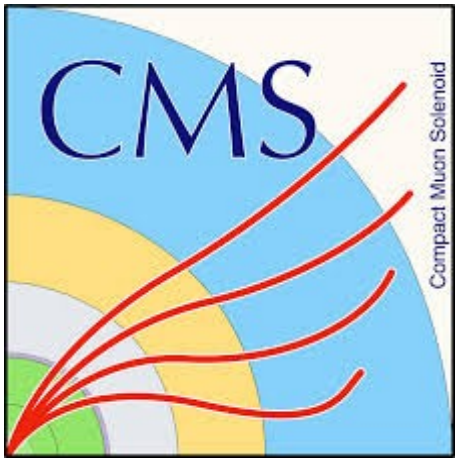


UCL
Université catholique de Louvain

Search for associated production of Higgs boson with a single top using 13 TeV CMS data

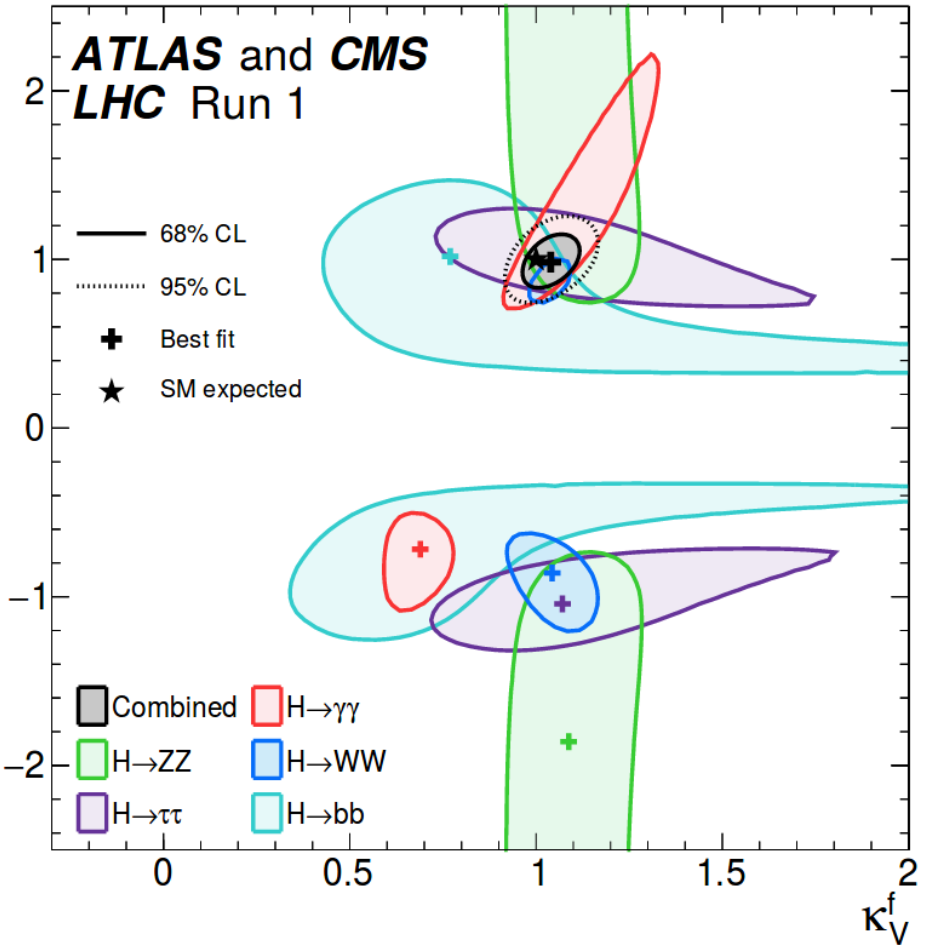
25th International Conference on Supersymmetry and the Unification of Fundamental Interactions

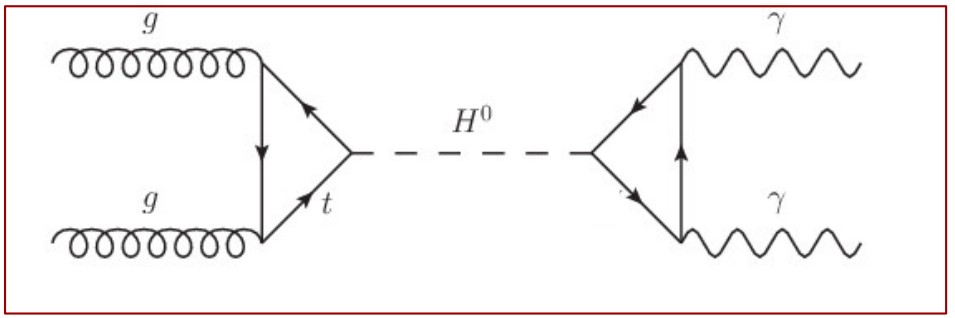
11-15 Dec 2017
Mumbai (India)

Hamed BAKHSHIANSOHI
Université catholique de Louvain

Higgs-Top coupling

- Particularly large Yukawa coupling for top
  - $|y_t| \sim 1.0$
- $\sigma_{ttH} \sim |y_t|$
  - ttH @ CMS+ATLAS RunI combination : 2.3σ
  - Run II : Evidence observed by CMS (3.2σ) and ATLAS (4.2σ)
- $|y_t|$ appears in Higgs branching fractions and other production cross sections ($H \rightarrow \gamma\gamma$ and $gg \rightarrow H$)



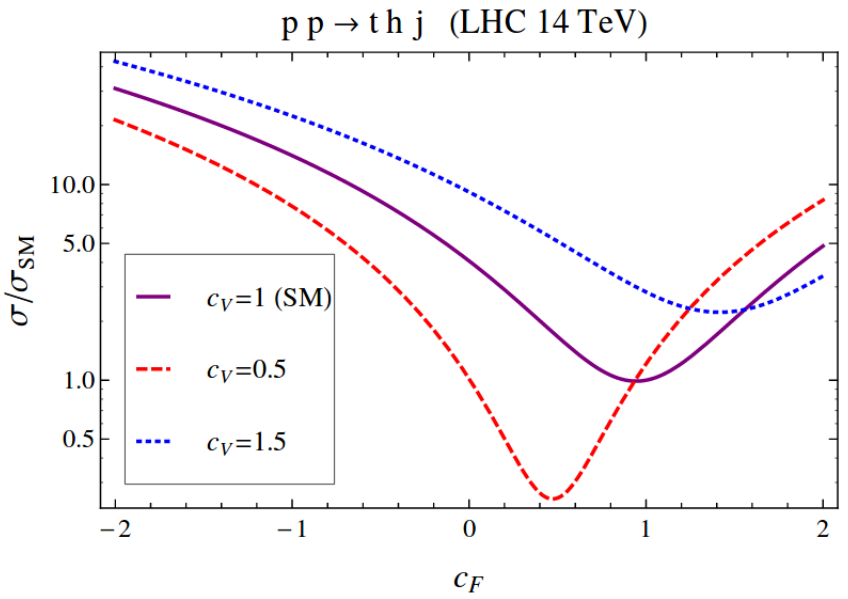


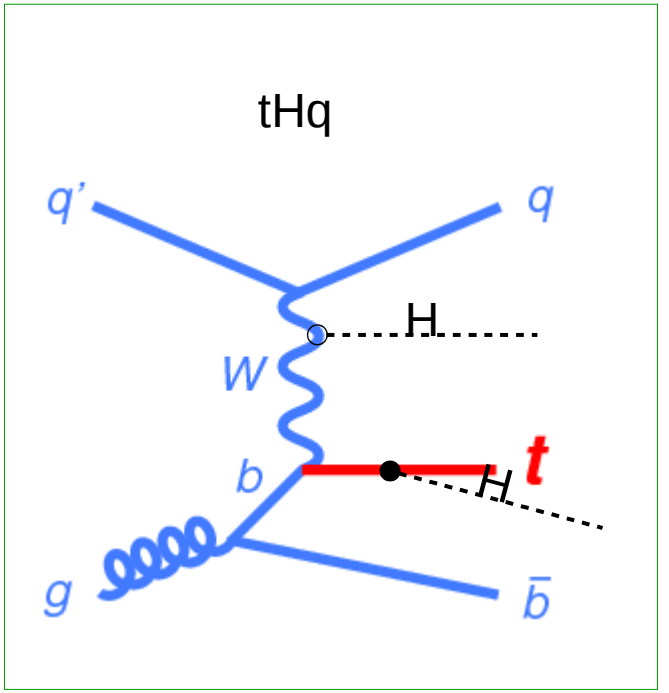
Single Top + Higgs

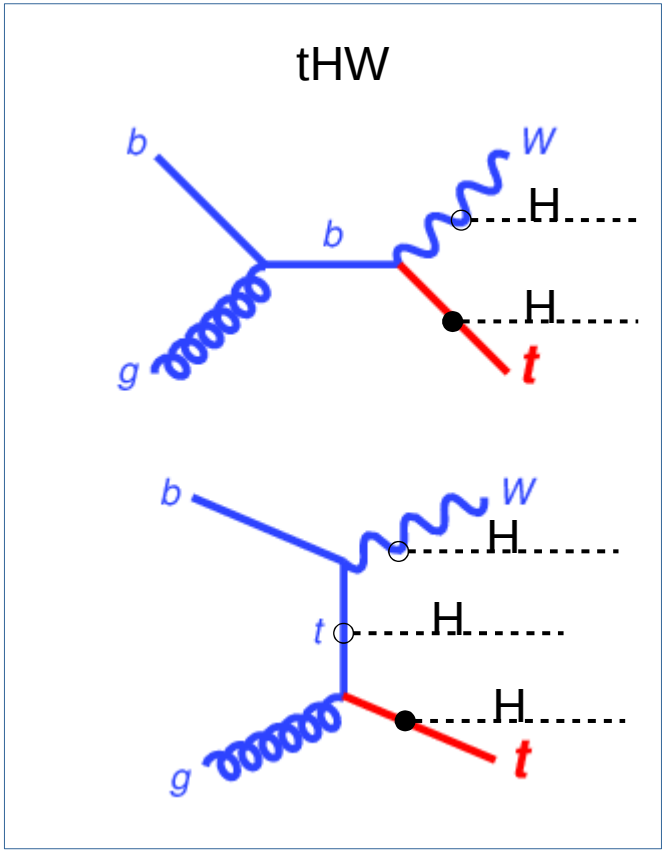
- Higgs couples to W and Top
- Interference

  $A \sim (Kt - Kv)\sqrt{S}$ + Other Terms

  - Fully destructive in SM
- Sensitive at Tree level to the Sign of Yukawa coupling of Higgs and Top





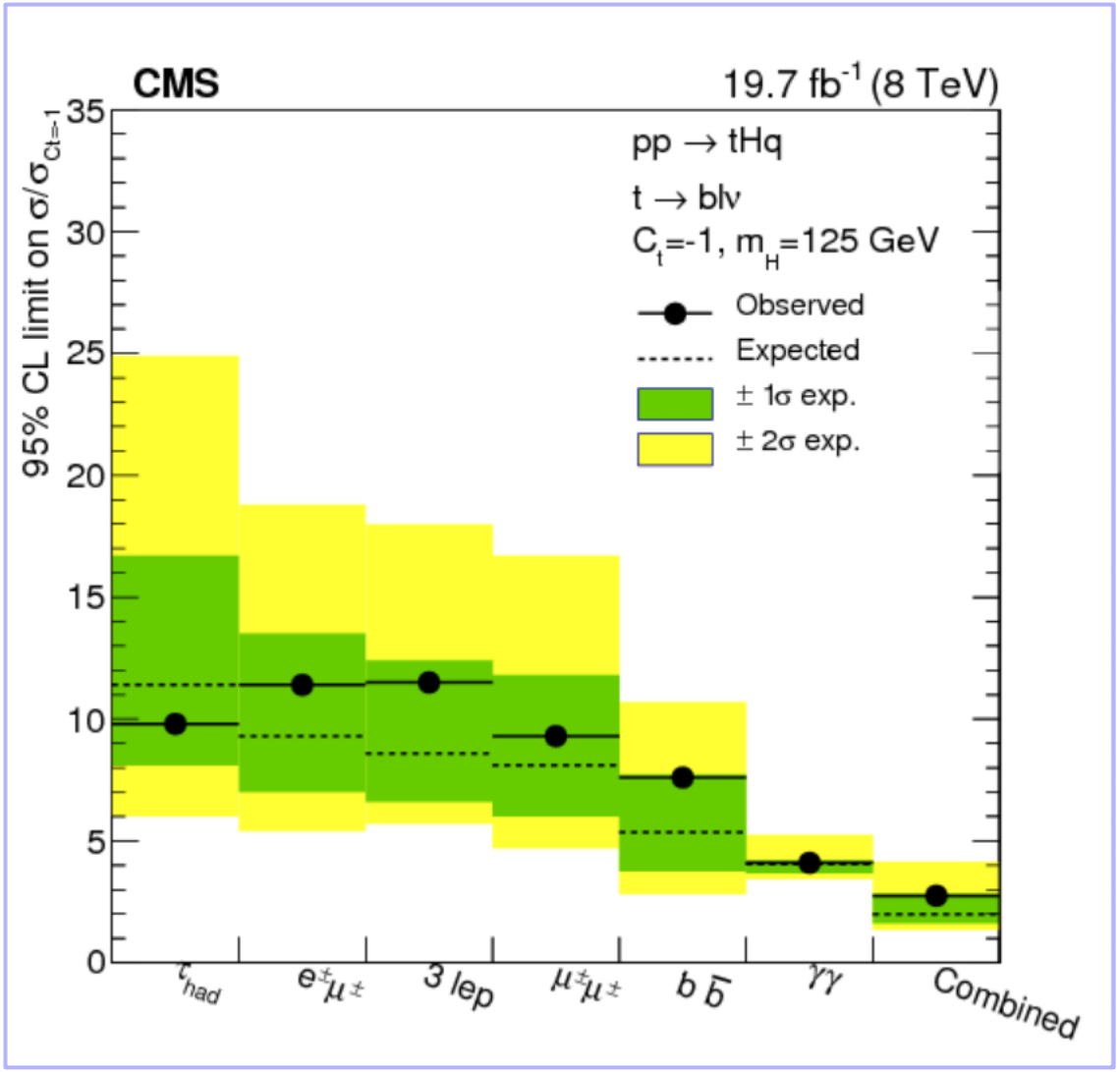


CMS Run I Summary

JHEP 06 (2016) 177

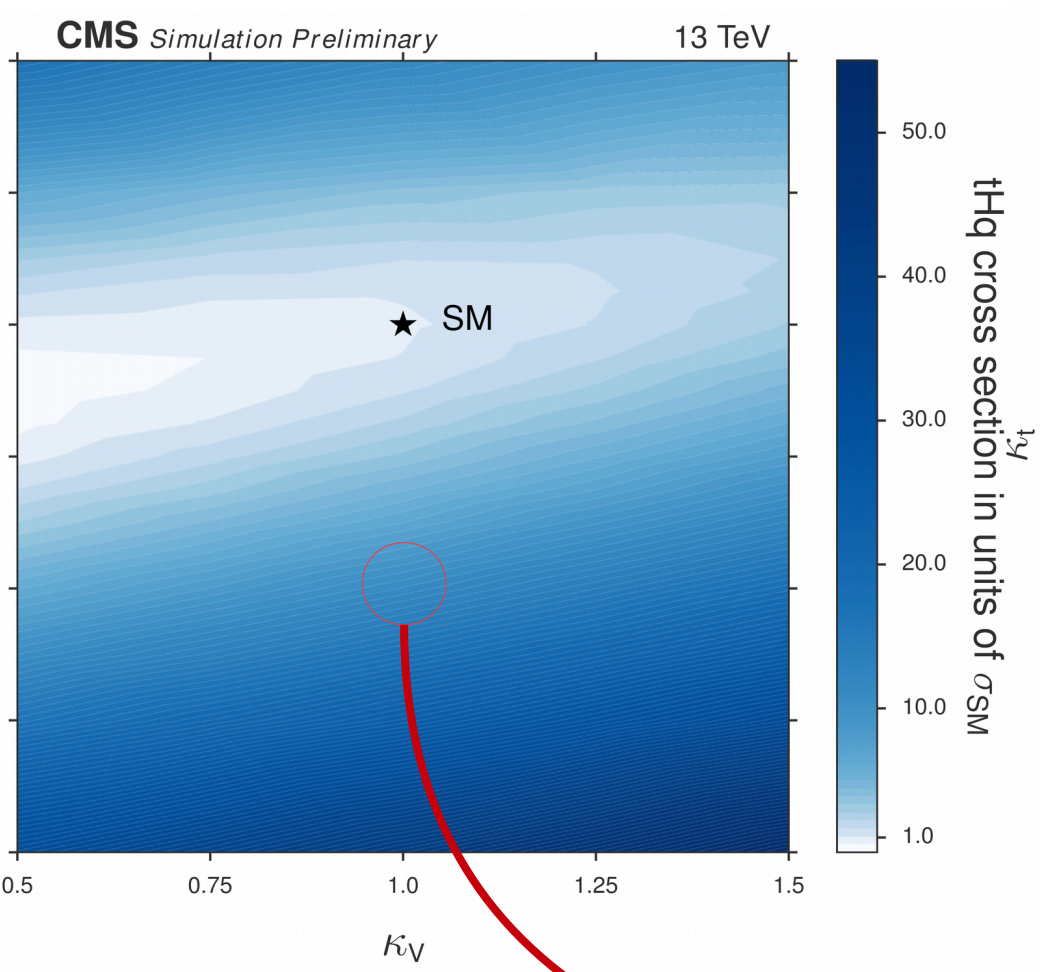
- Search only for $K_t = -1$

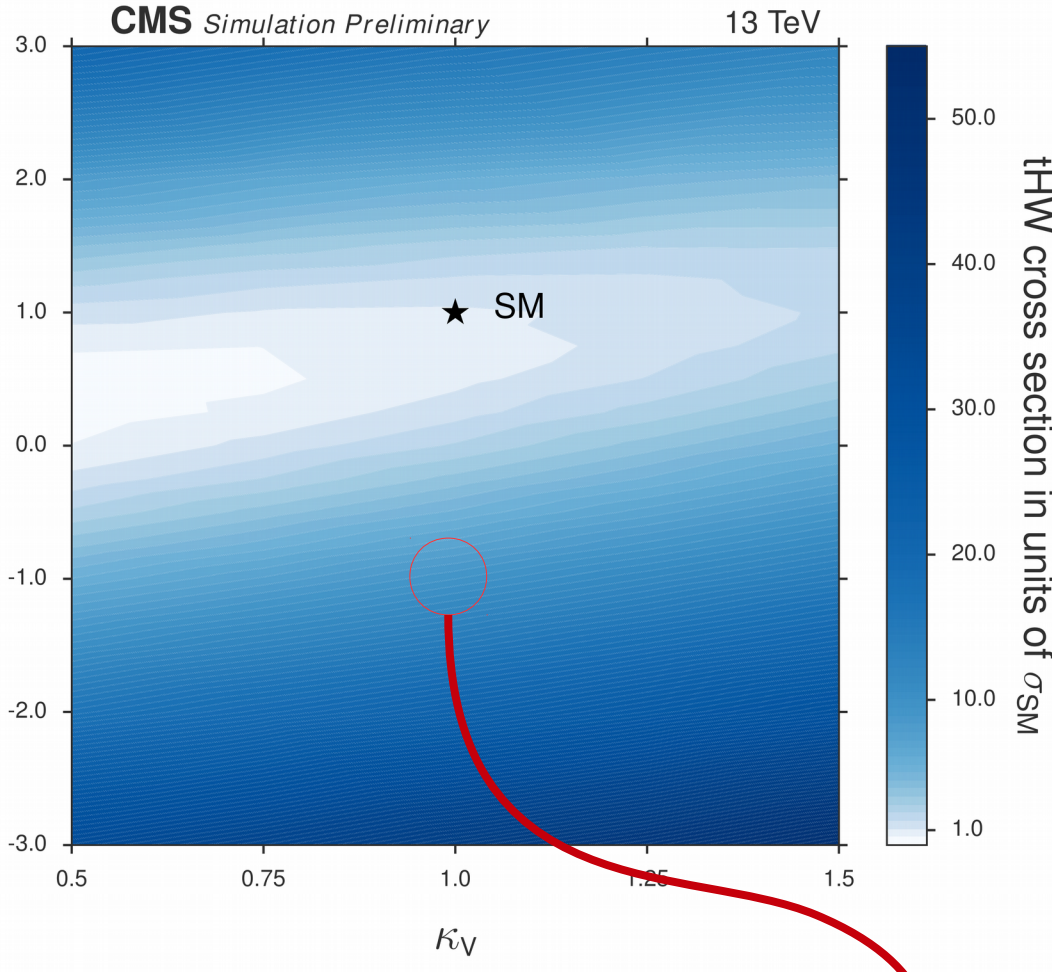
  (Inverted Top Coupling ITC)
- Different channels combined
- Combined 95% CL limit on signal strength : 2.8 (Exp:2.0)
- $\gamma\gamma$ is more sensitive : K_t appears also in the branching fraction



Cross sections @ 13 TeV

~4 times increase in the cross section from 8TeV → 13TeV





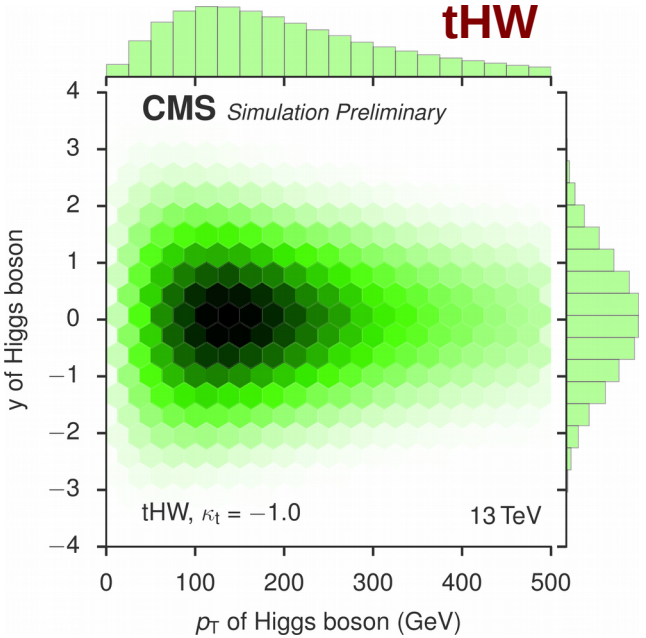
- Cross section depends on K_t and K_v
- Kinematics is a function of K_t/K_v only :

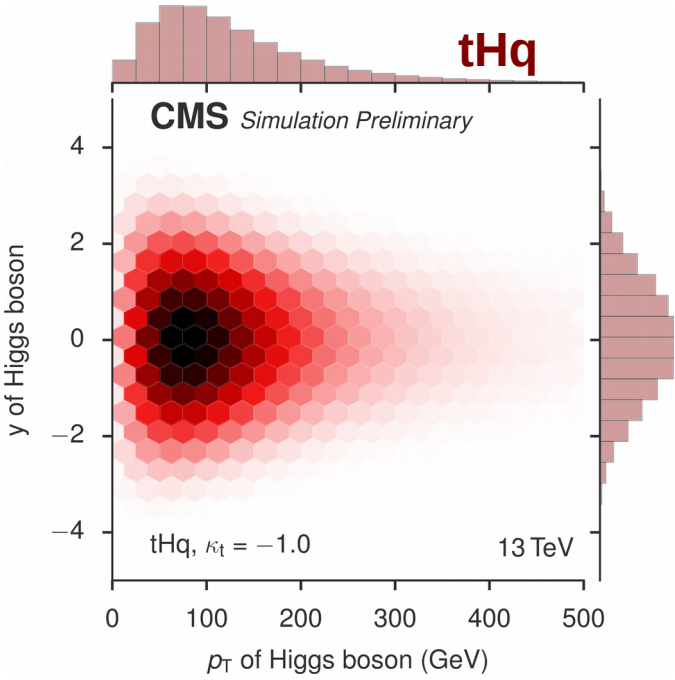
$$|\mathcal{M}|^2 = c_v^2[(c_t/c_v)^2|\mathcal{M}_t|^2 + (c_t/c_v)|\mathcal{M}_t||\mathcal{M}_v| + |\mathcal{M}_v|^2]$$

	tHq	tHW	ttH
SM	71 fb	16 fb	507 fb
ITC	739 fb	147 fb	

CMS Run II results

- tHq and tHW MC samples generated for a grid of K_t and K_v values @ LO
  - tHq : 4-flavor scheme
  - tHW : 5-flavor scheme
- Cross sections calculated at NLO
- Leptonic decay of the top
- CMS-HIG-16-019 : H→bb using 2015 dataset (2.3 fb^{-1})
- CMS-HIG-17-005 : H→Leptons using 2016 dataset (35.9 fb^{-1})





Search for tH association production in H→bb final state using 2015 dataset (2.3 fb^{-1})

Review of H→bb Analysis

1 electron or muon
3 or 4 b-tagged jets
at least 1 untagged jet

Signal enriched phase space

tHq reconstruction

ttbar reconstruction

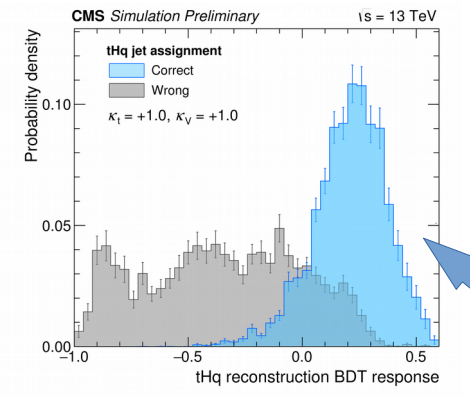
tHq variables

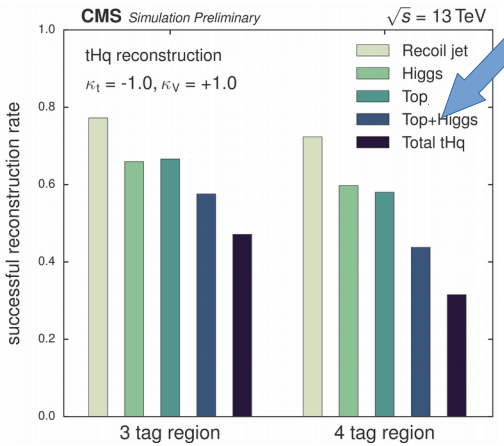
ttbar variables

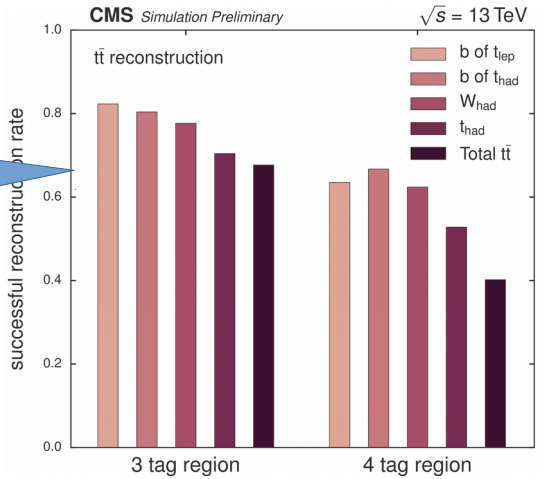
global variables

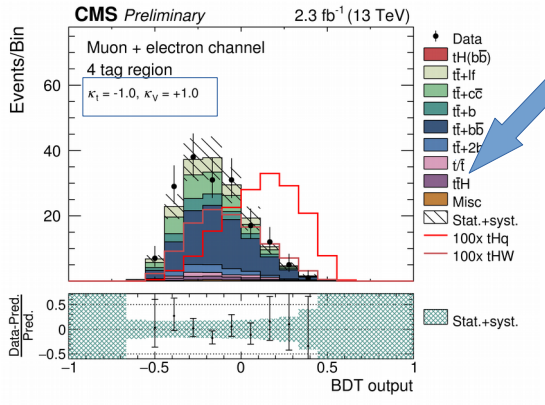
final MVA discriminator
tHq vs. backgrounds

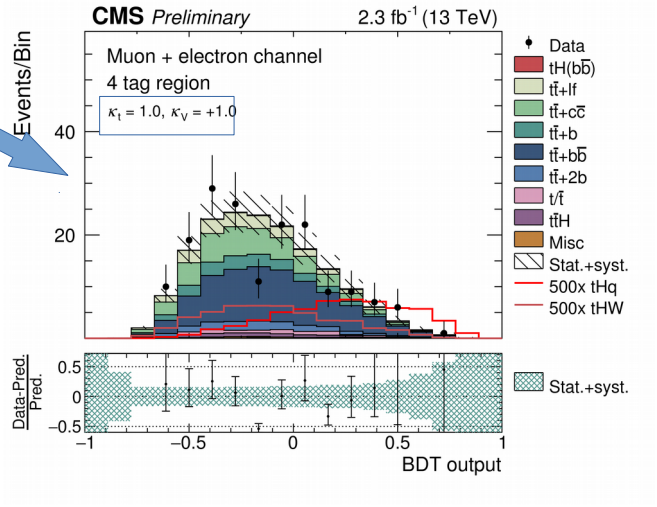
fit on MVA output





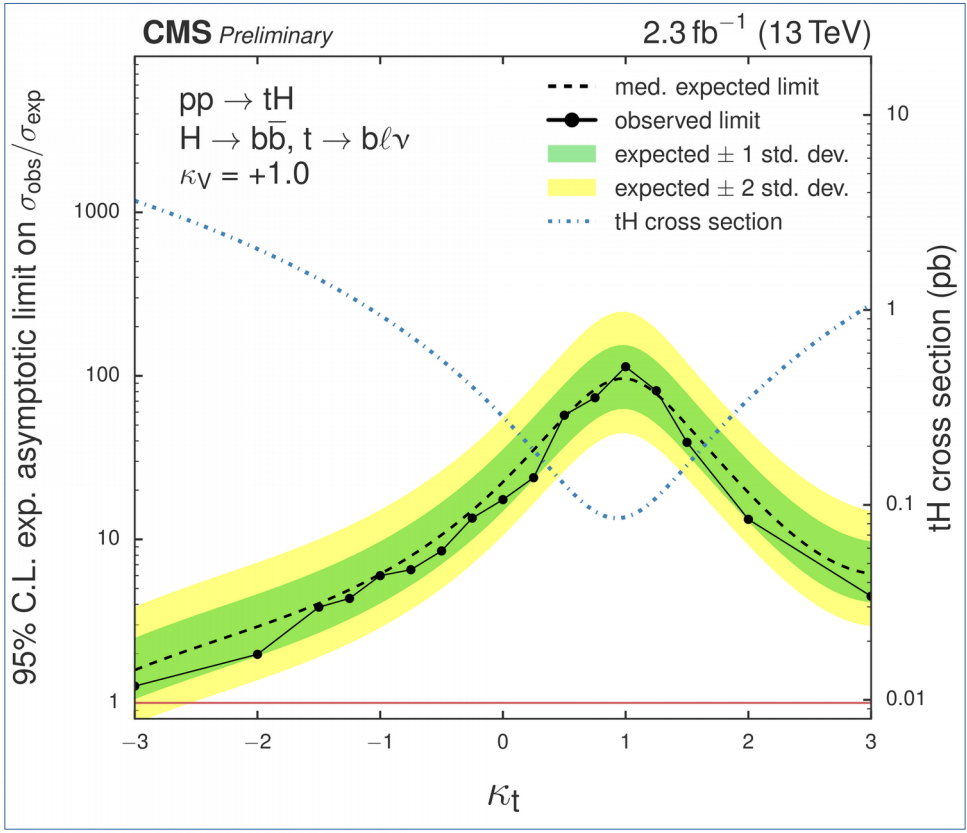


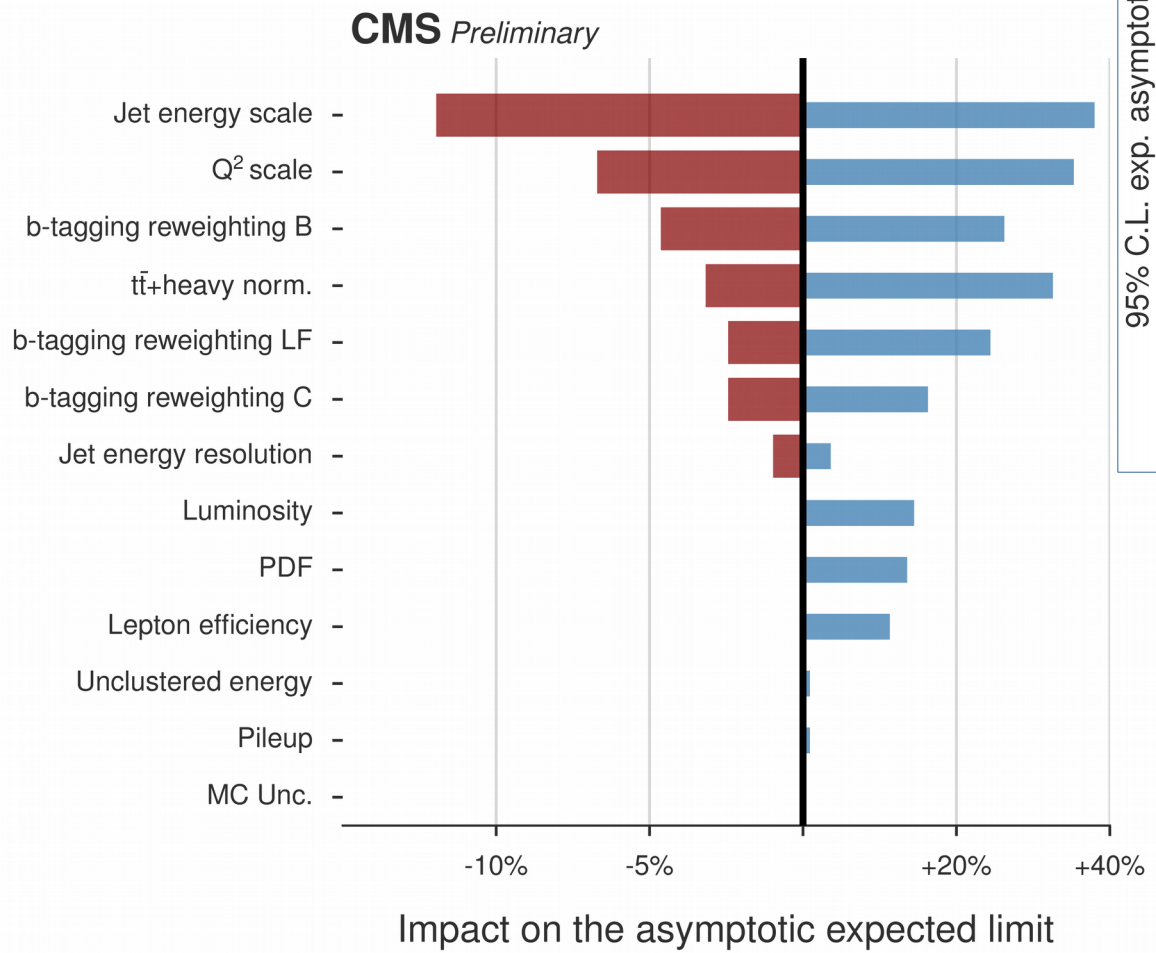




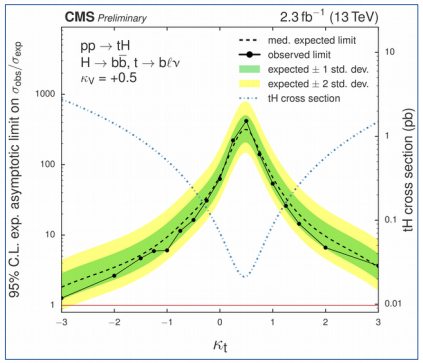
Results of the H→bb analysis

- Upper (expected) limit for the Inverted Top Coupling set to 6.0 (6.4)
  - Already improved w.r.t. Run-I
- Upper limit for the SM is 113.7 (98.6)

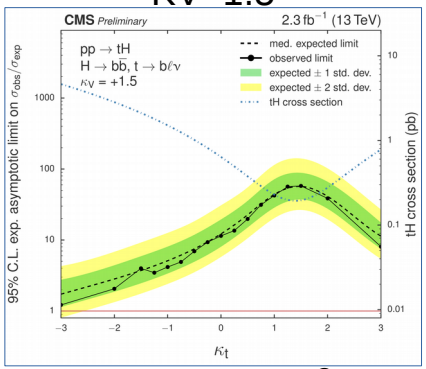




KV=0.5



KV=1.5

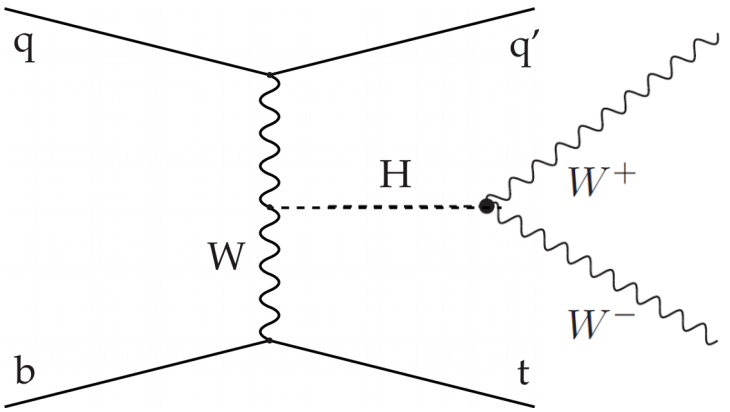


Dominated systematics uncertainty : Jet Energy Scale

Search for tH association production in H→MultiLepton final state using 2016 dataset (35.9 fb^{-1})

Search in multilepton final state

- Target : Higgs decay to WW
  - 3 leptons (e/μ)
  - 2 Same-sign leptons
- Higgs →ZZ/ττ are also selected



Selection :

Same-sign $\ell\ell$ channel ($\mu\mu$/eμ)	**$\ell\ell\ell$ channel**
No loose leptons with $m_{\ell\ell} < 12$ GeV One or more b tagged jets One or more non-tagged jets	
Exactly two tight same-sign leptons $p_T > 25/15$ GeV	Exactly three tight leptons $p_T > 25/15/15$ GeV No lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 15$ GeV

Backgrounds

- ttV taken from simulation
- WZ : Constrained using a 3l (1lepton + Z) + 2jets control region
  - Loose b-jets are vetoed to ensure no overlap with signal region
- Non prompt backgrounds
  - One lepton is produced inside a jet
  - Loose-to-tight probability extracted from data
    - QCD for leptons with p_T>30 and Z+jet for low p_T leptons
    - As a function of p_T and η of the lepton
  - Side band is defined by relaxing the lepton selection to loose
- Charge flip backgrounds :
  - Relevant in the same-sign channel
  - Probability of charge mis-identification for electron : 0.02% - 0.4%
  - For μ is negligible

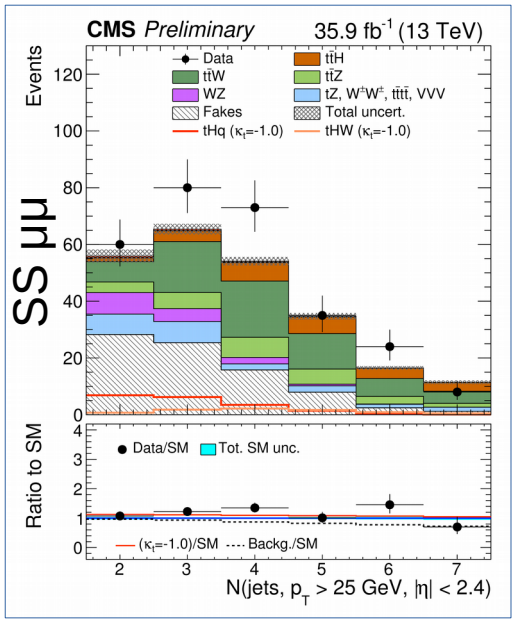
Process	$\ell\ell\ell$	$\mu\mu$	eμ
$t\bar{t}W^{\pm}$	22.50 ± 0.35	68.03 ± 0.61	97.00 ± 0.71
$t\bar{t}Z/t\bar{t}\gamma$	32.80 ± 1.79	25.89 ± 1.12	64.82 ± 2.42
WZ	8.22 ± 0.86	15.07 ± 1.19	26.25 ± 1.57
ZZ	1.62 ± 0.33	1.16 ± 0.29	2.86 ± 0.45
$W^{\pm}W^{\pm}qq$	–	3.96 ± 0.52	6.99 ± 0.69
$W^{\pm}W^{\pm}$(DPS)	–	2.48 ± 0.42	4.17 ± 0.54
VVV	0.42 ± 0.16	2.99 ± 0.34	4.85 ± 0.43
tttt	1.84 ± 0.44	2.32 ± 0.45	4.06 ± 0.57
tZq	3.92 ± 1.48	5.77 ± 2.24	10.73 ± 3.03
tZW	1.70 ± 0.12	2.13 ± 0.13	3.91 ± 0.18
γ conversions	7.43 ± 1.94	–	23.81 ± 6.04
Non-prompt	25.61 ± 1.26	80.94 ± 2.02	135.34 ± 2.83
Charge flips	–	–	58.20 ± 0.30
Total Background	106.05 ± 3.45	210.74 ± 3.61	443.30 ± 8.01
$t\bar{t}H$	18.29 ± 0.41	24.18 ± 0.48	35.21 ± 0.58
tHq (SM)	0.52 ± 0.02	1.43 ± 0.04	1.92 ± 0.04
tHW (SM)	0.62 ± 0.03	0.71 ± 0.03	1.11 ± 0.04
Total SM	125.48 ± 3.47	237.06 ± 3.64	481.54 ± 8.03
tHq ($\kappa_V = 1 = -\kappa_t$)	7.48 ± 0.14	18.48 ± 0.22	27.41 ± 0.27
tHW ($\kappa_V = 1 = -\kappa_t$)	7.38 ± 0.16	7.72 ± 0.17	11.23 ± 0.20
Data	**149**	**280**	**525**

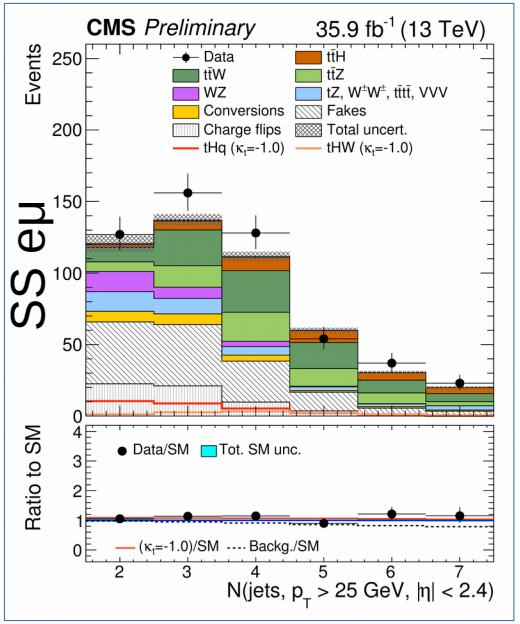
Analysis strategy

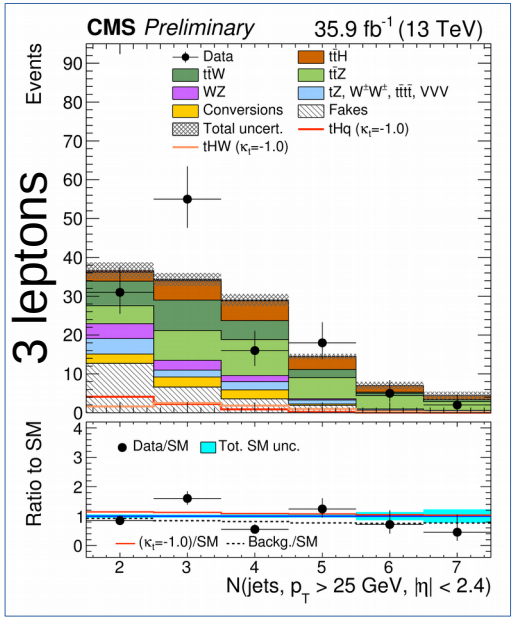
- Train two BDTs in each channel to separate tHq from $t\bar{t}V$ and $t\bar{t}$
  - $t\bar{t}H$ and tHW are more similar to $t\bar{t}V$ and are not used in the training

- Variables used for BDT training :
  - Related to forward jet activity
  - Leptons: kinematics and charge
  - Jet multiplicities

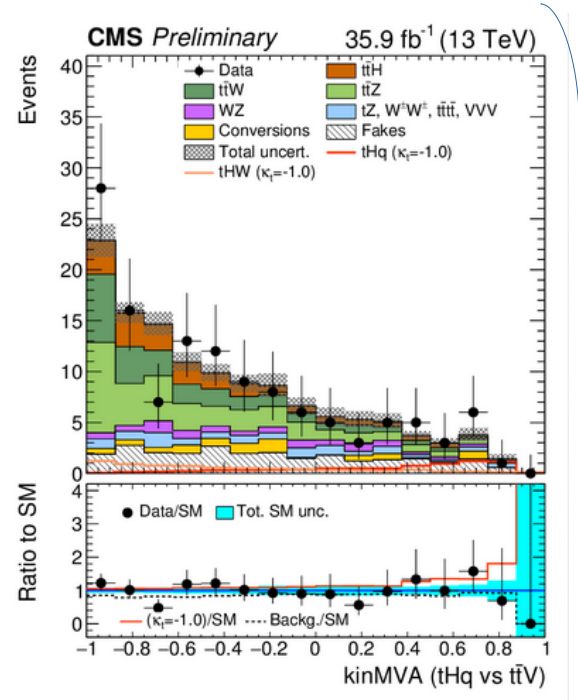
Number of jets with $p_T > 25\,\text{GeV}$, $\lvert\eta\rvert < 2.4$
Maximum $\lvert\eta\rvert$ of any (non-b-tagged) jet ("forward jet")
Sum of lepton charges
Number of non-b-tagged jets with $\lvert\eta\rvert > 1.0$
$\Delta\eta$ between forward light jet and leading b-tagged jet
$\Delta\eta$ between forward light jet and sub-leading b-tagged jet
$\Delta\eta$ between forward light jet and closest lepton
$\Delta\phi$ of same-sign lepton pair
Minimum ΔR between any two leptons
p_T of sub-leading (or 3^{rd}) lepton

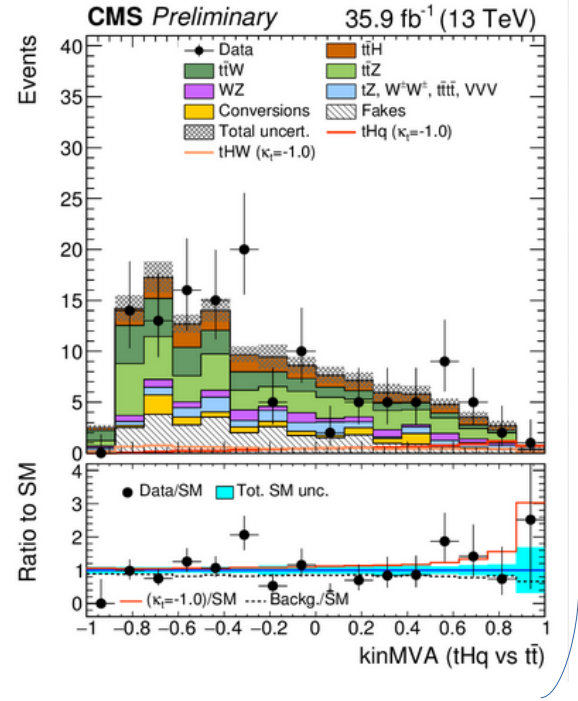




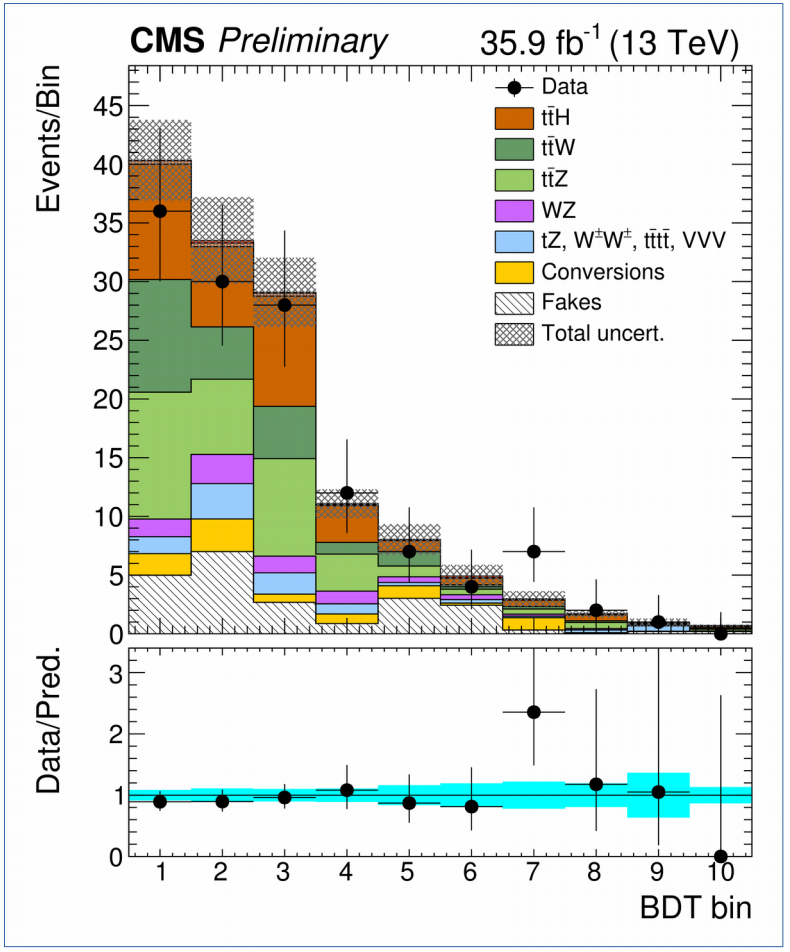


Signal Extraction





- 10 categories are defined using the output of two BDT's
  - Optimized for each channel separately
- Fitting on the shape of the 1-d output



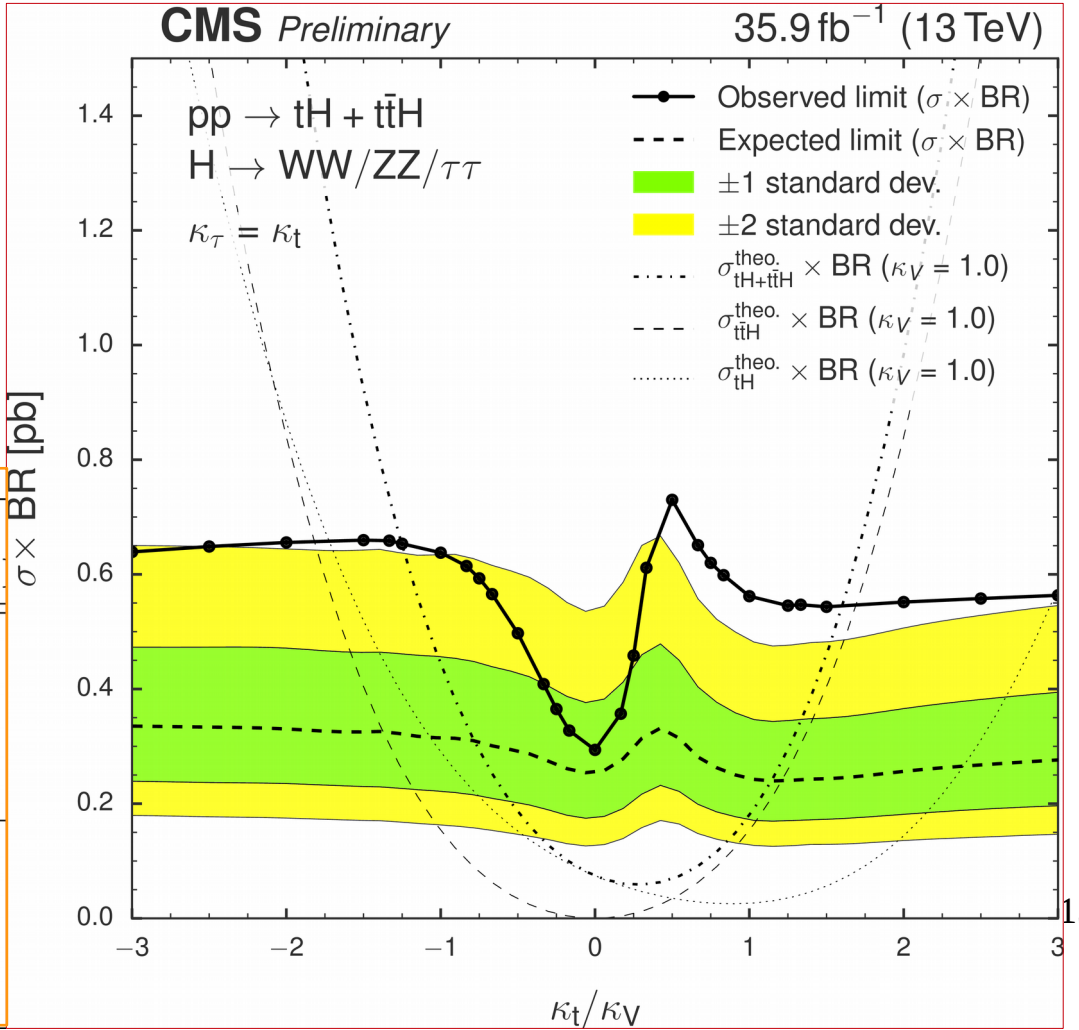
Results

- Upper limit on

$$\sigma(pp \rightarrow tH + ttH) \times BR(H \rightarrow WW + \tau\tau + ZZ)$$

- vs. K_t/K_v
- Assumption : $K_t = K_\tau$
- Observed > Expected :
  - Sign of ttH

Scenario	Channel	Obs. Limit (pb)
$\kappa t/\kappa_V = -1$	$\mu\mu$	1.00
	eμ	0.84
	$\ell\ell\ell$	0.70
	Combined	**0.64**
$\kappa t/\kappa_V = 1$ (SM-like)	$\mu\mu$	0.87
	eμ	0.59
	$\ell\ell\ell$	0.54
	Combined	**0.56**



Summary

- Single-top + Higgs events help in understanding the Higgs-Top coupling
- CMS has an extensive program to study it in different decay channels
- Results for H→bb (2015) and H→Multileptons presented
  - Stay tuned for more results and combination


Thanks
ERECTED TO COMMEMORATE THE LANDING
IN INDIA OF THEIR IMPERIAL MAJESTIES
KING GEORGE V AND QUEEN MARY
ON THE SECOND OF DECEMBER MCMXI

BACKUP

tHq/H→bb
Yields table

	3 tag	4 tag
$t\bar{t}$+LF	2119 ± 651	21.3 ± 21.6
$t\bar{t}$+c$\bar{c}$	852 ± 624	39 ± 46
$t\bar{t}$+b	324 ± 203	18.7 ± 15.3
$t\bar{t}$+b$\bar{b}$	333 ± 298	71 ± 67
$t\bar{t}$+2b	177 ± 102	13.0 ± 9.6
Single top	156 ± 44	6.0 ± 2.4
$t\bar{t}$H	20.3 ± 9.7	5.3 ± 2.9
$t\bar{t}$Z	9.4 ± 2.3	1.8 ± 1.7
$t\bar{t}$W	8.0 ± 2.5	0.4 ± 0.4
W+jets	42 ± 35	0.0 ± 0.0
Z+jets	10.2 ± 5.0	0.0 ± 0.0
Sum of Backgrounds	4051 ± 978	177 ± 86
tHq (SM)	0.77 ± 0.21	0.12 ± 0.04
tHW (SM)	0.61 ± 0.09	0.09 ± 0.02
tHq (ITC)	11.2 ± 3.1	1.7 ± 0.6
tHW (ITC)	6.7 ± 1.0	1.1 ± 0.3
Observed	**3603**	**171**

tHq/H→bb
Variables used to train BDT for jet assignment, tHq hypothesis

Variable	Description
log m(H)	Invariant mass of the reconstructed Higgs boson
log m(t)	Invariant mass of the reconstructed top quark
ΔR(Higgs jets)	ΔR between the two jets from the Higgs boson decay
ΔR(b_t, W)	ΔR between the jet assigned to the b quark from the top quark decay and the W boson
relative H_T	Ratio of p_T(H) + p_T(t) + p_T(recoil jet) to the scalar sum of p_T of all jets, charged lepton, and E_T^{miss}
cos θ(t, ℓ)	Cosine of the angle between the top quark momentum and the sum of momenta of top quark and charged lepton, in their common rest frame
CSV(Higgs jet 2)	Output of the CSVv2 b-tagging algorithm for the second hardest jet assigned to the Higgs boson
CSV(b_t)	Output of the CSVv2 b-tagging algorithm for the jet assigned to the b quark from the top quark decay
$\lvert\eta(\text{recoil jet}) - \eta(b_t)\rvert$	Absolute difference of pseudorapidities of the recoil jet and of the b jet from the top quark decay
CSV(Higgs jet 1)	Output of the CSVv2 b-tagging algorithm for the hardest jet assigned to the Higgs boson
$\lvert\eta(b_t)\rvert$	Absolute pseudorapidity of the jet assigned to the b quark of the top quark decay
$\lvert\eta(t) - \eta(H)\rvert$	Absolute difference of pseudorapidities of reconstructed top quark and the reconstructed Higgs boson
log min(p_T(H jets))	Lower transverse momentum of the two jets assigned to the Higgs boson decay products
$\lvert\eta(\text{recoil jet})\rvert$	Absolute pseudorapidity of the recoil jet
ΔE(recoil jet, b_t)	Energy difference between the recoil jet and the jet assigned to the b quark from the top quark decay

tHq/H→bb
Variables used to train BDT for jet assignment, $t\bar{t}$ hypothesis

Variable	Description
log m(W_{had})	Invariant mass of the two jets assigned to the W boson of t_{had}
log (m(t_{had}) - m(W_{had}))	Difference between the invariant masses of reconstructed t_{had} and W_{had}
log m(t_{lep})	Invariant mass of the reconstructed t_{lep}
CSV(W_{had} jet 1)	CSVv2 output of the hardest jet assigned to W_{had}
ΔR($b_{t_{lep}}$,W_{lep})	ΔR between the b quark of the reconstructed t_{lep} and W_{lep}
CSV(W_{had} jet 2)	CSVv2 output of the second hardest jet assigned to W_{had}
ΔR(W_{had} jets)	ΔR between the two jets assigned to the W boson of t_{had}
relative H_T	Ratio of $p_T(t_{had}) + p_T(t_{lep})$ to the scalar sum of p_T of all jets, charged lepton, and E_T^{miss}
ΔR($b_{t_{had}}$, W_{had})	ΔR between the b quark of the reconstructed t_{had} and W_{had}
log p_T(t_{had})	Transverse momentum of the reconstructed t_{had}
log p_T(t_{lep})	Transverse momentum of the reconstructed t_{lep}

tHq/H→bb
Variables used to train BDT tHq/$t\bar{t}$ separation

Variable	Description
Variables independent of any reconstruction	
aplanarity	Aplanarity of the event
log m3	Invariant mass of three hardest jets in the event
Fox-Wolfram #1	First Fox-Wolfram moment of the event
q(ℓ)	Electric charge of the lepton
Variables based on objects reconstructed under the $t\bar{t}$ hypothesis	
log m(t_{had})	Invariant mass of t_{had}
CSV(W_{had} jet 1)	CSVv2 output of the hardest jet assigned to W_{had}
ΔR(W_{had} jets)	ΔR between the two jets from the decay of W_{had}
CSV(W_{had} jet 2)	CSVv2 output of the second hardest jet assigned to W_{had}
Variables based on objects reconstructed under the tHq hypothesis	
$\lvert\eta$**(recoil jet)**$\rvert$	Absolute pseudorapidity of the recoil jet
CSV(Higgs jet 2)	CSVv2 output of the second hardest jet assigned to the Higgs boson
CSV(Higgs jet 1)	CSVv2 output of the hardest jet assigned to the Higgs boson
log p_T(recoil jet)	Transverse momentum of the recoil jet
log p_T(Higgs)	Transverse momentum of the Higgs boson
$\lvert\eta$**(Higgs)**$\rvert$	Absolute pseudorapidity of the Higgs boson
cos θ(t,ℓ)	Cosine of the angle between the top quark momentum and the sum of top quark and charged lepton, in their common rest frame

tHq/H → bb
Limit details

	Region	Observed Limit	Expected Limit		
			Median	$\pm 1\sigma$	$\pm 2\sigma$
SM scenario	3 tag	124.0	114.3	[73.6, 184.4]	[52.0 , 295.2]
	4 tag	195.8	174.6	[112.9, 287.4]	[78.8 , 464.4]
	Combination	**113.7**	**98.6**	**[64.0 , 159.2]**	**[45.3 , 254.8]**
ITC scenario	3 tag	7.4	7.4	[4.9 , 11.6]	[3.5 , 17.8]
	4 tag	9.2	10.0	[6.5 , 16.3]	[4.5 , 26.3]
	Combination	**6.0**	**6.4**	**[4.2 , 10.1]**	**[3.0 ,15.7]**