Measurements of Higgs production and decay in final states involving quarks

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on behalf of the CMS Collaboration
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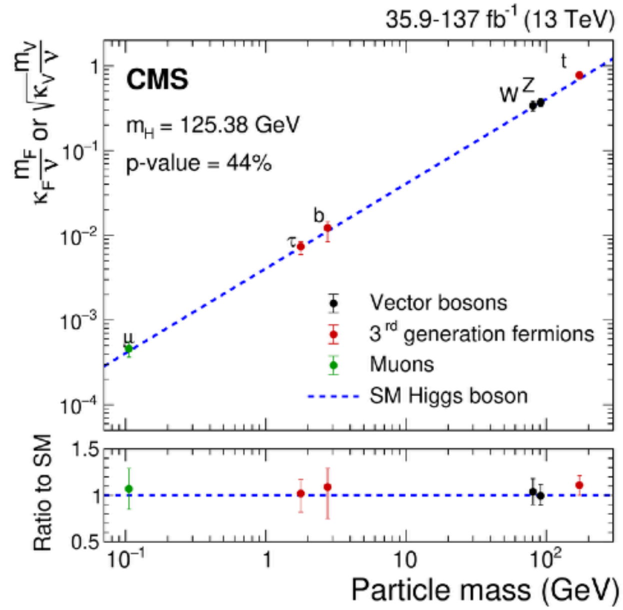
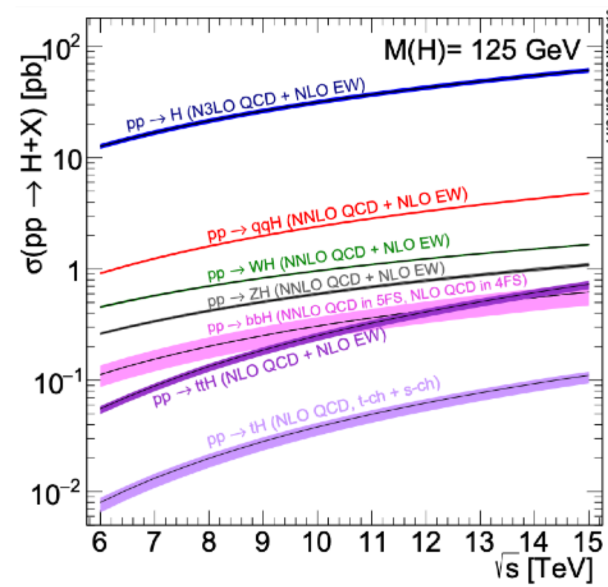
Introduction



- Since the observation of the Higgs boson almost 9 years ago in $H \to \gamma\gamma$ and $H \to ZZ^*$:
  - Efficient b(c)-tagging
  - More statistics
  - Improved analysis techniques
  - ➡ Allowed the measurements of 2nd and 3rd generation couplings



- Most recent CMS results on partial Run 2 data:
  - tH ($H \to b\bar{b}$)
  - ttH ($H \to b\bar{b}$)
  - VH ($H \to b\bar{b}$)
  - VH ($H \to c\bar{c}$, 20 times lower BR than $H \to b\bar{b}$)
  - ggH ($H \to b\bar{b}$)

Larger σ

tH ($H \rightarrow b\bar{b}$)

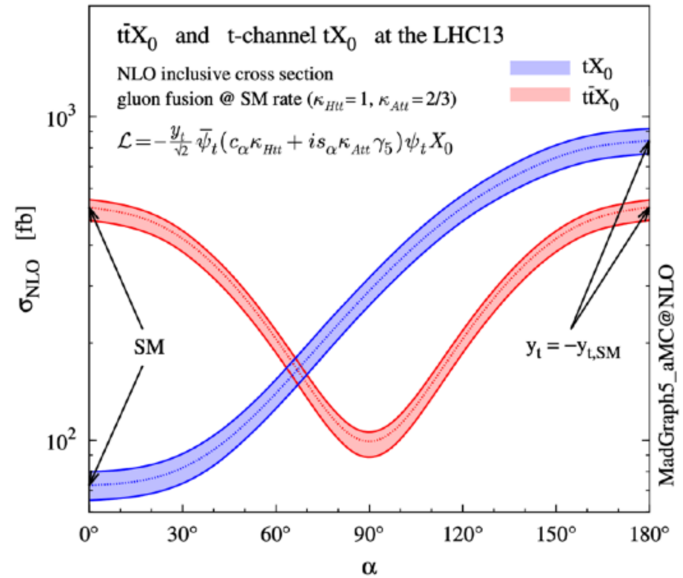
L=35.9 fb^{-1}@13 TeV

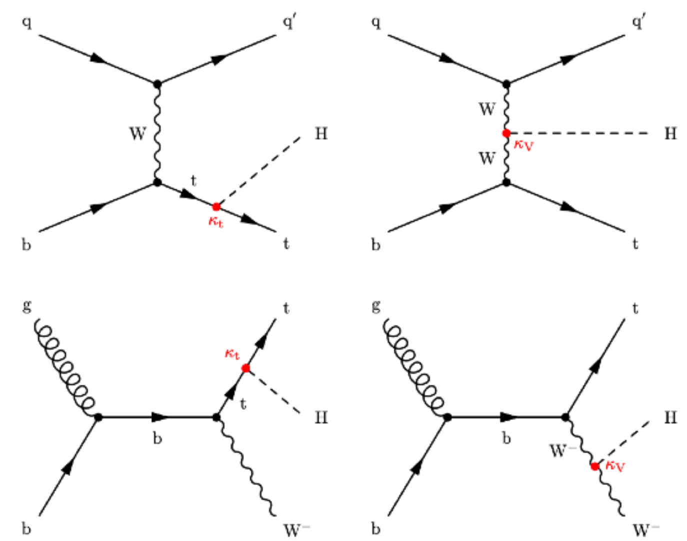
tH ($H \to b\bar{b}$)

Overview

[Phys. Rev. D 99, 092005]

- tH processes very rare in SM
  - Destructive interference between top and W couplings
- Can be greatly enhanced in BSM scenarios
  - Sensitive to the relative phase between top and W couplings
  - Sensitive to the value and the sign of y_t
  - Inverted top coupling leads to 10x increase in production



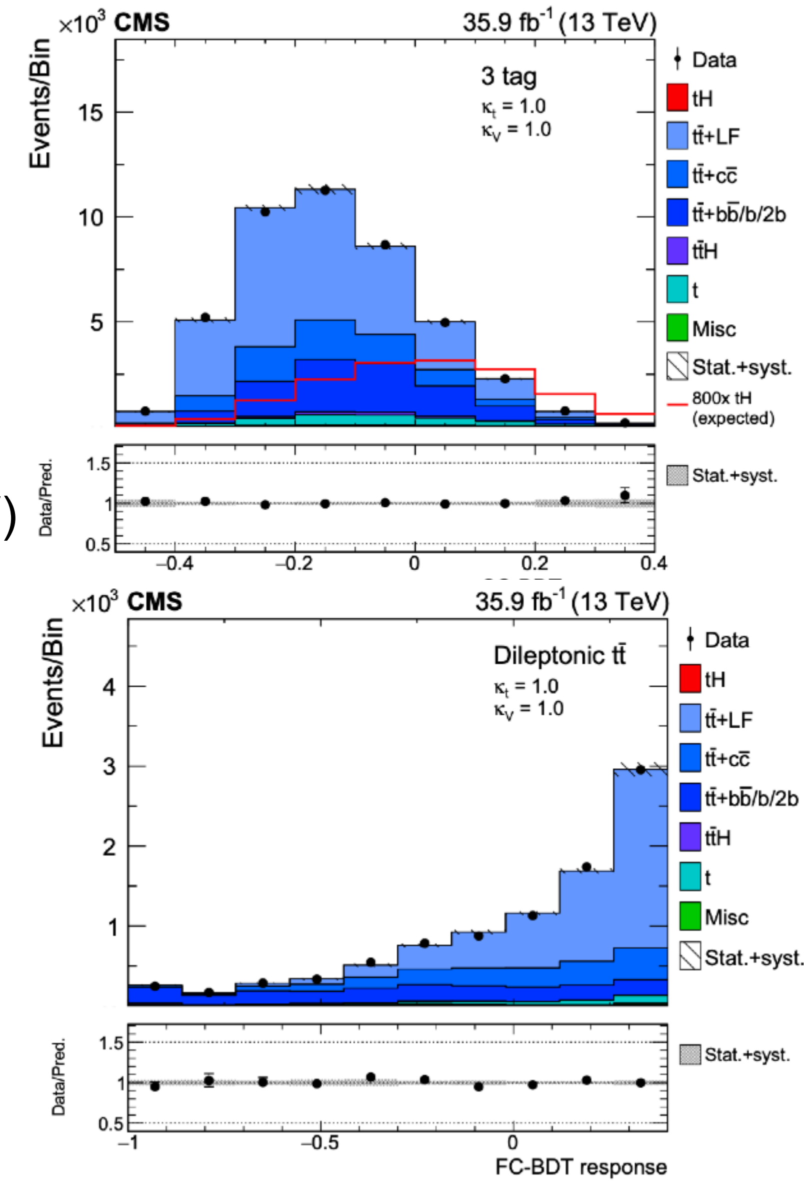


[Phys. Rev. D 99, 092005]

tH ($H \rightarrow b\bar{b}$)

Analysis strategy

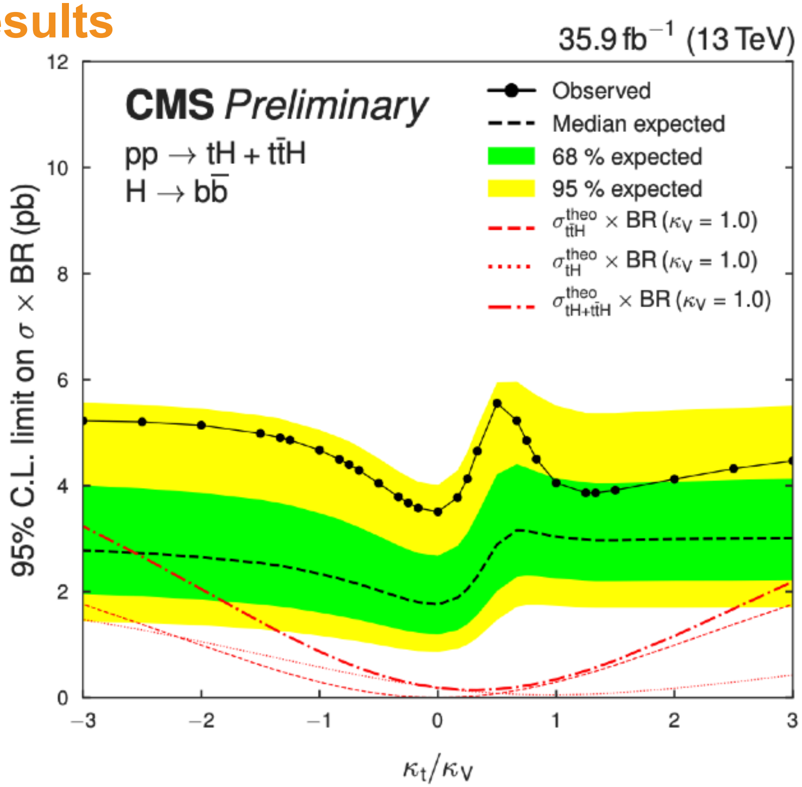
- Categorisation:
  - 3 and 4 b-tag SR,1 lepton, MET
  - 2 b-tag CR, 2 leptons, MET
- Jet Assignment BDT (tHq vs. tt vs. tHW)
  - Kinematics and b-tag as input
- $t\bar{t}$+jets: $t\bar{t}$+LF, $t\bar{t}$+$c\bar{c}$, $t\bar{t}$+$b\bar{b}$, $t\bar{t}$+b, $t\bar{t}$+2b
- 2 BDTs:
  - tHq vs. $t\bar{t}$+jets and ttV (SC-BDT)
  - $t\bar{t}$+bottom vs. $t\bar{t}$+light (FC-BDT)

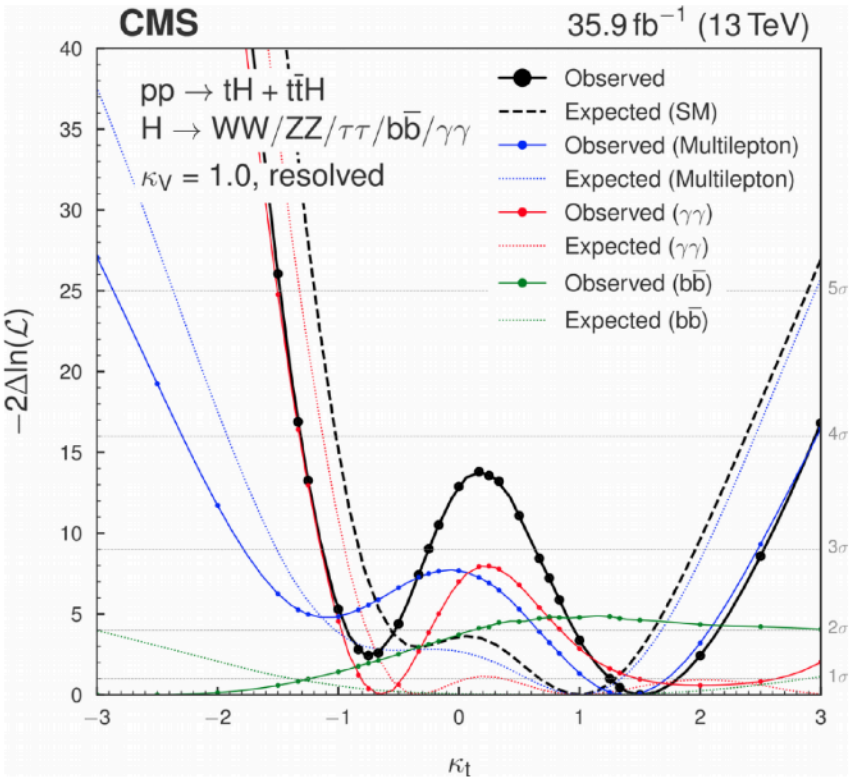


[Phys. Rev. D 99, 092005]

tH (H → $b\bar{b}$)

Results





- The tH (H → $b\bar{b}$) 35.9 fb^{-1}analysis upper limits are set at 6.88 pb
- Not sensitive enough to observe the channel, but important for constraints on κ_t
- Entered the combination paper:
  excluding κ_t < -0.9, -0.5 < κ_t < 0.9, κ_t > 2 at 95% C.L.

$t\bar{t}H$ ($H \rightarrow b\bar{b}$)

$L=35.9+41.5\ \mathrm{fb}^{-1}$@13 TeV

$t\bar{t}H$ ($H \rightarrow b\bar{b}$)

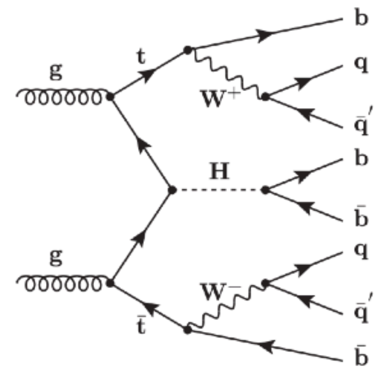
[CMS PAS HIG-18-030]

Overview

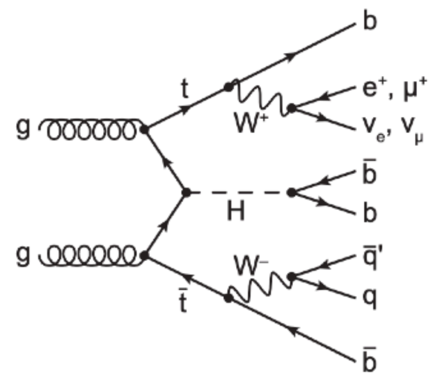
- The best production mode to directly measure the top-Higgs coupling
- Rare process (~1% of Higgs events), but clean $t\bar{t}$ signature
- $H \rightarrow b\bar{b}$ largest BR (58%)

Results in a complex final state:

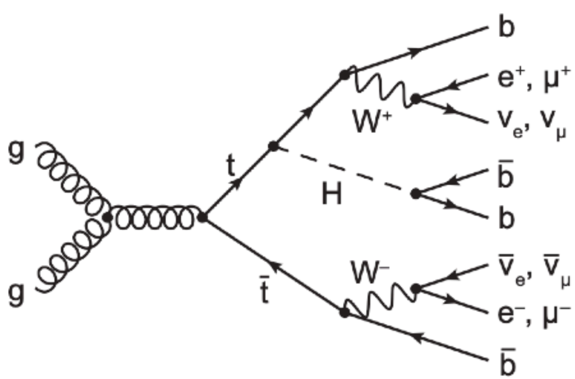
- Split to 3 channels by W decay modes: FH, SL, DL
- Important background:
  - $t\bar{t}$+Jets (FH, SL, DL)
  - QCD multijet (FH)



Fully Hadronic channel (FH)



Semileptonic channel (SL)



Dileptonic channel (DL)

$t\bar{t}H$ ($H \rightarrow b\bar{b}$)

Analysis strategy

Full hadronic channel:

- 6 categories: jet (7, 8, ≥9) and b-tag (3, ≥4) multiplicities
- Major **QCD multi-jet background** estimated from data
- Signal extraction: Matrix Element Method

Dileptonic channel:

- 5 categories: jet (3,4) and b-tag (2,3,≥3, ≥4) multiplicities
- Major **$t\bar{t}$ + jets background** (tH categorisation) estimated from simulation
- BDT trained for each category

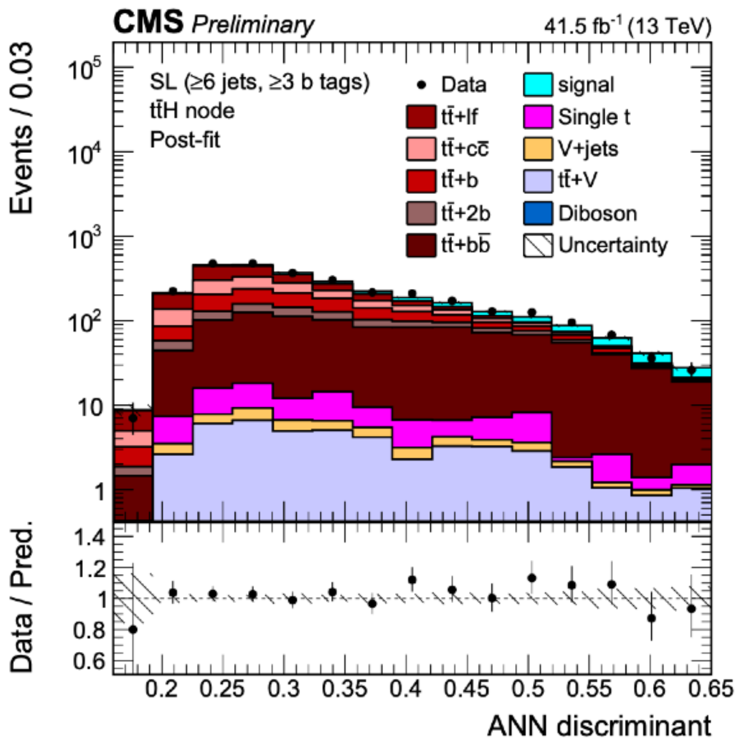
Semileptonic channel:

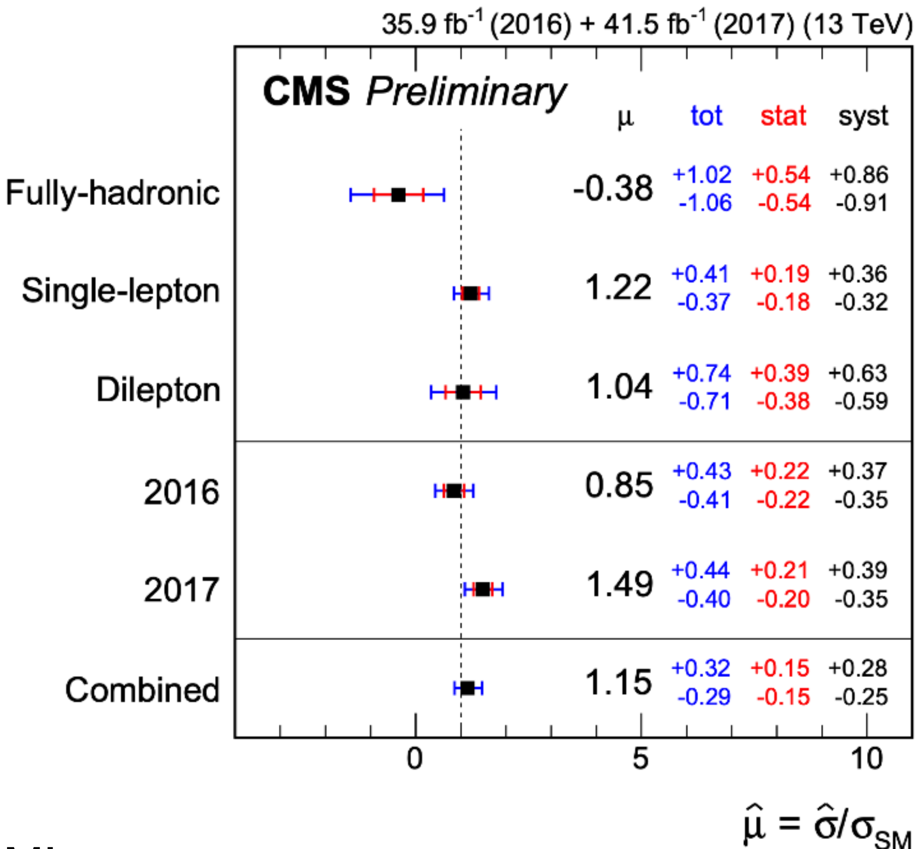
- 3 categories: (4, 5, ≥6) jets and at least ≥3 b-tagged jets
- Major **$t\bar{t}$ + jets background** estimated from simulation
- Further categorisation via multi-class NN: 1 signal node and 5 flavour-dependent nodes for $t\bar{t}$ + jets
- ANN output used as final discriminant

$t\bar{t}H$ ($H \rightarrow b\bar{b}$)

Results

[More post-fit plots]





- Excellent agreement with the SM!
- Limited by systematic uncertainties: theory uncertainties of signal and $t\bar{t}$+HF

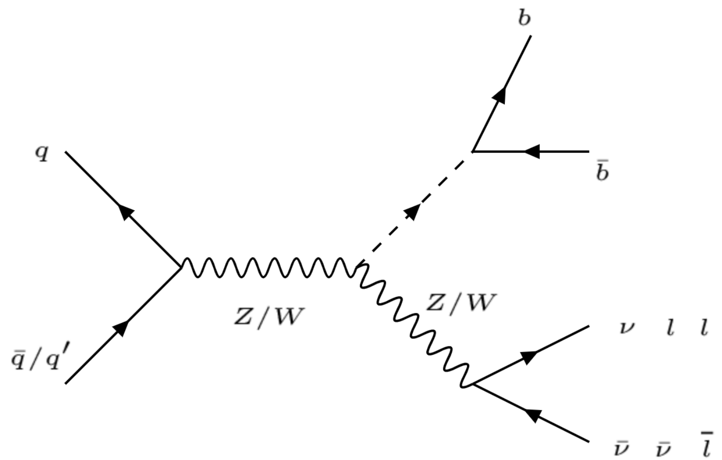
VH ($H \rightarrow b\bar{b}$)

L=35.9+41.5 fb^{-1}@13 TeV

[Phys. Rev. Lett. 121, 121801]

VH ($H \to b\bar{b}$)

Analysis strategy



- 3 channels are considered:
  - 0-lepton ($Z \to \nu\nu$),
  - 1-lepton ($W \to l\nu$)
  - 2 lepton ($Z \to \mu\mu$/ee)
- Higgs decay:
  - AK4 b-tagged jets (DeepCSV discriminator), DNN based regression [link]
- Background normalisation is obtained from control regions:
  - $t\bar{t}$; V + Heavy Flavour (HF) jets; V + Light Flavour (LF) jets
- Signal is extracted using DNN, + multi-output DNN in HF $Z \to \nu\nu$ and $W \to l\nu$ categories
- 2 cross-check analyses: VZ($b\bar{b}$) measurement and mass based analysis

[Phys. Rev. Lett. 121, 121801]

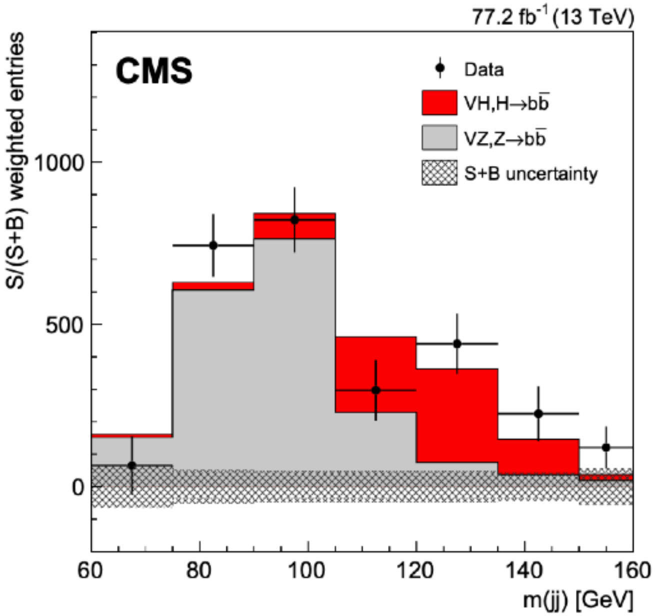
VH ($H \rightarrow b\bar{b}$)

Results

- The observation analysis for VH ($H \rightarrow b\bar{b}$) process
- The partial Run 2 analysis was combined with Run 1 measurement
- Consistent with the SM and statistically dominated [details]

$$[0.17\,(\mathrm{stat}) \pm 0.09\,(\mathrm{exp}) \pm 0.06\,(\mathrm{MC}) \pm 0.08\,(\mathrm{theo})]$$

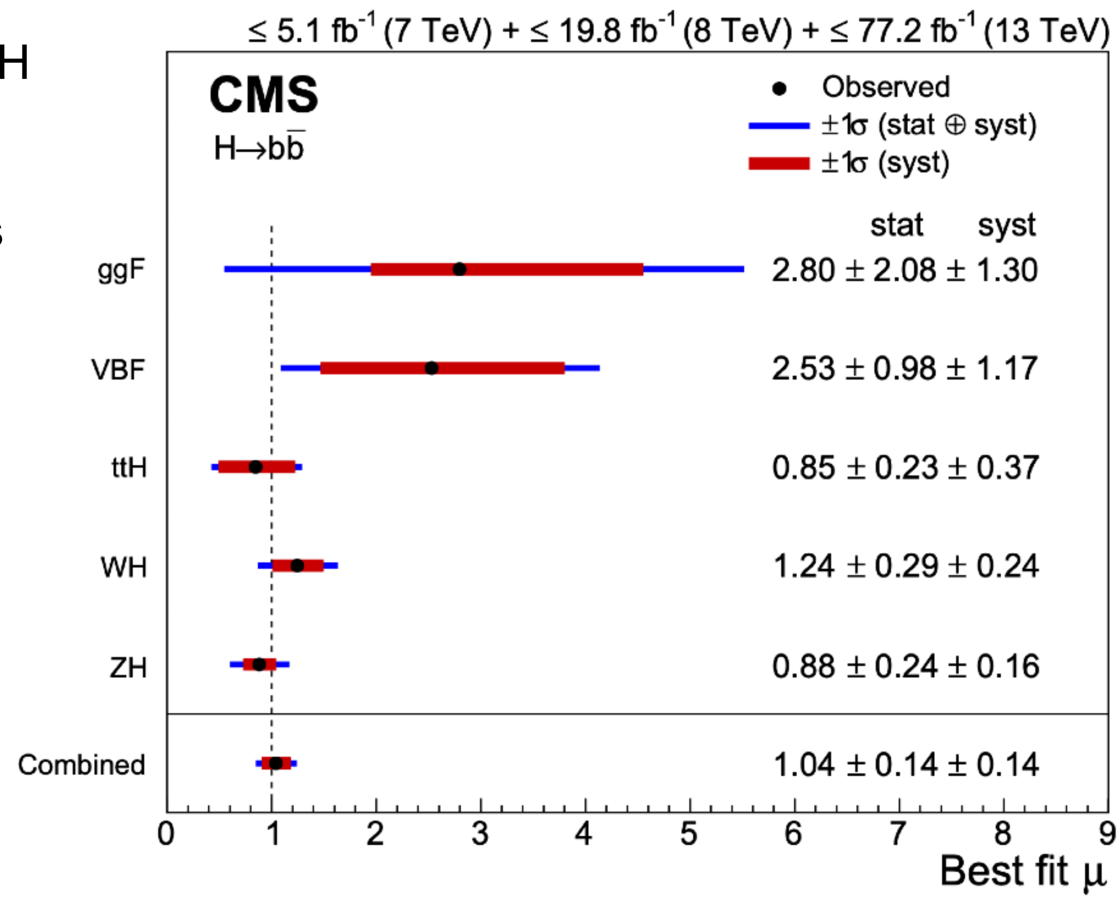
Data set	Significance (σ) Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.22



VH ($H \to b\bar{b}$)

Results

- The observation analysis for VH ($H \to b\bar{b}$) process
- The partial Run 2 analysis was combined with Run 1 measurement
- Consistent with the SM and statistically dominated
- Enters the combination with other production modes
- Full Run 2 measurement is on the way!



VH ($H \to c\bar{c}$)

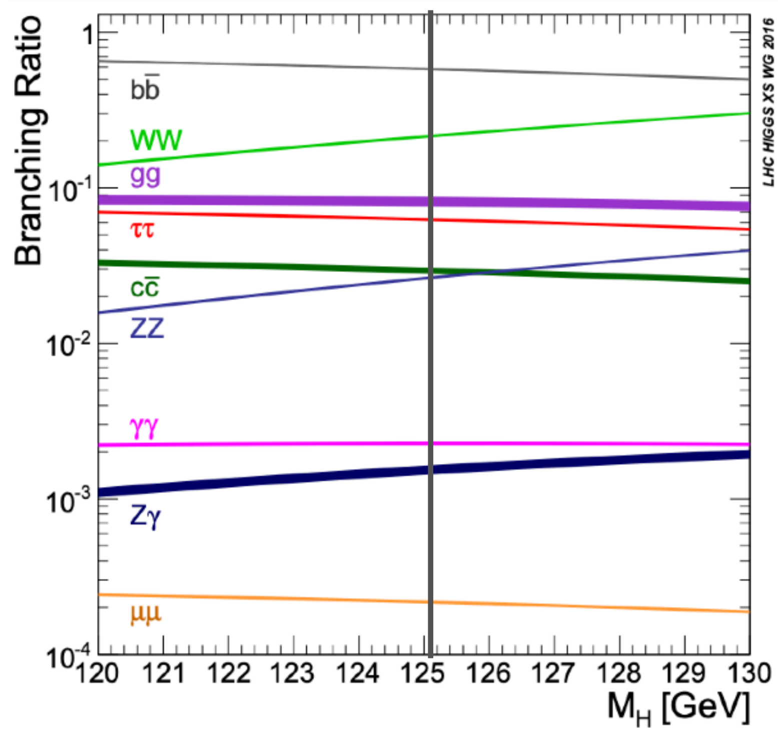
L=35.9 fb^{-1}@13 TeV

[J. High Energ. Phys. 2020, 131 (2020)]

VH (H → c$\bar{c}$)

Overview

- So far only the coupling to the 3rd generation observed (recent evidence of H → $\mu\mu$ from CMS in Silvio's talk)
- H → c$\bar{c}$
  - Relatively small BR (2.9%)
  - H → b$\bar{b}$ is a background in this search
  - Heavily relying on charm-tagging
  - Heavily contaminated with hadronic backgrounds
- VH production mode provides clean event signature (triggering and QCD suppression)

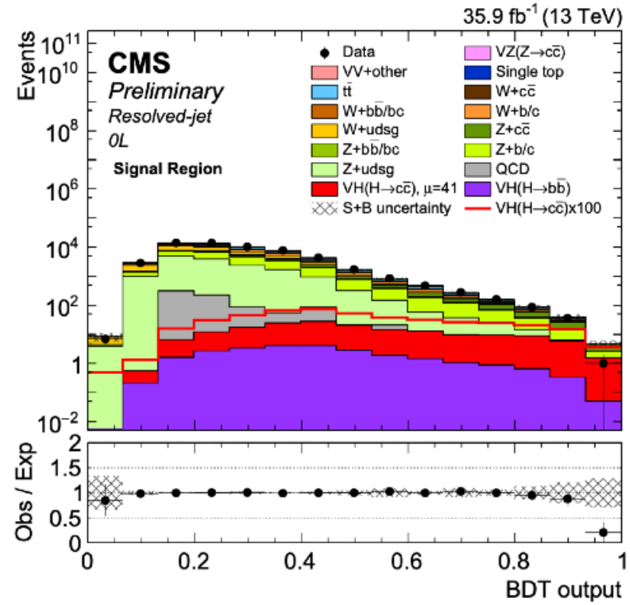


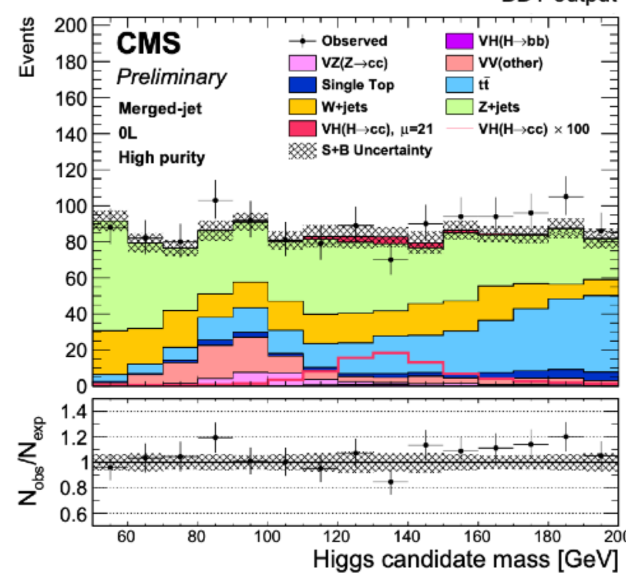
[J. High Energ. Phys. 2020, 131 (2020)]

VH (H → $c\bar{c}$)

Analysis strategy

- 3 decay channels:
  - 0-lepton,1-lepton, 2 lepton
- 2 Higgs decay topologies (two complementary analyses)
  - 2 resolved jets (R=0.4); 1 merged jet (R=1.5)
- V+jets one of the major background
  - Using control regions to constrain different V+jets flavours as well as $t\bar{t}$
- Signal extraction
  - BDT in resolved analysis;
  - Higgs candidate mass in boosted, using additional kinematic BDT





[More post-fit plots]

[J. High Energ. Phys. 2020, 131 (2020)]

VH ($H \to c\bar{c}$)

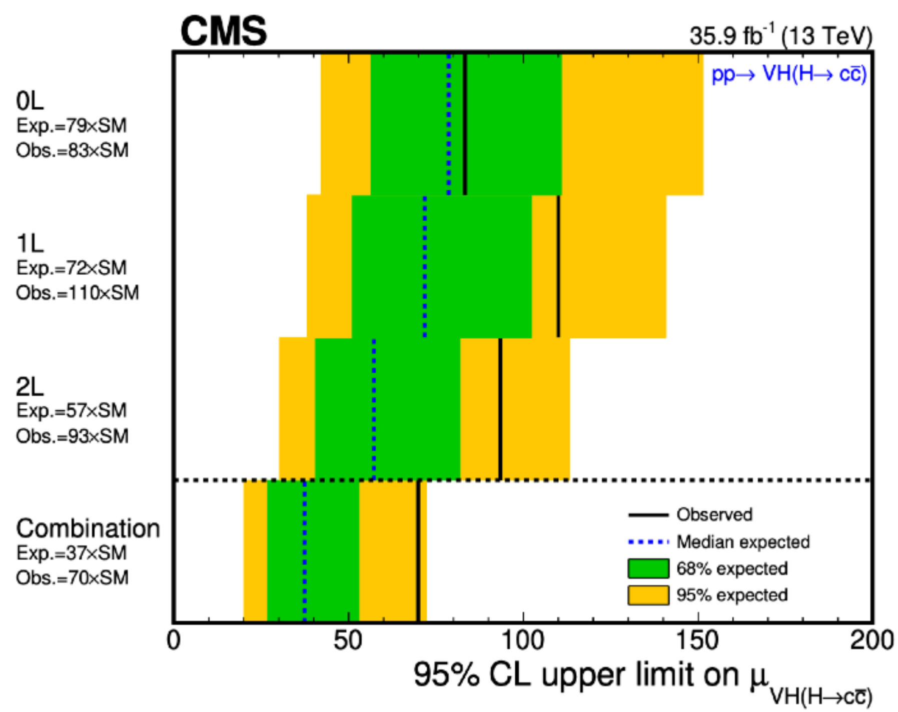
Results

	Resolved-jet (inclusive)				Merged-jet (inclusive)			
	0L	1L	2L	All channels	0L	1L	2L	All channels
Expected UL	84^{+35}_{-24}	79^{+34}_{-23}	59^{+25}_{-17}	38^{+16}_{-11}	81^{+39}_{-24}	88^{+43}_{-27}	90^{+48}_{-29}	49^{+24}_{-15}
Observed UL	66	120	116	75	74	120	76	71

No overlap because of mutually exclusive resolved-jet and merged-jet analyses

➡ Combined to improve sensitivity

- Compatible with SM
- Expect improvement with full Run 2 analysis



ggH ($H \rightarrow b\bar{b}$)

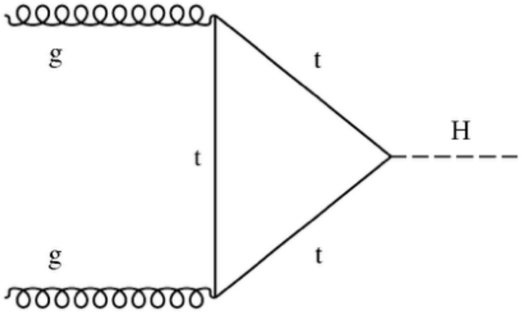
L=136.2 fb^{-1}@13 TeV

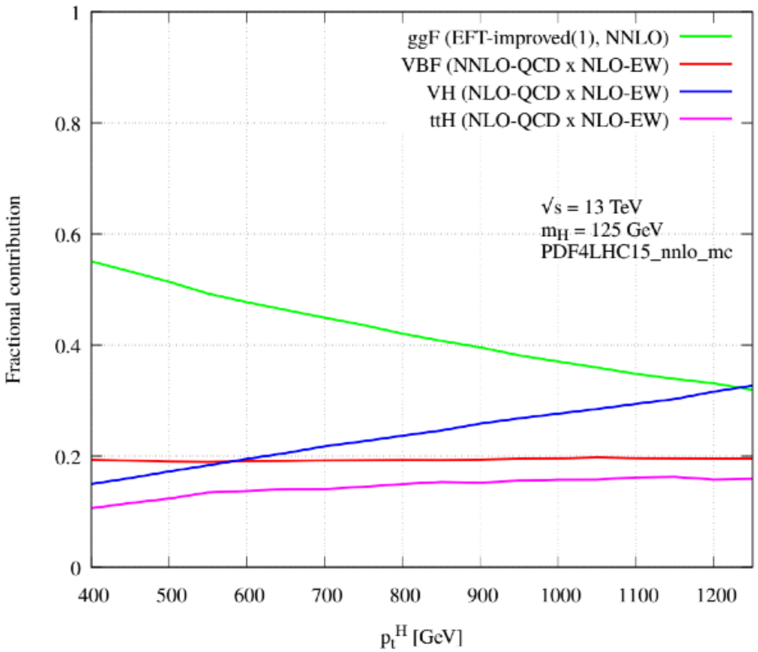
[J. High Energ. Phys. 2020, 85 (2020)]

ggH ($H \to b\bar{b}$)

Overview

- Alternative approach to probe y_t
- Analysis targeting inclusive in production mode high p_T Higgs
    - sensitivity to BSM
- ggF is the dominant ~ 50% (55% after selection)
- [previous CMS result] 1.5 σ (0.7 σ) wrt bkg. only





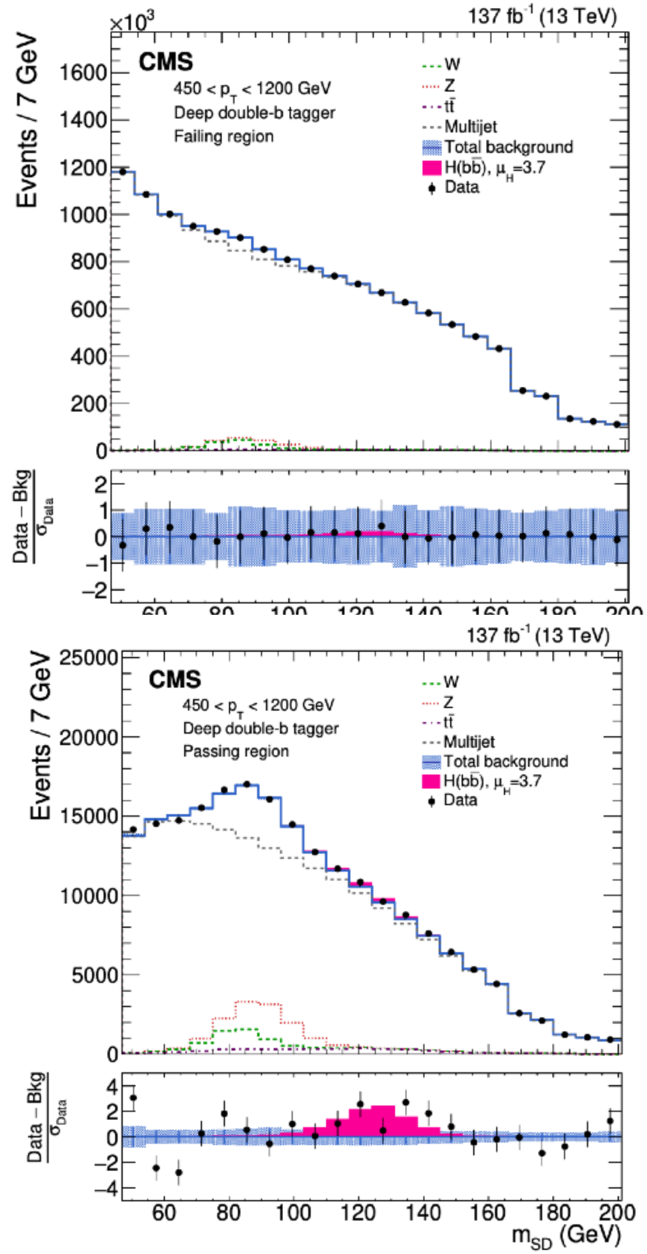
LHCHXSWG-2019-002

ggH ($H \to b\bar{b}$)

Analysis strategy

[J. High Energ. Phys. 2020, 85 (2020)]

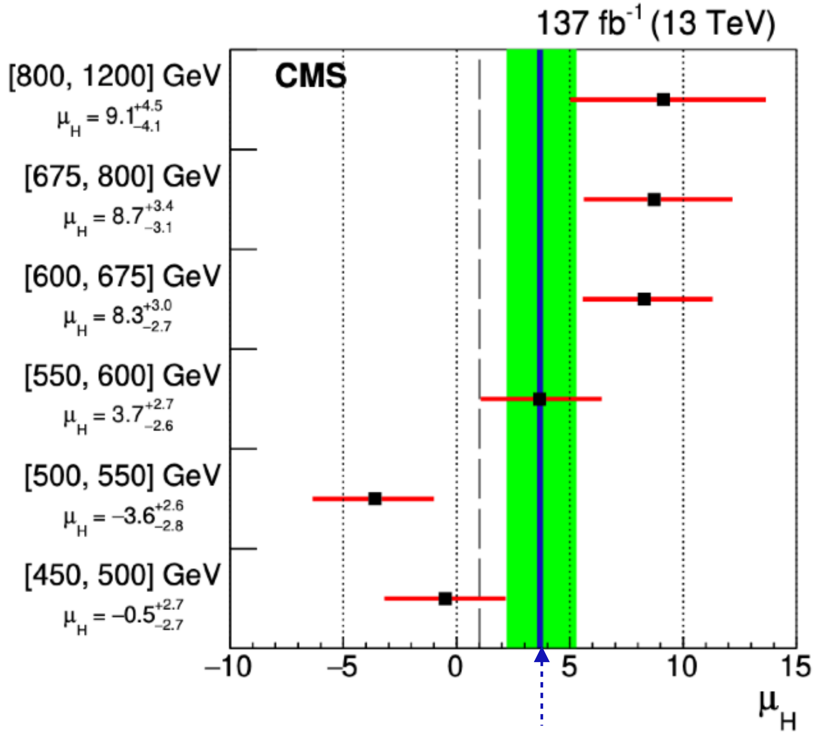
- Higgs reconstructed in boosted topology
  - new DeepDoubleBTag (DDBT) algorithm (1.6x signal efficiency)
- Signal model updated wrt. previous search, HJ-MiNLO
- QCD bkg. estimated using CR, populated with events failing DDBT selection.
  - Transferred to SR (Rhalphabet)
- Higgs candidate mass is fitted for signal extraction

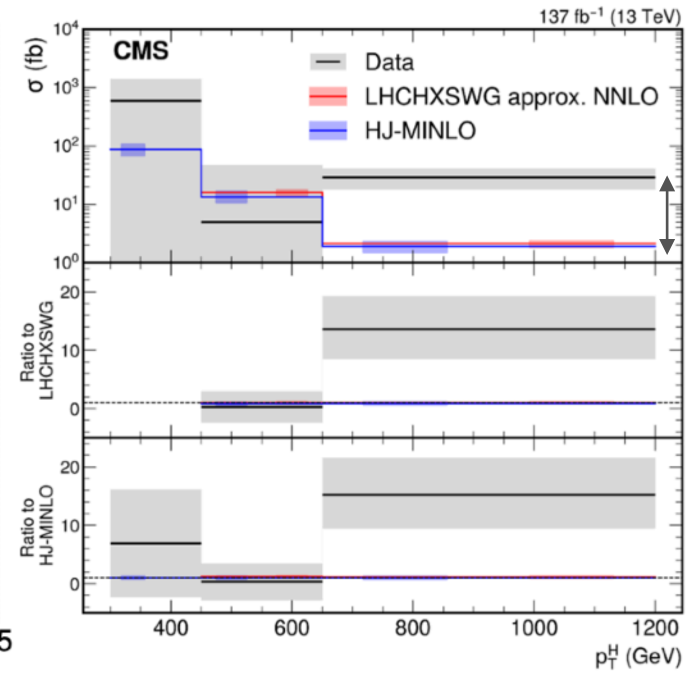


[J. High Energ. Phys. 2020, 85 (2020)]

ggH ($H \rightarrow b\bar{b}$)

Results





2.6 σ
(local, HJ-MINLO)

$$\mu_H = 3.7 \pm 1.2\,(\text{stat})^{+0.8}_{-0.7}\,(\text{syst})^{+0.8}_{-0.5}\,(\text{theo}) = 3.7^{+1.6}_{-1.5}$$

Other processes are fixed to SM prediction:

- 2.5 σ wrt. bkg only, 1.9 σ wrt. SM
- For differential measurement STXS bins are used; 2.6 σ local significance $p_T(H)$ > 650 GeV

Summary

- Covered recent results on Higgs cross section measurement in $c\bar{c}$ and $b\bar{b}$ final states
  - Based on partial (tH, ttH, VH $H \rightarrow b\bar{b}$,VH $H \rightarrow c\bar{c}$) and full (ggH $H \rightarrow b\bar{b}$) Run 2 data
  - All in agreement with the SM
  - Plenty of room for improvement (more statistics, better techniques)

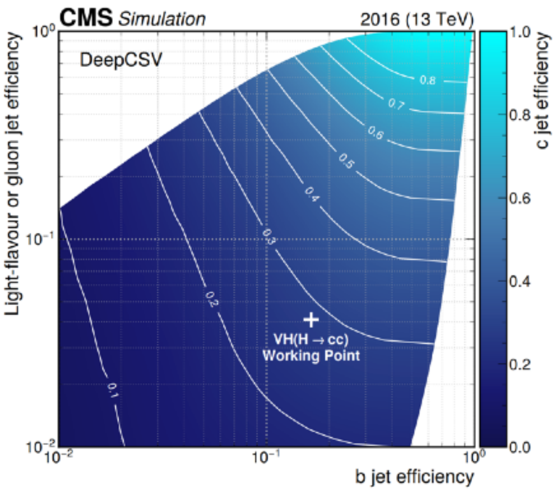
★ **Stay tuned for more full Run 2 results!**

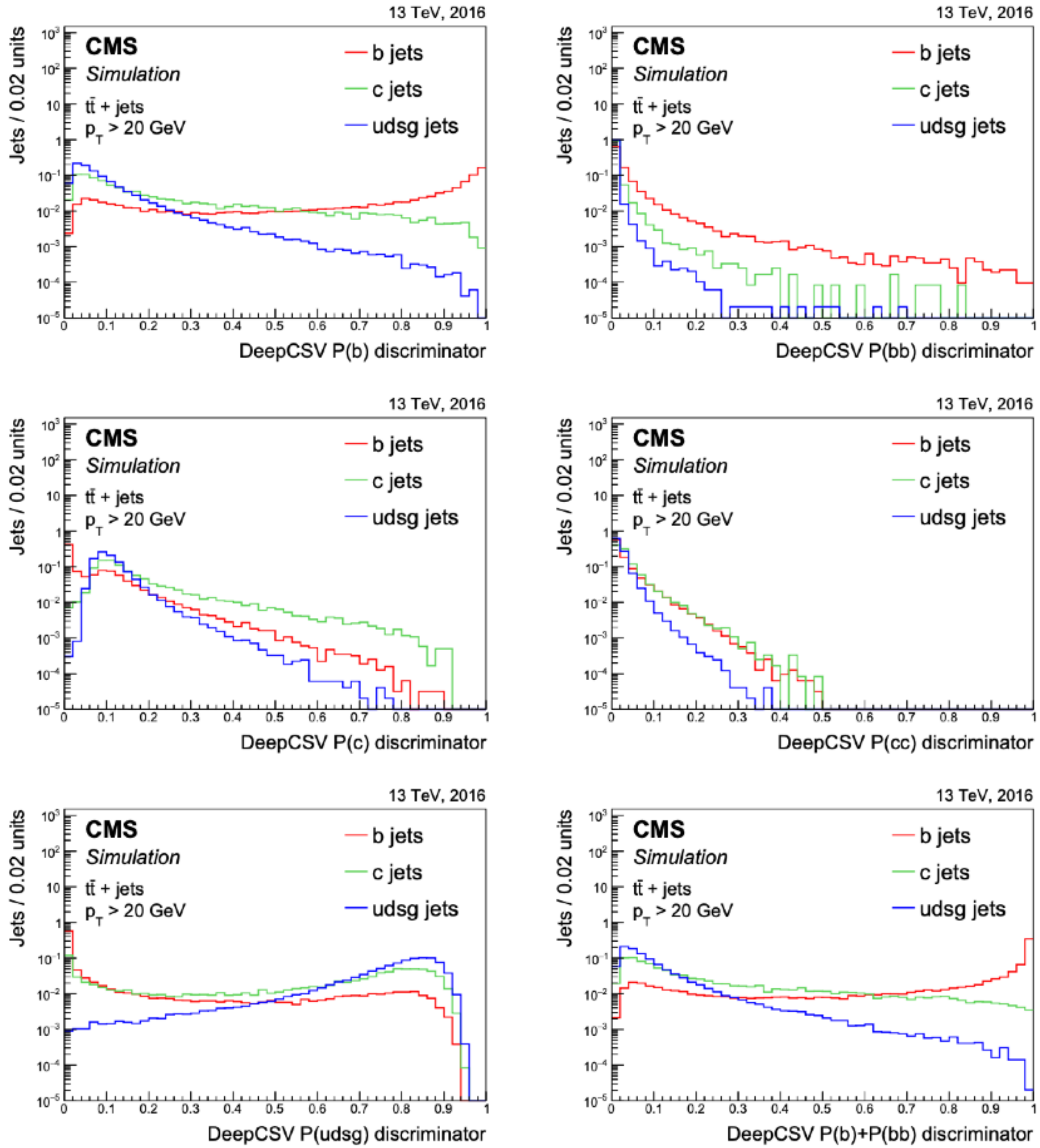
  - Expect improvement in the UL for VH ($H \rightarrow c\bar{c}$)
  - More granular measurements of $H \rightarrow b\bar{b}$ final state

Backup

DeepCSV

[CMS-PAS-BTV-20-001]

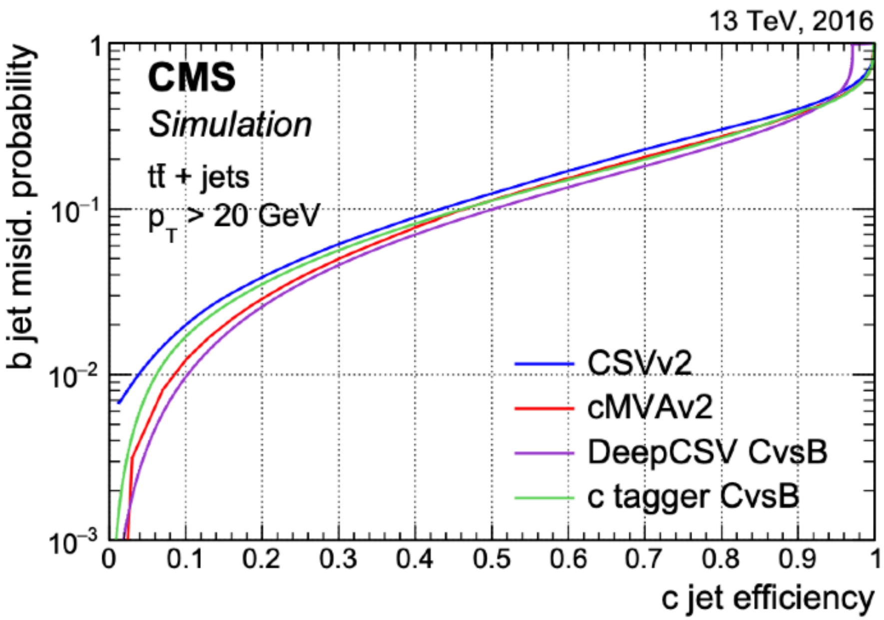


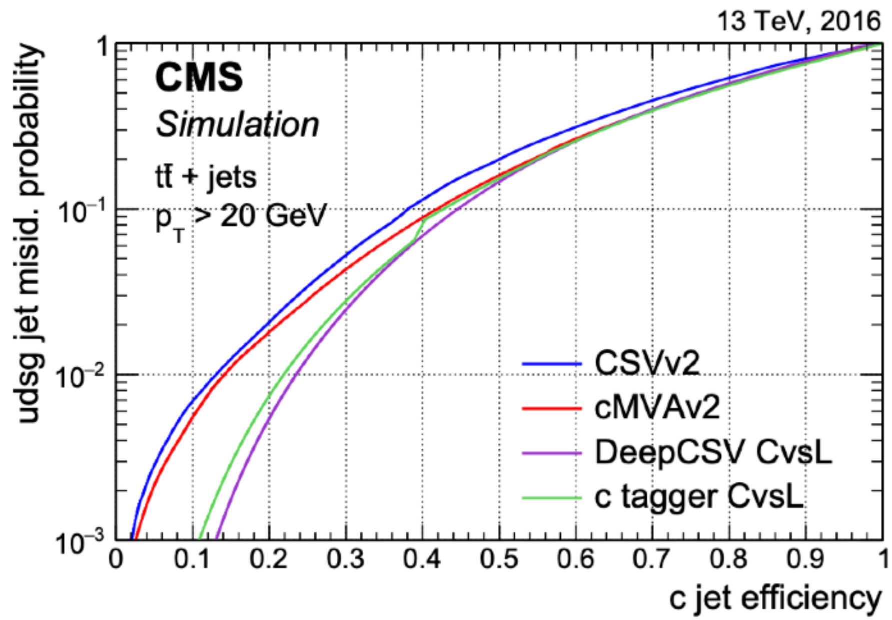


DeepCSV

c-tagging

JINST 13 P05011





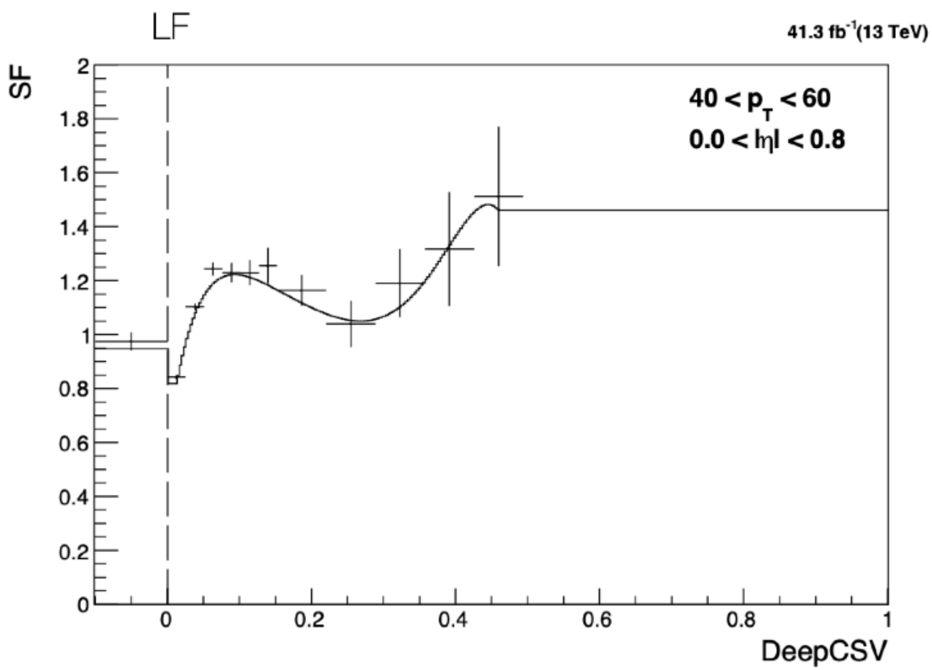
$$\text{DeepCSV CvsB} = \frac{P(\text{c}) + P(\text{cc})}{1 - P(\text{udsg})},$$

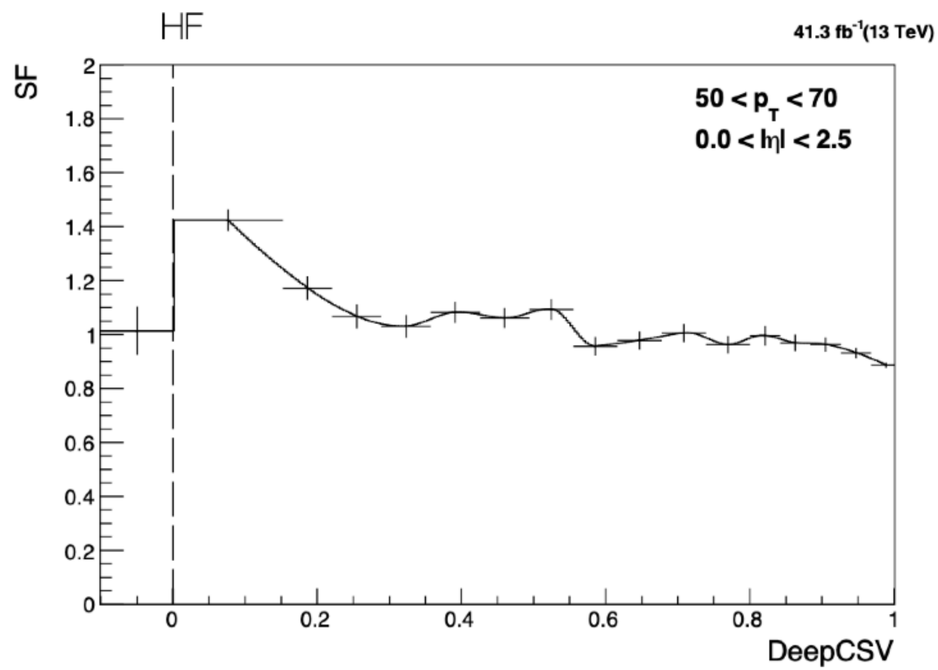
$$\text{DeepCSV CvsL} = \frac{P(\text{c}) + P(\text{cc})}{1 - (P(\text{b}) + P(\text{bb}))}$$

Working point	ε_c (%)	ε_b (%)	ε_{udsg} (%)
c tagger L	88	36	91
c tagger M	40	17	19
c tagger T	19	20	1.2

DeepCSV

b-tag SF

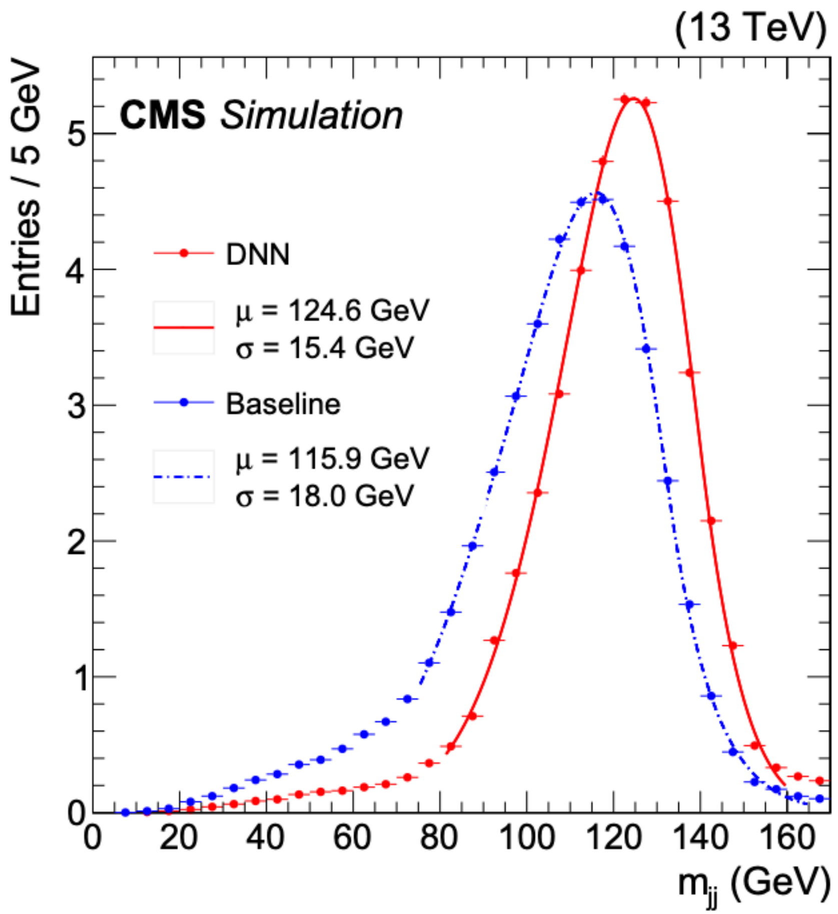




B-jet regression

VHbb

[link]



MC sample	Improvement
$t\bar{t}$	12.2%
$Z(\rightarrow \ell^+\ell^-)H(\rightarrow b\bar{b})$	12.8%
$H(\rightarrow b\bar{b})H(\rightarrow \gamma\gamma)$ SM	13.1%
$H(\rightarrow b\bar{b})H(\rightarrow \gamma\gamma)$ resonant 500 GeV	14.5%
$H(\rightarrow b\bar{b})H(\rightarrow \gamma\gamma)$ resonant 700 GeV	13.1%

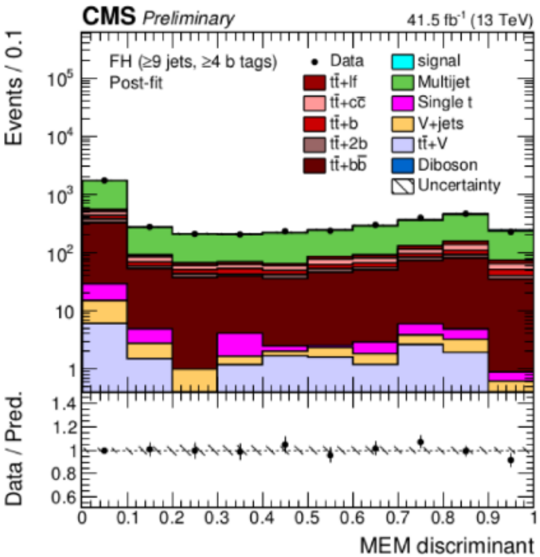
ttH selection

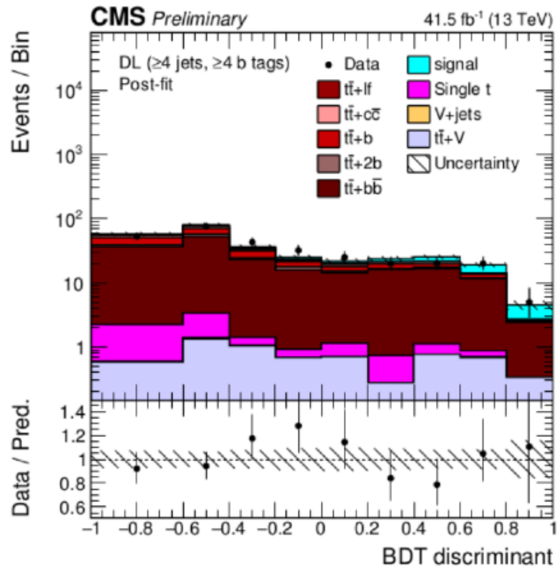
	FH channel	SL channel	DL channel
Number of leptons	0	1	2
p_T of leptons (e/μ) [GeV]	—	$> 30/29$	$> 25/25$ GeV
p_T of additional leptons [GeV]	< 15	< 15	< 15
$\lvert\eta\rvert$ of leptons	< 2.4	< 2.4	< 2.4
Number of jets	≥ 6	≥ 4	≥ 2
p_T of jets [GeV]	> 40	> 30	$> 30, 30, 20$
$\lvert\eta\rvert$ of jets	< 2.4	< 2.4	< 2.4
Number of b-tagged jets	≥ 2	≥ 2	≥ 1
p_T^{miss}	—	> 20 GeV	> 40 GeV

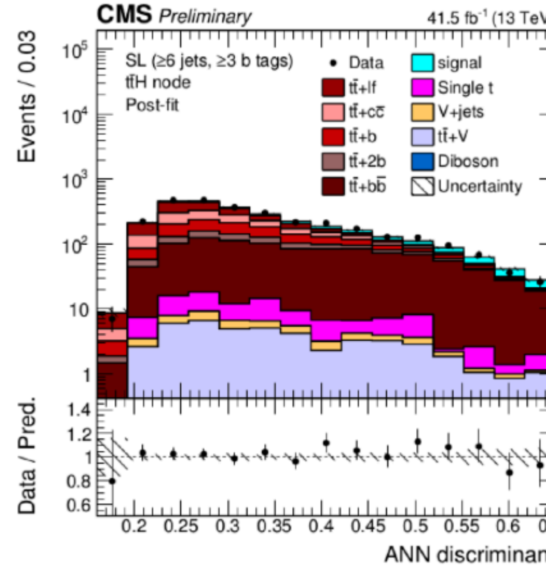
ttH FH, DL, SL

Post-fit

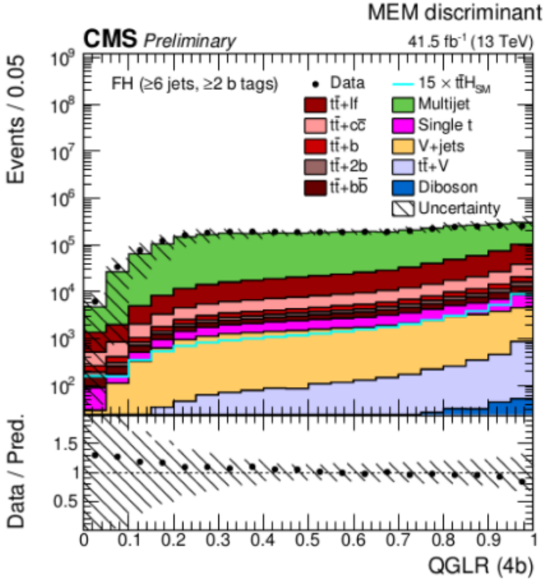
SR

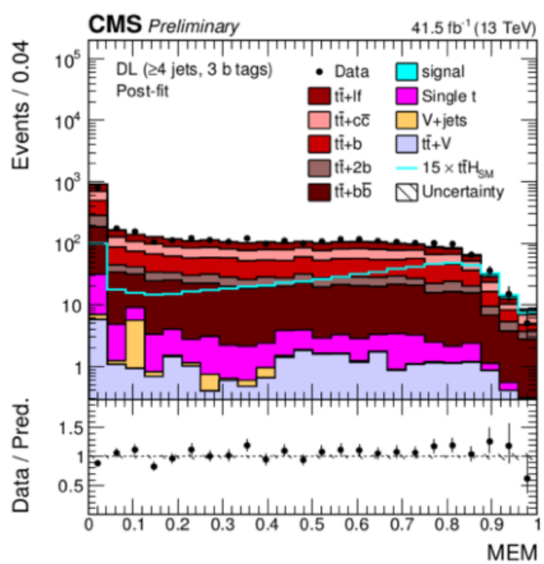


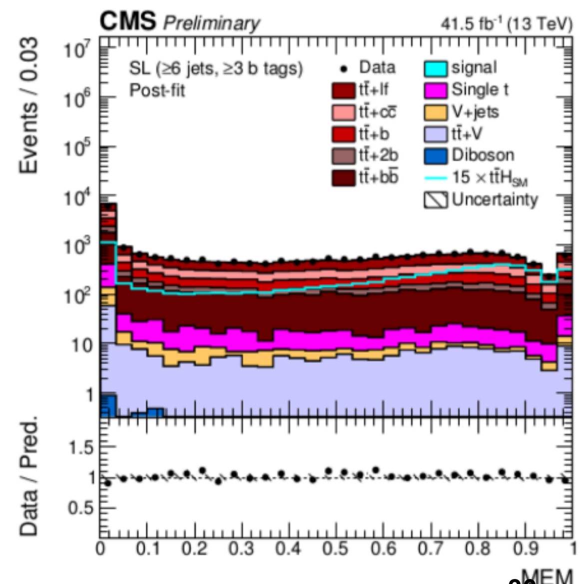




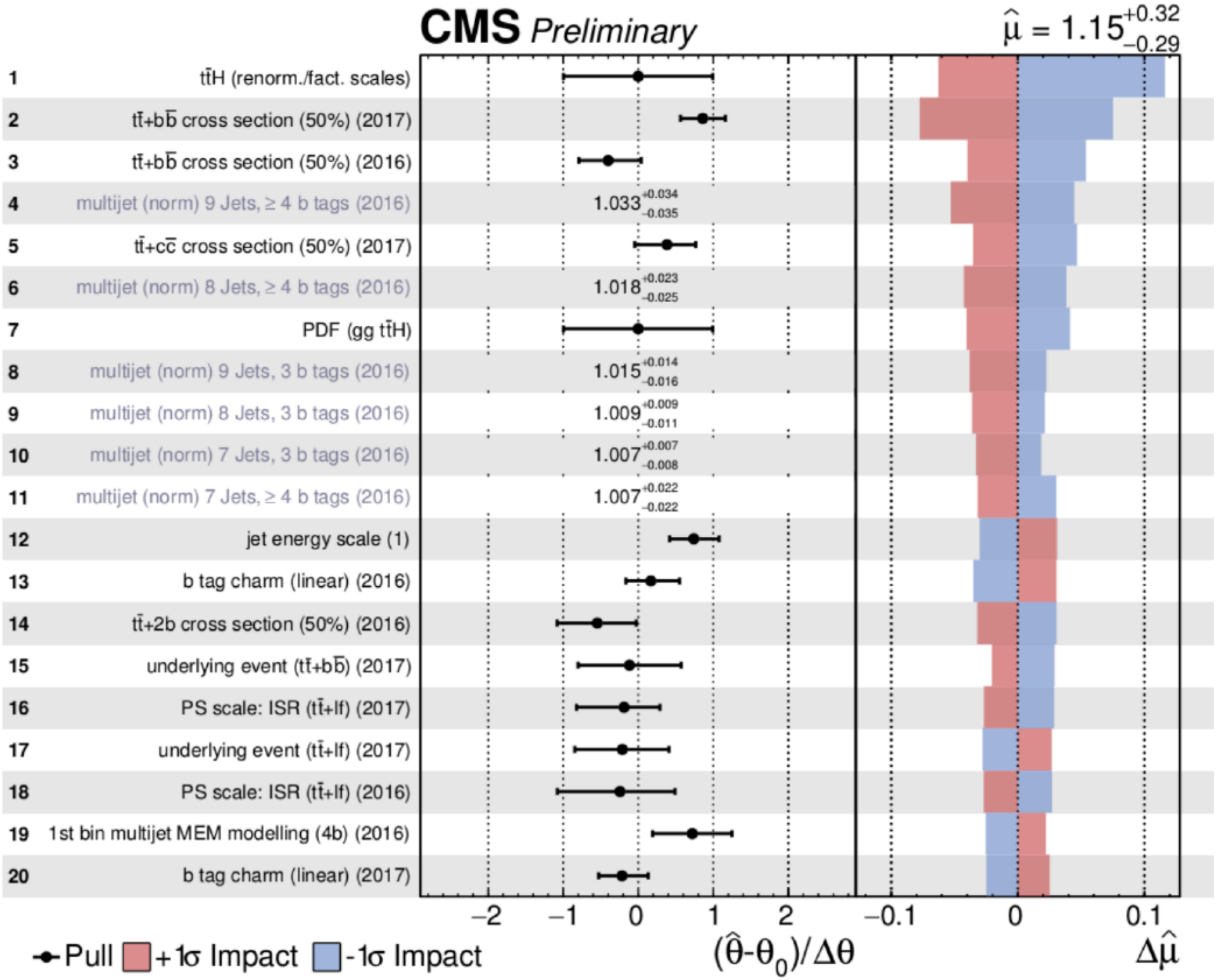
CR







ttH Impacts



CMS Preliminary
$\hat{\mu} = 1.15^{+0.32}_{-0.29}$
1 tt̄H (renorm./fact. scales)
2 tt̄+bb̄ cross section (50%) (2017)
3 tt̄+bb̄ cross section (50%) (2016)
4 multijet (norm) 9 Jets, ≥ 4 b tags (2016)
5 tt̄+cc̄ cross section (50%) (2017)
6 multijet (norm) 8 Jets, ≥ 4 b tags (2016)
7 PDF (gg tt̄H)
8 multijet (norm) 9 Jets, 3 b tags (2016)
9 multijet (norm) 8 Jets, 3 b tags (2016)
10 multijet (norm) 7 Jets, 3 b tags (2016)
11 multijet (norm) 7 Jets, ≥ 4 b tags (2016)
12 jet energy scale (1)
13 b tag charm (linear) (2016)
14 tt̄+2b cross section (50%) (2016)
15 underlying event (tt̄+bb̄) (2017)
16 PS scale: ISR (tt̄+lf) (2017)
17 underlying event (tt̄+lf) (2017)
18 PS scale: ISR (tt̄+lf) (2016)
19 1st bin multijet MEM modelling (4b) (2016)
20 b tag charm (linear) (2017)
$1.033^{+0.034}_{-0.035}$
$1.018^{+0.023}_{-0.025}$
$1.015^{+0.014}_{-0.016}$
$1.009^{+0.009}_{-0.011}$
$1.007^{+0.007}_{-0.008}$
$1.007^{+0.022}_{-0.022}$
−2 −1 0 1 2
−0.1 0 0.1
Pull +1σ Impact -1σ Impact
$(\hat{\theta}-\theta_0)/\Delta\theta$
$\Delta\hat{\mu}$

MEM ttH

Numerical integration

Momentum conservation

Resolution function

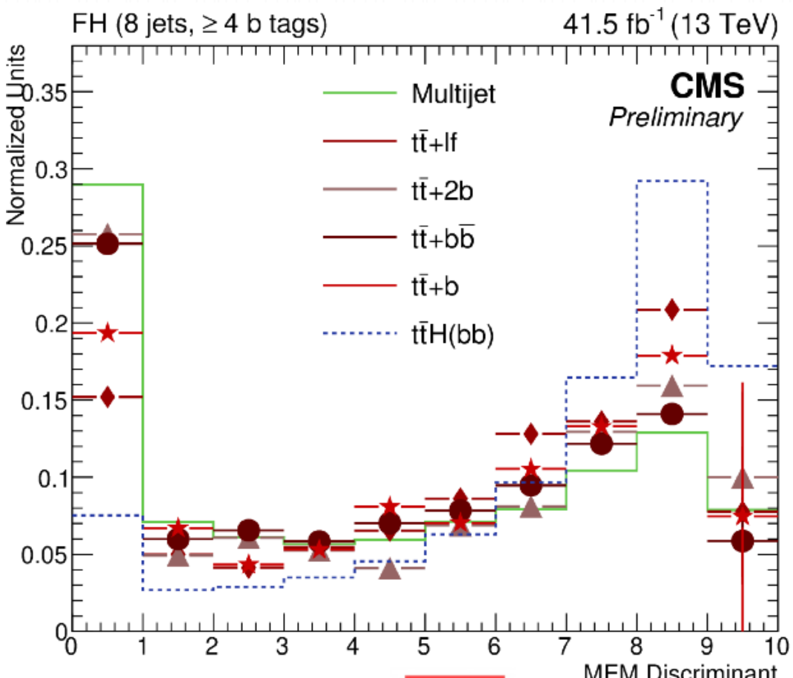
$$w(\vec{y}|\mathcal{H}) = \sum_{i=1}^{N_C} \int \frac{dx_a dx_b}{2x_a x_b s} \int \prod_{k=1}^{8} \left(\frac{d^3\vec{p}_k}{(2\pi)^3 2E_k} \right) (2\pi)^4 \delta^{(E,z)} \left(p_a + p_b - \sum_{k=1}^{8} p_k \right) \mathcal{R}^{(x,y)} \left(\vec{\rho}_T, \sum_{k=1}^{8} p_k \right)$$
$$\times g(x_a, \mu_F) g(x_b, \mu_F) |\mathcal{M}(p_a, p_b, p_1, \ldots, p_8)|^2 W(\vec{y}, \vec{p})$$

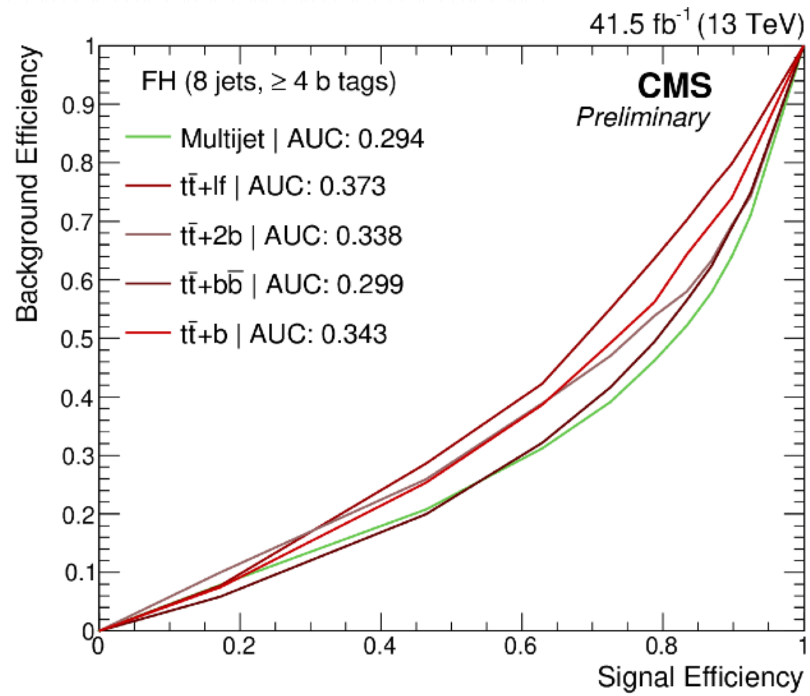
PDFs

LO amplitudes (OpenLoops)

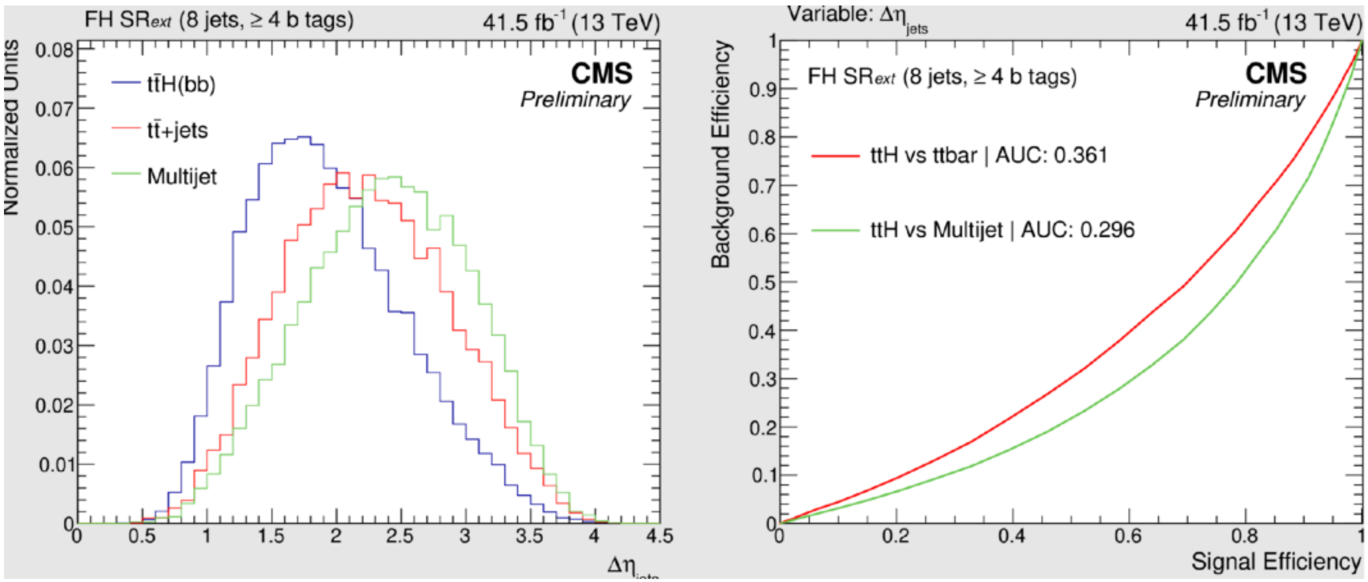
Detector transfer func.

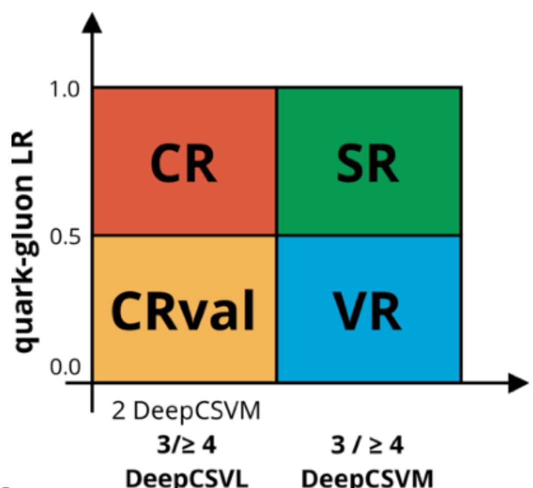
$$P_{s/b} = \frac{w(\vec{y}|t\bar{t}H)}{w(\vec{y}|t\bar{t}H) + k_{s/b} w(\vec{y}|t\bar{t}+b\bar{b})}$$





ttH FH QCD rejection





ttH MVAs

DL BDT

	(3 jets, 2 b-tags)	(3 jets, 3 b-tags)	(≥ 4 jets, 2 b-tags)	(≥ 4 jets, 3 b-tags)	(≥ 4 jets, ≥ 4 b-tags)
N_{trees}	747	580	1079	1432	1380
Shrinkage	0.019	0.029	0.045	0.050	0.048
Bagging Fraction	0.30	0.36	0.28	0.26	0.33
N_{cuts}	26	10	48	37	61
Depth	2	2	2	2	2
ROC AUC	0.78	0.77	0.79	0.78	0.81

SL ANN

	(4 jets, ≥ 3 b-tags)	(5 jets, ≥ 3 b-tags)	(≥ 6 jets, ≥ 3 b-tags)
nodes per hidden layer	100,100	100, 100	100,100
loss function	cross-entropy	cross-entropy	cross-entropy
dropout percentage	0.5	0.5	0.5
L2 regularization	10^{-5}	10^{-5}	10^{-5}
batchsize	5000	5000	5000
optimizer	ADAM(10^{-4})	ADAM(10^{-4})	ADAM(10^{-4})
activation function	ELU	ELU	ELU
last activation	softmax	softmax	softmax
earlystopping percentage	2%	2%	2%
earlystopping min epochs	50	50	50

Variable	Definition	SL (4 jets, ≥ 3 b-tags)	SL (5 jets, ≥ 3 b-tags)	SL (≥ 6 jets, ≥ 3 b-tags)	DL (3 jets, 2 b-tags)	DL (3 jets, 3 b-tags)	DL (≥ 4 jets, 2 b-tags)	DL (≥ 4 jets, 3 b-tags)	DL (≥ 4 jets, ≥ 4 b-tags)
MEM	maxtrix element method discriminant	+	+	+	−	−	−	+	+
BLR	likelihood ratio discriminating between events with 4 b quark jets and 2 b quark jets	+	−	+	−	−	−	−	−
$\mathrm{BLR}^{\mathrm{trans}}$	$\ln[\mathrm{BLR}/(1-\mathrm{BLR})]$	+	−	+	−	−	−	−	−
p_{T}(jet 1)	p_{T} of the 1. jet, ranked in jet p_{T}	−	+	−	−	−	−	−	−
p_{T}(jet 3)	p_{T} of the 3. jet, ranked in jet p_{T}	−	+	−	−	−	−	−	−
$H_{\mathrm{T}}^{\mathrm{b}}$	scalar sum of p_{T} of b-tagged jets	+	+	+	+	−	−	−	+
$\sum_{\mathrm{j,lep}} p_{\mathrm{T}}$	scalar sum of p_{T} of leptons and jets	−	−	−	+	+	−	+	−
$N_{\mathrm{b}}^{\mathrm{tight}}$	number of b-tagged jets at a working point with 0.1% probability of tagging gluon and light-flavour jets	+	+	−	−	−	−	−	−
d(jet 4)	b-tagging discriminant value of 4. jet, ranked in jet p_{T}	+	−	−	−	−	−	−	−
d_2	2. highest b-tagging discriminant value of all jets	+	+	+	−	−	−	−	−
$d_{\mathrm{j}}^{\mathrm{avg}}$	average b-tagging discriminant value of all jets	+	+	+	+	−	+	+	−
$d_{\mathrm{b}}^{\mathrm{avg}}$	average b-tagging discriminant value of all b-tagged jets	+	+	+	−	+	−	+	+
$d_{\mathrm{b}}^{\mathrm{min}}$	minimal b-tagging discriminant value of all b-tagged jets	+	+	−	−	−	−	−	−
$\frac{1}{N_b}\sum_b^{N_b}\left(d-d_{\mathrm{b}}^{\mathrm{avg}}\right)^2$	squared difference between the b-tagged discriminant value of a b-tagged jet and the average b-tagging discriminant values of all b-tagged jets, averaged over all b-tagged jets	+	−	+	−	−	−	−	−
m_{j}'	sum of the masses of all jets divided by the number of dijet pairs	−	−	+	−	−	−	−	−
$m_{\mathrm{b,b}}^{\mathrm{closest\ to\ 125}}$	mass of pair of b-tagged jets closest to 125 GeV	−	+	−	−	+	−	−	−
$m_{\mathrm{lep,b}}^{\min\Delta R}$	mass of pair of lepton and b-tagged jet closest in ΔR	−	−	+	−	−	−	−	−
$m_{\mathrm{j,j}}^{\min\Delta R}$	mass of pair of jets closest in ΔR	−	−	−	+	+	−	−	−
$m_{\mathrm{b,b}}^{\min\Delta R}$	mass of pair of b-tagged jets closest in ΔR	−	−	−	+	−	+	+	+

tH selection, tt+jets categorisation

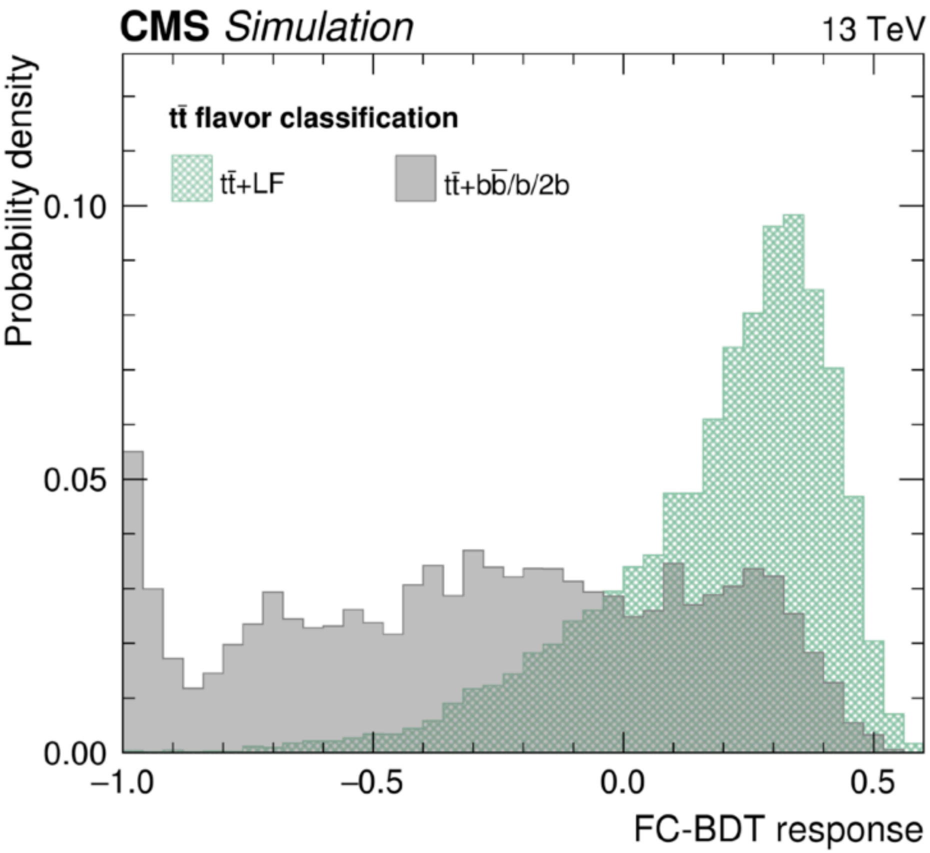
Signal region	
One muon (electron) with $p_T > 27(35)$ GeV	
No additional loose leptons	
Three or four medium b-tagged jets	
$p_T > 30$ GeV and $\lvert\eta\rvert < 2.4$	
One or more untagged jets	
$p_T > 30$ GeV for $\lvert\eta\rvert < 2.4$ or	
$p_T > 40$ GeV for $\lvert\eta\rvert \geq 2.4$	
$p_T^{miss} > 35(45)$ GeV for muons (electrons)	
Control region	
Two leptons: $p_T > 20/20$ GeV ($\mu^{\pm}\mu^{\mp}$)	
or $p_T > 20/15$ GeV ($e^{\pm}e^{\mp}/\mu^{\pm}e^{\mp}$)	
No additional loose leptons	
Two medium b-tagged jets	
$p_T > 30$ GeV and $\lvert\eta\rvert < 2.4$	
One or more additional loose b-tagged jets	
$p_T > 30$ GeV and $\lvert\eta\rvert < 2.4$	
$p_T^{miss} > 40$ GeV	

$t\bar{t}+b\bar{b}$	Two additional jets arising from b hadrons
$t\bar{t}+2b$	One additional jet arising from two merged b hadrons
$t\bar{t}+b$	One additional jet arising from one b hadron
$t\bar{t}+c\bar{c}$	The three former categories combined for c hadrons instead of b hadrons
$t\bar{t}+LF$	All events that do not meet the criteria of the other four categories

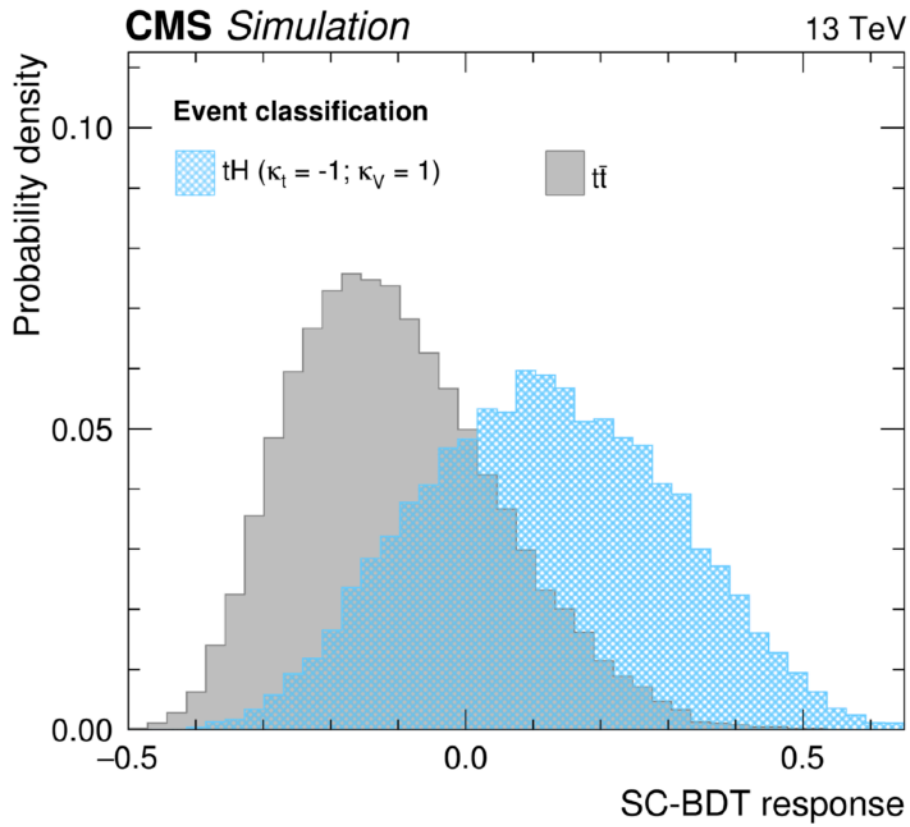
tH yields

Process	3 tags	4 tags	Dilepton
$t\bar{t}$+LF	24100 ± 5800	320 ± 180	5300 ± 1000
$t\bar{t}$+$c\bar{c}$	8500 ± 4900	340 ± 260	2100 ± 1200
$t\bar{t}$+$b\bar{b}$	4100 ± 2300	780 ± 430	750 ± 440
$t\bar{t}$+b	4000 ± 2100	180 ± 110	770 ± 430
$t\bar{t}$+2b	2300 ± 1200	138 ± 88	400 ± 230
Single top	1980 ± 350	78 ± 26	285 ± 37
$t\bar{t}$Z	202 ± 30	32.0 ± 6.6	54.8 ± 7.3
$t\bar{t}$W	90 ± 23	4.2 ± 2.8	31.4 ± 5.9
tZq	28.3 ± 5.7	2.9 ± 2.3	—
Z+jets	—	—	69 ± 32
Total background	45300 ± 8300	1880 ± 550	9700 ± 1700
$t\bar{t}$H	268 ± 31	62.0 ± 9.9	48.9 ± 5.9
tHq (SM)	11.1 ± 3.3	1.3 ± 0.3	0.31 ± 0.08
tHW (SM)	7.6 ± 1.1	1.1 ± 0.3	1.4 ± 0.2
Total SM	45700 ± 8300	1940 ± 550	9700 ± 1700
tHq ($\kappa_V = 1 = -\kappa_t$)	160 ± 38	19.1 ± 5.2	3.9 ± 1.0
tHW ($\kappa_V = 1 = -\kappa_t$)	92 ± 12	13.7 ± 2.3	17.6 ± 2.2
Data	44311	2035	9065

tH BDTs



CMS Simulation
13 TeV
Probability density
tt̄ flavor classification
tt̄+LF
tt̄+bb̄/b/2b
0.10
0.05
0.00
−1.0
−0.5
0.0
0.5
FC-BDT response



CMS Simulation
13 TeV
Probability density
Event classification
tH (κ_t = -1; κ_V = 1)
tt̄
0.10
0.05
0.00
−0.5
0.0
0.5
SC-BDT response

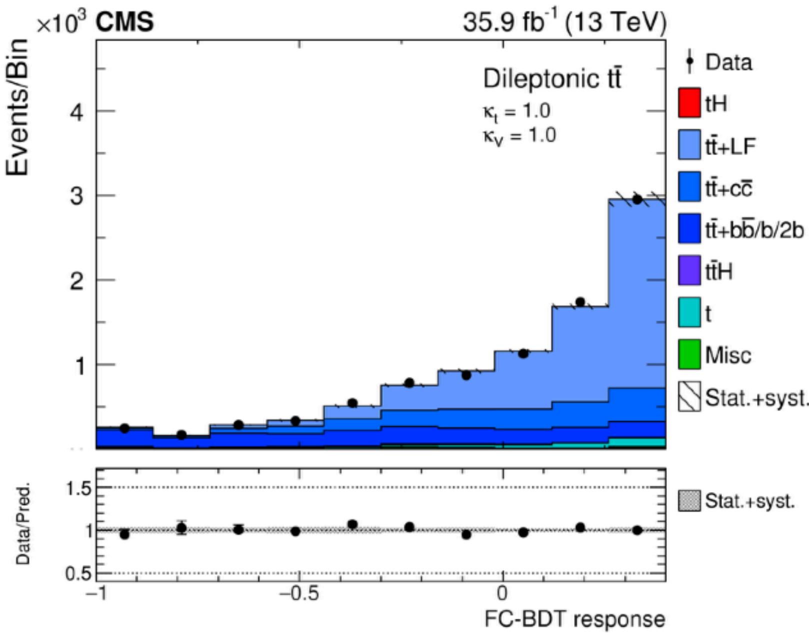
tH FC-BDT

Variable	Description
CSV(bjet 3)	Output of the b tagging discriminant for the b-tagged jet with the third-highest b tagging value in the event
n_{jets}(tight)	Number of jets in the event passing the tight working point of the b tagging algorithm
CvsL(jet p_T 3)	Output of the charm *vs.* light-flavor tagging algorithm for the jet with the third-highest transverse momentum in the event
CSV(b-tagged jet 2)	Output of the b tagging discriminant for the b-tagged jet with the second-highest b tagging value in the event
CvsL(jet p_T 4)	Output of the charm *vs.* light-flavor tagging algorithm for the jet with the fourth-highest transverse momentum in the event
CvsB(jet p_T 3)	Output of the charm *vs.* bottom flavor tagging algorithm for the jet with the third-highest transverse momentum in the event
CSV(b-tagged jet 4)	Output of the b tagging discriminant for the b-tagged jet with the fourth-highest b tagging value in the event
n_{jets}(loose)	Number of jets in the event passing the loose working point of the b tagging algorithm

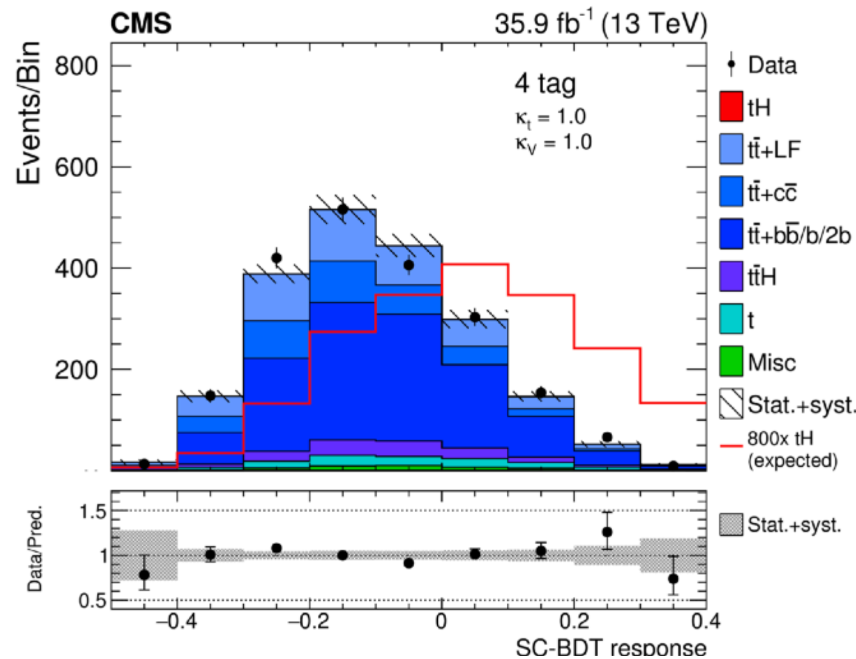
tH SC-BDT

Variable	Description
Event variables	
$\ln m_3$	Invariant mass of three hardest jets in the event
Aplanarity	Aplanarity of the event [?]
Fox–Wolfram #1	First Fox–Wolfram moment [?] of the event
$q(\ell)$	Electric charge of the lepton
$\mathrm{t\bar{t}}$ jet assignment variables	
$\ln m(\mathrm{t_{had}})$	Invariant mass of the reconstructed hadronically decaying top quark
CSV($\mathrm{W_{had}}$ jet 1)	Output of the b tagging discriminant for the first jet assigned to the hadronically decaying W boson
CSV($\mathrm{W_{had}}$ jet 2)	Output of the b tagging discriminant for the second jet assigned to the hadronically decaying W boson
$\Delta R(\mathrm{W_{had}}$ jets)	ΔR between the two light jets assigned to the hadronically decaying W boson
tHq jet assignment variables	
$\ln p_{\mathrm{T}}(\mathrm{H})$	Transverse momentum of the reconstructed Higgs boson candidate
$\lvert\eta$(light-flavor jet)$\rvert$	Absolute pseudorapidity of light-flavor forward jet
$\ln m(\mathrm{H})$	Invariant mass of the reconstructed Higgs boson candidate
CSV(H jet 1)	Output of the b tagging discriminant for the first jet assigned to the Higgs boson candidate
CSV(H jet 2)	Output of the b tagging discriminant for the second jet assigned to the Higgs boson candidate
$\cos\theta(\mathrm{b_t}, \ell)$	Cosine of the angle between the b-tagged jet from the top quark decay and the lepton
$\cos\theta^*$	Cosine of the angle between the light-flavor forward jet and the lepton in the top quark rest frame
$\lvert\eta(\mathrm{t}) - \eta(\mathrm{H})\rvert$	Absolute pseudorapidity difference of reconstructed Higgs boson and top quark
$\ln p_{\mathrm{T}}$(light jet)	Transverse momentum of the light-flavor forward jet
tHW jet assignment variable	
JA-BDT response	Best output of the tHW JA-BDT

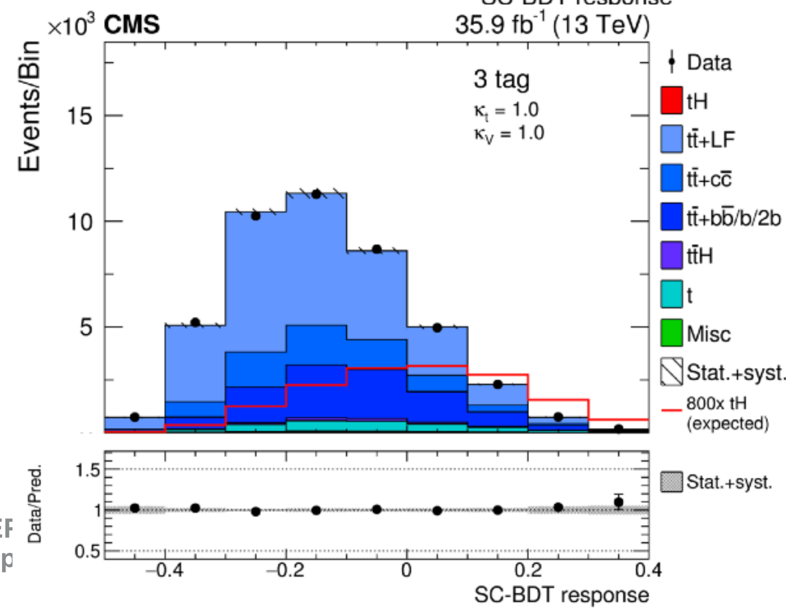
tH post-fit



×10^3 CMS
35.9 fb^-1 (13 TeV)
Events/Bin
Dileptonic tt̄
κt = 1.0
κV = 1.0
Data
tH
tt̄+LF
tt̄+cc̄
tt̄+bb̄/b/2b
tt̄H
t
Misc
Stat.+syst.
Data/Pred.
Stat.+syst.
FC-BDT response



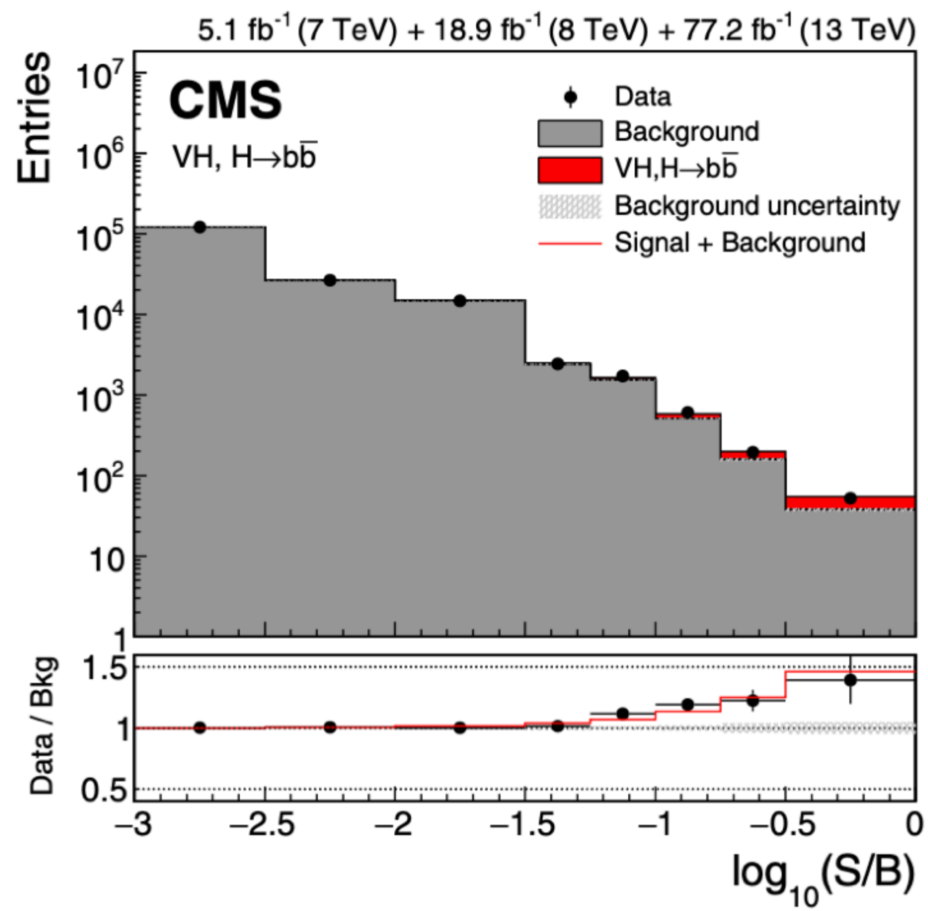
CMS
35.9 fb^-1 (13 TeV)
Events/Bin
4 tag
κt = 1.0
κV = 1.0
Data
tH
tt̄+LF
tt̄+cc̄
tt̄+bb̄/b/2b
tt̄H
t
Misc
Stat.+syst.
800x tH
(expected)
Data/Pred.
Stat.+syst.
SC-BDT response



×10^3 CMS
35.9 fb^-1 (13 TeV)
Events/Bin
3 tag
κt = 1.0
κV = 1.0
Data
tH
tt̄+LF
tt̄+cc̄
tt̄+bb̄/b/2b
tt̄H
t
Misc
Stat.+syst.
800x tH
(expected)
Data/Pred.
Stat.+syst.
SC-BDT response

VHbb systematics and DNN post-fit

Uncertainty source	$\Delta\mu$	
Statistical	+0.26	−0.26
Normalization of backgrounds	+0.12	−0.12
Experimental	+0.16	−0.15
b-tagging efficiency and misid	+0.09	−0.08
V+jets modeling	+0.08	−0.07
Jet energy scale and resolution	+0.05	−0.05
Lepton identification	+0.02	−0.01
Luminosity	+0.03	−0.03
Other experimental uncertainties	+0.06	−0.05
MC sample size	+0.12	−0.12
Theory	+0.11	−0.09
Background modeling	+0.08	−0.08
Signal modeling	+0.07	−0.04
Total	+0.35	−0.33



VHcc systematics

Source	Type	0-lepton	1-lepton	2-lepton
Size of simulated samples	shape	✓	✓	✓
Jet energy scale	shape	✓	✓	✓
Jet energy resolution	shape	✓	✓	✓
MET unclustered energy	shape	✓	✓	
c tagging efficiency	shape	✓	✓	✓
Lepton efficiency	shape (rate)		✓	✓
Pileup reweighting	shape	✓	✓	✓
top p_T reweighting	shape	✓	✓	✓
$p_T(V)$ reweighting	shape	✓	✓	✓
PDF	shape	✓	✓	✓
Renormalization and factorization scales	shape	✓	✓	✓
VH: $p_T(V)$ NLO EWK correction	shape	✓	✓	✓
Luminosity	rate	2.5%	2.5%	2.5%
MET trigger efficiency	rate	2%		
Single top cross section	rate	15%	15%	15%
Diboson cross section	rate	10%	10%	10%
VH: cross section (PDF)	rate	✓	✓	✓
VH: cross section (scale)	rate	✓	✓	✓

VHcc BDT

Resolved

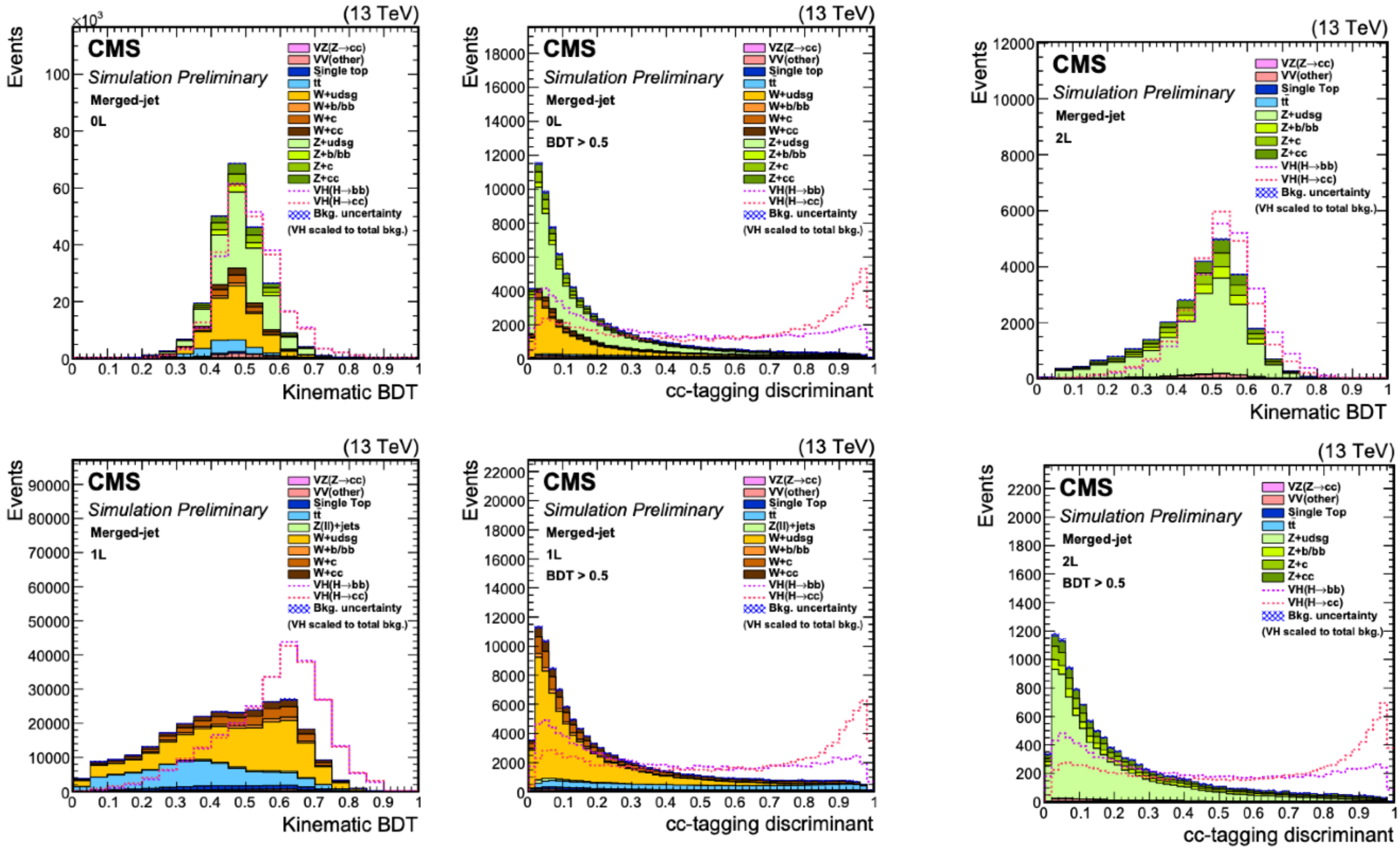
Variable	Description	0L	1L	2L
$m(\mathrm{H_{cand}})$	$\mathrm{H_{cand}}$ mass	✓	✓	✓
$p_T(\mathrm{H_{cand}})$	$\mathrm{H_{cand}}$ transverse momentum	✓	✓	✓
$p_T(\mathrm{V})$	vector boson transverse momentum	✓	✓	✓
$m(\mathrm{V})$	vector boson mass			✓
$m_T(\mathrm{V})$	vector boson transverse mass		✓	
p_T^{miss}	missing transverse momentum	✓	✓	
$p_T(\mathrm{V})/p_T(\mathrm{H_{cand}})$	ratio between vector and $\mathrm{H_{cand}}$ transverse momentum	✓	✓	✓
$CvsL_{max}$	$CvsL$ tagger value of the leading $CvsL$ jet	✓	✓	✓
$CvsB_{max}$	$CvsB$ tagger value of the leading $CvsL$ jet	✓	✓	✓
$CvsL_{min}$	$CvsL$ tagger value of the subleading $CvsL$ jet	✓	✓	✓
$CvsB_{min}$	$CvsB$ tagger value of the subleading $CvsL$ jet	✓	✓	✓
p_{Tmax}	p_T of the leading $CvsL$ jet	✓	✓	✓
p_{Tmin}	p_T of the subleading $CvsL$ jet	✓	✓	✓
$\Delta\phi(\mathrm{V},\mathrm{H_{cand}})$	azimuthal angle between vector boson and $\mathrm{H_{cand}}$	✓	✓	✓
$\Delta R(j_1, j_2)$	ΔR between leading and subleading $CvsL$ jet		✓	✓
$\Delta\phi(j_1, j_2)$	azimuthal angle between leading and subleading $CvsL$ jet	✓	✓	
$\Delta\eta(j_1, j_2)$	difference in pseudorapidity between leading and subleading $CvsL$ jet	✓	✓	✓
$\Delta\phi(\ell_1, \ell_2)$	azimuthal angle between leading and subleading p_T leptons			✓
$\Delta\eta(\ell_1, \ell_2)$	difference in pseudorapidity between leading and subleading p_T leptons			✓
$\Delta\phi(\ell_1, j_1)$	azimuthal angle between leading p_T lepton and leading $CvsL$ jet		✓	
$\Delta\phi(\ell_2, j_1)$	azimuthal angle between subleading p_T lepton and leading $CvsL$ jet			✓
$\Delta\phi(\ell_2, j_2)$	azimuthal angle between subleading p_T lepton and subleading $CvsL$ jet			✓
$\Delta\phi(\ell_1, p_T^{miss})$	azimuthal angle between leading p_T lepton and missing transverse momentum		✓	
N_{aj}	number of small-R jets minus the number of FSR jets	✓	✓	✓
N_5^{soft}	multiplicity of soft track-based jets with $p_T > 5\,\mathrm{GeV}$	✓	✓	✓

VHcc BDT

Boosted

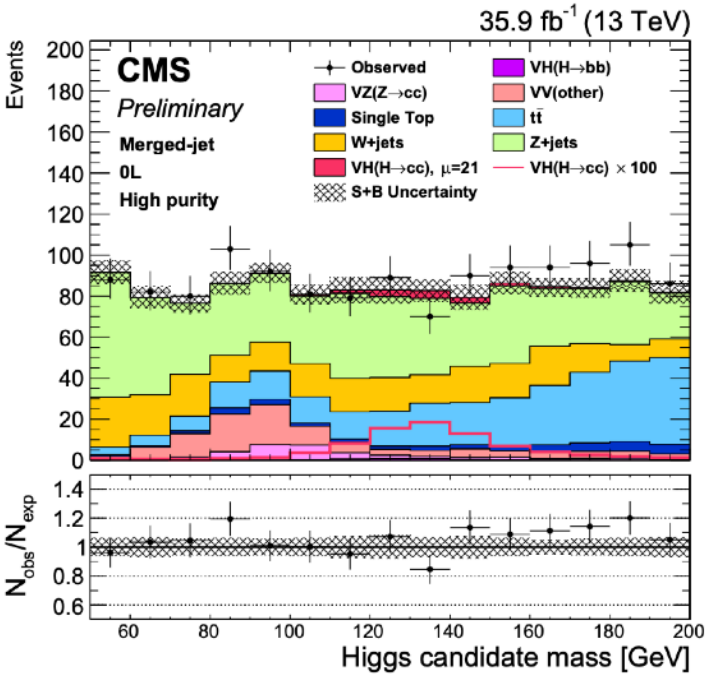
Variable	Description	0L	1L	2L
$p_T(V)$	vector boson transverse momentum	✓	✓	✓
$p_T\,(H_{cand})$	H_{cand} transverse momentum	✓	✓	✓
$\lvert\eta(H_{cand})\rvert$	absolute value of the H_{cand} pseudorapidity	✓		
$\Delta\phi(V, H_{cand})$	azimuthal angle between vector boson and H_{cand}	✓	✓	✓
p_T^{miss}	missing transverse momentum		✓	
$\Delta\eta(H_{cand}, \ell)$	difference in pseudorapidity between H_{cand} and the lepton		✓	
$\Delta\eta(H_{cand}, V)$	difference in pseudorapidity between H_{cand} and vector boson			✓
$\Delta\eta(H_{cand}, j)$	min. difference in pseudorapidity between H_{cand} and small-R jets	✓	✓	✓
$\Delta\eta(\ell, j)$	min. difference in pseudorapidity between the lepton and small-R jets		✓	
$\Delta\eta(V, j)$	min. difference in pseudorapidity between vector boson and small-R jets			✓
$\Delta\phi(\vec{p}_T^{miss}, j)$	azimuthal angle between $\vec{p}_T^{miss}$ and closest small-R jet	✓		
$\Delta\phi(\vec{p}_T^{miss}, \ell)$	azimuthal angle between $\vec{p}_T^{miss}$ and lepton		✓	
m_T	transverse mass of lepton $\vec{p}_T + \vec{p}_T^{miss}$		✓	
N_{aj}	number of small-R jets	✓	✓	✓

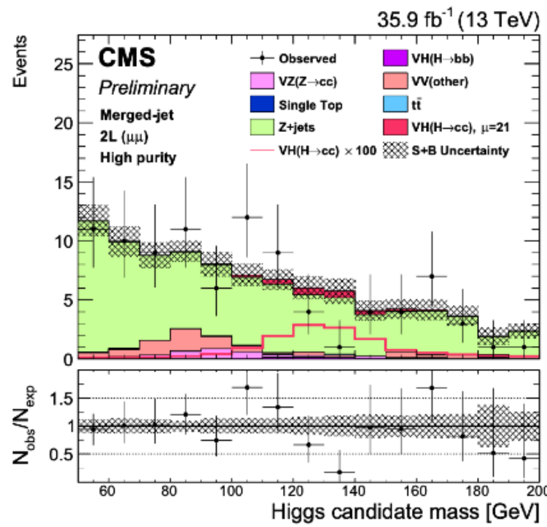
VHcc c-tagging and BDT in boosted

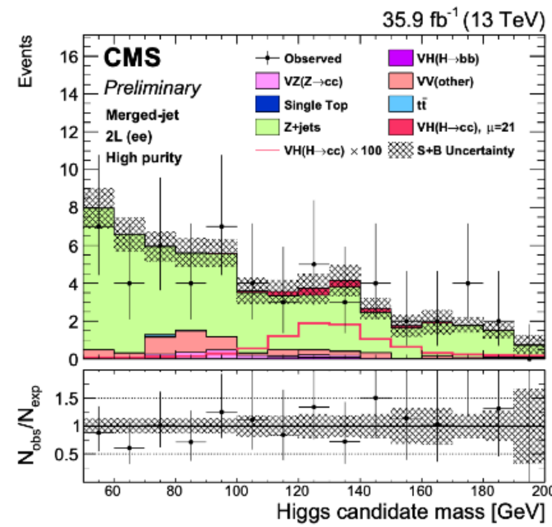


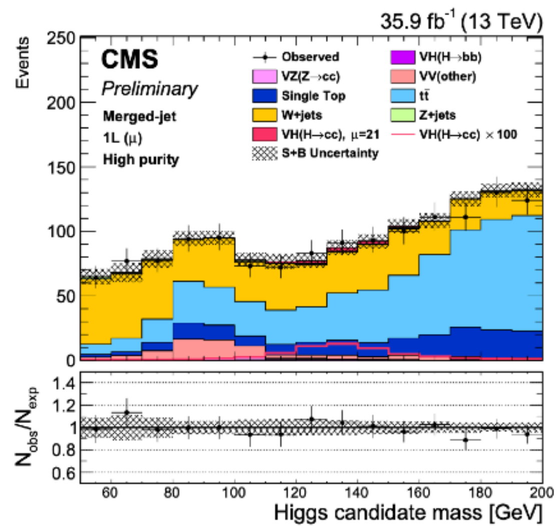
VHcc post-fit

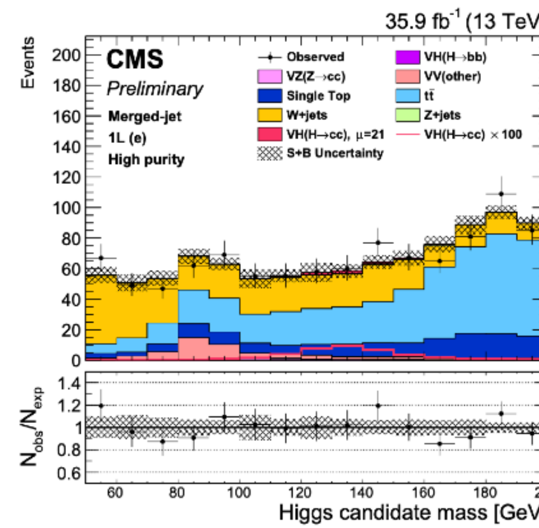
Boosted





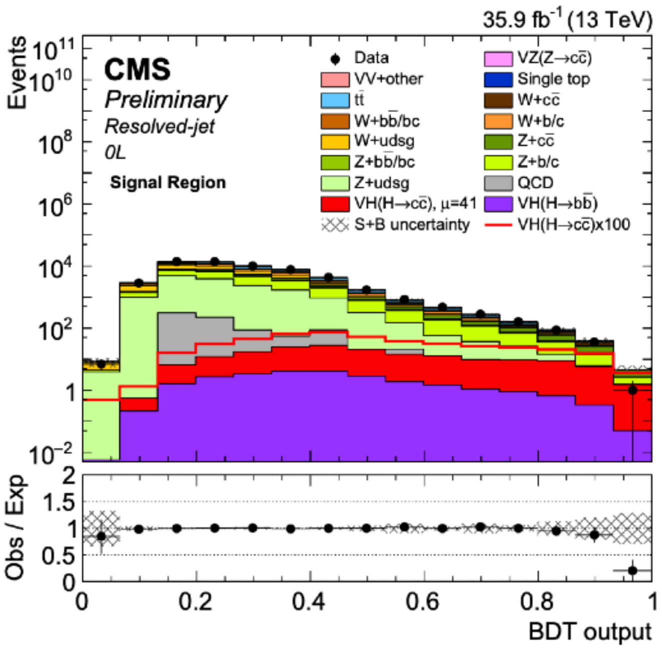


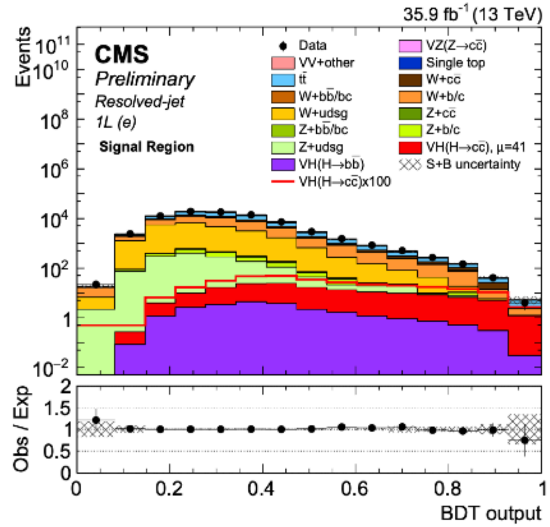


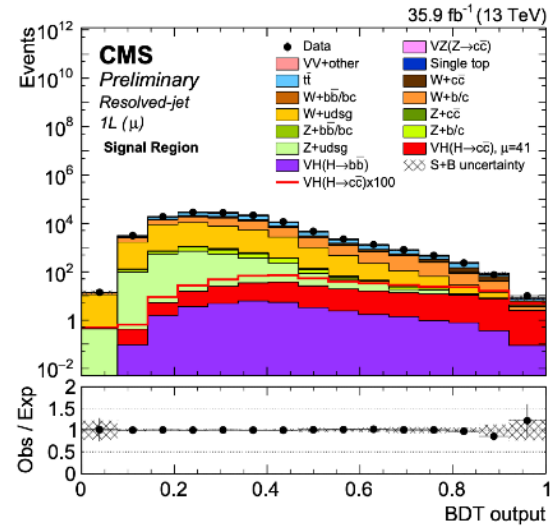


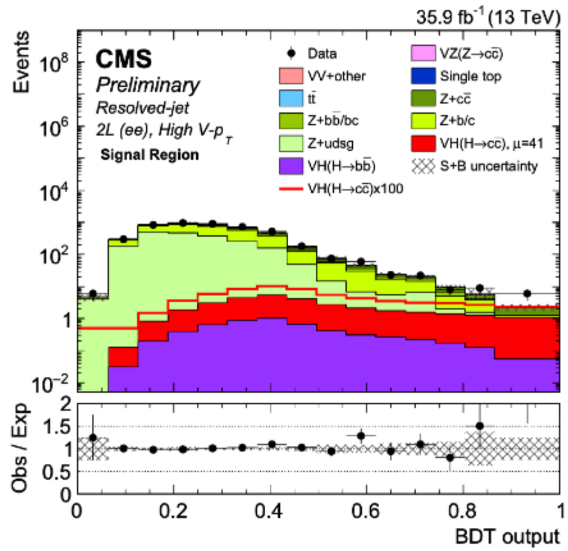
VHcc post-fit

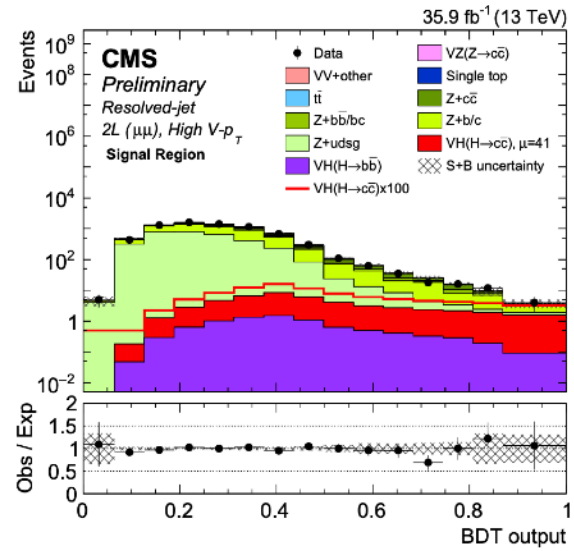
Resolved



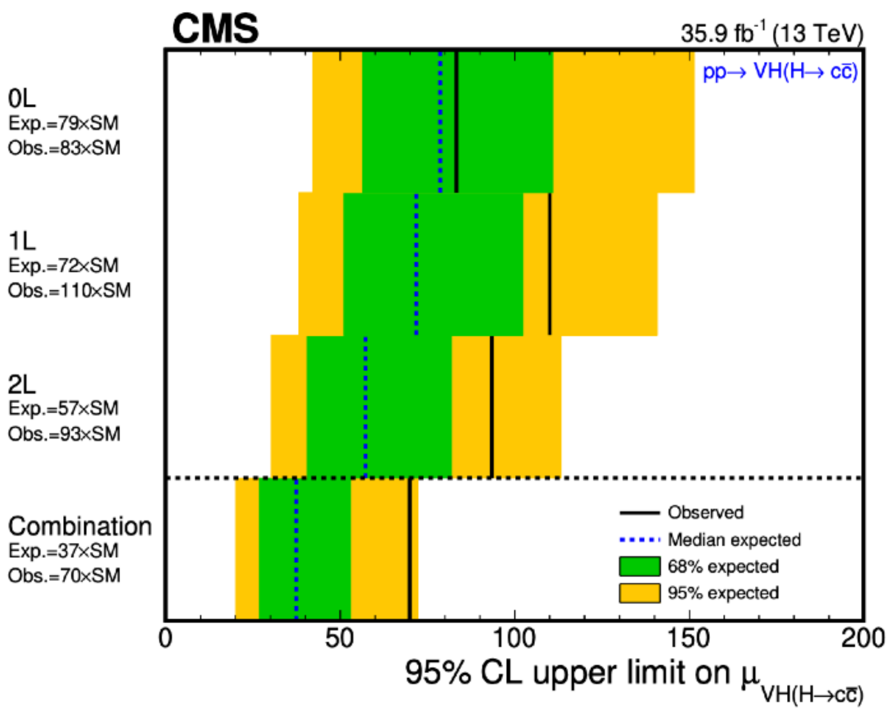








VHcc ATLAS



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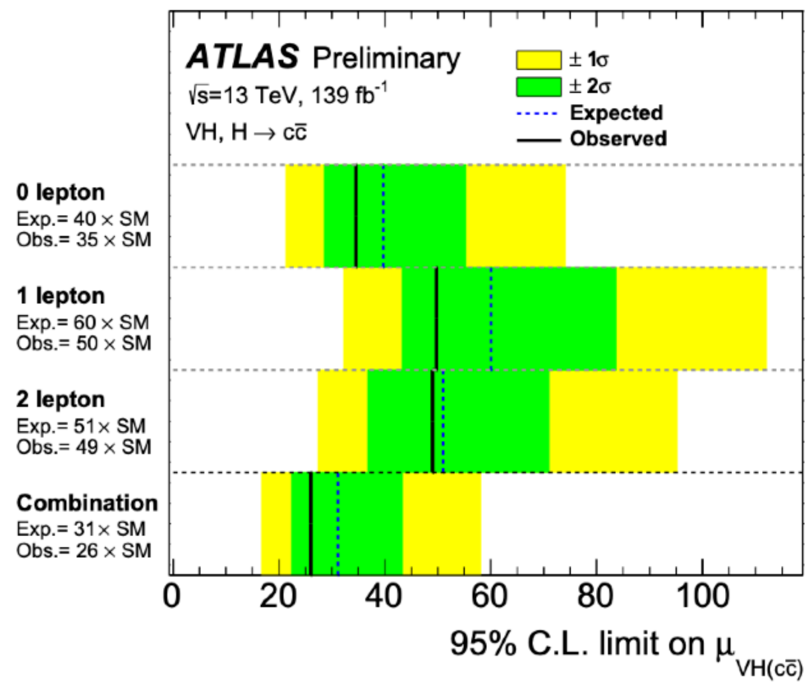
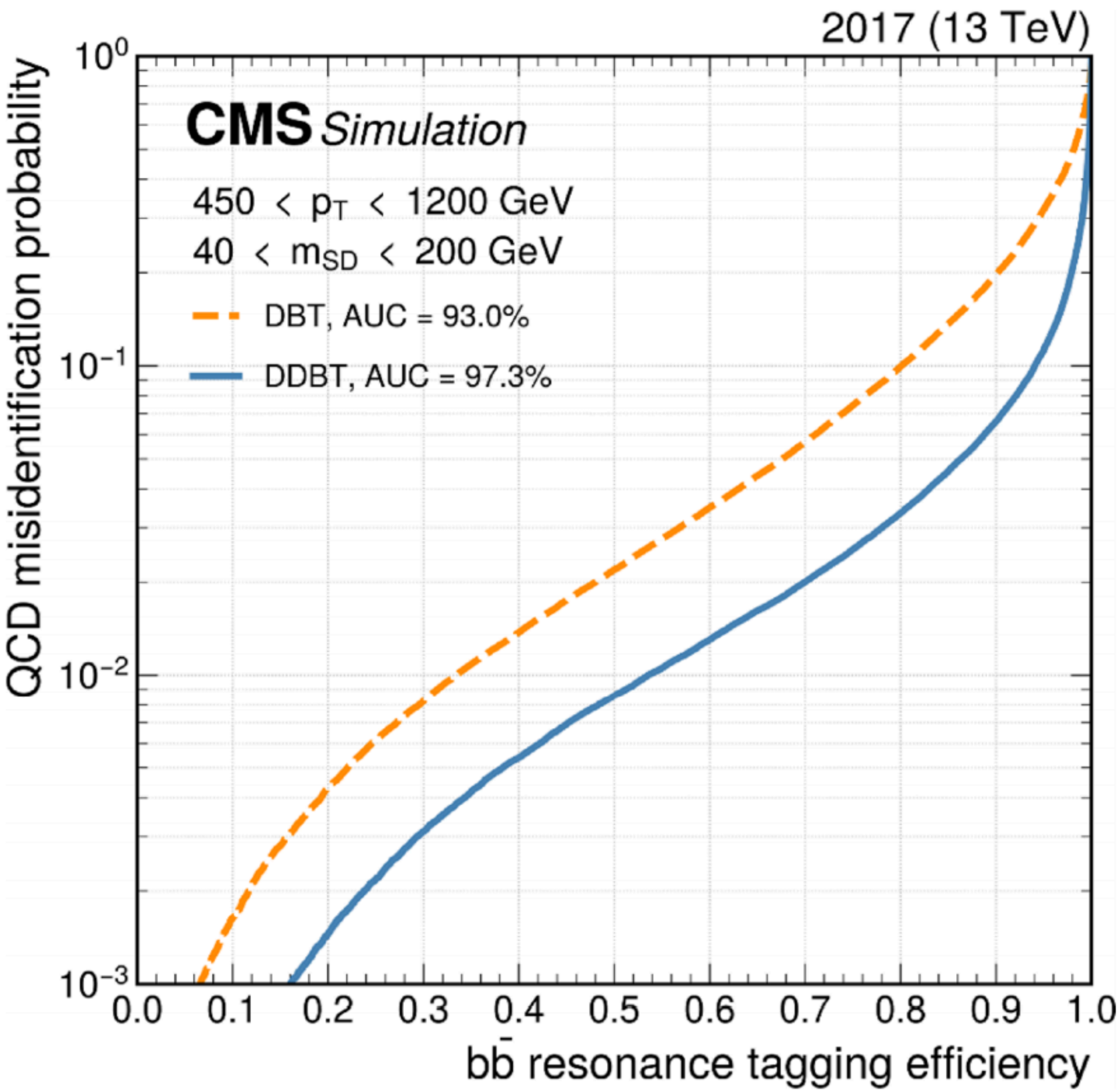
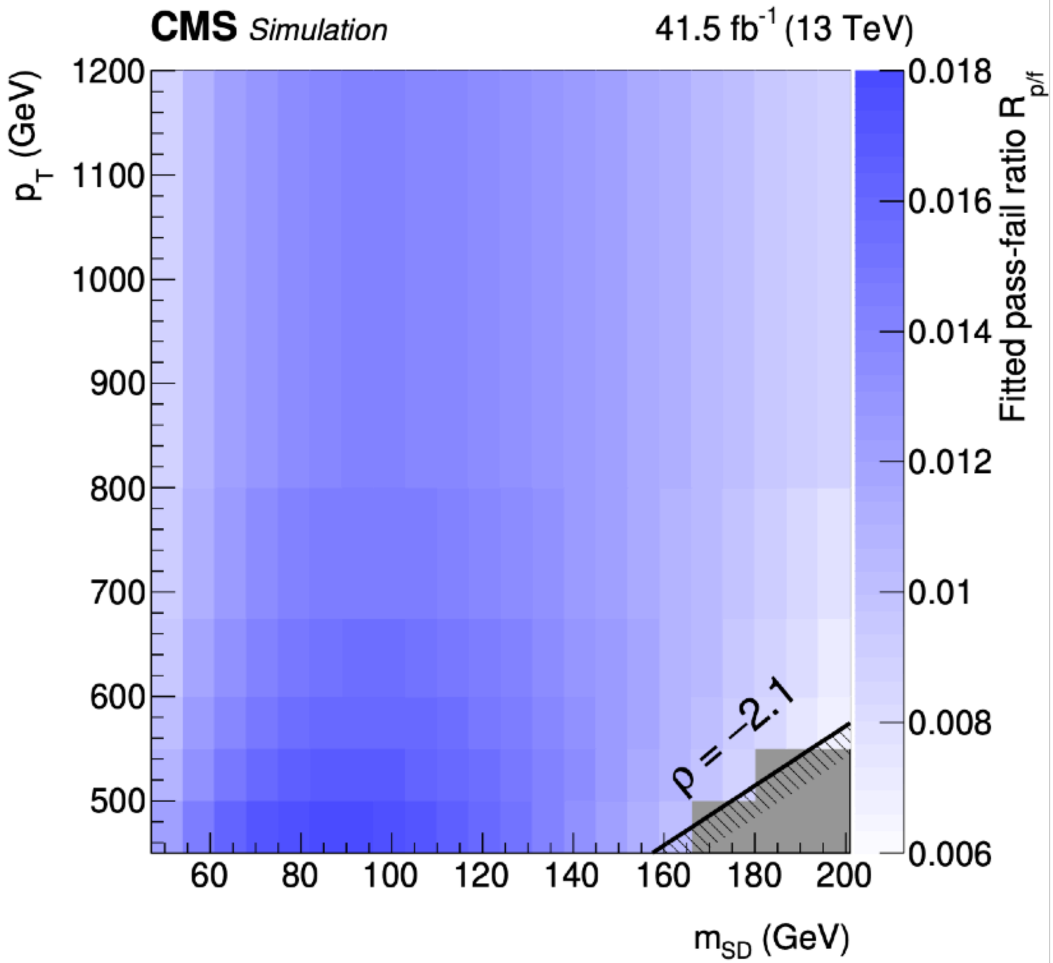


DeepDoubleB



ggH


CMS Simulation
41.5 fb^-1 (13 TeV)
p_T (GeV)
1200
1100
1000
900
800
700
600
500
60
80
100
120
140
160
180
200
m_SD (GeV)
ρ = −2.1
0.018
0.016
0.014
0.012
0.01
0.008
0.006
Fitted pass-fail ratio R_p/f

ggH systematics

Uncertainty source	$\Delta\mu_{H}$	
Statistical	+1.2	−1.2
Signal extraction	+0.9	−0.8
QCD pass-fail ratio (data correction)	+0.8	−0.7
$t\bar{t}$ normalization and misidentification	+0.4	−0.4
Systematic	+0.8	−0.7
QCD pass-fail ratio (simulation)	+0.6	−0.6
DDBT efficiency	+0.3	−0.1
Jet mass scale and resolution	+0.3	−0.3
Jet energy scale and resolution	+0.1	−0.1
Simulated sample size	+0.2	−0.1
Other experimental uncertainties	+0.1	−0.1
Theoretical	+0.8	−0.5
V+jets modeling	+0.6	−0.4
H modeling	+0.5	−0.3
Total	+1.6	−1.5

ggH detailed results

	2016	2017	2018	Combined
Expected μ_Z	$1.00^{+0.38}_{-0.28}$	$1.00^{+0.42}_{-0.29}$	$1.00^{+0.43}_{-0.29}$	$1.00^{+0.23}_{-0.19}$
Observed μ_Z	$0.86^{+0.32}_{-0.24}$	$1.11^{+0.48}_{-0.33}$	$0.91^{+0.37}_{-0.26}$	$1.01^{+0.24}_{-0.20}$
HJ-MINLO [32, 33]				
Expected μ_H	$1.0^{+3.3}_{-3.5}$	1.0 ± 2.5	$1.0^{+2.3}_{-2.4}$	1.0 ± 1.4
Observed μ_H	$7.9^{+3.4}_{-3.2}$	$4.8^{+2.6}_{-2.5}$	1.7 ± 2.3	$3.7^{+1.6}_{-1.5}$
Expected H significance ($\mu_H = 1$)	$0.3\,\sigma$	$0.4\,\sigma$	$0.4\,\sigma$	$0.7\,\sigma$
Observed H significance	$2.4\,\sigma$	$1.9\,\sigma$	$0.7\,\sigma$	$2.5\,\sigma$
Expected UL μ_H ($\mu_H = 0$)	<6.8	<5.0	<4.7	<2.9
Observed UL μ_H	<13.9	<9.3	<5.9	<6.4
Ref. [23] H p_T spectrum				
Expected μ_H	1.0 ± 1.5	$1.0^{+1.1}_{-1.0}$	$1.0^{+1.1}_{-1.0}$	$1.0^{+0.7}_{-0.6}$
Observed μ_H	$4.0^{+1.9}_{-1.6}$	$2.2^{+1.4}_{-1.2}$	1.1 ± 1.1	$1.9^{+0.9}_{-0.7}$
Expected H significance ($\mu_H = 1$)	$0.7\,\sigma$	$0.9\,\sigma$	$1.0\,\sigma$	$1.7\,\sigma$
Observed H significance	$2.6\,\sigma$	$1.8\,\sigma$	$1.1\,\sigma$	$2.9\,\sigma$
Expected UL μ_H ($\mu_H = 0$)	<3.4	<2.4	<2.3	<1.4
Observed UL μ_H	<7.4	<4.6	<3.2	<3.4

ggH cross-check