Higgs physics at the CMS experiment

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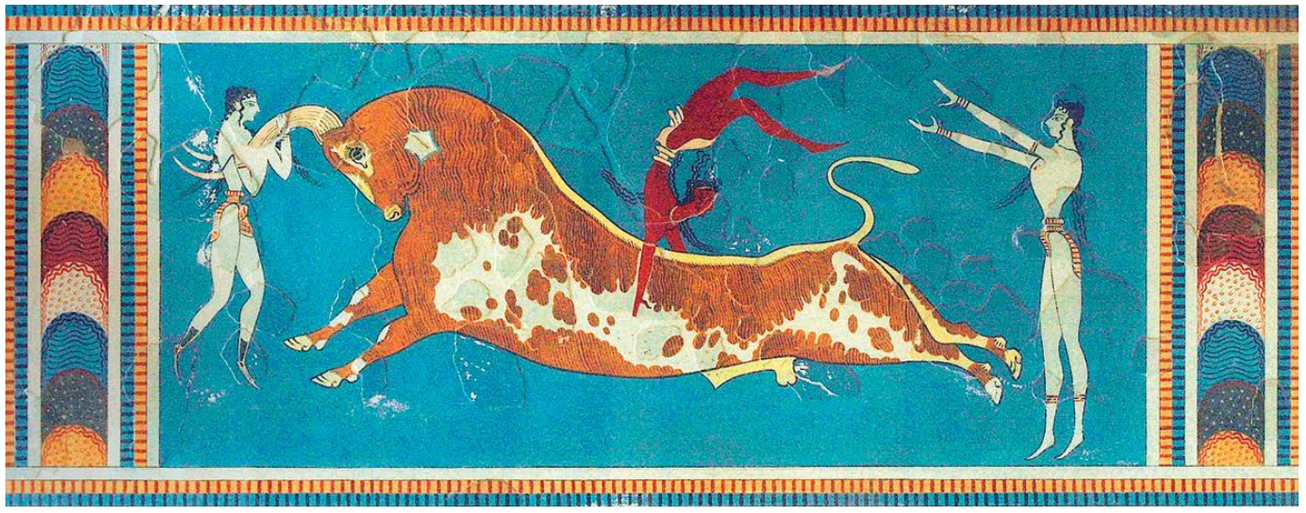
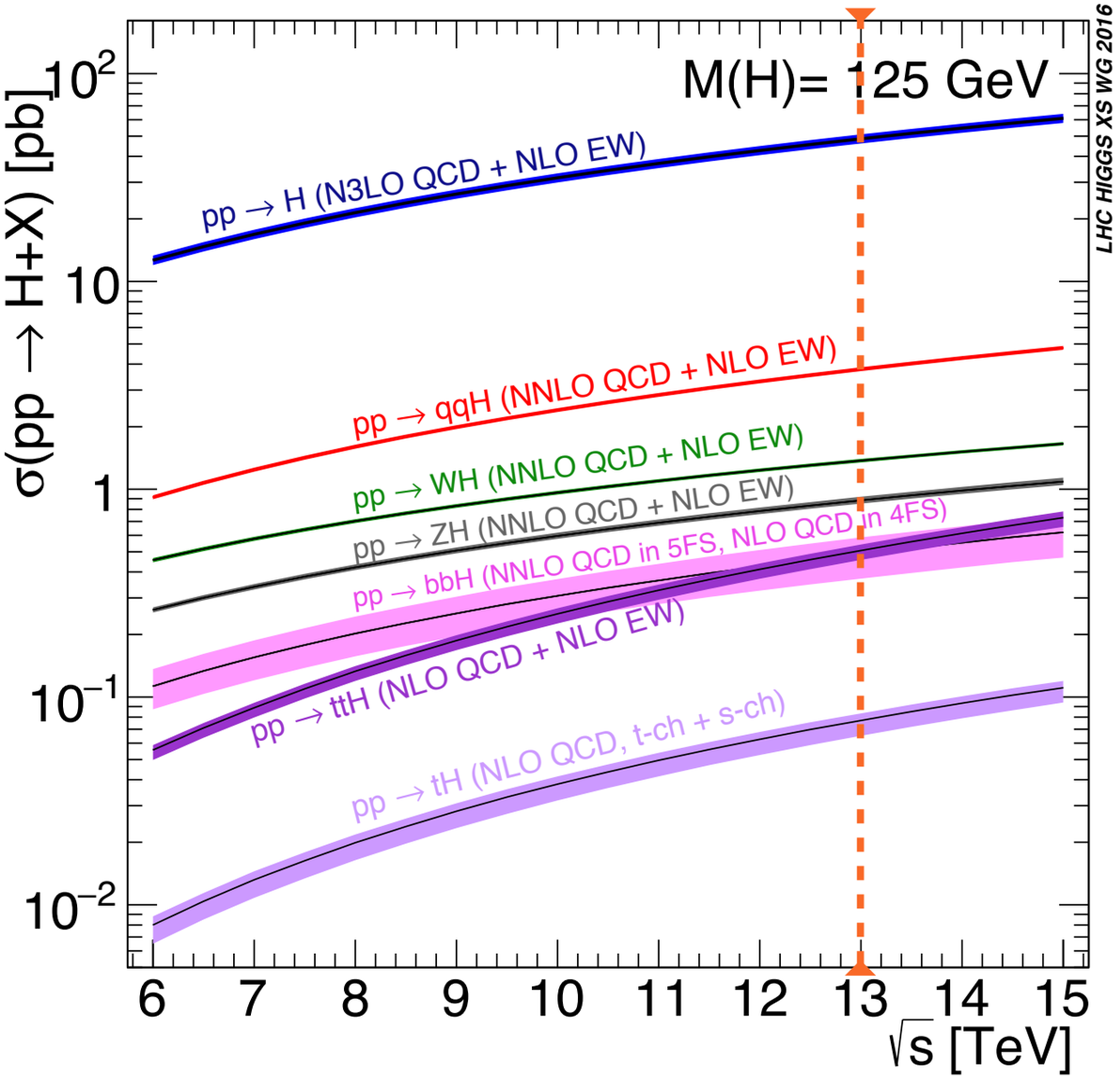


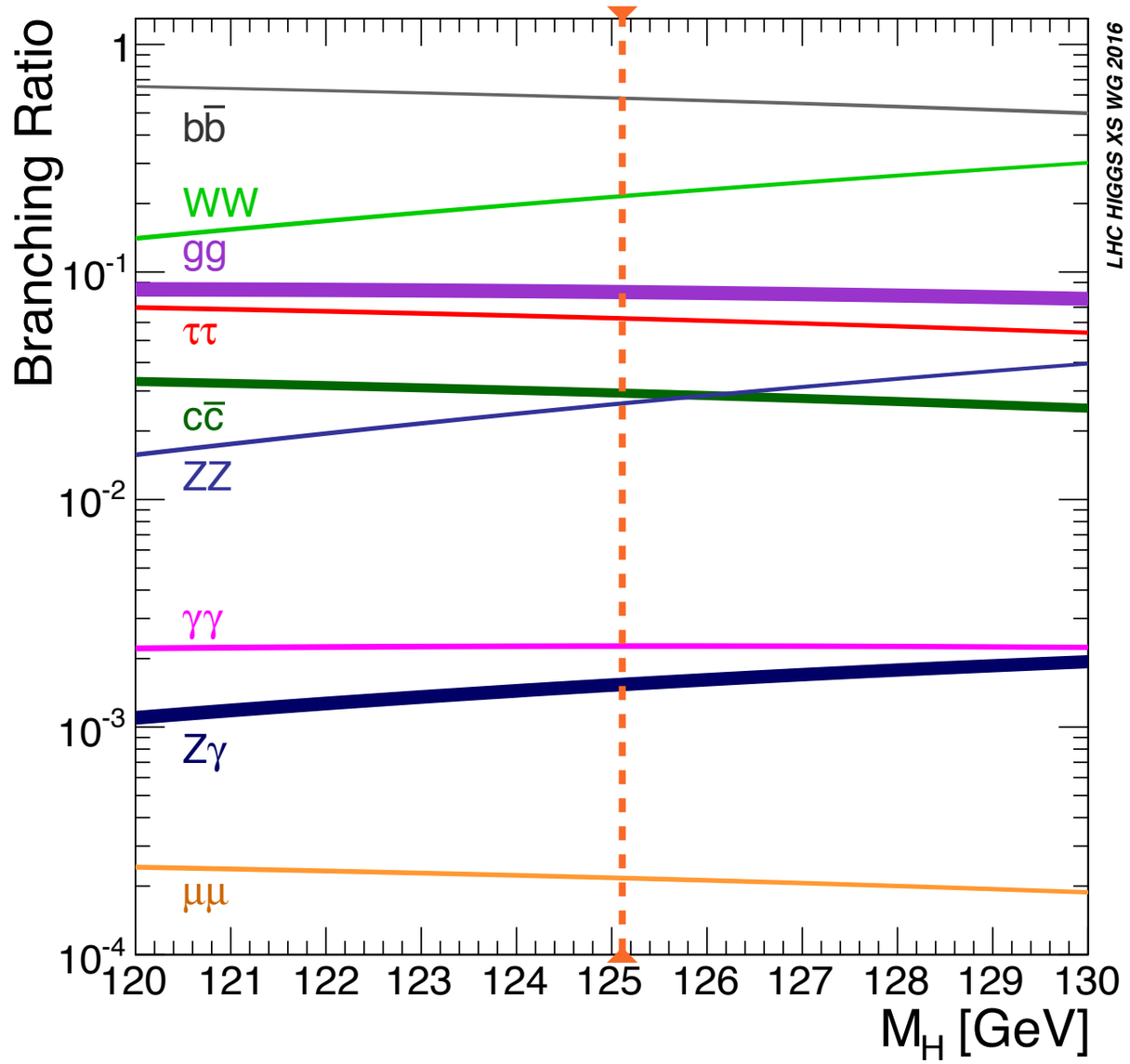
INTRODUCTION

- After the **Higgs discovery** in 2012, the emphasis shifted towards **measuring** the **properties of this new particle**.
  - The mass, the width, the spin and parity
  - Couplings, several models for physics beyond the SM predict (small) deviations in the couplings for the Higgs boson.
- This talk will review the latest results using the Run 2 CMS dataset.
  - Increased collision energy (13 TeV) means an increased cross section for signal and background, with the most significant gain for processes involving heavy particles like multiple top quarks.
  - Most of the Run 1 results have been reproduced using **2016 dataset** (35.9 fb^{-1}) and **combined** increasing the precision on couplings measurement.
  - **New results** with the **2016** dataset and **first results** with the **2017** data results (41.5 fb^{-1}) will be discussed

HIGGS BOSON

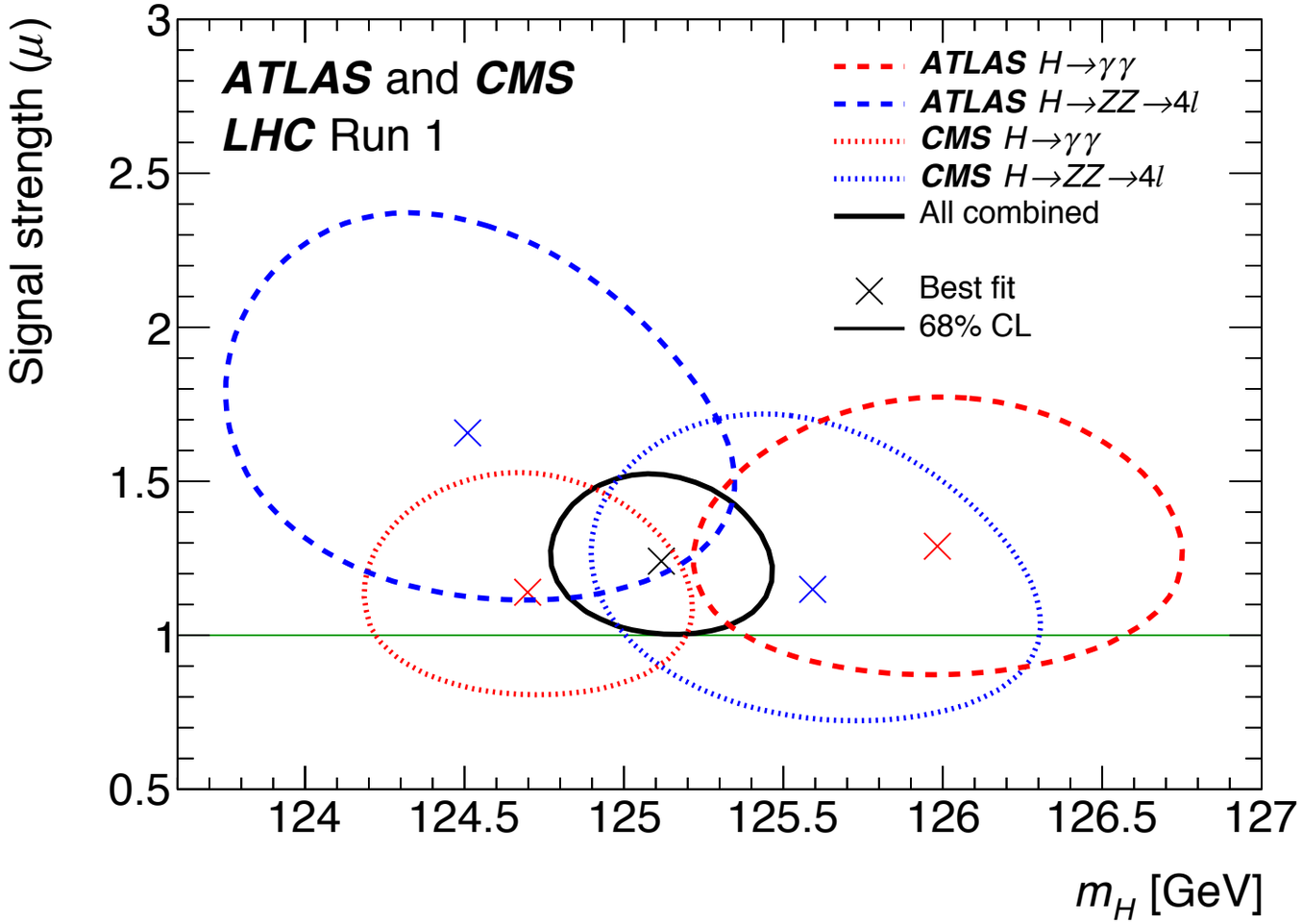
- Given the mass of 125 GeV, we know the branching fractions from theory.
- Several production modes of the Higgs boson possible at the LHC, sometimes with associated particles.

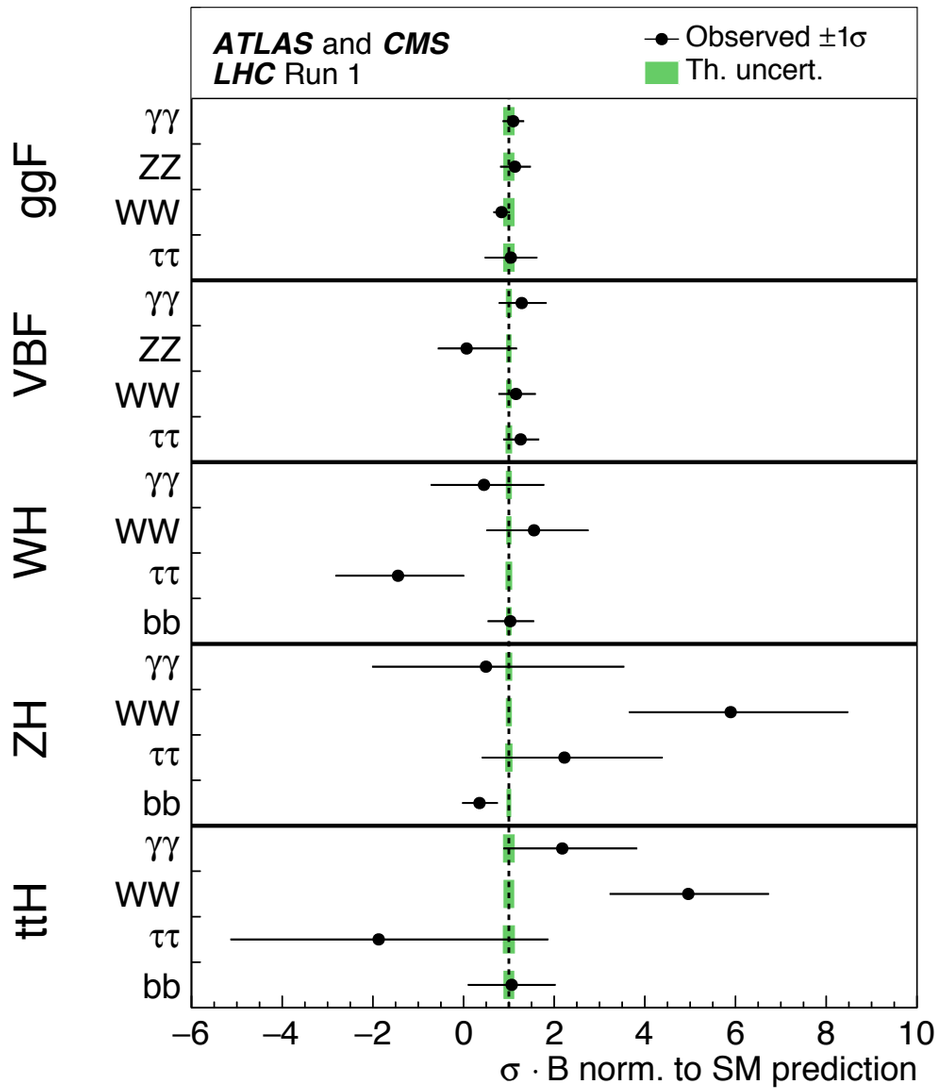


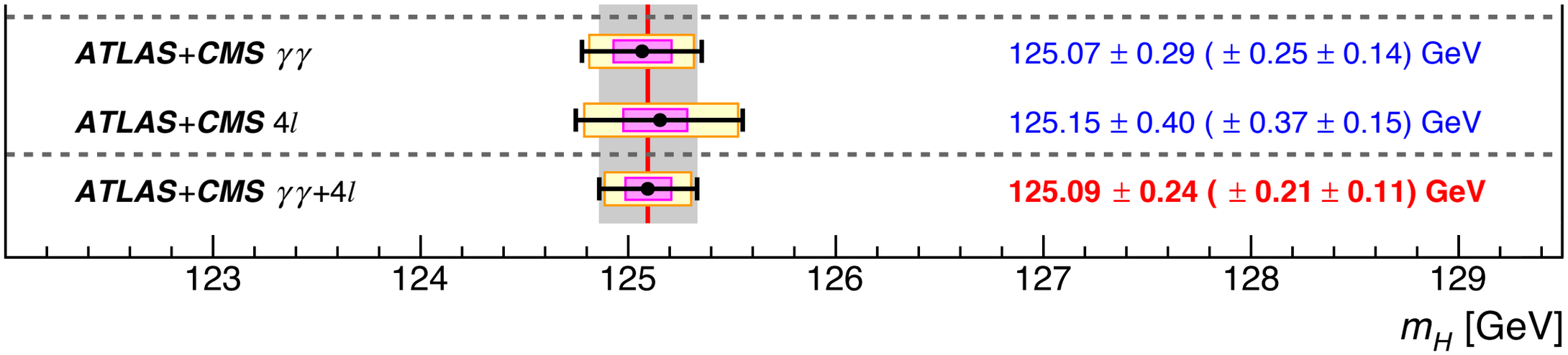


RUN 1 – MASS AND COUPLINGS

Phys. Rev. Lett. 114 (2015) 191803
J. HIGH ENERGY PHYS. 08 (2016) 045

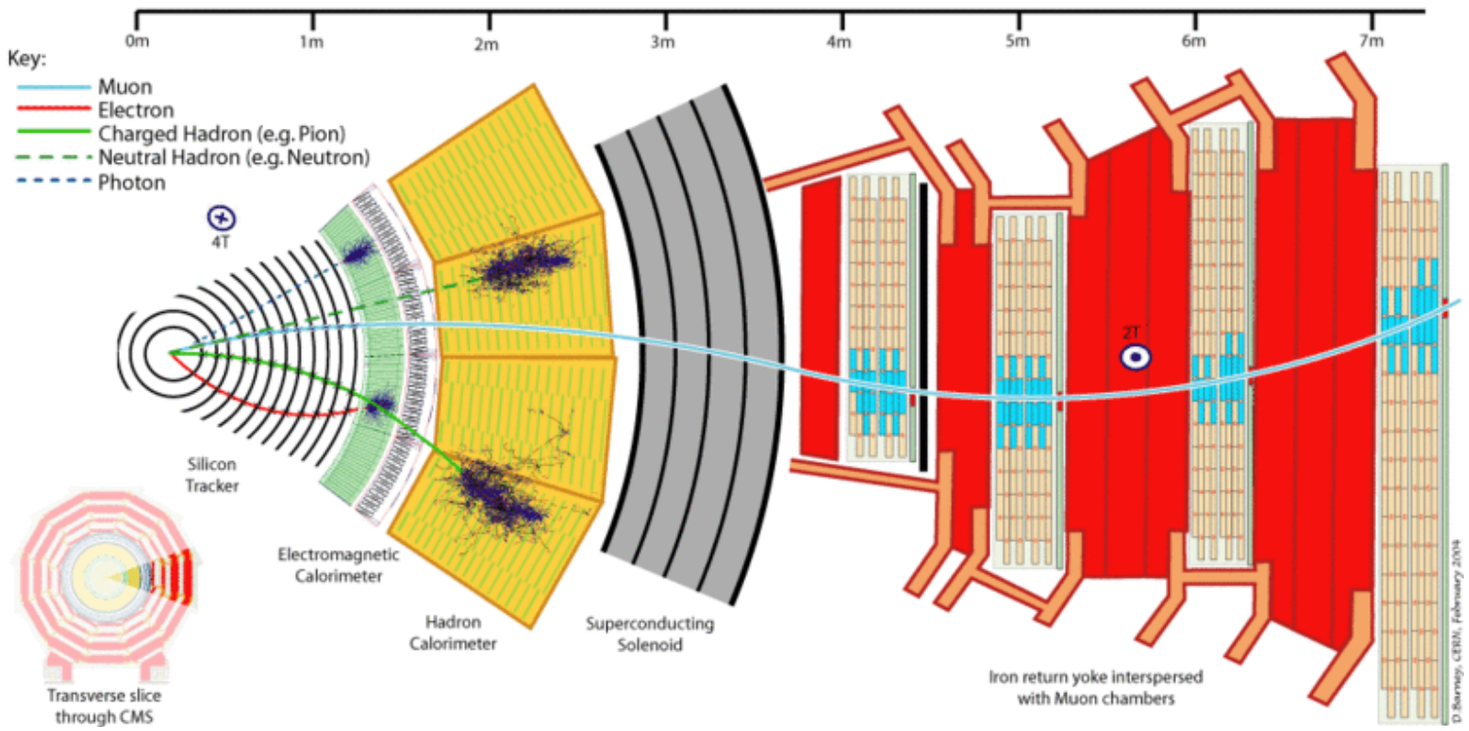


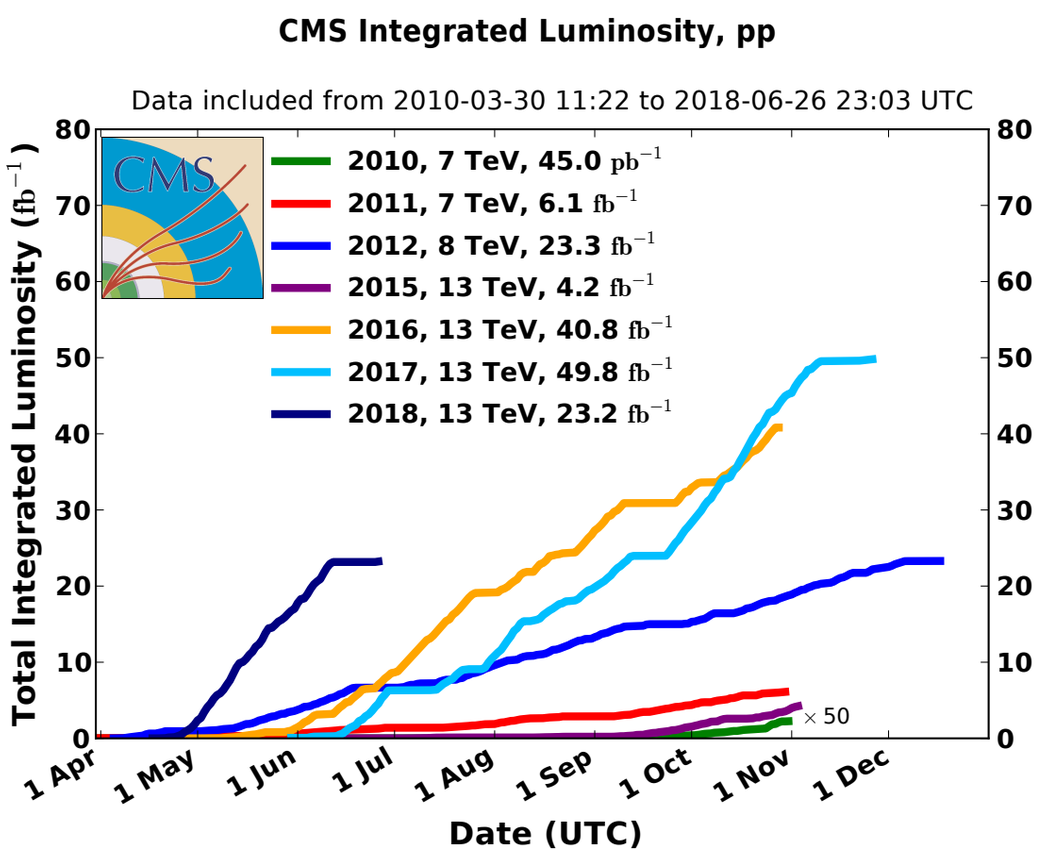


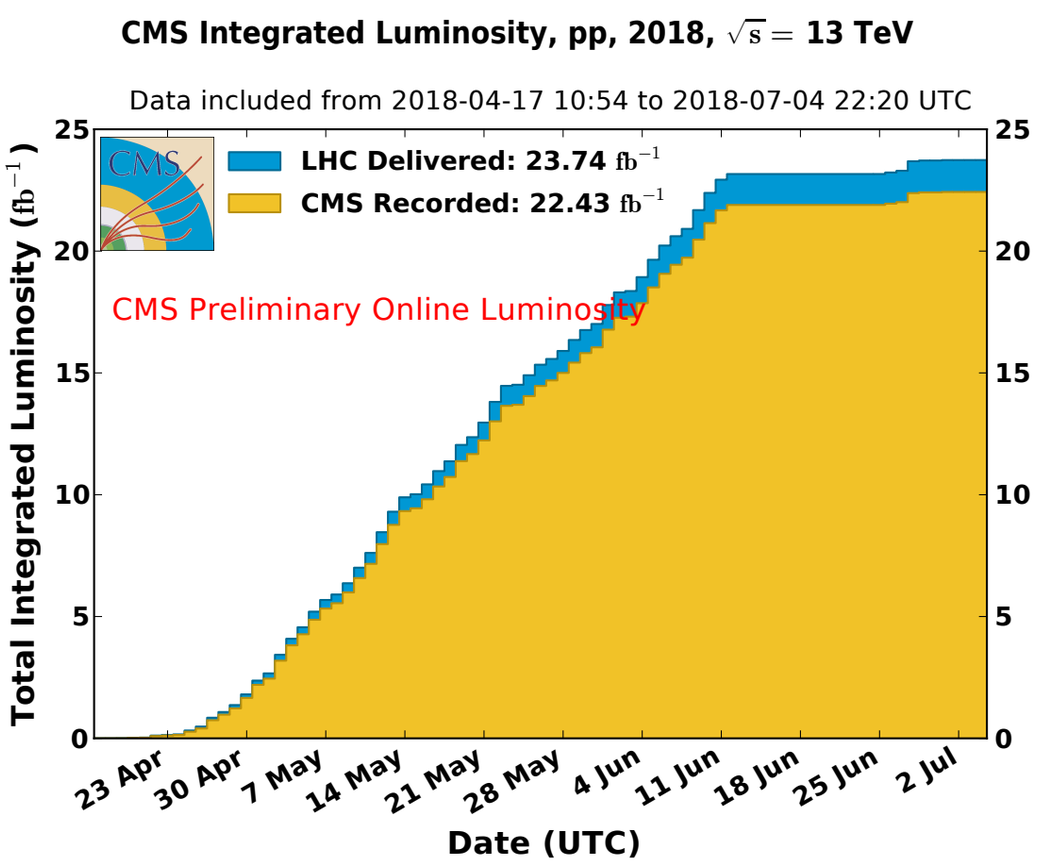


CMS DETECTOR

- Multipurpose detector at Large Hadron Collider
- Excellent performances of both CMS and LHC so far in Run-2
- CMS has recorded ~110 fb-1 of 13 TeV data, of which ~90% certified as good for physics analysis







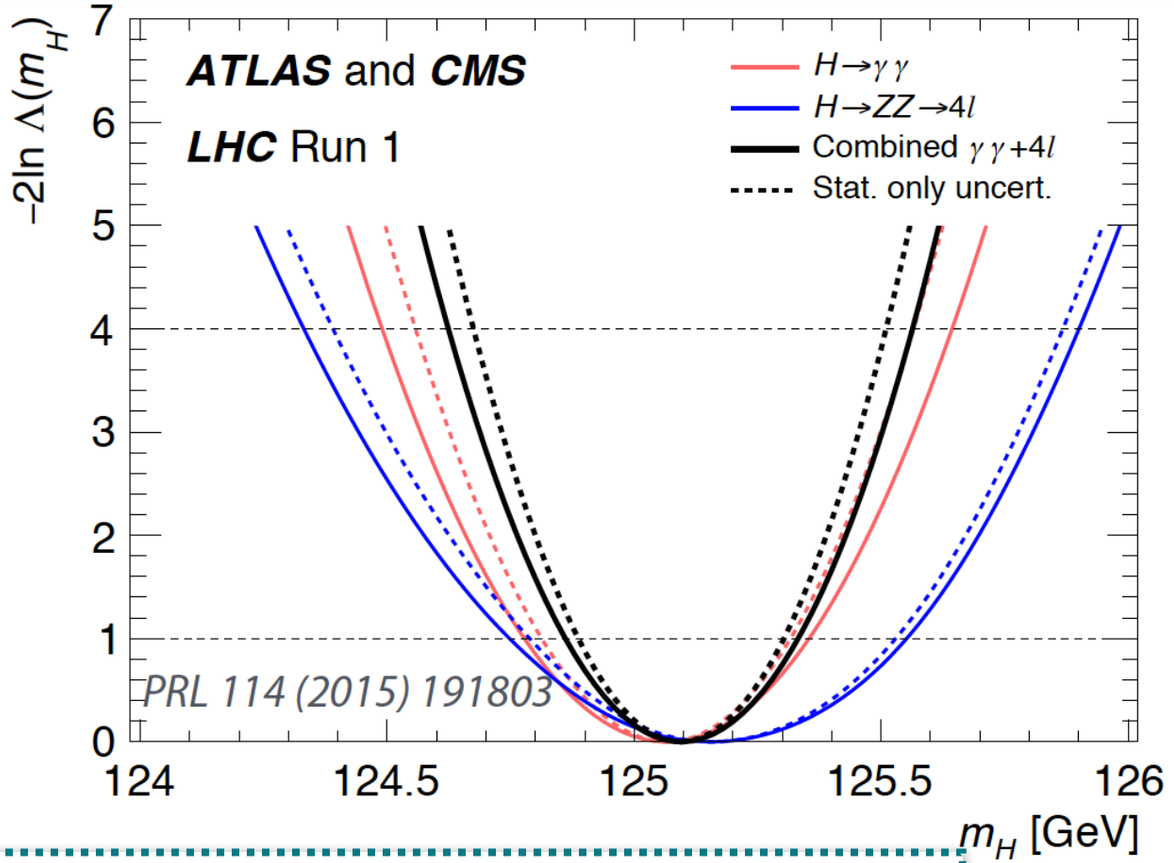
Run 2 – Couplings

Higgs Boson Couplings

CMS-PAS-HIG-17-031

- Higgs boson discovery via the benchmark H→ZZ→4l and H→γγ channels the legacy of Run 1
- Focus in **Run 2** is making **precise measurements** of its properties to assess compatibility with the SM
- High precision measurement of the couplings essential as **BSM physics** can manifest as **percent-level deviations**

- All combined measurements presented assume fixed m_H
  - Use Run 1 CMS+ATLAS combination of high resolution H→γγ and H→ZZ→4l channels



$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$$

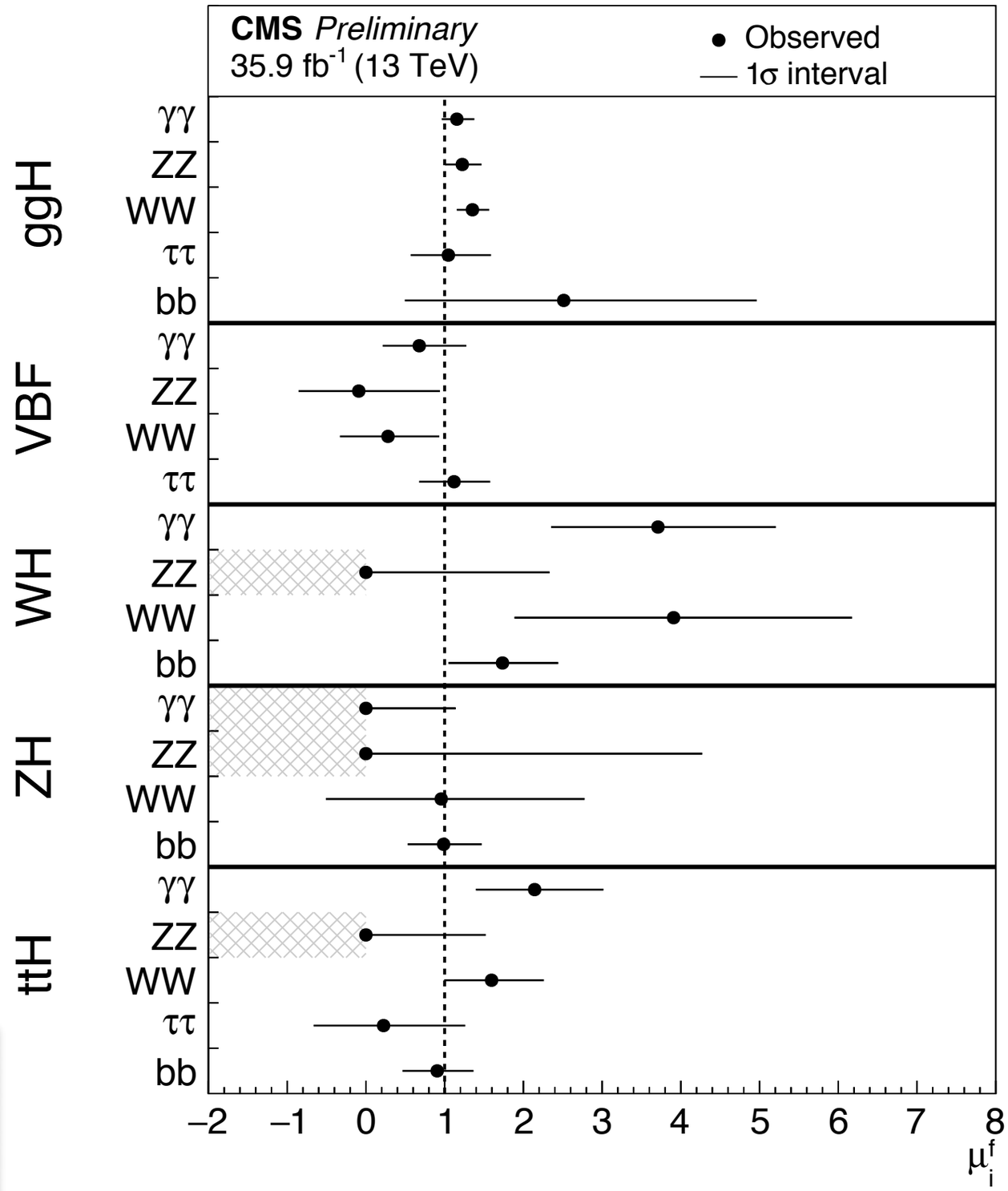
Higgs Boson Couplings

CMS-PAS-HIG-17-031

- **Analyses used** for combination cover all main production and decay modes on **2016 13 TeV dataset** (35.9 fb^{-1})
  - VH(→ττ) missing
- Total of **250** individual categories (counting signal and control regions) and ~ **5400** nuisance parameters in the combined fit
- Signal strength measurements
  - Parameters scale cross sections and BRs relative to SM

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{SM}}$$

$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{SM}} = \mu_i \times \mu^f$$

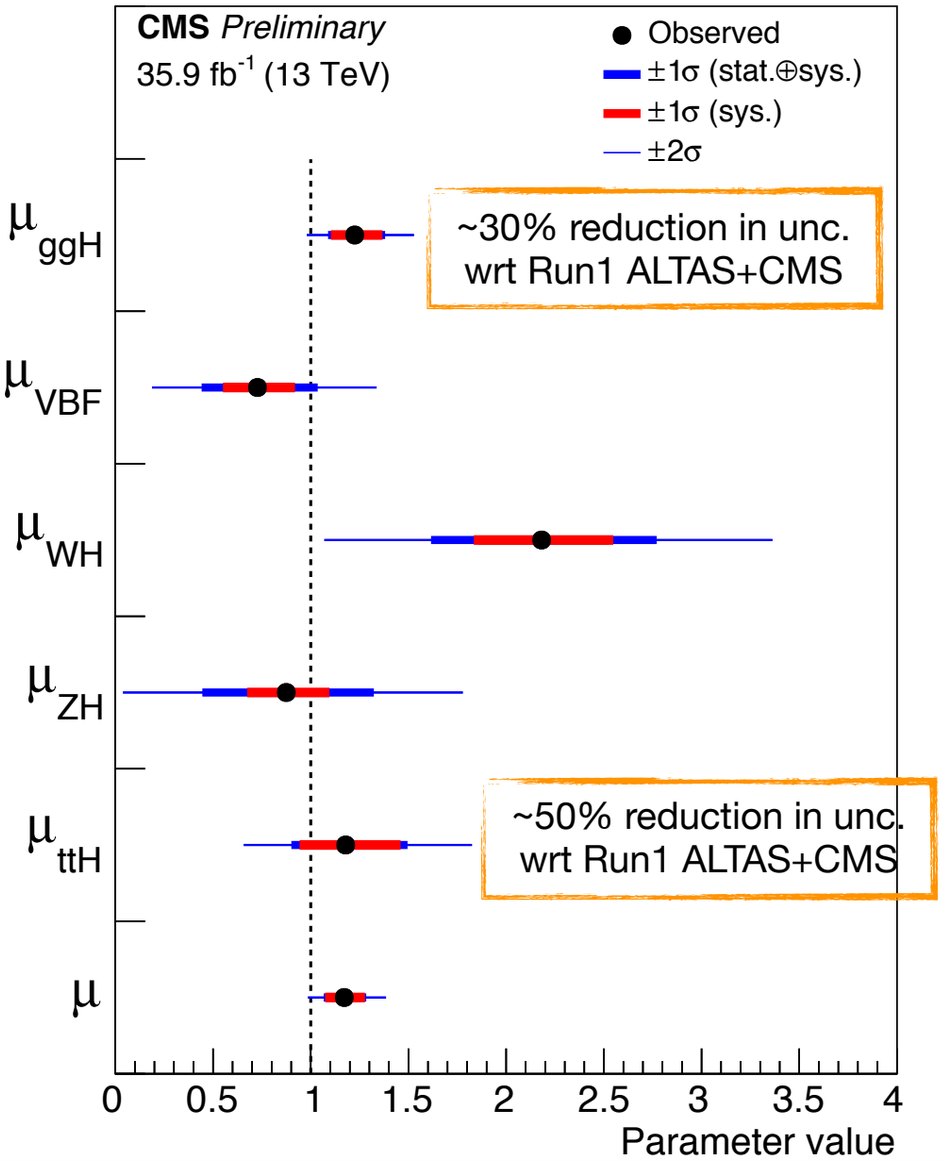


Higgs Boson Couplings

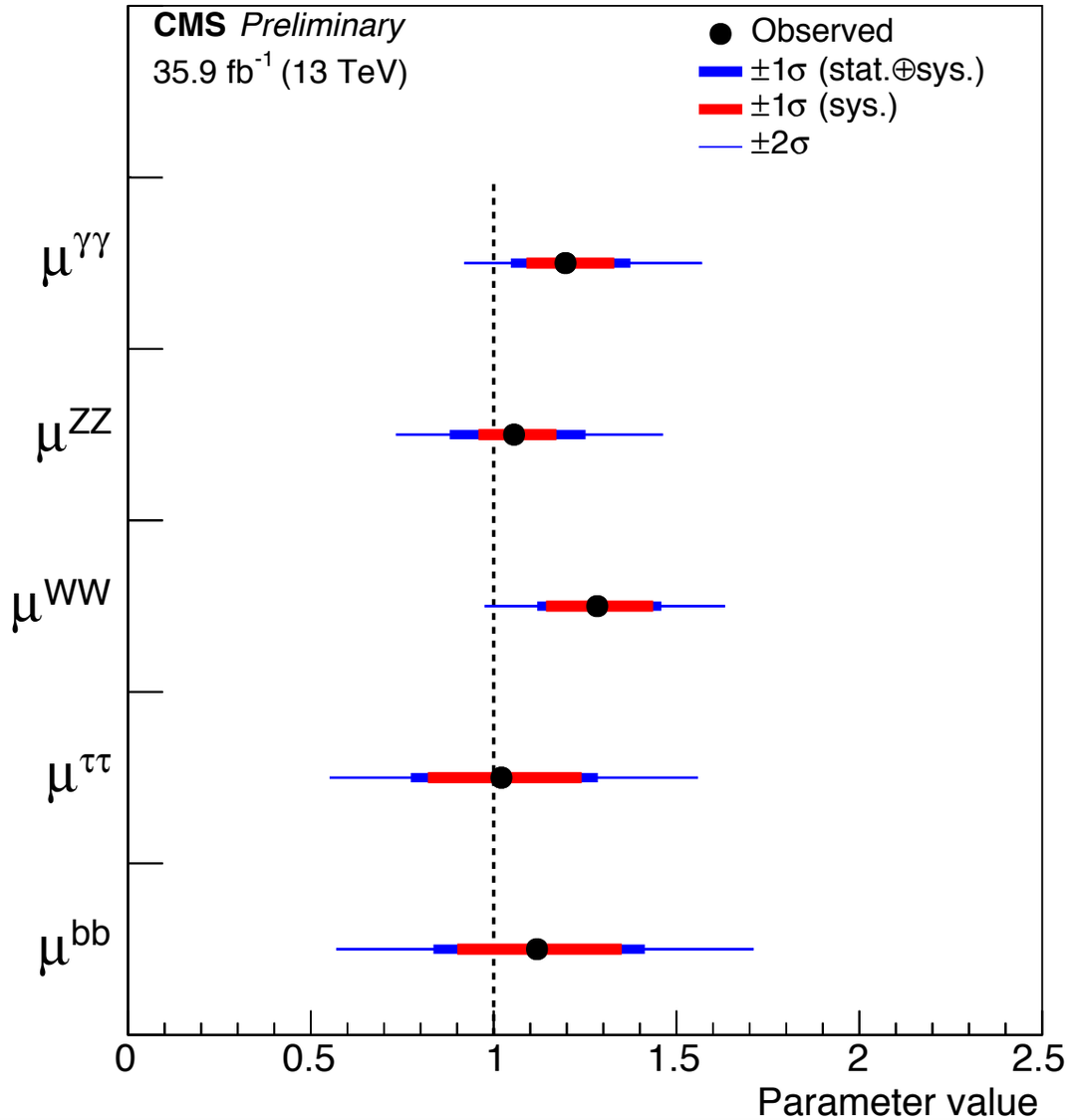
CMS-PAS-HIG-17-031

- Signal strength measurements

Production Mode



Decay Mode



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

Higgs Boson Couplings

CMS-PAS-HIG-17-031

- Use the LO coupling modifier or "kappa" framework to probe for deviations from the SM
  - Parameters scale cross sections and partial widths relative to SM
- Option to consider decay to BSM particles via BR_{BSM} term which also scale total width

$$\kappa_j^2 = \sigma_j/\sigma_j^{\mathrm{SM}} \quad \kappa_j^2 = \Gamma_j/\Gamma_j^{\mathrm{SM}}$$

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

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

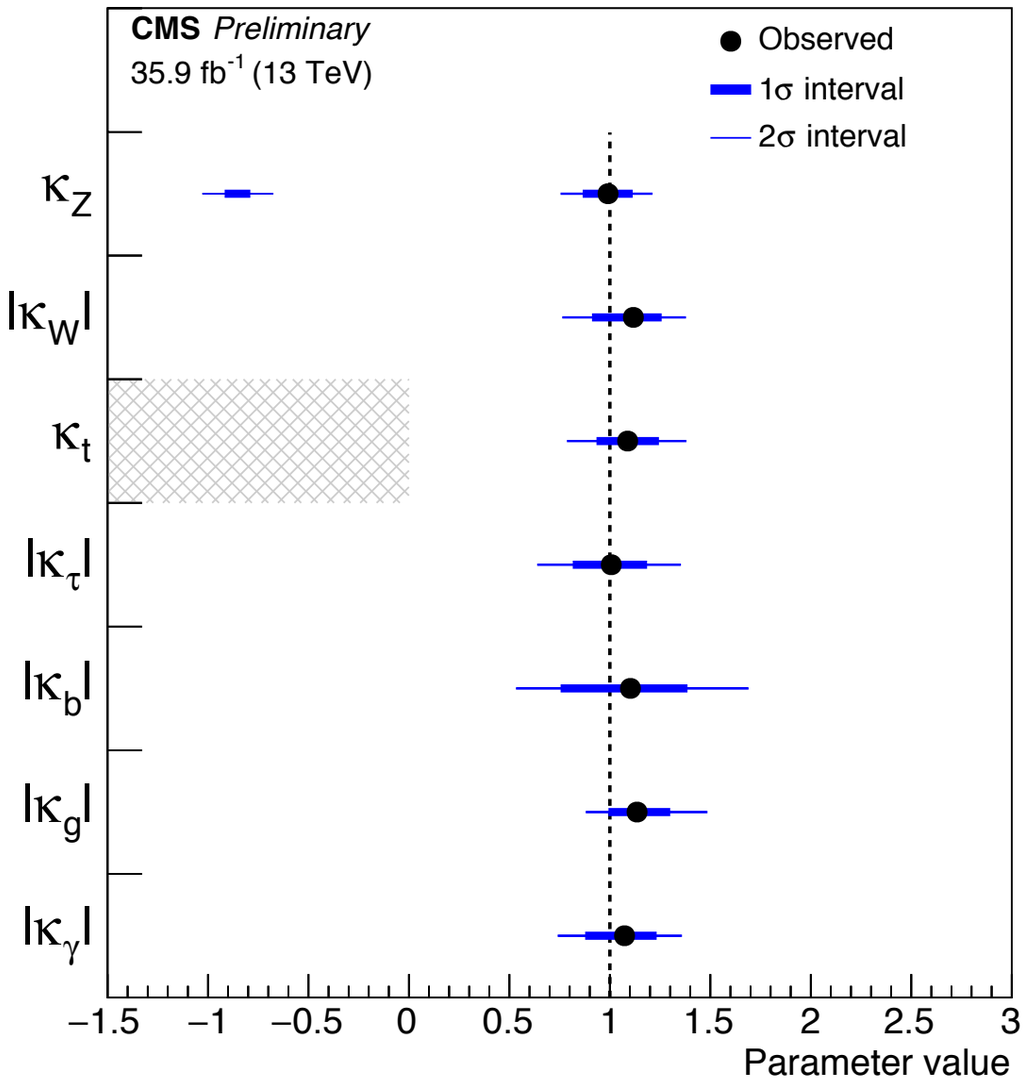
$$\kappa_H^2 = \sum_j \mathrm{BR}_{\mathrm{SM}}^j \kappa_j^2$$

$$\mathrm{BR}_{\mathrm{BSM}} = \mathrm{BR}_{inv.} + \mathrm{BR}_{undet.}$$

Higgs Boson Couplings

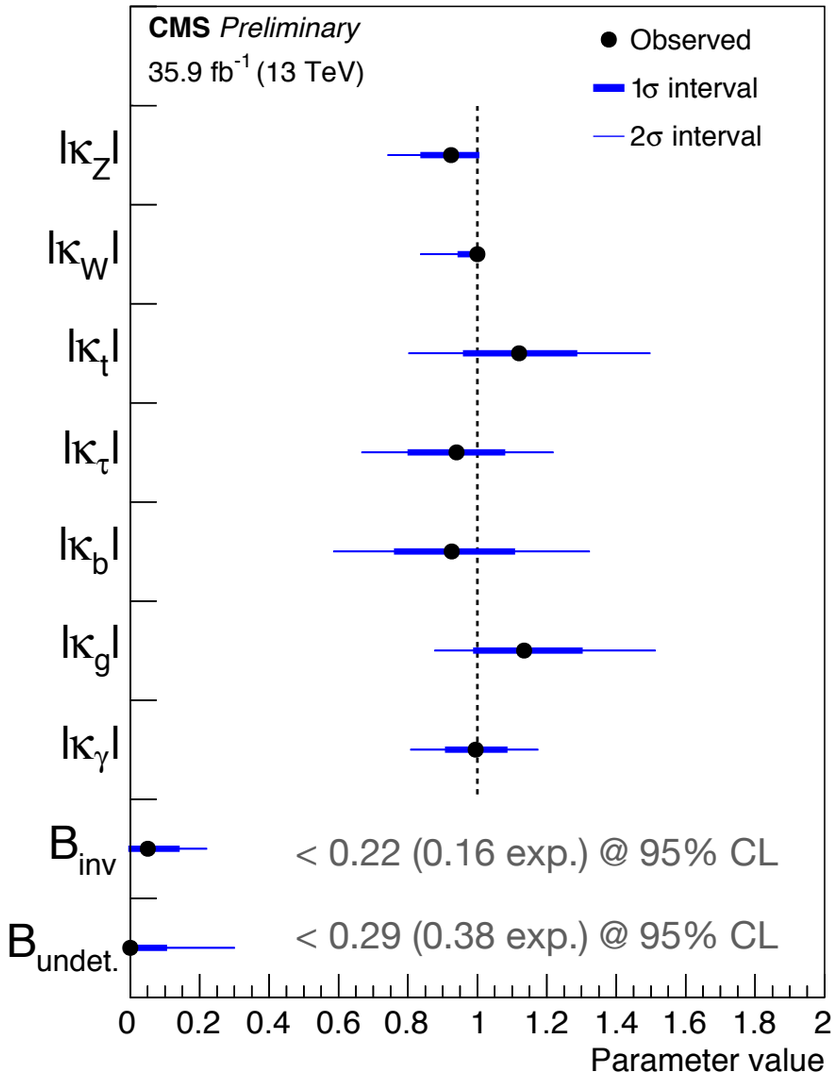
CMS-PAS-HIG-17-031

$BR_{inv} = 0$, $BR_{undet} = 0$



- Sensitive to relative κ_Z and κ_t sign via ggZH interference

$BR_{inv} > 0$, $BR_{undet} > 0$

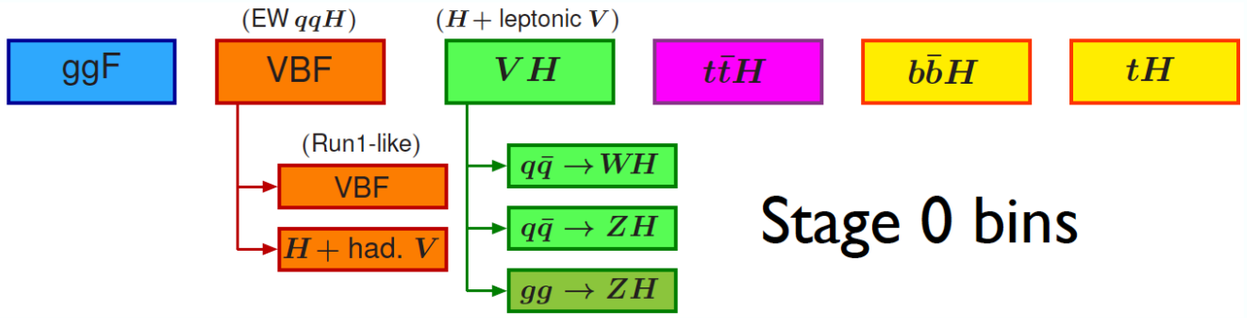


- Add direct H→inv search channels and allow floating B_{inv} and B_{undet}
- CMS+ATLAS Run-1: $BR_{undet+inv} < 0.34(0.39\ exp.)$

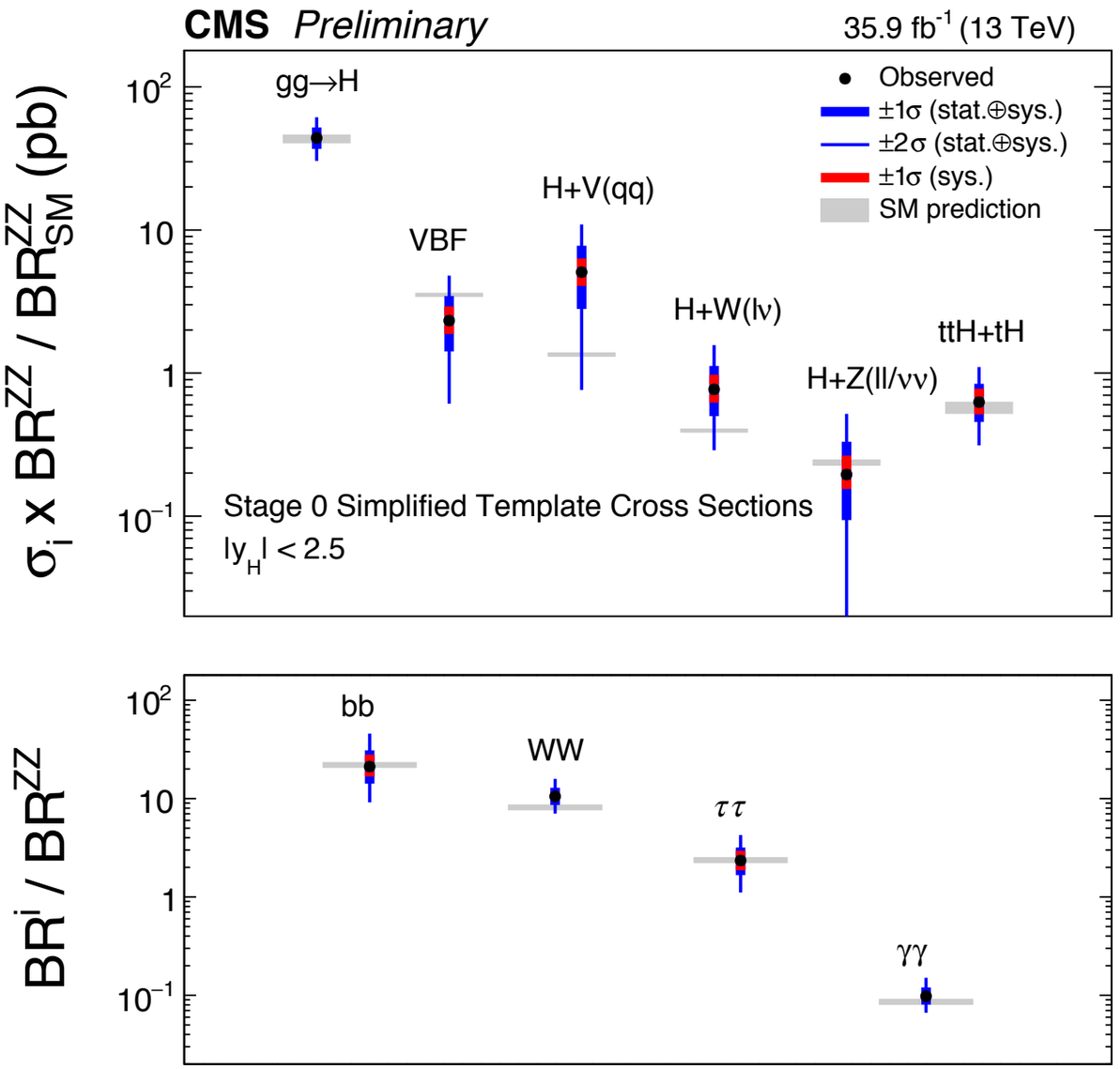
Higgs Boson Couplings

CMS-PAS-HIG-17-031

- In Run-2 CMS and ATLAS will make consistent fiducial cross section measurements (arXiv1610.07922)

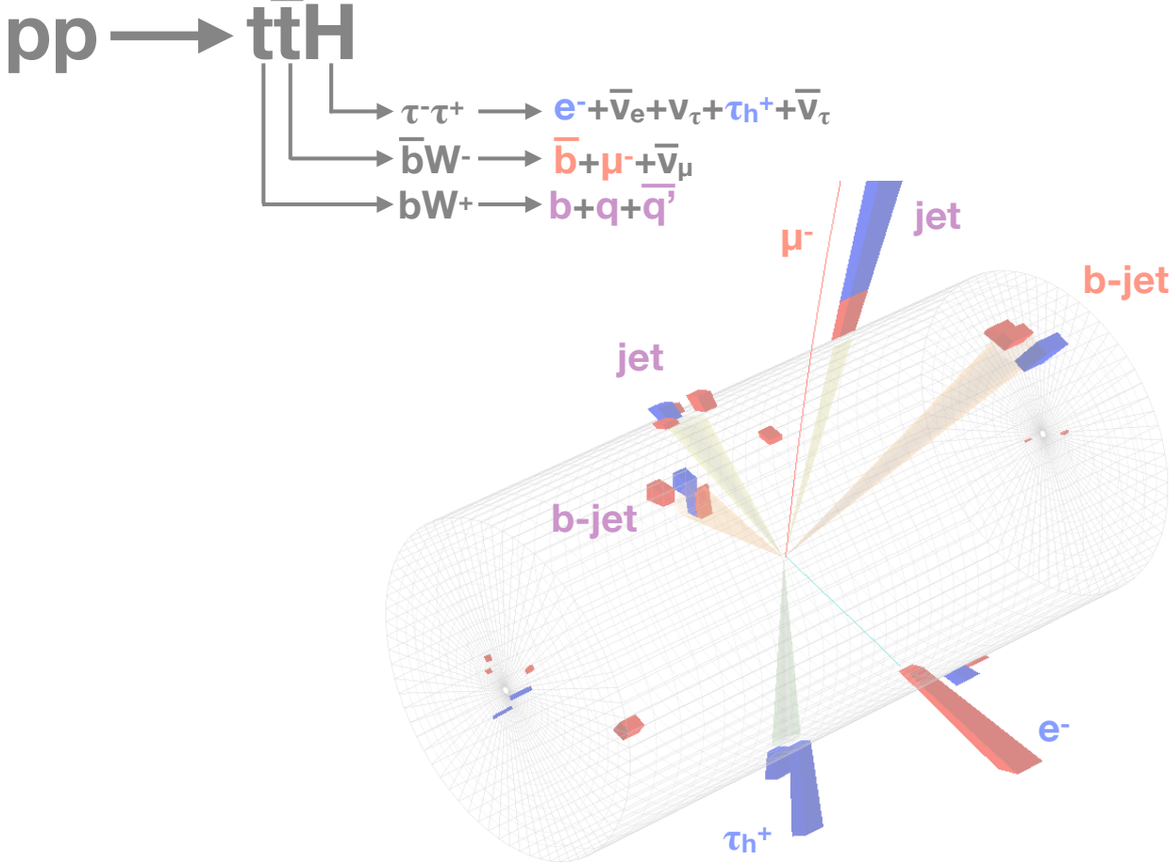


- Contrary to signal strength results, VH split
- One parameter for each cross section, with floating ratios of the decay BRs
- First STXS results using combination of 5 decay channels



- Inclusive **theory uncertainties** not included in the fit, shown as **uncertainty on SM prediction instead**

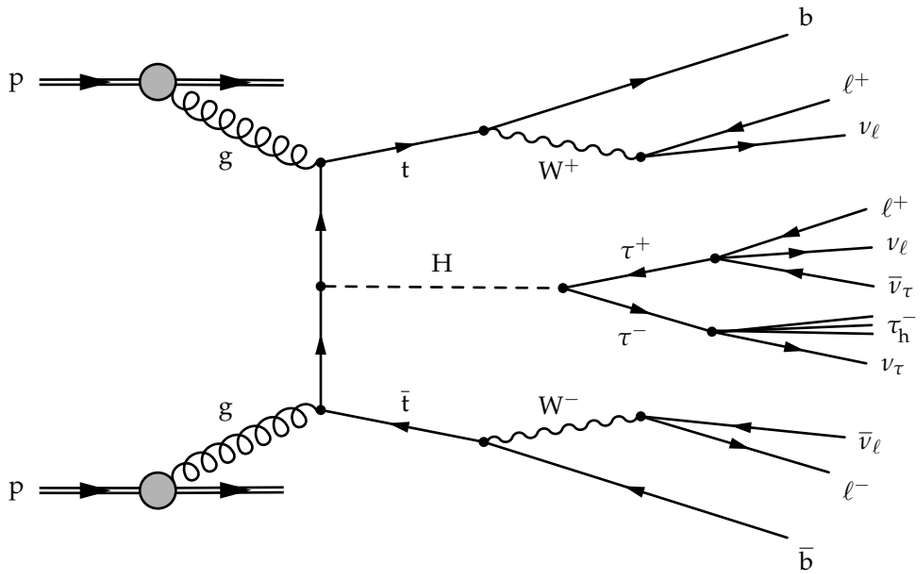
Run 2 – ttH

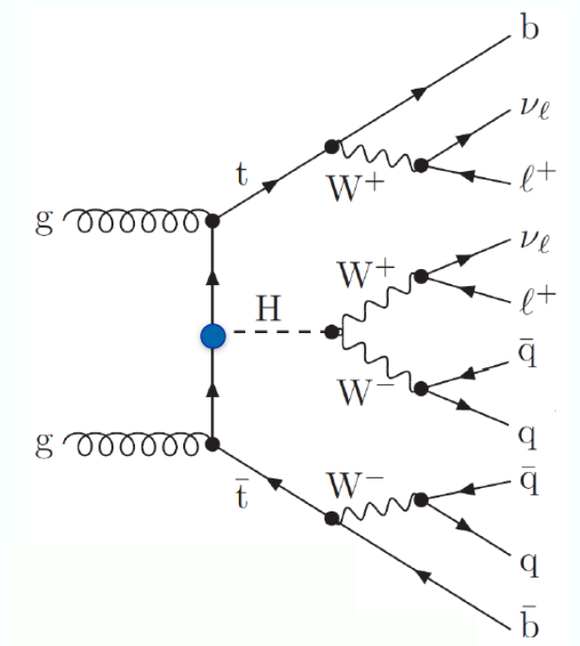


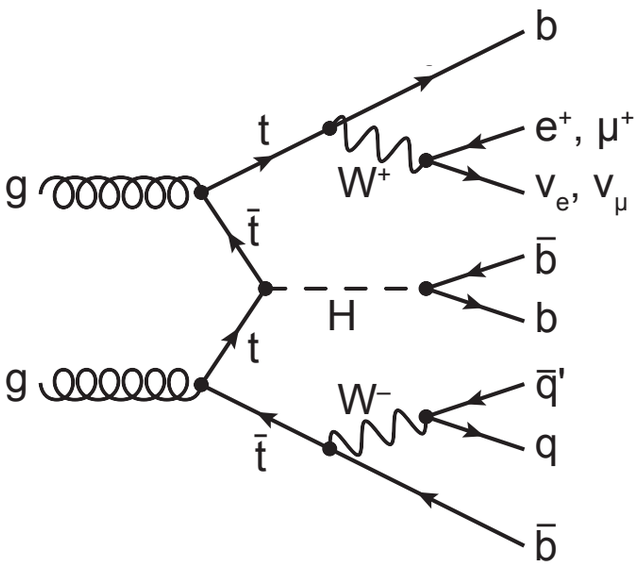
ttH Observation

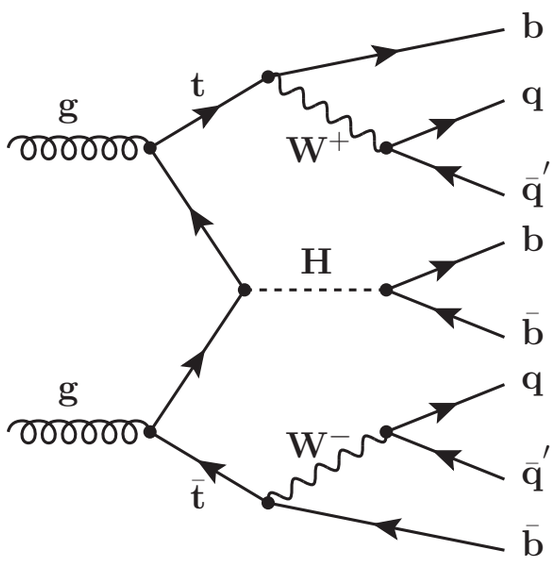
Phys. Rev. Lett. 120 (2018) 231801

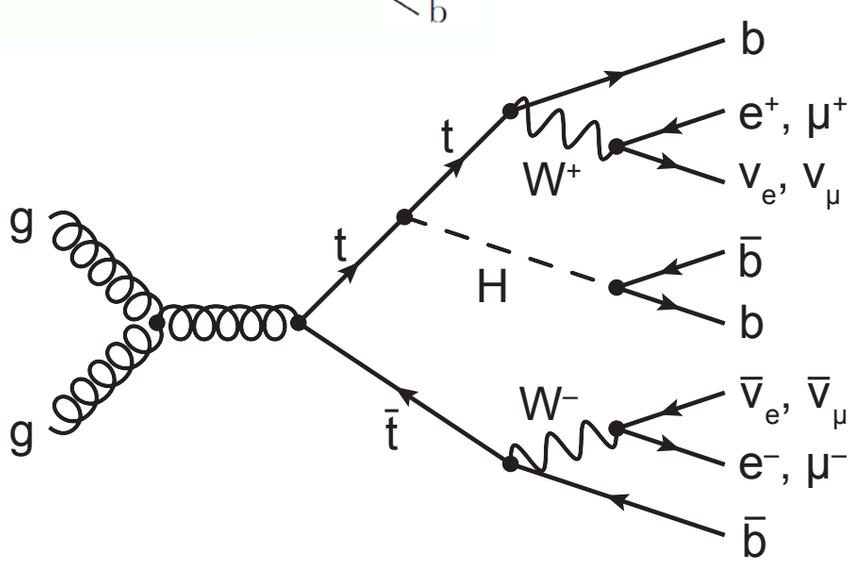
- **ttH** production **rare in the SM** (~1% of ggF cross section)
- final state characterised by multiple jets, b-tagged jets and leptons allows for discrimination from background and increased sensitivity









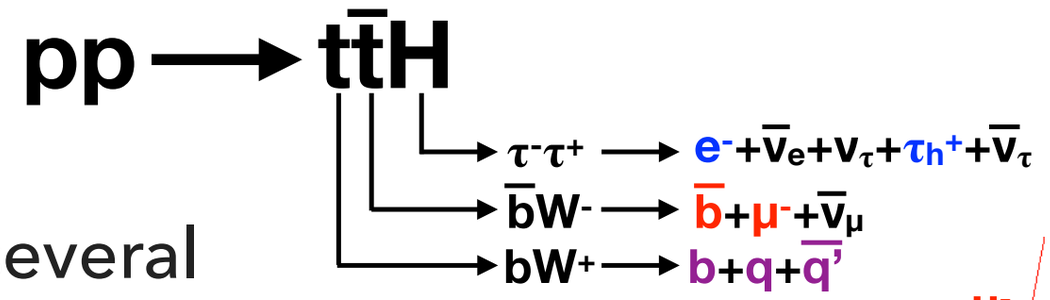


ttH Observation

Phys. Rev. Lett. 120 (2018) 231801

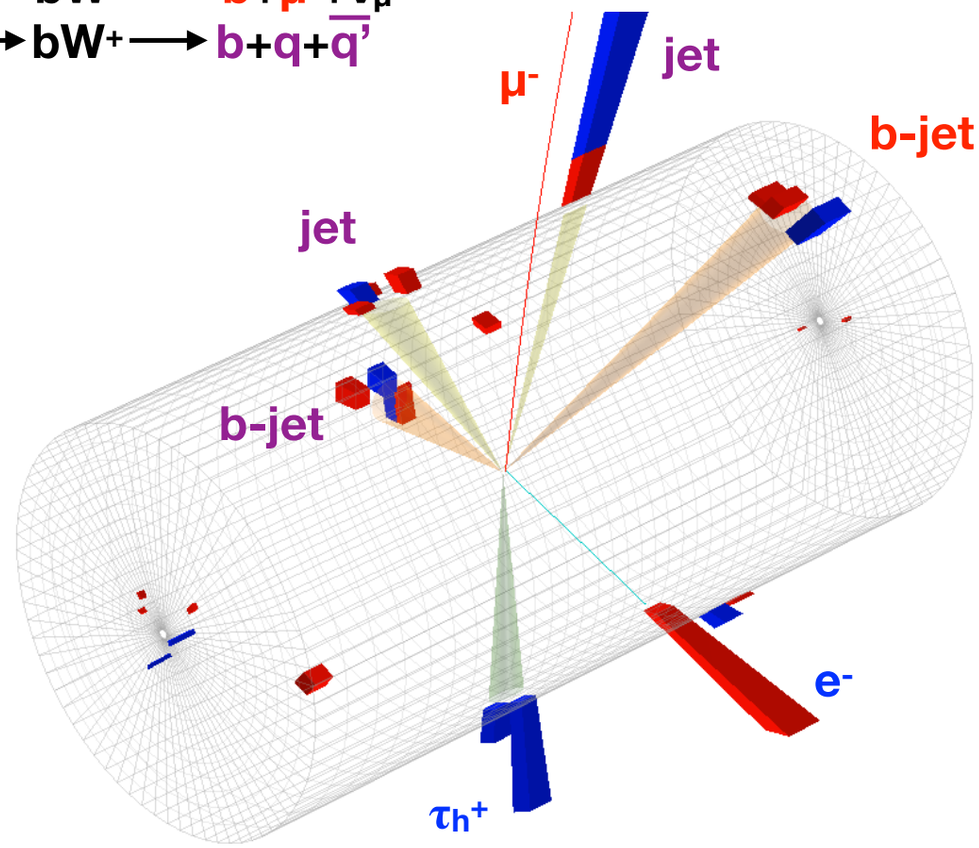
- Combination of Run 1 and 2016 CMS data:

$$7\ \text{TeV}\ (5.1\ \text{fb}^{-1}),\ 8\ \text{TeV}\ (19.7\ \text{fb}^{-1})\ \text{and}\ 13\ \text{TeV}\ (35.9\ \text{fb}^{-1})$$



- Independent analyses of several final-states topologies:

$$H \to WW^*,\ ZZ^*,\ \gamma\gamma,\ \tau^+\tau^-,\ b\bar{b}$$



- For 7-8 TeV analysis, Higgs boson mass updated to 125.09 GeV, signal, normalisation and uncertainties updated to latest values from LHC Higgs XS WG
- Correlations between Run 1 and Run 2 studies, experimental uncertainties largely uncorrelated

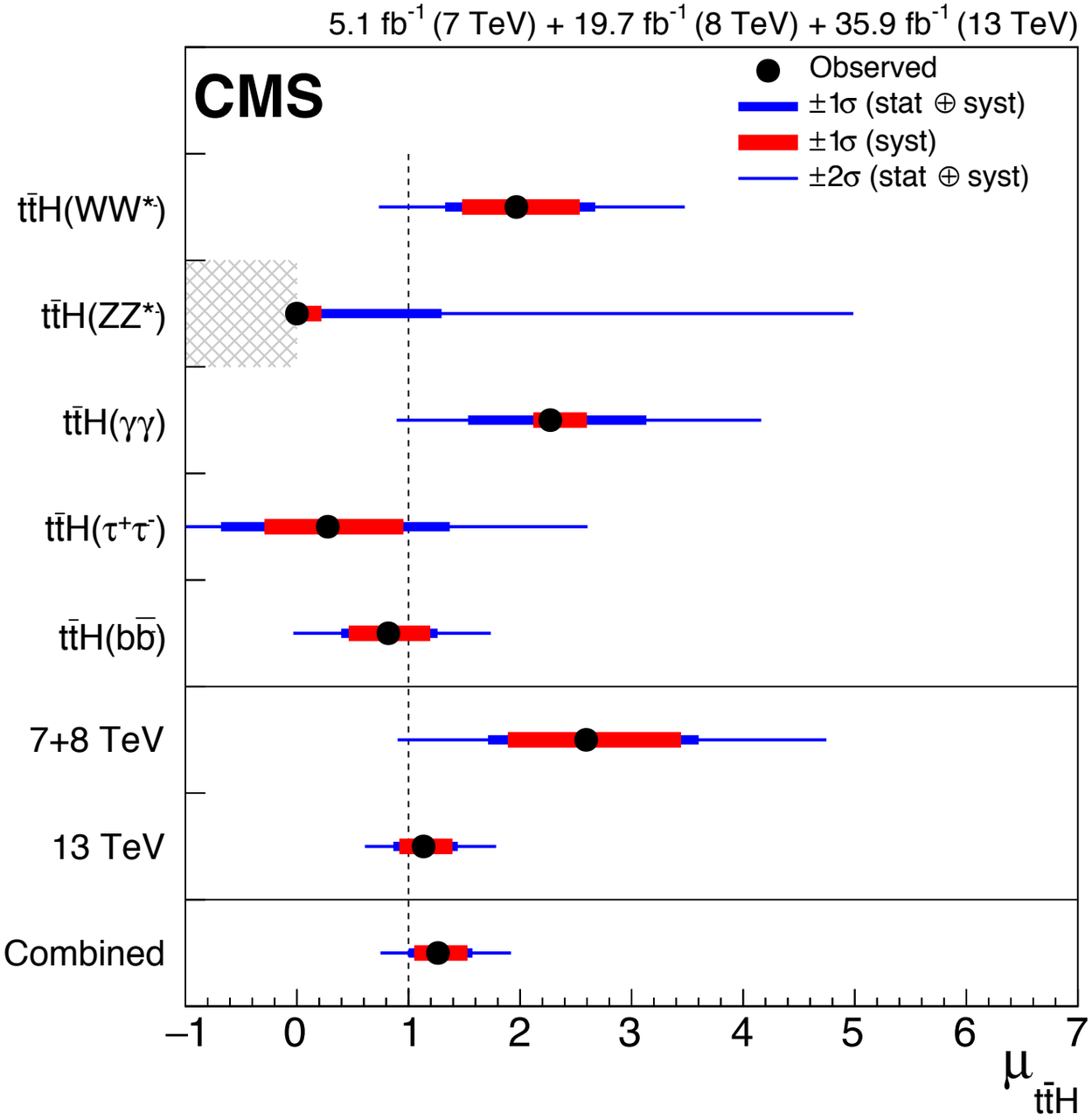
ttH Observation

Phys. Rev. Lett. 120 (2018) 231801

- **5 independent signal strength modifiers** for the decay channels considered, all **compatible within uncertainties**
- tt(H → ZZ, γγ) still dominated by statistics uncertainties

$$\mu_{t\bar{t}H}$$

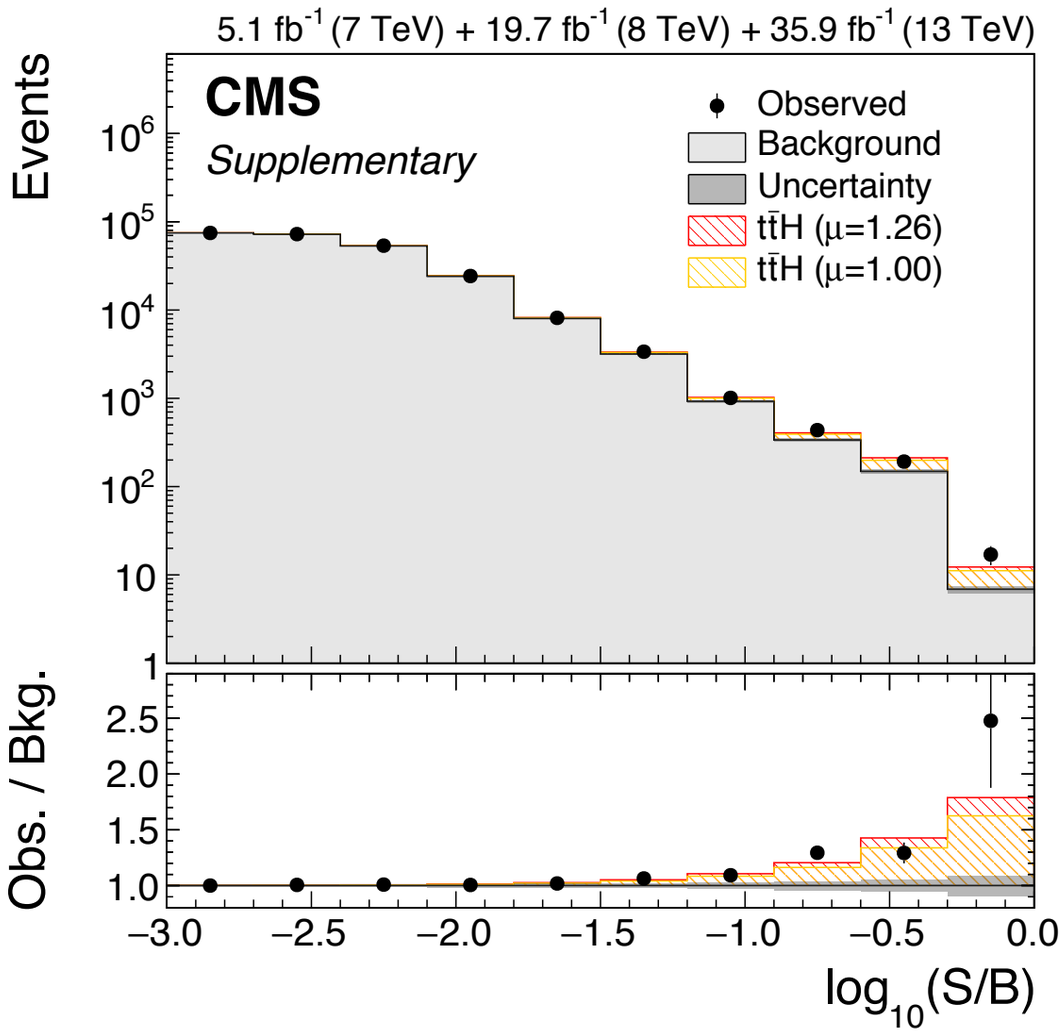
compatible with SM within 1σ

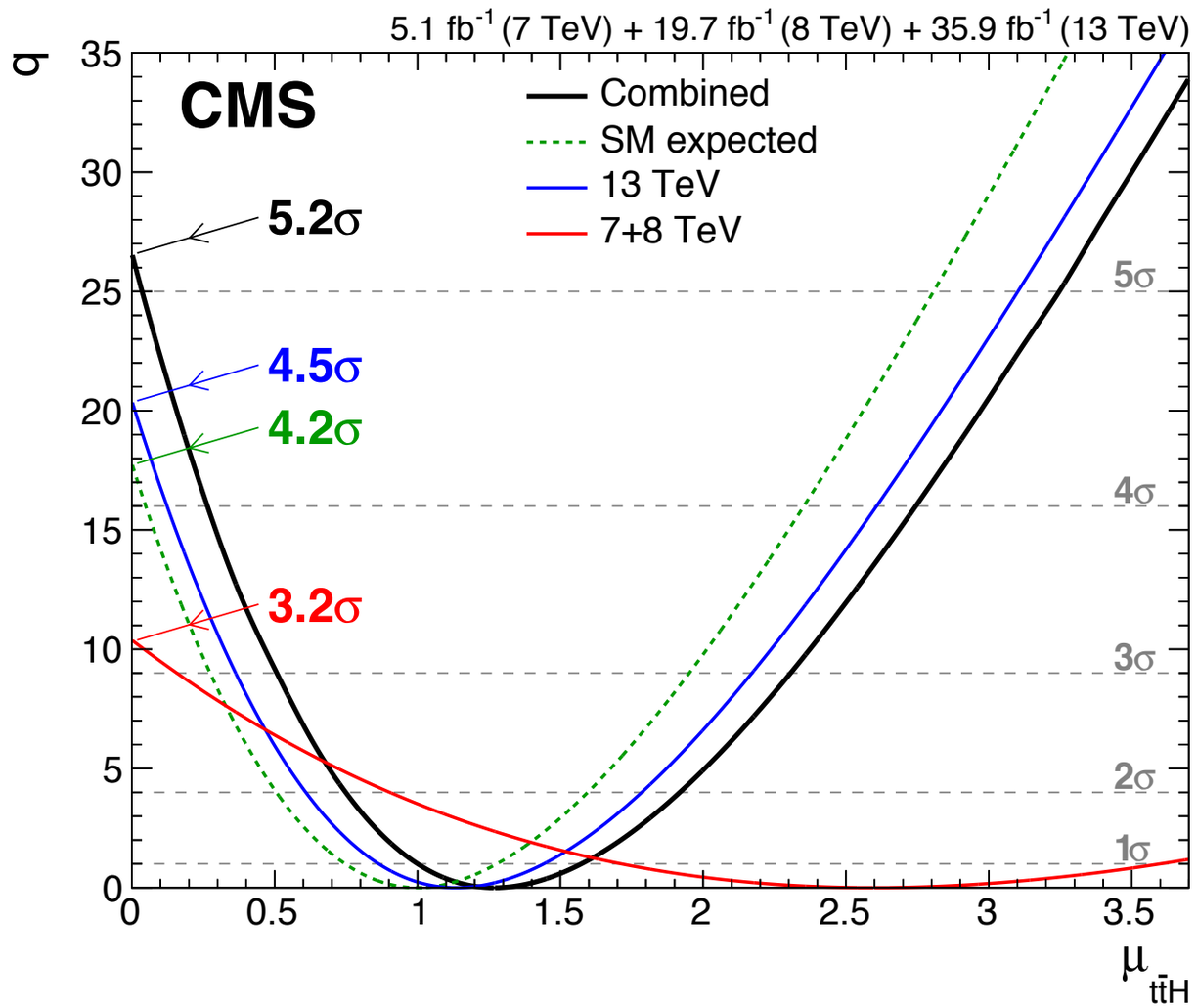


$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat.})^{+0.17}_{-0.15}(\text{exp.})^{+0.14}_{-0.13}(\text{bkg.th.})^{+0.15}_{-0.07}(\text{sig.th.})$$

ttH Observation

Phys. Rev. Lett. 120 (2018) 231801

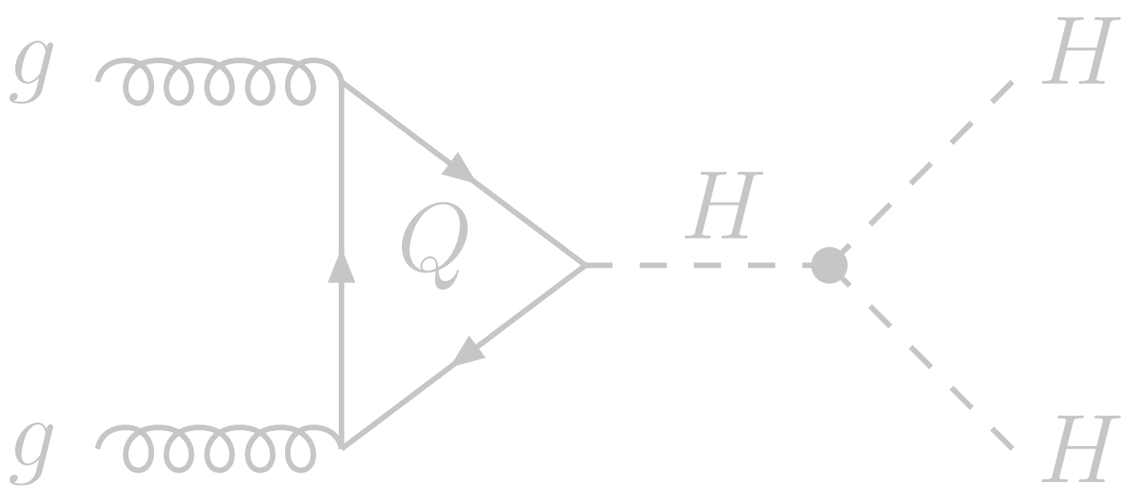


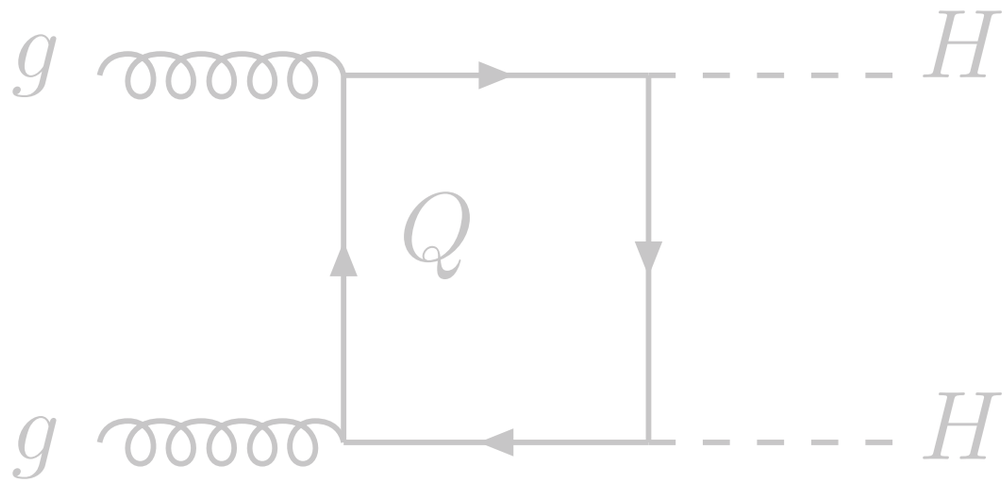


- 88 event categories combined. Excess best seen in the distribution of all events as a function of $\log_{10}(S/B)$.
- **Clear excess** in the most signal-sensitive bins
- Observed significance is **5.2σ** (4.2σ exp.)

First observation of the ttH production

Run 2 – HH Combination

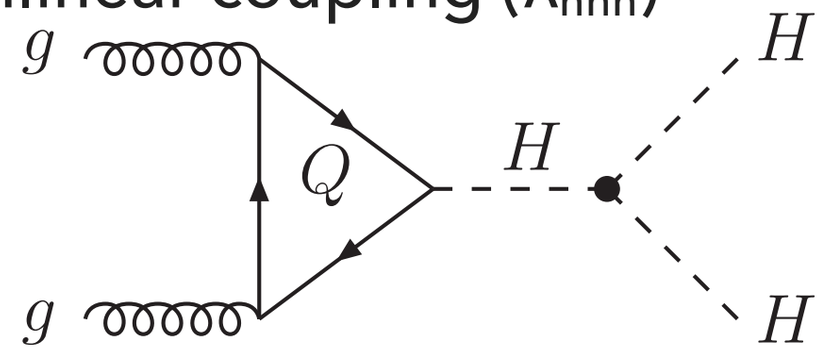


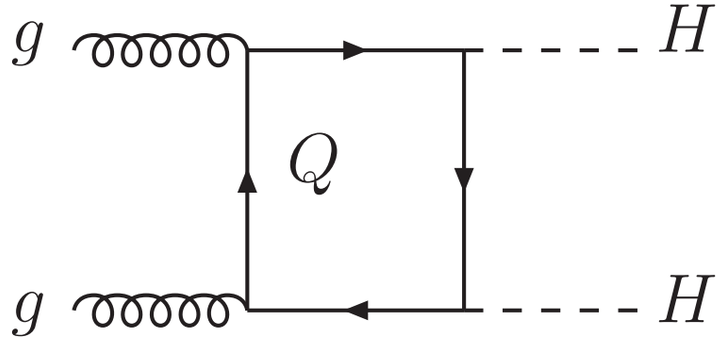


HH Combination

CMS-PAS-HIG-17-030

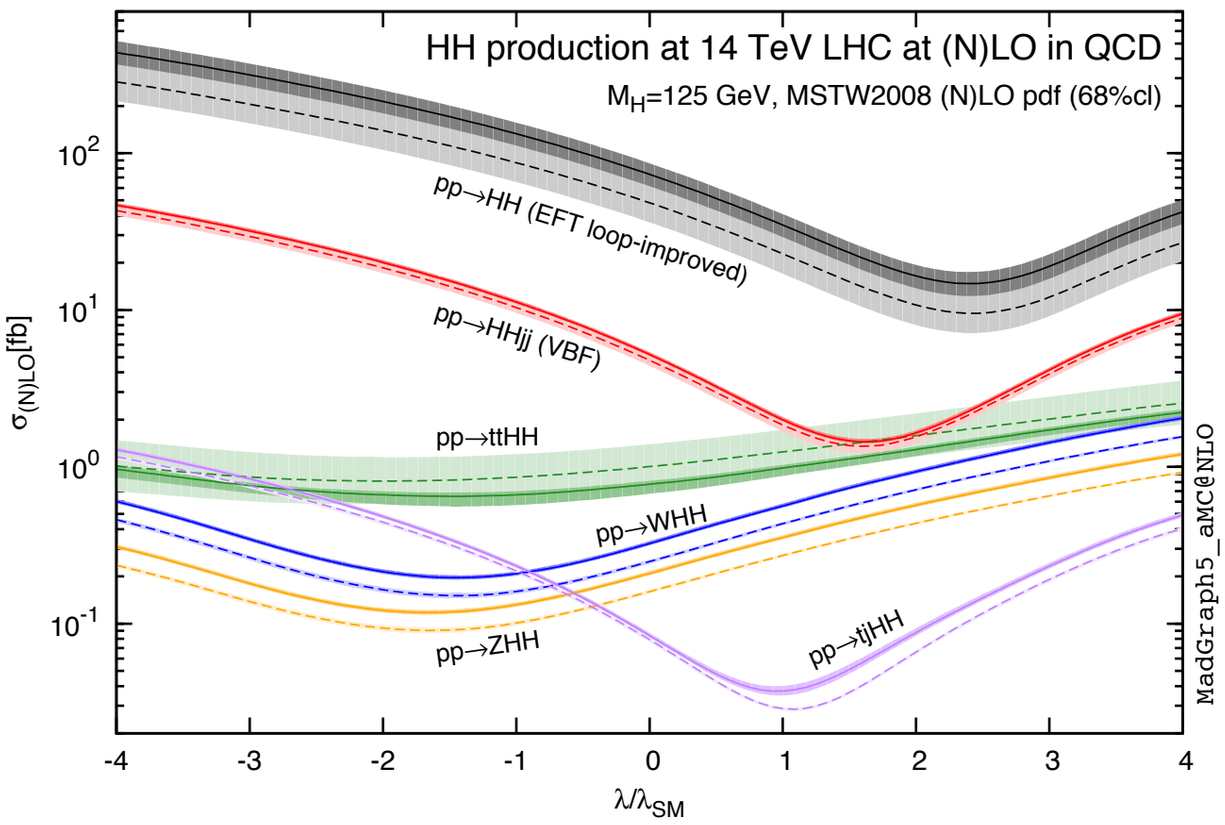
- Double Higgs production is the principal way to extract info about the Higgs trilinear coupling (λ_{hhh})





$$\sigma_{HH}^{SM} = 33.45\,\text{fb}\,^{+4.3\%}_{-6.0\%}\,(\text{scale unc.}) \pm 3.1\%\,(\text{PDF} + \alpha_S\,\text{unc})$$ [1]

- Run2 will not give us enough sensitivity to measure λ_{hhh}
- Many **BSMs** are in agreement with the measured Higgs' properties, although they predict a **different λ_{hhh}**
  - BSMs could lead to an enhancement of non-resonant di-Higgs production

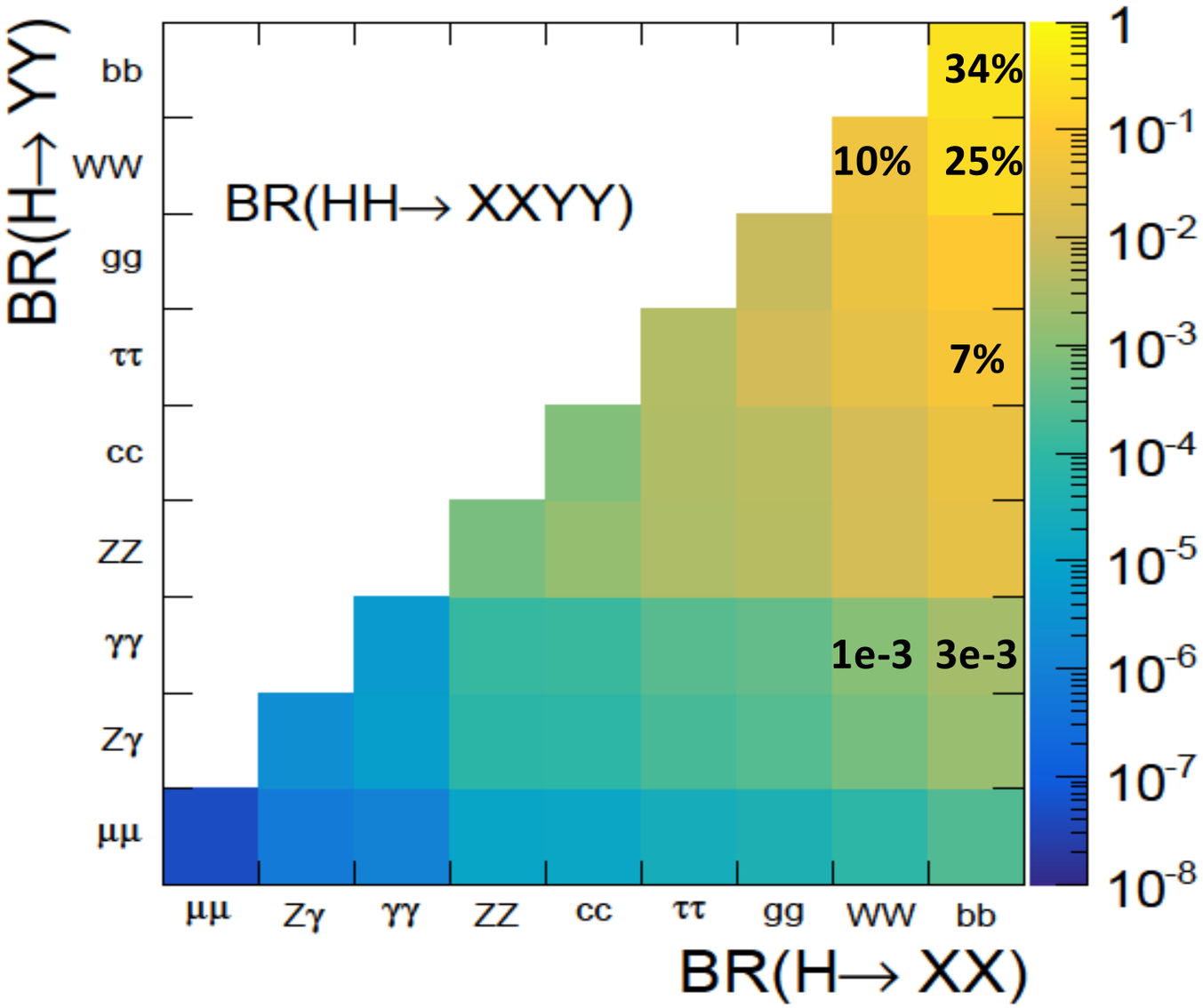


[1] LHCHXSWG Yellow Report 4

HH Combination

CMS-PAS-HIG-17-030

- Four final states used for the non-resonant combination
- Analyses performed using the full 2016 dataset (35.9 fb^{-1})



- **bb bb** : higher BR, high QCD/tt contamination
- **bb WW** : high BR, large irreducible tt
- **bb ττ** : relatively low background
- **bb γγ** : high purity, very low BR

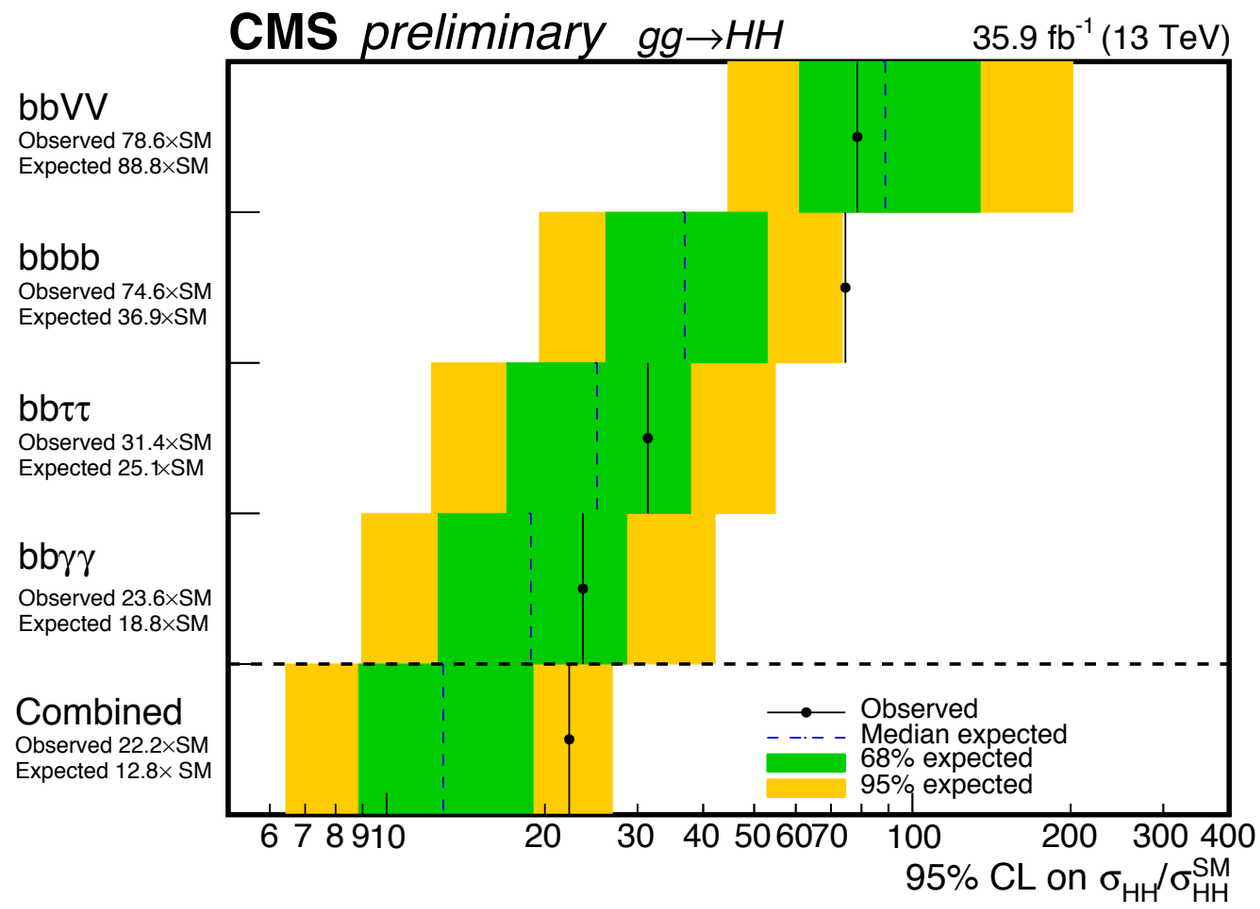
Channel	SM
bbγγ	**24 (19)**
bbττ	**31 (25)**
bbWW	**79 (89)**
bbbb	**75 (37)**

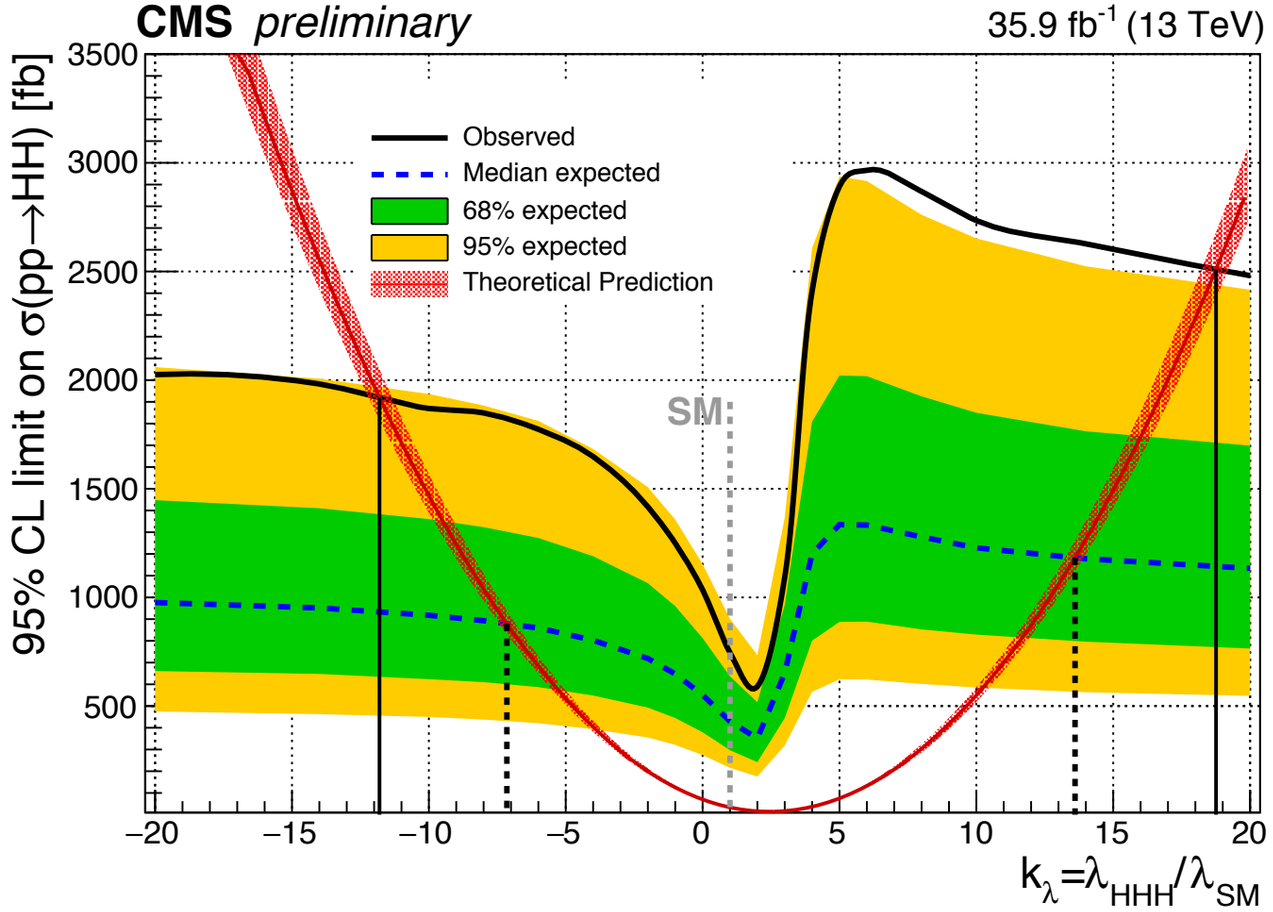
HH Combination

CMS-PAS-HIG-17-030

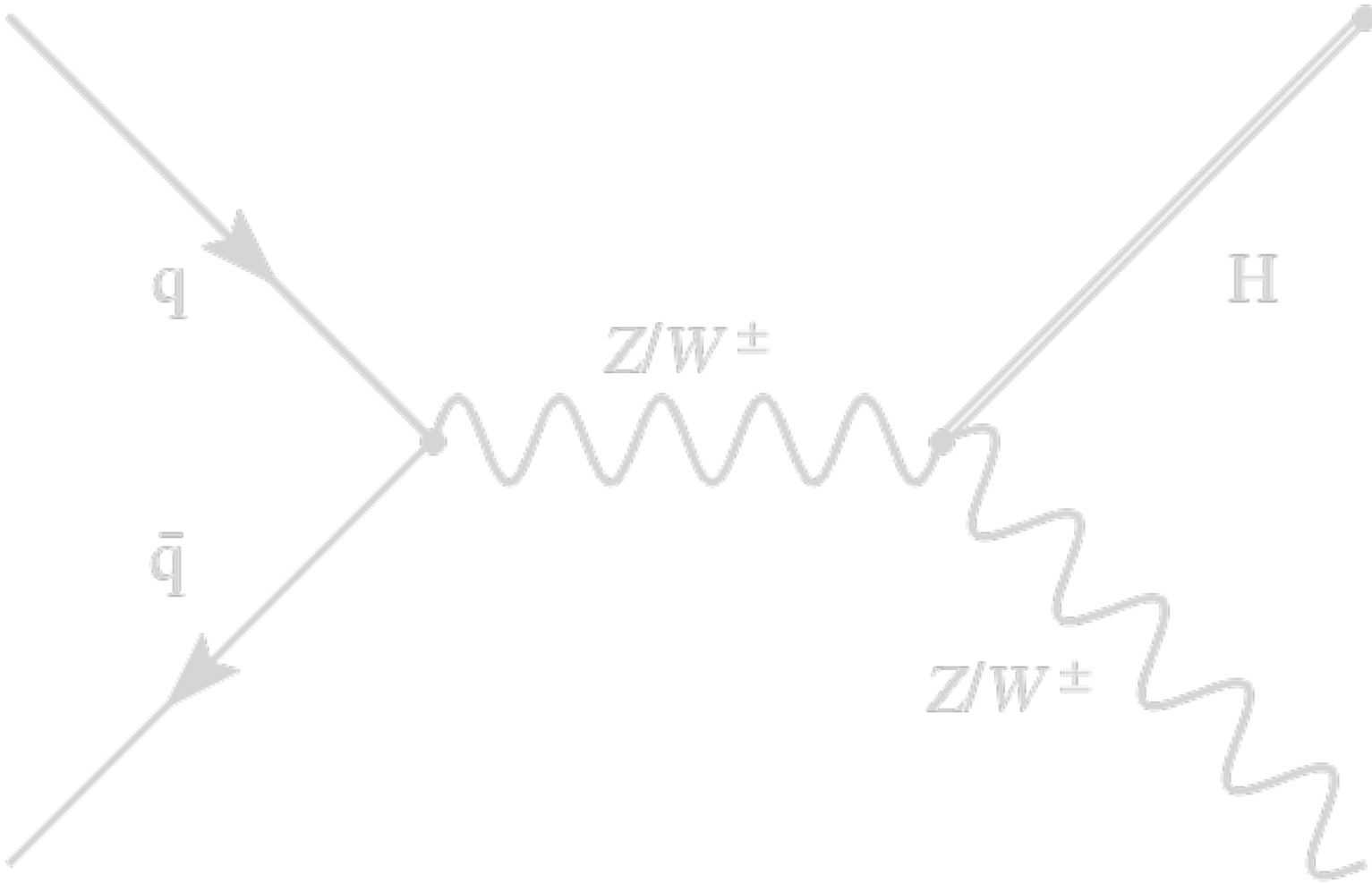
- 450 nuisances
- 30% improvement on bbγγ result alone for SM.
- The upper limit observed (expected) at 95% CL on the production cross section is

$$\sigma_{HH} = 21.8\,(12.4) \times \sigma_{HH}^{SM}$$





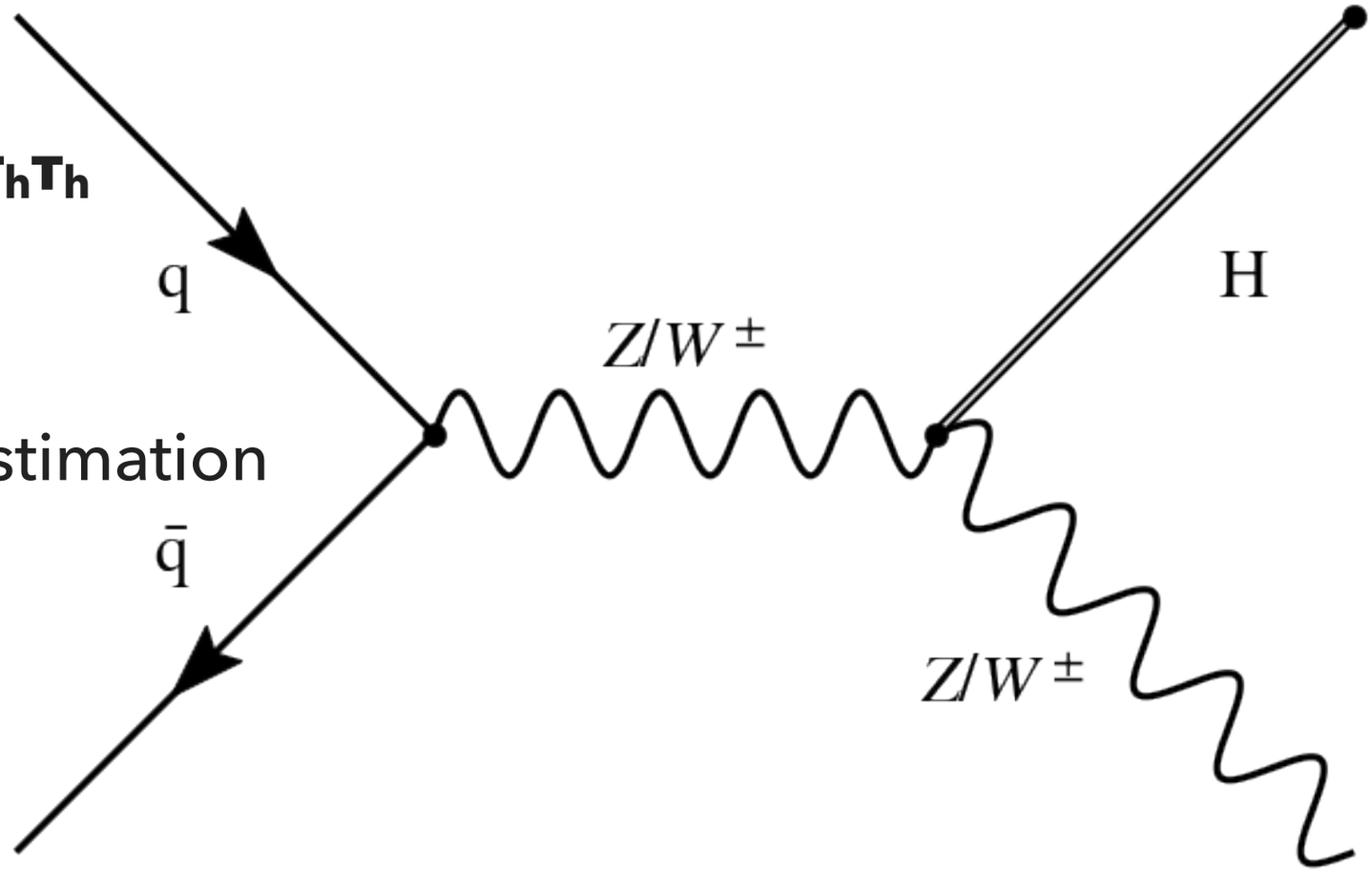
Run 2 - VH(→ττ)



VH, H(→ττ)

CMS-PAS-HIG-18-007

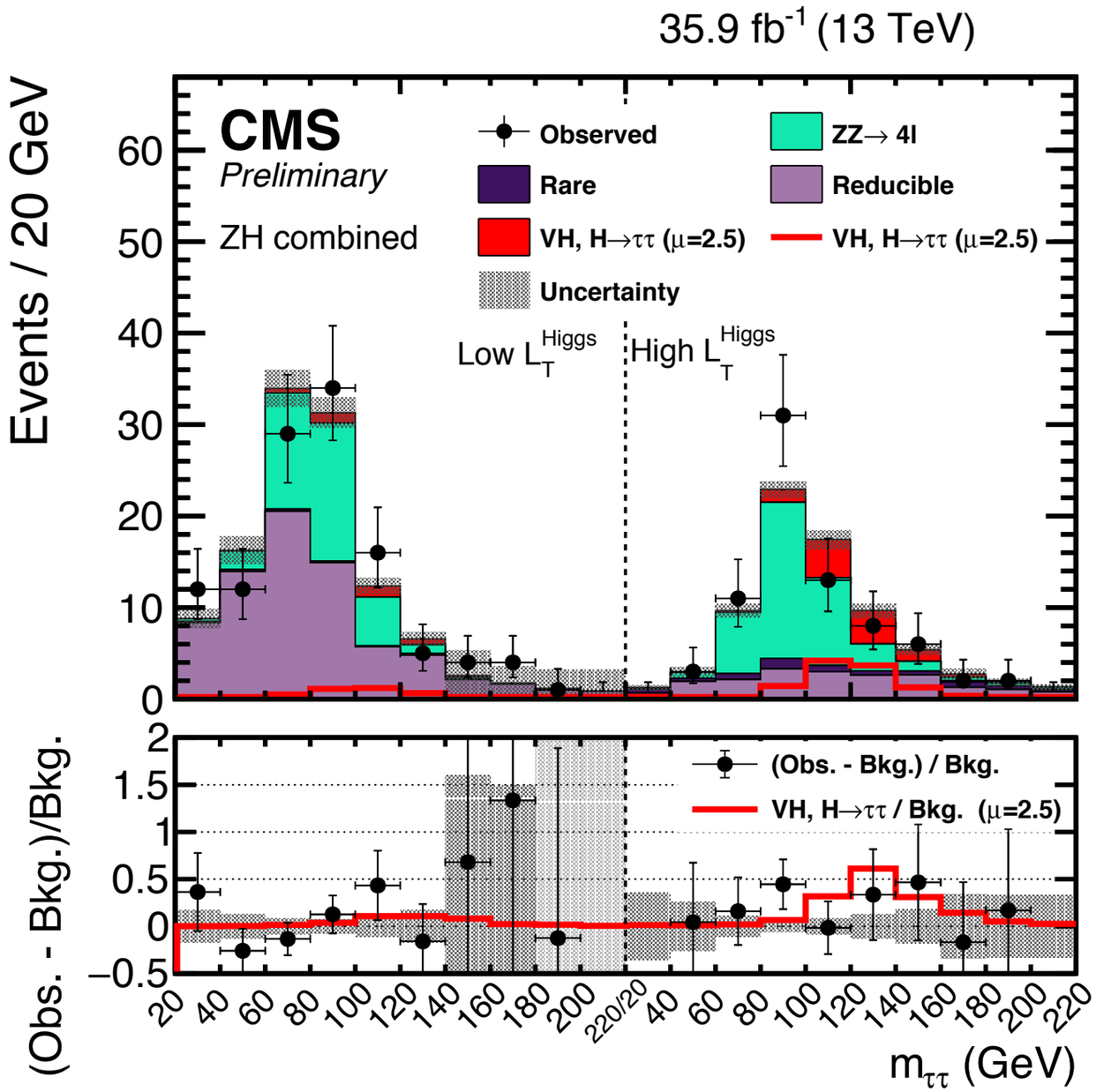
- VH production allows **directly and independently probe WH** and **ZH couplings**
- The H→ττ decay is the second most sensitive channel to establish VH production. It is the last missing piece for 2016 grand combination
- Multiple final states depending on decay mode of vector bosons and tau leptons (l= e, μ)
  - WH semi-leptonic: l**μτ$_h$**, l**τ$_h$τ$_h$**
  - ZH: ll**eμ**, ll**eτ$_h$**, ll**μτ$_h$**, ll**τ$_h$τ$_h$**,
- Data-Driven technique for estimation of fake contribution



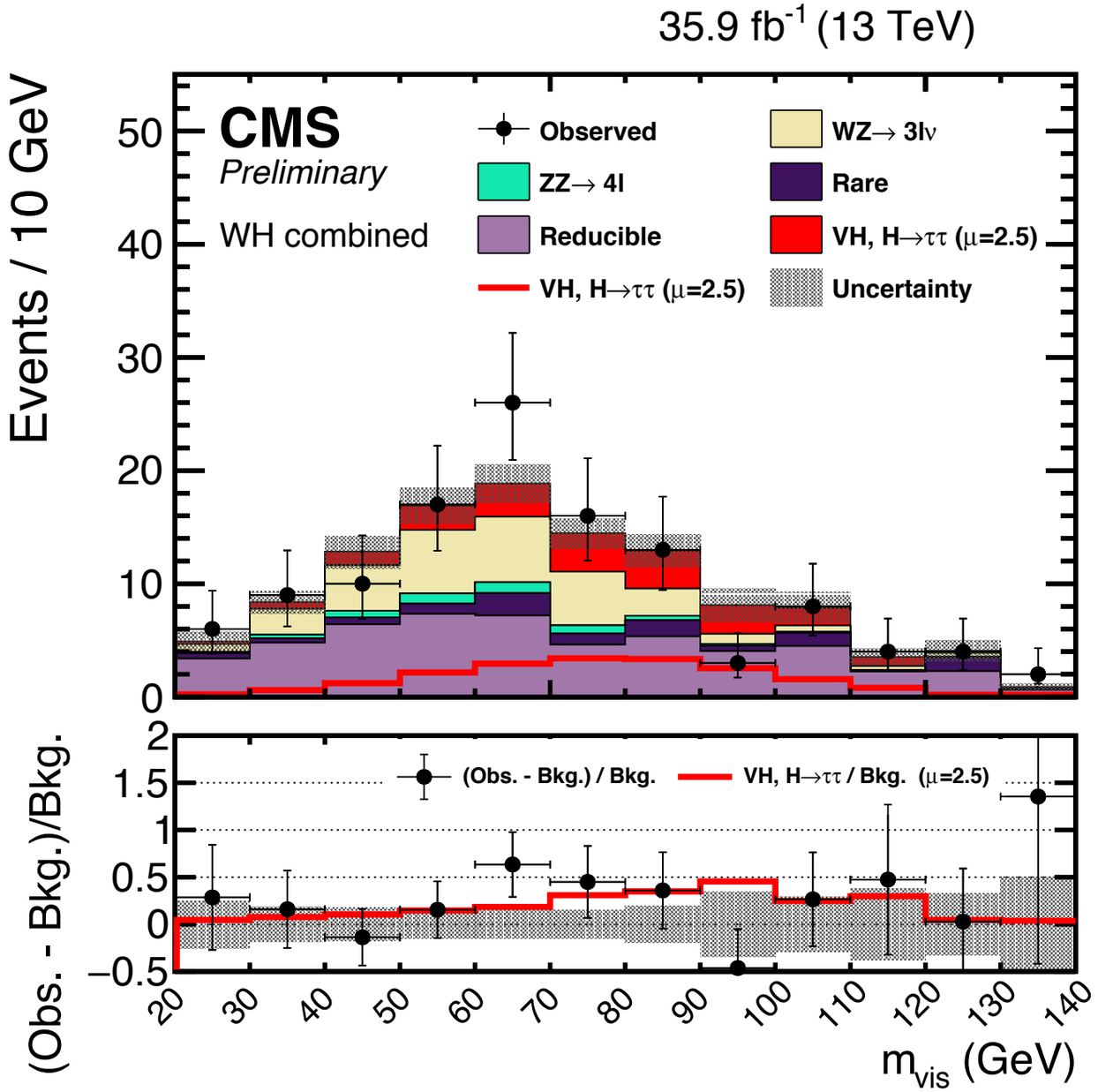
VH, H(→ττ)

CMS-PAS-HIG-18-007

ZH

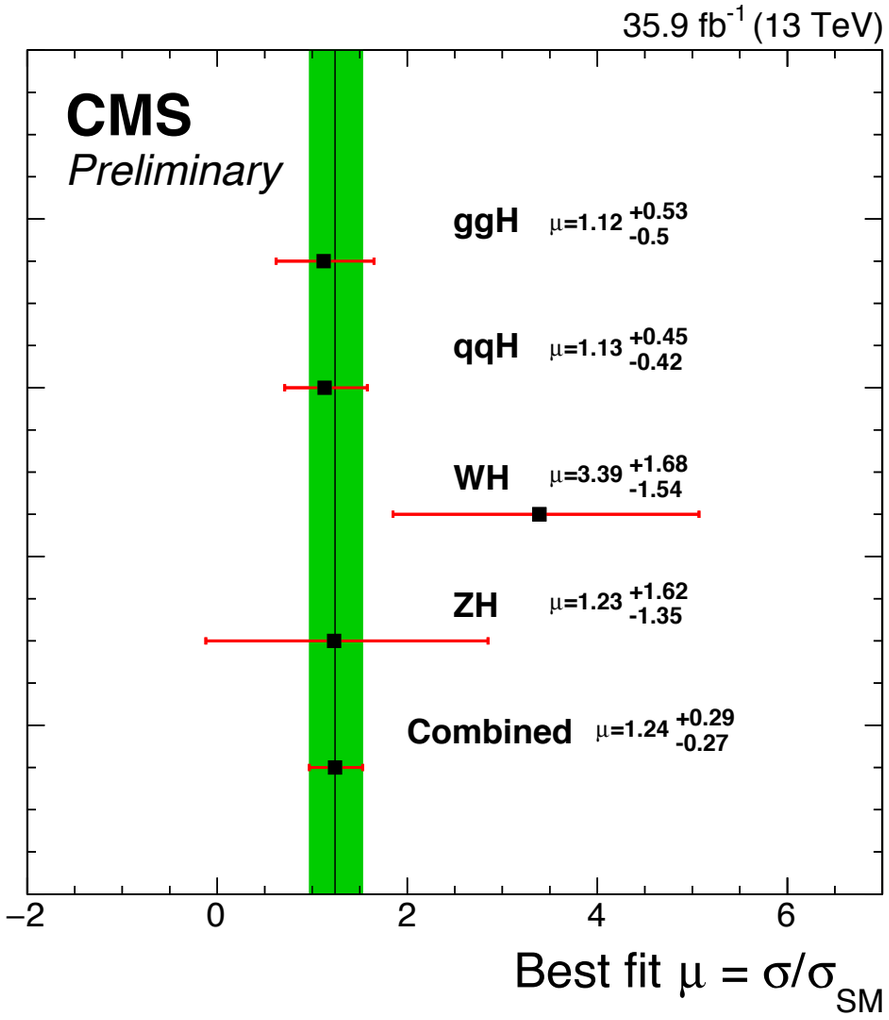


WH



VH, H(→ττ)

CMS-PAS-HIG-18-007

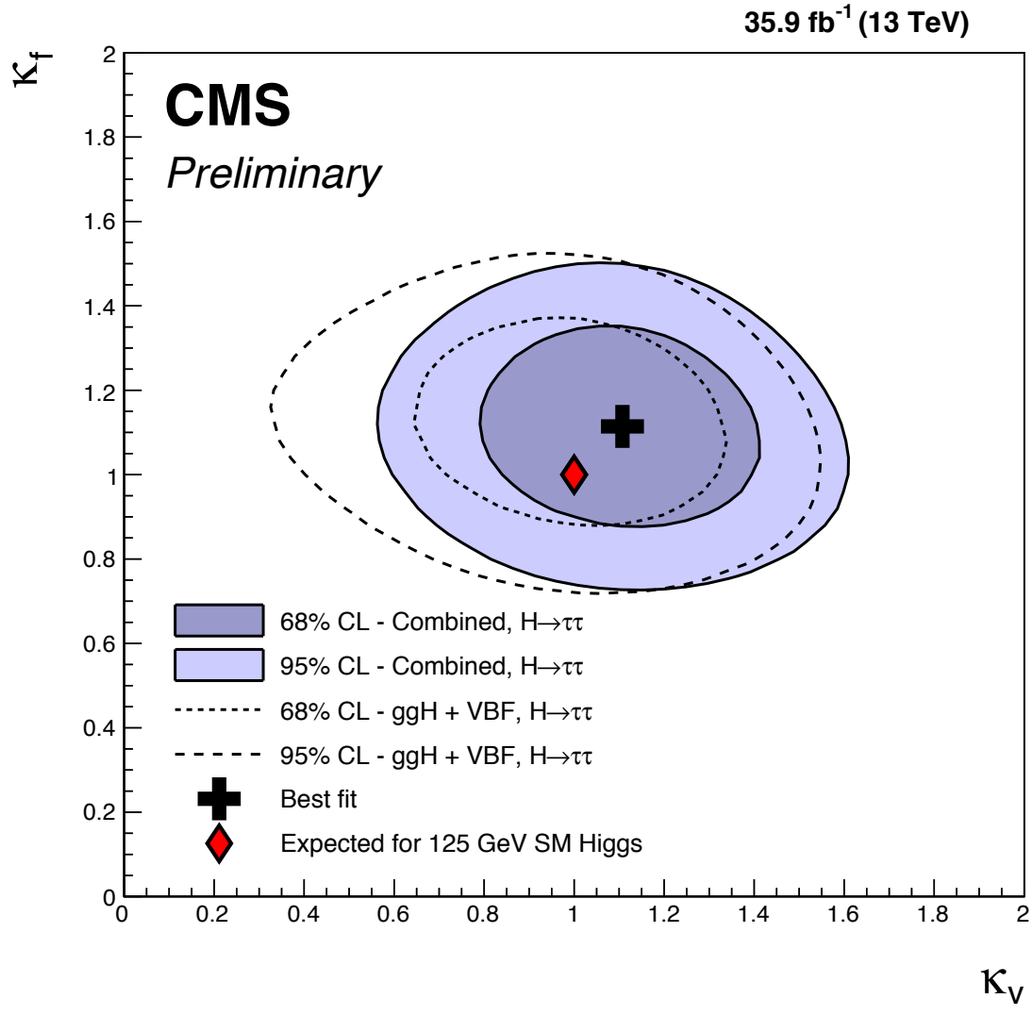


- The best-fit signal strength for VH

$$\mu = 2.54^{+1.35}_{-1.26} (\mu = 1.0^{+1.08}_{-0.97}\ exp.)$$

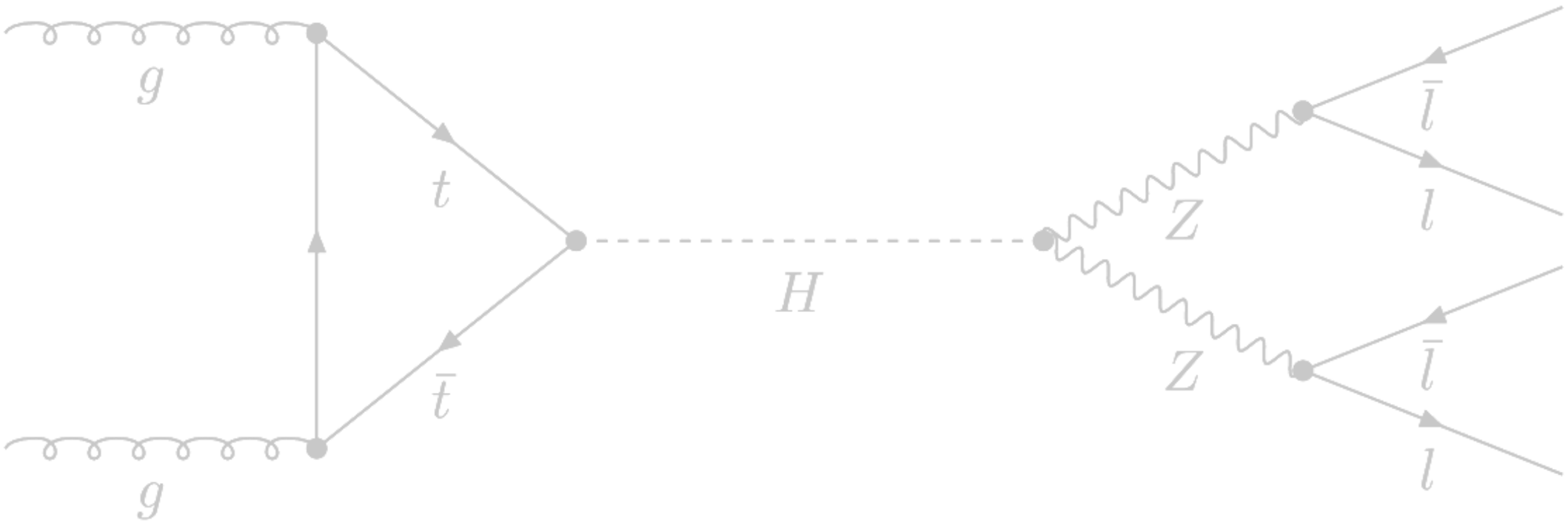
- Combining with ggH(ττ) and VBF-H(ττ) observed signal strength is

$$\mu = 1.24^{+0.29}_{-0.27}$$



- k_V-k_F scan for m_H = 125.09 GeV.
- Combination VH, ggH and VBF with H(ττ)
  - ggH+VBF dashed lines
- Better constrain on k_V

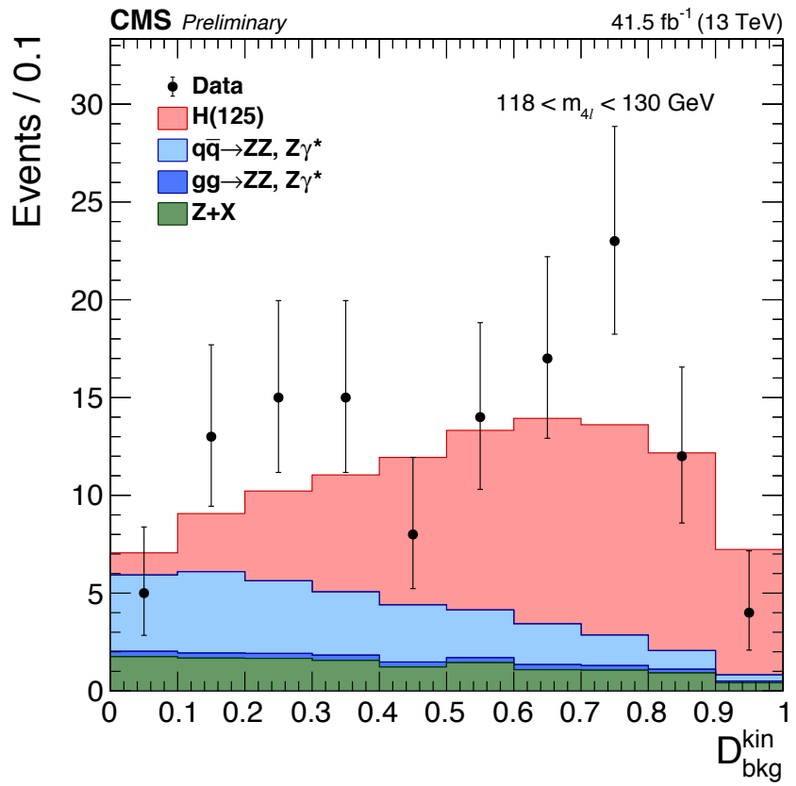
H→ZZ*→4l (2017 dataset)

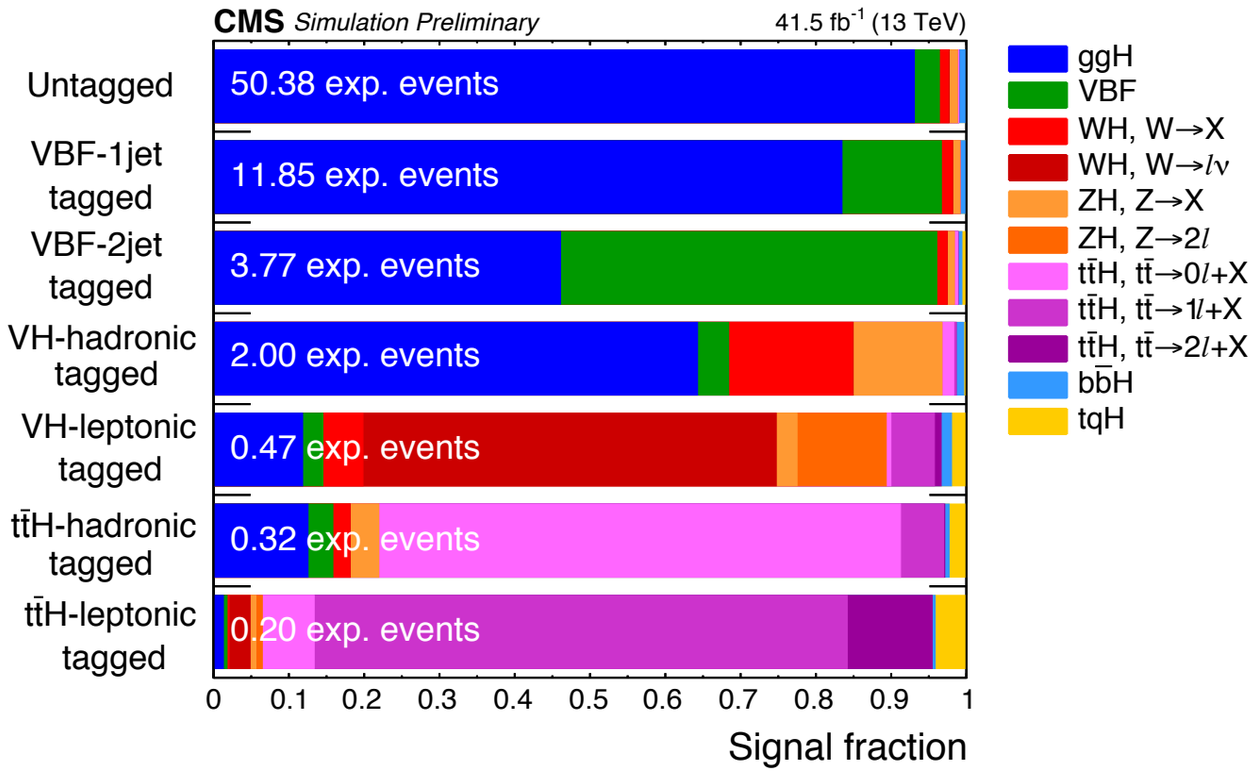


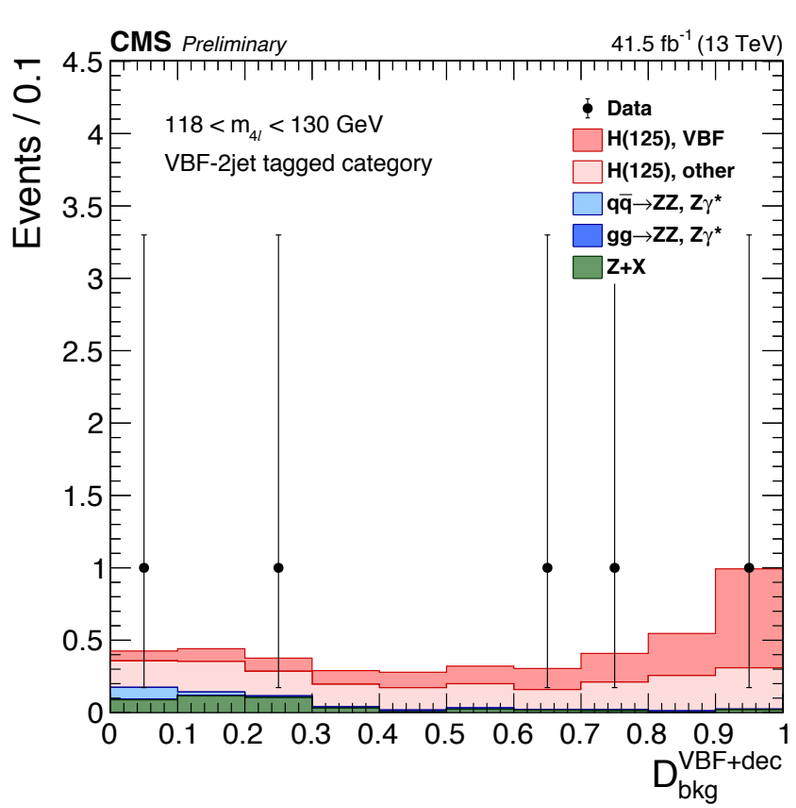
H→ZZ*→4l

CMS-PAS-HIG-18-001

- Low signal rate, but very clear signal topology over a small, flat background (mainly qqZZ, Z+jets)
  - 4 isolated leptons in final state combined in 2 Z pairs
  - Kinematical information (matrix element KD discriminants) to separate signal and backgrounds and categorised the events

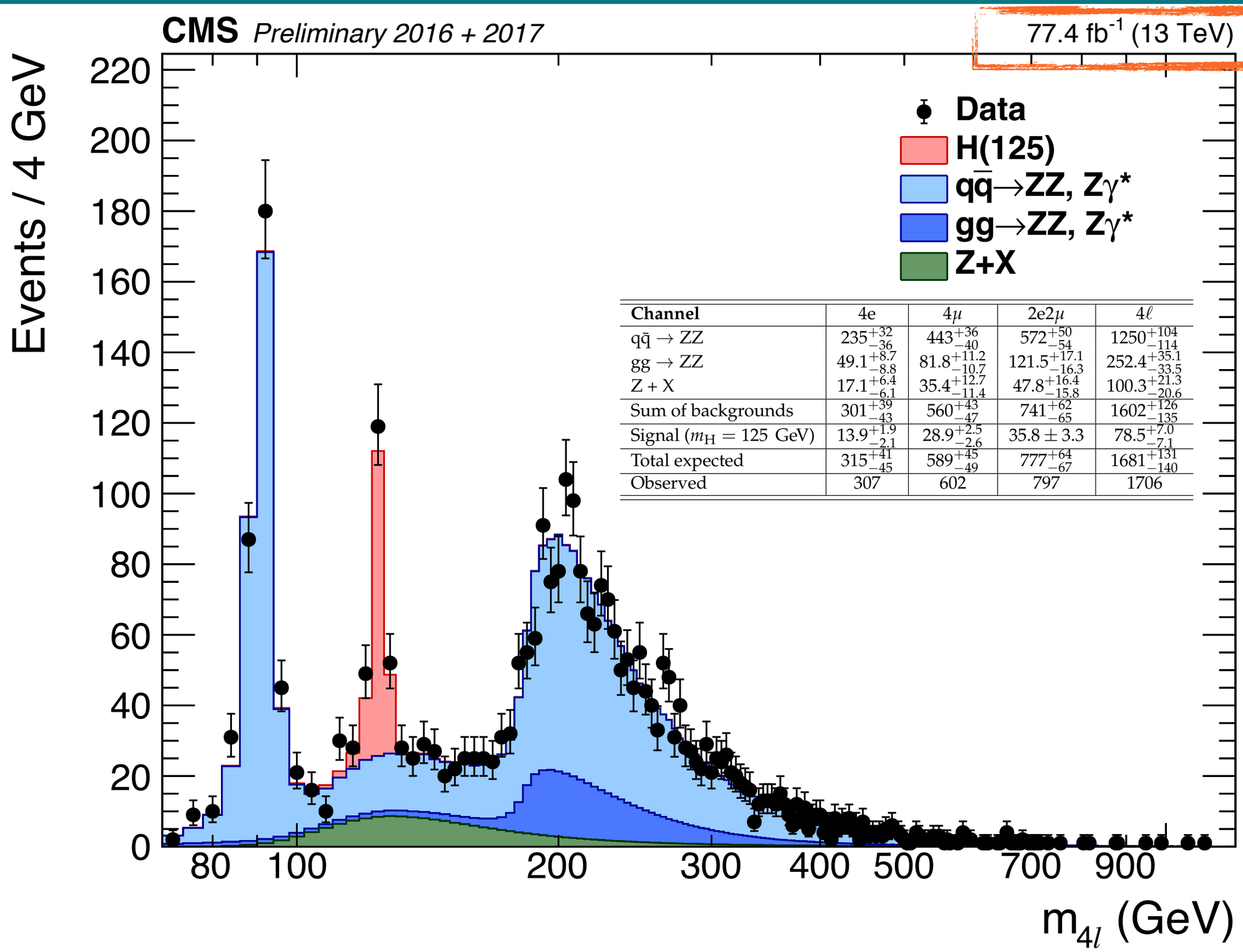






H→ZZ*→4l

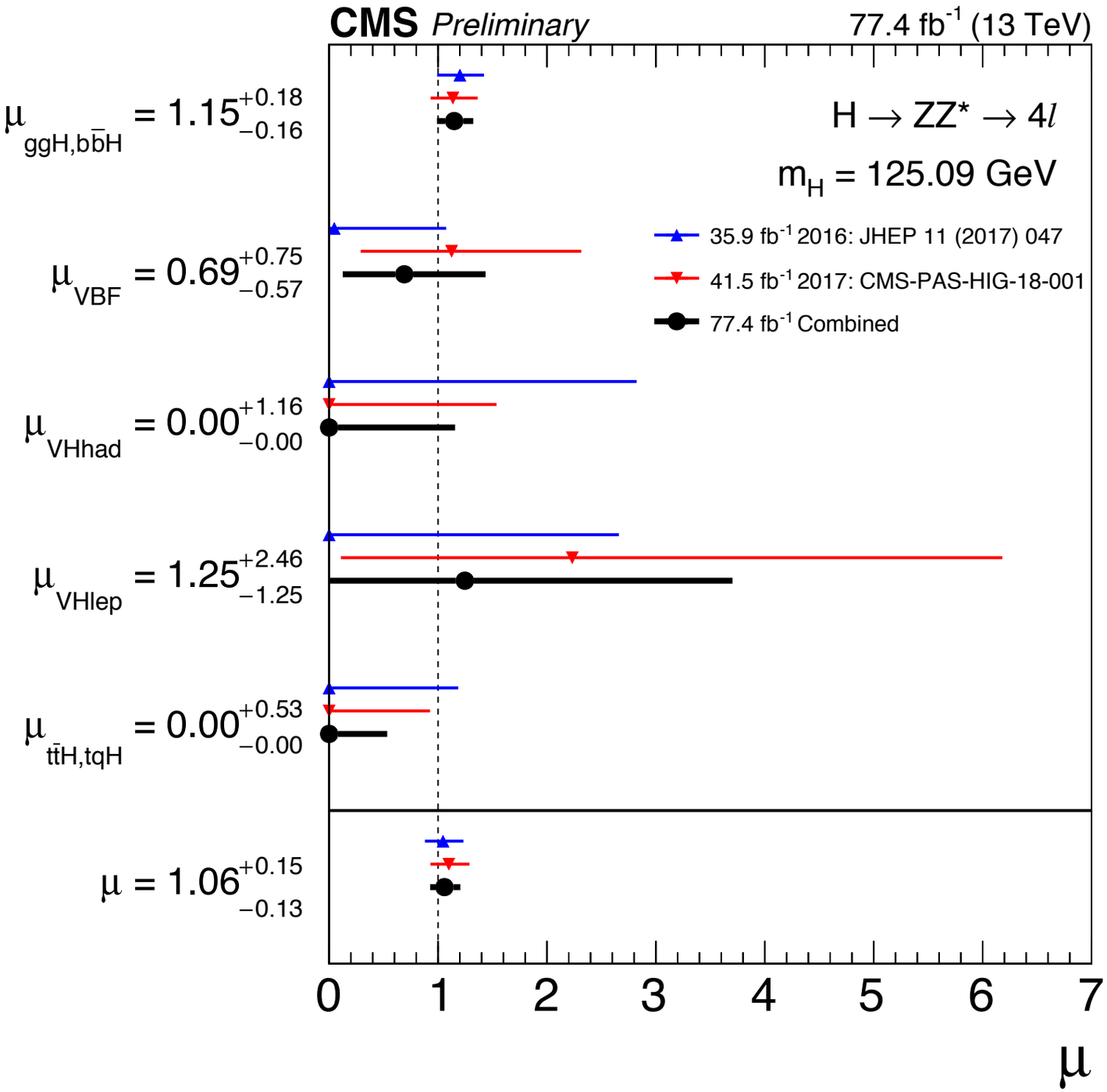
CMS-PAS-HIG-18-001



Channel	4e	4μ	2e2μ	4ℓ
$q\bar{q} \to ZZ$	235^{+32}_{-36}	443^{+36}_{-40}	572^{+50}_{-54}	1250^{+104}_{-114}
$gg \to ZZ$	$49.1^{+8.7}_{-8.8}$	$81.8^{+11.2}_{-10.7}$	$121.5^{+17.1}_{-16.3}$	$252.4^{+35.1}_{-33.5}$
$Z + X$	$17.1^{+6.4}_{-6.1}$	$35.4^{+12.7}_{-11.4}$	$47.8^{+16.4}_{-15.8}$	$100.3^{+21.3}_{-20.6}$
Sum of backgrounds	301^{+39}_{-43}	560^{+43}_{-47}	741^{+62}_{-65}	1602^{+126}_{-135}
Signal ($m_H = 125$ GeV)	$13.9^{+1.9}_{-2.1}$	$28.9^{+2.5}_{-2.6}$	35.8 ± 3.3	$78.5^{+7.0}_{-7.1}$
Total expected	315^{+41}_{-45}	589^{+45}_{-49}	777^{+64}_{-67}	1681^{+131}_{-140}
Observed	307	602	797	1706

H→ZZ*→4l

CMS-PAS-HIG-18-001



- Improvement for VBF production
- The measured signal strength modifier is

$$\mu = 1.10^{+0.19}_{-0.17}$$

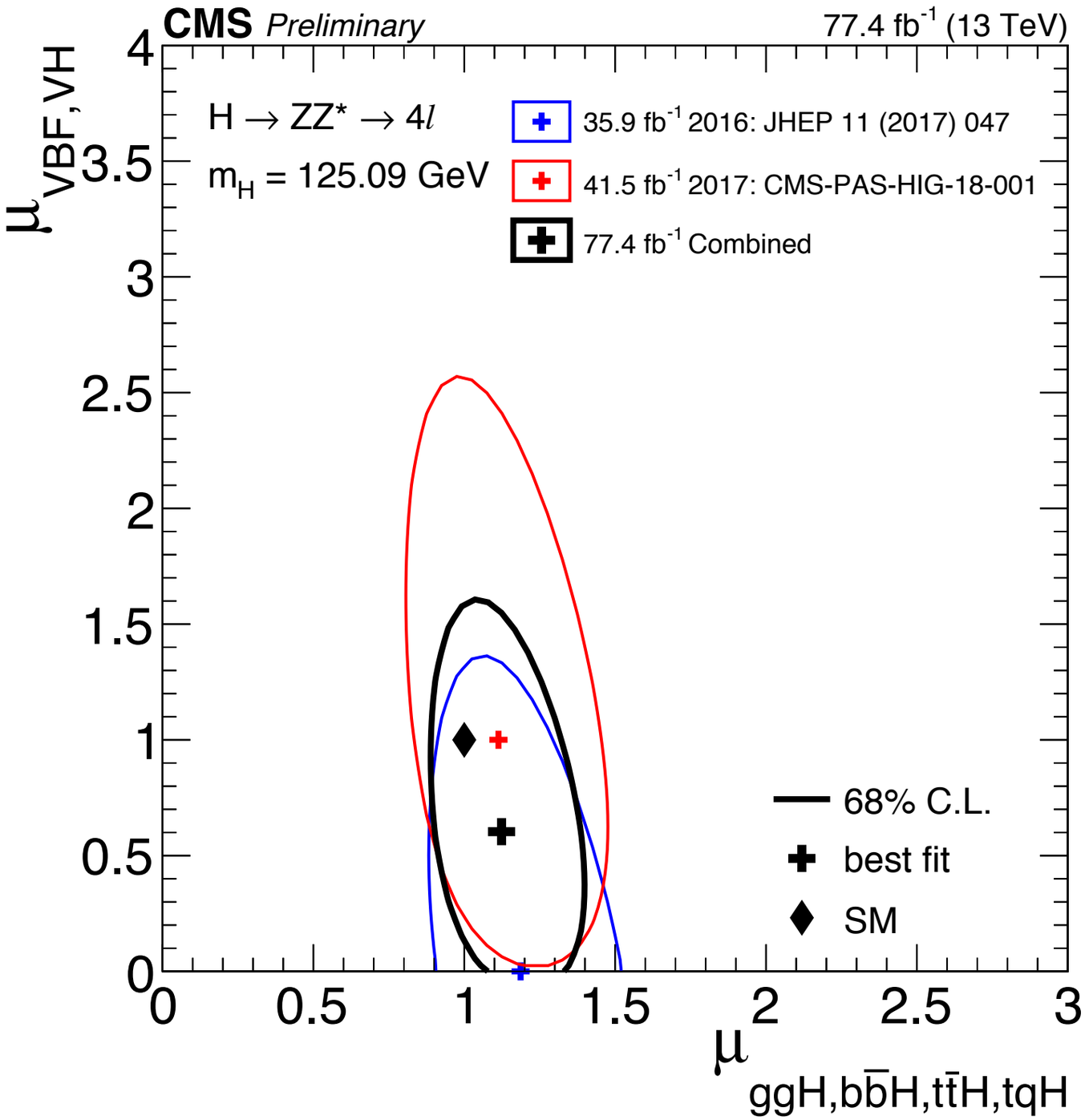
- Signal strength modifier combining 2016+2017 is:

$$\mu = 1.06^{+0.15}_{-0.13}$$

H→ZZ*→4l

CMS-PAS-HIG-18-001

- Measurements of signal strength modifiers associated with fermions and vector bosons are performed
- Better coverage in the 2017 analysis
- Improvement performing the combination



Conclusions

Conclusions

- From the **Run 1 data**, all **Higgs boson properties** are **consistent** with the expectations from the **standard model**
- A **combination** of all the results in the various Higgs boson channels can be **used to determine the Higgs boson couplings** to other particles.
- The **Run 2** data **significantly improve** the **precision** of the Higgs measurement performed during Run 1 and the **sensitivity** on the most rare processes.
  - ttH production is the channel that gains the most from the increased collision energy (Observation)
- With the **Run 2 full dataset** (around 150 fb^{-1}) the sensitivity of the **analyses dominated by statistical errors** will significantly **improve**.

Thank you for your attention

Backup

Higgs Boson Couplings

CMS-PAS-HIG-17-031

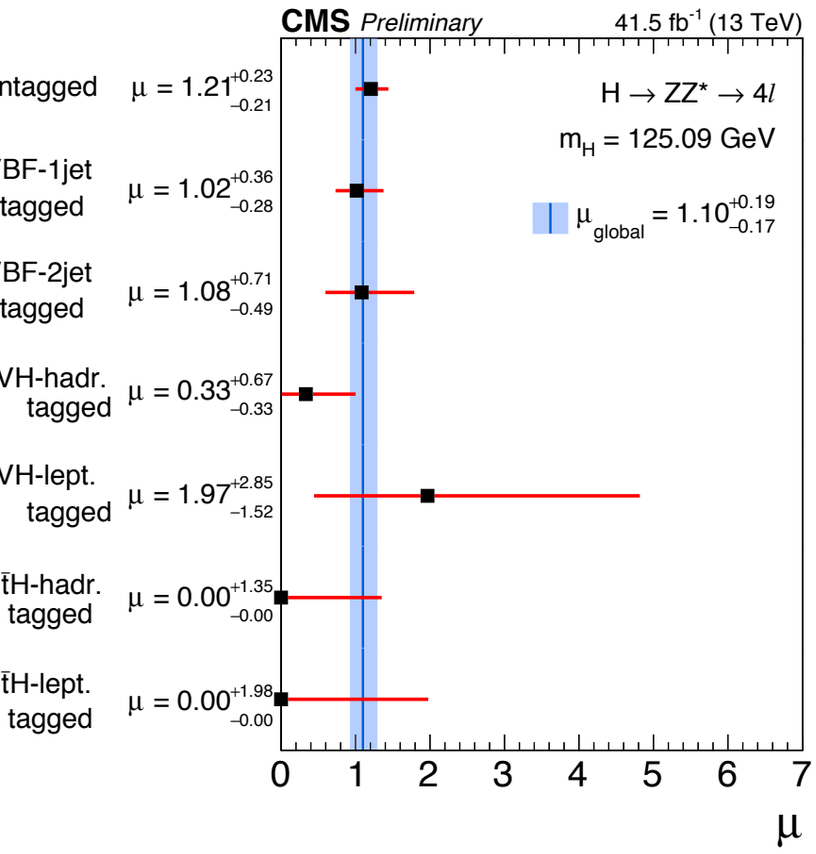
- Summary of how all production and decay processes scale as a function of the k parameters:

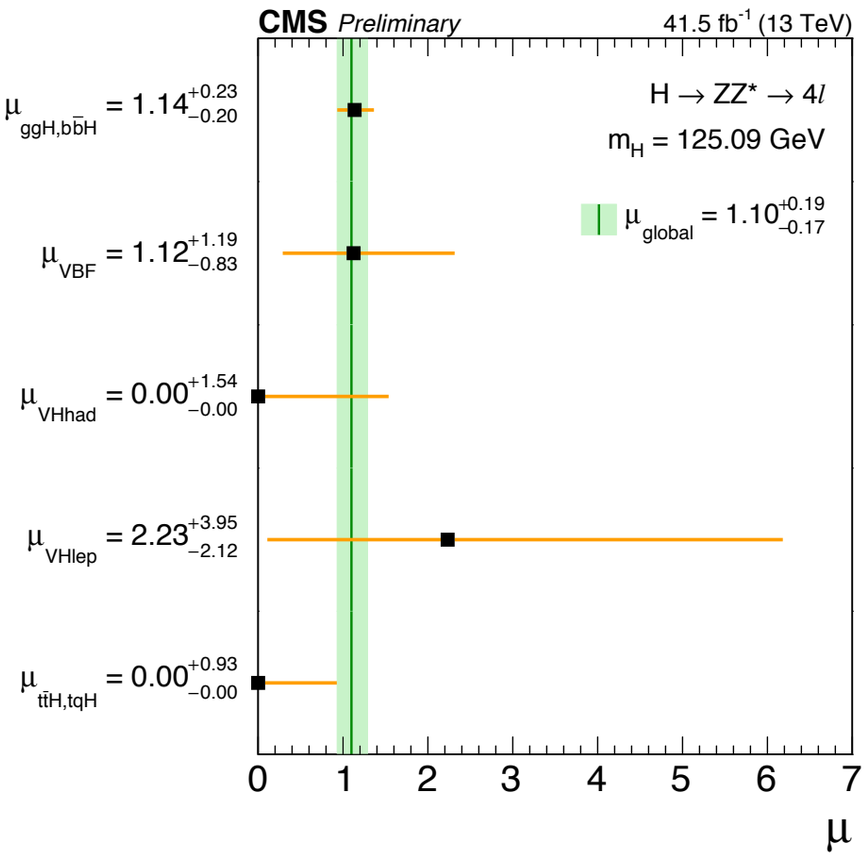
Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggH)$	✓	$b-t$	κ_g^2	$1.04\cdot\kappa_t^2+0.002\cdot\kappa_b^2-0.038\cdot\kappa_t\kappa_b$
$\sigma(VBF)$	–	–		$0.73\cdot\kappa_W^2+0.27\cdot\kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg\to ZH)$	–	–		κ_Z^2
$\sigma(gg\to ZH)$	✓	$Z-t$		$2.46\cdot\kappa_Z^2+0.47\cdot\kappa_t^2-1.94\cdot\kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb\to WtH)$	–	$W-t$		$2.91\cdot\kappa_t^2+2.40\cdot\kappa_W^2-4.22\cdot\kappa_t\kappa_W$
$\sigma(qb\to tHq)$	–	$W-t$		$2.63\cdot\kappa_t^2+3.58\cdot\kappa_W^2-5.21\cdot\kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W-t$	κ_γ^2	$1.59\cdot\kappa_W^2+0.07\cdot\kappa_t^2-0.67\cdot\kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width for $BR_{BSM}=0$				
Γ_H	✓	–	κ_H^2	$0.58\cdot\kappa_b^2+0.22\cdot\kappa_W^2+0.08\cdot\kappa_g^2+$ $+0.06\cdot\kappa_\tau^2+0.026\cdot\kappa_Z^2+0.029\cdot\kappa_c^2+$ $+0.0023\cdot\kappa_\gamma^2+\ 0.0015\cdot\kappa_{Z\gamma}^2+$ $+0.00025\cdot\kappa_s^2+0.00022\cdot\kappa_\mu^2$

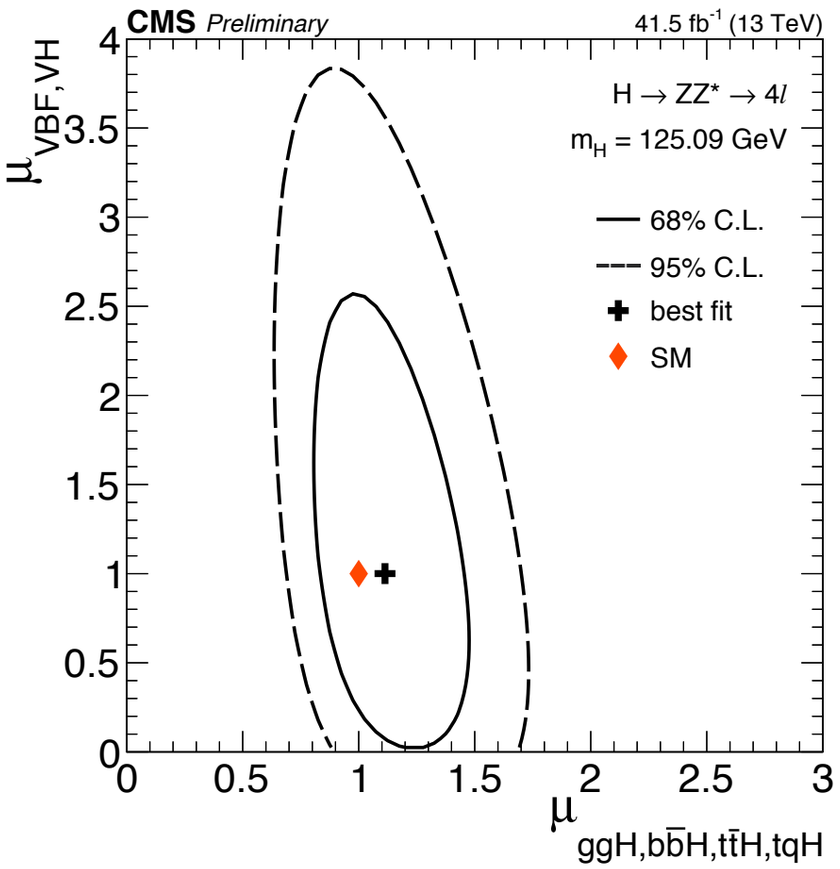
H→ZZ*→4l

CMS-PAS-HIG-18-001

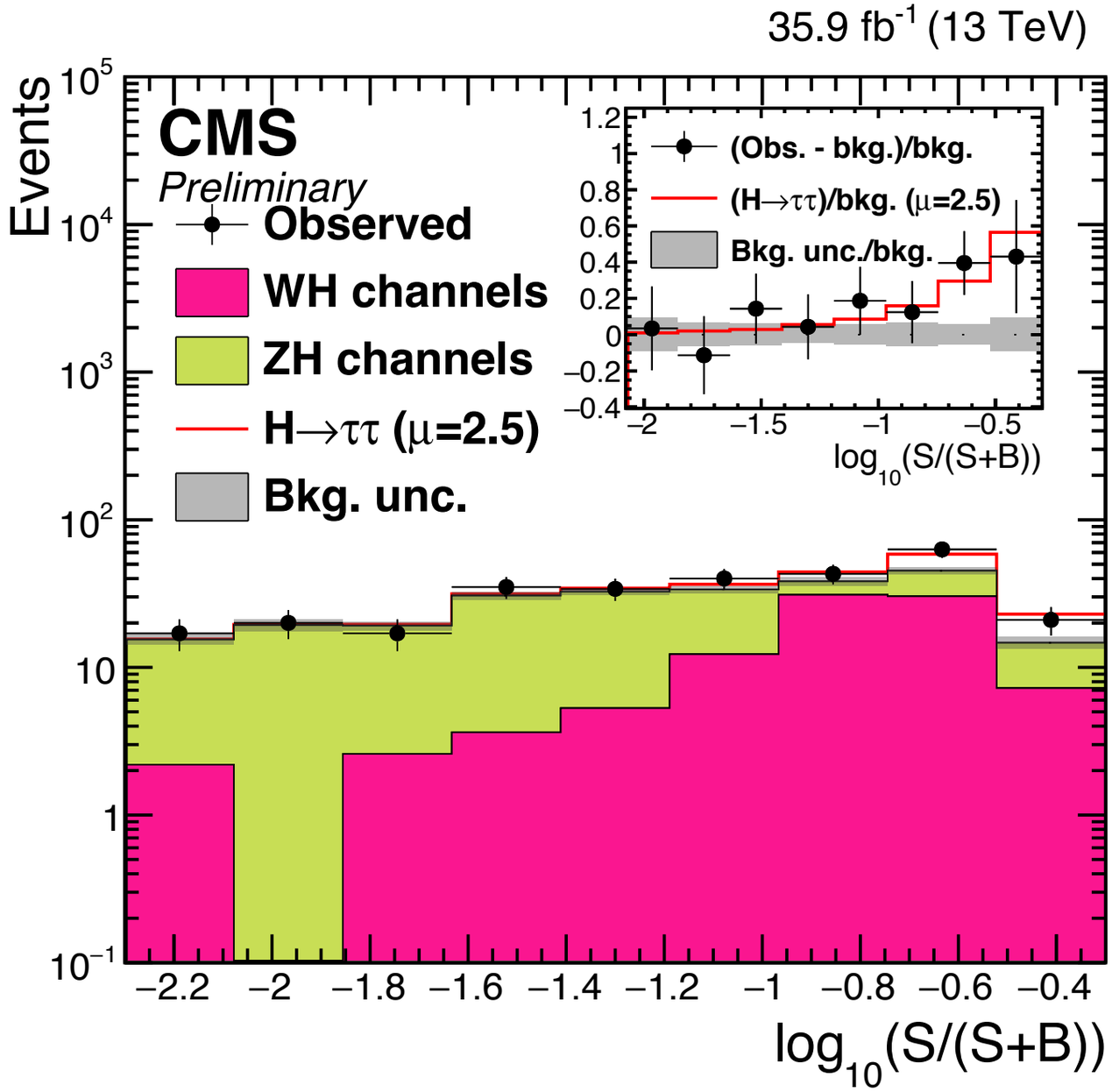
- The measured signal strength modifier is $\mu = 1.10^{+0.19}_{-0.17}$
- Measurements of signal strength modifiers associated with fermions and vector bosons are performed







VH, H(→ττ)

CMS-PAS-HIG-18-007

- significance of 2.3 standard deviations (1.0 expected)
- Combining this analysis with the analysis ggH(ττ) and VBF-H(ττ) observed significance is 5.5 standard deviations (4.8 expected)