Highlights from Higgs Physics at CMS

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on behalf of the CMS Collaboration

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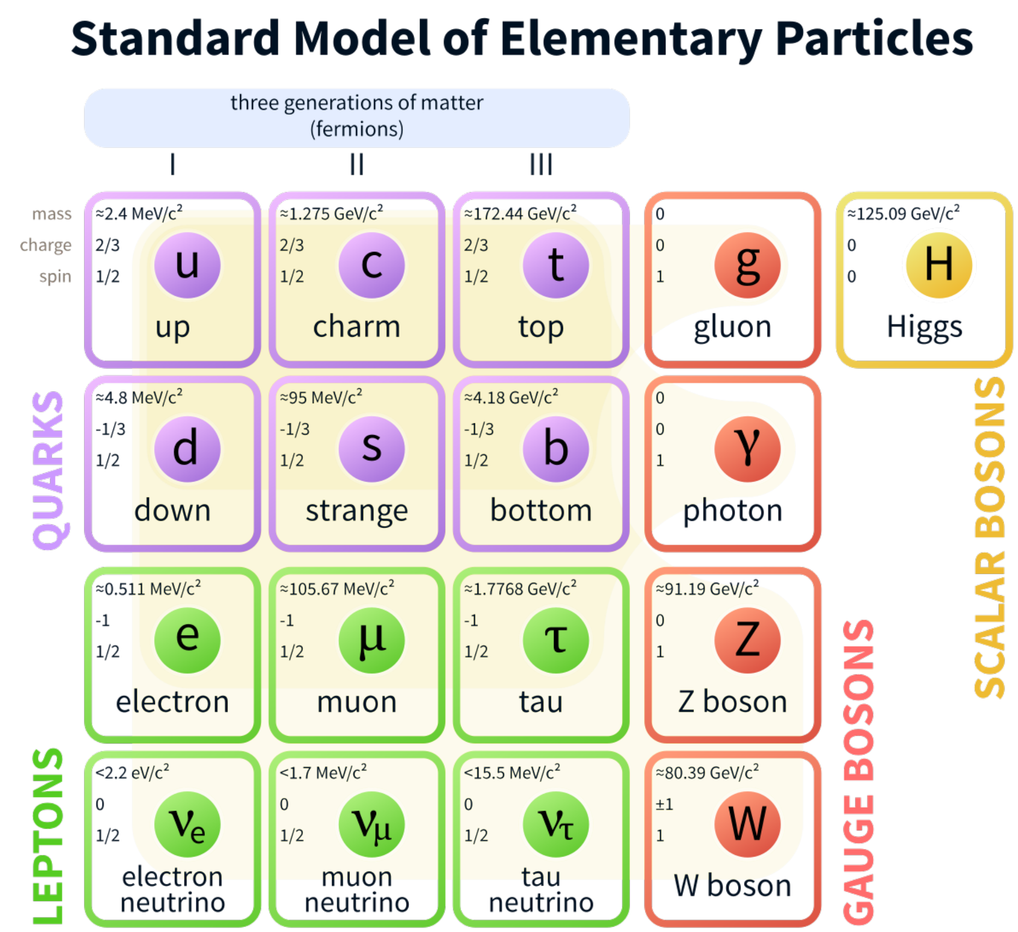
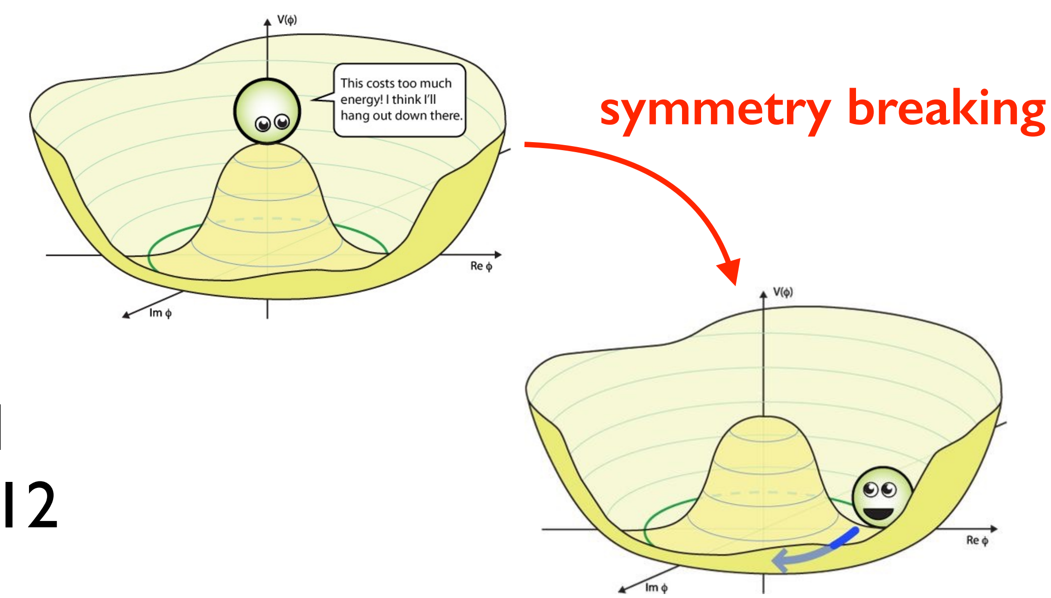
Introduction

- ★ **The Standard model (SM)** of particle physics explains a wide variety of microscopic phenomena in a unified framework (Quantum Field Theory)
  - ◉ matters consist of quarks and leptons
  - ◉ interaction between particles governed by gauge bosons
- ★ **The Higgs mechanism** is responsible for assigning mass to particles
  - ◉ Higgs boson is an evidence of the Higgs field
- ★ **A main goal of the LHC** is the in-depth investigation of electroweak symmetry breaking
- ★ **A SM-like Higgs boson = H(125)** was discovered by ATLAS and CMS experiments of the LHC in 2012



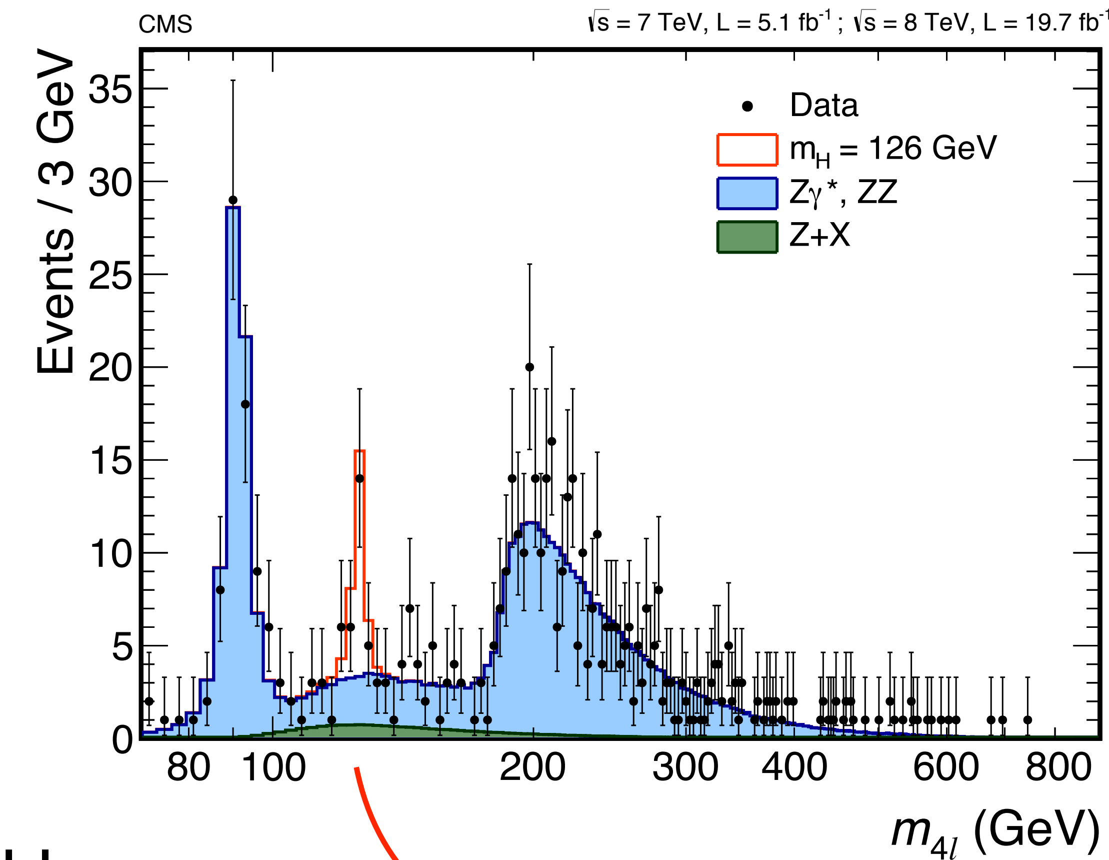


Introduction

★ 6 years after the discovery, the story continues

- ◉ precise measurements of properties
  - mass, couplings/cross-section
- ◉ discover other Higgs decay channels and production modes
  - $H\rightarrow\tau\tau$, $H\rightarrow bb$, ttH production
- ◉ rare processes : $H\rightarrow\mu\mu$, $H\rightarrow$invisible
- ◉ search for Higgs bosons beyond the SM

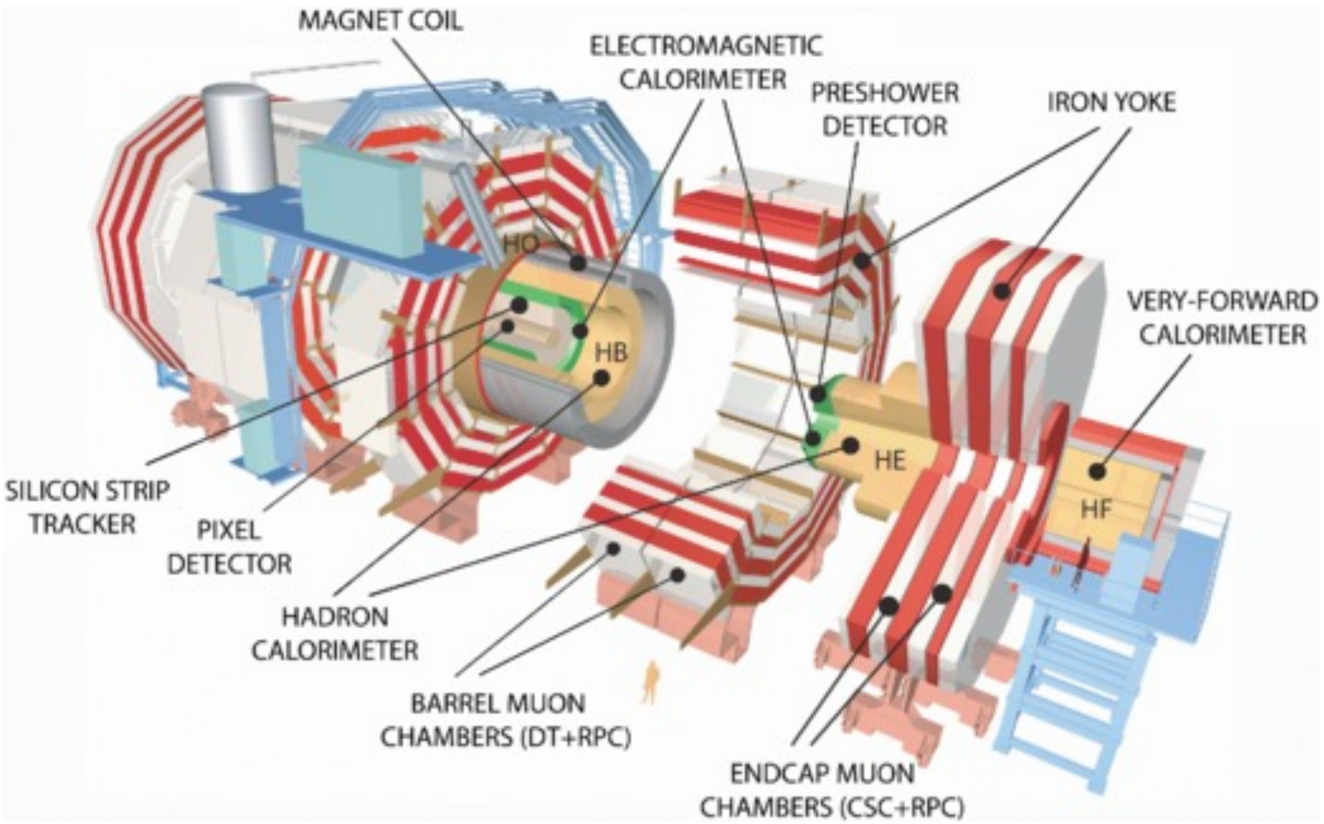
PRD 89 (2014) 092007



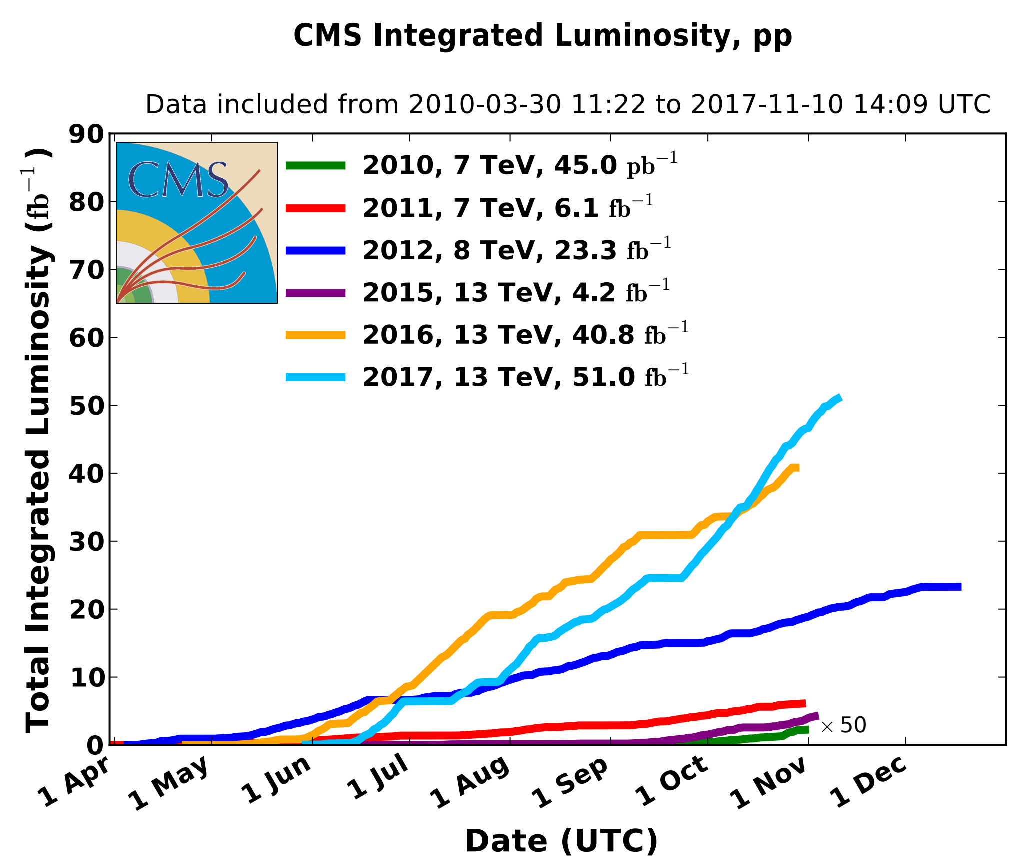
★ This talk will focus on the latest results available with the full 2016 data (L ~ 36 fb^{-1})

- ◉ properties of H(125)
- ◉ BSM Higgs searches

Compact Muon Solenoid (CMS)



- ★ One of two large general purpose detectors of the LHC
- ★ Smaller in dimension than ATLAS, but heavier
  - ◉ CMS : 15m diameter, 20m length, 12500 tons
  - ◉ ATLAS : 22m diameter, 46m length, 7000 tons



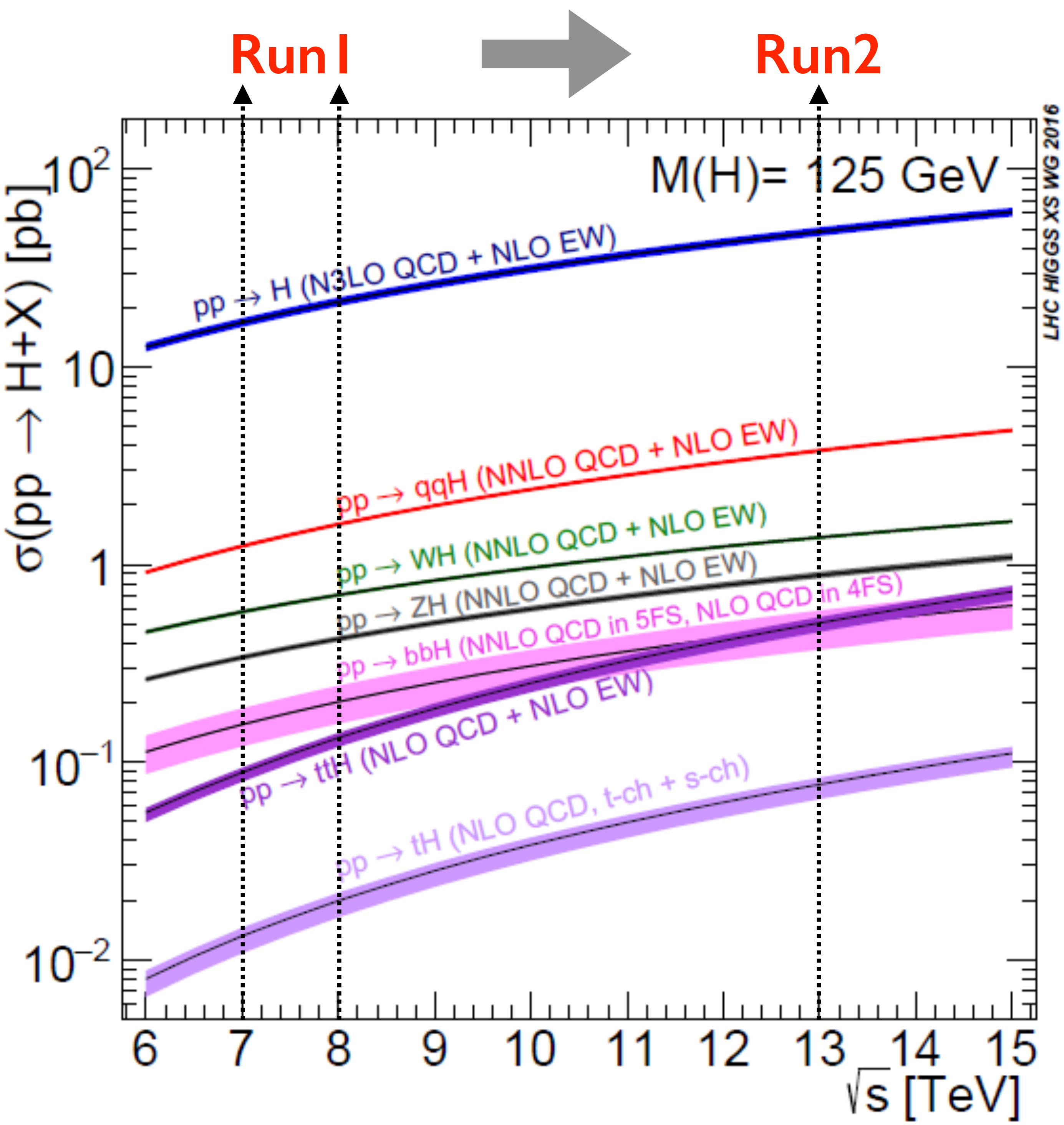
- ★ 5 years of data taking and being analyzed
  - ★ 2011 at 7 TeV, L ~ 5 fb^{-1}
  - ★ 2012 at 8 TeV, L ~ 20 fb^{-1}
  - ★ 2015 at 13 TeV, L ~ 3 fb^{-1}
  - ★ 2016 at 13 TeV, L ~ 36 fb^{-1}
  - ★ 2017 at 13 TeV, L ~ 42 fb^{-1}

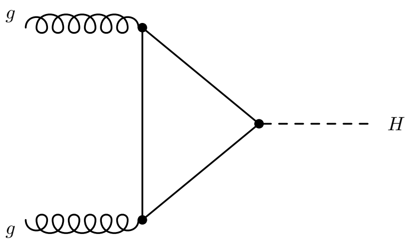
Run1 (2011–2012)

Run2 (2015–2017)

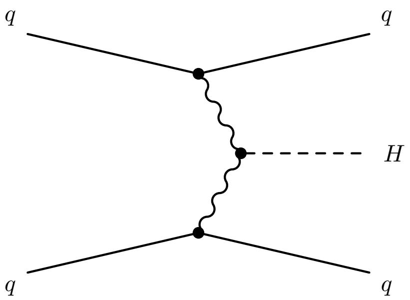
>100 fb-1

Higgs Production at LHC

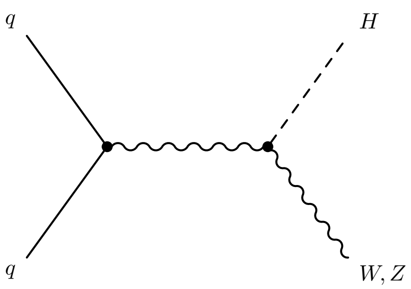




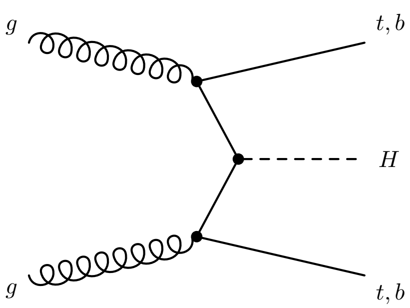
gluon fusion (ggH)
48.3 pb



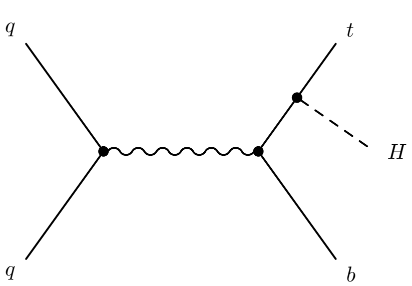
W/Z fusion (VBF)
3.77 pb



WH 1.36 pb
ZH 0.88 pb



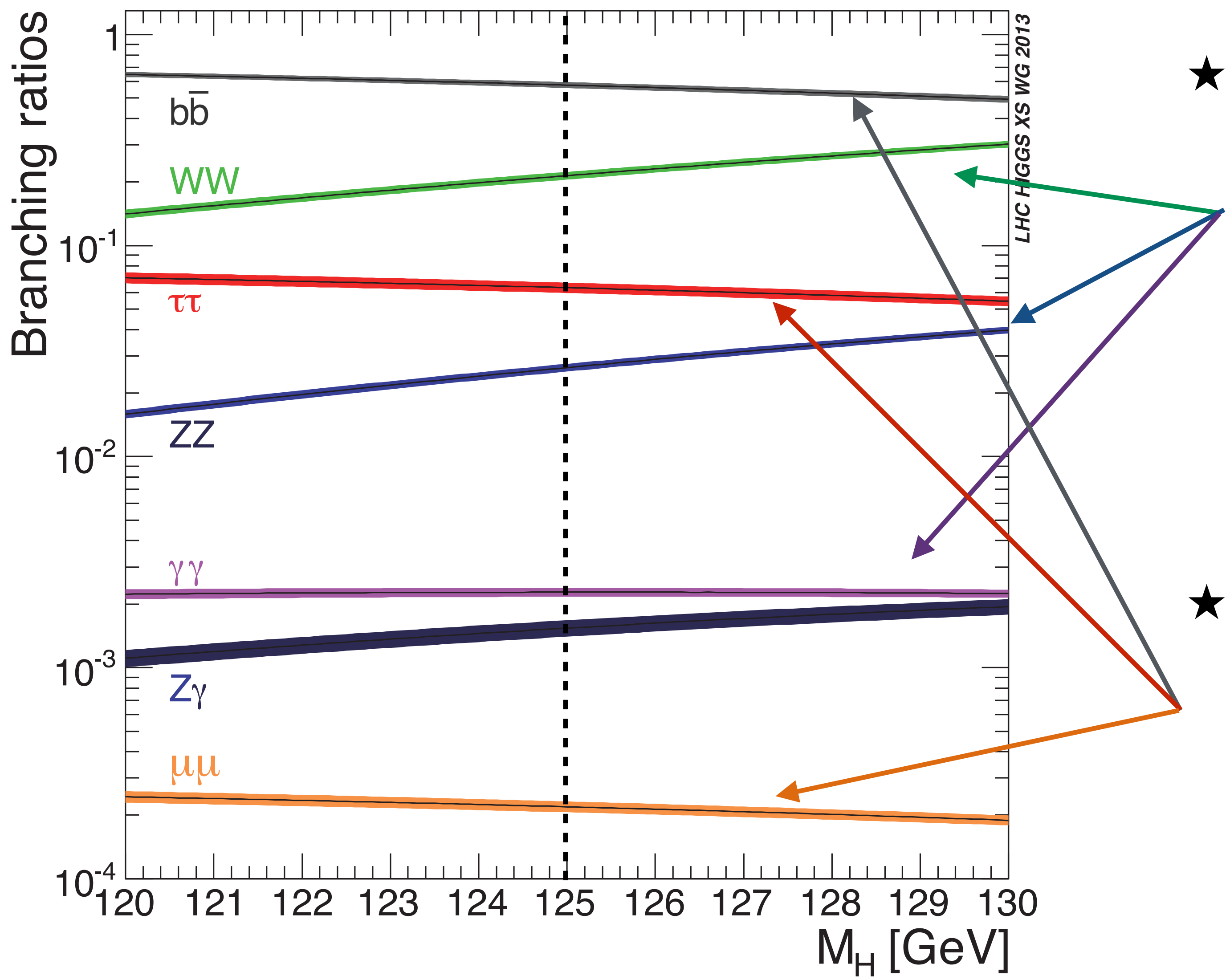
ttH
0.50 pb



tHq
0.074 pb

Higgs Decay

★ Most of the H(125) decays accessible at the LHC



★ Bosonic decay : ZZ (3%), γγ (0.2%) as the discovery channels with clean final states, including WW (22%) for precise measurements

★ Fermionic decay : bb (58%) dominant channel, ττ (6%) and μμ (0.02%) as rare decay not discovered yet in Run1 → Highlights of Run2!

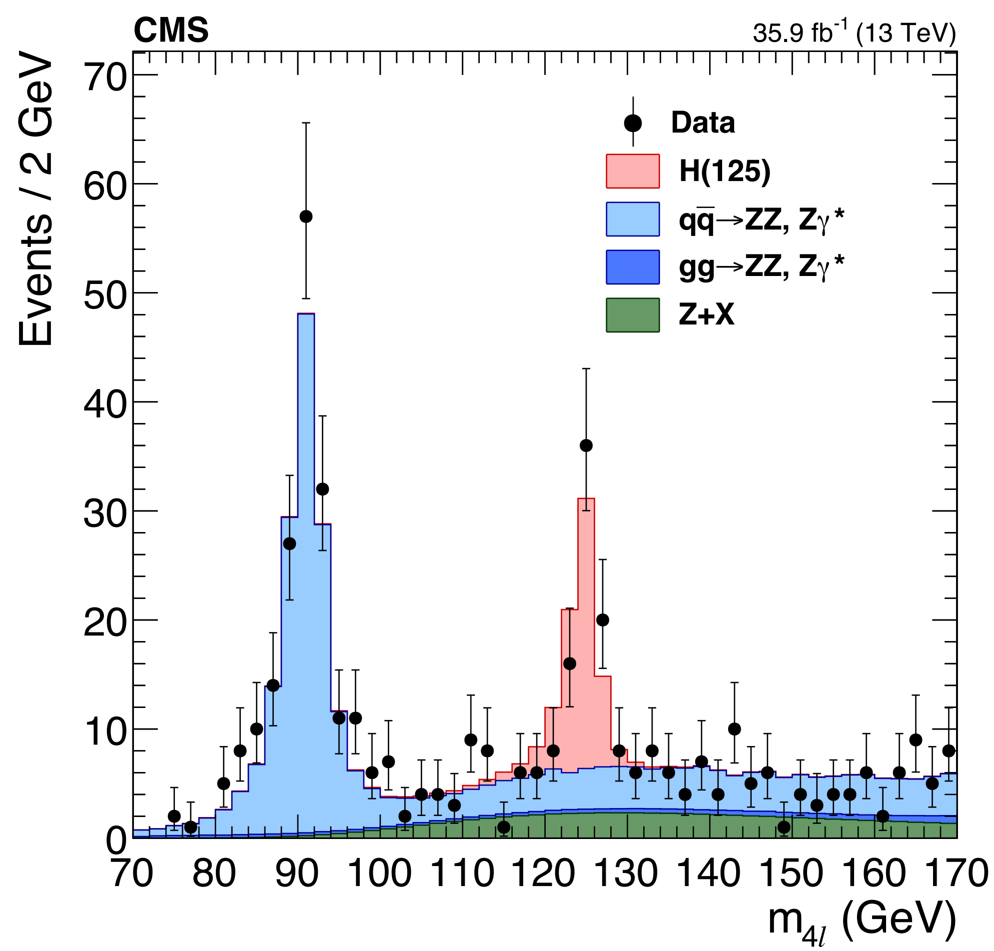
5 main production processes x 6 decay modes
=30 exclusive final states contributed to H(125)

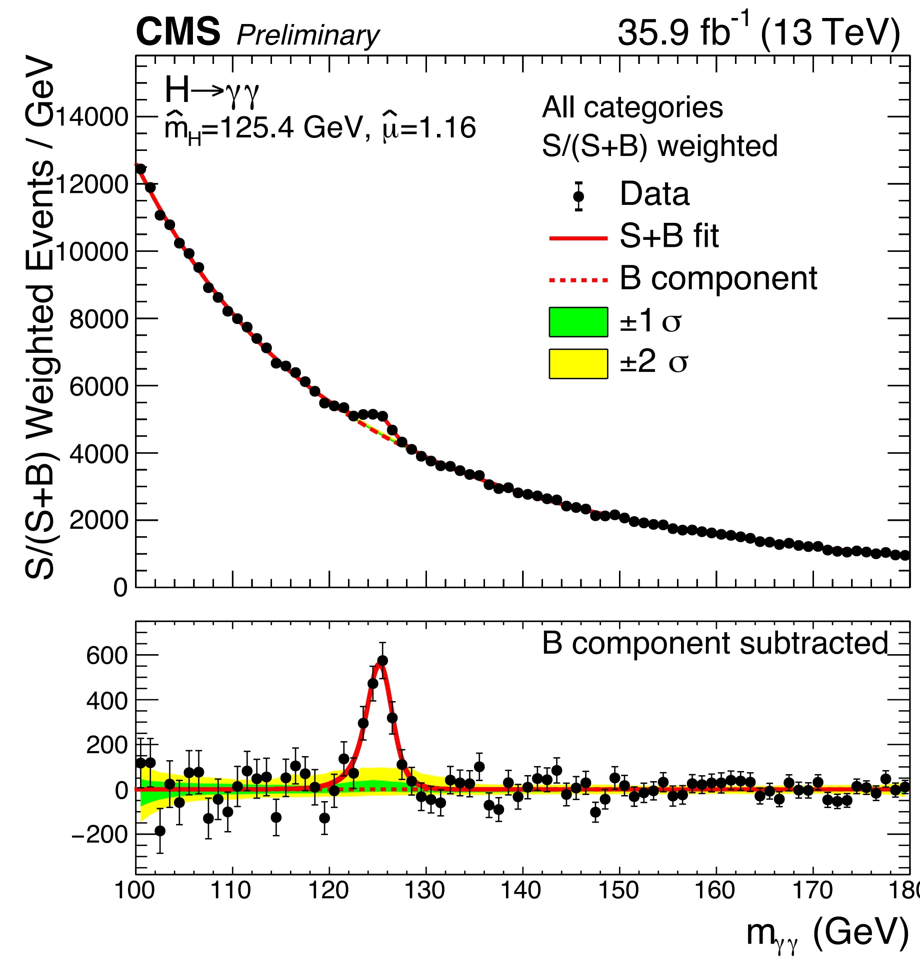
JHEP 11 (2017) 047
CMS PAS HIG-16-040
CMS PAS HIG-17-015

H→ZZ & H→γγ

★ Measurement of mass of H(125) decaying to 4 leptons and diphoton channels

- sensitivity enhanced by event categorizations





mass (H→ZZ) : m_H = 125.26 ± 0.20 stat. ± 0.08 syst. GeV

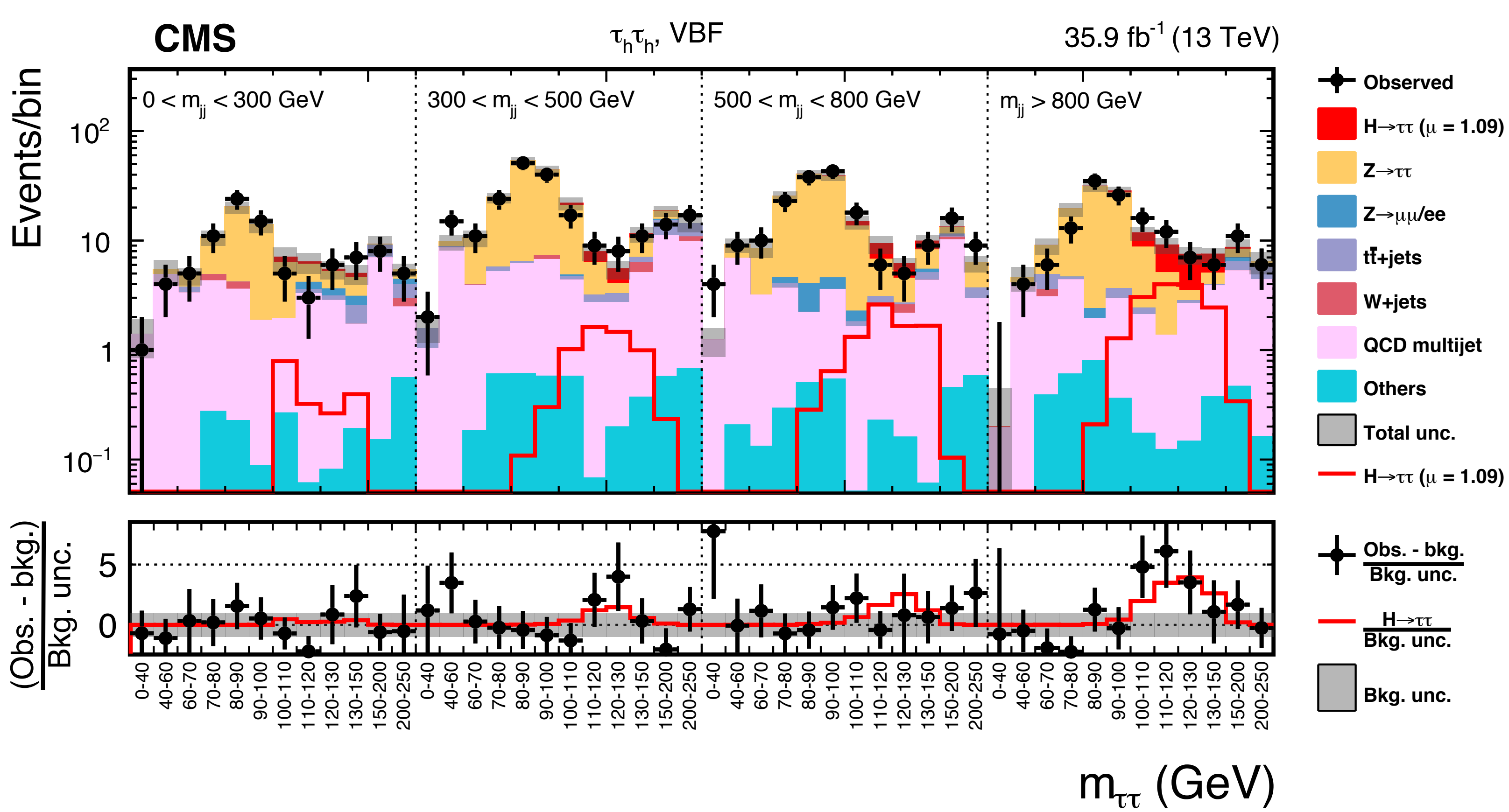
12% more precise compared to Run1 ATLAS+CMS combination

PLB 779 (2018) 283

$H \rightarrow \tau\tau$

- ★ Second largest branching ratio (~6.3%) among fermionic decay channel
  - ◉ lower background compare to bb
- ★ 4 most sensitive channels ($e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$) x 3 event categories (0-,1-,2-jets)
  - ◉ targeting ggH and VBF processes
- ★ Clear excess at m_H=125 GeV
- ★ **First observation of $H \rightarrow \tau\tau$ from single experiment**

4.9σ (4.7σ expected)
5.9σ combined with CMS Run1

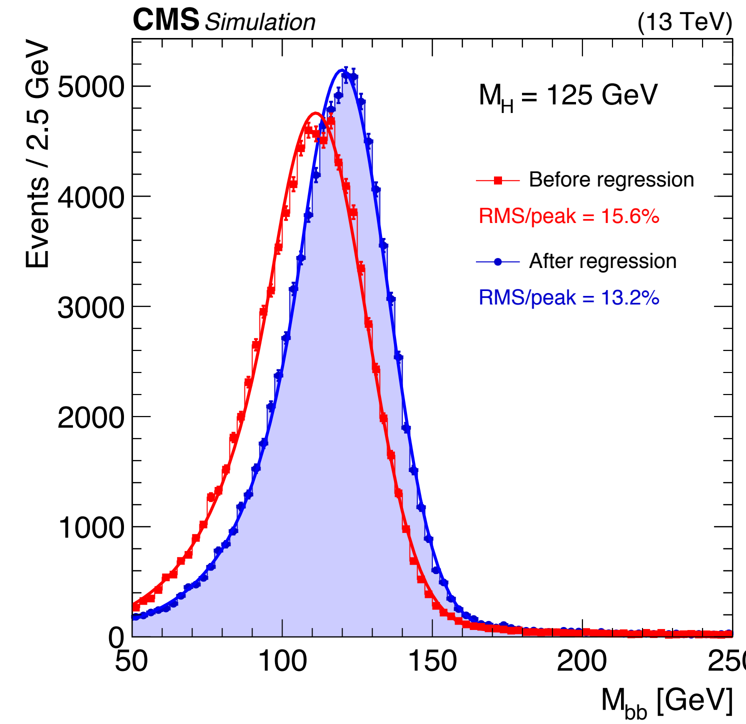


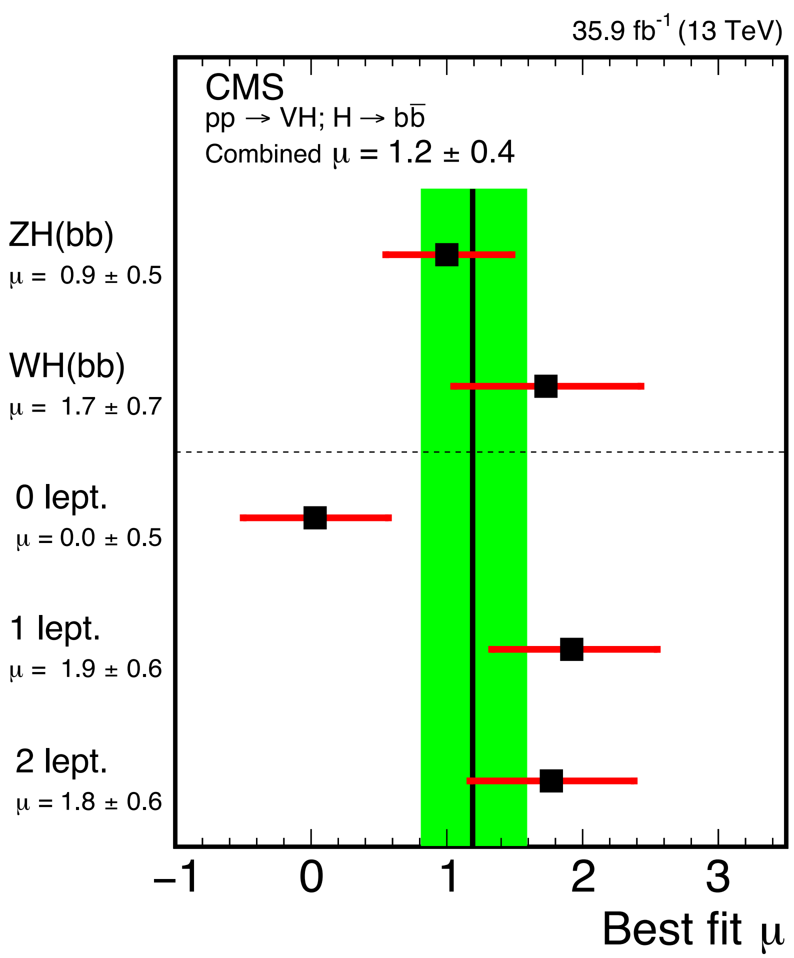
- ★ Signal strength μ (the ratio of the measured Higgs boson rate to its SM prediction) is compatible with SM

$\mu = 0.98 \pm 0.18$ (Run1+Run2)

VH H→bb

- ★ Dominant decay mode (~58%) in SM, but not yet discovered due to large background
  - ◉ recoiling against W/Z boson is advantageous
- ★ 3 channels (0-, 1-, 2- leptons) from W/Z→$\ell\ell,\ell\nu,\nu\nu$
- ★ Multivariate regression to improve mass resolution
- ★ Signal extraction using multivariate analysis technique





Evidence of H→bb which can lead to the discovery!

Data used	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
Combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$

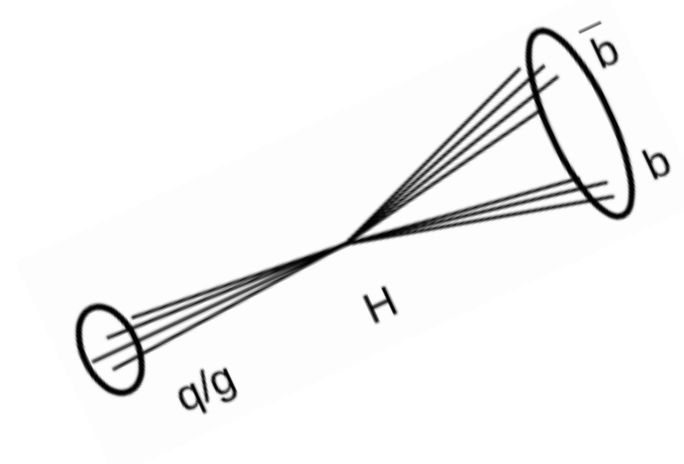
PRL 120 (2018) 071802

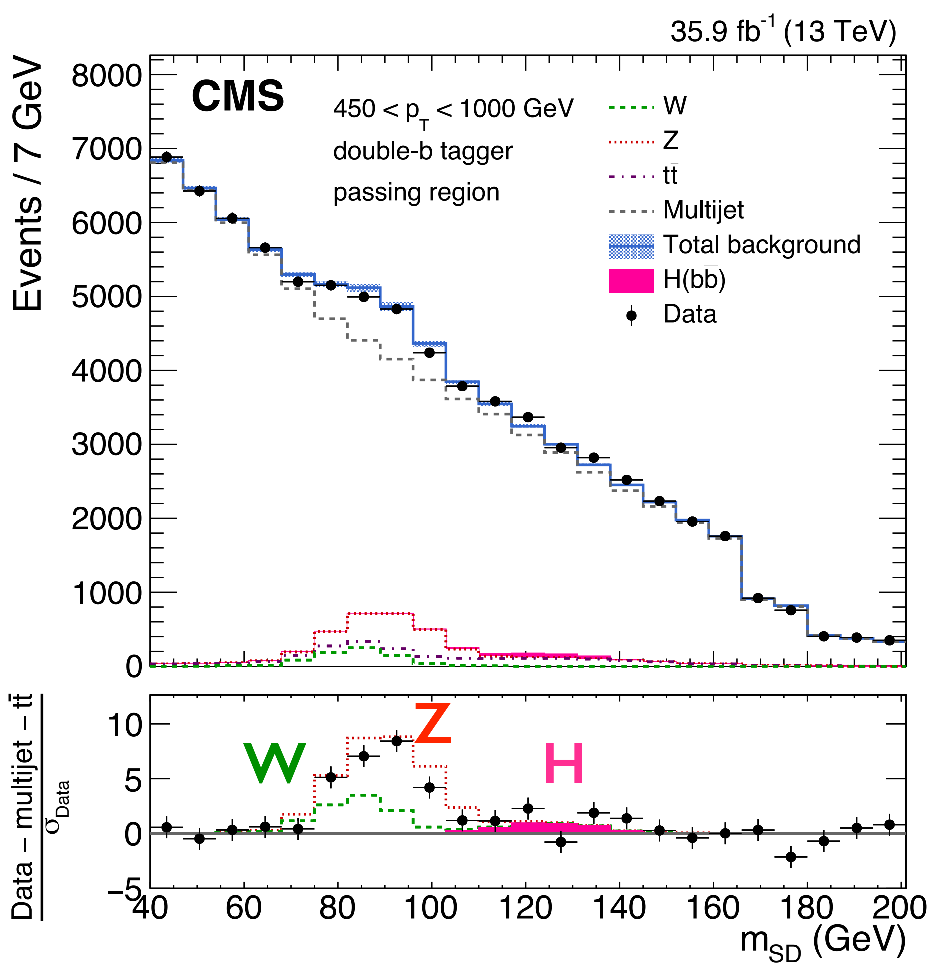
Boosted H→bb

★ Studying H→bb in inclusive production (without W/Z boson) was usually considered impossible due to overwhelming QCD background

★ New idea introduced in "**boosted topology**"

- boosted H→bb candidate recoiling against ISR jet
- dedicated jet substructure techniques to tag large-radius jets containing two b quarks





★ **A respectable sensitivity for H→bb** in a brand new regime of ggH with $p_T > 450$ GeV using promising method

★ **Clear observation of resonant Z→bb signal**

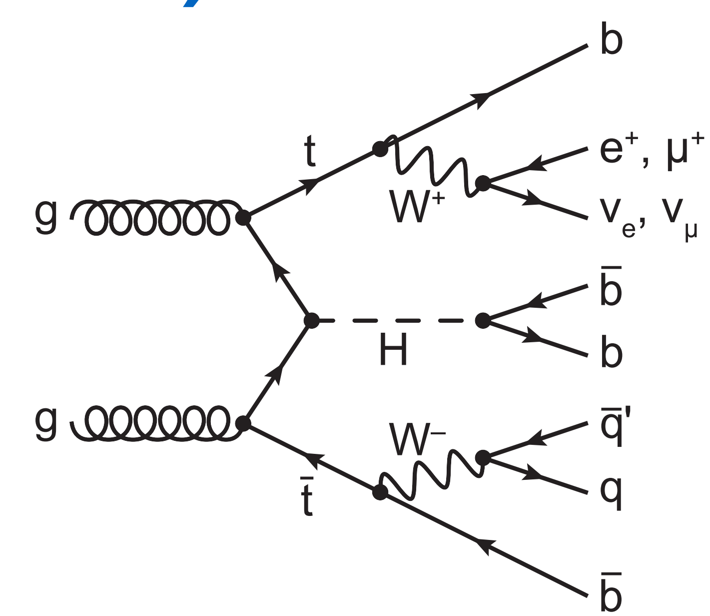
significance 5.1σ (5.8σ expected)

	H	H no p_T corr.	Z
Observed signal strength	$2.3^{+1.8}_{-1.6}$	$3.2^{+2.2}_{-2.0}$	$0.78^{+0.23}_{-0.19}$
Expected UL signal strength	< 3.3	< 4.1	—
Observed UL signal strength	< 5.8	< 7.2	—
Expected significance	0.7σ	0.5σ	5.8σ
Observed significance	1.5σ	1.6σ	5.1σ

NEW

ttH H→bb (leptonic)

- ★ Direct probe of the top-Higgs Yukawa couplings
  - ◉ cross section increased by a factor of 3.9 in Run2
  - ◉ gain from largest BR(H→bb)
- ★ At least one lepton from top decay → higher purity
- ★ Complex final states require more sophisticated methods
  - ◉ 3 different multivariate analysis techniques
- ★ Limited by tt+HF and b-tagging uncertainties

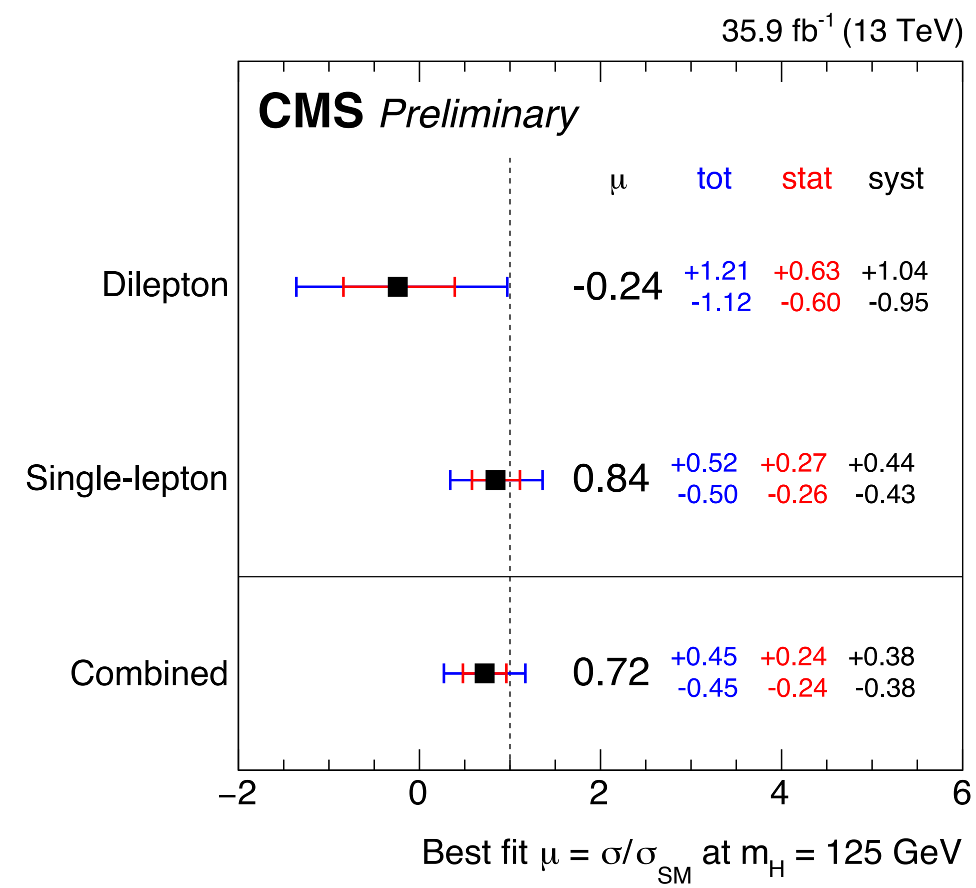


semileptonic ttH diagram

Best-fit μ = 0.72 ± 0.45

significance 1.6σ (2.2σ expected)

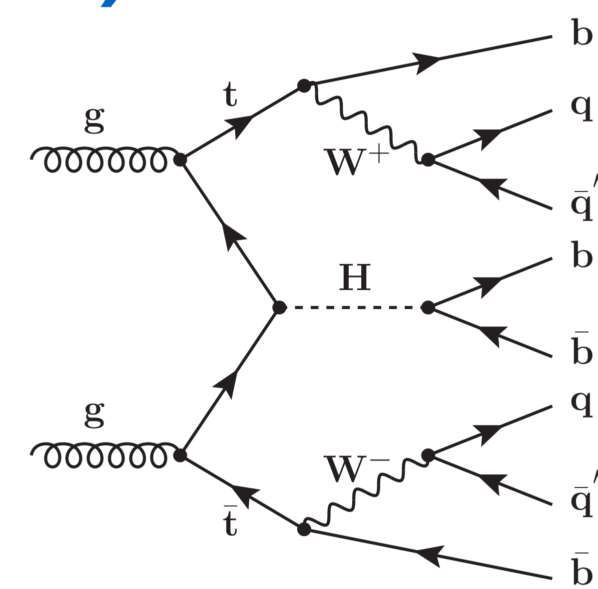
huge improvement in sensitivity than Run1



NEW

ttH H→bb (hadronic)

★ Hadronic top decay → higher rate (46%) but more challenging
- ≥7 jets in an event requires dedicated all-jet triggers
- fully reconstructed final state to the Higgs candidate



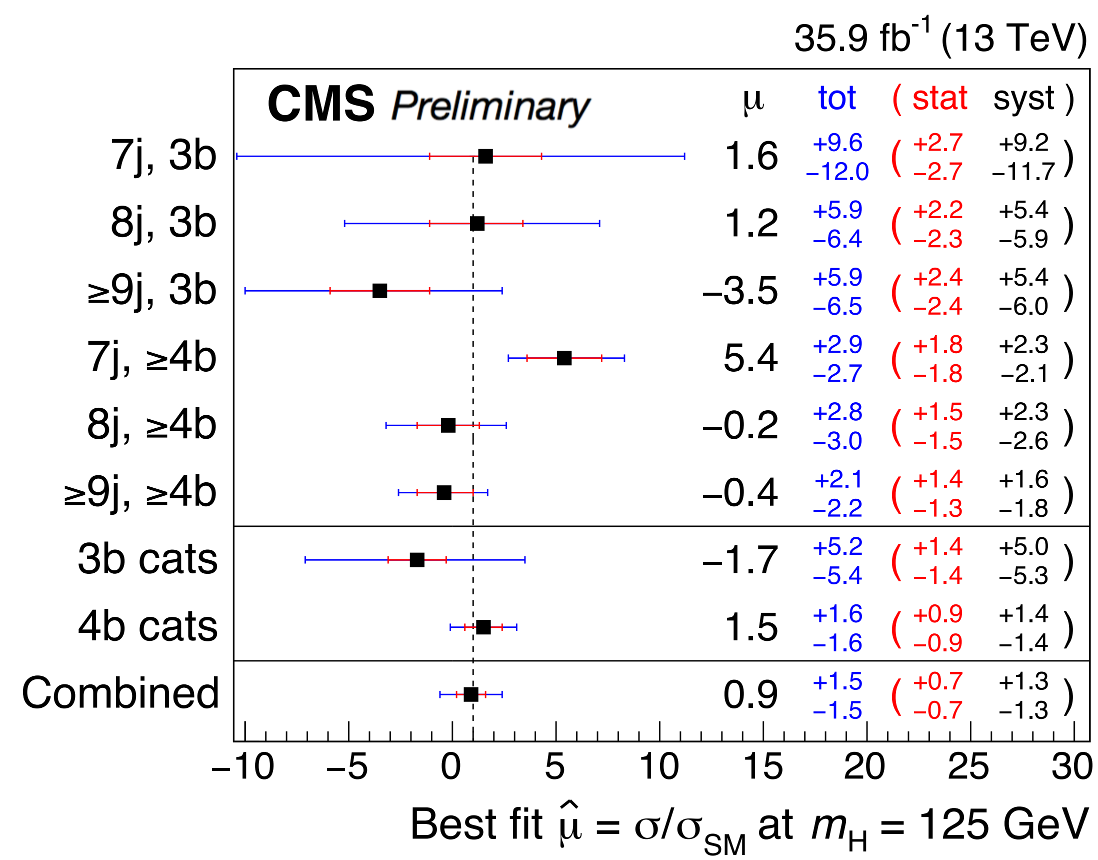
fully hadronic ttH diagram

★ Enhanced quark-jet final states by quark-gluon jet discriminant
- reduce QCD multijet background

★ Two levels of multivariate methods to separate signal and background

★ Provided supplementary sensitivity to the overall search for ttH production

Best-fit μ = 0.9 ± 1.5,
upper observed limit μ < 3.8 at 95% CL



NEW

CMS PAS HIG-16-040
CMS PAS HIG-17-018
CMS PAS HIG-17-022
CMS PAS HIG-17-026

ttH Summary

★ A variety of final states, studied with different experimental techniques:
- tt + b-jets: large branching ratio, but complex multijet final state
- tt + leptons (H→WW, ZZ, $\tau\tau$): lower rate, low SM backgrounds
- tt + $\gamma\gamma$, 4ℓ: small branching ratio, but very clean final state

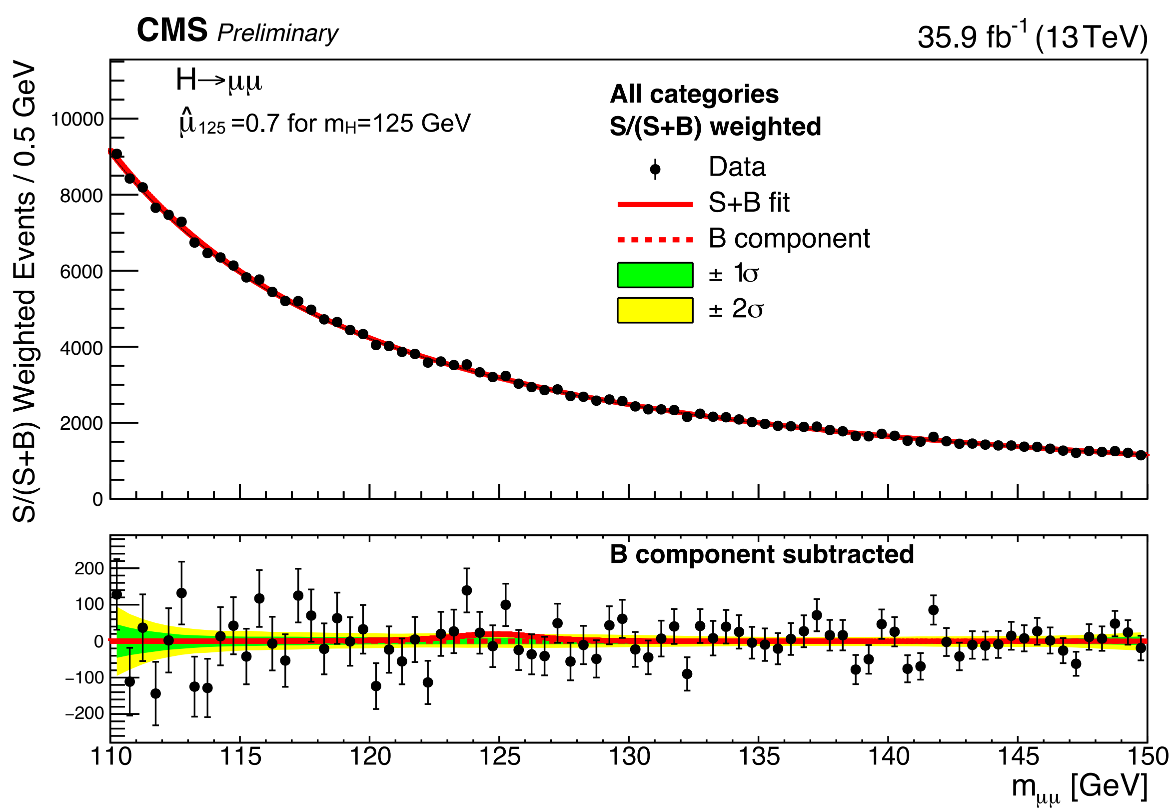
decay mode	best fit μ	significance
H→$\gamma\gamma$	2.2 (+0.9/-0.8)	3.3σ (1.6σ exp.)
H→WW, ZZ, $\tau\tau$	1.23 (+0.45/-0.43)	3.2σ (2.8σ exp.)
H→bb, 0ℓ	0.9 (+1.5/-1.5)	0.6σ (0.7σ exp.)
H→bb, 1ℓ + 2ℓ	0.72 (+0.45/-0.45)	1.6σ (2.2σ exp.)

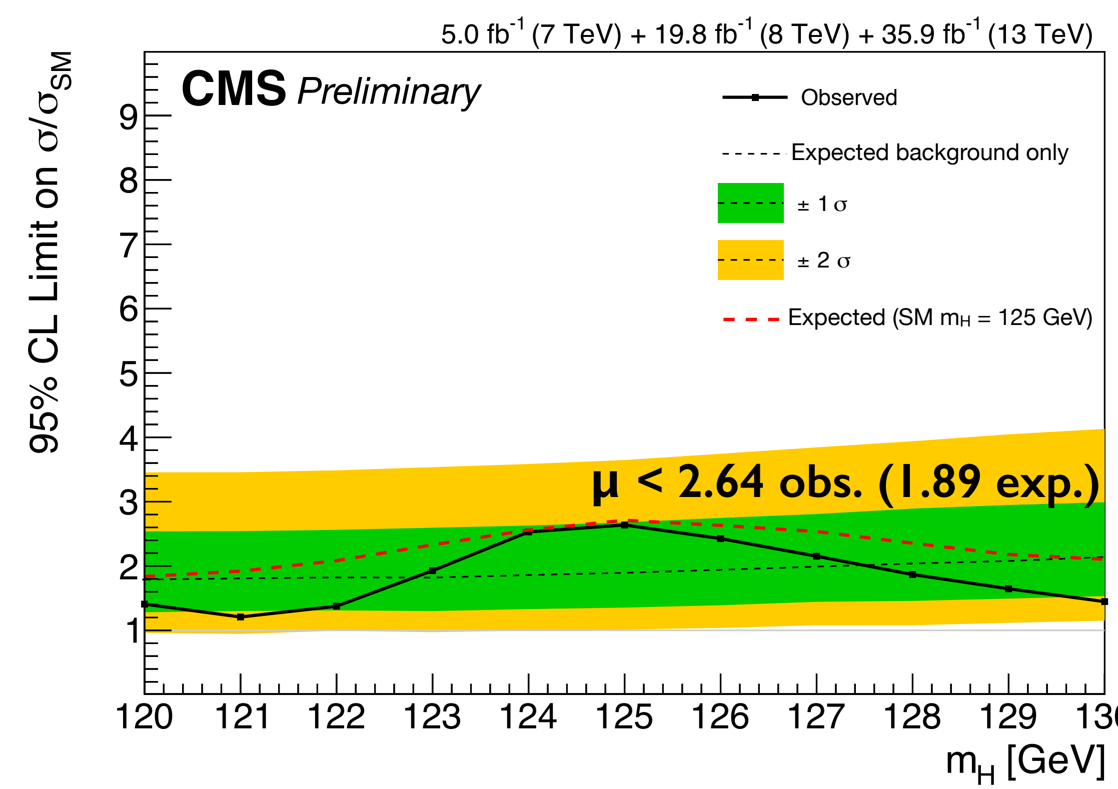
★ The ttH combination is not yet available but all above channels enter the combination of couplings measurement (slide 15-16)

Rare H→μμ

- ★ Probe of H(125) couplings to 2nd generation of leptons
  - very low BR (~0.02%)
  - beneficial from excellent dimuon mass resolution
- ★ No significant excess is observed
  - 95% CL upper limit on the signal strength

Run1+Run2 : best-fit μ = 0.9 ± 1.0 significance of 0.98σ (1.09σ expected)



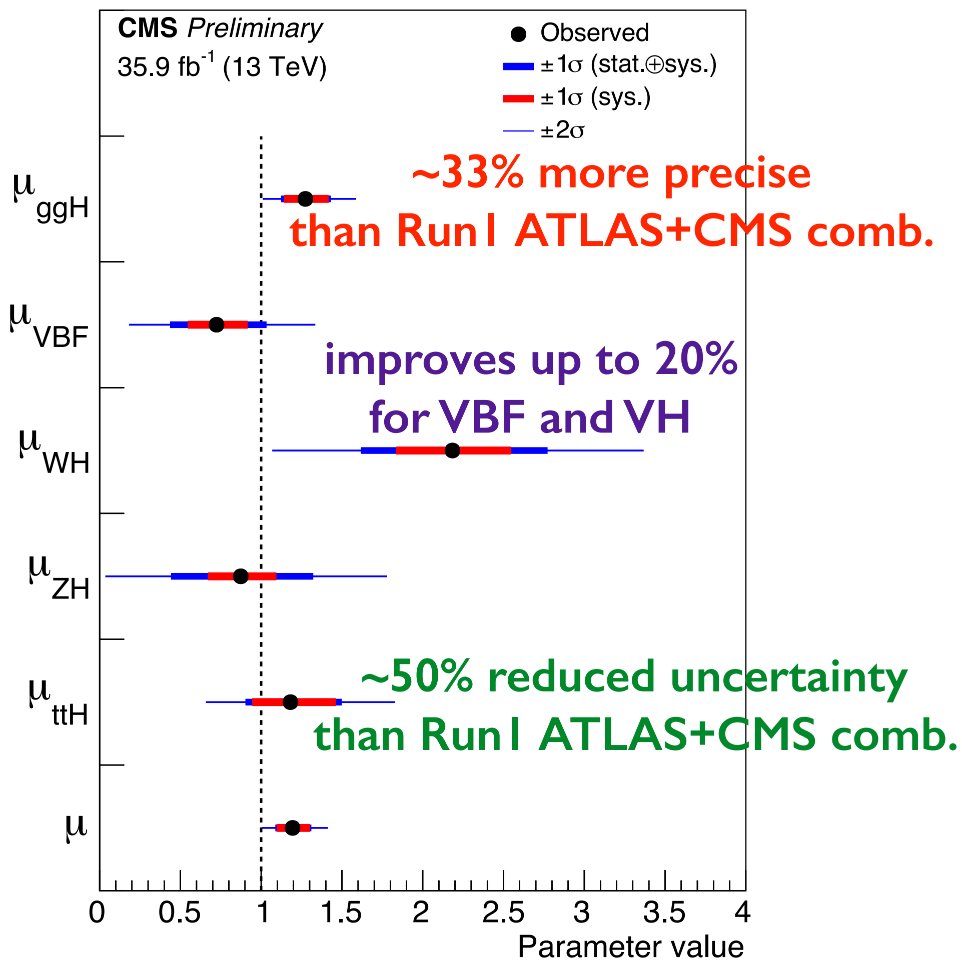


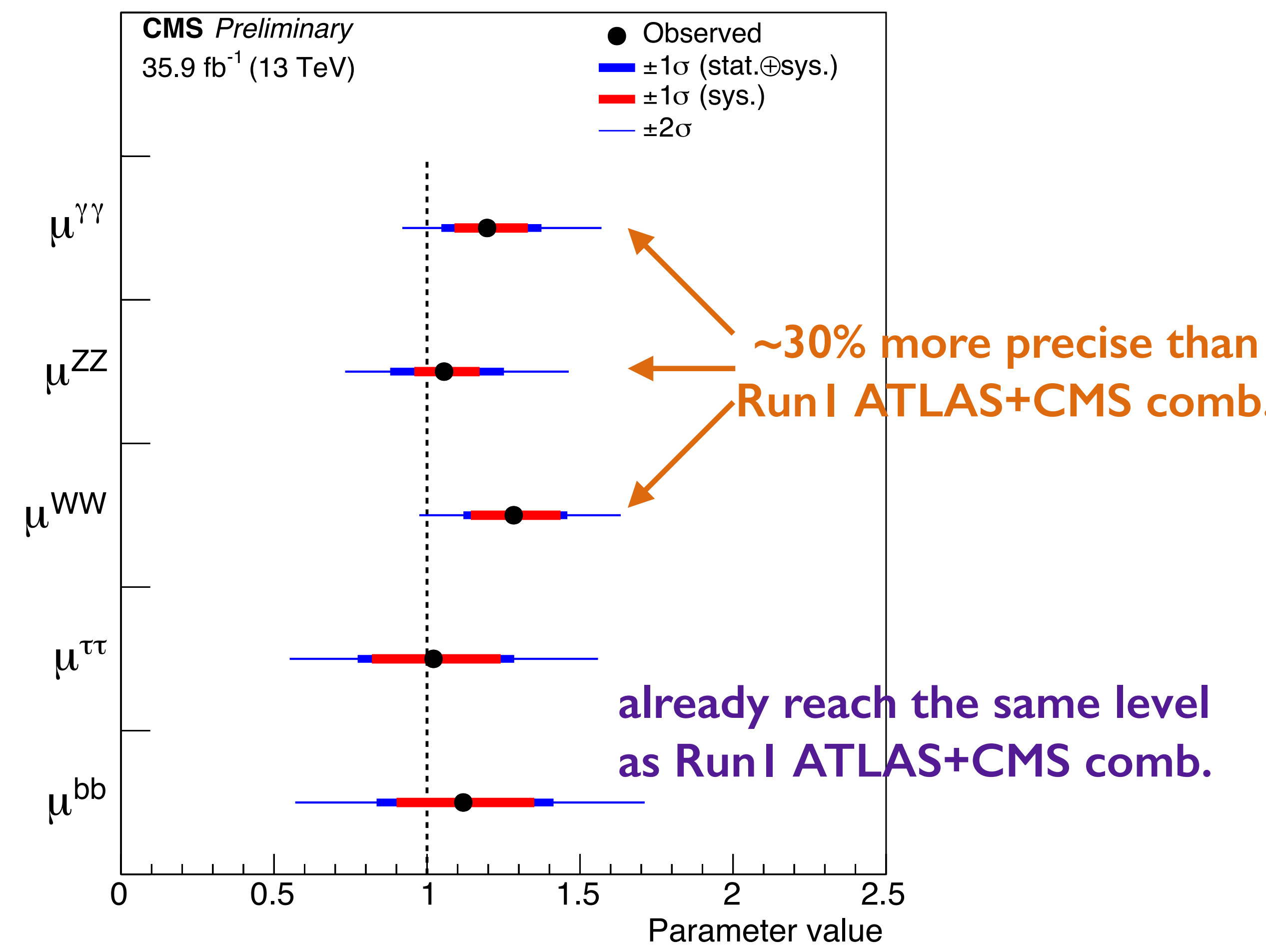
NEW

H(125) Combination

★ Cover a wide range of H(125) measurements using the full 2016 data
- combined analysis sensitive to 22 out of 25 possible production x decay channels

★ Signal strengths for the production and decay are compatible with SM expectations

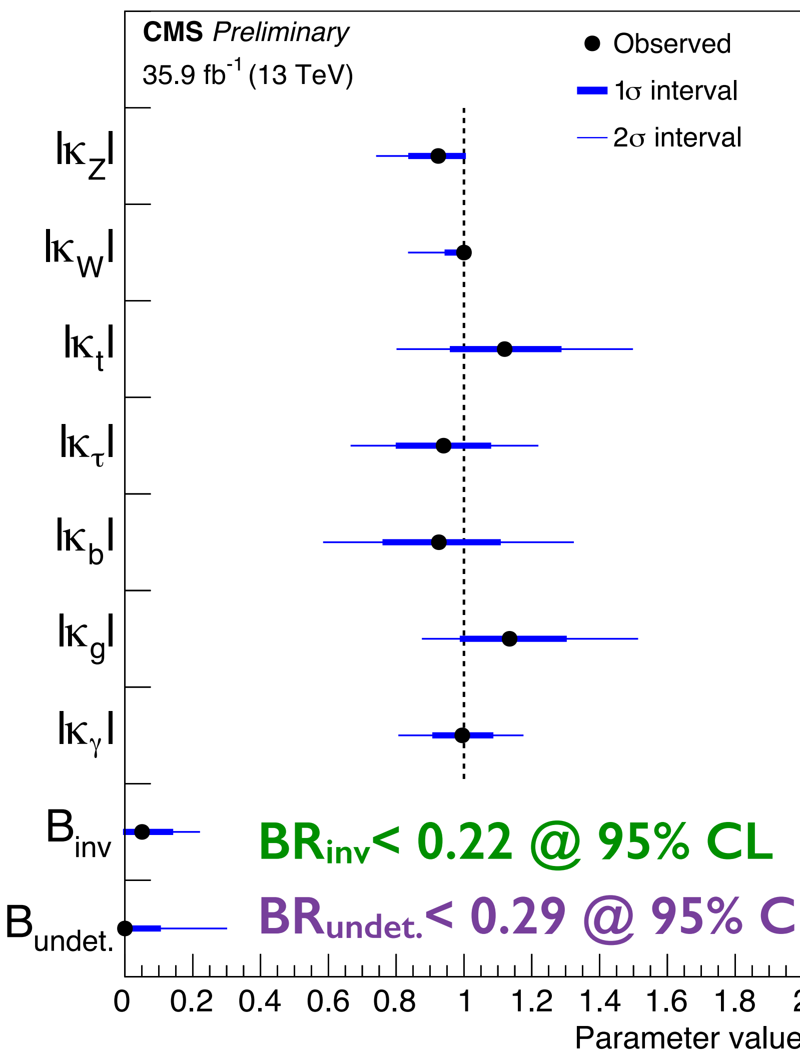




$$\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\,(\text{stat.})\,^{+0.06}_{-0.05}\,(\text{sig. th.})\,^{+0.06}_{-0.06}\,(\text{other sys.})$$

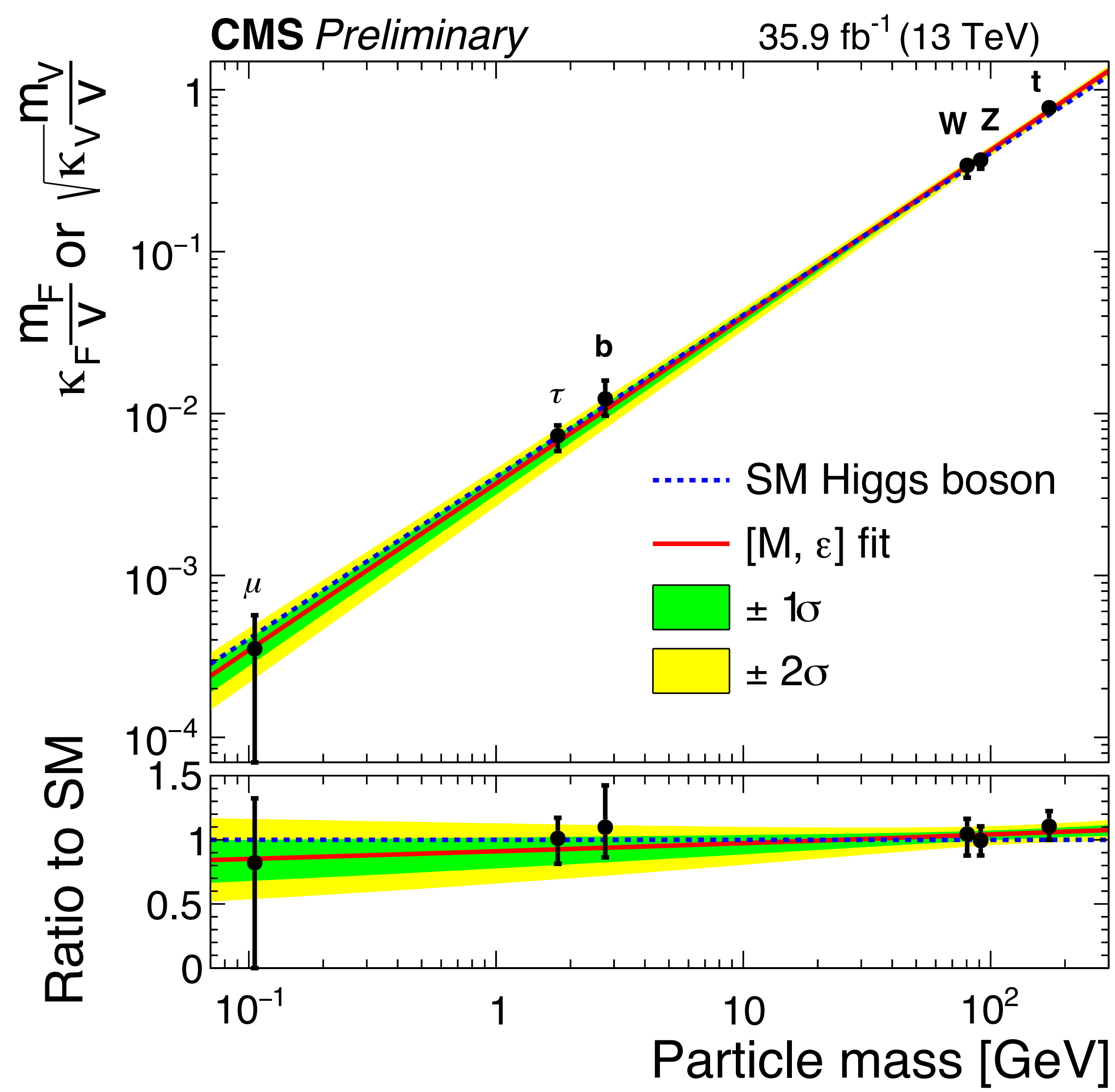
Couplings of H(125)

- ★ In κ-framework, κ represents the deviations from SM predictions of the Higgs boson couplings to SM bosons and fermions
- ★ By allowing BR(H→BSM) to vary in the fit, indirect constraints on Higgs couplings to invisible and undetected particles can be obtained
- ★ **H(125) still looks SM-like up to now**



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

$BR_{undet.} < 0.29$ @ 95% CL

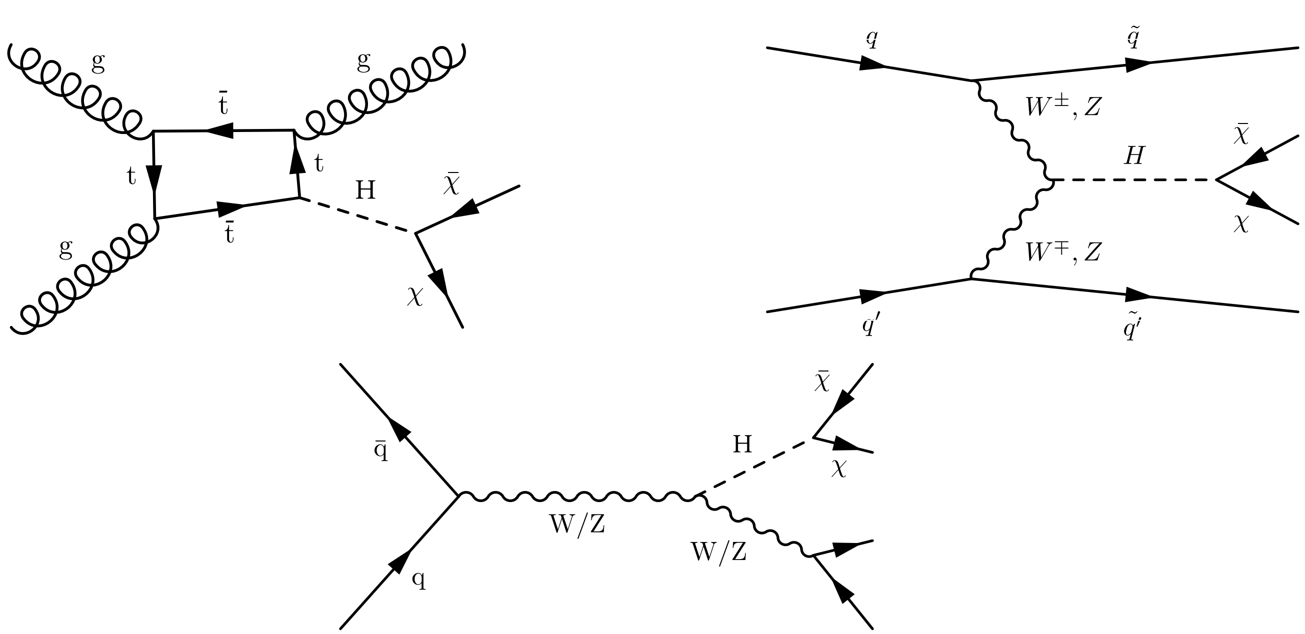


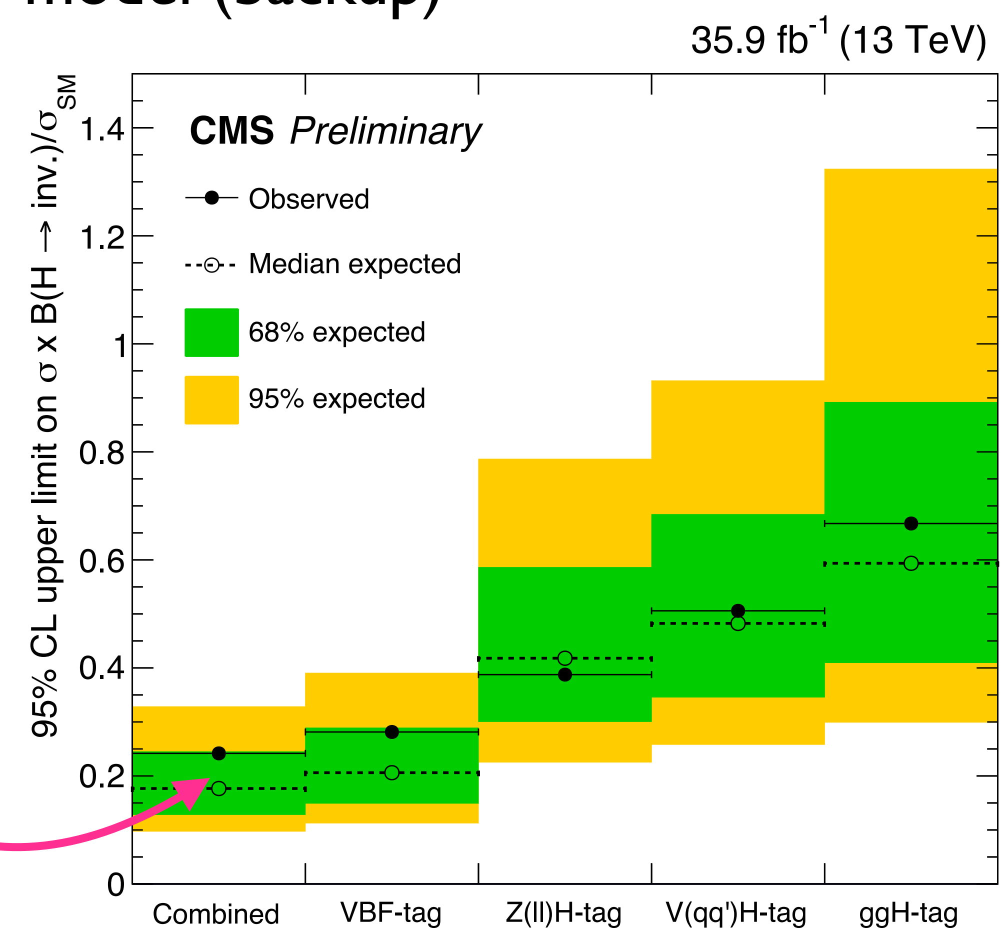
NEW

CMS PAS HIG-17-023

H→invisible

- ★ Direct searches performed in channels where H(125) recoils against visible system
  - ◉ monojet (ggH), 2-jets (VBF and VH), 2-leptons (ZH)
- ★ The SM expectation (H→ZZ→4ν) is essentially zero → a sign of new physics
- ★ **No significant deviations** from the SM expectations are observed
  - ◉ 95% CL upper limits on **σxBR** relative to SM production is estimated
- ★ Interpretation in the context of Higgs-Dark matter model (backup)

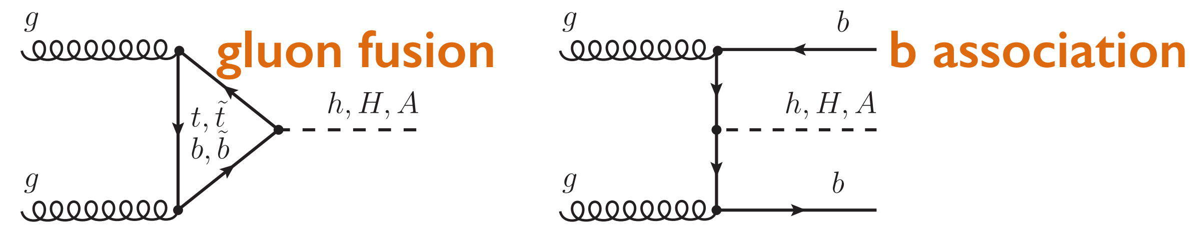


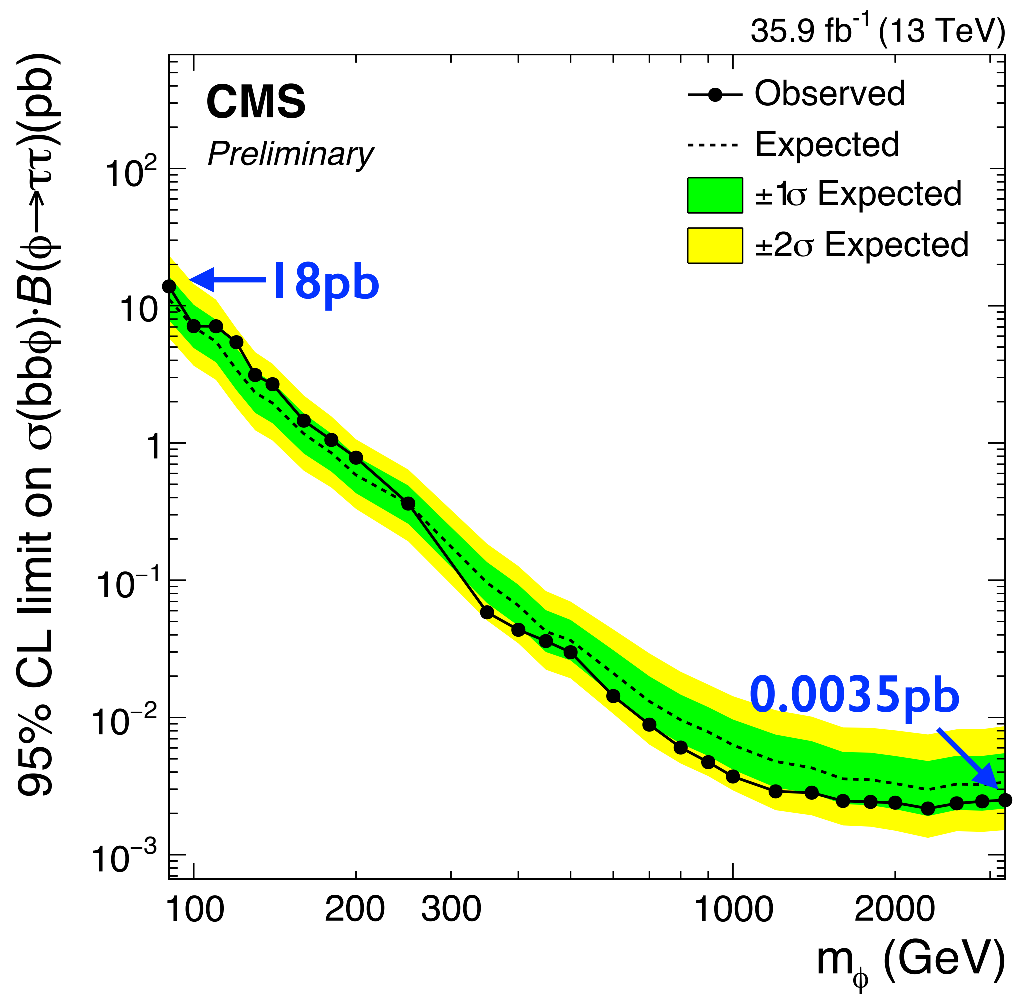


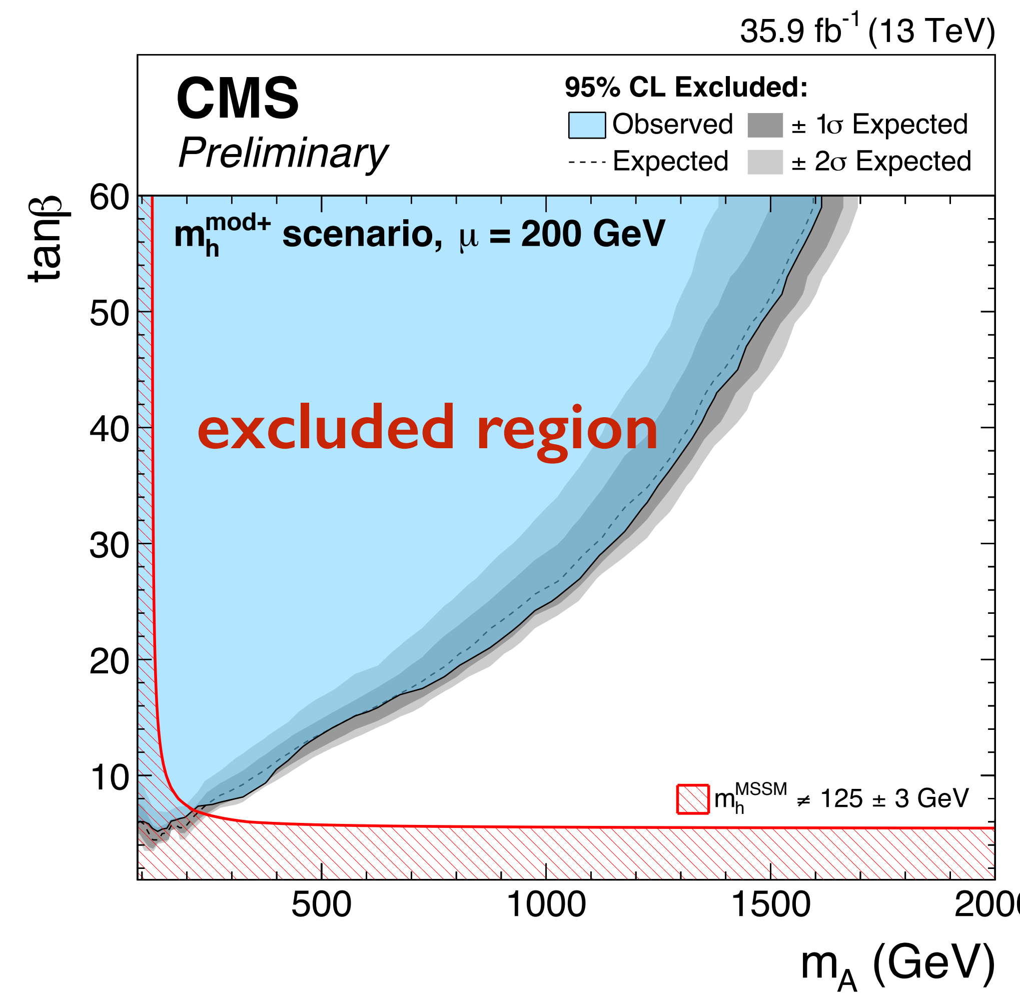
BR(H→invisible) < 0.24 (0.18) obs (exp)
for m_H = 125 GeV at 95% CL

Extended Higgs Sectors

- ★ Search for additional neutral Higgs bosons in the ditau final state
  - ◉ focus on Minimal Supersymmetric Standard Model (MSSM)
- ★ 4 most sensitive channels : $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$ (τ_h = hadronic tau)
- ★ 2 categories for two production modes
- ★ No excess is observed



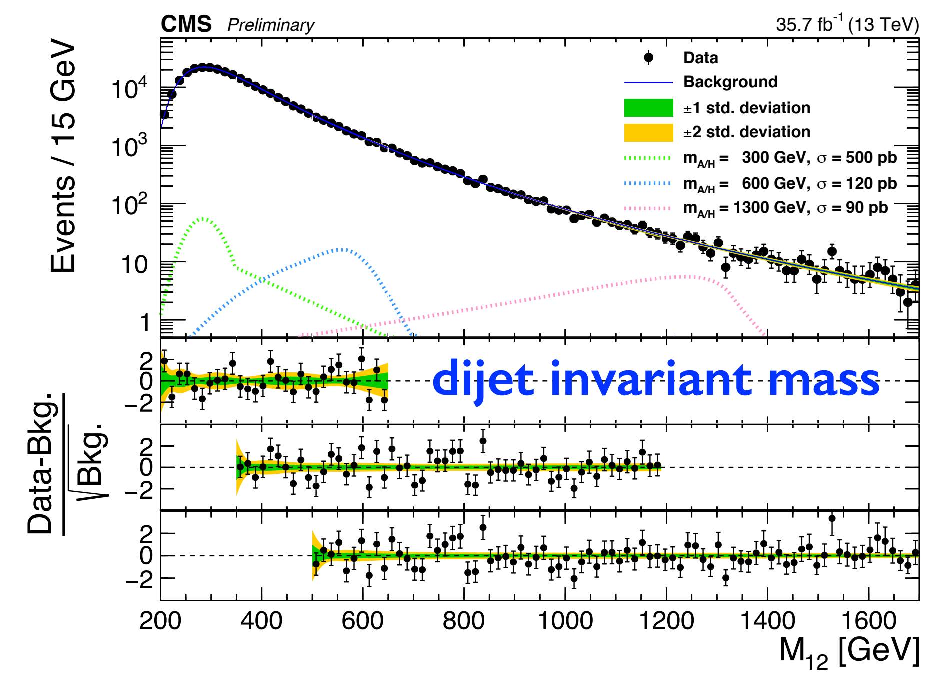


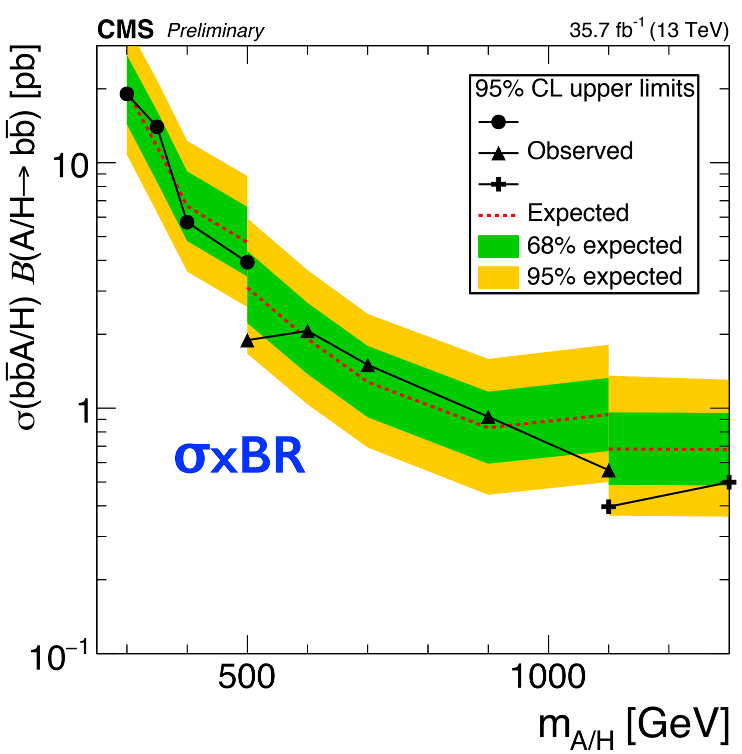


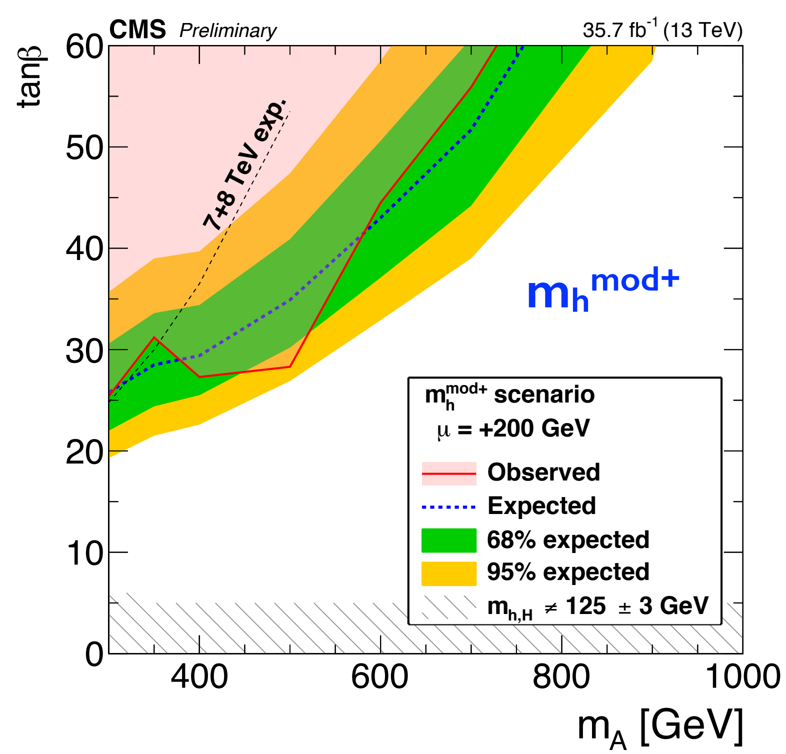
NEW

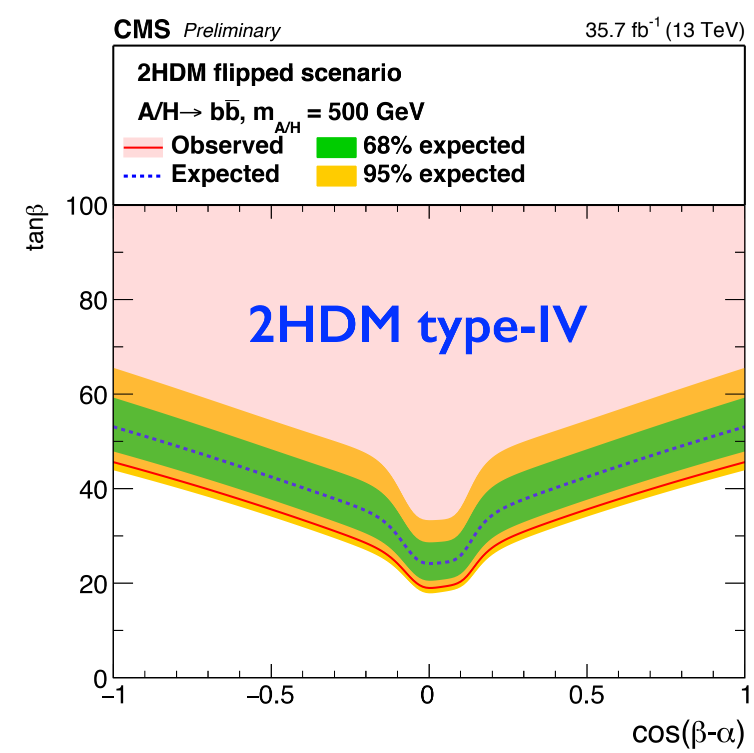
Extended Higgs Sectors

- ★ Search for additional neutral Higgs bosons in the bottom quarks final state
  - ◉ only possible with dedicated triggers requiring b-jets
- ★ Sensitivity enhanced with b-associated production
- ★ CMS analysis is unique at the LHC so far
- ★ No evidence for a signal is found
- ★ Interpretation in the context of MSSM and 2HDM









Summary

- ★ CMS has a broad program of Higgs boson related searches since Run1 and continuing in Run2

- ★ Using the first Run2 data (~36 fb^{-1}), everything is more precise
  - ◉ improved sensitivity of couplings and properties
  - ◉ refinement of methods
  - ◉ unprecedented studies on fermionic decays of H(125)

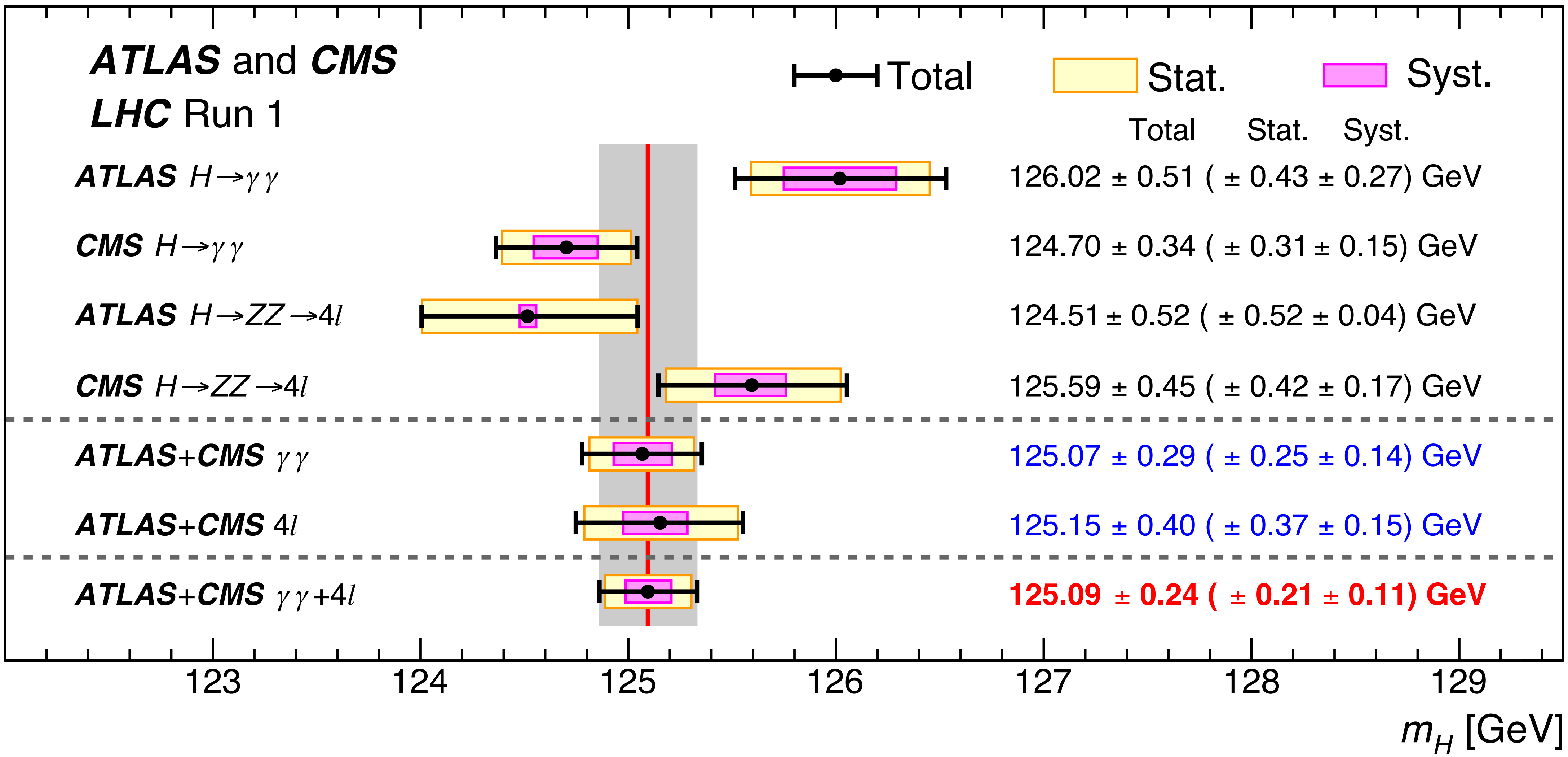
- ★ More Run2 data (2017+2018) to be analyzed and included
  - ◉ watch this space!

- ★ CMS Publications : http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html

Backup

Run1 Legacy

★ The combination based on the discovery channels $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$

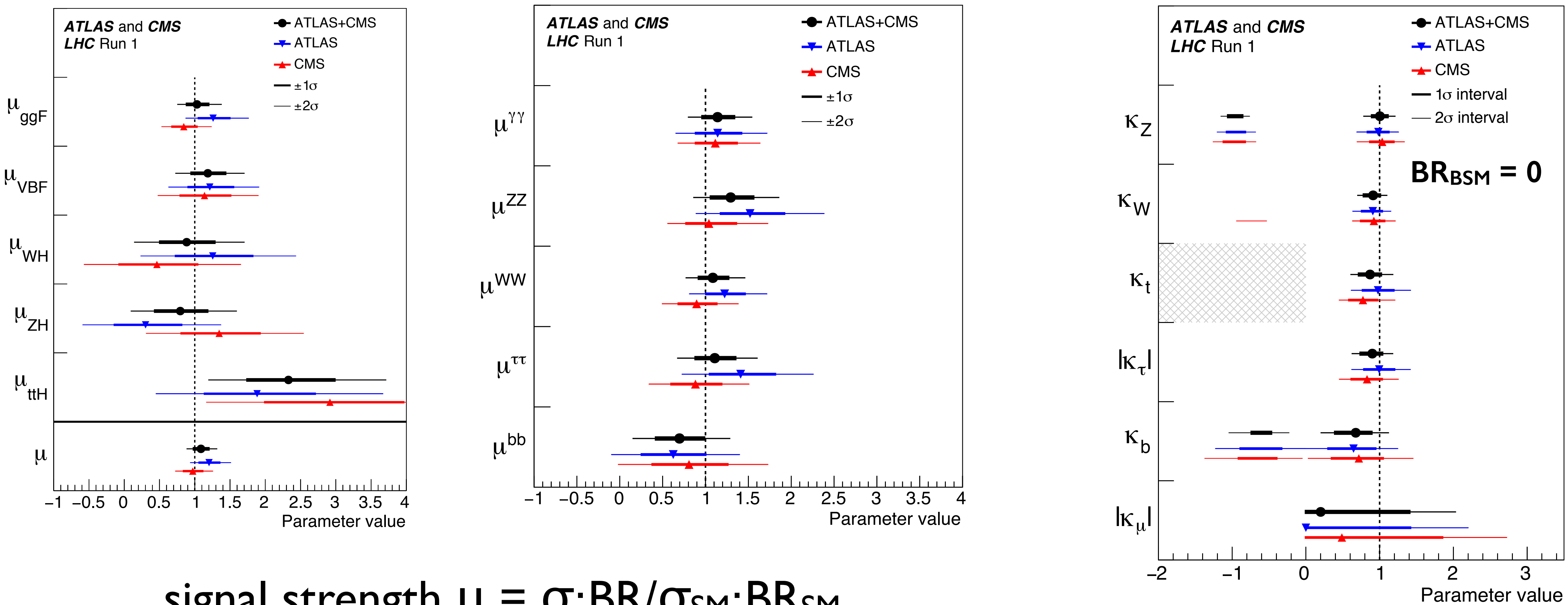


m_H = 125.09 ± 0.24 (± 0.21 stat. ± 0.11 syst.) GeV

JHEP 08 (2016) 045

Run I Legacy

★ The combination based on 5 production processes and 6 decay modes



signal strength $\mu = \sigma \cdot BR / \sigma_{SM} \cdot BR_{SM}$

★ **Production and decays** are compatible with SM Higgs : **global $\mu = 1.09 \pm 0.11$**

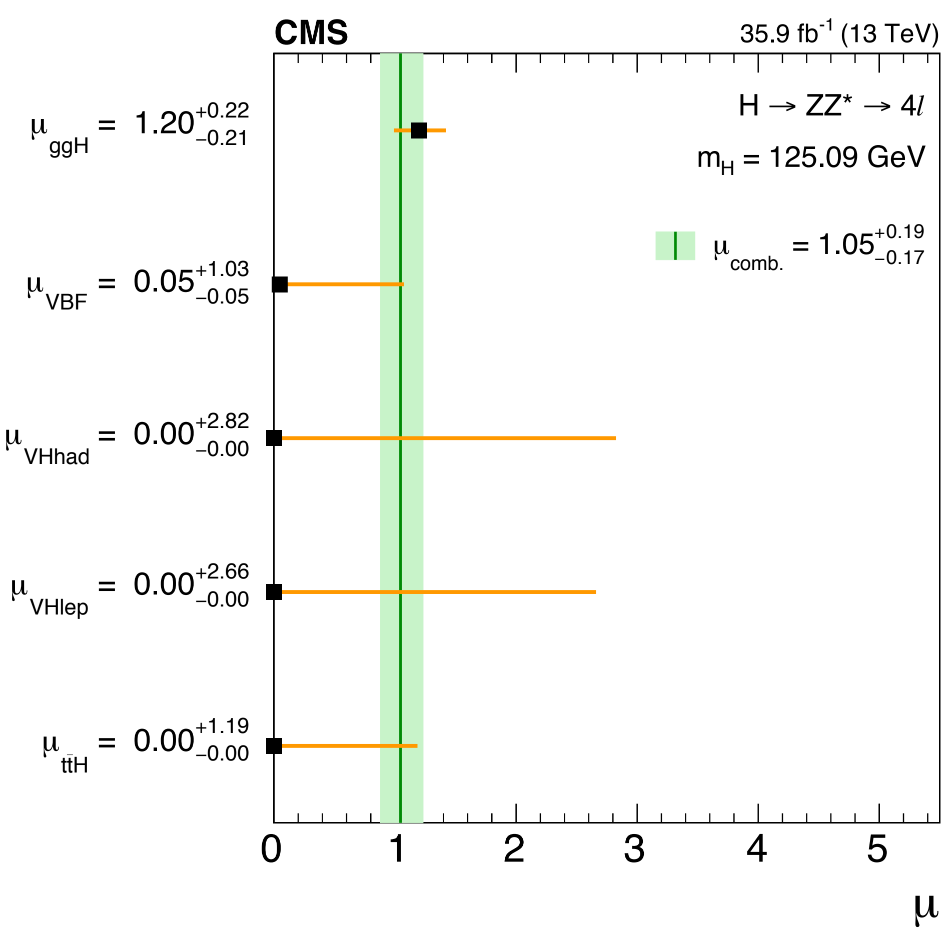
★ **Couplings** compatible with SM < 2σ

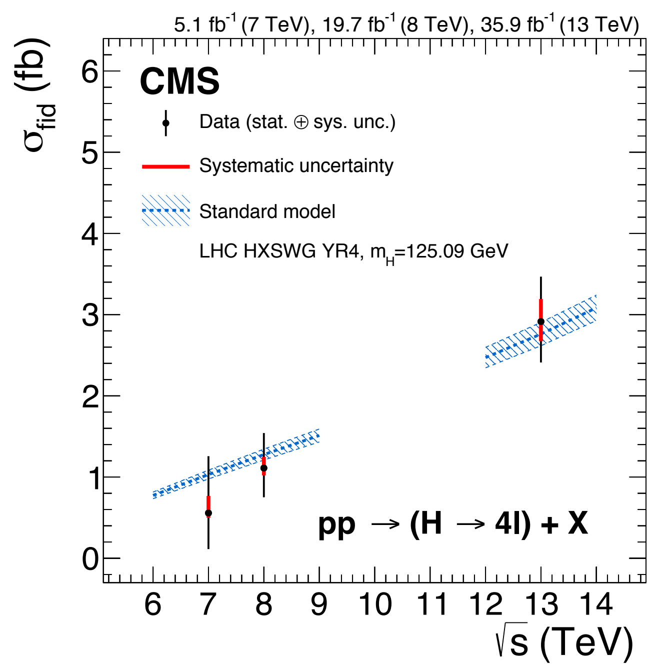
★ No hint of BSM particles in the loop (ggH, H→γγ), **$BR_{BSM} < 0.34$ at 95% CL**

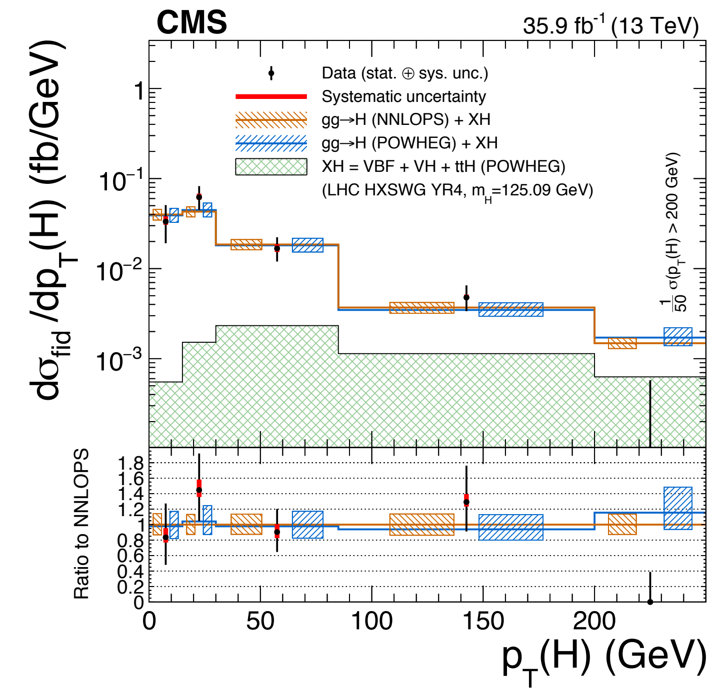
JHEP 11 (2017) 047

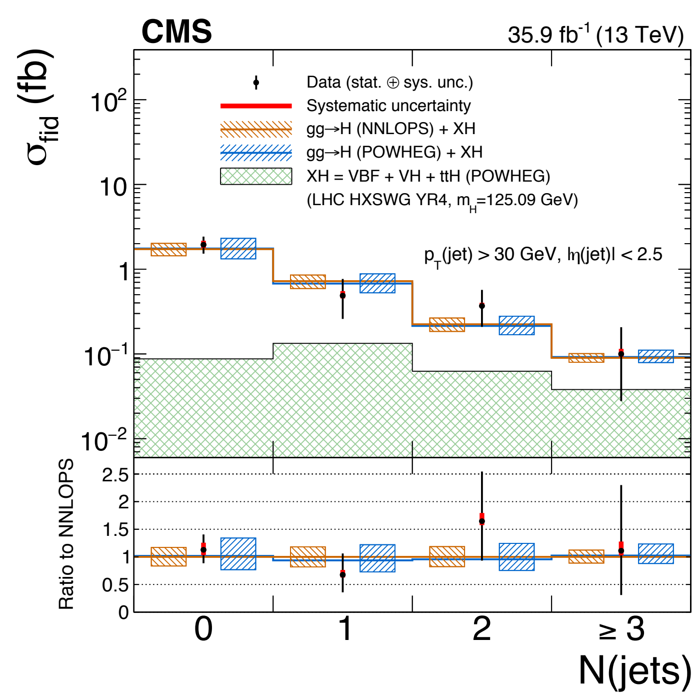
$H \to ZZ \to 4\ell$

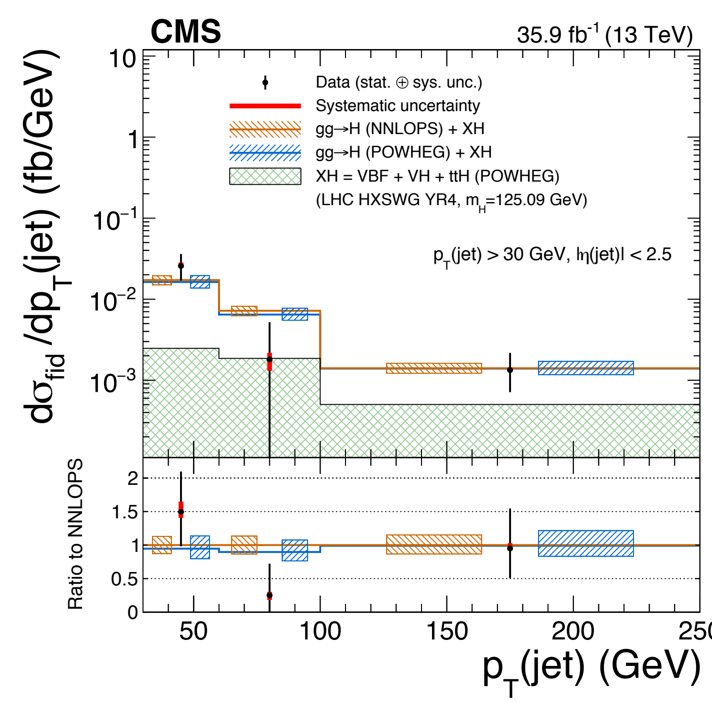
★ Signal strength on each production mode, integrated fiducial and differential cross sections of H(125)





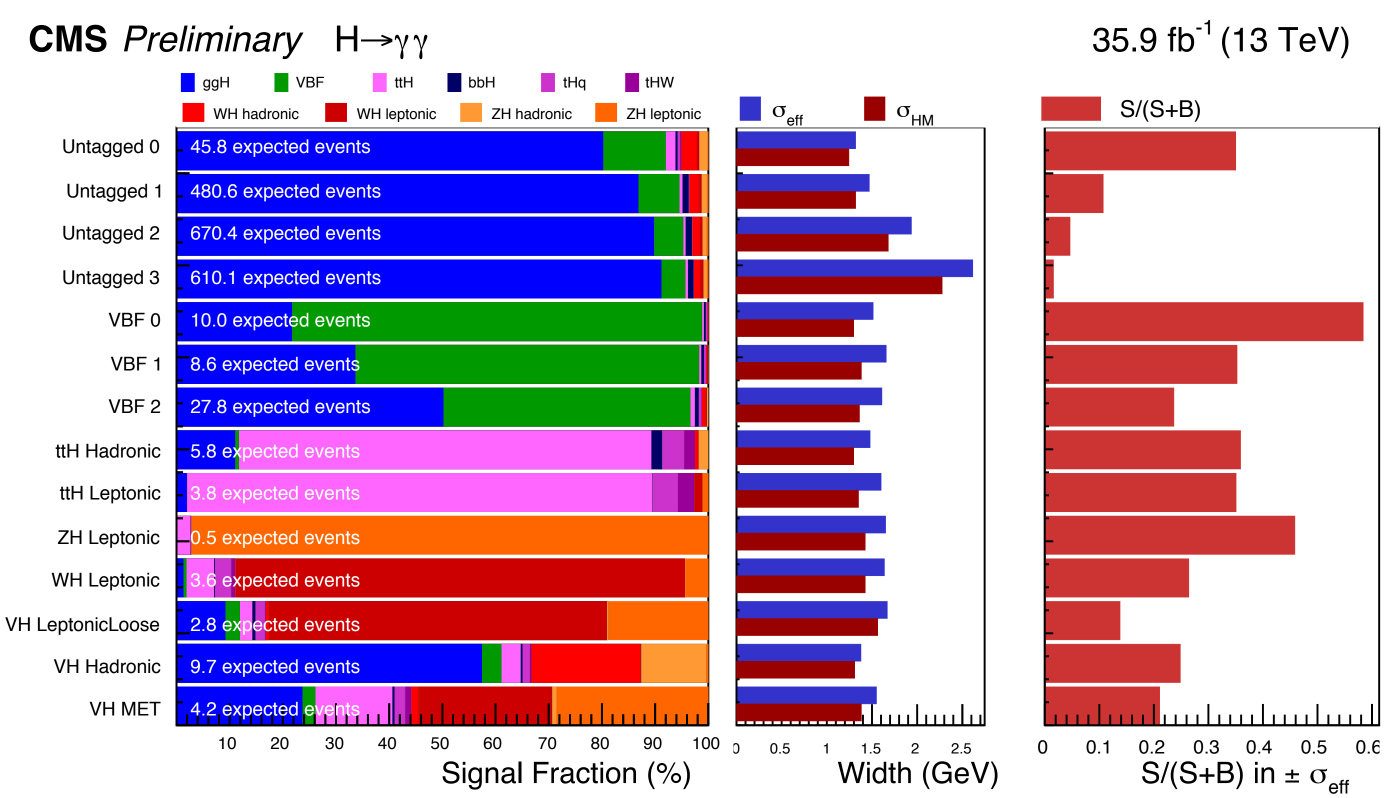


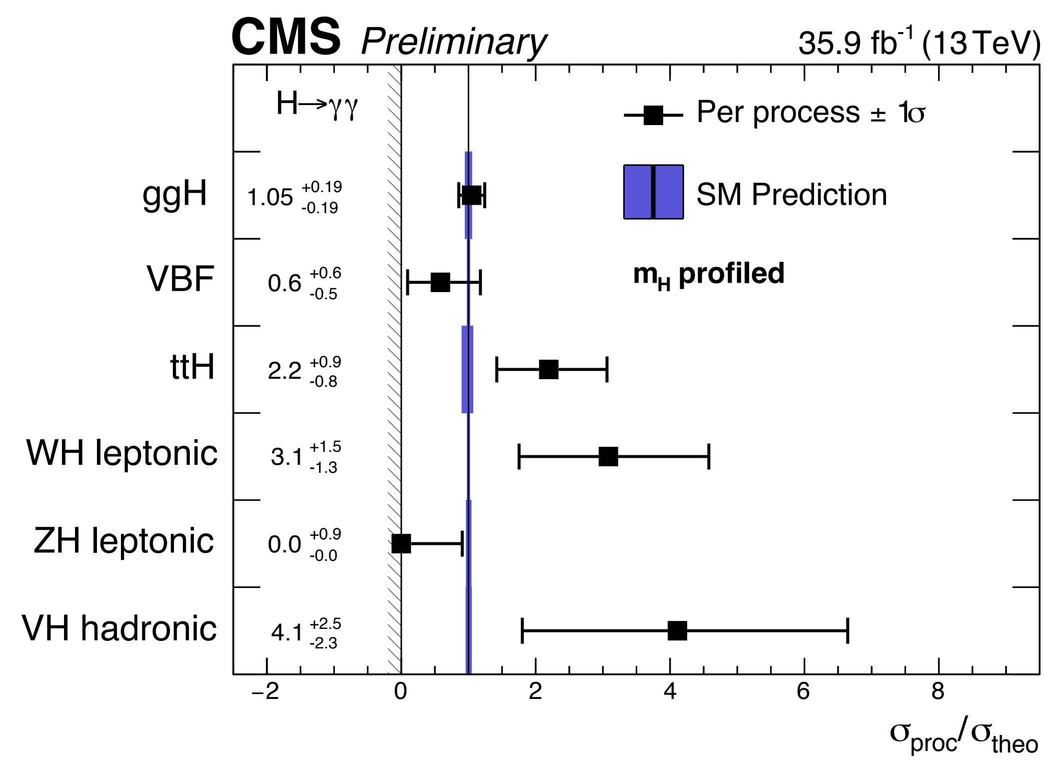




$H \to \gamma\gamma$

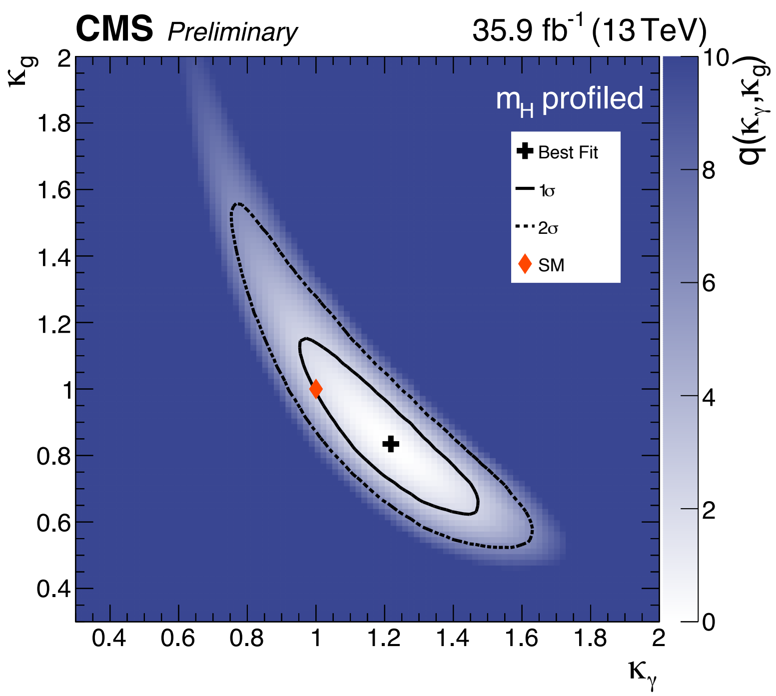
- ★ Events are classified according to mass resolution and S/B in the VBF, VH, ttH and gluon fusion categories
  - ◉ standard preselection $p_{T1}/m_{\gamma\gamma} > 0.33$, $p_{T2}/m_{\gamma\gamma} > 0.25$, $100 < m_{\gamma\gamma} < 180$ GeV
- ★ A likelihood scan of the signal strength is performed, profiling all other nuisances including the Higgs mass
- ★ Cross section ratios measured for each process (black points) in the Higgs Simplified Template Cross Section framework

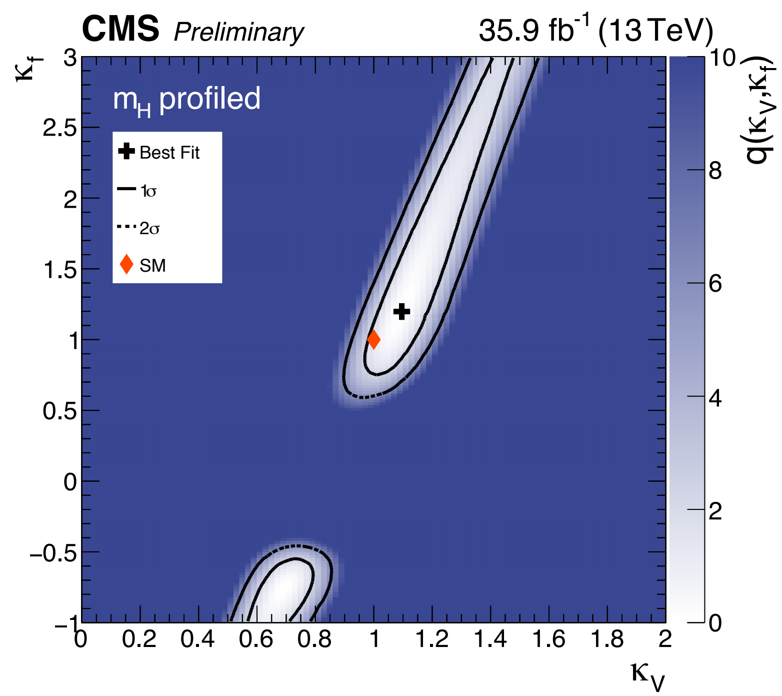




CMS PAS HIG-16-040
CMS PAS HIG-17-015

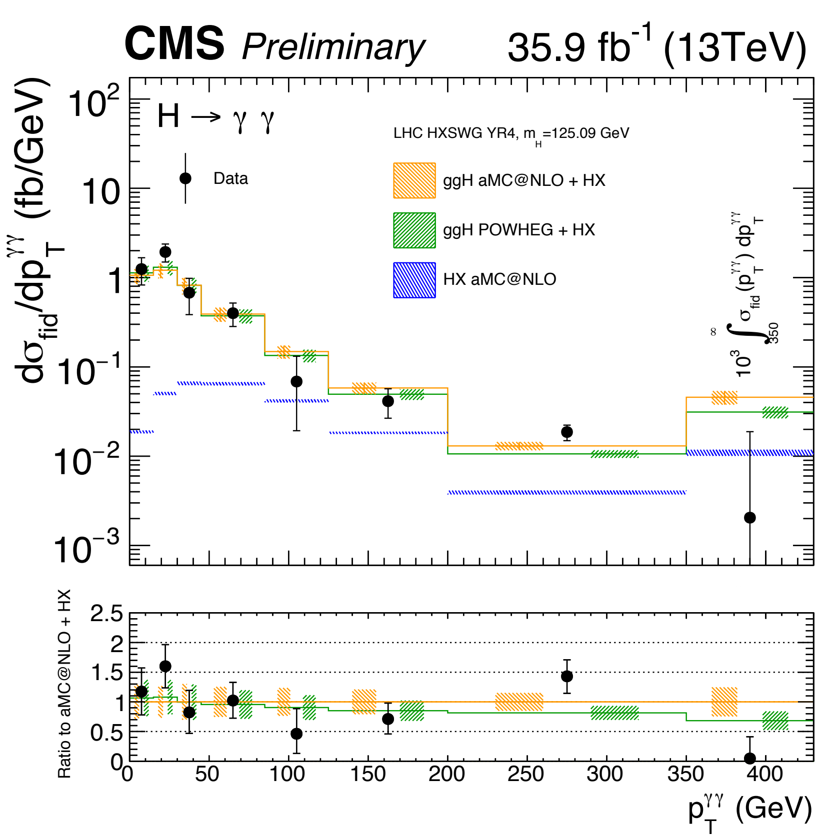
$H \rightarrow \gamma\gamma$

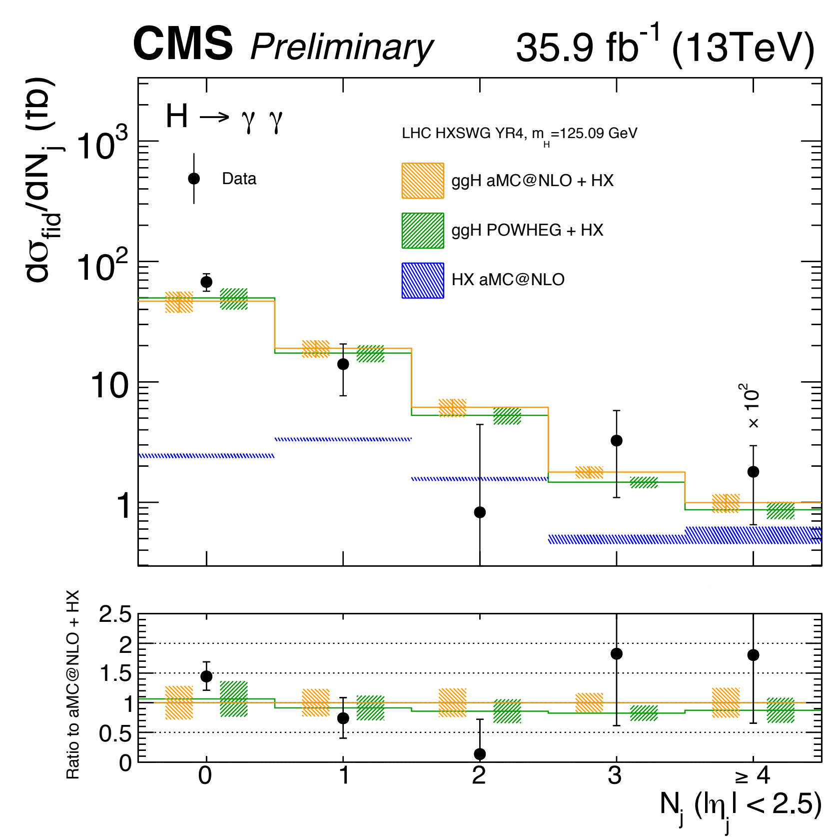




Two-dimensional likelihood scans of the Higgs boson coupling modifiers

Differential cross section



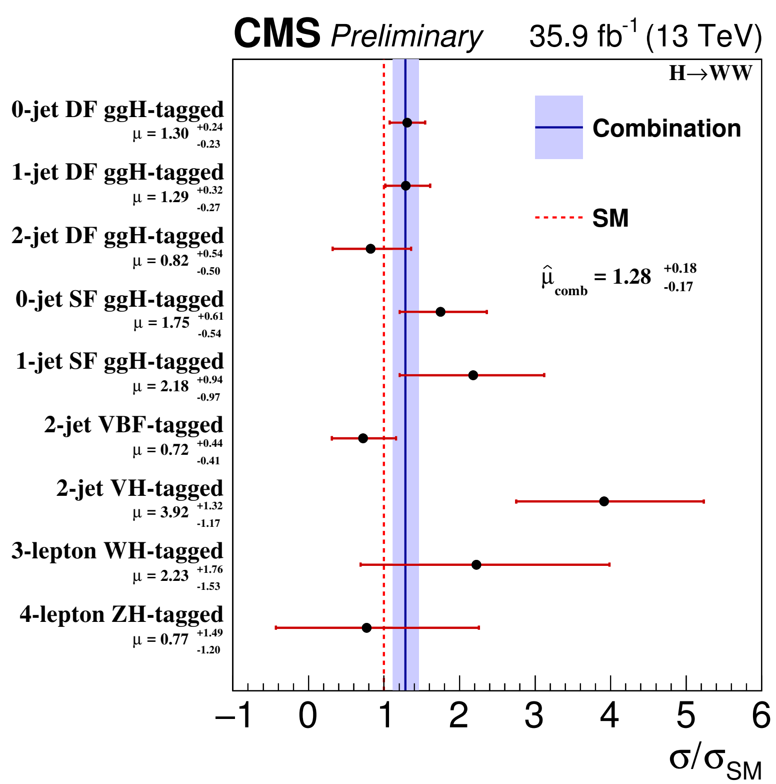


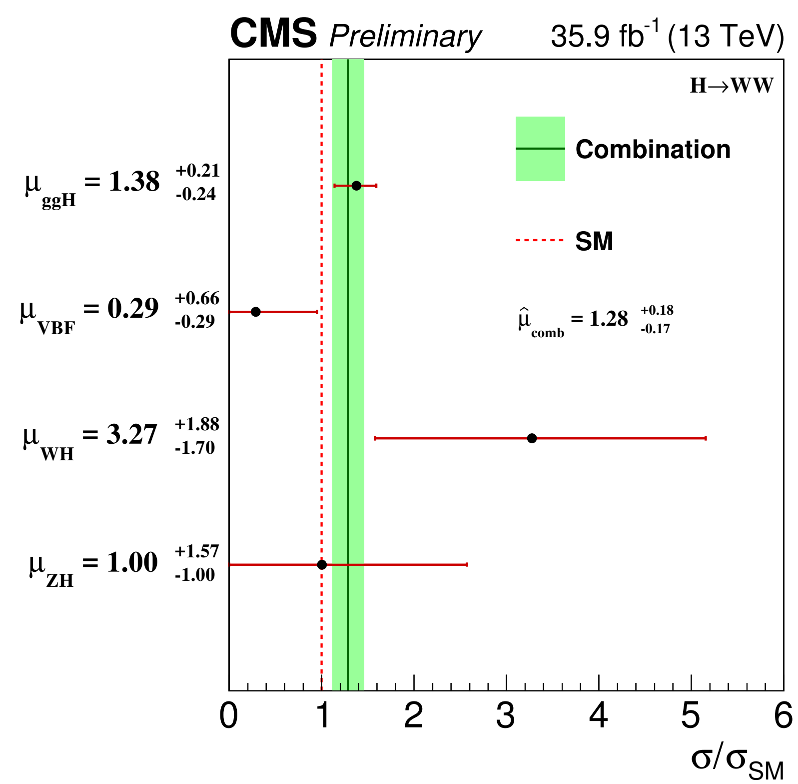
NEW

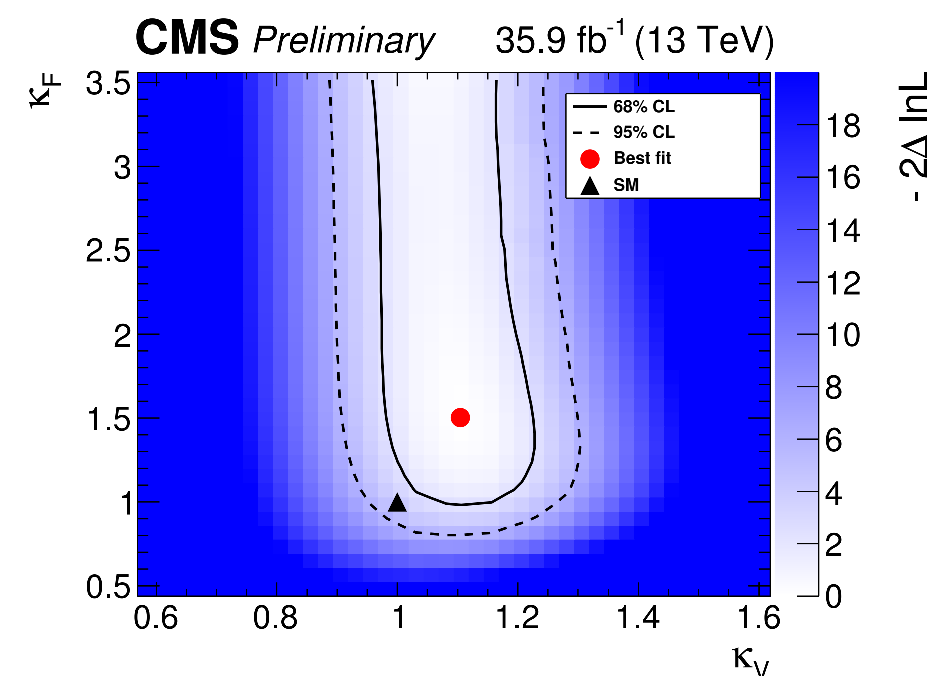
CMS PAS HIG-16-042

H→WW→2ℓ2ν

- ★ **The first observation above 5σ** from H→WW channel (eμ, ee, μμ) at CMS
  - ◉ combining ggH, VBF, ZH and WH productions
- ★ Signal strength shows compatibility with the SM predictions
  - ◉ some deviation observed in 2-jet VH-tagged category (hadronic decay of W/Z)







κ_V = 1.10 ± 0.08

κ_F = 1.52 ± 0.48

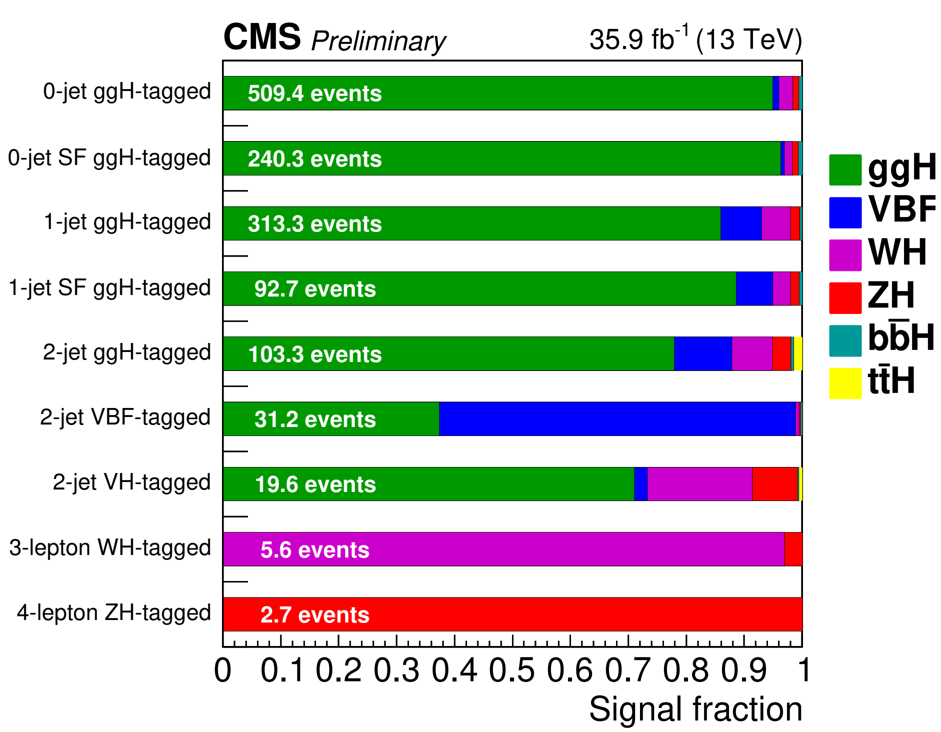
$$\hat{\mu} = 1.28^{+0.18}_{-0.17} = 1.28 \pm 0.10(\text{stat})^{+0.11}_{-0.11}(\text{syst})^{+0.10}_{-0.07}(\text{theo.})$$

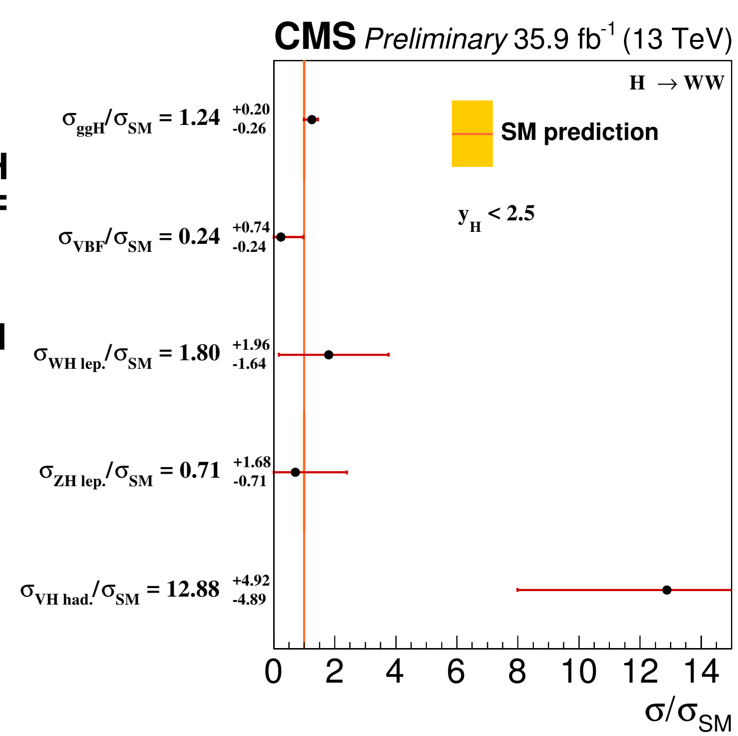
- ★ Main systematic uncertainties from lepton ID, luminosity and background rates

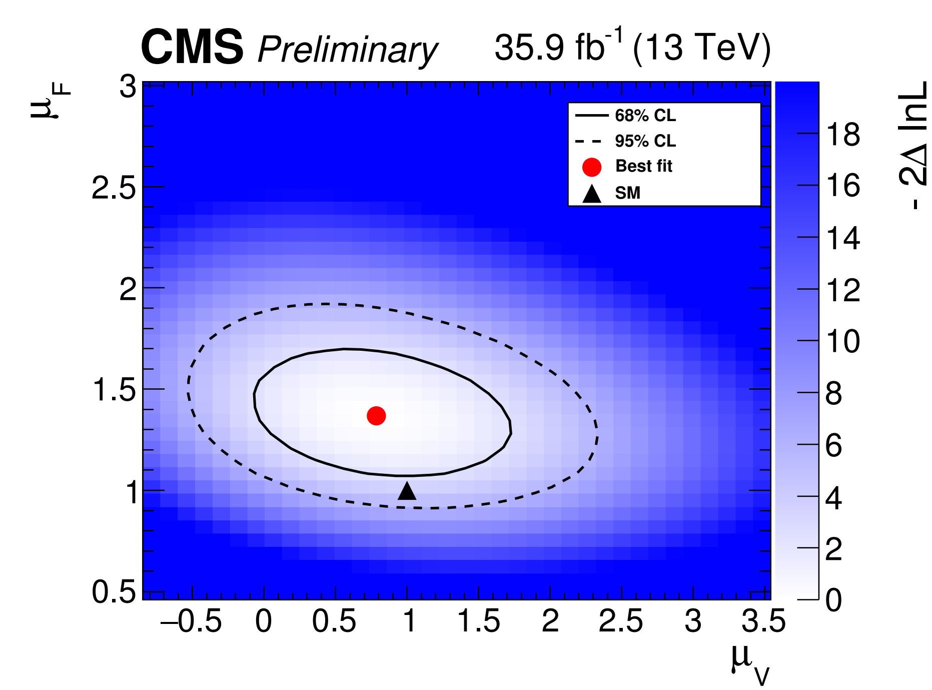
NEW

$H \to WW \to 2\ell 2\nu$

- ★ A summary of the expected fraction of different signal production modes in each category
- ★ A similar simultaneous fit has been performed to measure the cross section ratios corresponding to five Higgs boson production mechanisms, using a simplified fiducial phase space, as specified in the "stage-0" STXS framework
- ★ Additional simultaneous fits are performed to probe the Higgs boson couplings to fermions and vector bosons
  - ◉ μ_F → signal strength associated to ggH, bbH, ttH
  - ◉ μ_V → signal strentgth associated to VBF, VH





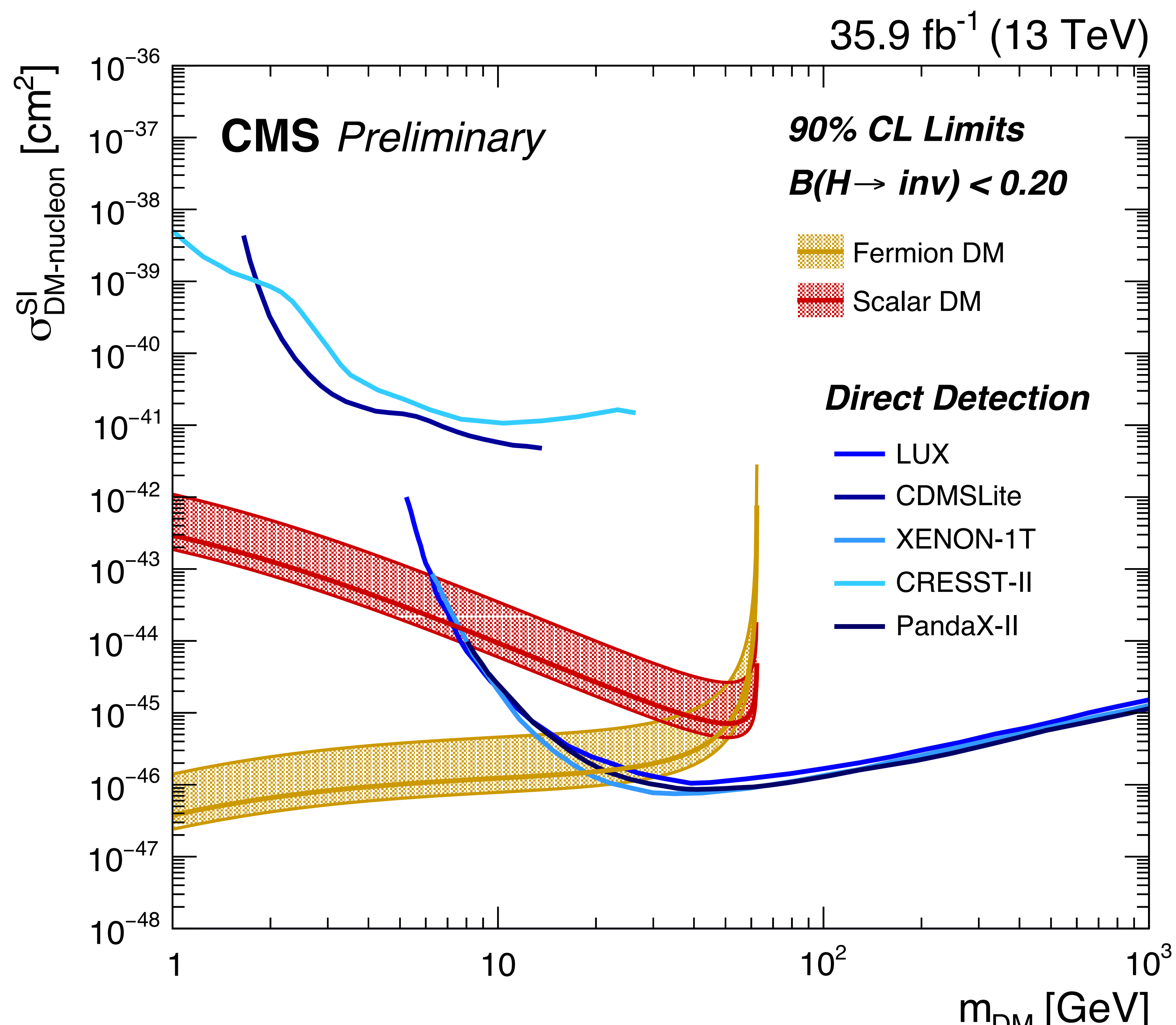


NEW

CMS PAS HIG-17-023

Combination H→invisible

★ **BR(H→invisible)** translated into **DM-nucleon spin-independent cross section** limits as a function of DM mass (if DM mass < $m_h/2$)*



★ Assuming **scalar**, **fermion** dark matters

★ 90% CL to compare with direct detection experiments

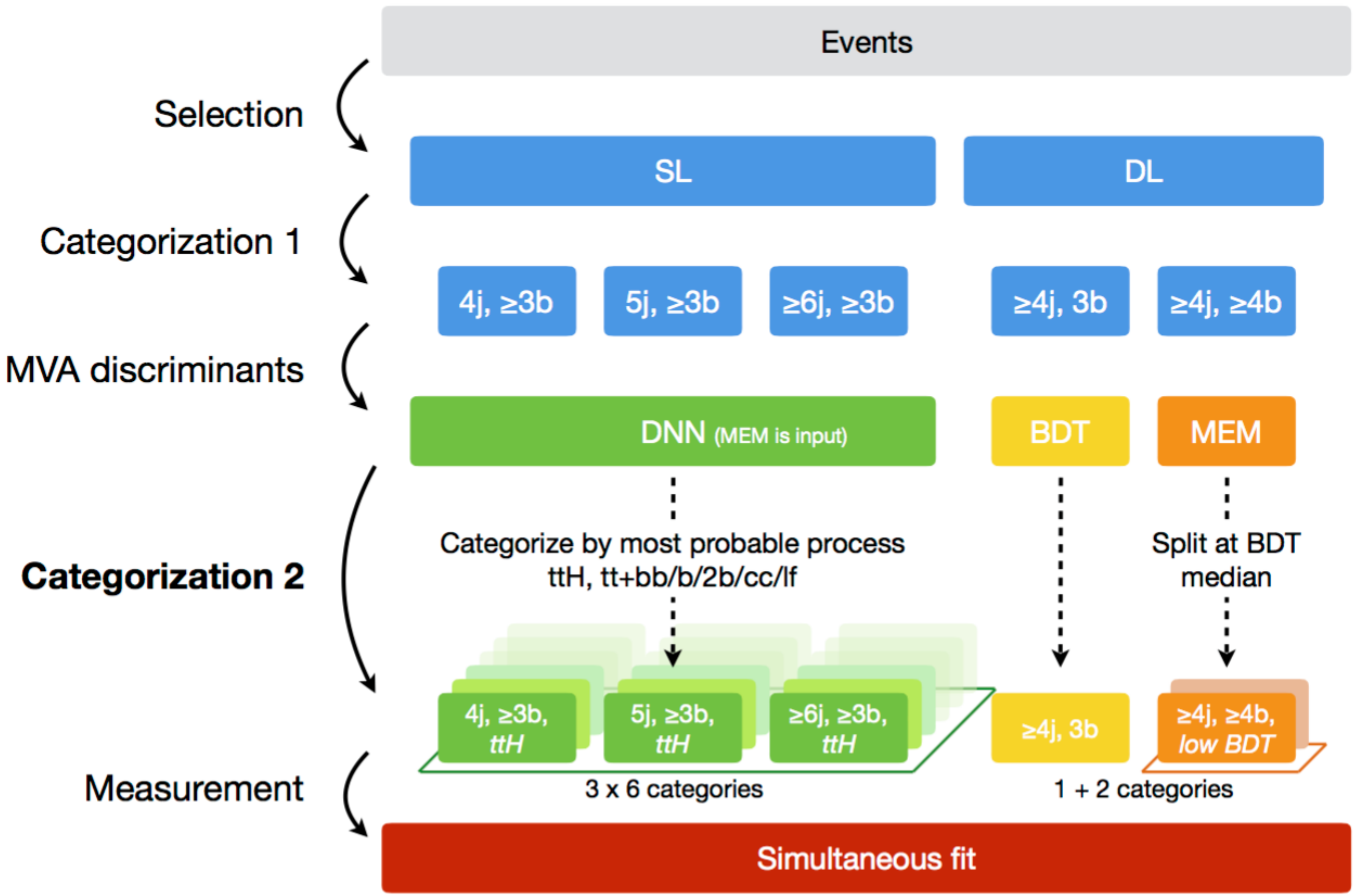
★ CMS limits complementary to direct detection experiments

*A. Djouadi et al, Phys. Lett. B 709 (2012)

NEW

CMS PAS HIG-17-026

ttH H→bb (leptonic)

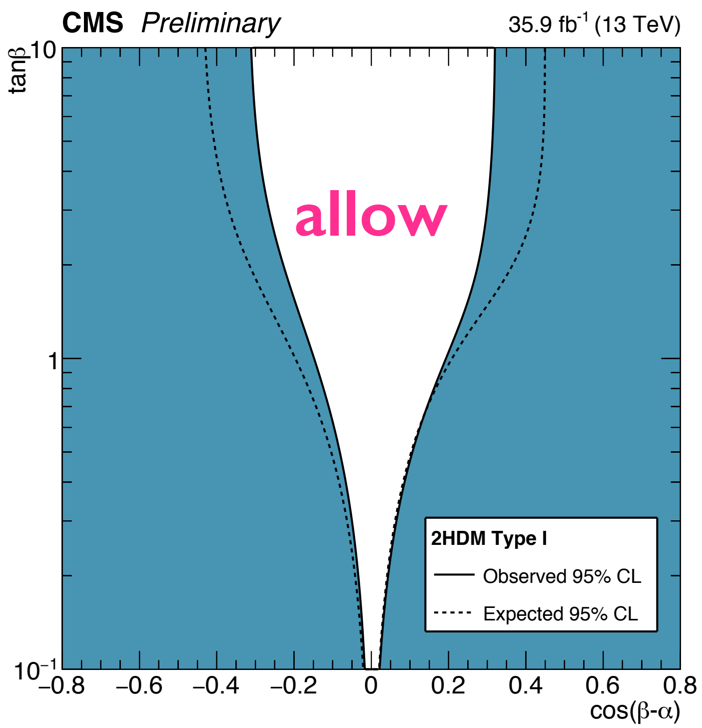


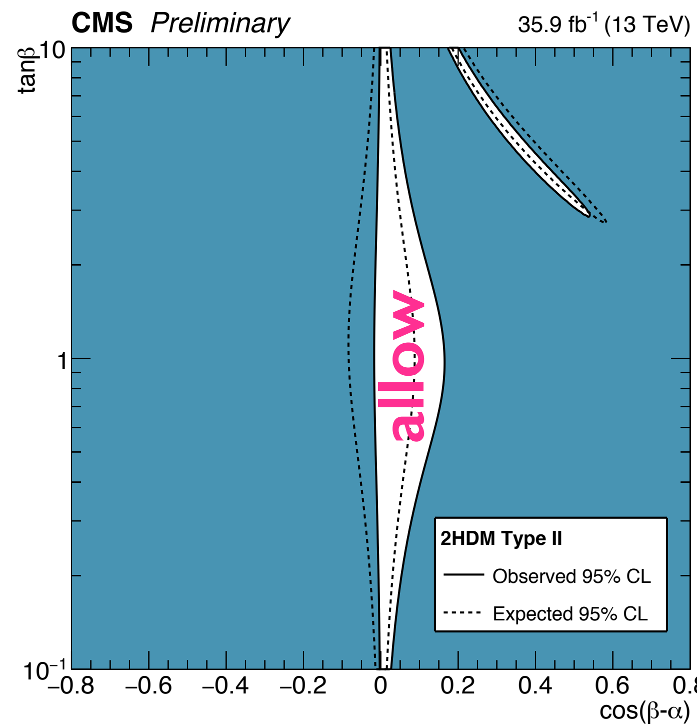
CMS PAS HIG-17-031

H(125) Combination

★ Constraints on benchmark BSM which contains a second Higgs doublet (2HDM)

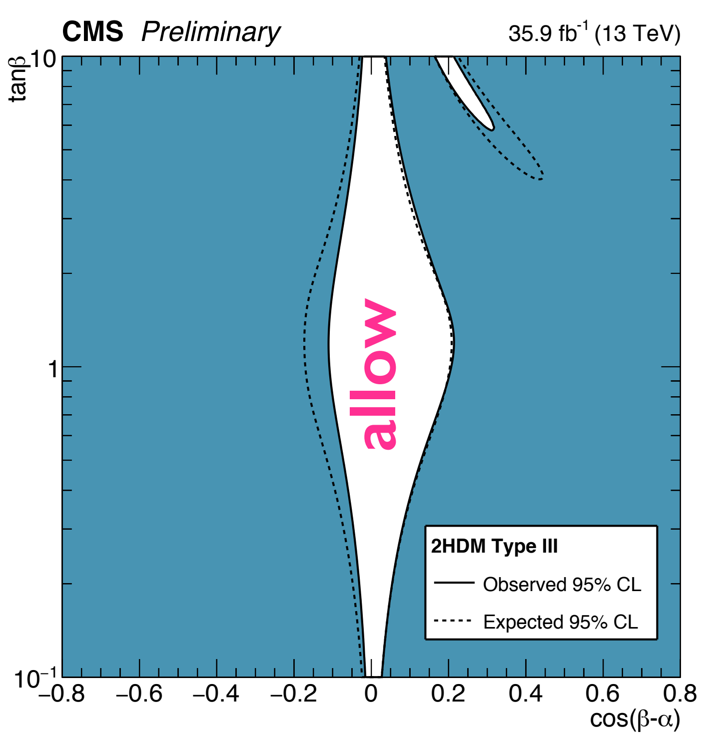
2HDM Type-I
all fermions
coupling to one
Higgs doublet

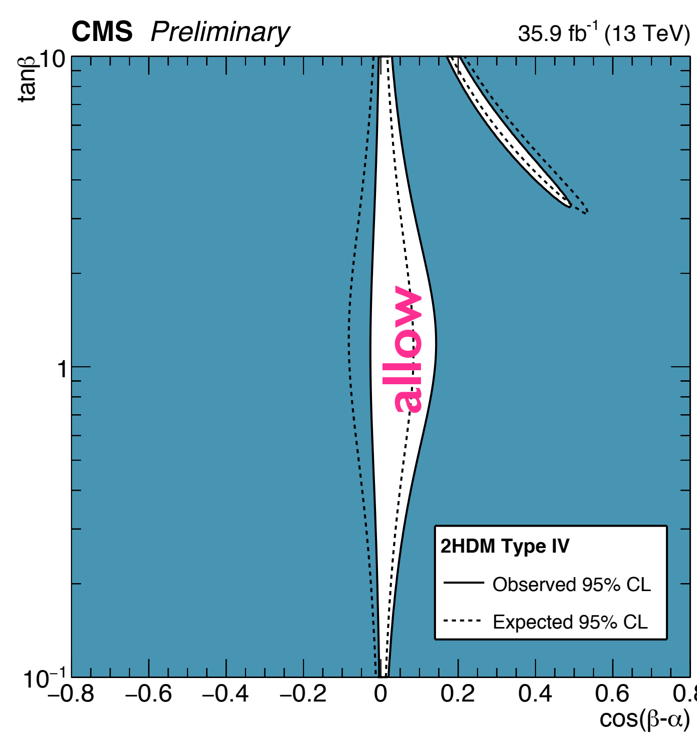




2HDM Type-II
up-type fermions
coupling to one
Higgs doublet
down-type to another

2HDM Type-III
“lepton specific”
quarks coupling to one
Higgs doublet
leptons to another





2HDM Type-IV
“flipped”
up-type quarks and
leptons coupling to
one Higgs doublet
down-type quark to
another

MSSM H→ττ

- 95% confidence level (CL) upper limits are set on the product of the cross section and branching fraction
- Differences in the sensitivity of the analysis only occur at low masses, where the p_T of the Higgs boson significantly contributes to the p_T of its decay products
  - the expected limit using either only the b quark or only the t quark for the modeling of the Higgs boson p_T spectrum