Status of the ttH searches at ATLAS and CMS

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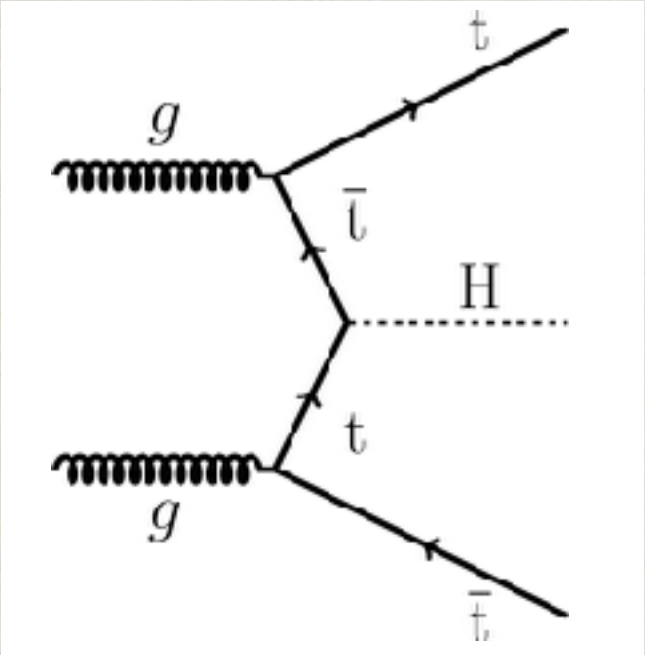
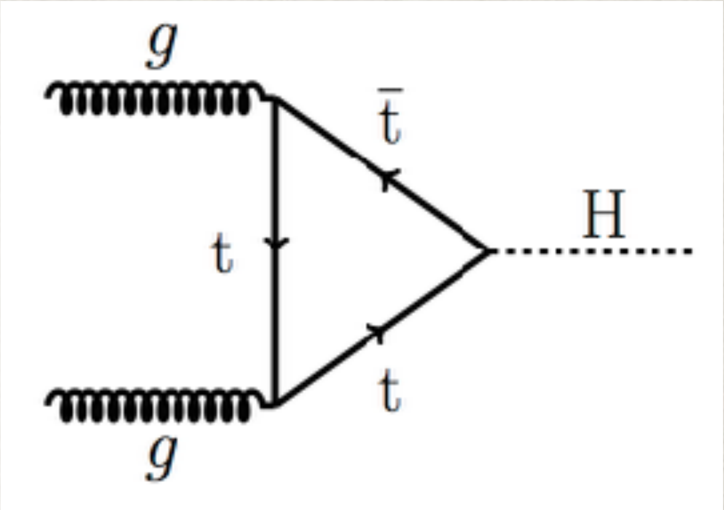
Apr. 11th 2018

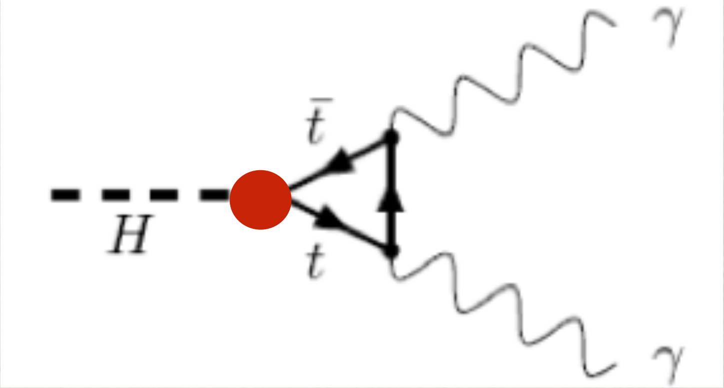
CMS Heavy flavour tagging workshop 2018, Apr.11-13, VUB

WHY TTH?



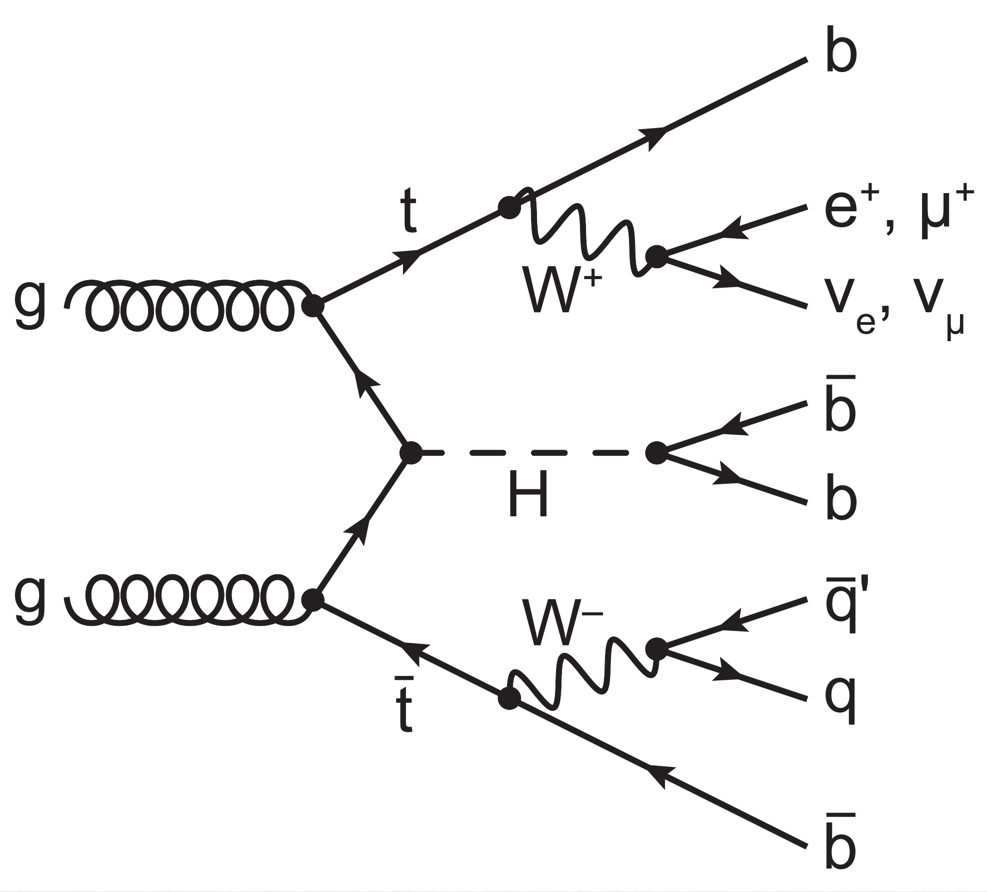


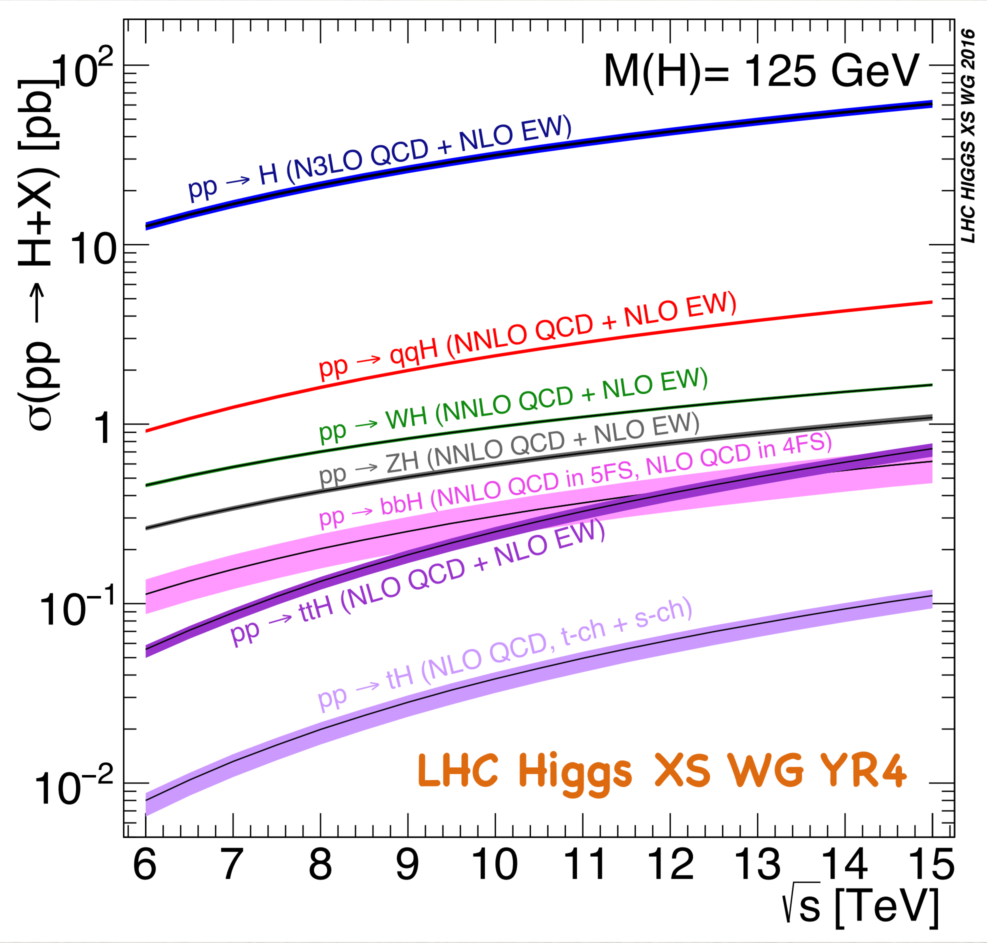
t, b/W, (New Physics?)



- Direct probe of Top-Higgs Yukawa coupling Y_T
- Precise measurement of Y_T probes BSM contributions in Higgs production and decay loops

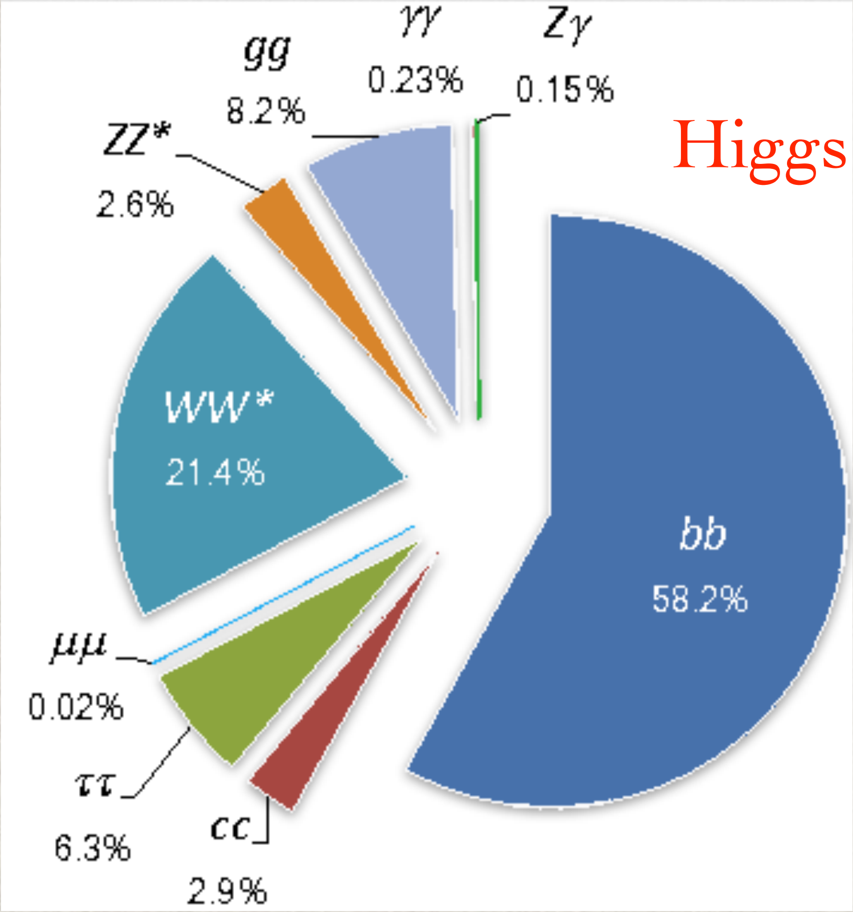
CHALLENGES



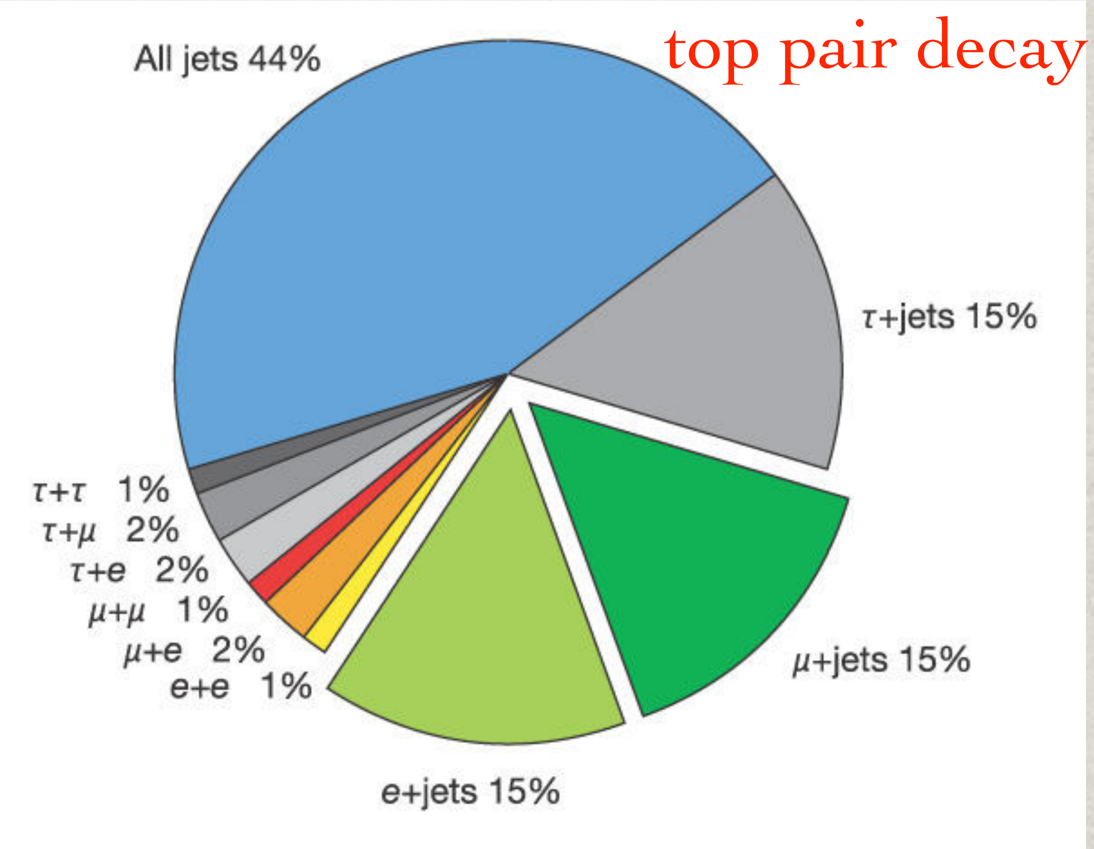


- Tiny production cross section
- Complex final states: leptons(e,μ,τ), γ, jets(b-jets), ν
- Large irreducible backgrounds: e.g. ttV or ttbb

GENERAL STRATEGY



Higgs decay

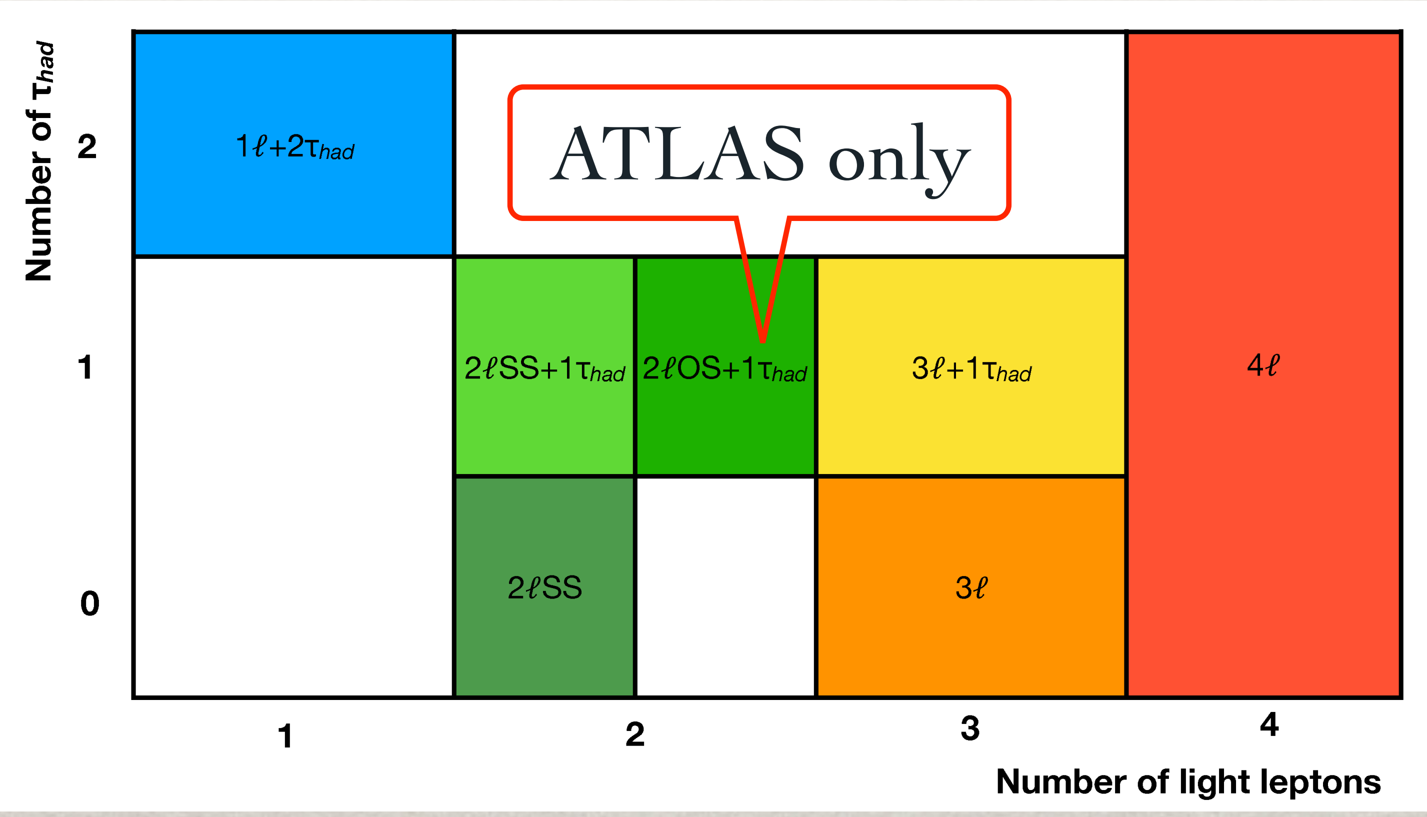


top pair decay

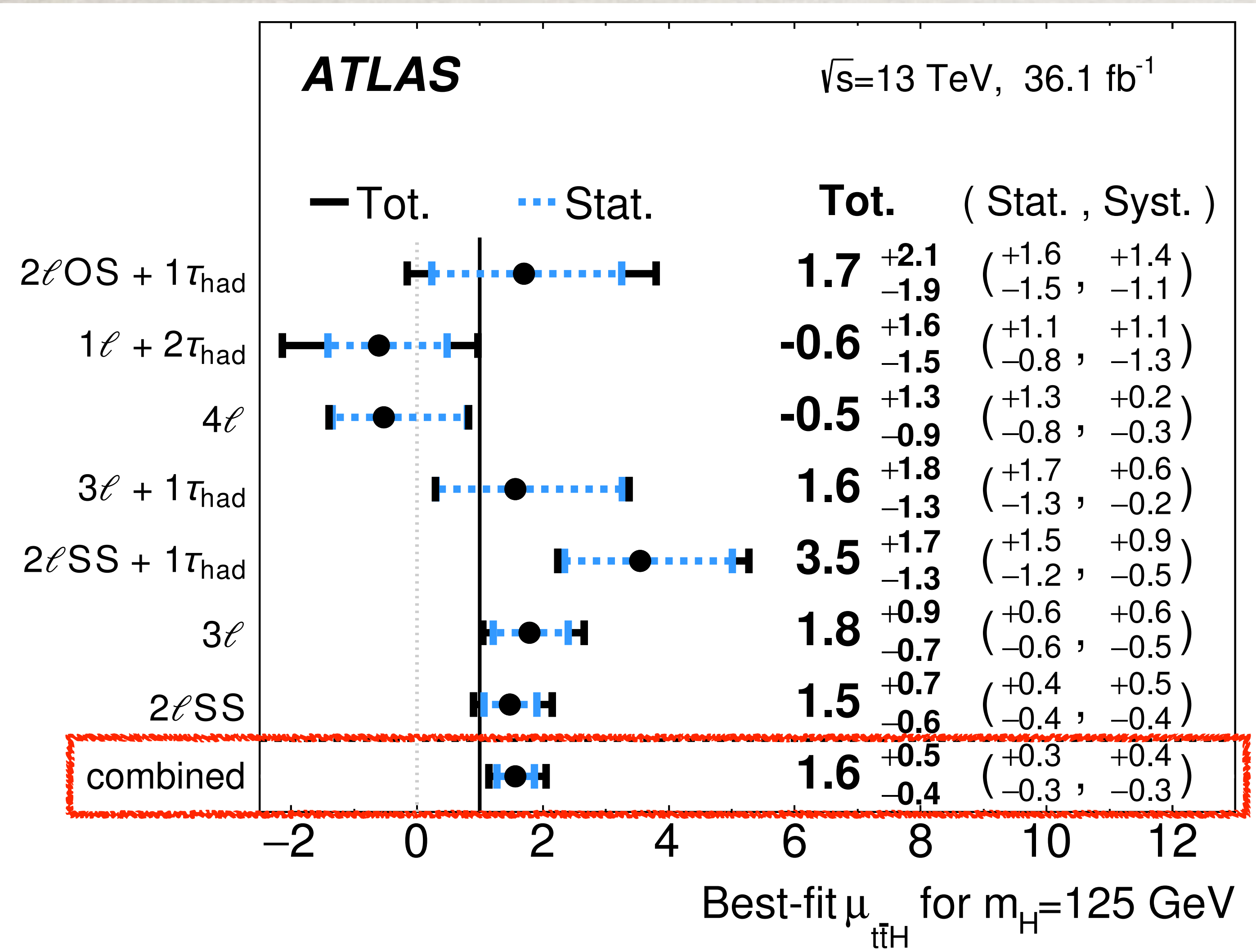
- Different channels for Higgs decay modes: bb, WW*/ZZ*/$\tau\tau$, $\gamma\gamma$
  - sub-channels based on top pair decay
- Categorize events based on N_leptons, N_jets, N_btags
- Use MVA techniques to discriminate signal from bkg*
- Dedicated MVA/MEM to address irreducible bkg

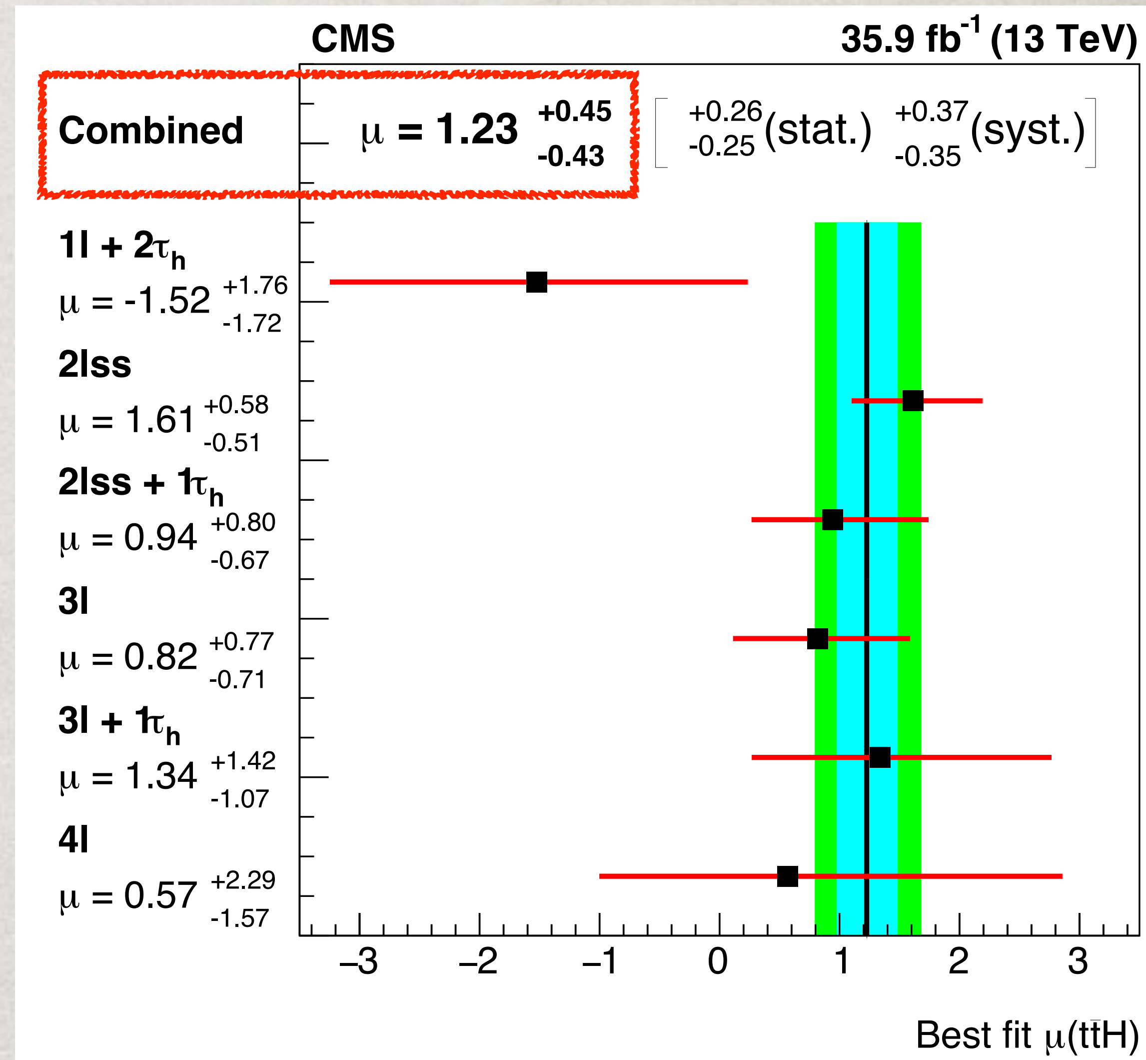
ttH(multilepton)

- Higgs decay modes: WW*(→$\ell\nu$qq, $\ell\nu\ell\nu$), ZZ*(→$\ell\ell$qq, $\ell\ell\nu\nu$), $\tau\tau$(→$\ell\tau_h$+ν's, $\tau_h\tau_h$)
- Main sources of background:
  - irreducible: ttW and ttZ
  - reducible: non-prompt leptons from HF decay or charge mis-ID in tt events



TTH (MULTILEPTON)

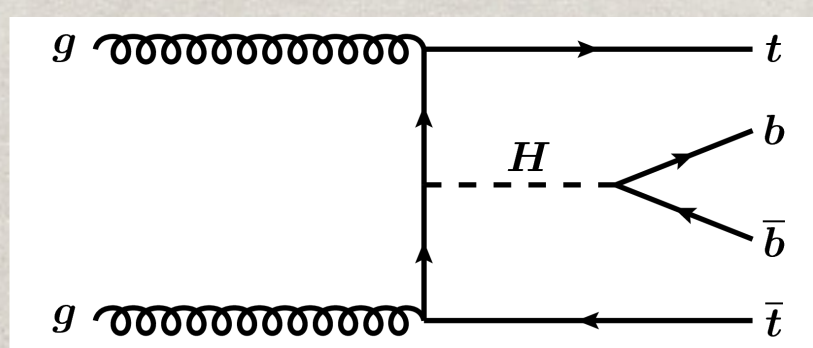


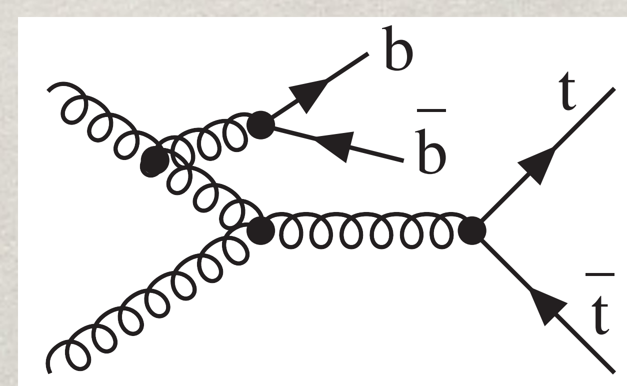


- Evidence for ttH production in both experiments
  - ATLAS: 4.1σ (2.8σ expected)
  - CMS: 3.2σ (2.8σ expected)

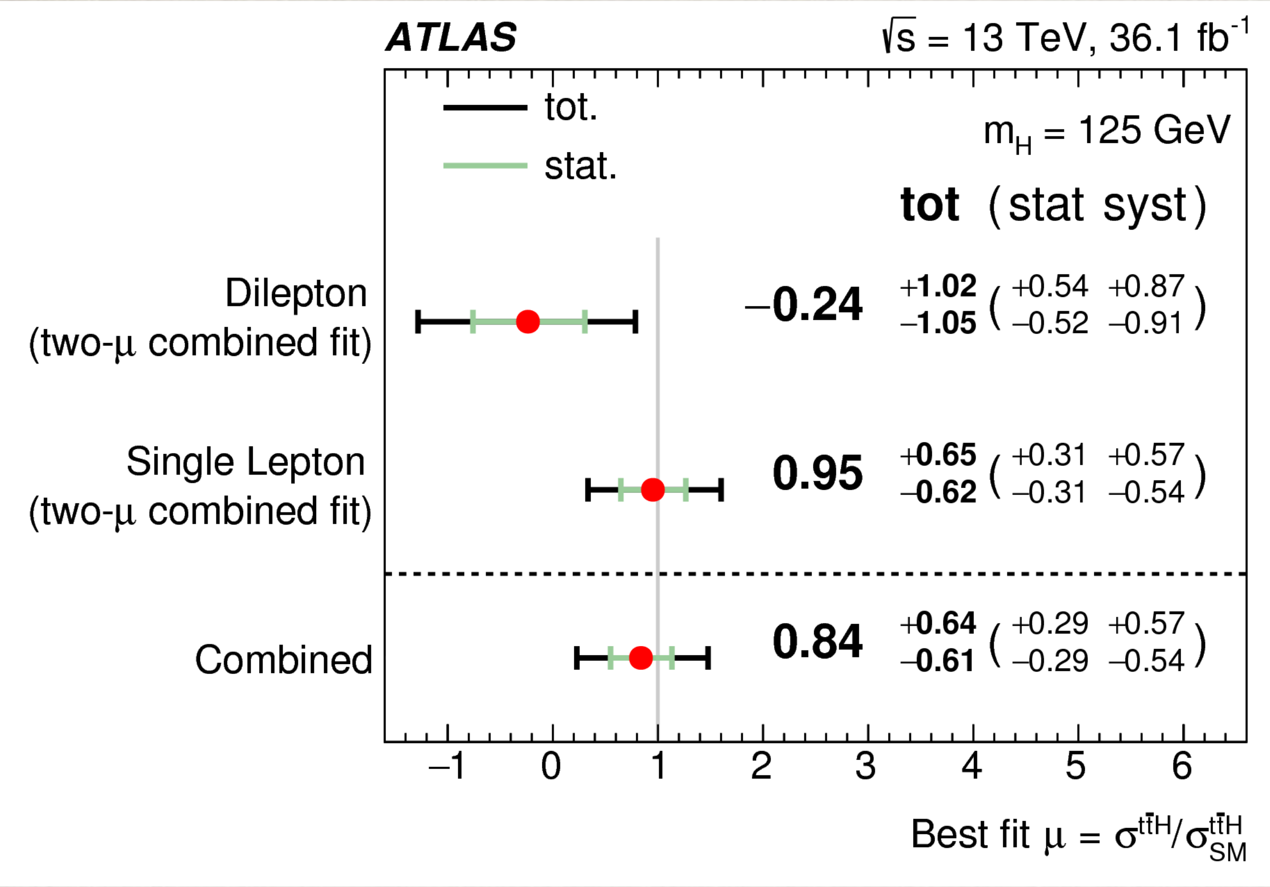
ttH(bb)

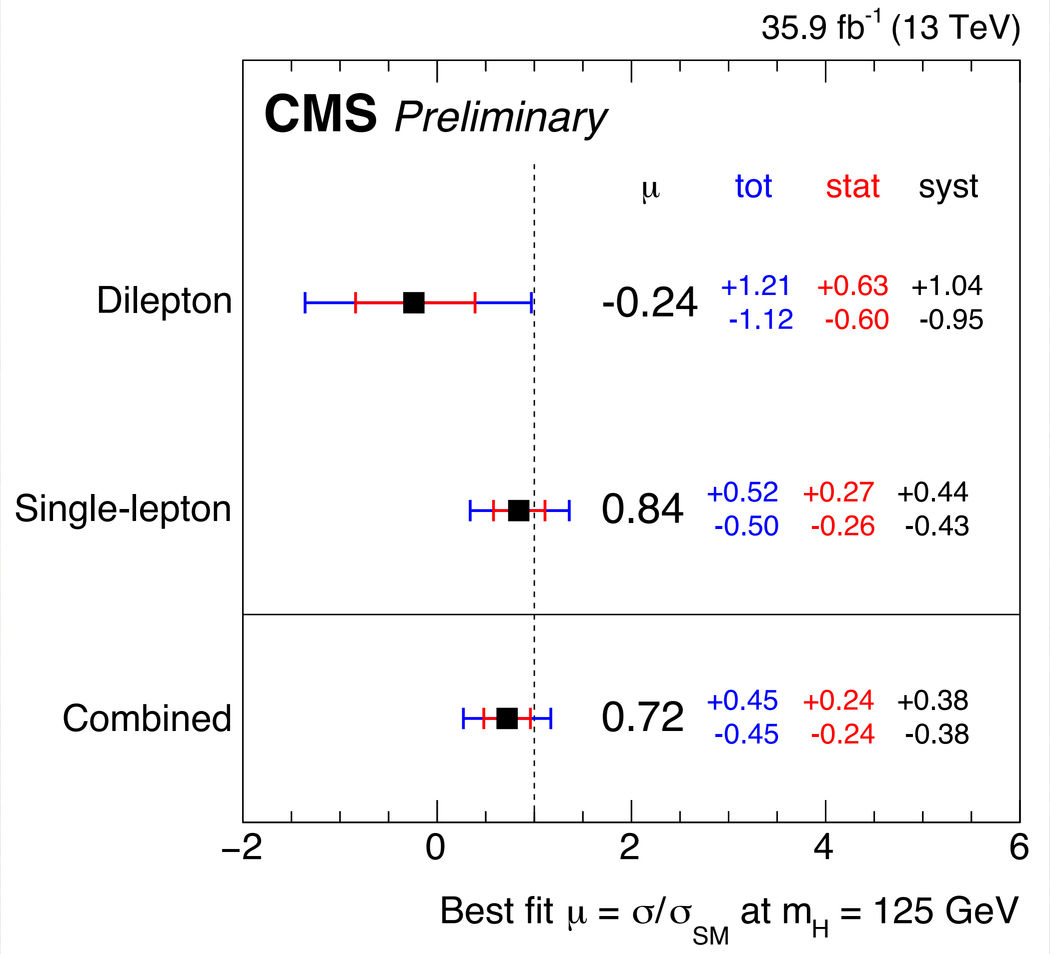
- Higgs decay mode H→bb, largest branching ratio, huge background
  - challenging jet combinatorics, limited bb mass resolution
  - b-jet tagging and leptons from top pair help reduce bkg
- Channels: X(0,1,2) leptons + Y jets + Z b-jets
  - 0 lepton channel for CMS only*
- Main sources of bkg:
  - irreducible: tt+Heavy Flavor(HF) —> MEM
  - reducible: tt+Light Flavor(LF) or QCD —> BDT/DNN





tt(1ℓ, 2ℓ)H(bb)

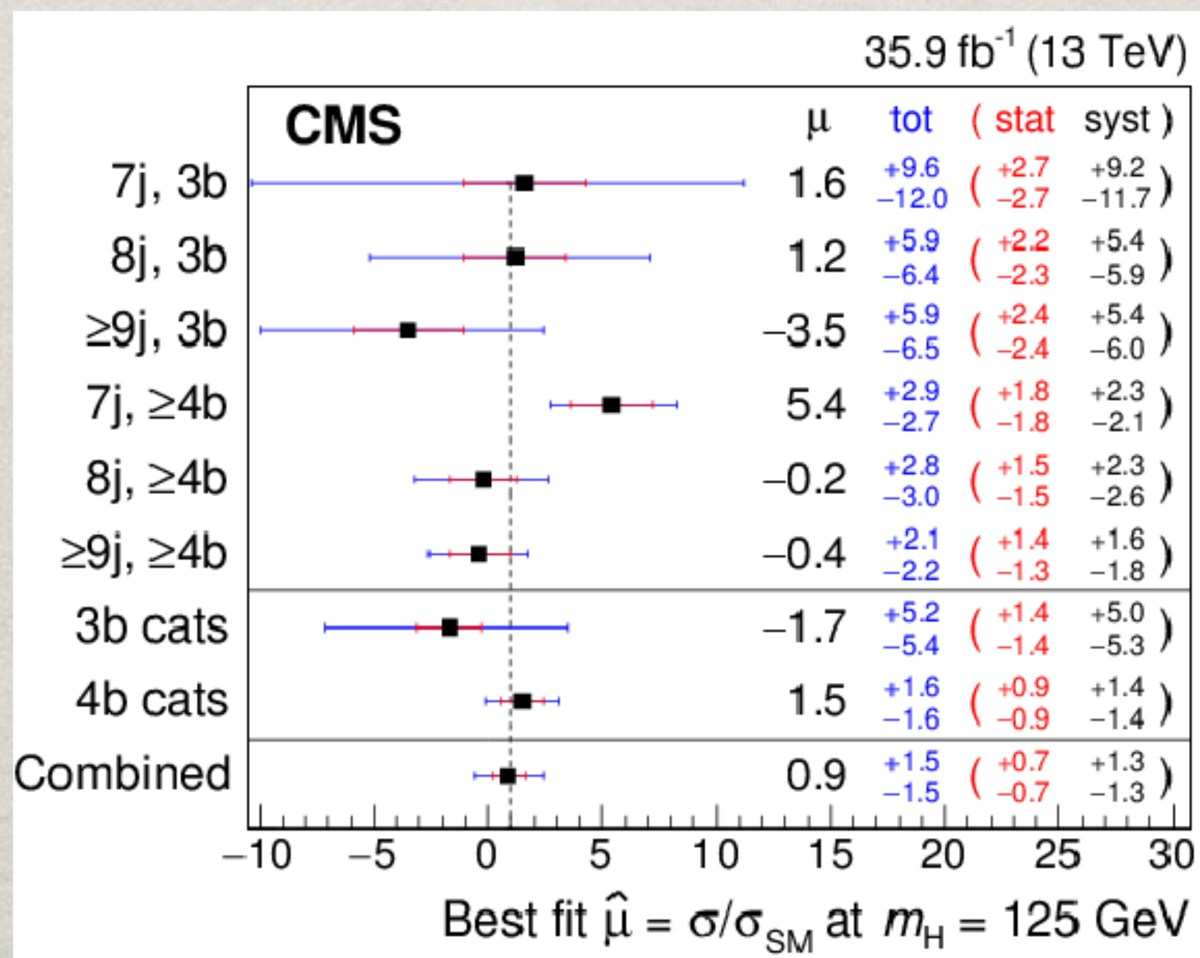




- Significance for ttH(bb):
  - ATLAS: 1.4σ (1.6σ expected)
  - CMS: 1.6σ (2.2σ expected)

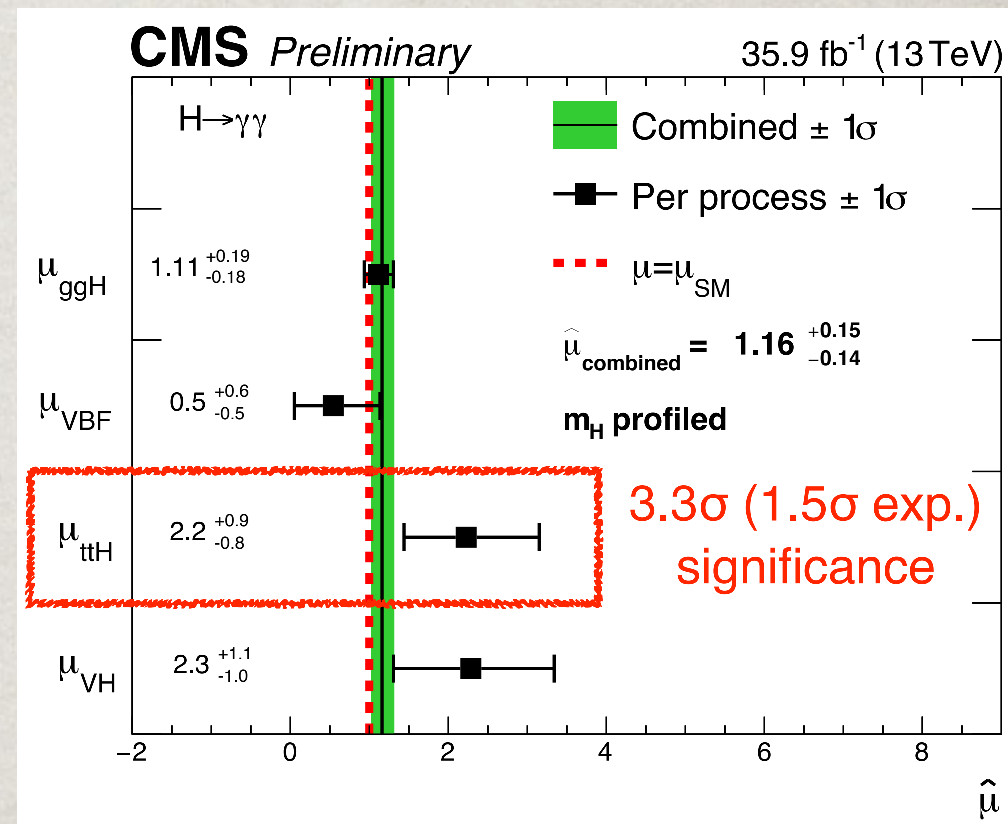
TT(0ℓ)H(BB)

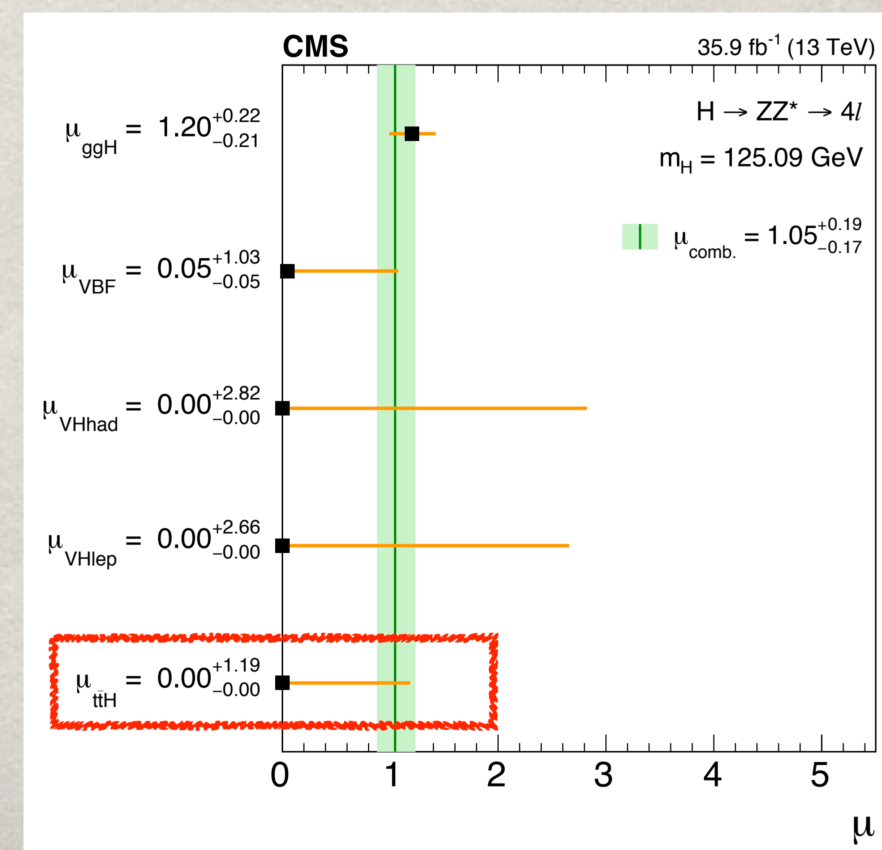
- Fully hadronic final state, categorize in #jets, b-jets
- Dedicated b-tag triggers: 6 jets, large Ht, 1 or 2 b-jets
- Main background: QCD(quark-gluon jet discriminator) and tt+HF(MEM)



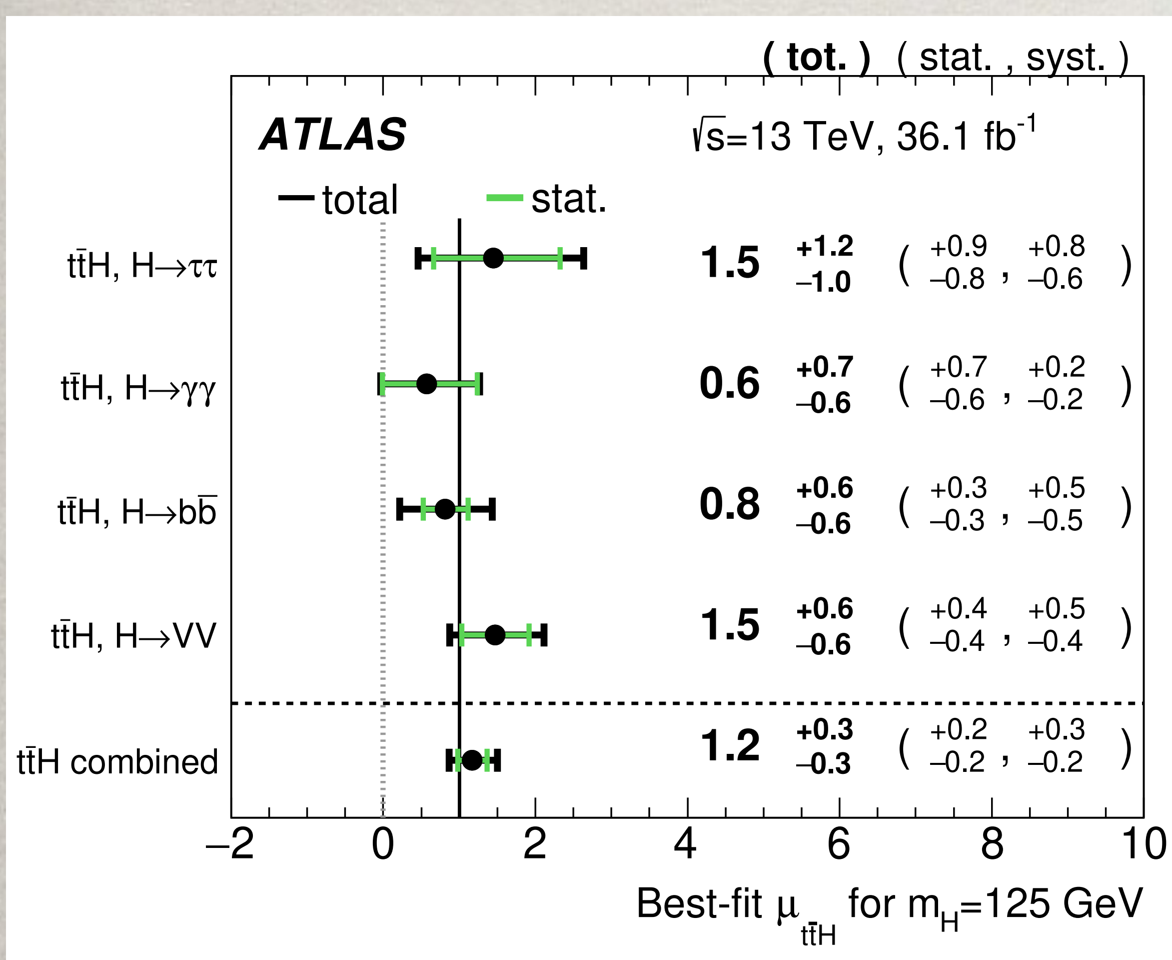
ttH($\gamma\gamma$, ZZ*→4ℓ)

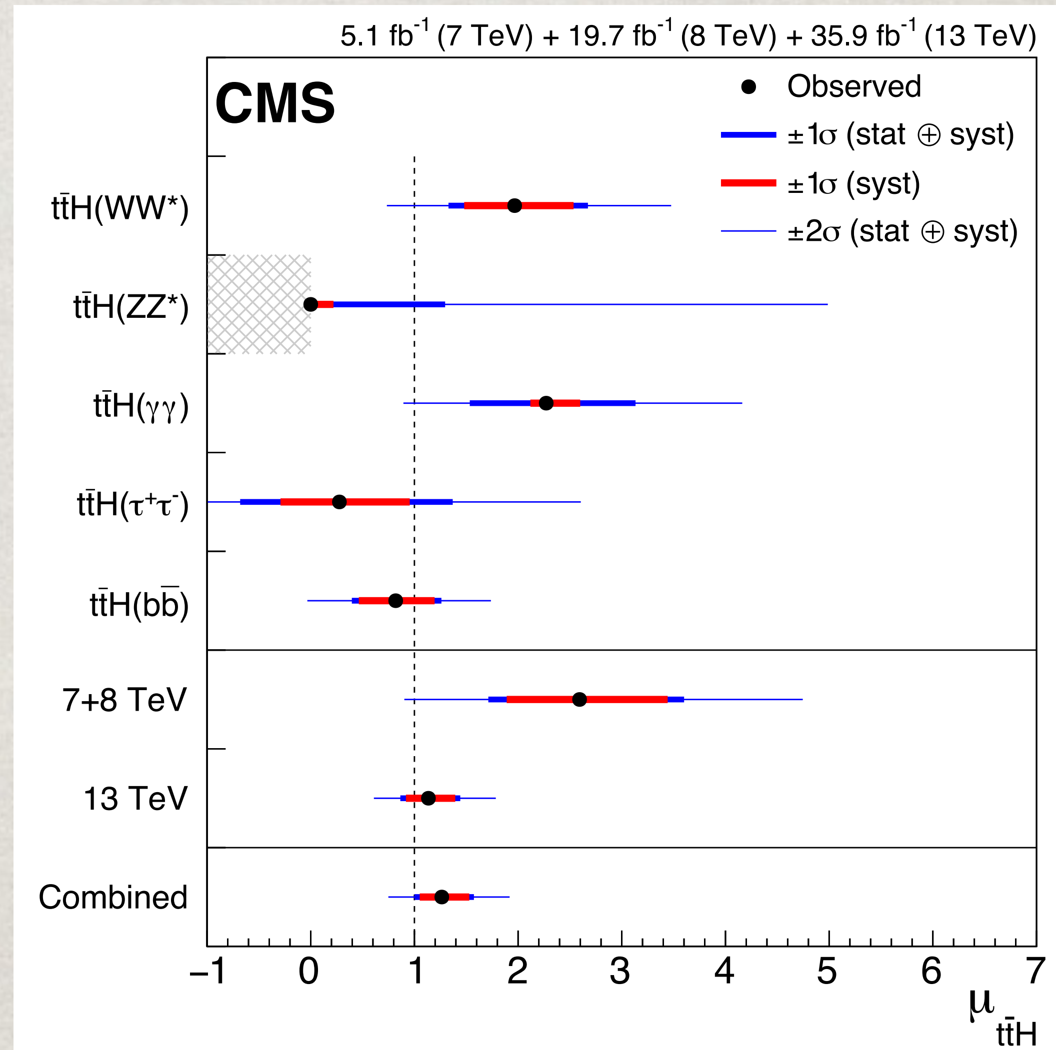
- Studied within general $\gamma\gamma$ or ZZ*(4ℓ)analysis
- Dedicated selection to enhance ttH signature
- H→$\gamma\gamma$
  - Leptonic: ≥1ℓ + ≥2jets + ≥1b-jet
  - Hadronic: ≥3jets + ≥1b-jet
- H→4ℓ
  - ≥4jets + ≥1b-jet or one additional lepton





TTH COMBINATION





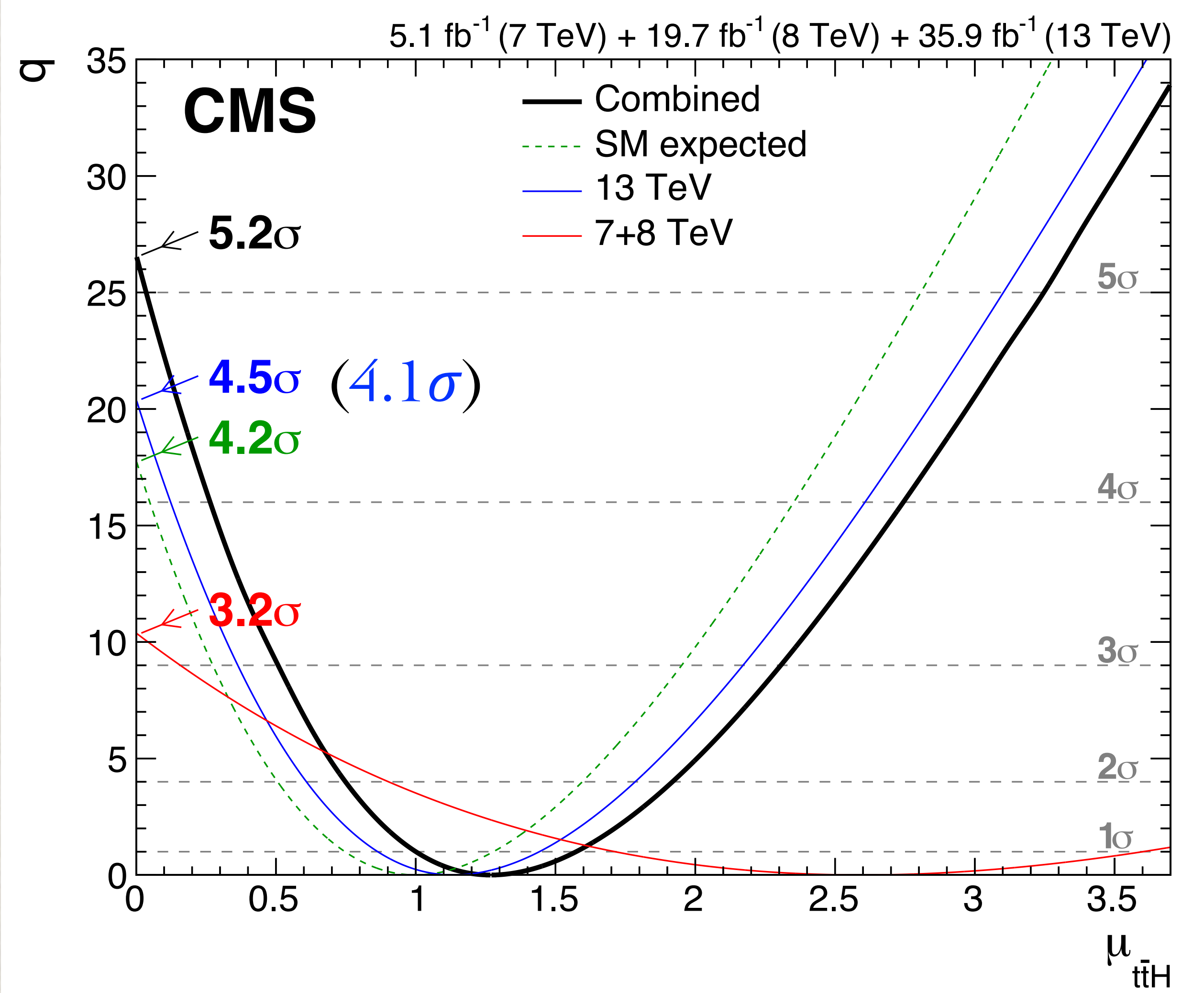
Parameter	Best fit
$\mu_{\mathrm{t\bar{t}H}}^{\mathrm{WW^*}}$	$1.97^{+0.71}_{-0.64}$ $\left(^{+0.57}_{-0.54}\right)$
$\mu_{\mathrm{t\bar{t}H}}^{\mathrm{ZZ^*}}$	$0.00^{+1.30}_{-0.00}$ $\left(^{+2.89}_{-0.99}\right)$
$\mu_{\mathrm{t\bar{t}H}}^{\gamma\gamma}$	$2.27^{+0.86}_{-0.74}$ $\left(^{+0.73}_{-0.64}\right)$
$\mu_{\mathrm{t\bar{t}H}}^{\tau^+\tau^-}$	$0.28^{+1.09}_{-0.96}$ $\left(^{+1.00}_{-0.89}\right)$
$\mu_{\mathrm{t\bar{t}H}}^{\mathrm{b\bar{b}}}$	$0.82^{+0.44}_{-0.42}$ $\left(^{+0.44}_{-0.42}\right)$
$\mu_{\mathrm{t\bar{t}H}}^{\mathrm{7+8\,TeV}}$	$2.59^{+1.01}_{-0.88}$ $\left(^{+0.87}_{-0.79}\right)$
$\mu_{\mathrm{t\bar{t}H}}^{\mathrm{13\,TeV}}$	$1.14^{+0.31}_{-0.27}$ $\left(^{+0.29}_{-0.26}\right)$
$\mu_{\mathrm{t\bar{t}H}}$	$1.26^{+0.31}_{-0.26}$ $\left(^{+0.28}_{-0.25}\right)$

- Overall consistent with SM
- Excess in some decay modes or datasets

LATEST RESULTS

ATLAS 36.1 fb^{-1}(13 TeV)

Channel	Best-fit μ		Significance	
	Observed	Expected	Observed	Expected
Multilepton	$1.6\ ^{+0.5}_{-0.4}$	$1.0\ ^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \to b\bar{b}$	$0.8\ ^{+0.6}_{-0.6}$	$1.0\ ^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \to \gamma\gamma$	$0.6\ ^{+0.7}_{-0.6}$	$1.0\ ^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \to 4\ell$	< 1.9	$1.0\ ^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2\ ^{+0.3}_{-0.3}$	$1.0\ ^{+0.3}_{-0.3}$	4.2σ	3.8σ



- ATLAS 13TeV significance: $4.2\sigma(3.8\sigma)$
- CMS 7+8+13TeV significance: $5.2\sigma(4.2\sigma)$

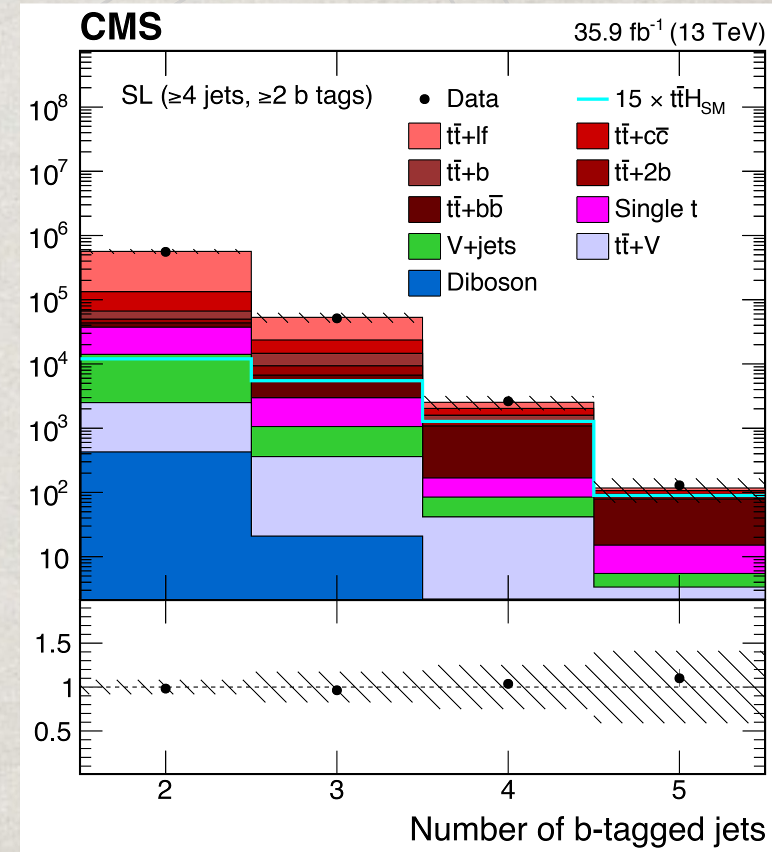
ttH @ CMS

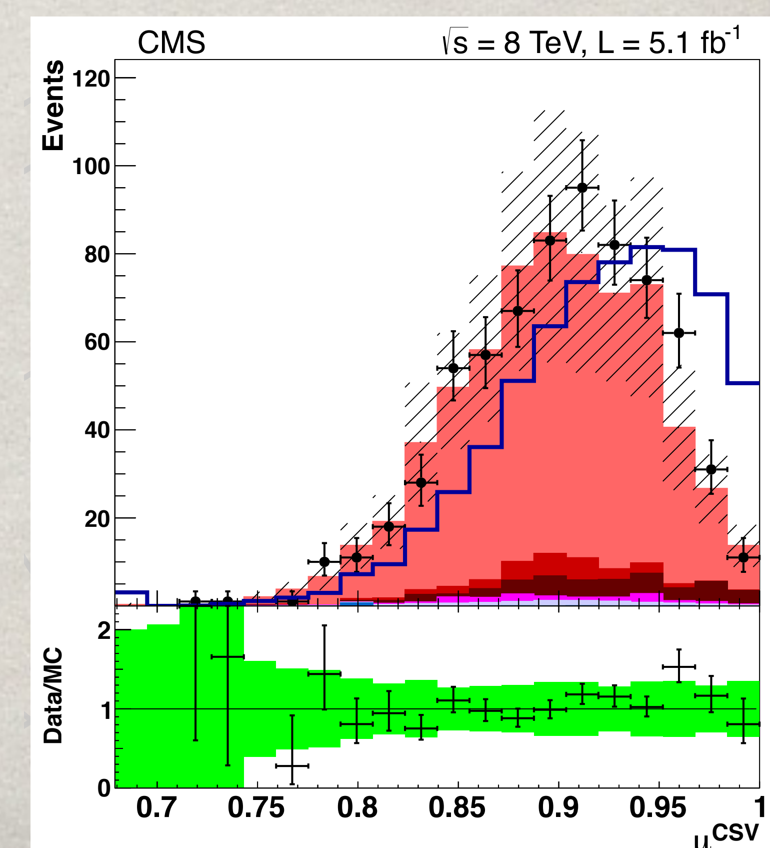
	Decay Mode	Paper	Data(fb^{-1})
7TeV	bb	x	5
8TeV	bb/ ττ/WW/ZZ/γγ	1 bb* 1 combination	19.5
13TeV(2016)	bb/ ττ/WW/ZZ/γγ	2 bb 1 ττ/WW/ZZ 1 comb.	35.9

- ttH effort started in H→bb mode
- B-tagging has played a big role in ttH, especially in ttH(bb)

TTH(BB) & B-TAGGING

- Lots of b-jets in the final state for ttH(bb)
- Several reasons we need to model the b-tagging discriminants of jets correctly
  - events are categorized based on #b-tagged jets(b-jets)
  - discriminant distributions have good separation power between S and B
- A new calibration method to correct the jet b-tagging modeling in MC was developed within the ttH(bb) effort
  - one of the official BTV recipes
  - benefits many analyses involving b-jets





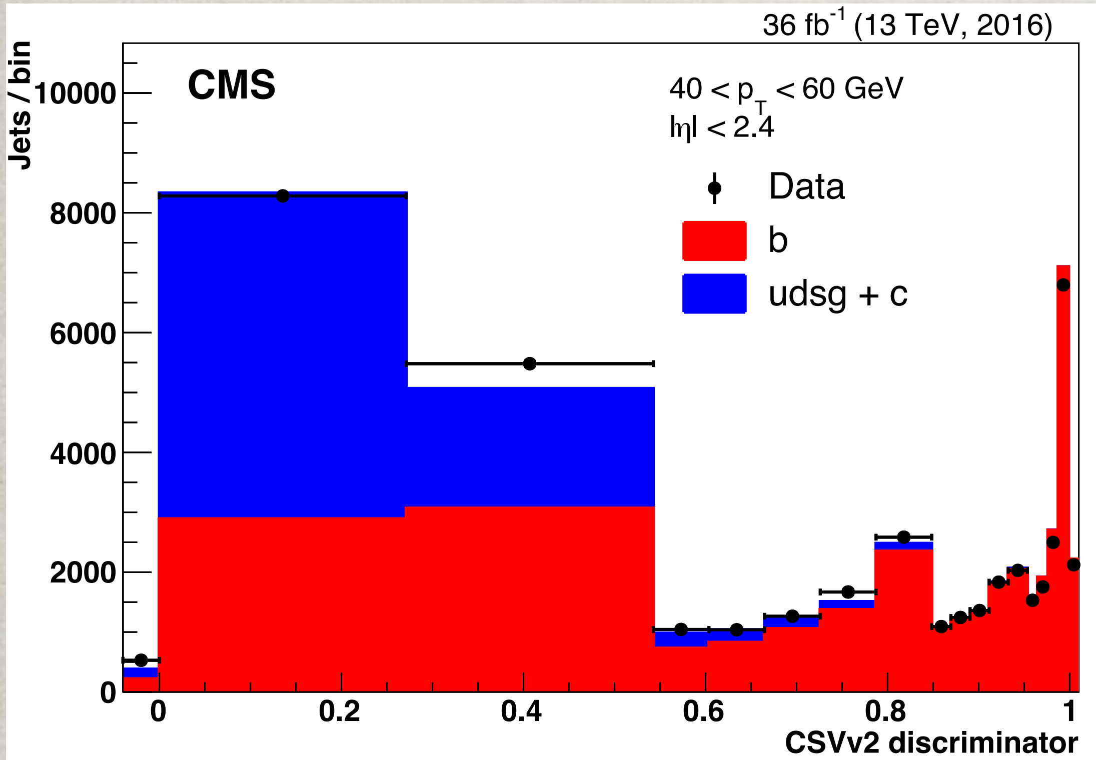
TAG AND PROBE

- Tag and probe method to calculate CSV* scale factors bin-by-bin
  - **Heavy flavor SF**: **DIL ttbar** enriched control region (2 jets, ≥1 b-tag)
  - **Light flavor SF**: **DIL Z+jets** enriched control region (2 jets, ≤1 b-tag)
- Require one jet to be (anti) tagged, account for LF (HF) contamination(charm is always subtracted), correct the overall probe jet CSV distribution in MC to match the data
- Scale factors defined as: $$SF(CSV, p_T, \eta) = \frac{Data - MC_A}{MC_B}$$

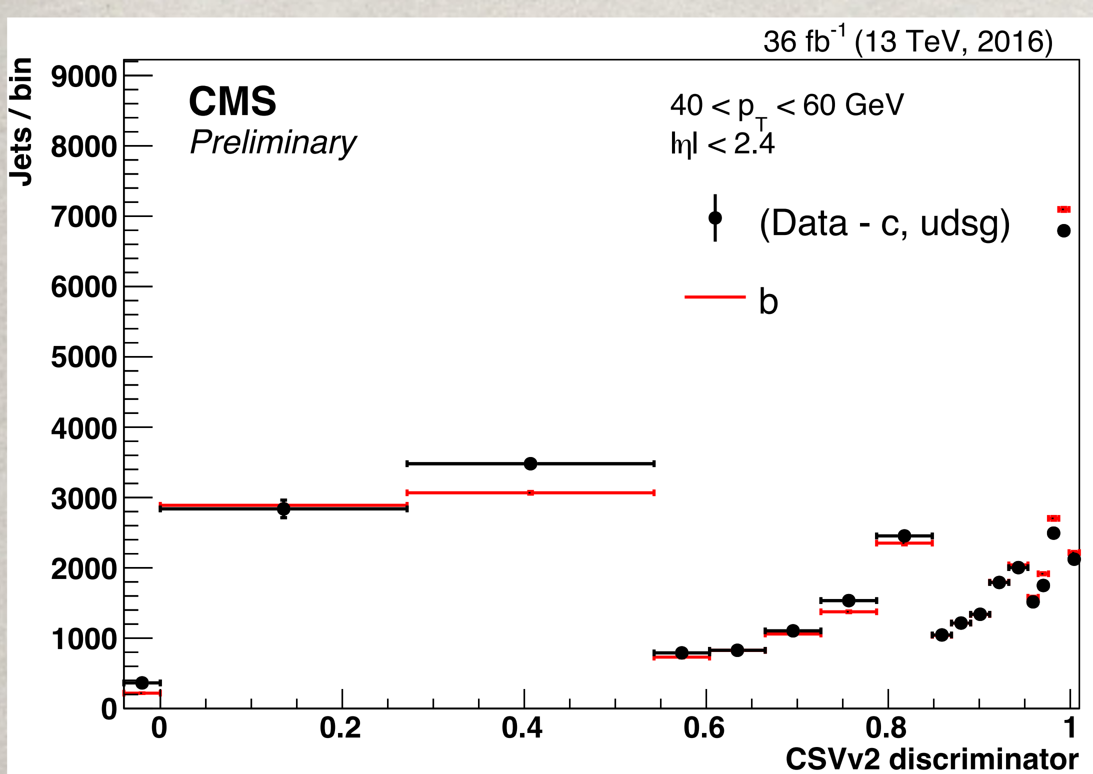
  [A/B = HF/LF]

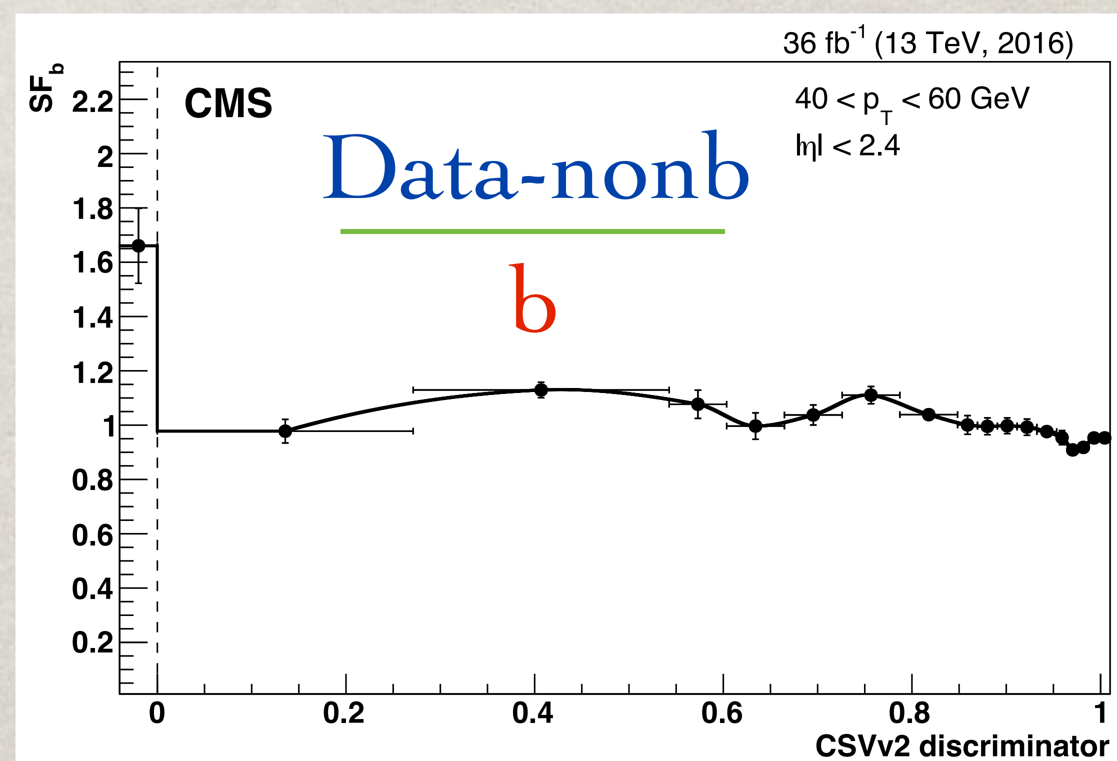
- Test method in semi-leptonic ttbar enriched control sample

HEAVY FLAVOR SCALE FACTOR

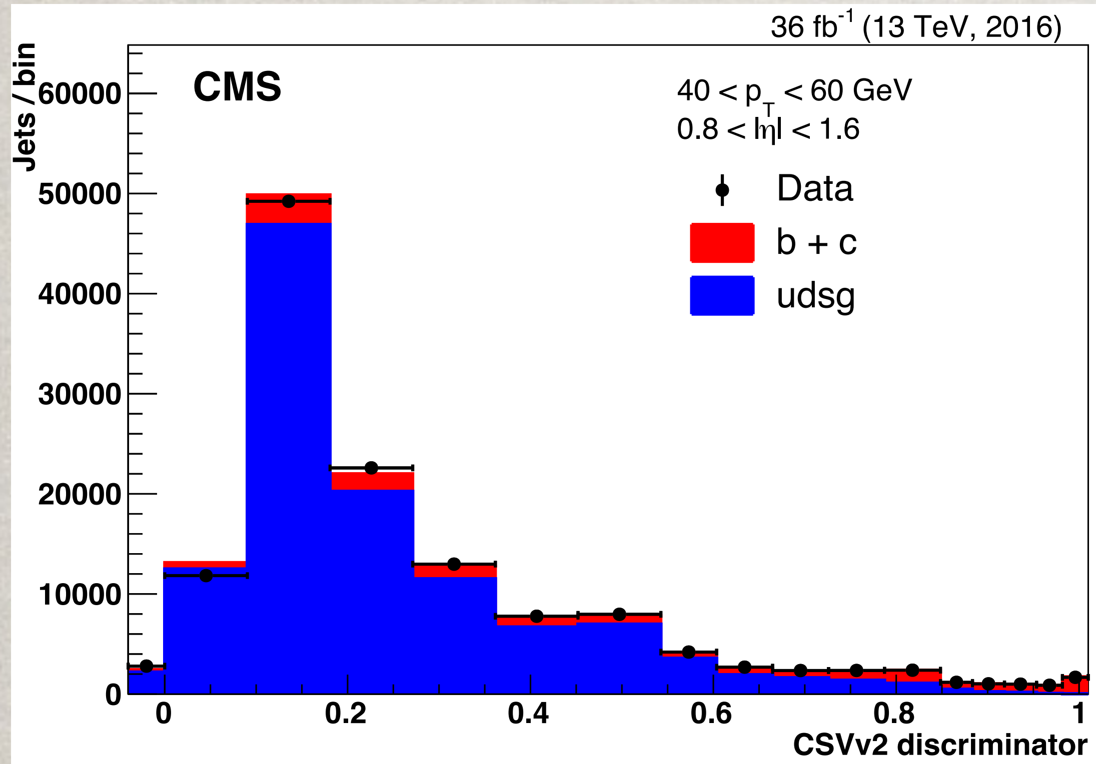


- DIL ttbar enriched control region
  - 2 leptons(ee,μμ,eμ) and 2 jets
  - $|M_{ll}-91|>10$GeV, MET>50GeV
  - Tag jet passes WPMedium
- P_T bins: [20, 30], [30, 50], [50, 70], [70, 100], [≥100]GeV
- η bins: [0, 2.4]

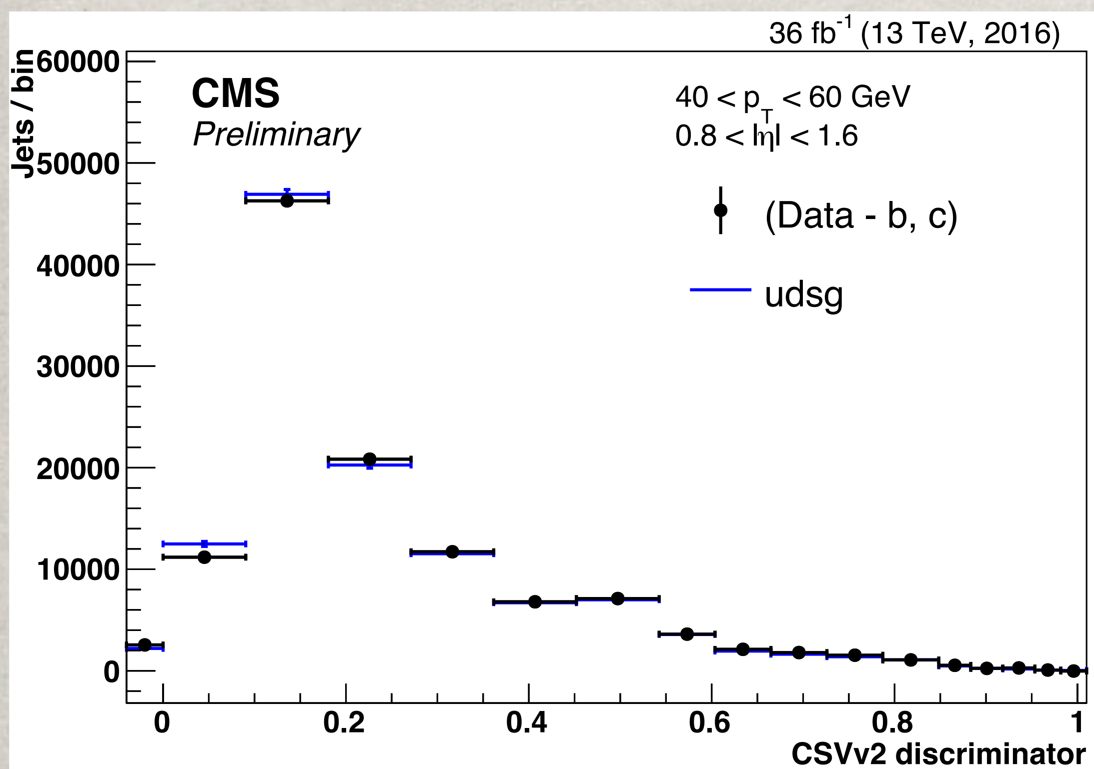


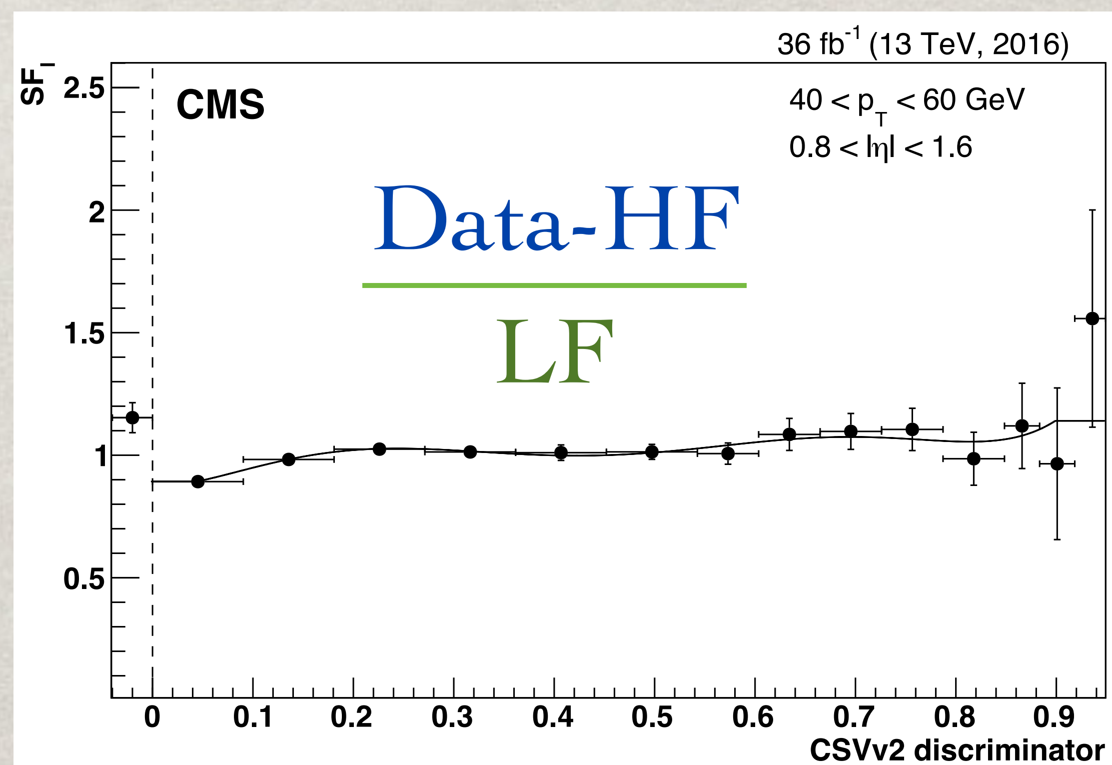


LIGHT FLAVOR SCALE FACTOR



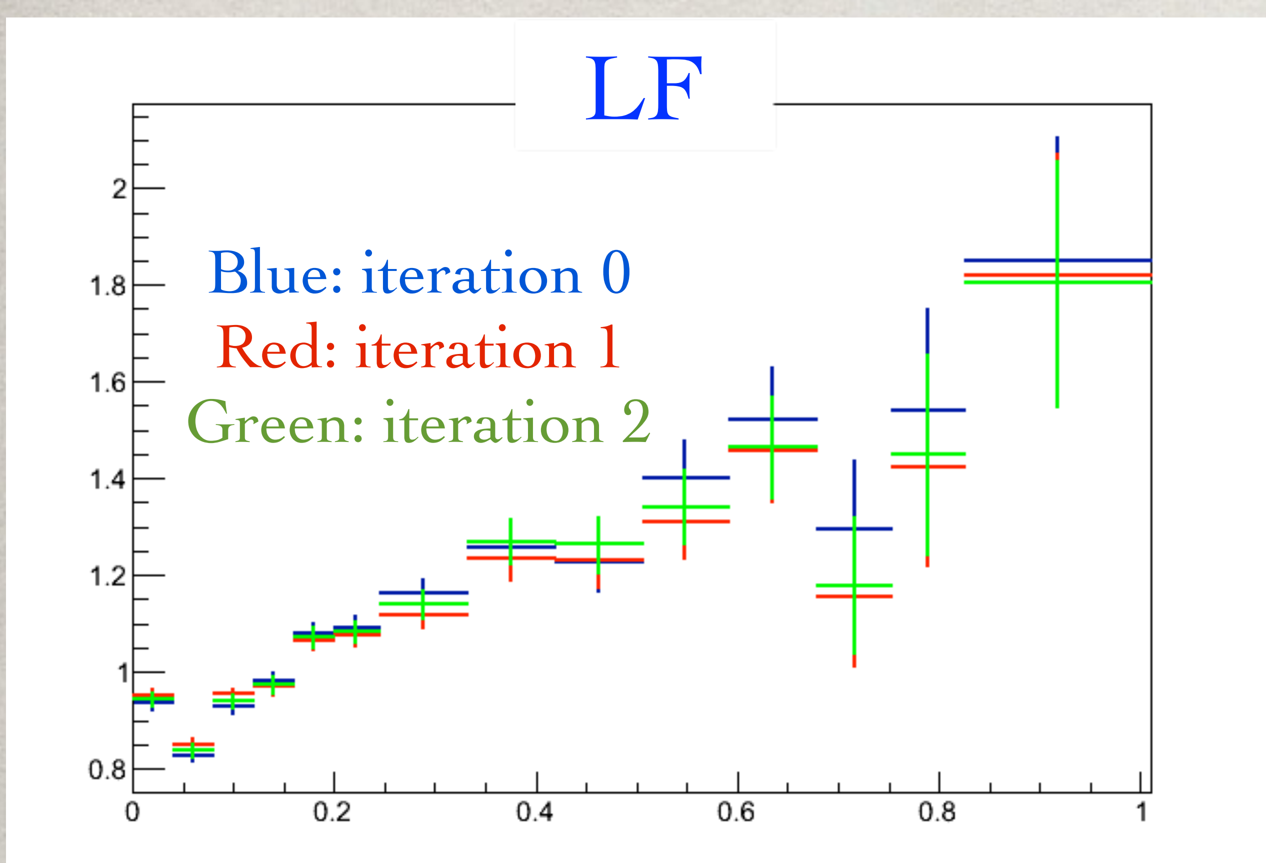
- DIL Z+jets enriched control region
  - 2 leptons(ee,μμ) and 2 jets
  - $|M_{ll}-91|<10$GeV, MET<30GeV
  - Tag jet fails WPLoose
- P_T bins: [20, 30], [30, 40], [40, 60], [≥60]GeV
- η bins: [0, 0.8], [0.8, 1.6], [1.6, 2.4]

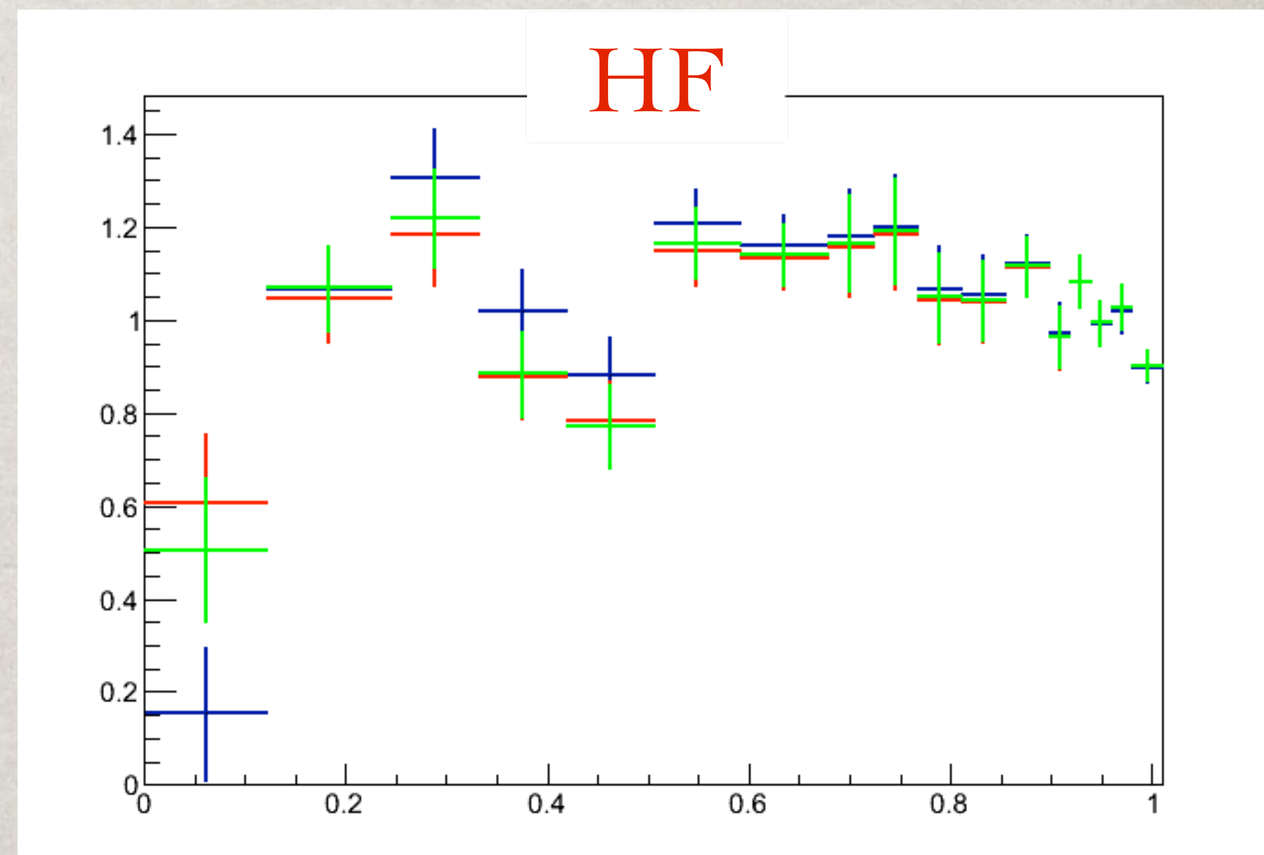




ITERATIVE TECHNIQUE

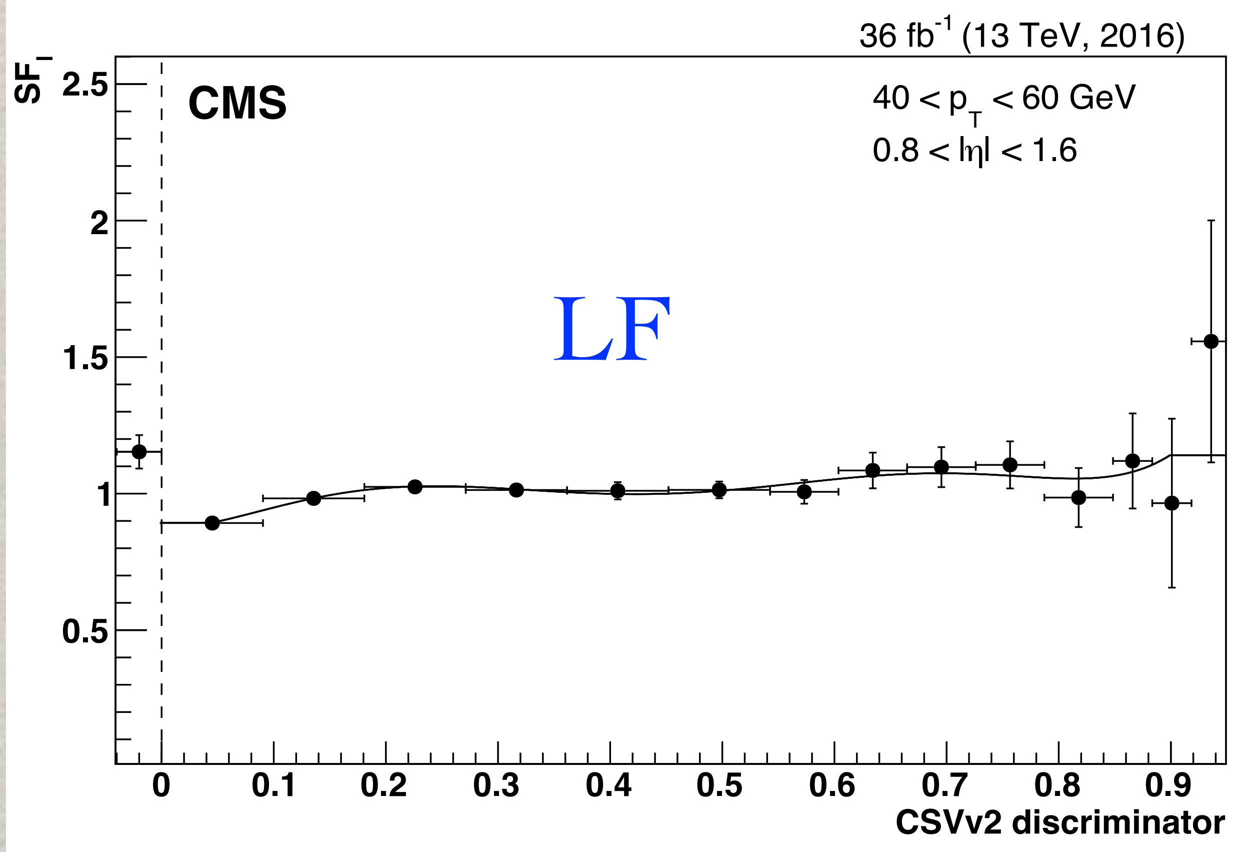
- During the calculation of the scale factors, apply the scale factors we got previously
- This is necessary because one needs the LF/HF SF to subtract the HF/LF contamination in the control region
- Scale factors converge after a few iterations

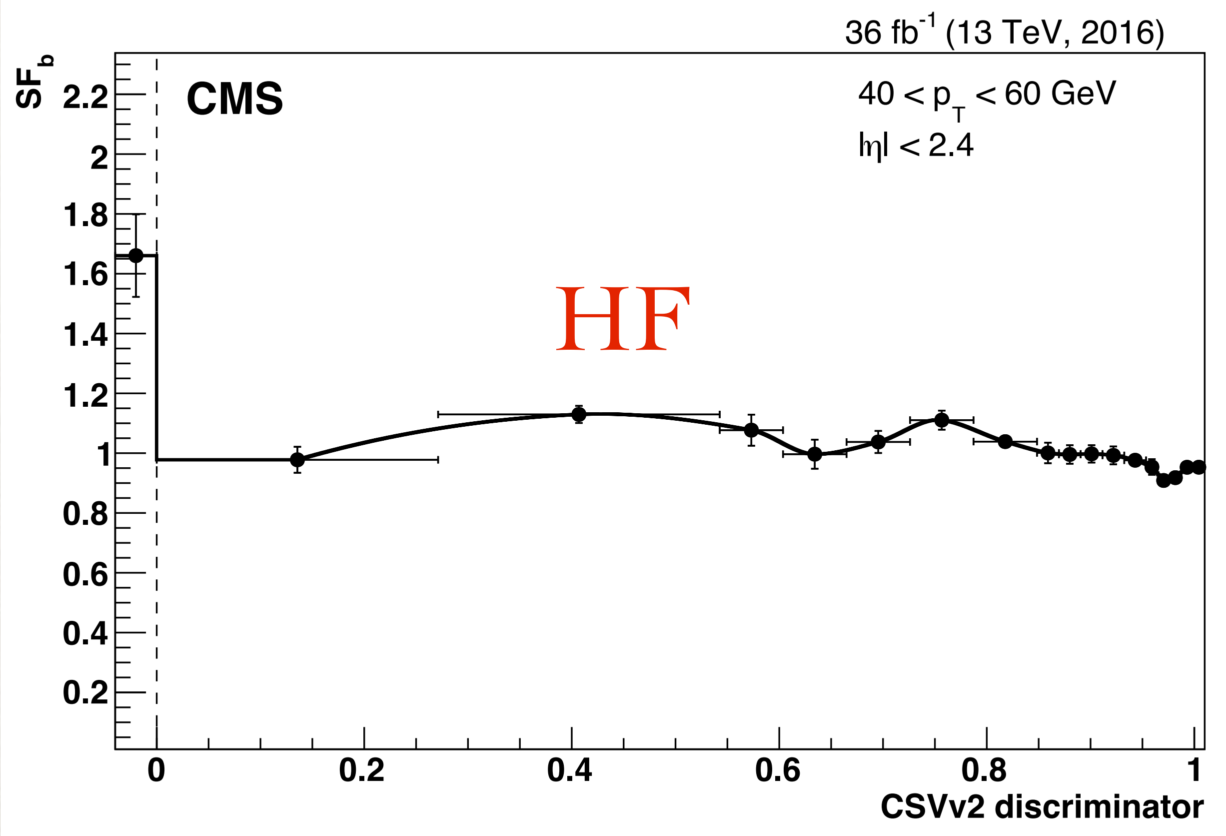




FITTING/INTERPOLATION

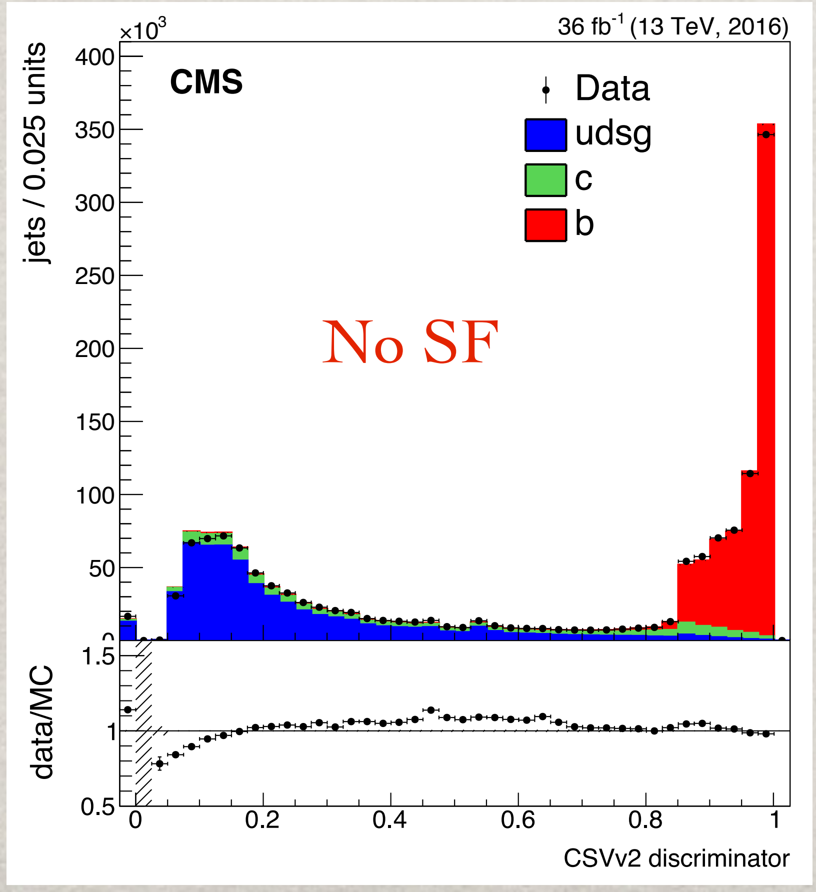
- Instead of binned scale factors, try to get a continuous form
- LF SF: fit to 6th order polynomial
- HF SF: complicated shape difficult to parameterize, interpolate between points

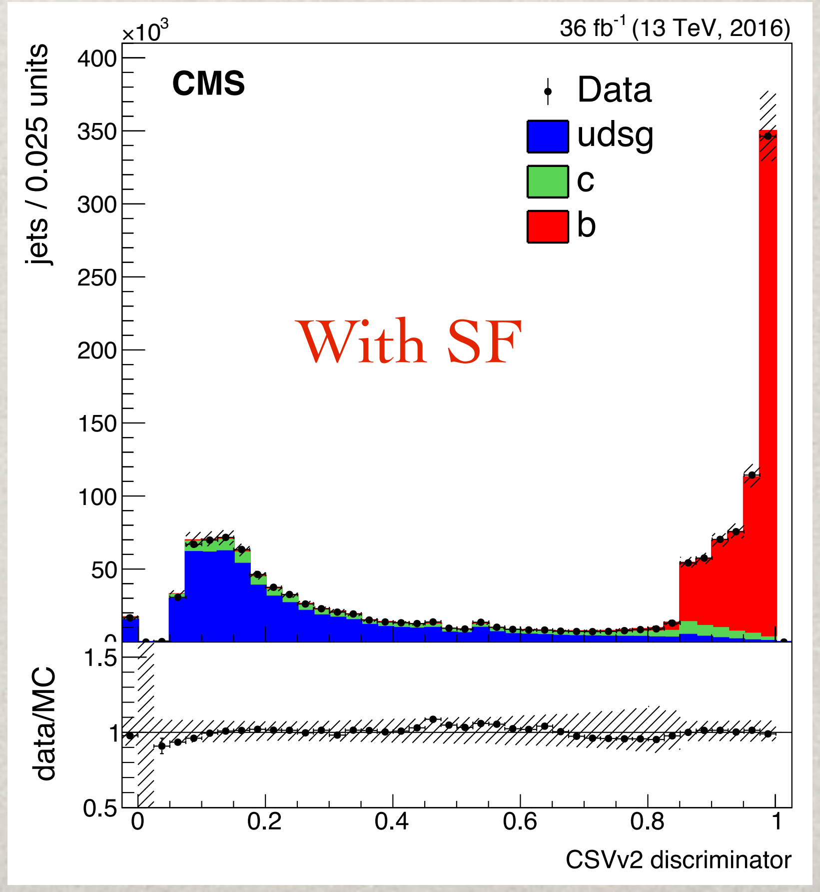




SF APPLICATION

- Apply the Scale Factors based on jet flavor:
  - for b jets, assign heavy flavor SF
  - for light jets, assign light flavor SF
  - for c jets, no correction
- Final scale factor for each event is: $SF_{total} = SF_{jet1} * SF_{jet2} * \ldots$
- SFs applied in ttH(bb) and ttH(multi-lepton) channels, significant improvement for Data/MC agreement





MORE B-TAGGING

- Better flavor tagging would help ttH in many ways
  - a small increase in tagging efficiency would multiply for final states with many b-jets (e.g. ttH(bb))
  - sophisticated algorithms could enable us to find control regions to better model tt+b/2b/bb/cc processes
- B-tagging at trigger level
  - crucial for tt(0ℓ)H(bb)
  - lepton+b-tagging cross triggers to increase efficiency
- B-tagging in boosted region at 13TeV
  - identify boosted Top or Higgs decaying to "b-jets", improve event reconstruction efficiency

SUMMARY

- ttH directly probe Top-Higgs Yukawa coupling
- Latest ttH results at LHC:
  - ATLAS: evidence@13TeV with $4.2\sigma(3.8\sigma)$
  - CMS: observation@7+8+13TeV with $5.2\sigma(4.2\sigma)$
- B-tagging played a big role in ttH in various aspects
- Future improvement from b-tagging will further increase the sensitivity of ttH searches
- We need to continue the nice collaboration between the ttH group and the BTV group

BACKUP

SAMPLES AND SELECTION

- This method uses the same di-lepton datasets as ttH:
  - DoubleMu, DoubleElectron and MuEG
- MC samples: mainly ttbar, Z+jets samples, including other small contribution samples as well (ttV, wjets, single top and diboson)
- General selection:
  - two oppositely charged leptons(e or μ)
  - exactly two jets

B-TAGGING VARIABLES

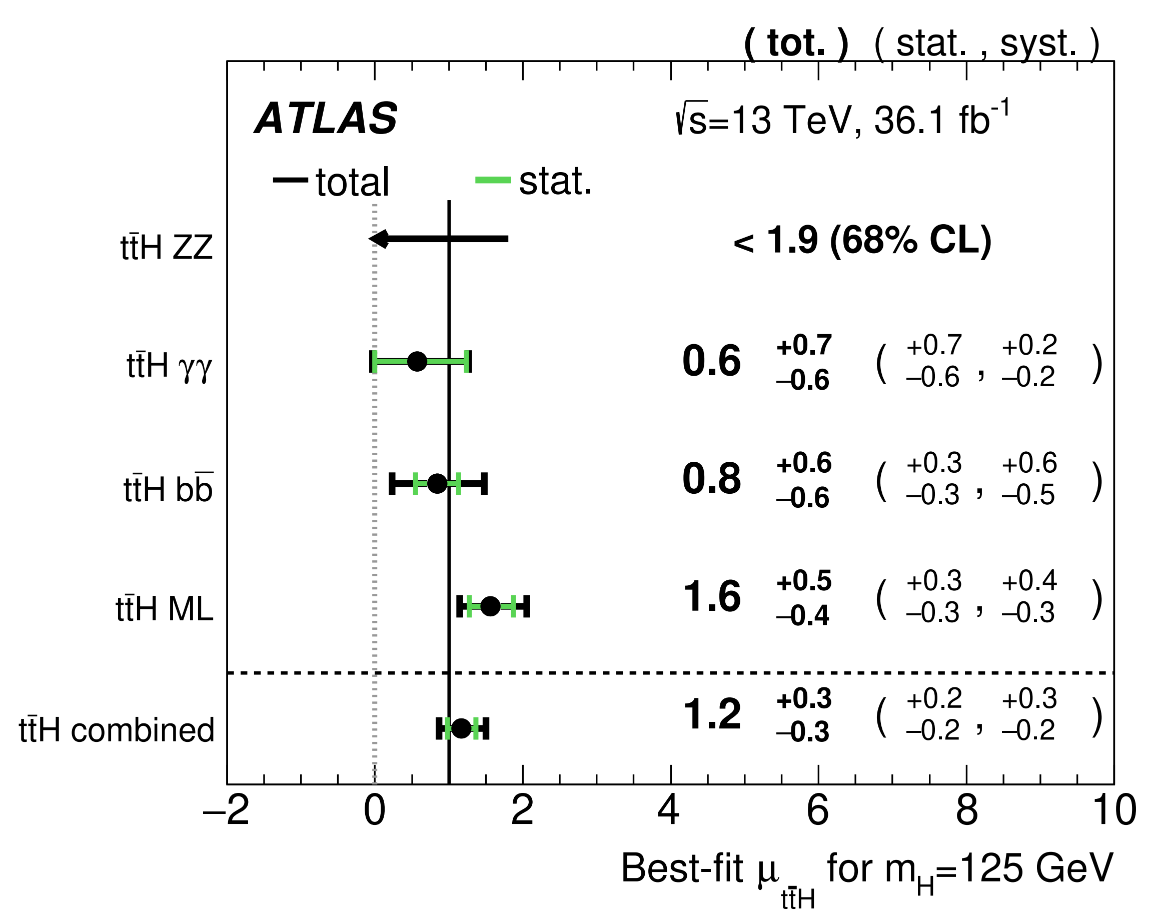
Variable	Definition	SL (4jets, ≥ 3b tags)	SL (5jets, ≥ 3b tags)	SL (≥ 6jets, ≥ 3b tags)	DL (≥ 4jets, 3b tags)	DL (≥ 4jets, ≥ 4 b tags)
N_b (tight)	number of b-tagged jets at the tight b tagging working point with 0.1% mis-tag rate	+	+	+	-	-
BLR	likelihood ratio discriminating between 4 b quark jets and 2 b quark jets events	+	+	+	-	-
BLR^{trans}	transformed BLR defined as $\ln[BLR/(1.0 - BLR)]$	+	+	+	-	-
d_j^{avg}	average b tagging discriminant value of all jets	+	+	+	-	-
d_b^{avg}	average b tagging discriminant value of b-tagged jets	+	+	+	+	+
d_{non-b}^{avg}	average b tagging discriminant value of non-b-tagged jets	-	-	-	+	+
$\sum_b (d - d_b^{avg})$	squared difference between the b tagging discriminant value of a b-tagged jet and the average b tagging discriminant values of all b-tagged jets, summed over all b-tagged jets	+	+	+	-	-
d_j^{max}	maximal b tagging discriminant value of all jets	+	+	+	-	-
d_b^{max}	maximal b tagging discriminant value of b-tagged jets	+	+	+	-	-
d_j^{min}	minimal b tagging discriminant value of all jets	+	+	+	-	-
d_j^{min}	minimal b tagging discriminant value of b-tagged jets	+	+	+	-	-
d_2	second highest b tagging discriminant value of all jets	+	+	+	-	-

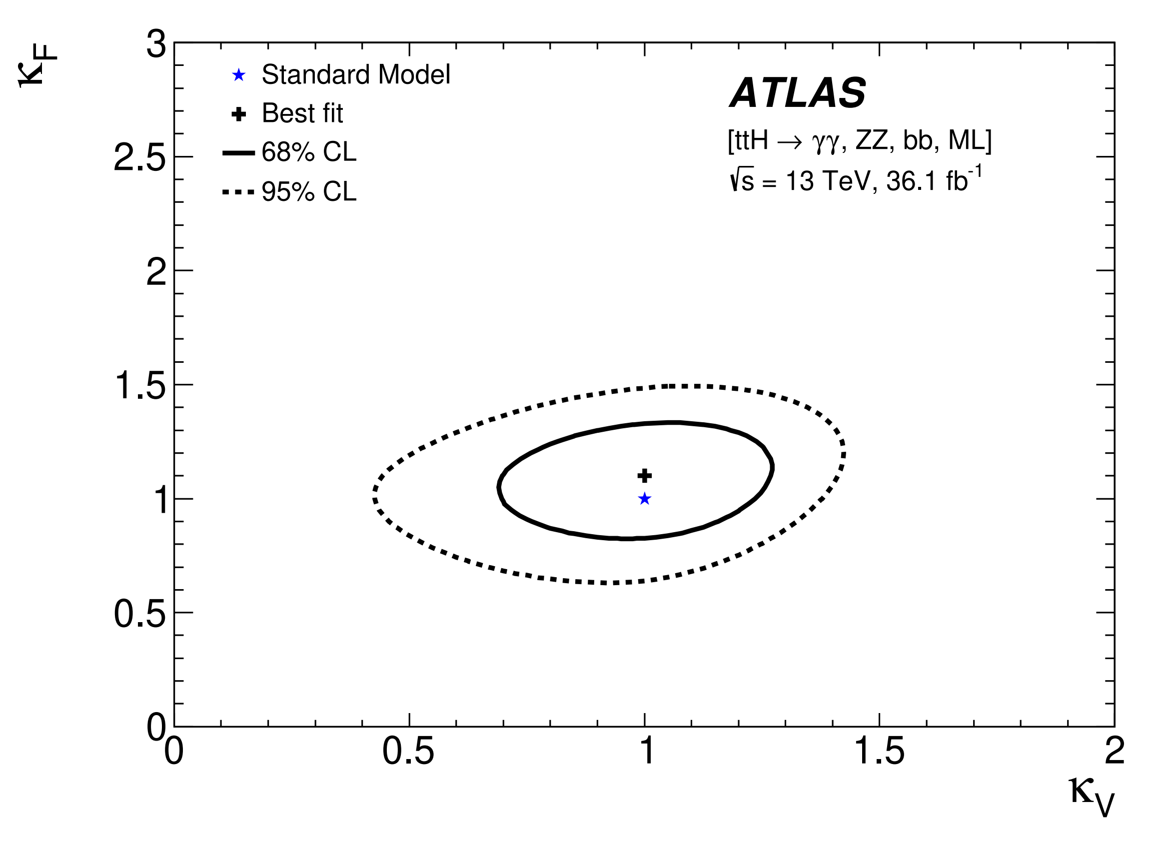
TTH@LHC

- Most recent $t\bar{t}H$ results by ATLAS and CMS (significance, $\mu_{t\bar{t}H} = \sigma_{t\bar{t}H}/\sigma_{SM}$)

	ATLAS 36.1 fb^{-1}	CMS
Run-1 combination	JHEP **1608** (2016) 045 4.4σ (exp: 2.0σ) $\mu_{t\bar{t}H} = 2.3^{+0.7}_{-0.6}$	
$t\bar{t}H(b\bar{b})$	**ATLAS-CONF-2017-076** 1.4σ μ= 0.84 $^{+0.64}_{-0.61}$	CMS-PAS-HIG-16-038 (13 fb^{-1}) $\mu_{t\bar{t}H} = -0.19 \pm 0.8$
$t\bar{t}H$ multilepton	**ATLAS-CONF-2017-077** 4.1σ μ= 1.6 $^{+0.5}_{-0.4}$	CMS-PAS-HIG-17-004 (ℓ only) 3.3σ (exp: 2.5σ) $\mu_{t\bar{t}H} = 1.5 \pm 0.5$ CMS-PAS-HIG-17-003 (τ_{had}) 1.4σ (exp: 1.8σ) $\mu_{t\bar{t}H} = 0.72^{+0.62}_{-0.53}$
$t\bar{t}H(ZZ \to 4\ell)$	ATLAS-CONF-2017-043 $\mu_{t\bar{t}H} < 7.7$	arXiv:1706.09936 $\mu_{t\bar{t}H} < 1.18$
$t\bar{t}H(\gamma\gamma)$	ATLAS-CONF-2017-045 1.8σ (exp: 1.0σ) $\mu_{t\bar{t}H} = 0.5 \pm 0.6$	CMS-PAS-HIG-16-040 3.3σ (exp: 1.5σ) $\mu_{t\bar{t}H} = 2.2^{+0.9}_{-0.8}$

TTH COMB @ATLAS



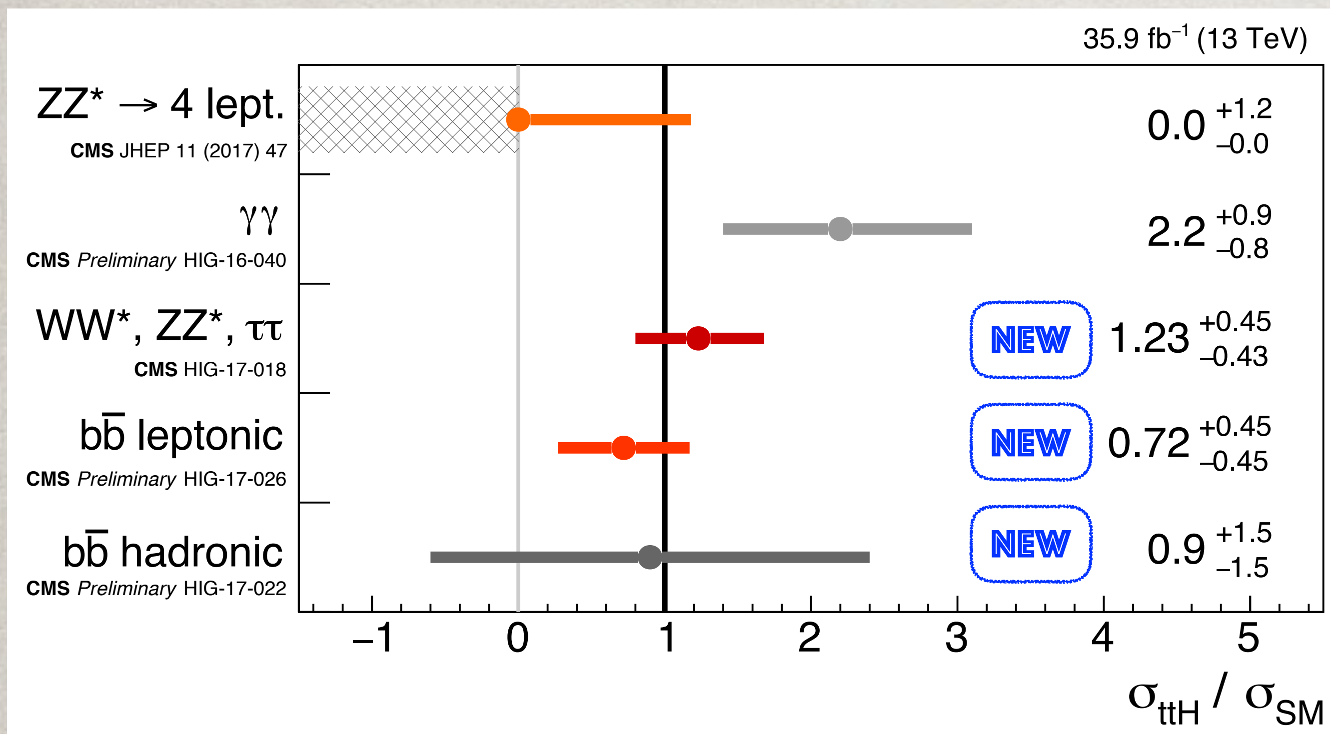


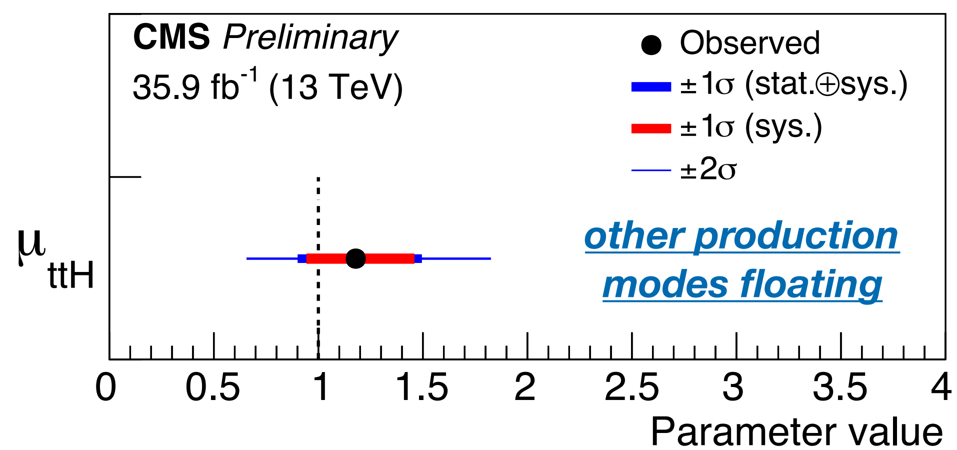
Channel	Best-fit μ Observed	Best-fit μ Expected	Significance Observed	Significance Expected
Multilepton	$1.6\ ^{+0.5}_{-0.4}$	$1.0\ ^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \to b\bar{b}$	$0.8\ ^{+0.6}_{-0.6}$	$1.0\ ^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \to \gamma\gamma$	$0.6\ ^{+0.7}_{-0.6}$	$1.0\ ^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \to 4\ell$	< 1.9	$1.0\ ^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2\ ^{+0.3}_{-0.3}$	$1.0\ ^{+0.3}_{-0.3}$	4.2σ	3.8σ

ttH comb @CMS

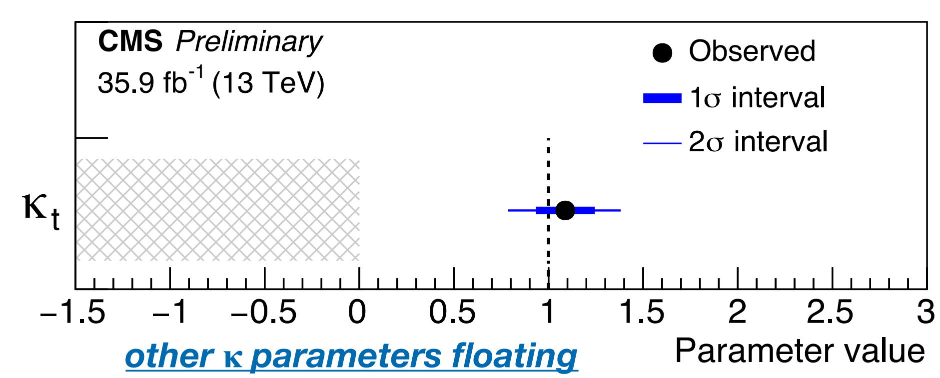
Analysis	CADI	Status	Categorie	Result (μ_{ttH})
H→ZZ→4l	HIG-16-041	Published	3	$0.00^{+1.19}_{-0.00}$
H→γγ	HIG-16-040	CWR-ended	2	$2.2^{+0.9}_{-0.8}$ $3.3\sigma(1.5\sigma)$
ttH→WW/ZZ/ττ	HIG-17-018	Submitted	19	$1.23^{+0.45}_{-0.43}$ 3.2σ (2.8σ)
ttH→bb (leptonic)	HIG-17-026	CWR	21	0.72 ± 0.45 1.6σ (2.2σ)
ttH→bb (hadronic)	HIG-17-022	Submitted	6	0.9 ± 1.5 $0.x\sigma(0.x\sigma)$
Run 1 (7+8 TeV) bb/ττ/WW/ZZ/γγ	HIG-13-029	Published	37	2.8 ± 1.0

TTH COMB @CMS





ttH		
Best fit value	Uncertainty Stat.	Syst.
$1.18 ^{+0.31}_{-0.27}$	$^{+0.16}_{-0.16}$	$^{+0.26}_{-0.21}$
$\left(^{+0.28}_{-0.25}\right)$	$\left(^{+0.16}_{-0.16}\right)$	$\left(^{+0.23}_{-0.20}\right)$



Best fit	Uncertainty Stat.	Syst.
$1.09 ^{+0.14}_{-0.14}$	$^{+0.08}_{-0.08}$	$^{+0.12}_{-0.12}$
$\left(^{+0.14}_{-0.15}\right)$	$\left(^{+0.08}_{-0.09}\right)$	$\left(^{+0.12}_{-0.12}\right)$