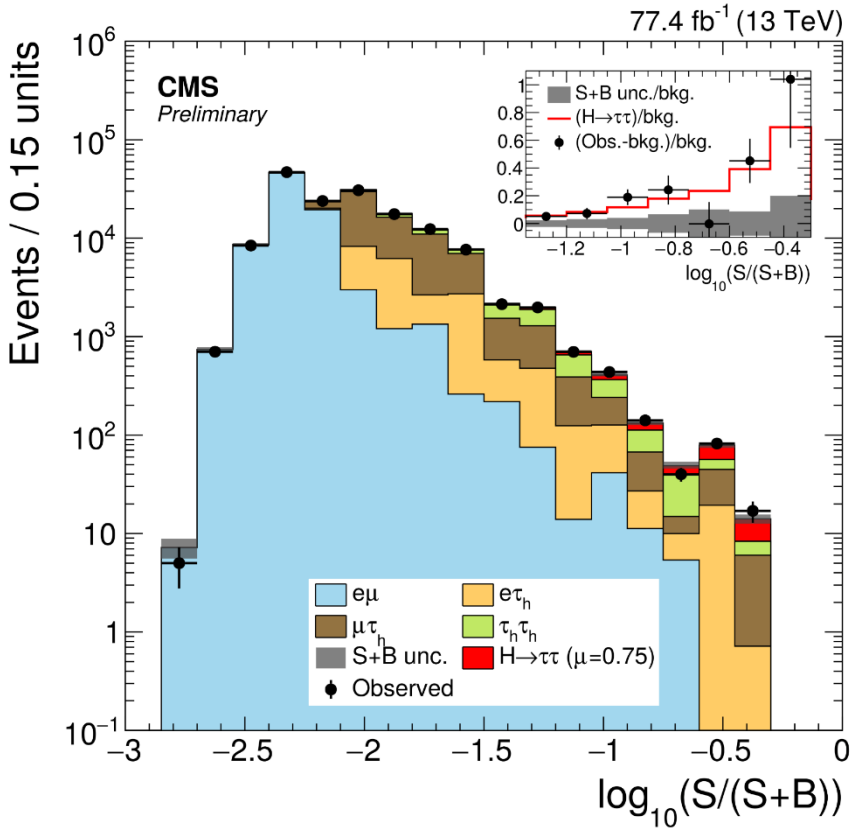


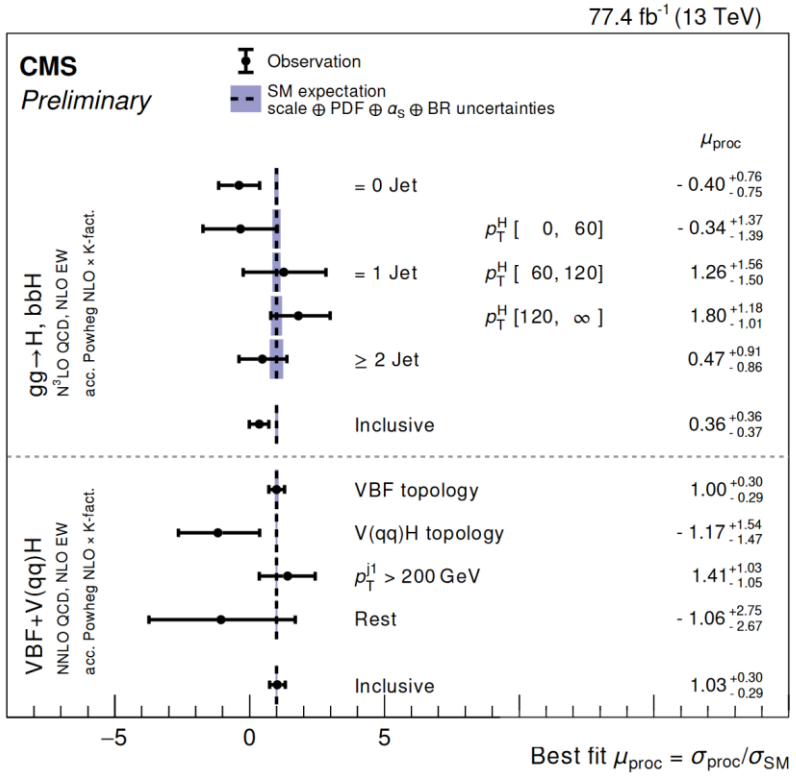


Coupling to 3rd gen fermions: τ-H

CMS-PAS-HIG-18-032

- After H→$\tau\tau$ independent observation [PLB 779 (2018) 283]:
  - Analysis extended to 2016+17 dataset
  - Categorization using ML for ggH and VBF
  - STXS Stage 1 measurements



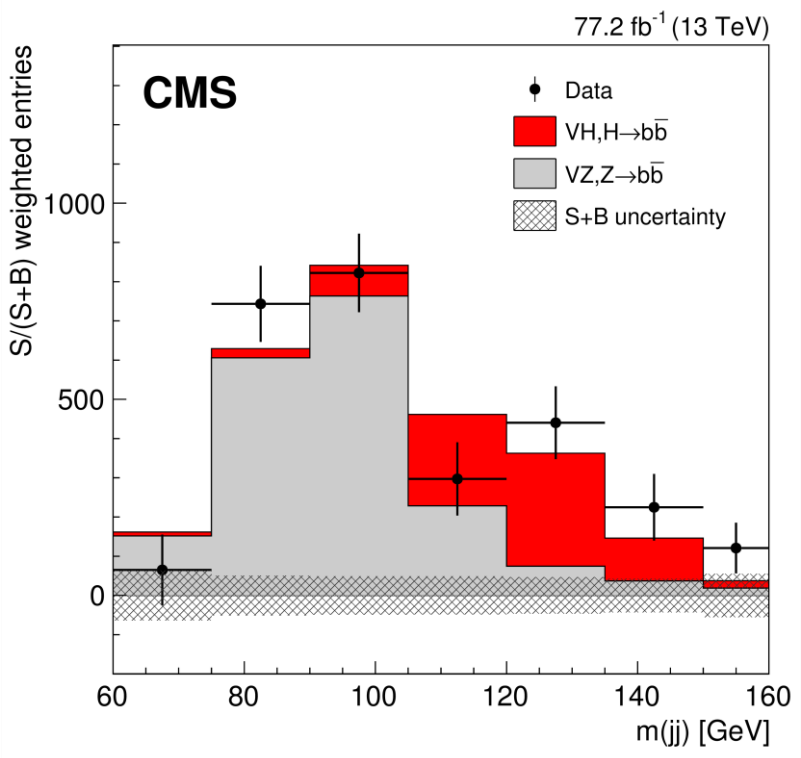


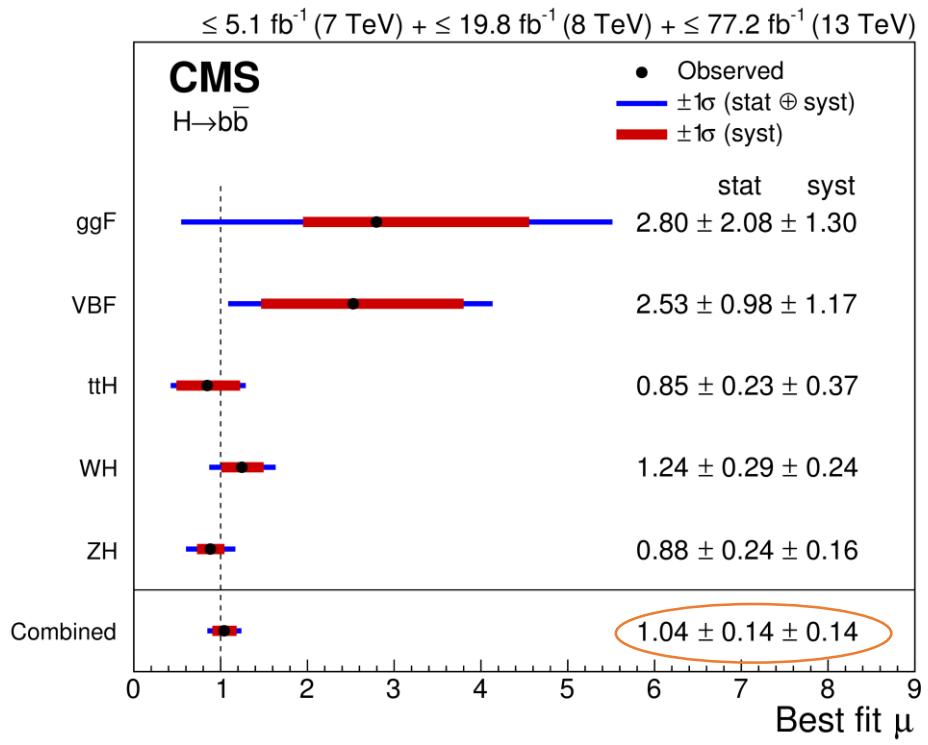
Coupling to 3rd gen fermions: b-H

PRL 121 (2018) 121801

- H → bb : Large BR, but difficult due to background
- VH production most sensitive; analysis updated with 2016-17 data
- Combining with earlier results from all production modes:

  5.6 σ (5.5 exp.) → **Observation in 2018**

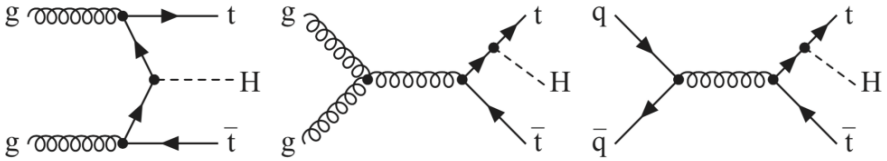




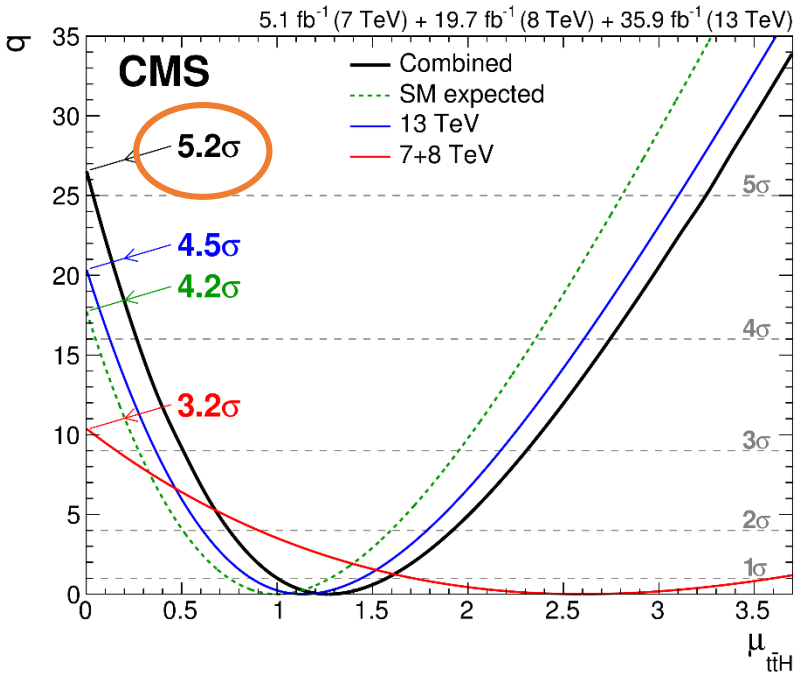
Coupling to 3rd gen fermions: t-H

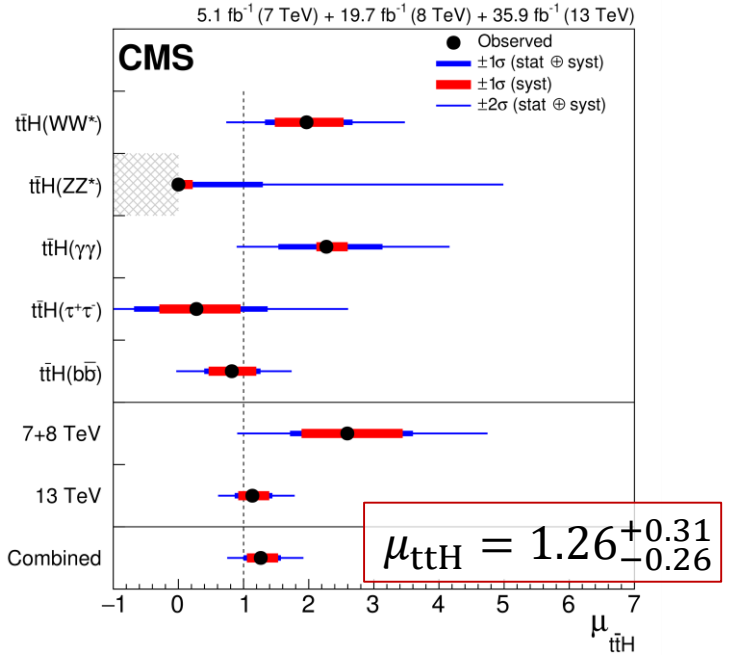
PRL 120 (2018) 231801

- Can be probed directly only in production (ttH, tH)
- **ttH: direct observation in 2018**



  - from combination of bb, WW, $\tau\tau$, $\gamma\gamma$, ZZ analyses with Run 1 + 2016 data

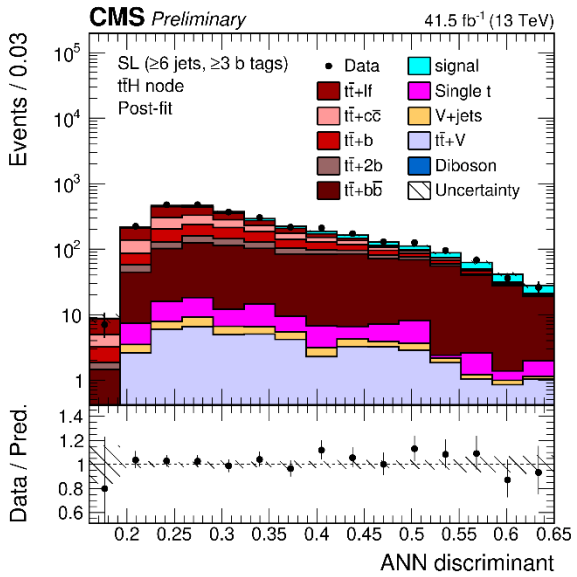


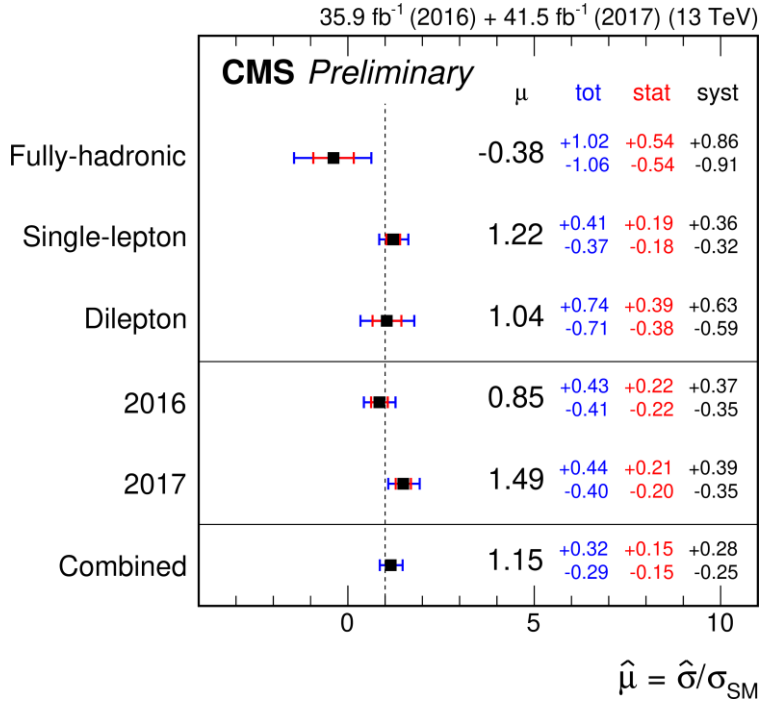


Coupling to 3rd gen fermions: t-H

- **ttH (H→bb)** updated to 2016+2017 data:
  - 0, 1, 2ℓ final states
  - Improvements in MVA techniques and *b*-jet identification
  - Significance: 3.9 σ (3.5 exp.)
  - **evidence of decays to *bb* based on *ttH* alone**

CMS-PAS-HIG-18-030





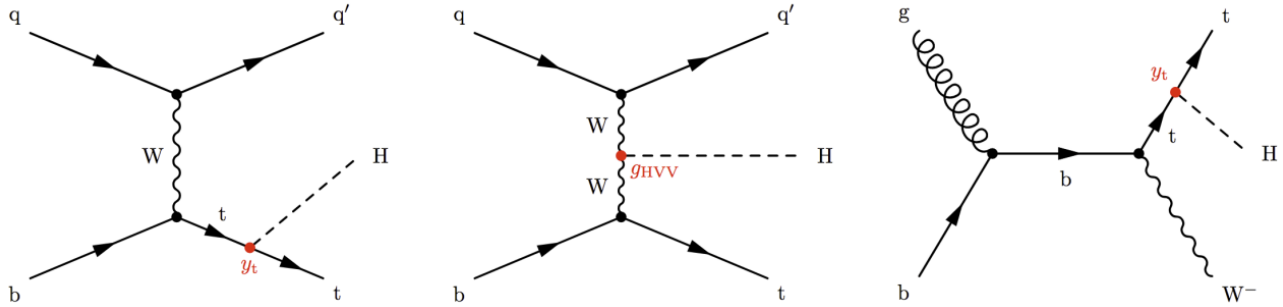
Also, updated CMS results from:

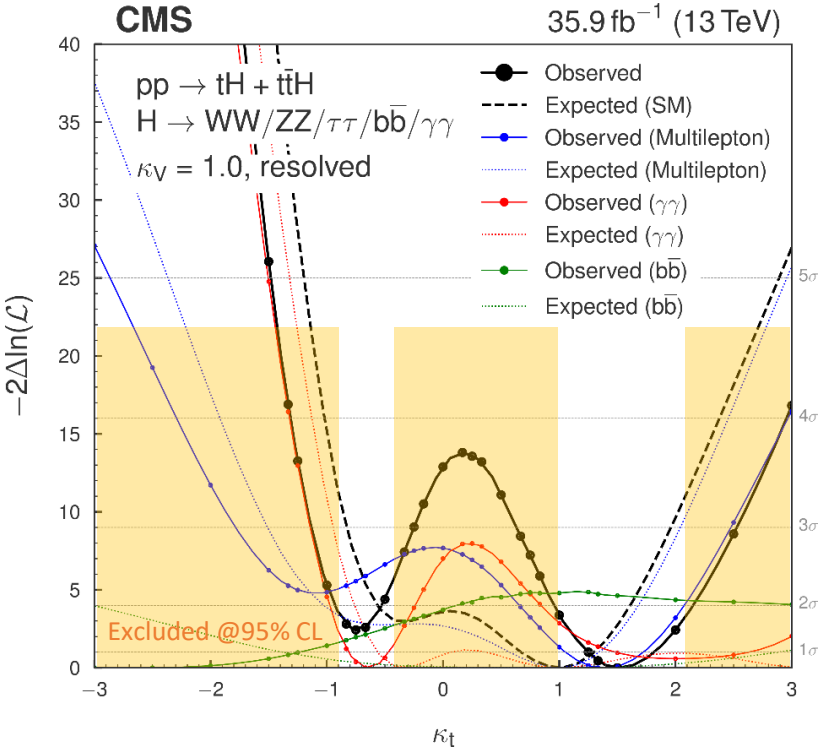
- **ttH (H → WW/ττ)** [CMS-PAS-HIG-18-019]
- **ttH (H → γγ)** [CMS-PAS-HIG-18-018]
- **ttH (H → 4ℓ)** from the H→4ℓ analysis mentioned earlier [CMS-PAS-HIG-19-001]

t-H coupling from tHq/tHW production

PRD 99 (2019) 092005

- Cross-section is tiny (~90 fb), but process is very sensitive to **H-t and H-V couplings**, and their **relative sign** (because of interference)





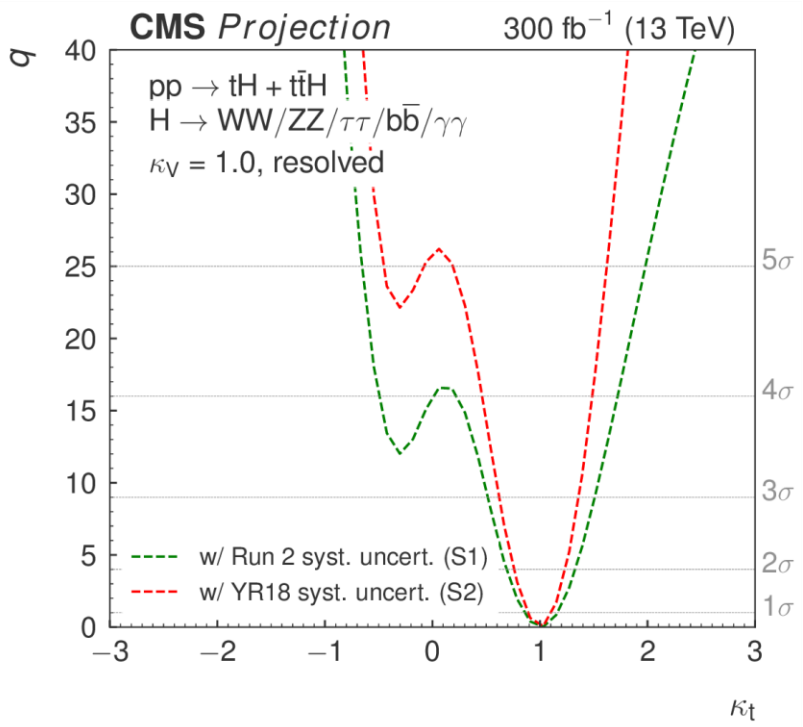
- CMS analysis with 2016 data
- Combines H→bb, γγ and multilepton channels
- 95% upper limit on SM-like tH signal strength: 25 (12 exp.)
- Analysis constrains κ_t; positive value favored by ~1.5 σ

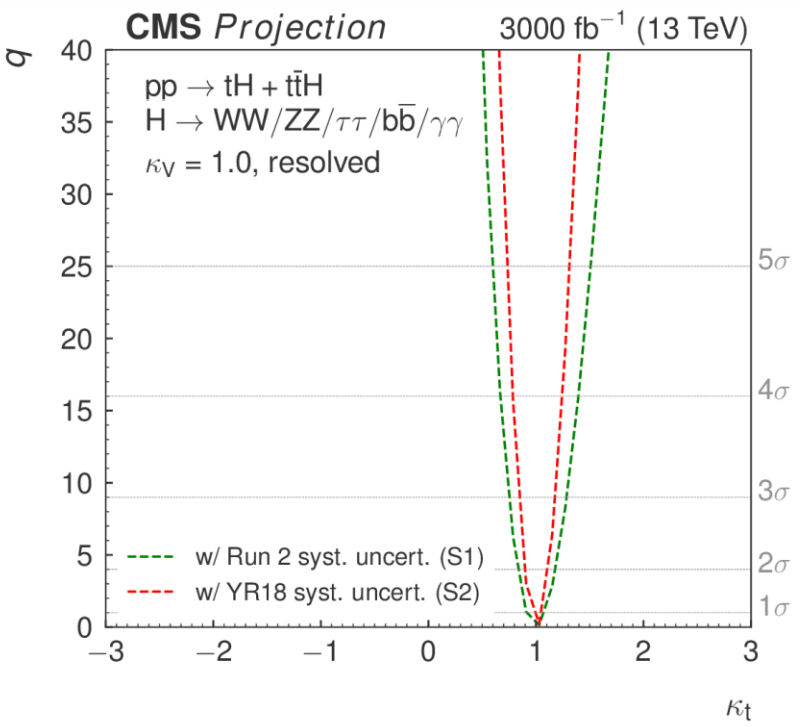
tH production: future projections

CMS-PAS-FTR-18-011

arXiv:1902.00134

- Extrapolations to 300 and 3000 fb^{-1}



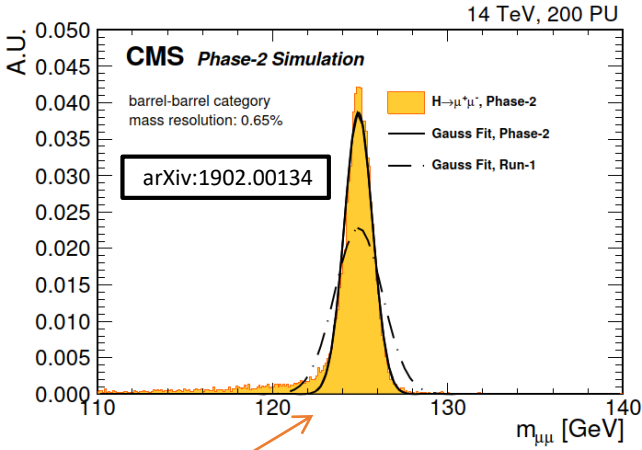


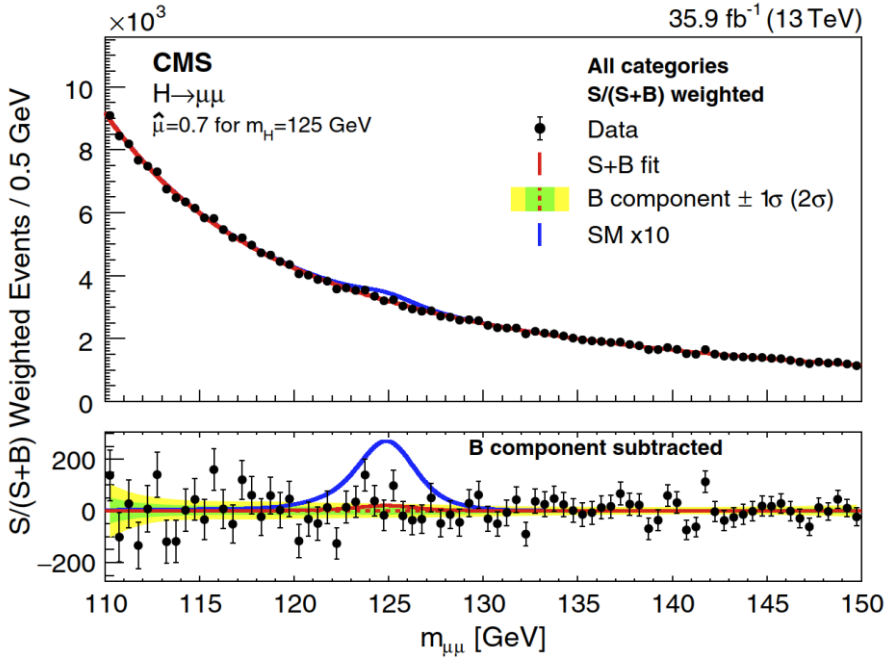
Couplings to 2nd gen fermions: μ-H

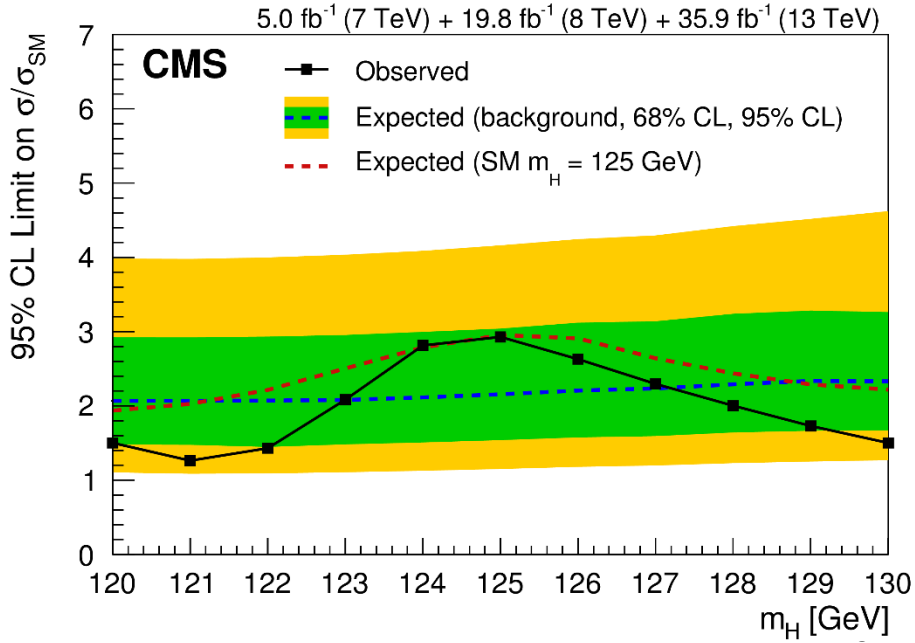
PRL 122 (2019) 021801

- H→μμ: very small BR, large bkg. (Z/γ*, VV, tt)
  - Invariant mass resolution is critical
- Results with Run 1 + 2016 data
  - Sophisticated techniques for categorization
  - Significance: **0.9 σ (1.0 exp.)**
  - Still statistically limited
  - Expect 10-13% precision on signal strenght with 3000 fb^{-1}

  (benefits also of improved mass resolution in Phase2)



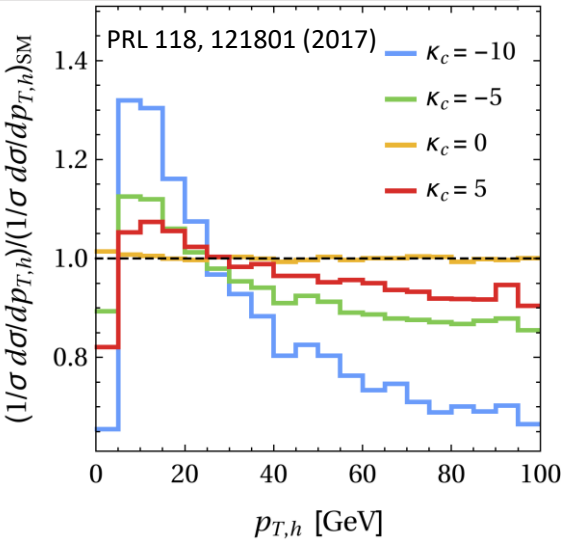


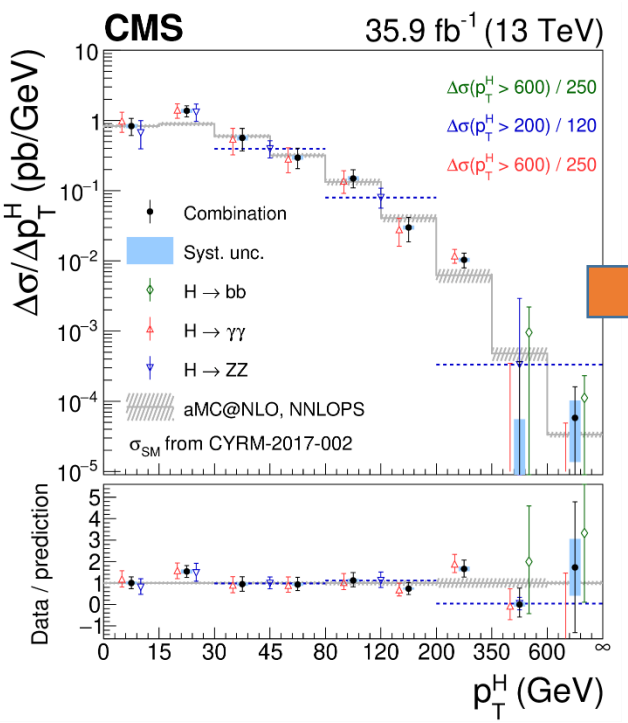


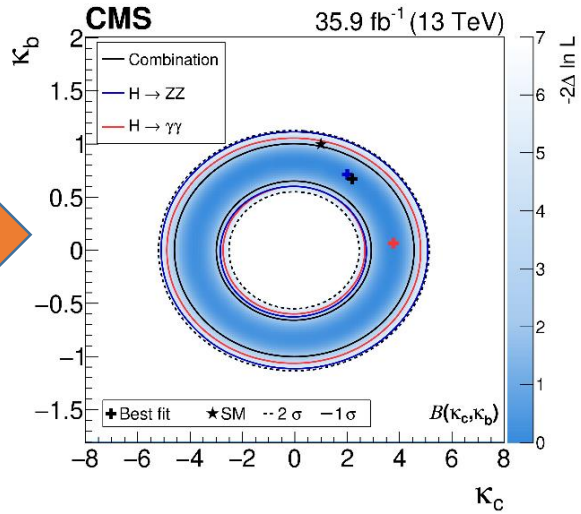
Couplings to 2nd gen fermions: c-H

PLB 792 (2019) 369

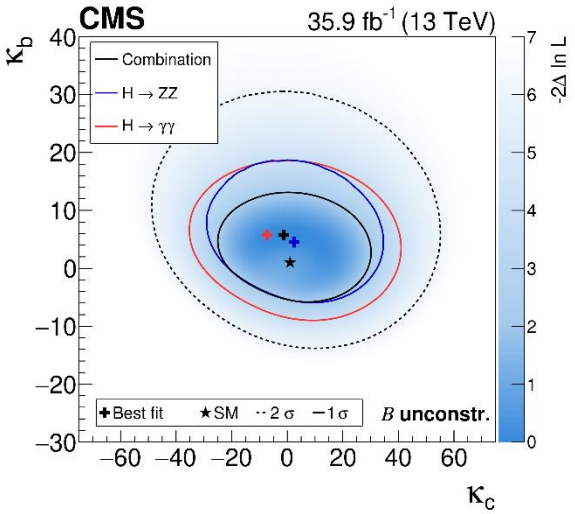
- **Direct search H→cc very challenging**
  - Low x-section; need *c*-tagging; large backgrounds
- **Indirect constraint from p_T^H** differential x-section
  - sensitive to κ_c due to interference between c- and t-mediated loops in ggH production
  - Constrain κ_c (and κ_b), setting $\kappa_t = 1$
  - Results from combination of **H→ZZ, H→γγ,** 2016 data







Assume SM dependence of BRs and Γ_H on couplings
(Γ_H and overall normalization contribute to constraint)



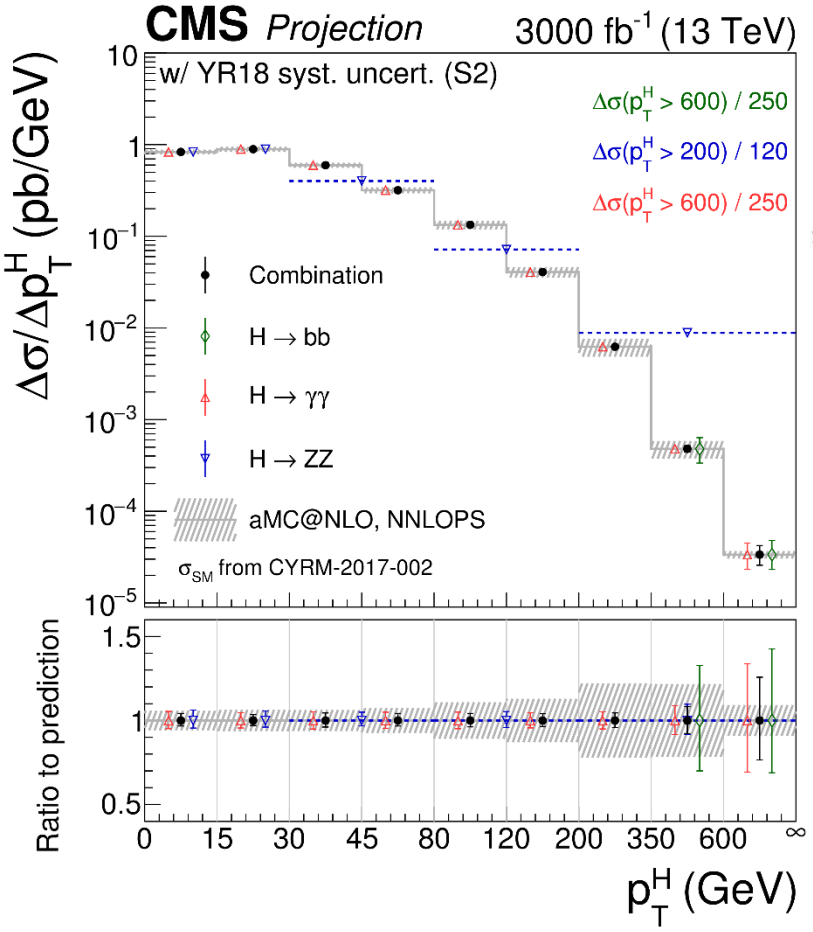
Freely floating BRs
(use p_T^H shape information only)

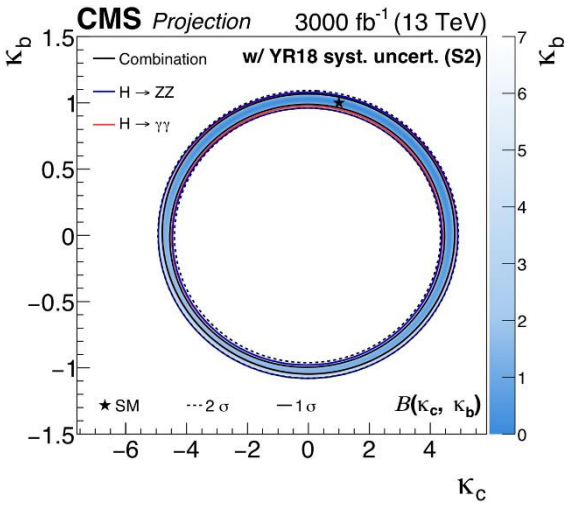
Differential distributions: projections

CMS-PAS-FTR-18-011

arXiv:1902.00134

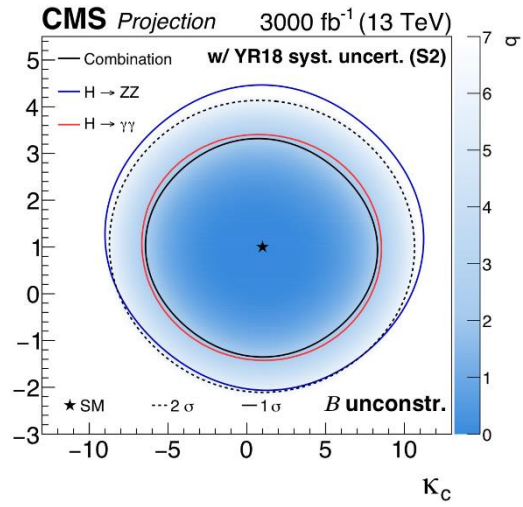
- Obvious improvement expected in differential measurement with statistics
- Extrapolations 3000 fb^{-1}





Assume SM dependence of BRs and Γ_H on couplings

(Γ_H and overall normalization contribute to constraint)



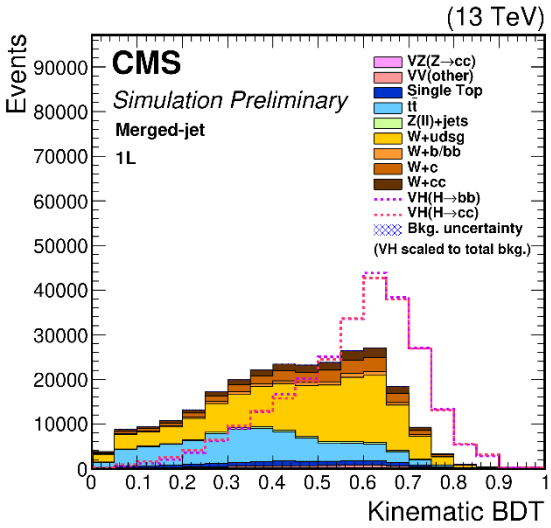
Freely floating BRs

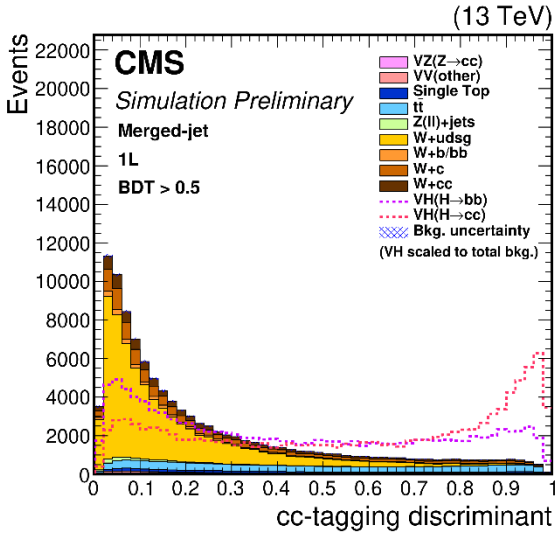
(use p_T^H shape information only)

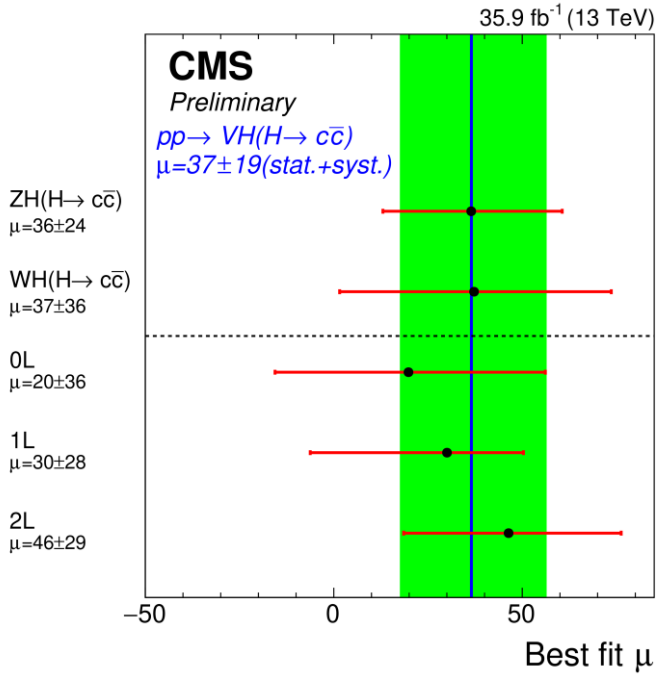
Couplings to 2nd gen fermions: c-H

CMS-PAS-HIG-18-031

- **First CMS results on direct H→cc search** in VH (H→cc)
  - using 2016 data
  - Separate analysis according to lepton multiplicity of V decays and for resolved or merged c-jets
  - Advanced techniques for c-tagging
  - Limit at $\mu < 70$ (37 exp.)



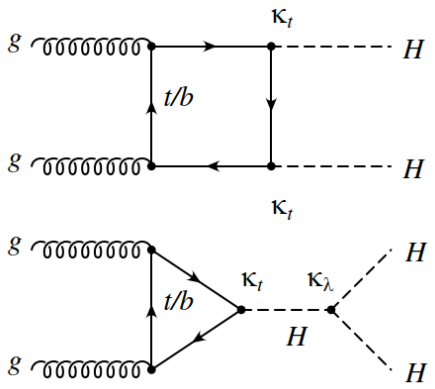


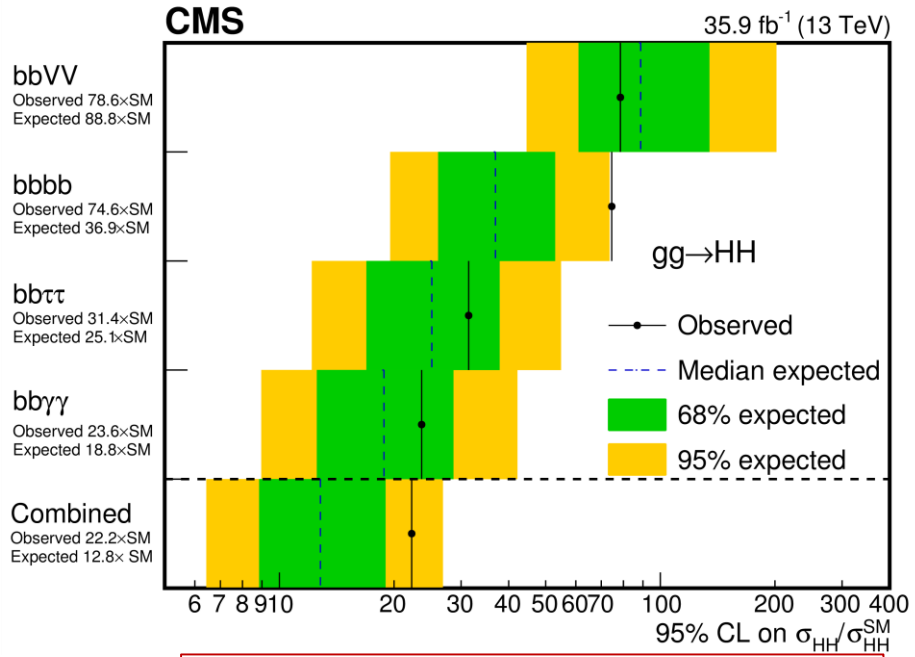


Probing the H self-coupling

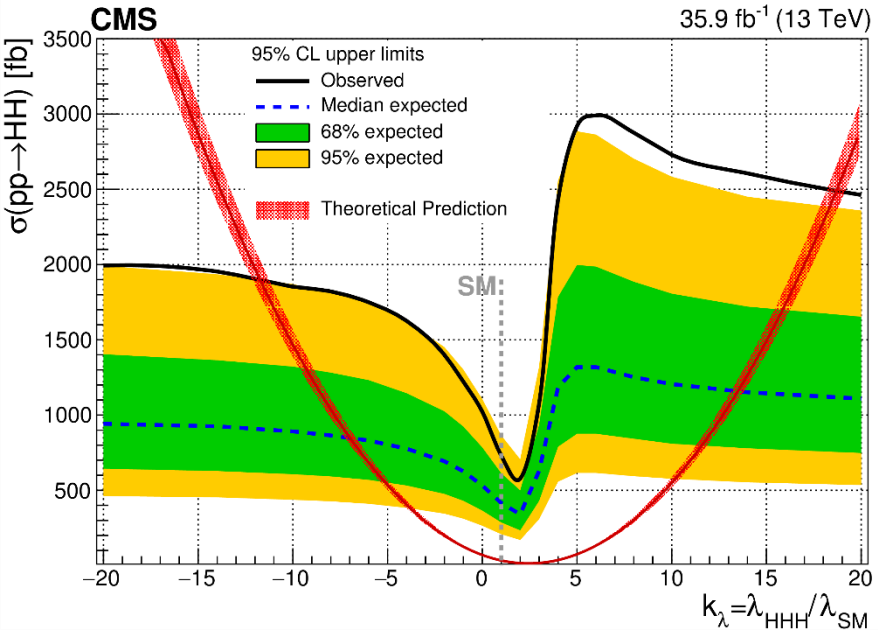
PRL 122 (2019) 121803

- HH production probes directly the Higgs boson trilinear coupling λ_{HHH}
  - Strong destructive interference
- Combination of CMS results from nonresonant search in **bbγγ, bbττ, bbbb, bbVV channels** with 2016 data





μ_{HH} < 22.2 (12.8 exp) at 95% CL



$-11.8 < k_\lambda < 18.8$ @ 95% CL

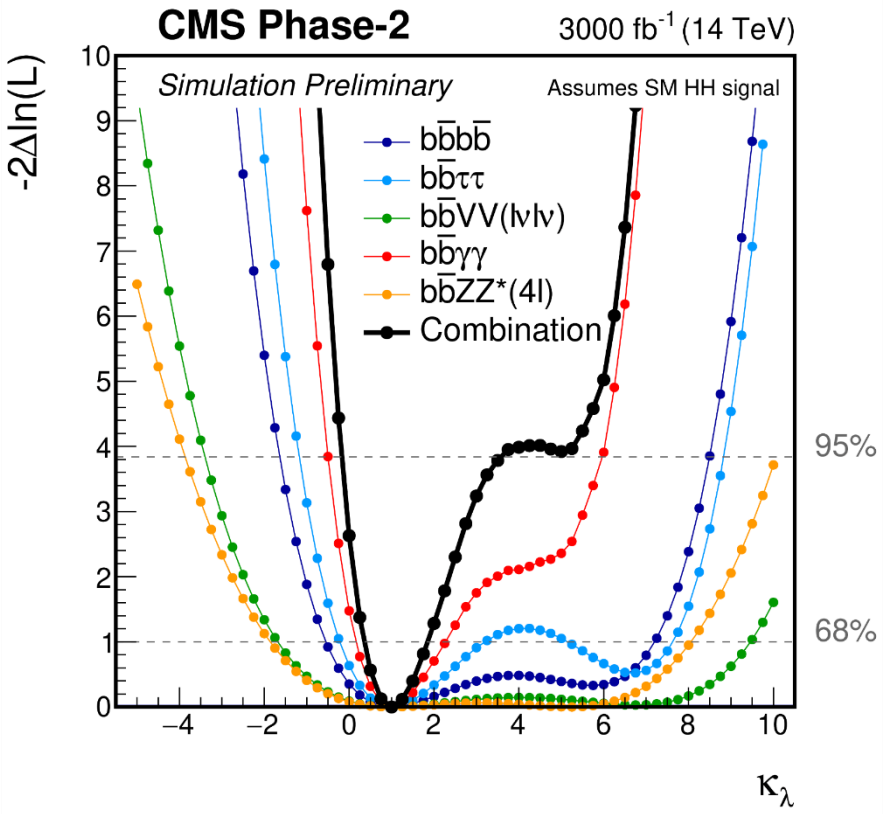
H self-coupling at the HL-LHC

CMS-PAS-FTR-18-019

arXiv:1902.00134

- Extrapolation of nonresonant HH search to 3000 fb^{-1}

Channel	Significance	
	Stat. + syst.	Stat. only
bbbb	0.95	1.2
bb$\tau\tau$	1.4	1.6
bbWW($\ell\nu\ell\nu$)	0.56	0.59
bb$\gamma\gamma$	1.8	1.8
bbZZ($\ell\ell\ell\ell$)	0.37	0.37
Combination	2.6	2.8

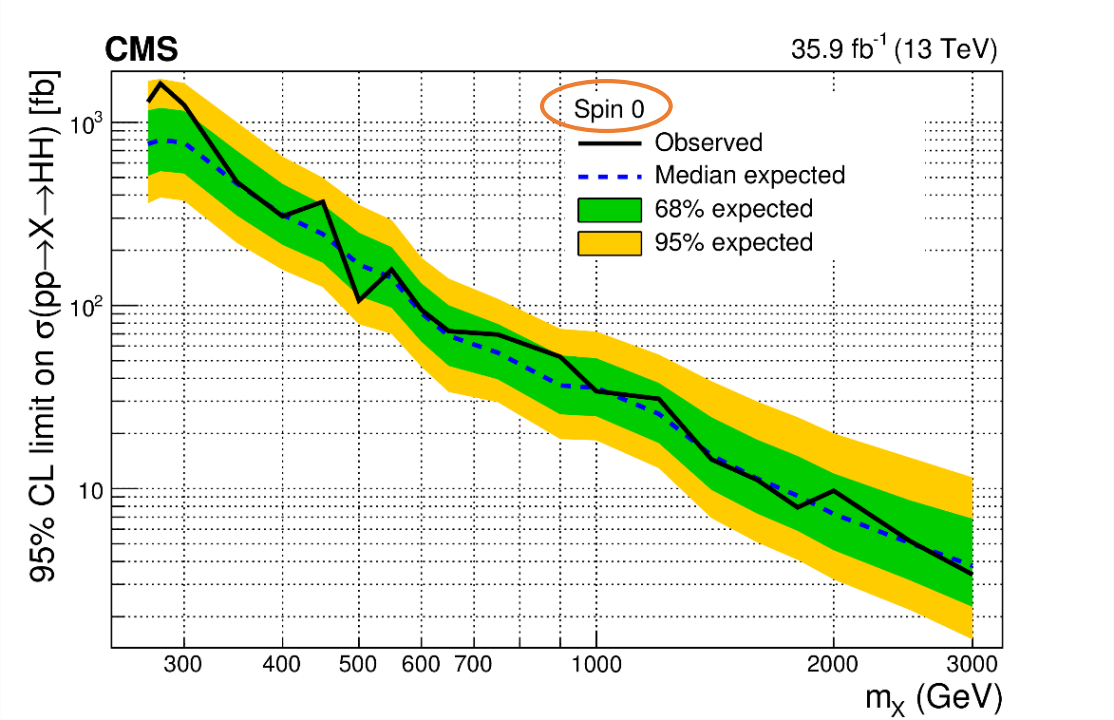


[0.35, 1.9] at 68% CL

Resonant HH search

PRL 122 (2019) 121803

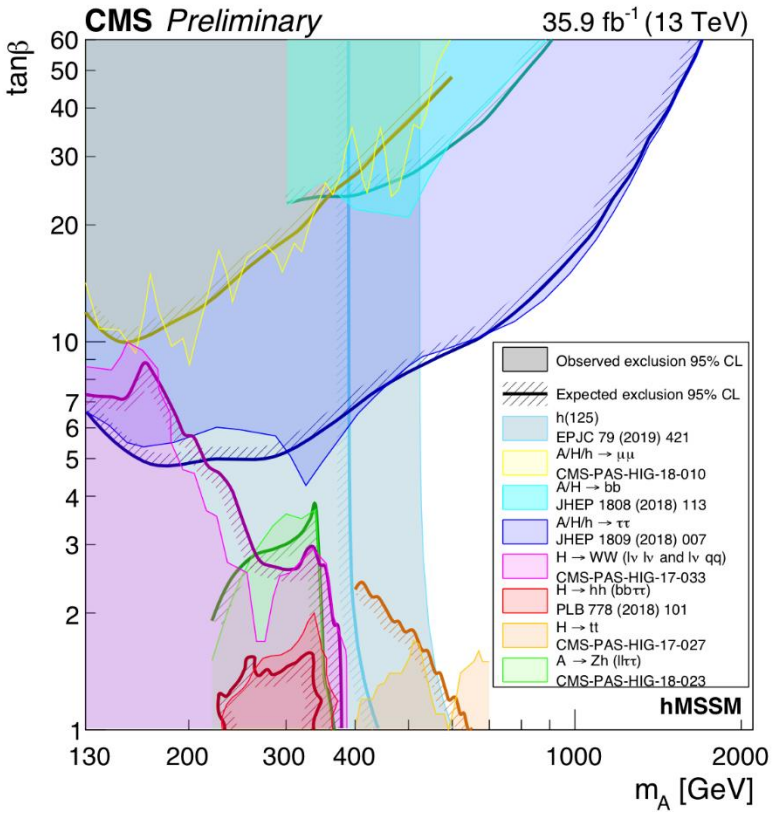
Limits for narrow resonances decays to HH also obtained from the combination of 2016 data analyses of bbγγ, bbττ, bbbb, bbVV channels



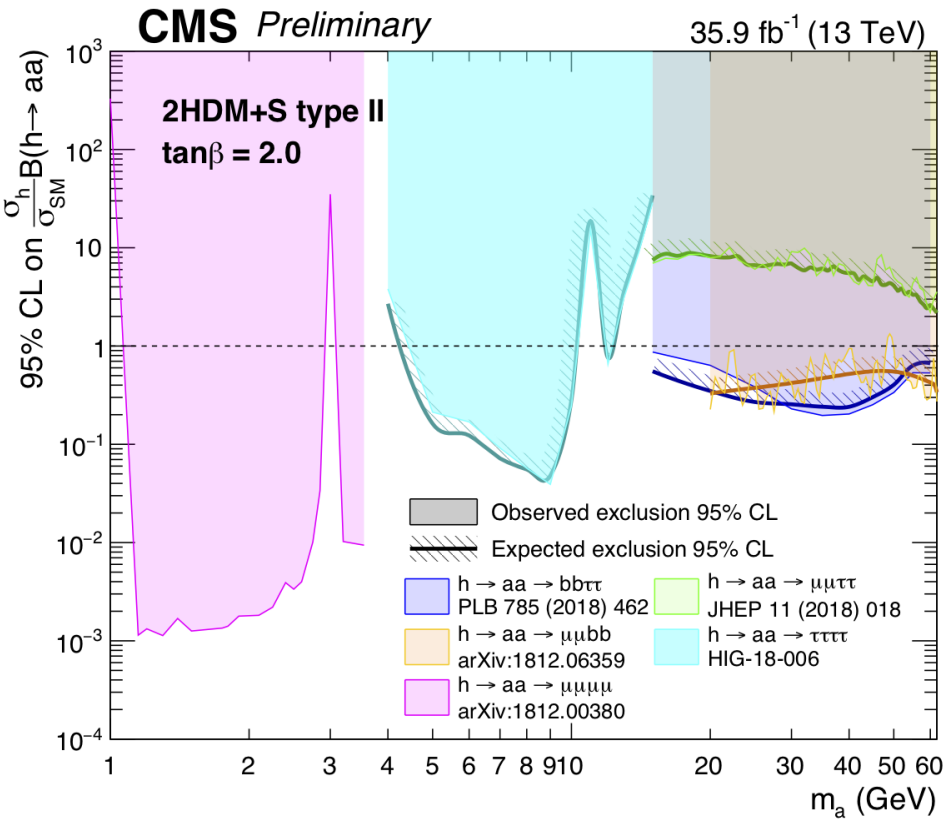
Also, recent new results for resonant HH → bbZZ → bbℓℓjj, bbℓℓνν [CMS-PAS-HIG-18-013]

BSM searches

- Variety of searches for additional Higgs bosons and exotic decays of H(125)
- So far no excess or evidence and only exclusions in theory parameter space



Summary of searches in the hMSSM scenario with 2016 data



Summary of 2HDM+Singlet searches with 2016 data

Summary & Outlook

- **A broad Higgs physics program** is ongoing with **Run 2 data**
  - Most of the measurements of Higgs boson properties are well established
  - Established all main **production** (ggH, VBF, VH, ttH) **and decay modes** (ZZ, WW, $\gamma\gamma$, $\tau\tau$, bb)
  - Precision channels well into **STXS and differential cross-section** measurements
  - Couplings to 3rd generation fermions already contributing to property measurements
  - Start chasing **rare processes**

- No significant deviation from SM prediction observed so far

- Results are being updated with entire Run 2 dataset – stay tuned!

- Much more to come with HL-LHC

Find all CMS Higgs-related publications and preliminary risults at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG