MEASUREMENTS OF THE HIGGS H(125) BOSON AT CMS

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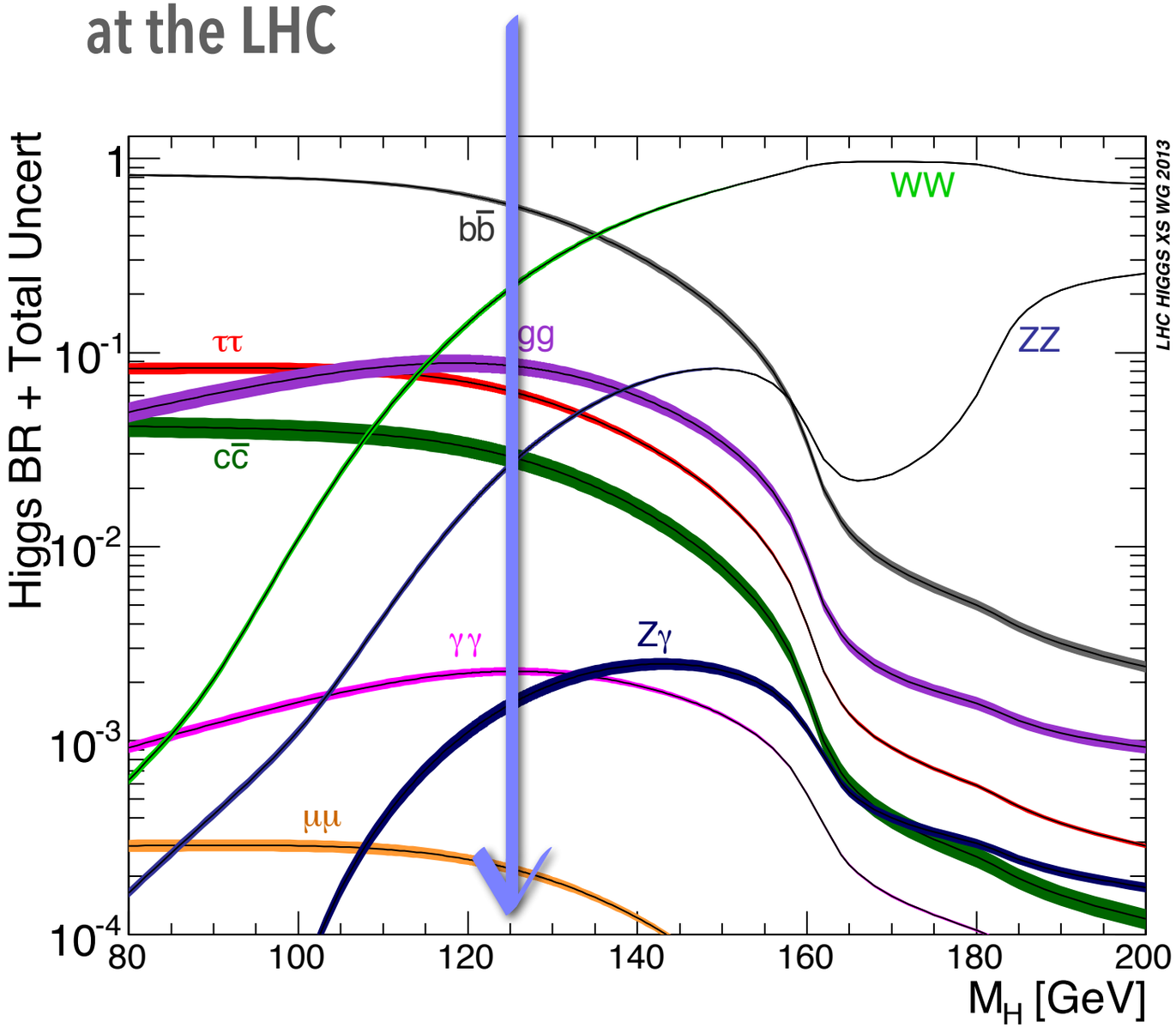
on behalf of the CMS Collaboration

International Conference on New Frontiers in Physics - Crete, 17-26 August 2017

INTRODUCTION

- Discovery of the Higgs H(125) boson five years ago by ATLAS and CMS
- Mass of 125 GeV makes it possible to experimentally probe many decay modes at the LHC



- Large number of analyses in Higgs physics
  - to characterise the discovered particle
  - to search for additional Higgs bosons

IN THIS TALK…

- Overview of the most recent results from CMS on the "standard-model-like" Higgs boson H(125)
  - Made a selection of the most recent results @ 13 TeV
  - There are many more: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

- In other dedicated talks:
  - Higgs properties (mass, spin, width…)
  - Searches for double Higgs, rare, exotic and LFV decays, low mass Higgs
  - Prospects at HL-LHC

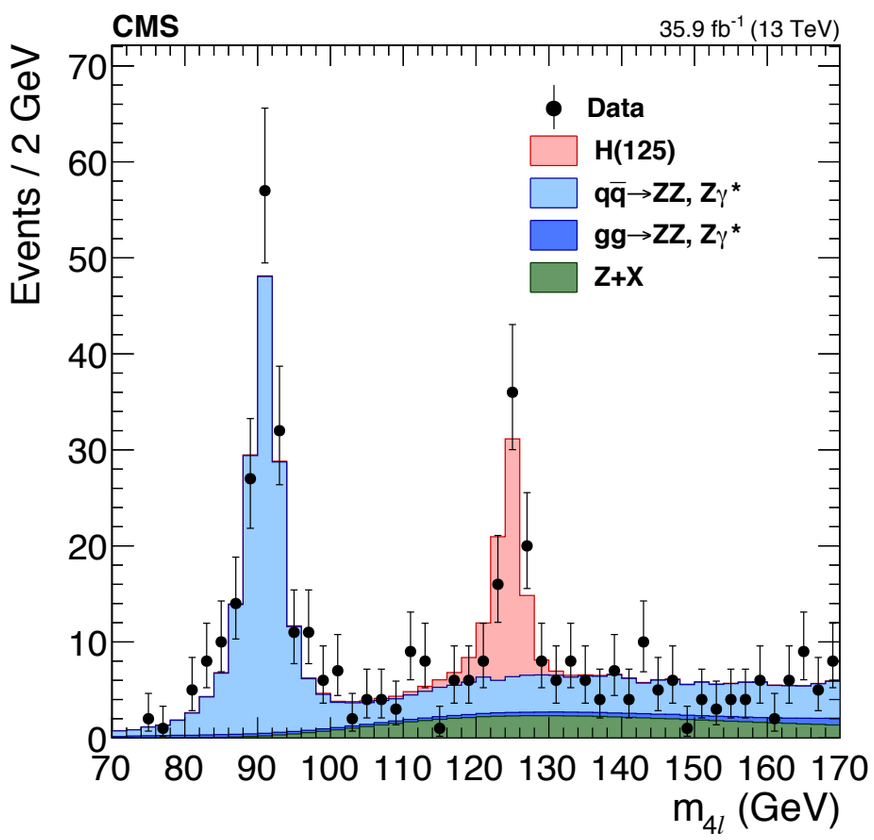
OUTLINE

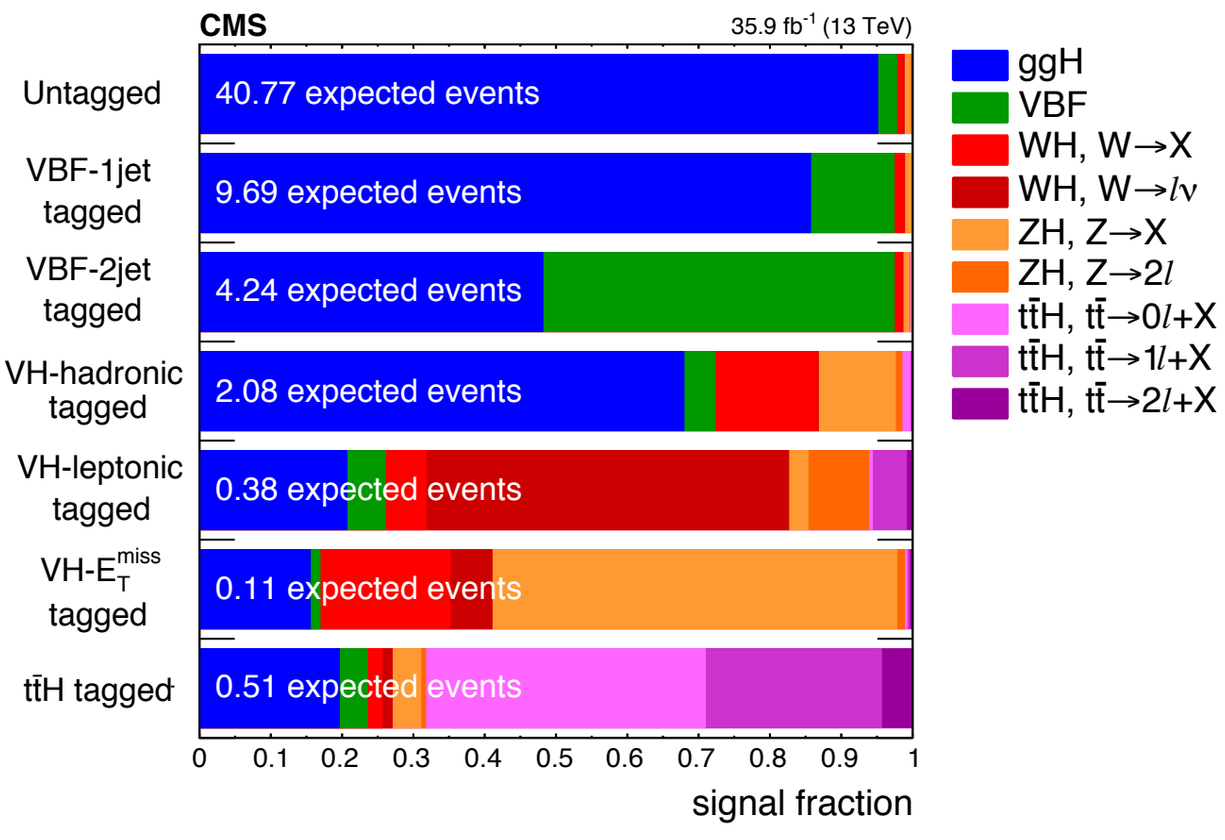
- Overview of the most recent results from CMS on the Higgs boson H(125).
  All results on pp-collisions data at $\sqrt{s}$ =13 TeV

Analysis	Luminosity	Reference	Status
H(ZZ)	35.9/fb	arXiv:1706.09936	Submitted to JHEP
H($\gamma\gamma$)	35.9/fb	CMS-PAS-HIG-17-015 CMS-PAS-HIG-16-040	Preliminary
H($\tau\tau$)	35.9/fb	arXiv:1708.00373	Submitted to PLB
VH(bb)	35.9/fb	CMS-PAS-HIG-16-044	Preliminary
H(bb) boost.	35.9/fb	CMS-PAS-HIG-17-010	Preliminary
ttH, leptons	35.9/fb	CMS-PAS-HIG-17-004	Preliminary
ttH, H($\tau\tau$)	35.9/fb	CMS-PAS-HIG-17-003	Preliminary (backup)
tHq, leptons	35.9/fb	CMS-PAS-HIG-17-005	Preliminary

H(ZZ) arXiv:1706.09936

- Four-lepton final states (4μ, 4e, 2μ2e), allowing full and precise reconstruction of the event kinematics
- Analysis based on kinematic discriminants using matrix element techniques
- New dedicated categories to target VBF, VH and ttH production, still limited in stat.
- Irreducible background is ZZ production (from simulation) , Z+jets and ttbar from data





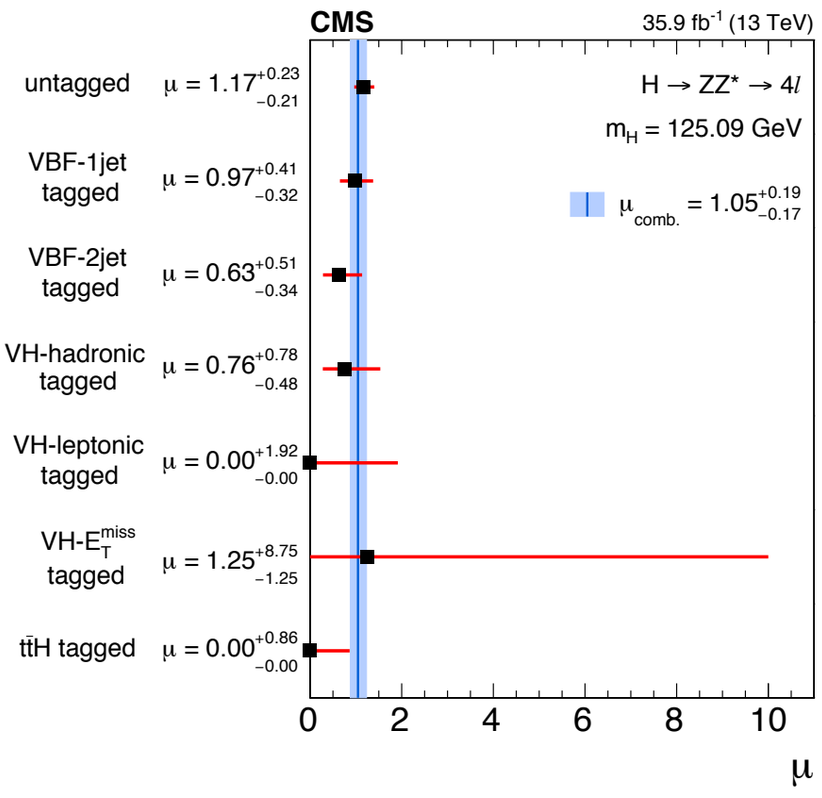
H(ZZ)

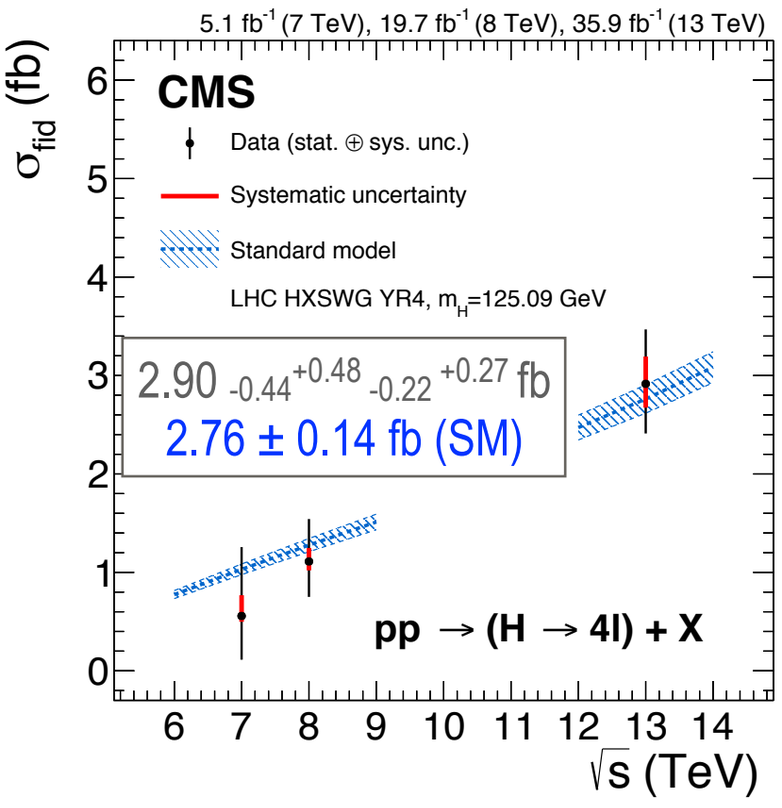
arXiv:1706.09936

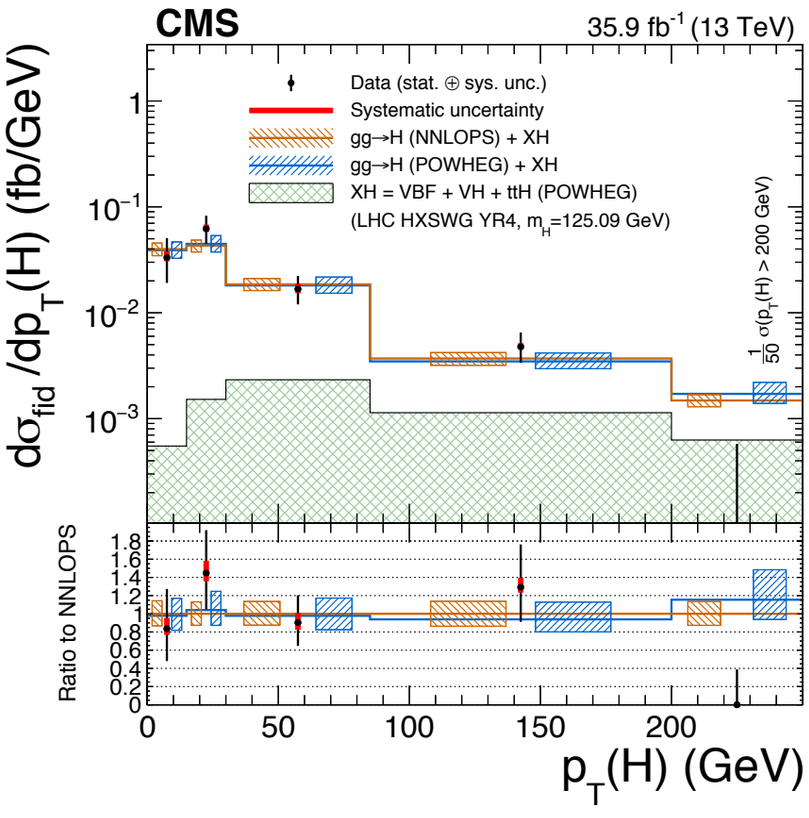
- Signal extracted from 2D likelihood fit $L = L(m_{4\ell})L(D^{kin}_{bkg} \mid m_{4\ell})$
- Signal strength

  $\mu = 1.05 \pm 0.18$
- Fiducial cross section

  (not using D^{kin}_{bkg}, no categories for prod. mode)
- Differential cross section







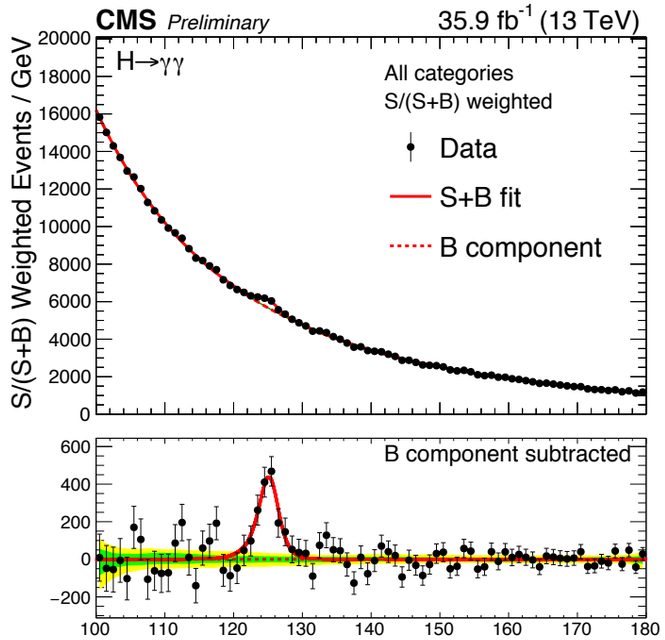
also N(jets) and p_T(jet)

- Results in good agreement with the predictions

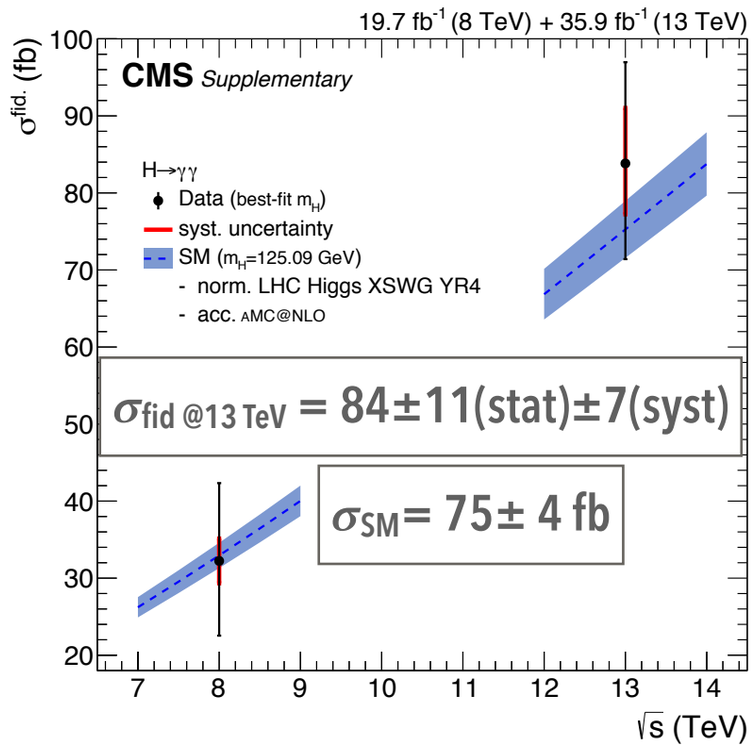
H(γγ)

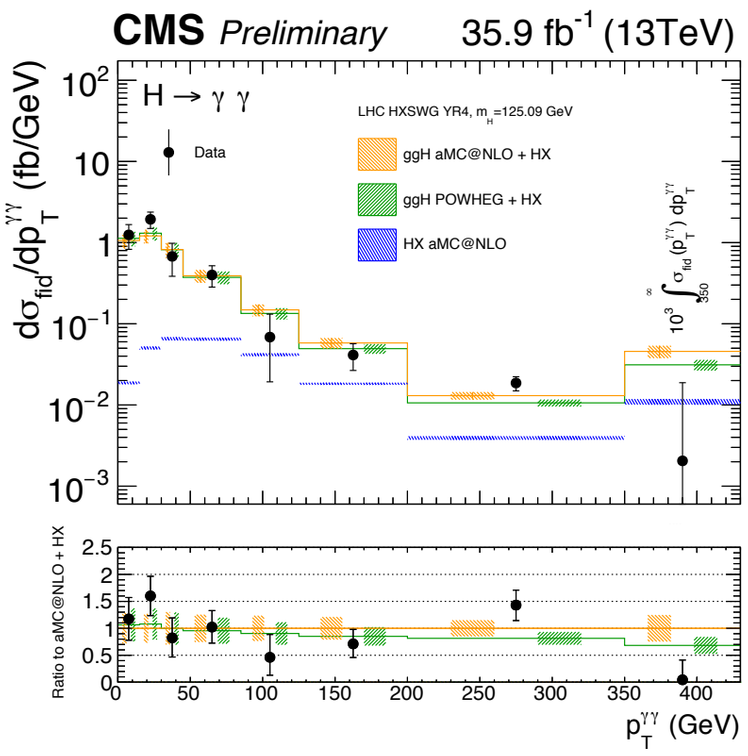
CMS-PAS-HIG-17-015

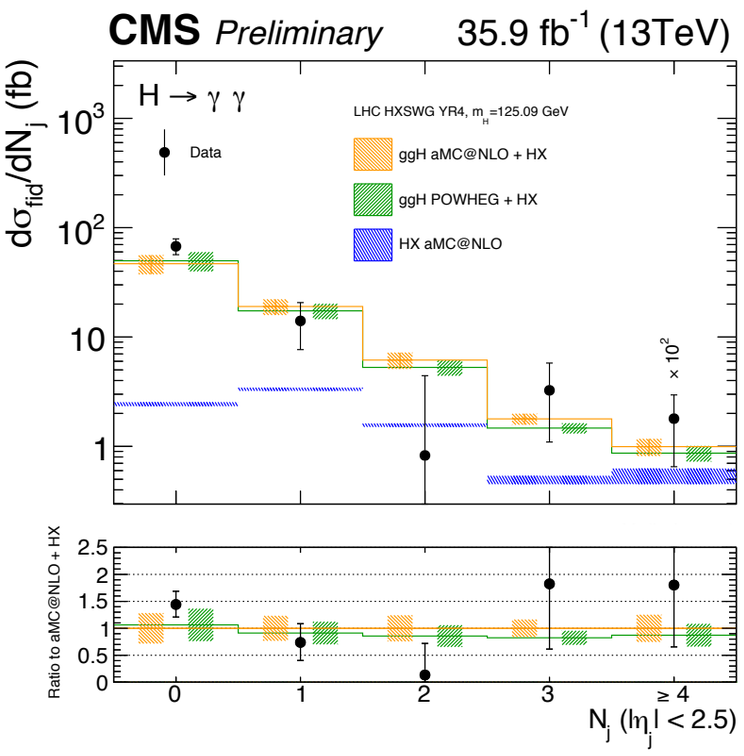
- Low branching ratio but very clean and high resolution
- Three event categories based on estimated mass resolution
- Fiducial cross sections, total and differential
  - $|\eta|<2.5$, $p_T/m_{\gamma\gamma} <1/3(1/4)$, signal acceptance = 0.60
- Results in good agreement with the predictions
  - Limited by statistics



Most precise measurement

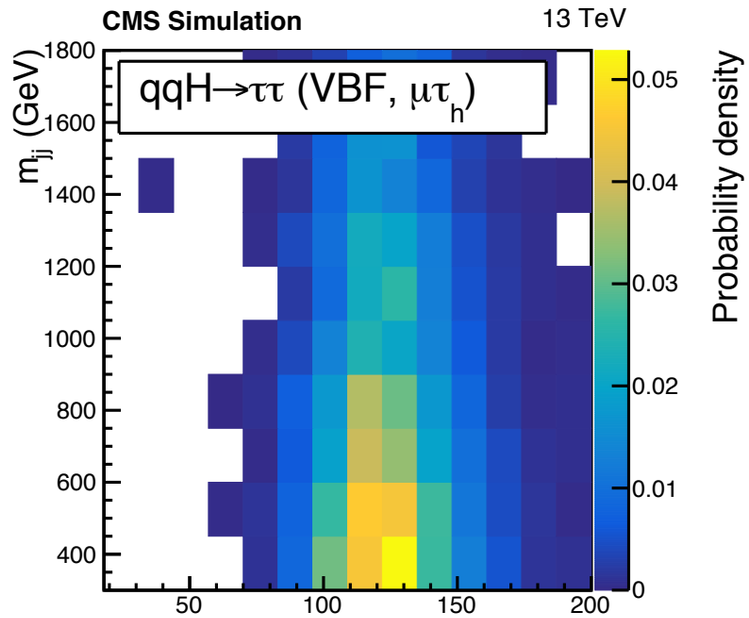


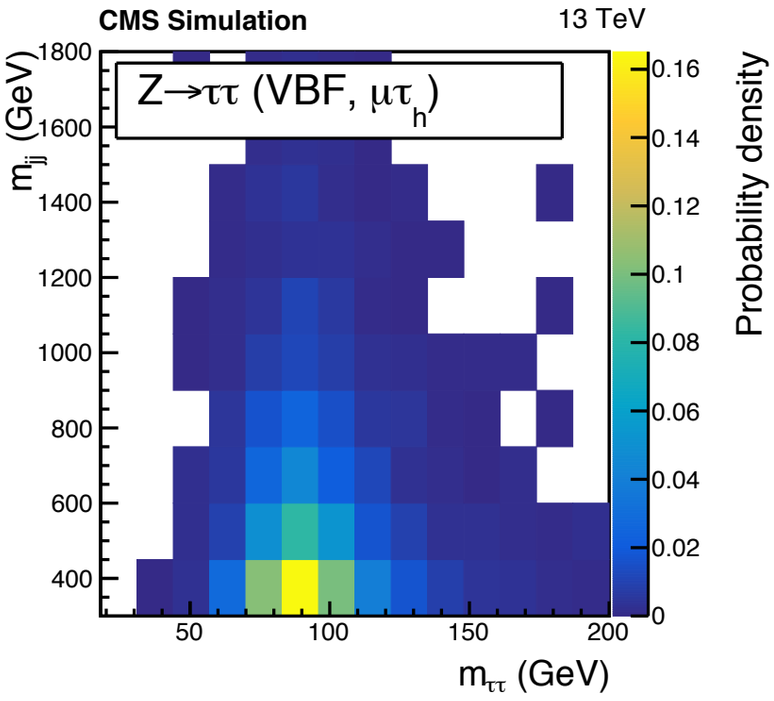




H($\tau\tau$) arXiv:1708.00373

- Most promising channel to probe direct Higgs Yukawa coupling to fermions
- Most likely final states for $\tau\tau$ pairs: $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$.
  - Tau ID eff. ~ 60% for 1% jet→τ_h fakes (CMS-PAS-TAU-16-002)
- Targeting VBF and ggH production
- ML fit to 2D distributions in three categories (0jet, VBF, Boosted)
- Irreducible background is Z($\tau\tau$), from MC with corrections
- Several control regions included in the fit to constraint bkg. normalisation from data (ttbar, QCD, W+jets)

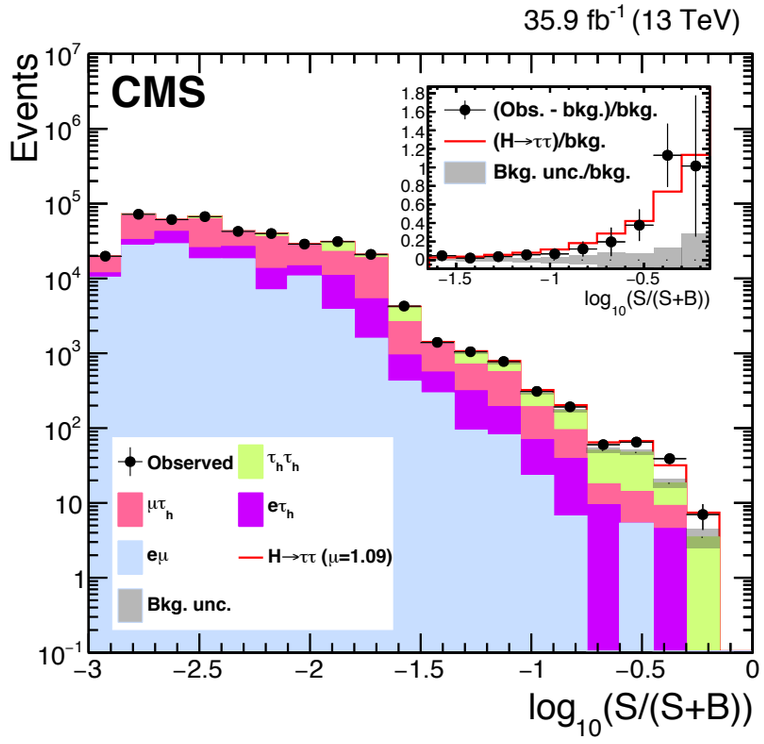


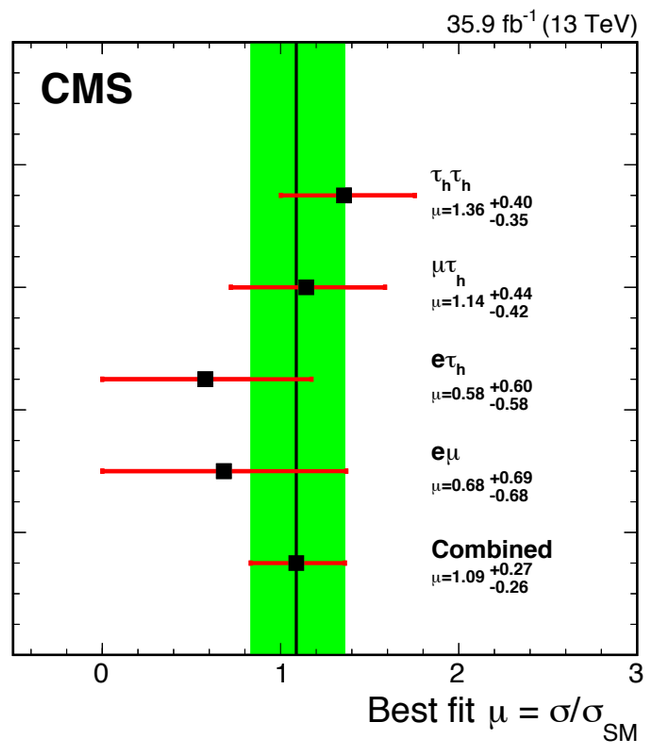


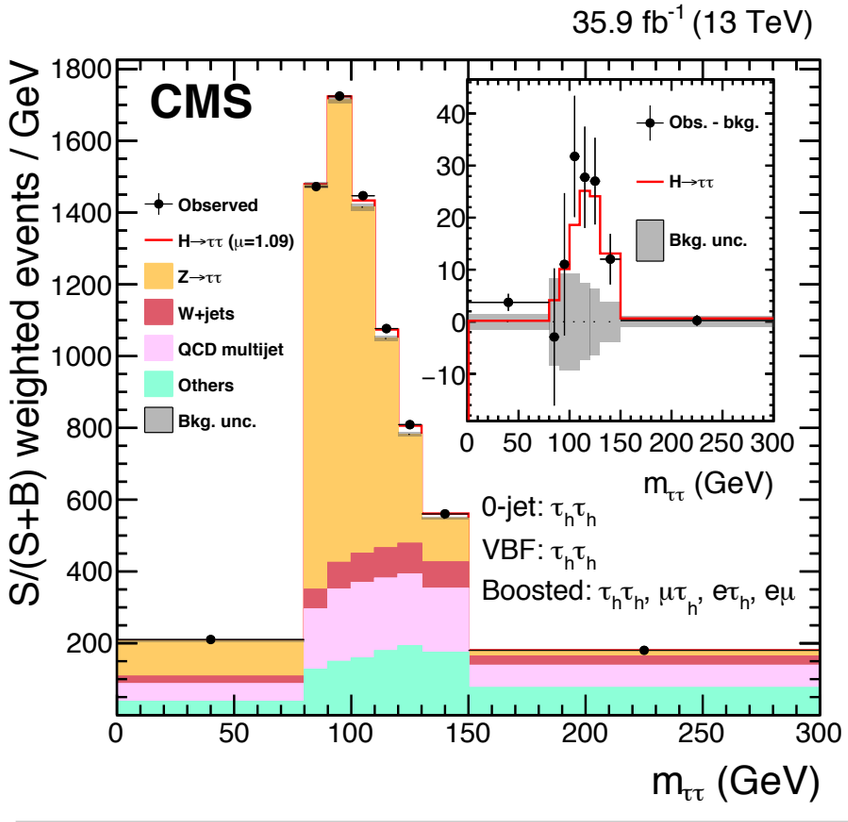
H($\tau\tau$)

arXiv:1708.00373

- Observed excess of events with significance 4.9 (4.7 exp.) σ
- Signal strength $\mu = 1.09 \pm 0.27$
  - Uncertainty dominated by statistics
  - Experimental uncertainties dominated by hadronic tau reconstruction





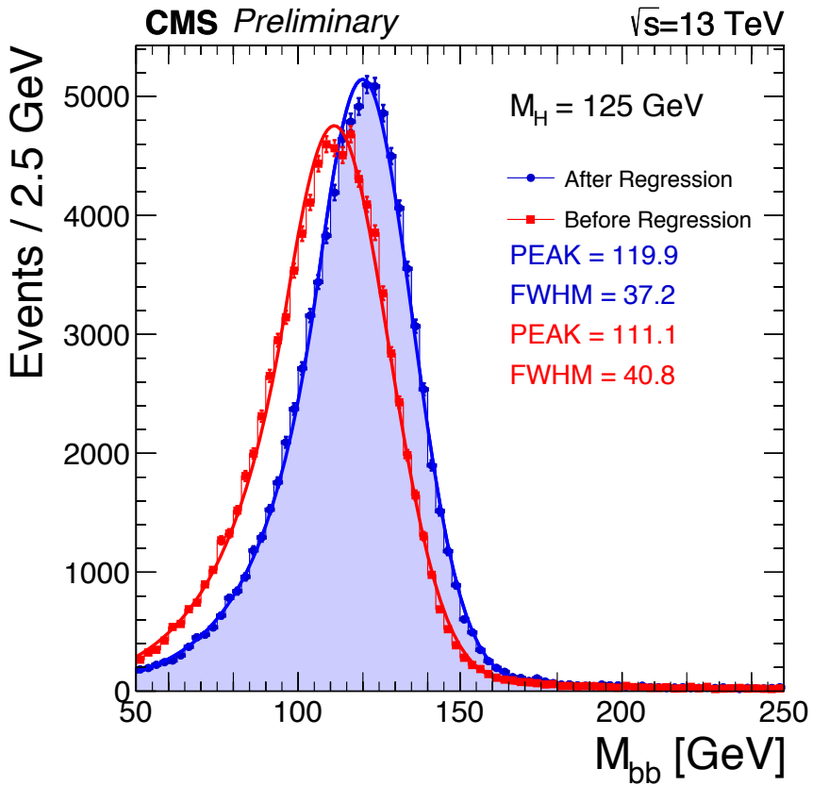


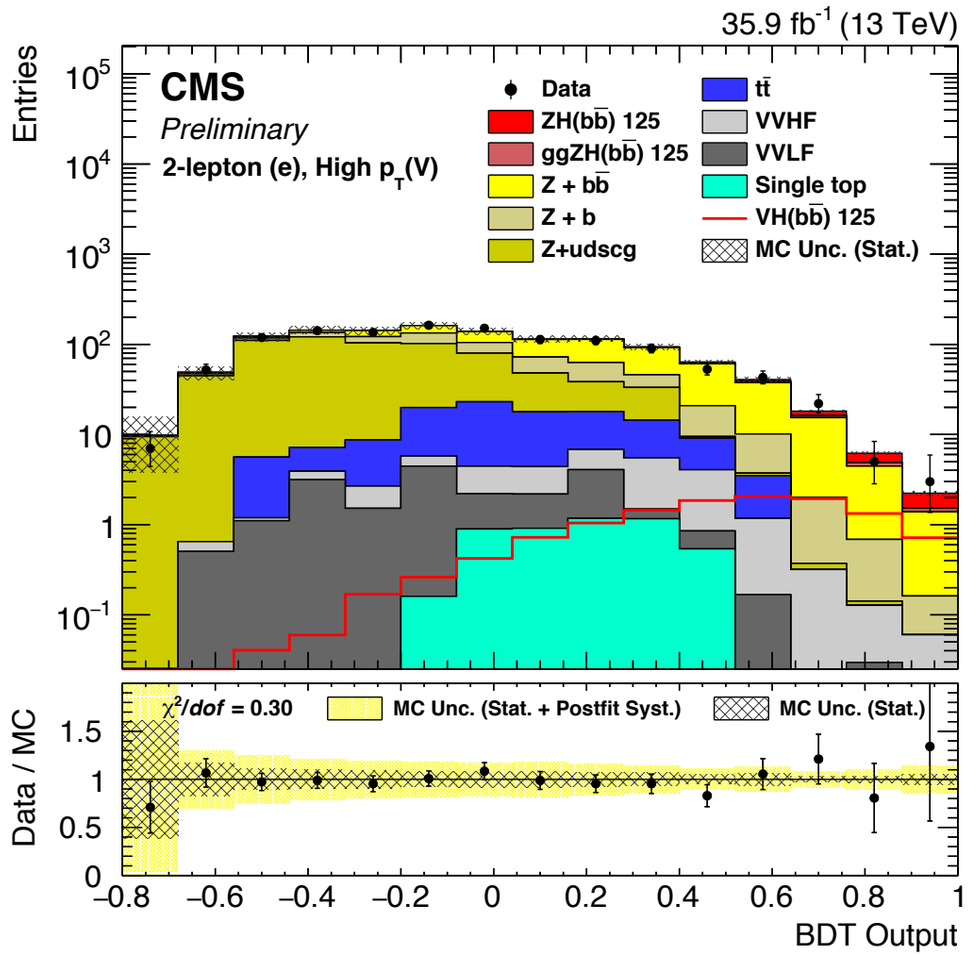
- Observed signal is compatible with SM H(125)
- Combined with CMS Run1 analysis, 5.9 (exp. 5.9) σ significance

First observation of H($\tau\tau$) from a single experiment

VH(bb) CMS-PAS-HIG-16-044 NEW

- H → bb has BR ~ 58% but overwhelming multi-jet background
  - Can be suppressed in VH production: Z(ℓℓ), Z(νν) ,W(ℓν), + H(bb) , with ℓ = e,μ
- A BDT is used to separate signal and backgrounds and perform ML fit
  - m(bb) resolution is ~10% → dedicated regression to correct the b-jet energy



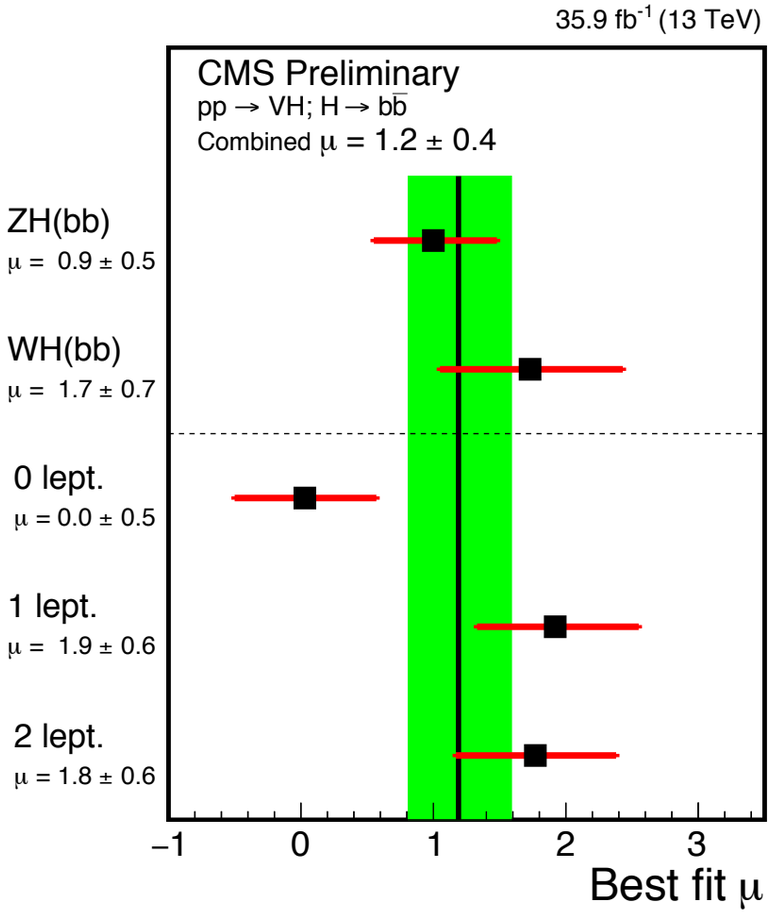


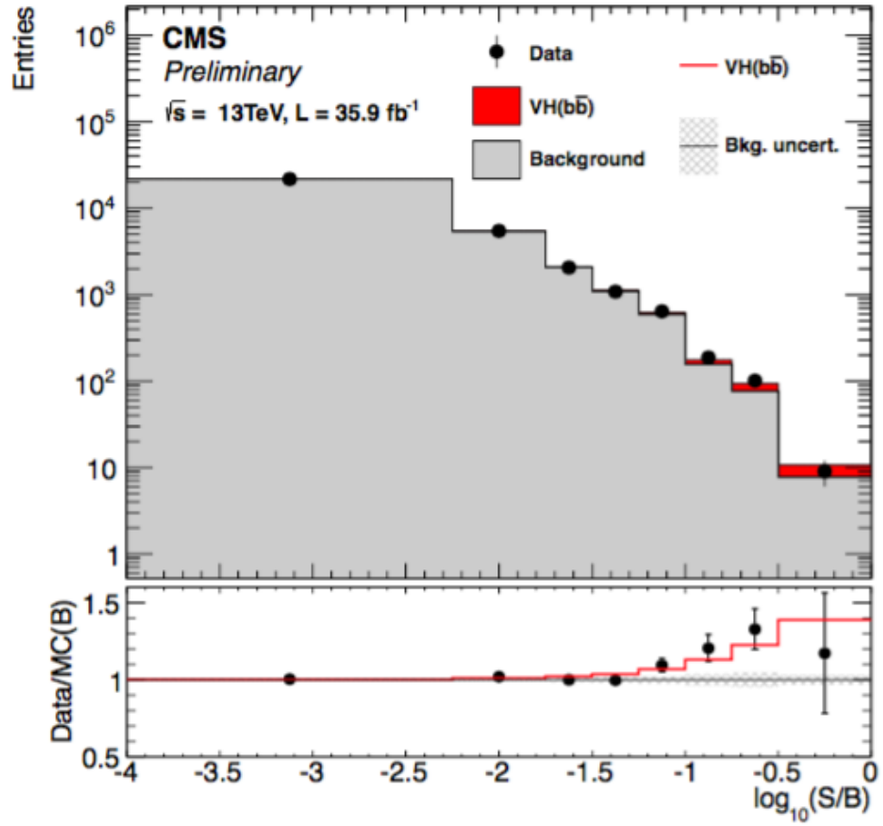
- Main bkg. is V+b-jets, form MC with corrections, many control regions in the fit

VH(bb) CMS-PAS-HIG-16-044 NEW

- Observed excess of events compatible with the H(125)

$m_H = 125\,GeV$	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	$1.06^{+0.31}_{-0.29}$





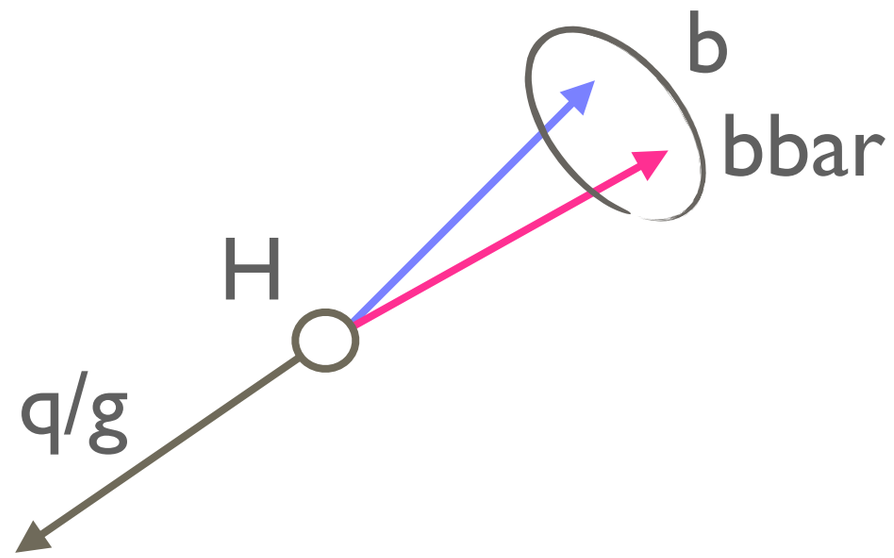
Strong evidence of H → bb decay, also seen by ATLAS

- Results for VZ(bb) validating the analysis strategy

Channel	Expected signal strength	Observed signal strength	Post-fit expected significance	Observed significance
0-lepton	1.00 ± 0.33	0.57 ± 0.32	3.1	2.0
1-lepton	1.0 ± 0.4	1.7 ± 0.5	2.6	3.7
2-lepton	1.00 ± 0.31	1.33 ± 0.34	3.2	4.5
Combined	1.00 ± 0.22	1.02 ± 0.22	4.9	5.0

BOOSTED H(bb) CMS-PAS-HIG-17-010

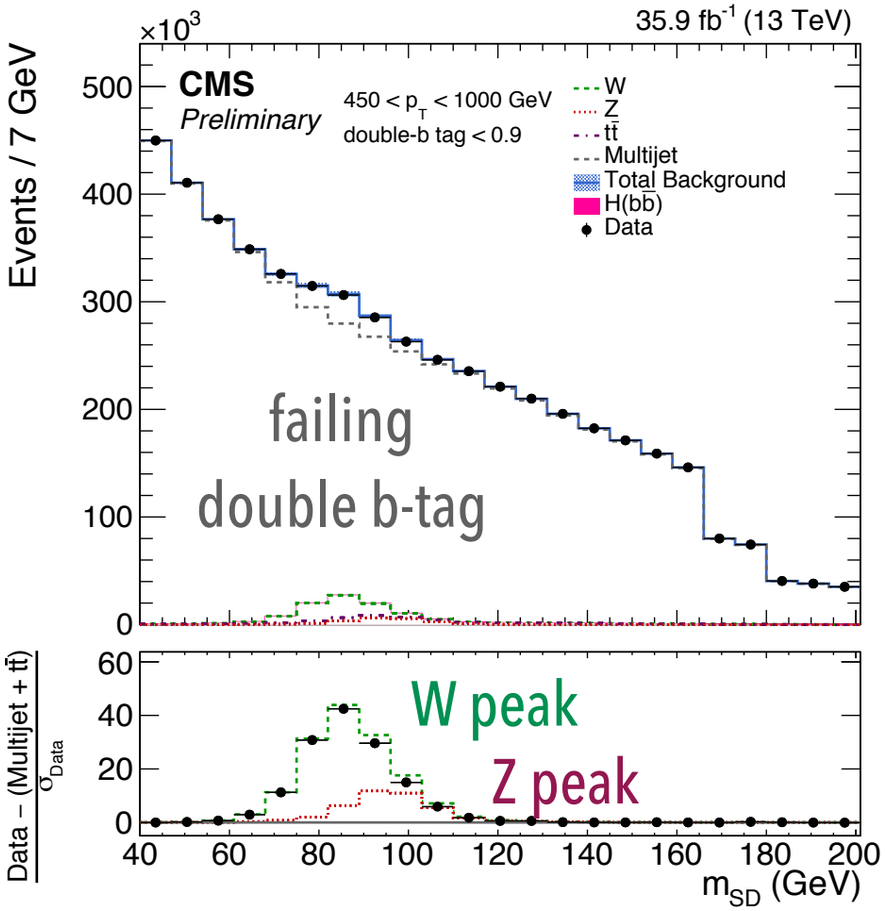
- First LHC search for boosted gg → H → bb
- Uses novel techniques for boosted object identification

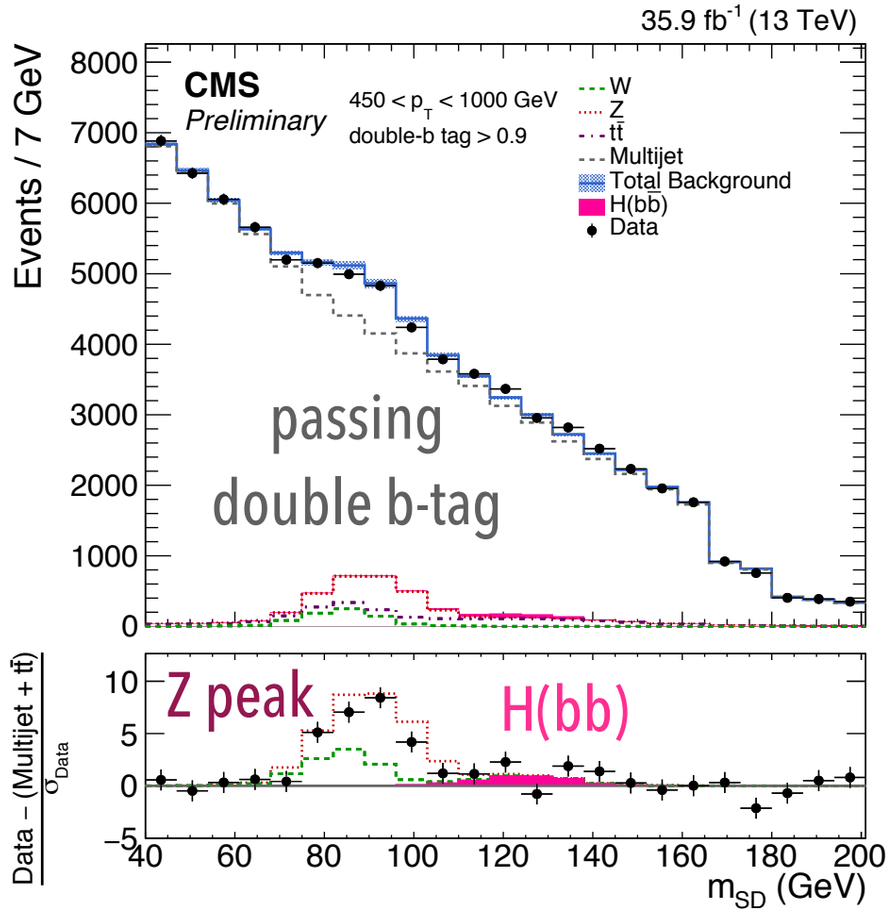


- In high p_T regime (Higgs p_T > 450 GeV), with a ISR jet (for triggering)
  - Single "fat" jet with 2-prong structure and double b-tagged
    - 2-prong discriminator eff ~ 58% and mistag ~ 26%
    - double b-tagging eff. ~ 33% for signal and 1% for QCD
- QCD estimation fully data-driven from events failing the double b-tag requirement

BOOSTED H(bb)

CMS-PAS-HIG-17-010





- **Result for H(bb) : 1.5σ (0.7σ) observed (expected) significance**
- **Measured cross section for ggH(bb), p_T(H)>450 GeV is $\sigma = 74 \pm 50$ fb.**

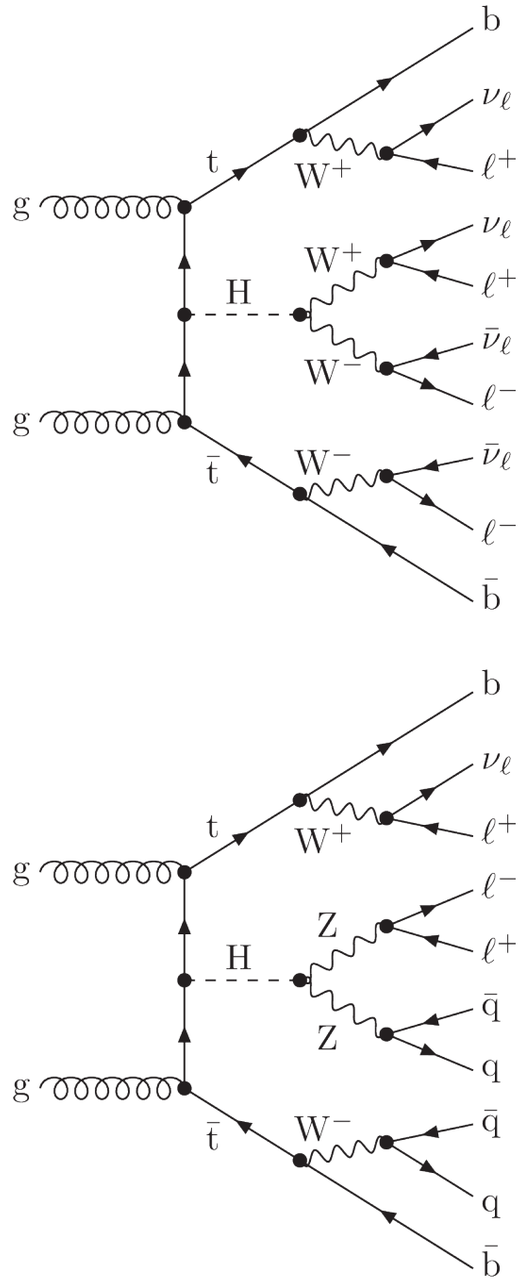
	H	Z
Observed best fit	$\mu H = 2.3^{+1.8}_{-1.6}$	$\mu Z = 0.78^{+0.23}_{-0.19}$
Expected significance	0.7σ ($\mu H = 1$)	5.8σ ($\mu_Z = 1$)
Observed significance	1.5σ	5.1σ

Use Z(bb) as standard candle:

First observation of Z(bb) in merged-jet topology

Analyses targeting ttH production mode

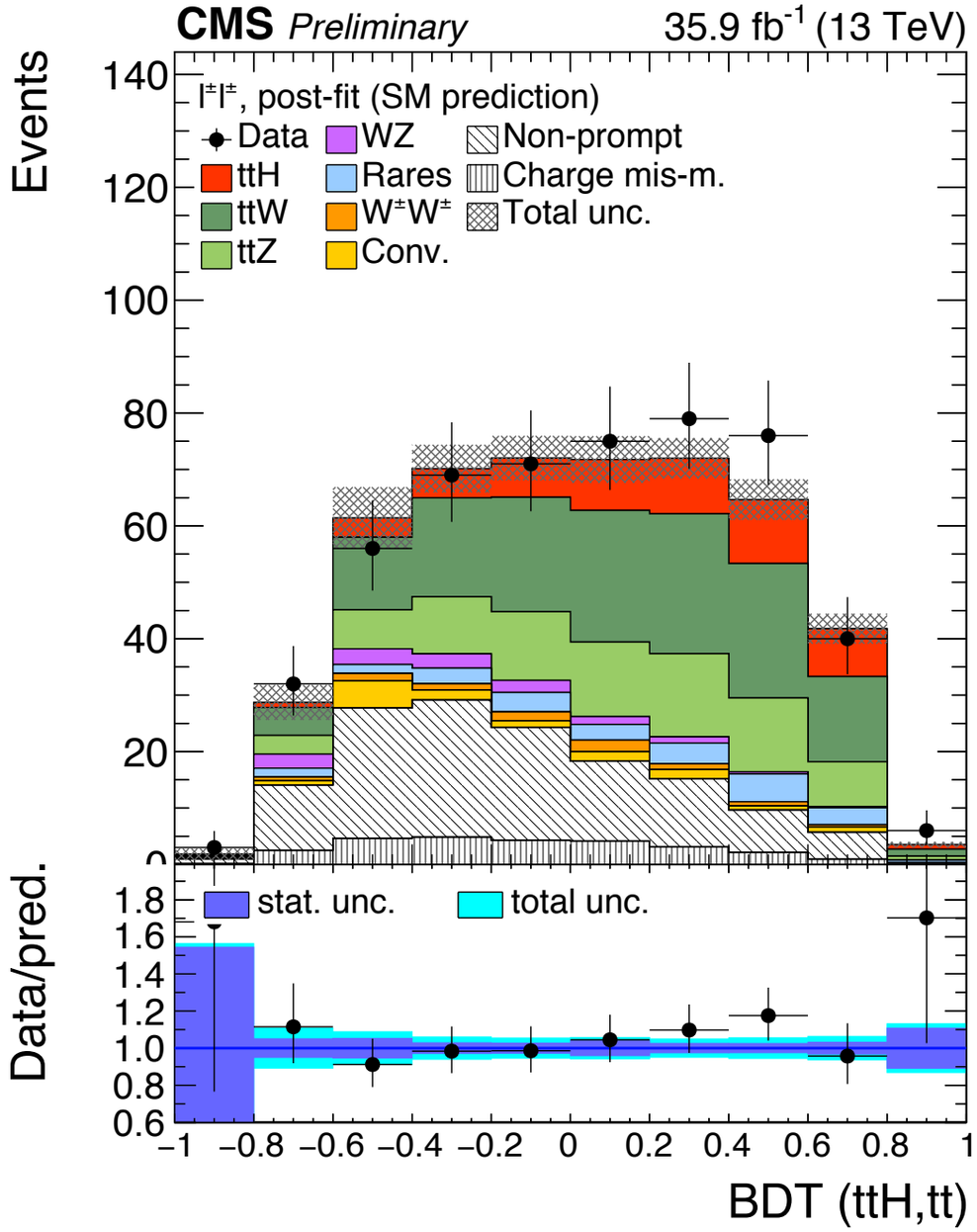
- ttH production provides direct probe of the top Yukawa coupling
  - BSM models predict enhanced ttH production
- It is a low rate process, even at 13 TeV (σ_{SM}=507 fb)
  - Large backgrounds from ttV+jets and tt+jets
  - "Rare" backgrounds (WW same sign, tri-boson, lepton charge-flip, jet faking leptons)
- Make large use of MVA techniques
- The most promising channels are "multi-lepton" final states, with H(WW), H(ZZ) and H($\tau\tau$)
- Also, dedicated categories in H($\gamma\gamma$) and H(ZZ)



ttH, leptons

CMS-PAS-HIG-17-004

- Final states with e,μ (2,3,4 ℓ)
- Categorisation based on N(leptons), flavour and N(b-jets)
- Signal extracted by ML fit of 2 BDT discriminants (against tt and tt+V)
- Dedicated BDT against non-prompt leptons
- tt+V and VV backgrounds from simulation, O(10%) uncertainty
- Data-driven estimation of charge-flip and non-prompt leptons, O(30%) uncertainty

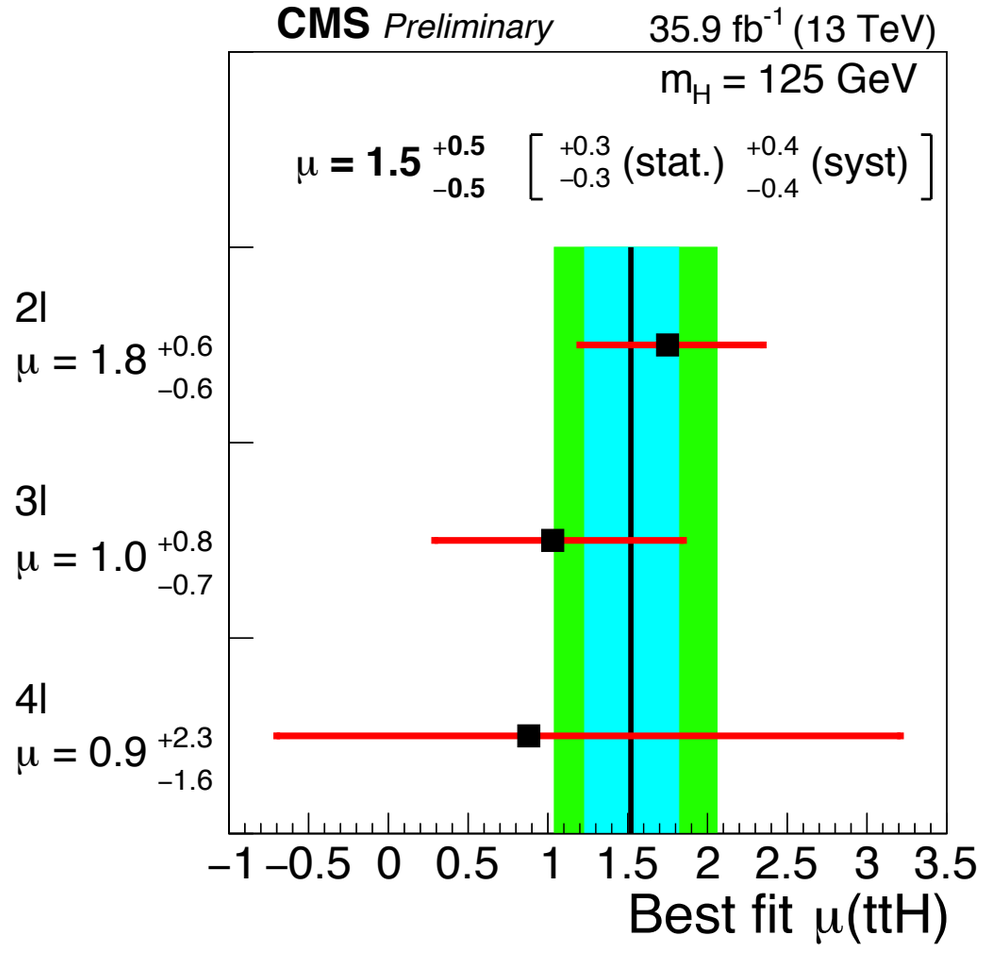


ttH, leptons

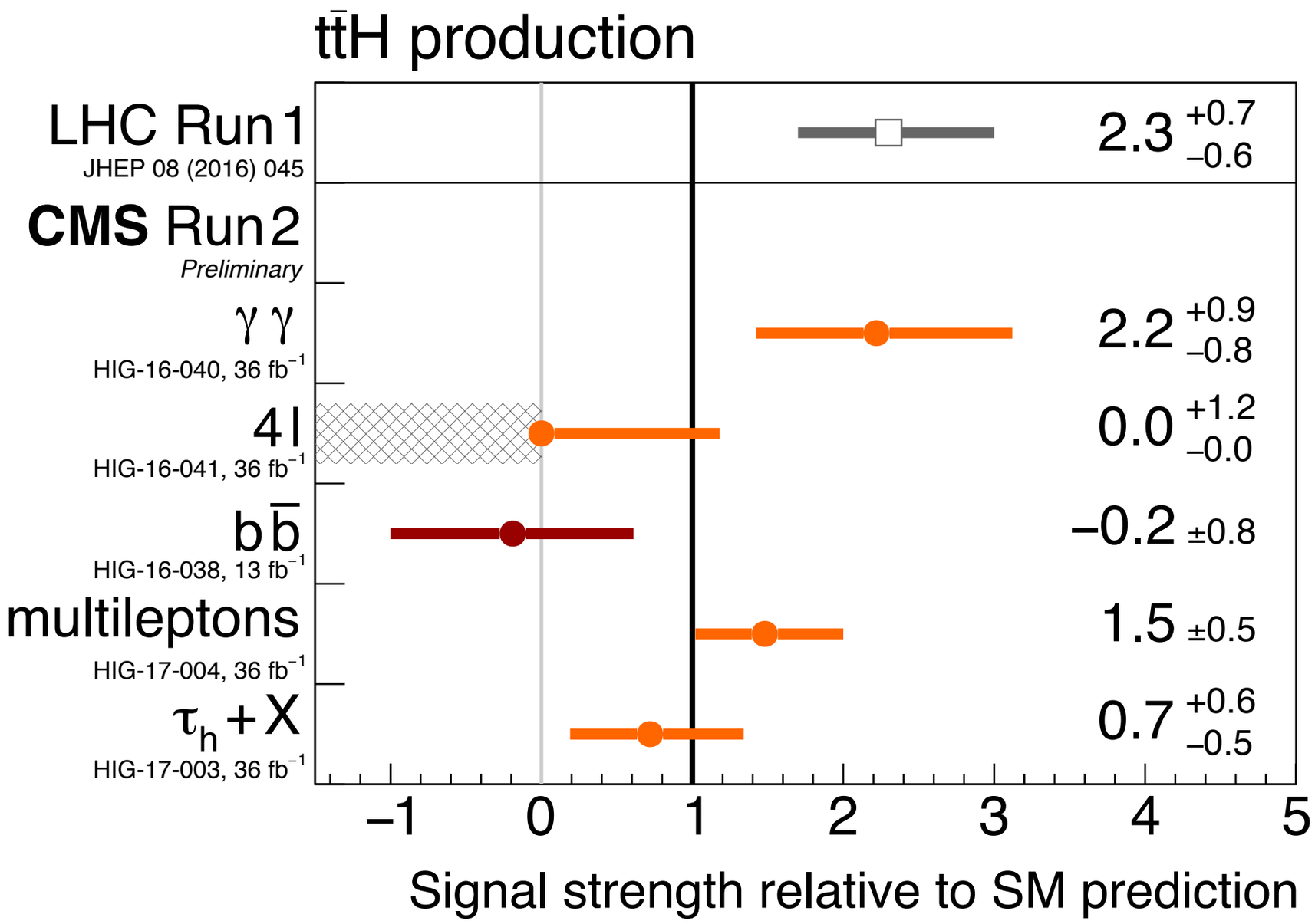
CMS-PAS-HIG-17-004

- Observed excess of events compatible with ttH signal
- Significance 3.3 (exp. 2.4)σ
- Signal strength $\mu = 1.5 \pm 0.5$

- Cross check
  - Fit introducing cross section modifiers for tt+Z and tt+W



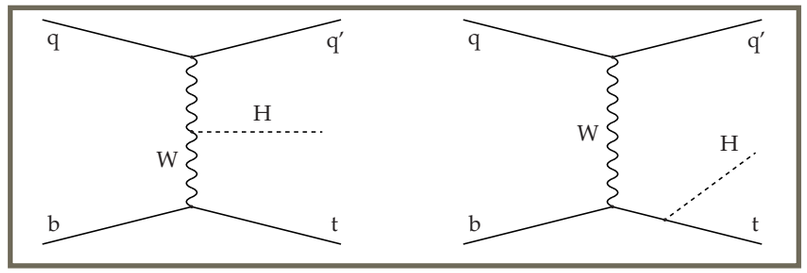
ttH results overview



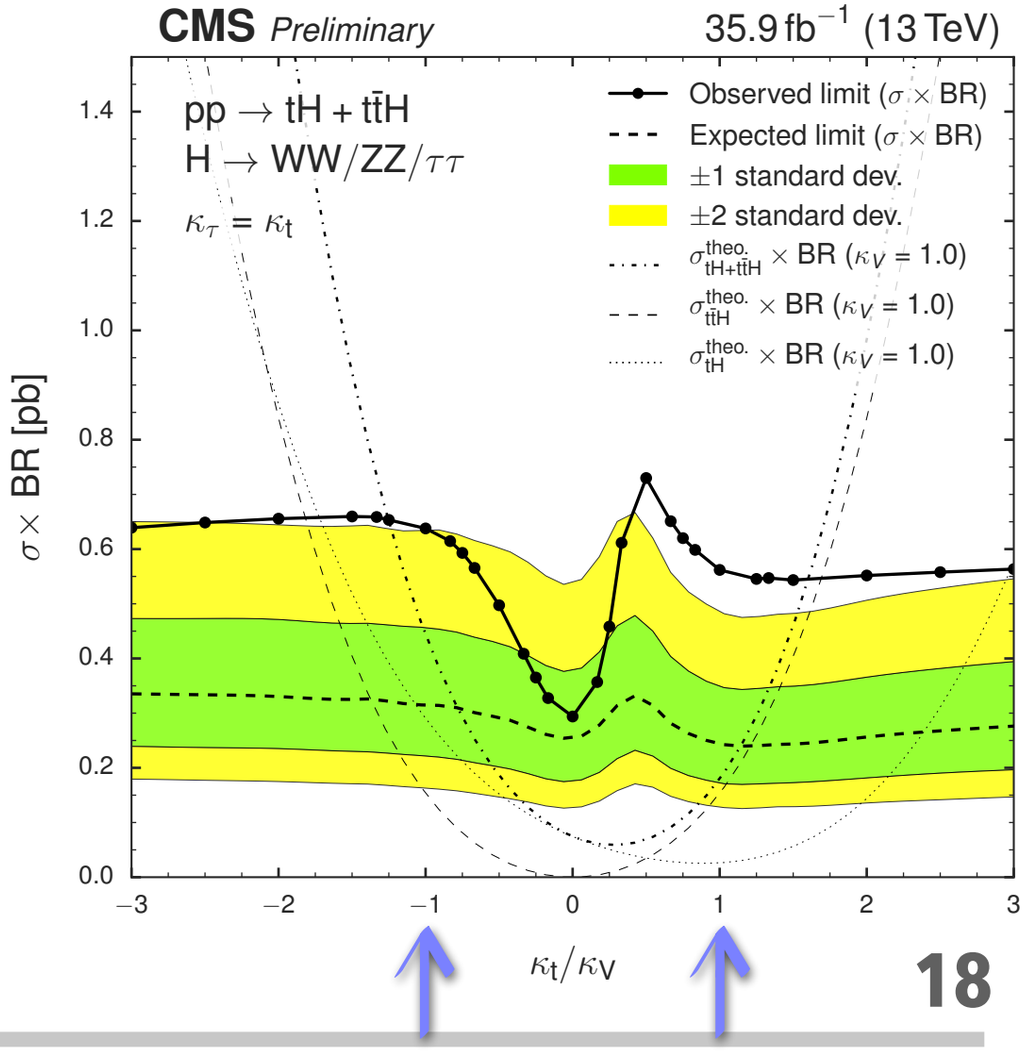
tHq, leptons

CMS-PAS-HIG-17-005

- Single top + Higgs production, sensitive to the sign of the top Yukawa coupling
- Targeting H(WW) with 2 or 3 W bosons decaying leptonically
- Also includes contributions from H($\tau\tau$) and H(ZZ)



- Upper limits on tH+ttH cross section x BR as a function of κ_t/κ_V
- For κ_t=1 (SM-like)
  - σ x BR < 0.56 (0.24 exp) fb
  - 2.7 (1.5 exp) σ for tH+ttH signal, μ = 1.8 ± 0.7
- For κ_t=-1
  - σ x BR < 0.64 (0.32 exp) fb
  - 1.7 (2.5 exp) σ for tH+ttH signal, μ = 0.7 ± 0.4
- κ_t<−1.25 or κ_t>+1.60 excluded at 95% C.L.



SUMMARY

- The latest results of the H(125) measurements performed at CMS have been presented
  - on the full 2016 dataset @ 13 TeV

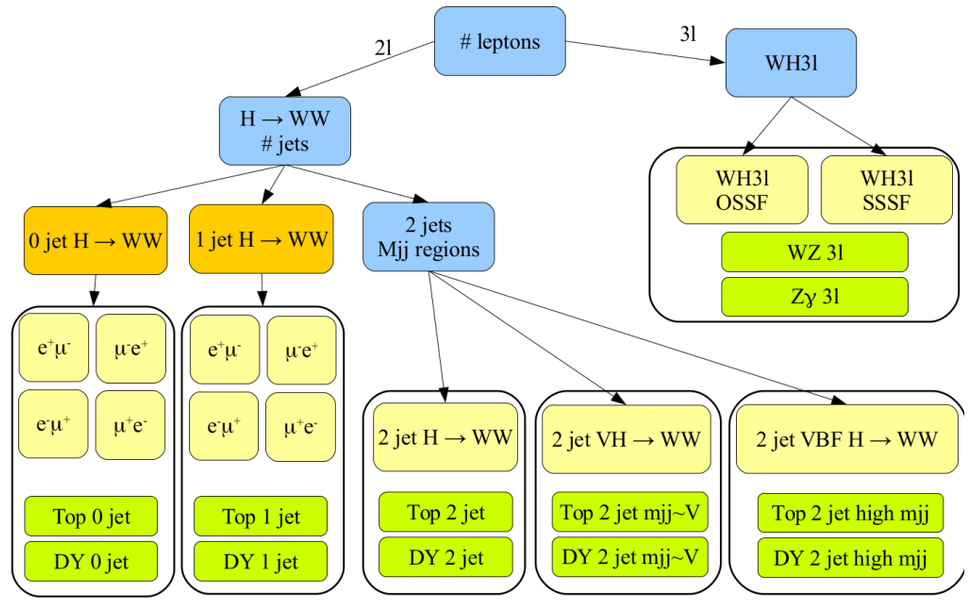
- In the H → ZZ and H → $\gamma\gamma$ channels, precision measurements are being performed
- Important milestones reached regarding the 3rd generation Yukawa couplings
  - Observation of H($\tau\tau$) decay mode by a single experiment
  - Evidence of H(bb) decay mode in VH production
  - First attempt searching for inclusive boosted gg → H → bb
- Analyses searching for ttH and tH are becoming more sensitive

- So far, no deviations from the SM are observed, but it is only 5 years after the Higgs discovery
  - Still a long way to go towards a precise picture of the Higgs
  - There is still room for deviations pointing to new physics

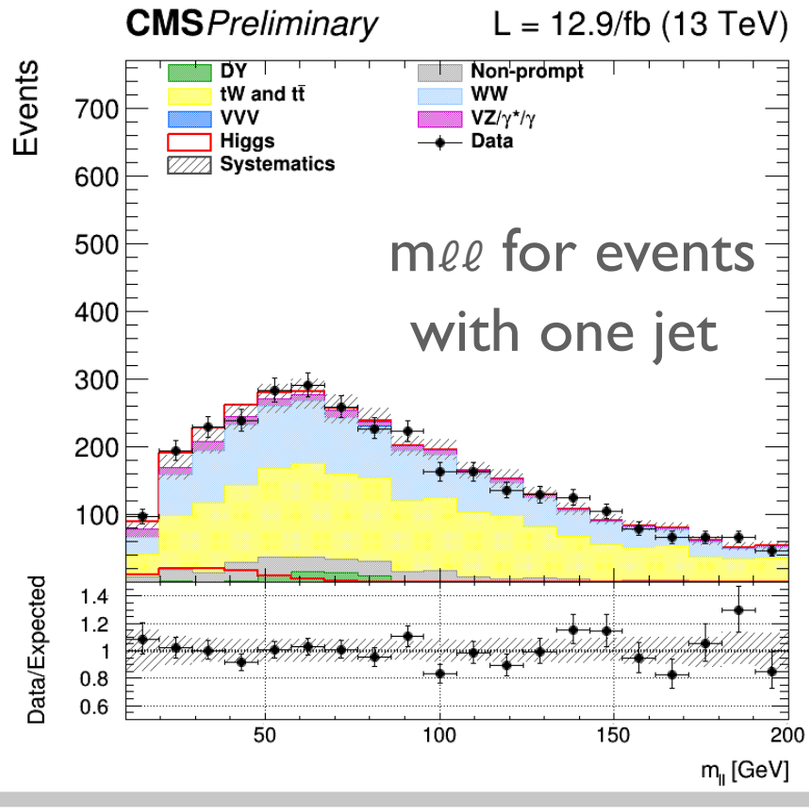
BACKUP - ADDITIONAL MATERIAL

H(WW) CMS-PAS-HIG-16-021

- Final state: H → WW → $e\mu$ (OS) + neutrinos
- Targeting ggH production mode, but also categories for VBF and VH
- Categorise by #leptons, jets and lep. charge (charge symmetry for signal but not for W+jets)
- Irreducible bkg. is WW production
  - lower $m_{\ell\ell}$ for signal than for WW or top
- Main bkg. is W+jets and tt+jets, with 1 jet faking a lepton, estimated from data
- Other bkg. from MC with corrections
- Signal extracted from ML fit to 2-D distributions in $m_{\ell\ell}$-m_{HT} (only 1D for VBF and VH categories)
- Including background control regions in the fit

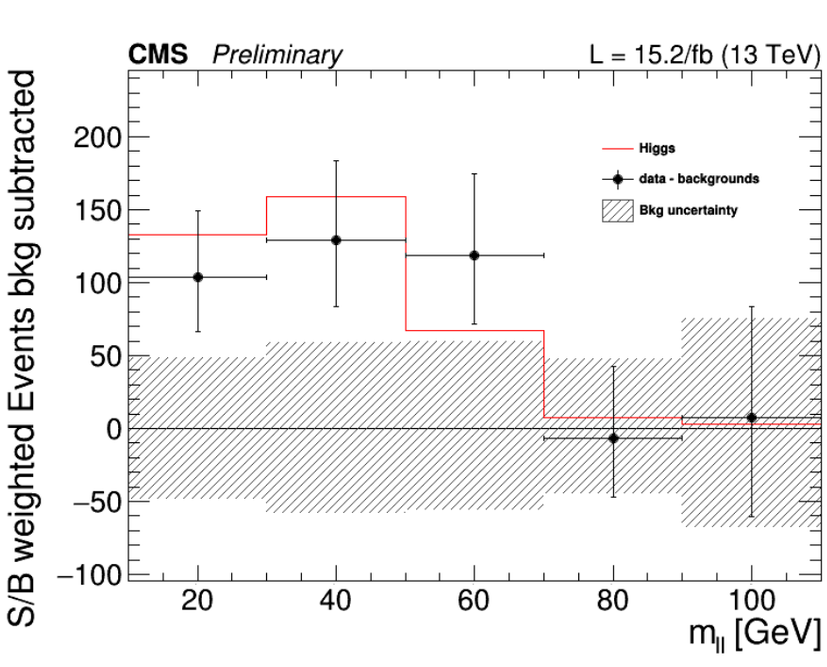


(b) Signal and background.



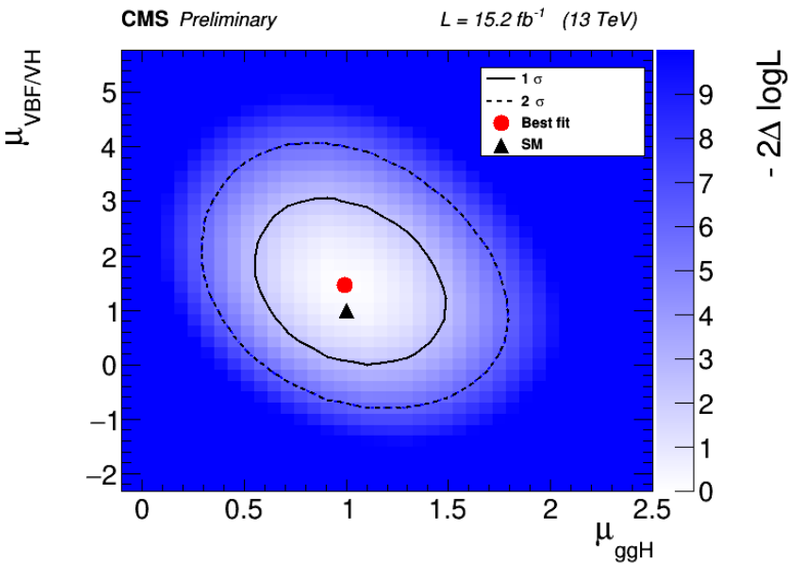
H(WW) CMS-PAS-HIG-16-021

- Results for 2015 (L=2.3/fb) + 2016 data (L = 12.9/fb)
- Excess of events compatible with H(WW) signal, 4.3(4.1 exp.) σ
- Signal strength $\mu = 1.05 \pm 0.25^{\text{stat}} \pm 0.03^{\text{theory}} \pm 0.07^{\text{syst}}$
- Analysis limited by stat. uncertainty



category	significance	σ/σ_{SM}
0-jet	2.7 (2.9)	$0.9^{+0.4}_{-0.3}$
1-jet	2.1 (2.5)	$1.1^{+0.4}_{-0.4}$
2-jet	2.0 (1.0)	$1.3^{+1.0}_{-1.0}$
VBF 2-jet	2.2 (1.5)	$1.4^{+0.8}_{-0.8}$
VH 2-jet	1.0 (0.4)	$2.1^{+2.3}_{-2.2}$
WH 3-lep	0.0 (0.5)	$-1.4^{+1.5}_{-1.5}$
combination	4.3 (4.1)	$1.05^{+0.27}_{-0.25}$

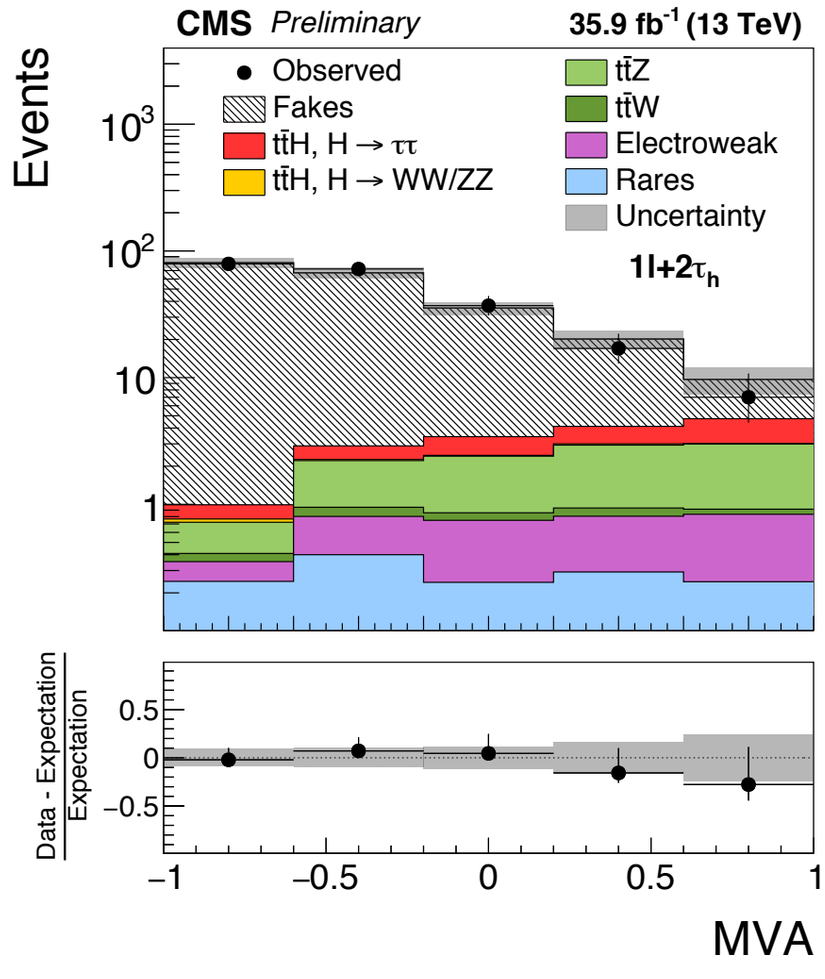
- Signal strength modifier scan for prod. modes dominated by fermion and boson couplings



ttH, H($\tau\tau$)

CMS-PAS-HIG-17-003

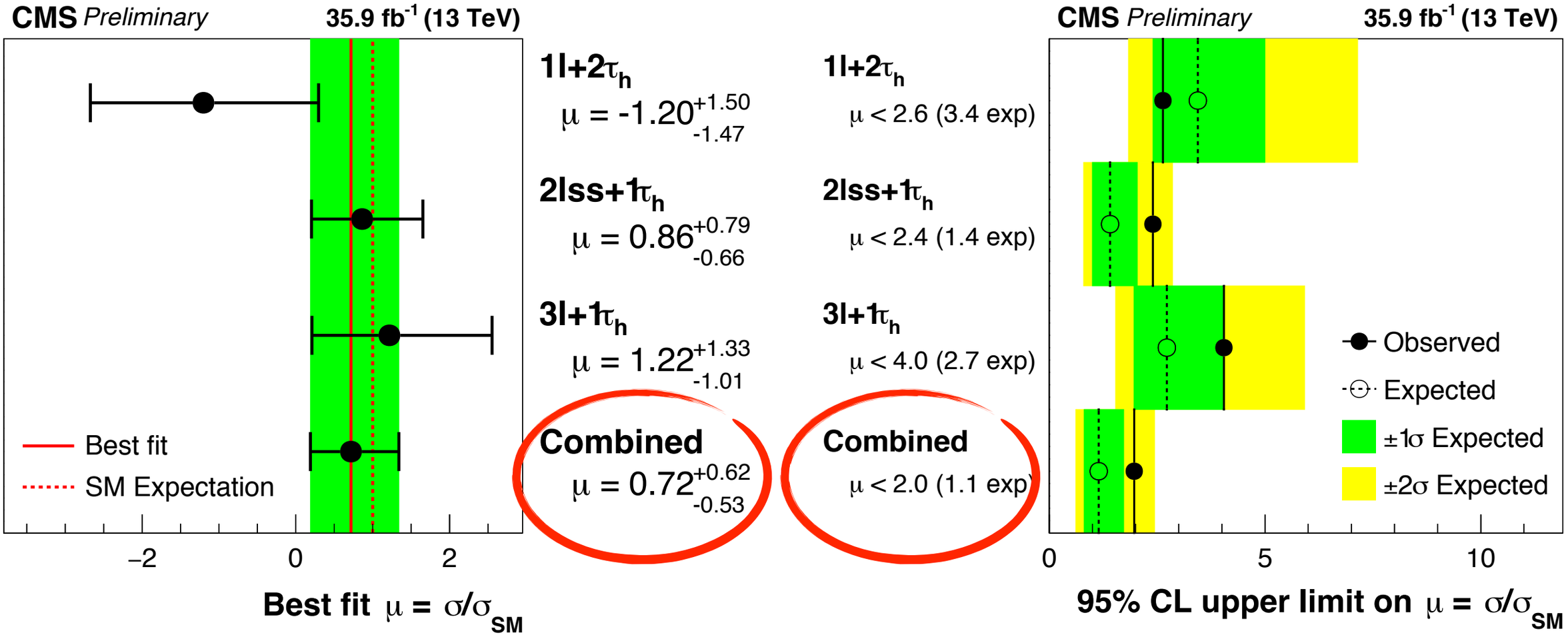
- Final states with hadronically decaying τ
- Sensitive to ttH, with H($\tau\tau$), H(WW) and H(ZZ).
  - $1\ell+2\tau_h$ OS
  - 2ℓ SS + $1\tau_h$
  - 3ℓ + $1\tau_h$
- Irreducible background (tt+V and VV+jets) from simulation
- Reducible bkg. data-driven with fake-factor method
- ML fit to a discriminating variable
  - BDT discriminants, different in every category, to maximise signal vs. bkg. shape separation



ttH, H($\tau\tau$)

CMS-PAS-HIG-17-003

- Significance for SM Higgs signal of 1.4 (exp. 1.8) σ
- Best fit $\mu = 0.72^{+0.62}_{-0.53}$, upper limit $\mu < 2.0$ (exp. 1.1)



ttH, H(bb) CMS-PAS-HIG-16-038

- Targets lepton+jets and dilepton ttbar decays
- Categories according to number of jets and b-jets
  - Higher jet and b-jet multiplicity for the ttH(bb) signal
- Use a combination of BDT discriminants and MEM weights.
- Analysed dataset = 12.9/fb @ 13 TeV
- Results