Search for a Higgs boson produced in association with a top pair (ttbarH) at the LHC

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Introduction

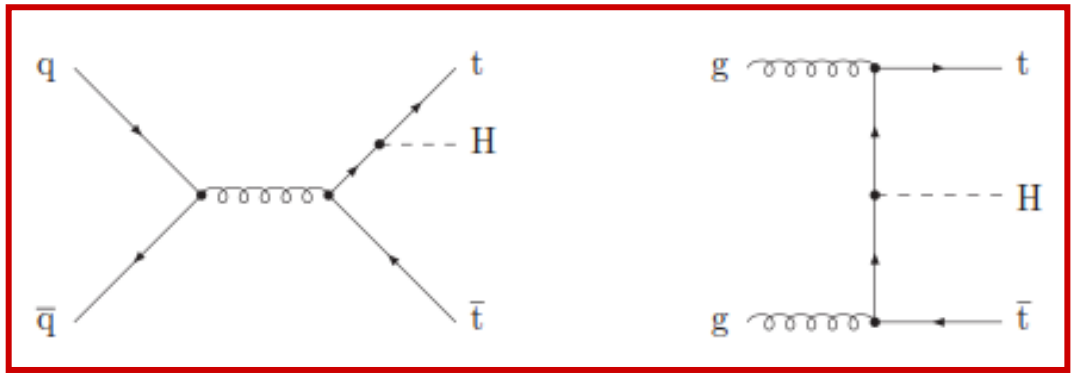
- Review of the experimental searches for a (SM) Higgs boson produced in association with a pair of top quarks.

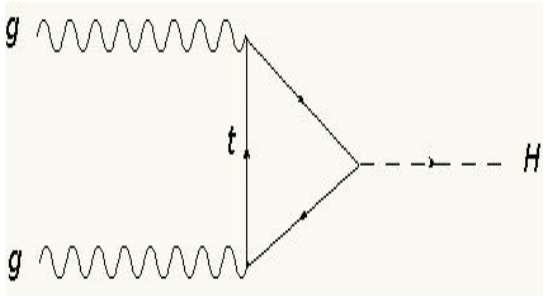
- Motivations :
  - Top-quark == heaviest quark (decay before it hardonizes) and Yukawa coupling close to 1 : important probe to test the EWK symmetry breaking mechanism.
  - Top mass > Higgs mass : top-Higgs coupling can only be studied **directly** at production level (Higgs do not decays into tops).
  - While top-Higgs couplings are already "investigated" in the direct Higgs production (ggF), and $\gamma\gamma$ decays, but ttH provide a direct probe.
  - Search for new physics.

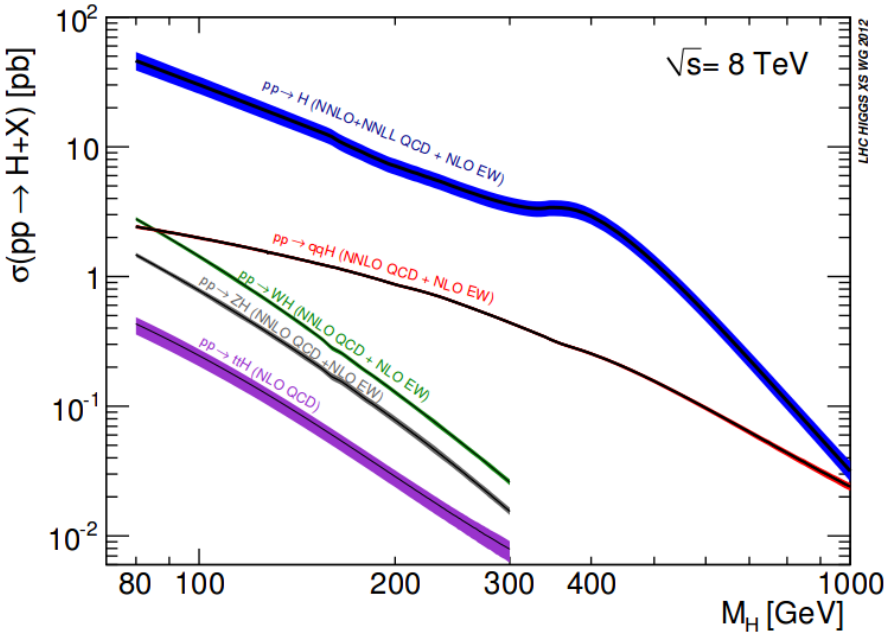
- Latest results, per channel and per experiment, will be presented.
- Focus on LHC results.

ttH production at the LHC

- ttbarH production cross section at the LHC = 130 fb (NLO, HXSWG) at the LHC, dominated by gluon fusion.



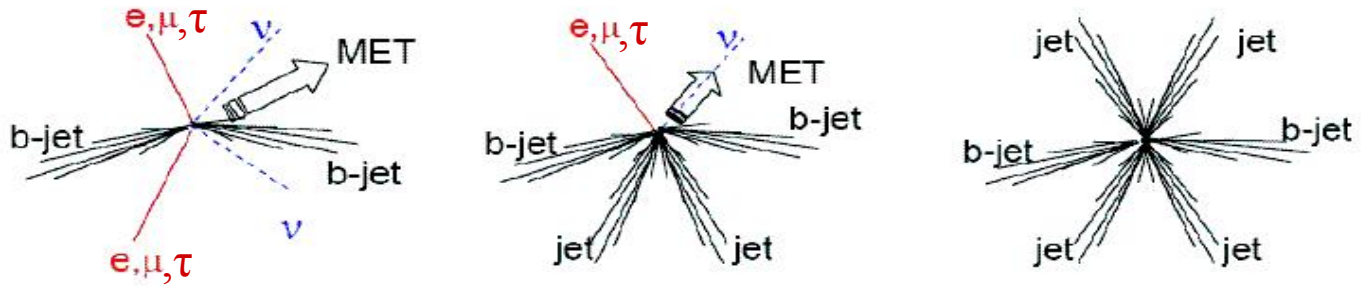




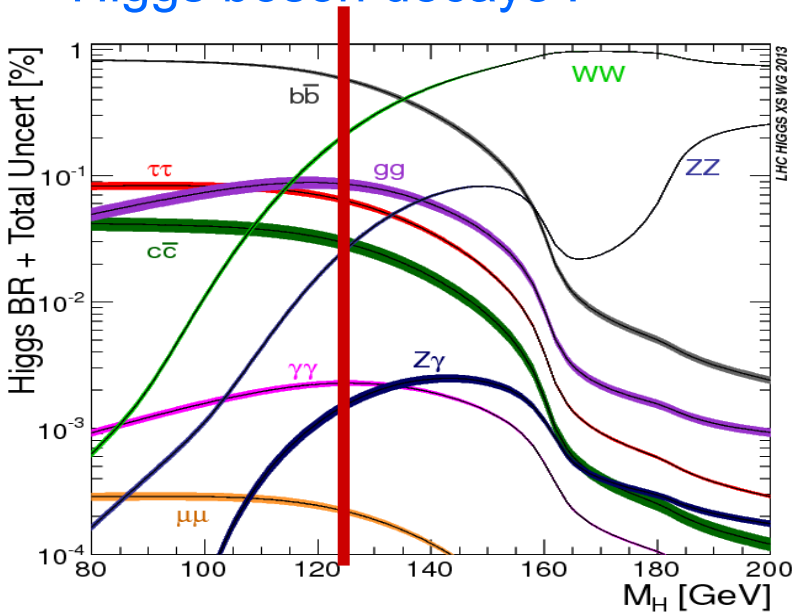
- **ttbarH are rare processes** :
  - Cross section $7e^{-3}$ smaller that ggF,
  - Only about 3k events expected (inclusive) at 8TeV,
  - Small compare to the main backgrounds : ttbar+X => highly dependent on our understanding of ttbar+X processes.

ttbarH decay channels

- ttbarH decay channels.
- Top decays :
  - Purity (statistic) increase (decrease) with lepton multiplicity.



- Higgs boson decays :



- For $m_H \approx 125$GeV, dominant decays are bbbar (≈60%) and WW (≈20%).
- Many signatures : high b-jets multiplicities, high lepton multiplicities, photons with many jets etc… etc…
- Each channel has its advantages and disadvantages.

ttbarH decay channels

- The decay channels covered at the LHC :

- ttbarH, H→bbbar ($\tau\tau$),
  - High statistic, can reconstruct tops, can reconstruct m_H,
  - Large background from ttbar+X (difficult to control), resolution on m_H,

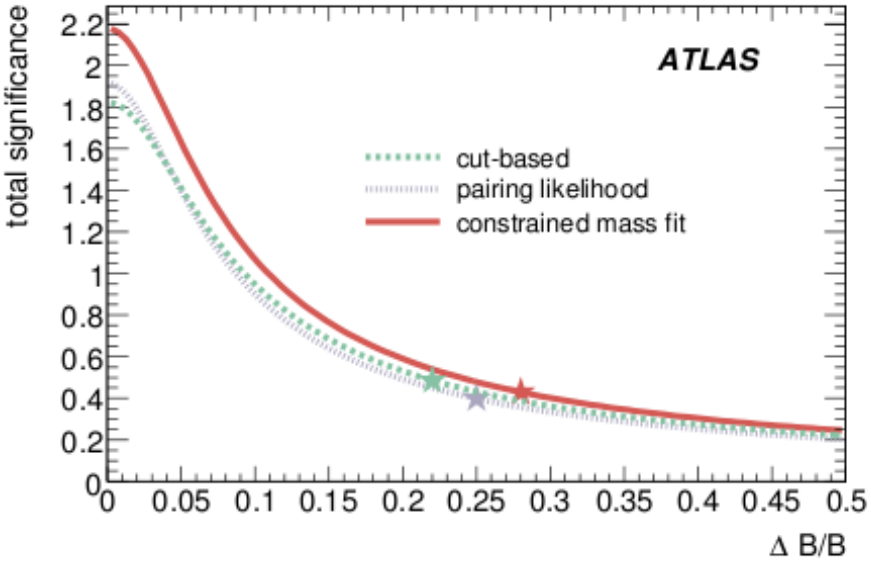
- ttbarH, H→$\gamma\gamma$,
  - High purity, can trigger on photons, good m_H resolution,
  - Very low statistic (Br≈2.10^{-3} for m_H=125 GeV).

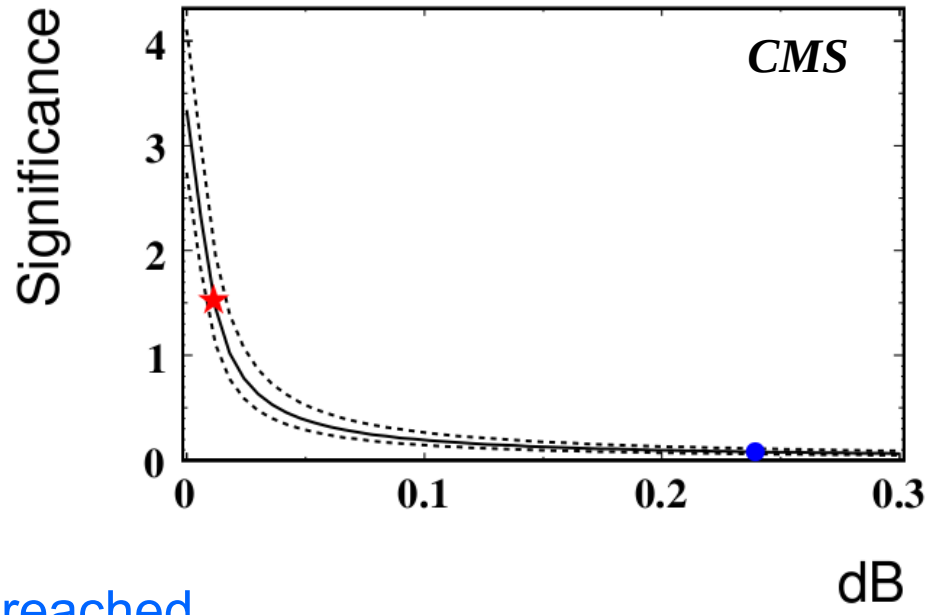
- ttbarH→multi-lepton (H→WW, ZZ, $\tau\tau$),
  - High purity, decent statistic,
  - Leptonic Br, low p_T leptons, can not reconstruct m_H.

Preliminary works

- Before the start of the LHC, preliminary works (MC-based) were done by ATLAS (CERN-OPEN-2008-020) and CMS (PTDR2).
- Predictions performed for a luminosity of 30 fb^{-1} at 14TeV, H→bb, with the semi-leptonic channel (ATLAS) and the 3 channels (CMS).

$$\text{Significance} = S/\sqrt{(B+dB^2)}$$





- A 2-3 sigma sensitivity was hardly reached.
- Search for ttbarH was expected to be very challenging.

Object selection (ttbar)

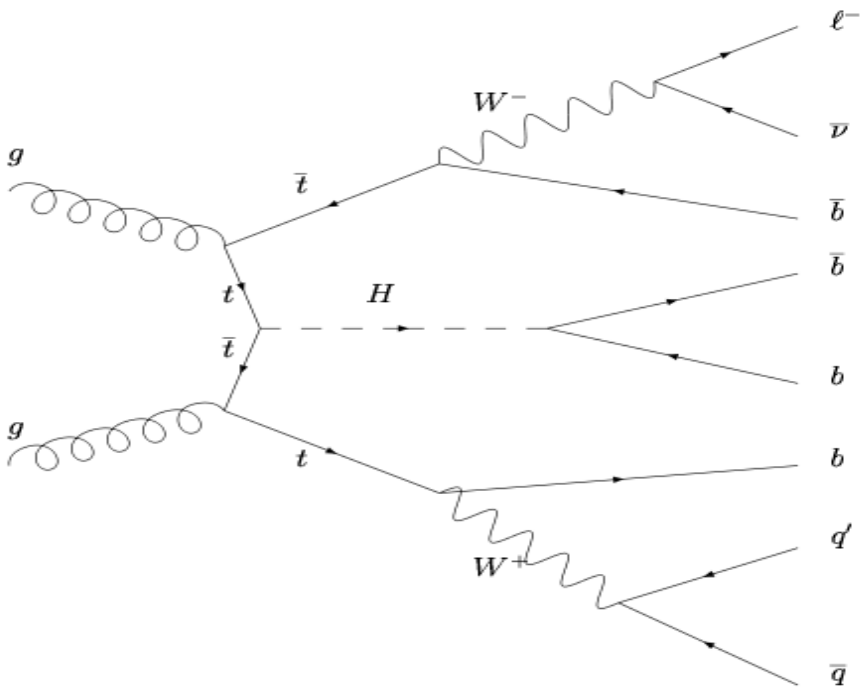
- **Object selection for the ttbar candidates.**

- **ATLAS**
  - Lepton p_T>15(10) GeV for electrons (muons),
  - Jets p_T>25 GeV,
  - B-tagging, working point :
    - Loose 80% efficiency, 4% mistag,
    - Medium 70% efficiency, 1% mistag.

- **CMS**
  - Leptons p_T>20 GeV,
  - Jet p_T>25(30) GeV,
  - B-tagging :
    - Loose 85% efficiency, 10% mistag.
    - Medium 70% efficiency, 1.5% mistag.

Selections on triggers, leptons and jets multiplicities, missing E_T (E_T^{miss}), H_T or missing H_T (H_T^{miss}) are analysis dependent.

ttbarH with H→bbar

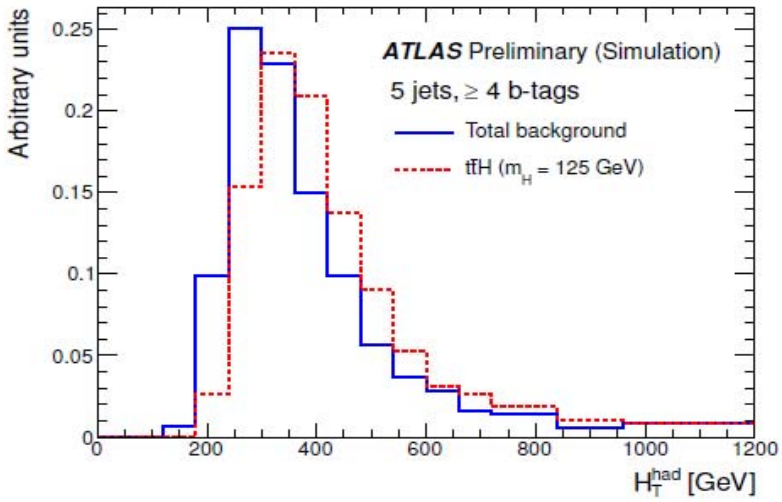


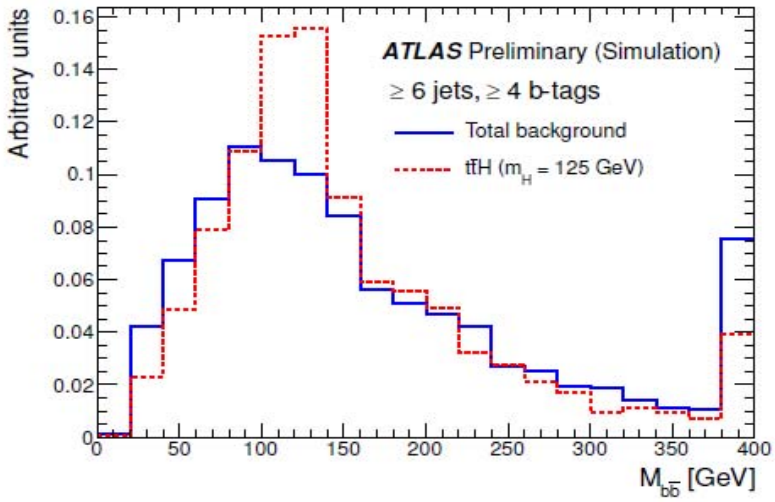
ATLAS at 7 TeV, 4.7 fb^{-1}

ATLAS-CONF-2012-135

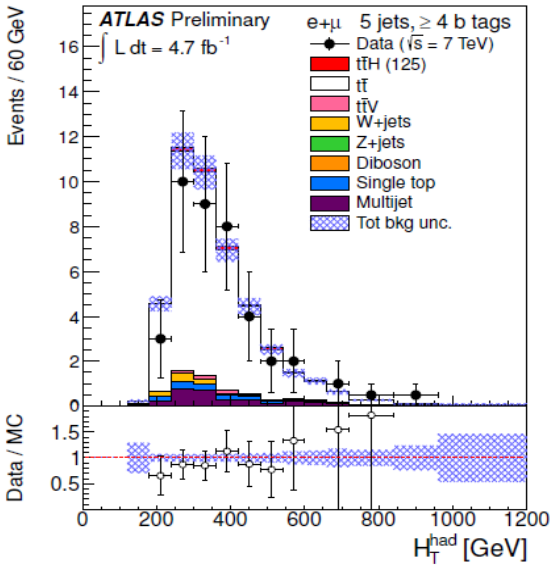
- Lepton+jets channels at 7TeV:
  - Triggered with single lepton 20-22 GeV for electrons, 18 GeV for muons.
  - ≥4Jets,
  - Electron+jets : E_T^{miss} >30GeV, m_T>30GeV
  - Muon+jets : E_T^{miss}>20GeV, $E_T^{miss}+m_T$>60GeV
  - Define 9 categories, Njets-Nbjets.

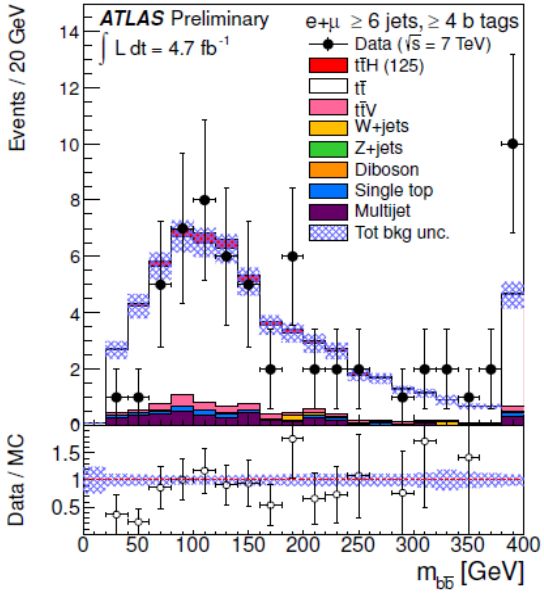
- Analysis strategy :
  - Data-driven : multijet from MM, W+jets from charge asymmetry.
  - ttbar kinematic reconstruction (when possible), identify b-jets from Higgs.
  - Fit of signal-background discriminating variables : m_{bb} or H_T^{had}.





ATLAS at 7 TeV, 4.7 fb-1





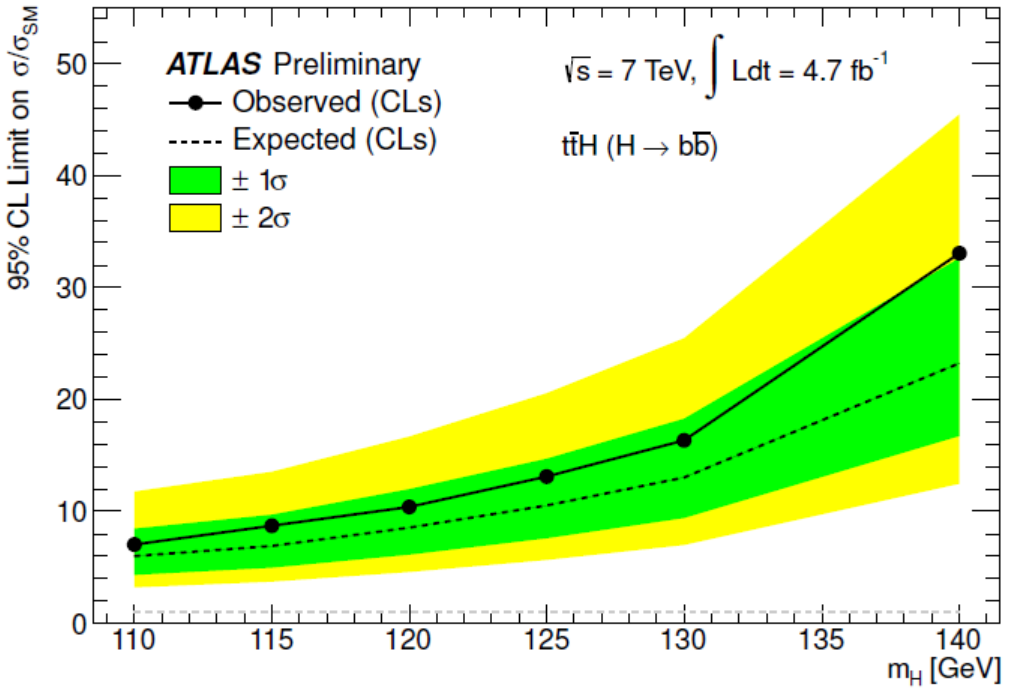
	4 jets, 0 b tags	4 jets, 1 b tags	4 jets, ≥ 2 b tags	5 jets, 2 b tags	5 jets, 3 b tags
$t\bar{t}H(125)$	0.20 ± 0.03	1.1 ± 0.1	3.0 ± 0.2	2.7 ± 0.2	2.3 ± 0.1
$t\bar{t}$+ jets	3440 ± 230	12600 ± 400	13040 ± 160	5900 ± 100	837 ± 24
W+jets	28350 ± 1000	5100 ± 470	655 ± 100	210 ± 50	16 ± 4
Z+jets	3700 ± 600	480 ± 70	33 ± 6	16 ± 4	1.1 ± 0.3
Single top	500 ± 30	1380 ± 70	820 ± 40	266 ± 15	31 ± 2
Diboson	411 ± 50	85 ± 10	15 ± 2	3.1 ± 0.4	0.26 ± 0.05
$t\bar{t}V$	12 ± 3	35 ± 9	30 ± 8	32 ± 9	6 ± 2
Multijet	3800 ± 700	1560 ± 280	460 ± 90	210 ± 50	23 ± 10
Total bkg.	40200 ± 280	21240 ± 200	15040 ± 150	6640 ± 80	915 ± 24
Data	40209	21248	15066	6653	878

	5 jets, ≥ 4 b tags	≥ 6 jets, 2 b tags	≥ 6 jets, 3 b tags	≥ 6 jets, ≥ 4 b tags
$t\bar{t}H(125)$	0.74 ± 0.04	3.4 ± 0.2	4.0 ± 0.2	2.2 ± 0.1
$t\bar{t}$+ jets	38 ± 3	3030 ± 90	560 ± 20	54 ± 5
W+jets	1.1 ± 0.4	74 ± 20	8 ± 3	0.7 ± 0.3
Z+jets	0.03 ± 0.01	6 ± 2	0.4 ± 0.2	0.01 ± 0.01
Single top	1.6 ± 0.2	92 ± 7	15 ± 1	1.5 ± 0.2
Diboson	0.01 ± 0.01	0.7 ± 0.1	0.09 ± 0.03	0.01 ± 0.01
$t\bar{t}V$	0.8 ± 0.2	45 ± 10	13 ± 4	2.7 ± 0.7
Multijet	3 ± 2	114 ± 30	34 ± 10	4 ± 3
Total bkg.	45 ± 3	3360 ± 80	634 ± 19	62 ± 5
Data	41	3340	676	65

ATLAS at 7 TeV, 4.7 fb-1

- Main systematic sources :
  - Fraction of HF in ttbar,
  - Jet Energy Scale,
  - B-tagging.

- Total uncertainty largely reduced by the profiling.



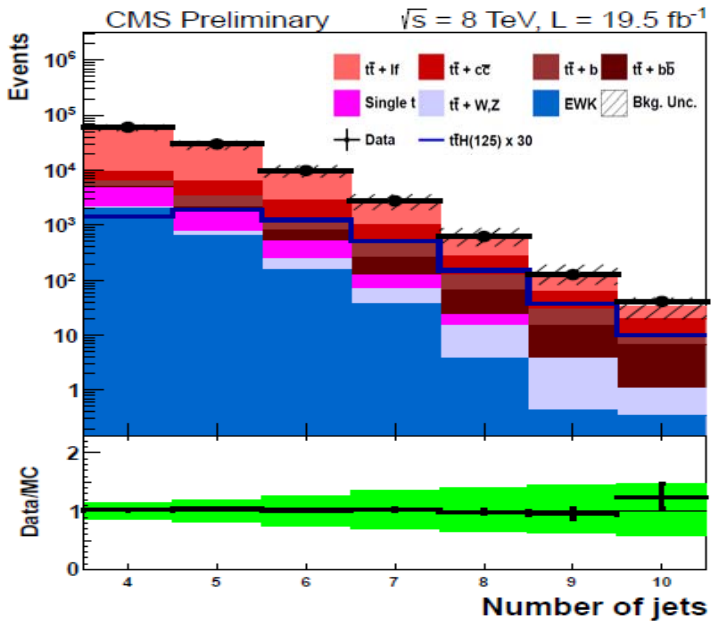
m_H (GeV)	observed	-2 s.d.	-1 s.d.	median	+1 s.d.	+2 s.d.	stat only
110	7.0	3.2	4.3	6.0	8.5	11.8	3.5
115	8.7	3.7	5.0	6.9	9.7	13.6	4.0
120	10.4	4.6	6.2	8.5	12.0	16.7	4.9
125	13.1	5.7	7.6	10.5	14.7	20.6	6.1
130	16.4	7.0	9.4	13.0	18.3	25.5	7.8
140	33.0	12.5	16.7	23.2	32.7	45.5	14.2

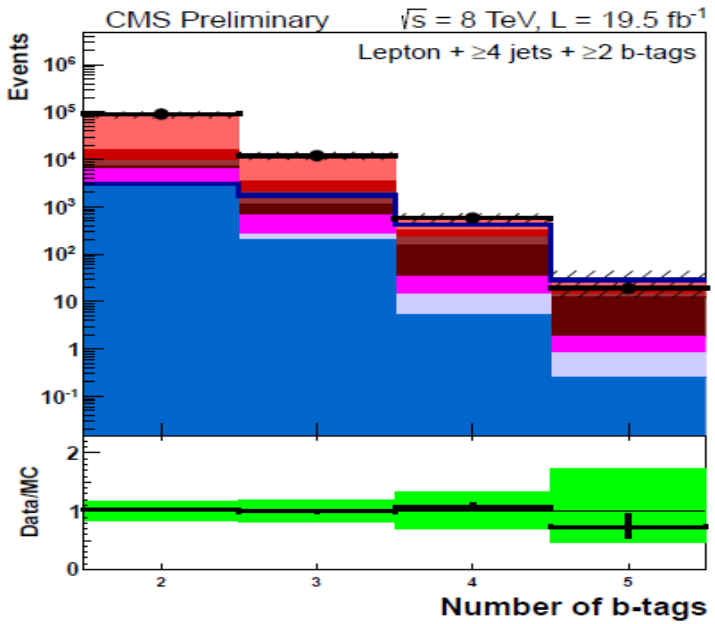
CMS at 8TeV, 19.5 fb^{-1}

PAS HIG-13-019

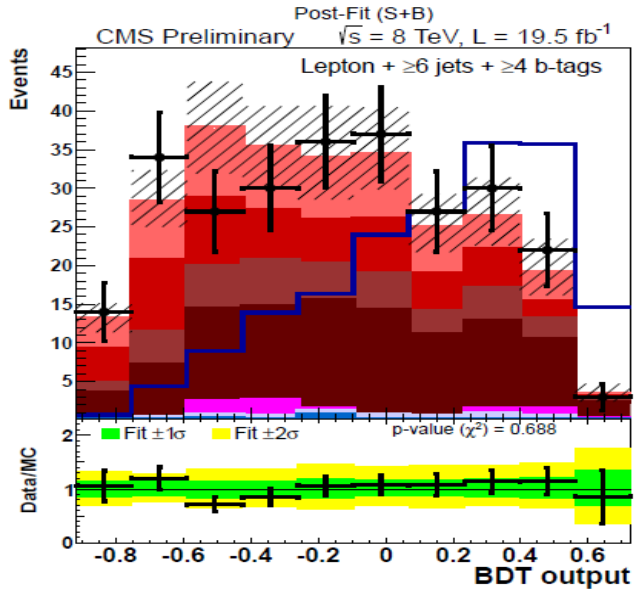
- Uses semi-leptonic and dileptonic channels at 8TeV.
  - LJ : single lepton trigger (27 GeV for electron, 24 GeV for muons).
  - DIL : combination of 2 leptons (dilepton trig. 17GeV and 8GeV).
  - ≥4Jets (+3 with p_T>40 in LJ).
  - Categorization in Njet vs NBjets.

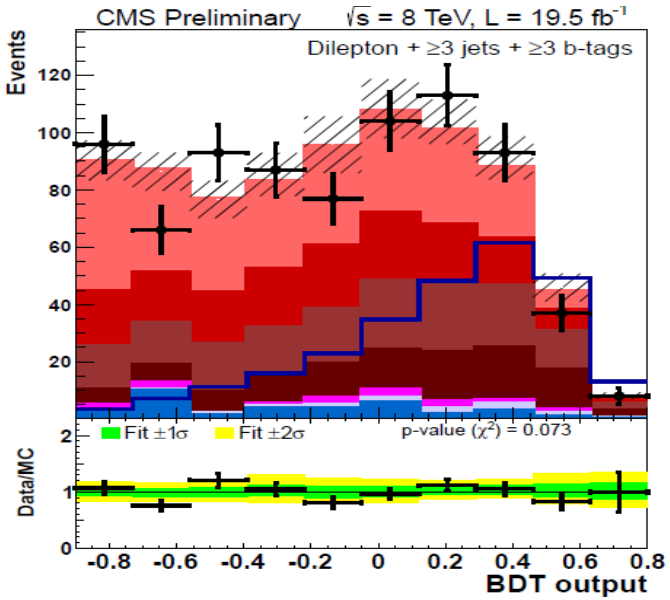
- Analysis strategy :
  - Perform ttbar kinematic reconstruction (when possible) in LJ, identify the 2 jets from H.
  - BDT constructed for each category : uses various kinematic variables, b-tagging discriminant and m_{bb} (when possible).





CMS at 8TeV, 19.5 fb-1





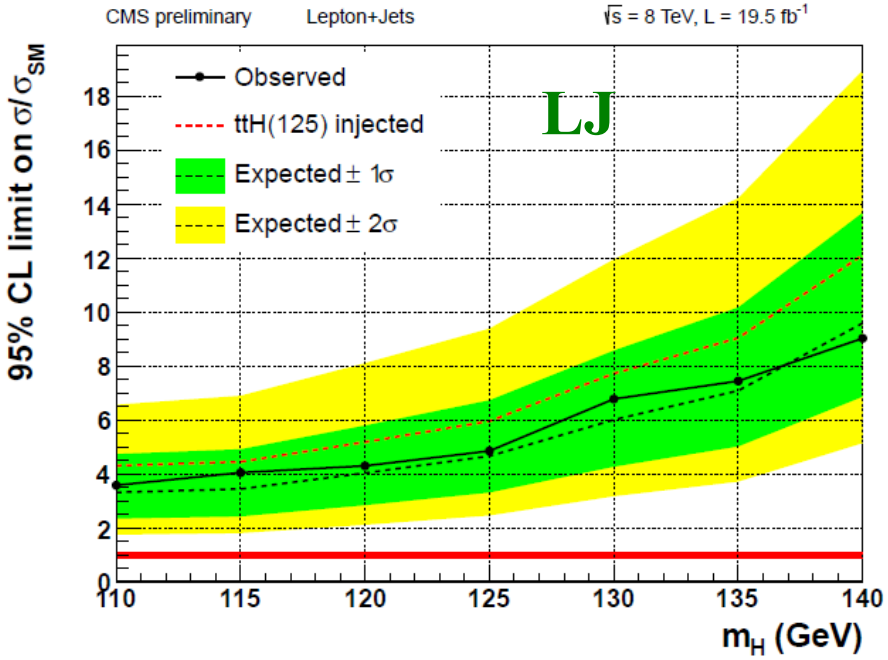
	≥6 jets 2 b-tags	4 jets 3 b-tags	5 jets 3 b-tags	≥6 jets 3 b-tags	4 jets 4 b-tags	5 jets ≥4 b-tags	≥6 jets ≥4 b-tags
$t\bar{t}H(125)$	33.4 ± 8.1	14.0 ± 3.0	21.1 ± 4.5	23.1 ± 5.5	1.8 ± 0.5	5.2 ± 1.4	8.3 ± 2.3
$t\bar{t}$+lf	7650 ± 2000	4710 ± 820	2610 ± 530	1260 ± 340	74 ± 30	79 ± 34	71 ± 36
$t\bar{t}$+b	530 ± 300	350 ± 190	360 ± 200	280 ± 160	21 ± 12	29 ± 17	33 ± 20
$t\bar{t} + b\bar{b}$	220 ± 120	99 ± 52	158 ± 85	200 ± 110	13.1 ± 7.3	38 ± 21	78 ± 47
$t\bar{t} + c\bar{c}$	1710 ± 1110	440 ± 230	520 ± 290	470 ± 280	19 ± 11	32 ± 18	52 ± 31
$t\bar{t}V$	99 ± 27	16.2 ± 3.8	23.9 ± 5.7	28.8 ± 7.4	1.1 ± 0.4	2.5 ± 0.7	5.8 ± 1.8
Single t	264 ± 54	235 ± 41	116 ± 22	55 ± 14	3.4 ± 1.6	10.3 ± 5.3	7.3 ± 3.1
V+jets	160 ± 110	122 ± 95	44 ± 38	29 ± 27	2.1 ± 2.4	1.9 ± 1.7	1.2 ± 1.3
Diboson	5.9 ± 1.6	6.3 ± 1.4	2.4 ± 0.7	1.0 ± 0.4	0.3 ± 0.2	0.1 ± 0.1	0.2 ± 0.1
Total bkg	10630 ± 2790	5970 ± 1060	3830 ± 790	2310 ± 620	133 ± 44	193 ± 62	249 ± 90
Data	10724	5667	3983	2426	122	219	260

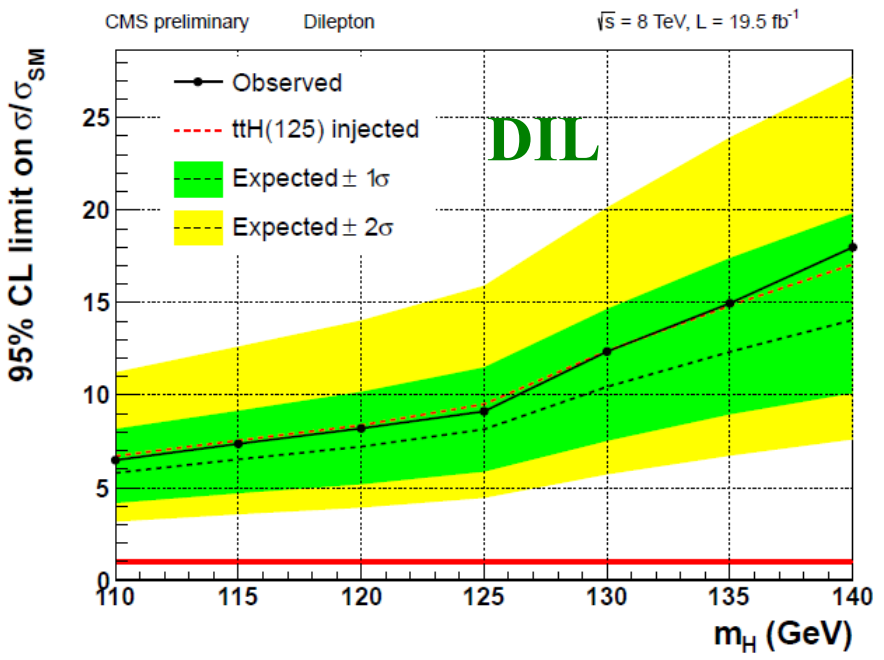
	3 jets + 2 b-tags	≥4 jets + 2 b-tags	≥3 b-tags
$t\bar{t}H(125)$	7.7 ± 1.4	16.1 ± 3.1	11.2 ± 2.5
$t\bar{t}$+lf	7460 ± 1060	3190 ± 680	289 ± 83
$t\bar{t}$+b	189 ± 97	172 ± 93	149 ± 82
$t\bar{t} + b\bar{b}$	38 ± 20	58 ± 31	80 ± 44
$t\bar{t} + c\bar{c}$	480 ± 260	510 ± 300	147 ± 79
$t\bar{t}V$	30.2 ± 6.3	54 ± 12	11.9 ± 2.9
Single t	229 ± 35	97 ± 16	17.3 ± 5.1
V+jets	350 ± 130	151 ± 66	40 ± 23
Diboson	10.4 ± 1.7	3.1 ± 0.6	0.7 ± 0.4
Total bkg	8770 ± 1250	4230 ± 850	740 ± 190
Data	9060	4616	774

CMS at 8TeV, 19.5 fb-1

Higgs Mass	Observed	Expected Median	Expected 68% C.L. Range	Expected 95% C.L. Range
110 GeV	3.6	3.3	[2.4,4.7]	[1.8,6.6]
115 GeV	4.1	3.5	[2.4,4.9]	[1.8,6.9]
120 GeV	4.3	4.0	[2.9,5.8]	[2.1,8.1]
125 GeV	4.9	4.7	[3.3,6.7]	[2.5,9.4]
130 GeV	6.8	6.0	[4.3,8.6]	[3.2,12.0]
135 GeV	7.4	7.1	[5.0,10.2]	[3.7,14.2]
140 GeV	9.0	9.6	[6.9,13.7]	[5.2,18.9]

Higgs Mass	Observed	Expected Median	Expected 68% C.L. Range	Expected 95% C.L. Range
110 GeV	6.5	5.8	[4.2,8.2]	[3.2,11.2]
115 GeV	7.4	6.5	[4.7,9.2]	[3.6,12.6]
120 GeV	8.2	7.2	[5.2,10.2]	[3.9,14.0]
125 GeV	9.1	8.2	[5.9,11.5]	[4.4,15.9]
130 GeV	12.4	10.5	[7.5,14.7]	[5.7,20.1]
135 GeV	15.0	12.3	[9.0,17.4]	[6.7,23.9]
140 GeV	18.0	14.1	[10.1,19.8]	[7.6,27.3]

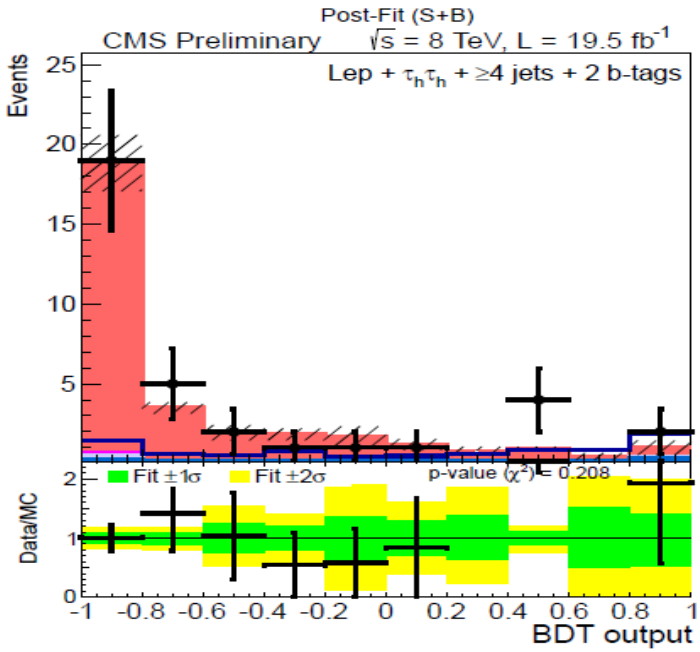




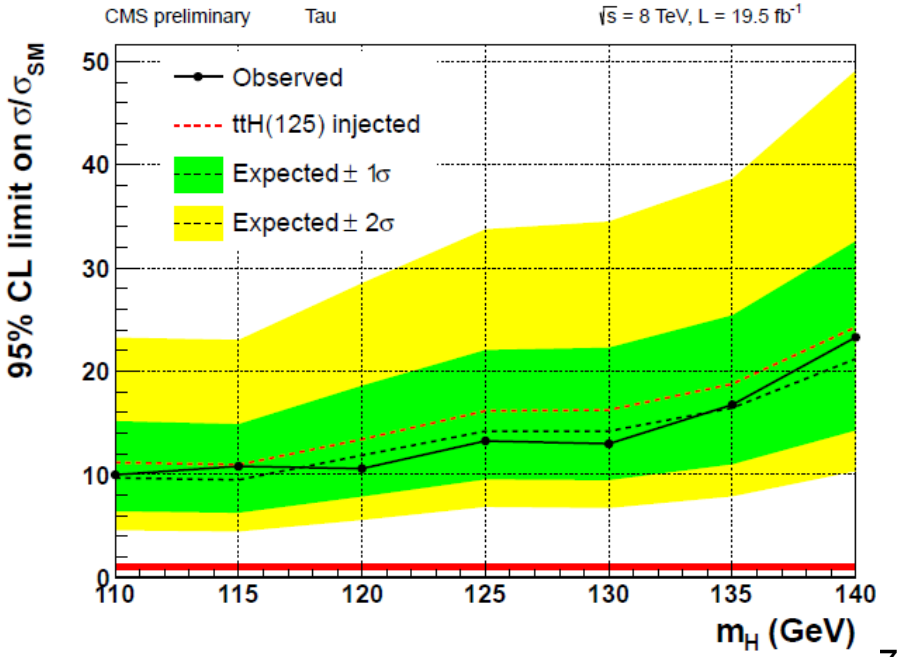
- Main systematics : ttbar+HF, b-tagging efficiency and mistag rates, Jet Energy Scale.
- Signal smaller than background uncertainties.
- Combination of channels : see slide 26.

CMS at 8TeV, 19.6 fb-1

- Similar analysis for H→ττ (LJ only): requires the presence of hadronic tau with >20 GeV.

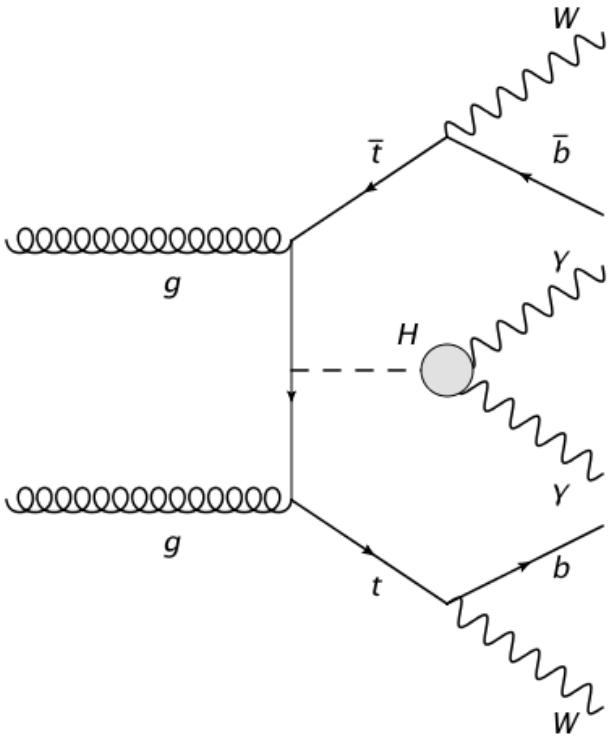


Higgs Mass	Observed	Expected Median	Expected 68% C.L. Range	Expected 95% C.L. Range
110 GeV	10.0	9.7	[6.4,15.2]	[4.6,23.3]
115 GeV	10.8	9.5	[6.3,14.9]	[4.5,23.0]
120 GeV	10.6	11.8	[7.9,18.6]	[5.6,28.5]
125 GeV	13.2	14.2	[9.5,22.0]	[6.8,33.7]
130 GeV	13.0	14.2	[9.4,22.3]	[6.7,34.5]
135 GeV	16.7	16.4	[11.0,25.4]	[7.9,38.7]
140 GeV	23.3	21.2	[14.3,32.6]	[10.3,49.1]



	2 jets 1 b-tag	3 jets 1 b-tag	≥4 jets 1 b-tag	2 jets 2 b-tags	3 jets 2 b-tags	≥4 jets 2 b-tags
ttH(125)	0.4 ± 0.1	0.6 ± 0.1	0.6 ± 0.2	0.1 ± 0.0	0.2 ± 0.1	0.4 ± 0.1
tt	225 ± 69	119 ± 38	64 ± 22	48 ± 15	38 ± 12	27.0 ± 9.1
ttV	1.1 ± 0.3	1.3 ± 0.3	1.4 ± 0.4	0.4 ± 0.1	0.6 ± 0.2	1.1 ± 0.3
Single t	11.2 ± 4.0	3.0 ± 1.4	1.1 ± 1.0	1.9 ± 1.1	0.9 ± 0.6	0.6 ± 0.7
V+jets	33 ± 17	11.7 ± 6.8	3.8 ± 2.8	1.4 ± 0.9	0.4 ± 0.3	0.5 ± 0.6
Diboson	0.9 ± 0.2	0.7 ± 0.2	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.1 ± 0.1
Total bkg	271 ± 82	135 ± 41	71 ± 24	52 ± 16	40 ± 12	29.2 ± 9.4
Data	292	171	92	41	48	35

ttbarH with H→γγ

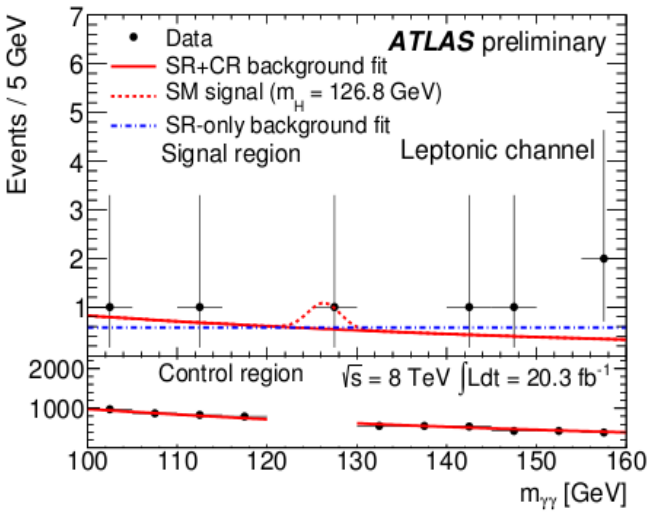


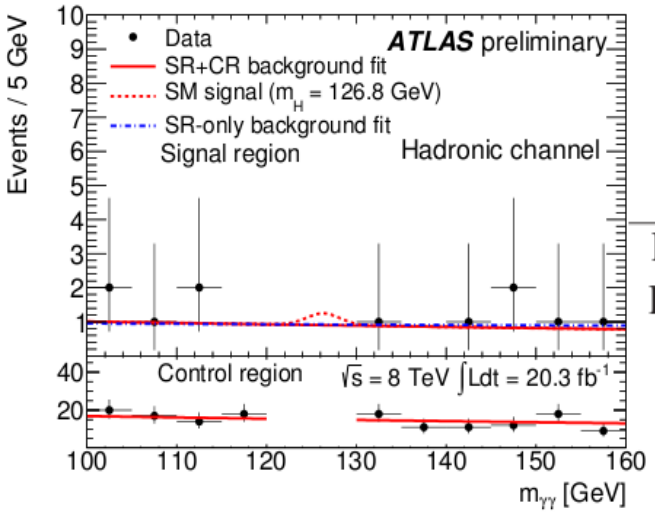
ATLAS at 8TeV, 20.3 fb^{-1}

ATLAS-CONF-2013-080

- Measurement in the semi-leptonic and full hadronic channels :
  - Trigger : diphoton (35, 25 GeV).
  - Semi-leptonic : ≥1lepton, ≥1b-jet, E_T^{miss} >20 GeV.
  - Full hadronic : ≥4jets, ≥2b-tag.
  - 2 isolation photons with 40/30GeV.
- Analysis strategy :
  - Fit the diphoton invariant mass, sum of Crystal Ball and Gaussian for signal, exponential for background.
  - Simultaneous fit of signal and control region (excluding expected Higgs mass window).

Channel	N_S	$ggF(\%)$	$VBF(\%)$	$WH(\%)$	$ZH(\%)$	$tH(\%)$	$t\bar{t}H(\%)$
Leptonic	0.55	0.6	0.3	7.7	2.4	6.1	82.8
Hadronic	0.36	5.3	1.1	1.1	1.3	—	91.2

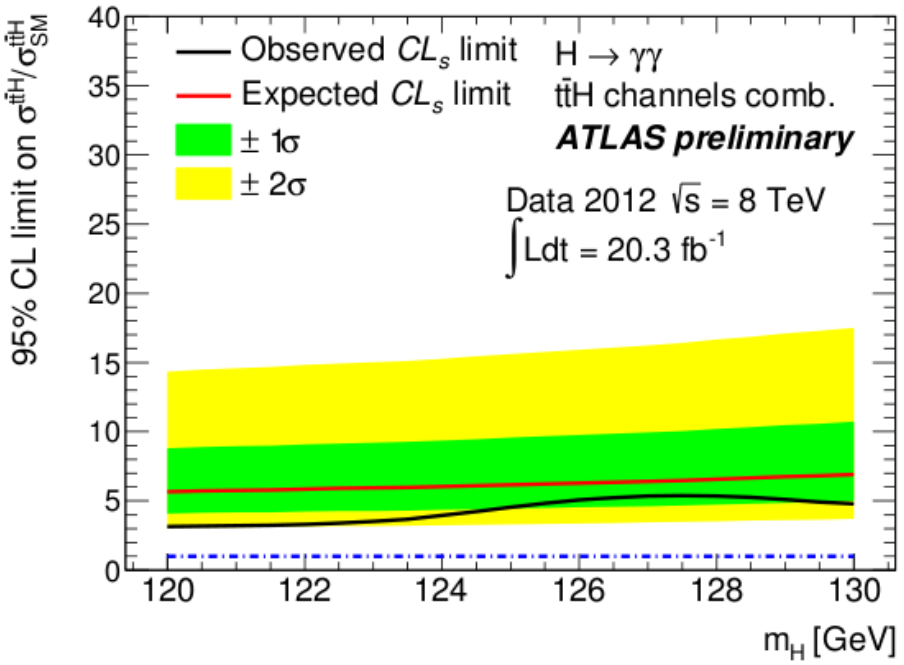




Channel	N_S	N_B	N_S/N_B
Leptonic	0.55	$1.2^{+0.6}_{-0.5}$	0.45
Hadronic	0.36	$1.9^{+0.7}_{-0.5}$	0.19

ATLAS at 8TeV, 20.3 fb-1

Systematic effect	Systematic uncertainty [%] Leptonic	Hadronic
Luminosity	±2.8	
Cross section	+8.7 / −12.1	
Branching ratio	+5.0 / −4.9	
QCD scale (acceptance only)	±3	±10
Trigger	±0.5	
Photon related	±13	
Electron related	±0.8	< ±0.1
Muon related	±0.2	< ±0.1
Jet energy scale	±0.4	±9.8
Jet energy resolution	±0.2	±3.4
Jet vertex fraction	±0.1	±1.0
b-jet energy scale	±0.2	±0.7
b-tagging	±2.1	±5.5



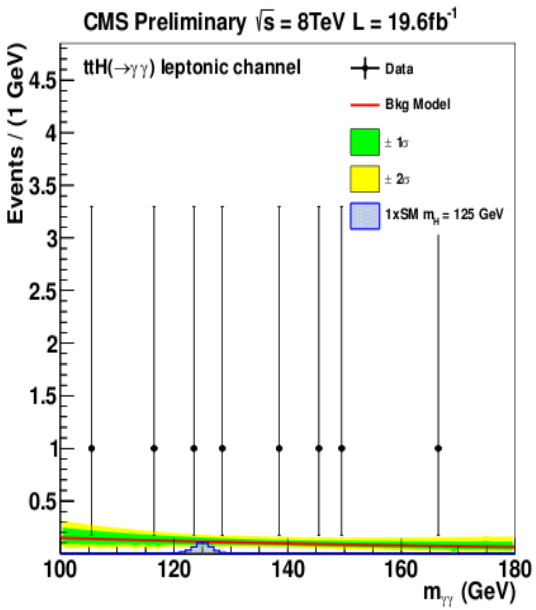
- Combined 95% CL upper limits on ttbarH : 5.3 (obs) and 6.4 (expct).

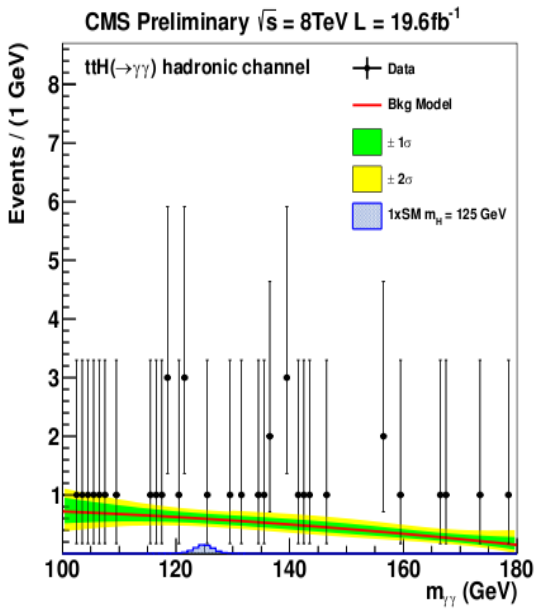
CMS at 8TeV, 19.6 fb^{-1}

PAS HIG-13-015

- Semi-leptonic and full hadronic channels :
  - Trigger : diphoton (28/18 and 36/22 GeV).
  - Semi-leptonic: ≥1 lepton, ≥2jets, ≥1b-tag.
  - Hadronic : ≥5 jets, ≥1b-tag.
  - 2 isolation photons with the leading photon >33 and $p_T > m_{\gamma\gamma} * 0.5$, and second leading photon >25GeV.

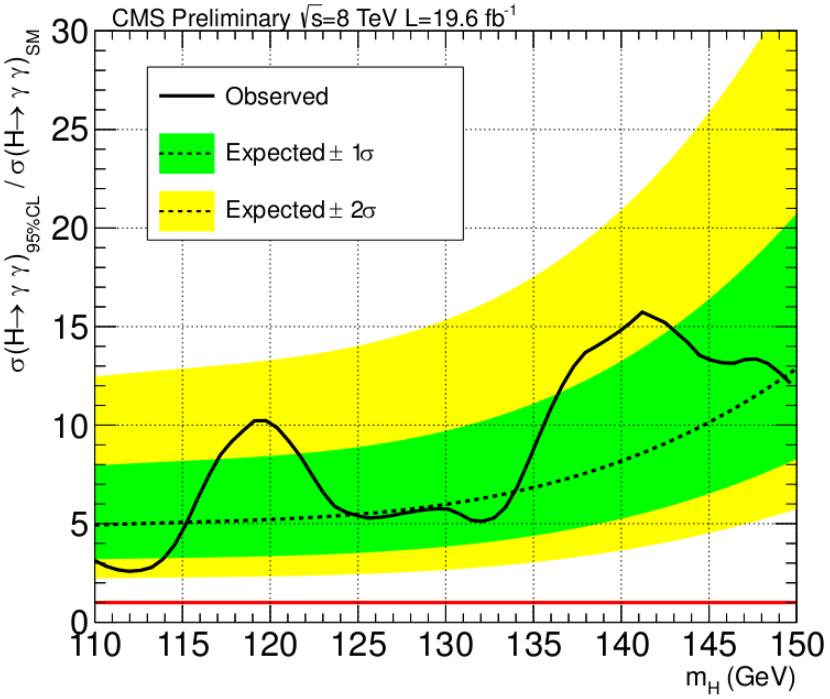
- Analysis strategy :
  - Fit the diphoton invariant mass,
  - Background model extracted from control region (single photon trigger + inverting photon ID).
  - Fit functions : exponential for semi-leptonic, 2nd order poly. for full-hadronic.





Process	Hadronic Channel	Leptonic Channel
$t\bar{t}H$	0.567 (87%)	0.429 (97%)
$gg \to H$	0.059 (9%)	0 (0%)
VBF H	0.006 (1%)	0 (0%)
WH/ZH	0.019 (3%)	0.013 (3%)
Total signal	0.65	0.44

CMS at 8TeV, 19.6 fb-1

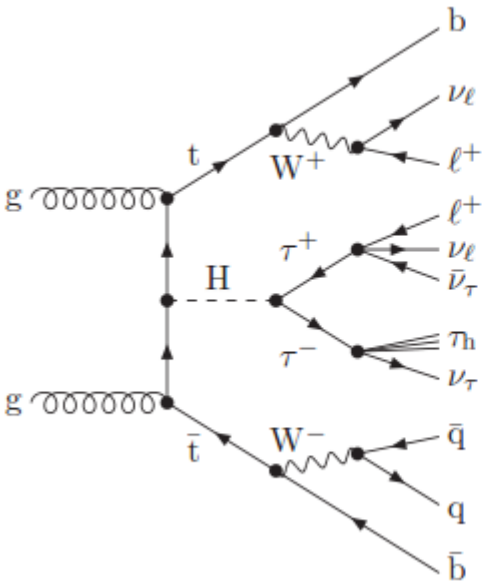


- Main systematics (input) :
  - Photon reconstruction and selection 3-4%,
  - Jet energy scale 2%(signal), 5%(backgrounds),
  - Lepton selection : 3% (electron) and 1% (muon),
  - gg→H contamination : 30% (background only)

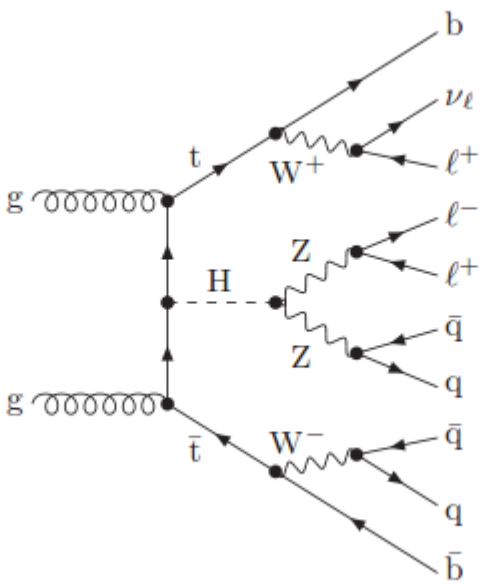
	Observed	Expected	Expected (No Syst.)
Hadronic Channel	6.8	9.2	8.8
Leptonic Channel	10.7	8.0	7.7
Combined	5.4	5.3	5.1

For a Higgs mass of 125.5 GeV, the signal strength $\mu_{ttH} = -0.2^{+2.4}_{-1.9}$

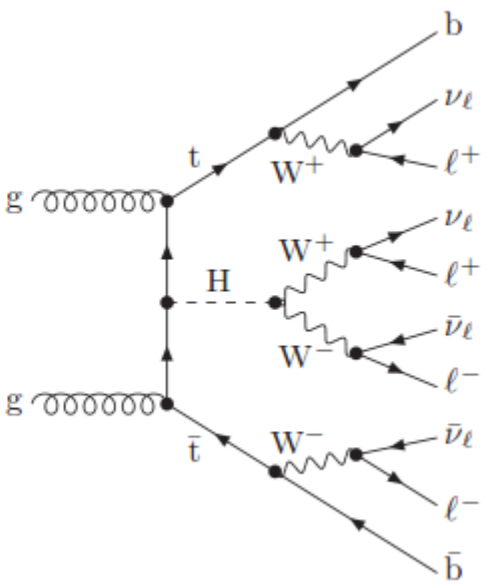
ttbarH in "multi-leptons"



Same-sign di-lepton



Tri-lepton



Quadri-lepton

CMS at 8TeV, 19.6 fb-1

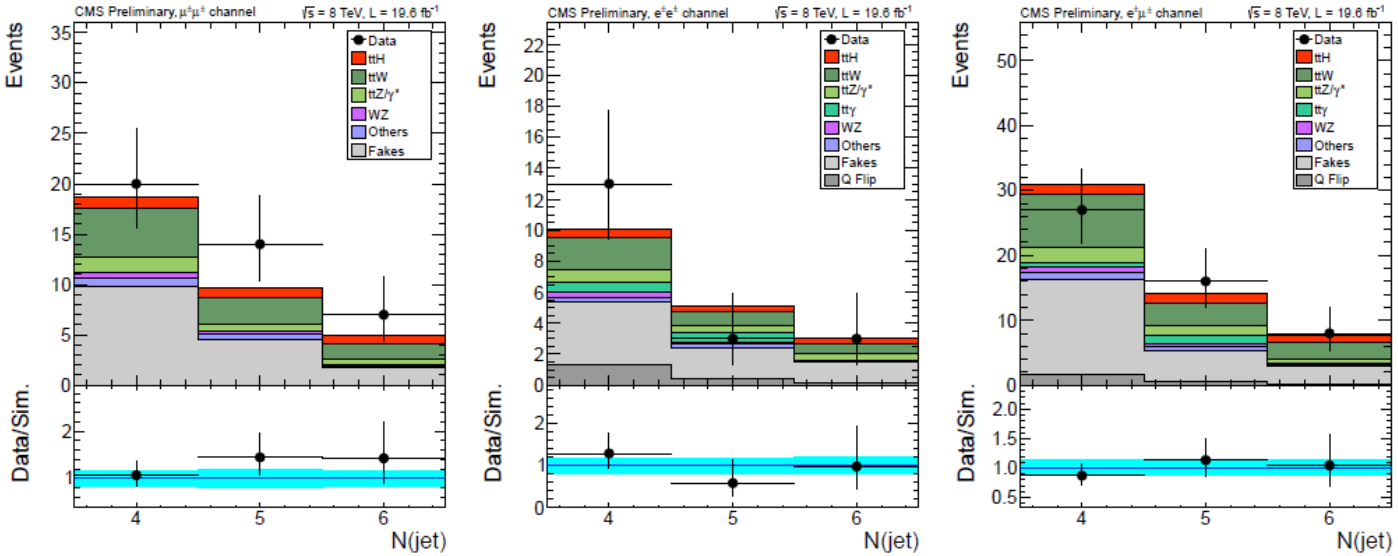
PAS HIG-13-020

- Event selection :
  - Requires di-lepton trigger, at least 2 leptons (20/10 GeV),
  - Any other leptons >7 GeV (electron) and 5 GeV (muons), Non-prompt leptons from b/c hadrons rejected using MVA. Efficiencies 60-98% for muons and 20-90% for electrons, depending on p_T and η.
  - "E_T^{miss} LD" > 20 GeV (combination of E_T^{miss} and H_T^{miss}).
  - Dilepton invariant mass > 12 GeV, non-compatible with Z mass (for opposite charges in tri/quadri-leptonic channels).
  - 2 loose b-tagged jets or ≥1 medium b-tagged jet.

	Same sign DIL	Tri-Lepton	Quadri-lepton
Z mass veto (10GeV)	Any pairs	Only opposite signs	Only opposite signs
Nlept	=2, 2nd lepton pT > 20 GeV.	=3	=4 (loose MVA)
Njets	≥4	≥2 jets	≥2 jets
E_T^{miss}	E_T^{miss} LD>0.2, E_T^{miss}+p_T leptons > 100 GeV	E_T^{miss} LD>0.2, not applied for Njets≥4	non

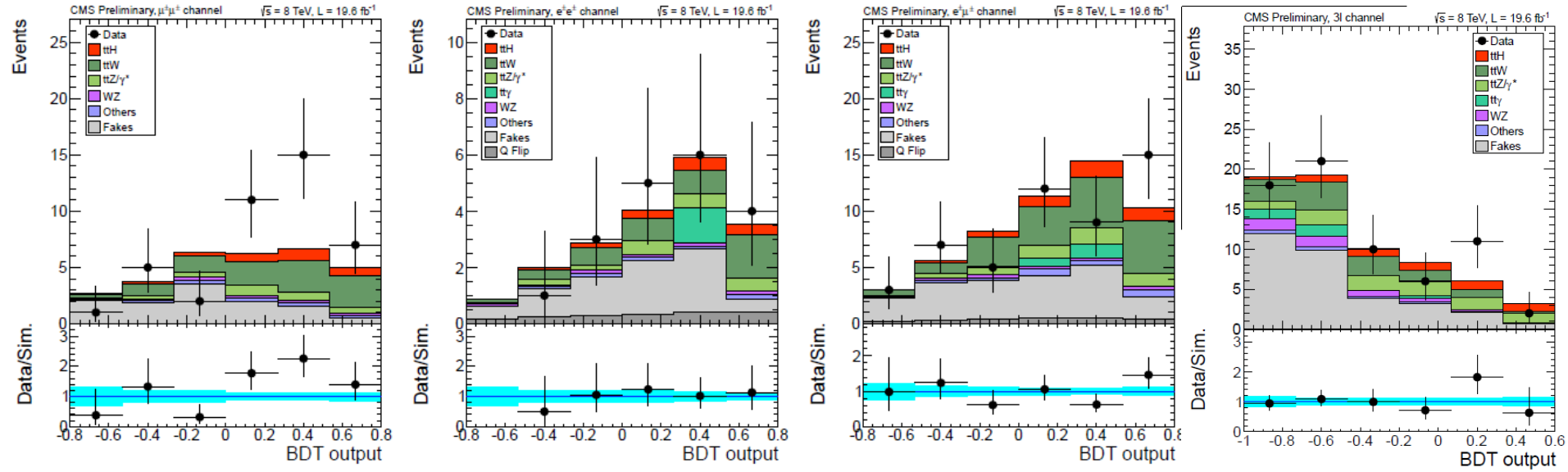
CMS at 8TeV, 19.6 fb-1

	$\mu\mu$	ee	eμ	3ℓ	4ℓ
$t\bar{t}H$, $H \to WW$	2.0 ± 0.3	0.9 ± 0.1	2.7 ± 0.4	3.2 ± 0.6	0.28 ± 0.05
$t\bar{t}H$, $H \to ZZ$	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H$, $H \to \tau\tau$	0.6 ± 0.1	0.3 ± 0.0	0.9 ± 0.1	1.0 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	8.2 ± 1.5	3.4 ± 0.6	13.0 ± 2.2	9.2 ± 1.9	-
$t\bar{t}Z/\gamma^*$	2.5 ± 0.5	1.6 ± 0.3	4.2 ± 0.9	7.9 ± 1.7	1.25 ± 0.88
$t\bar{t}WW$	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	-	1.3 ± 0.3	1.9 ± 0.5	2.9 ± 0.8	-
WZ	0.8 ± 0.9	0.5 ± 0.5	1.2 ± 1.3	4.2 ± 0.9	-
ZZ	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.4 ± 0.1	0.45 ± 0.09
rare SM bkg.	1.1 ± 0.0	0.4 ± 0.0	1.5 ± 0.0	0.8 ± 0.0	0.01 ± 0.00
non-prompt	10.8 ± 4.8	8.9 ± 4.5	21.2 ± 8.1	33.2 ± 12.3	0.53 ± 0.32
charge flip	-	1.9 ± 0.6	2.4 ± 0.8	-	-
all signals	2.7 ± 0.4	1.2 ± 0.2	3.7 ± 0.6	4.4 ± 0.8	0.52 ± 0.09
all backgrounds	23.7 ± 5.2	18.0 ± 4.7	45.9 ± 8.6	58.9 ± 12.7	2.28 ± 0.94
data	41	19	51	68	1



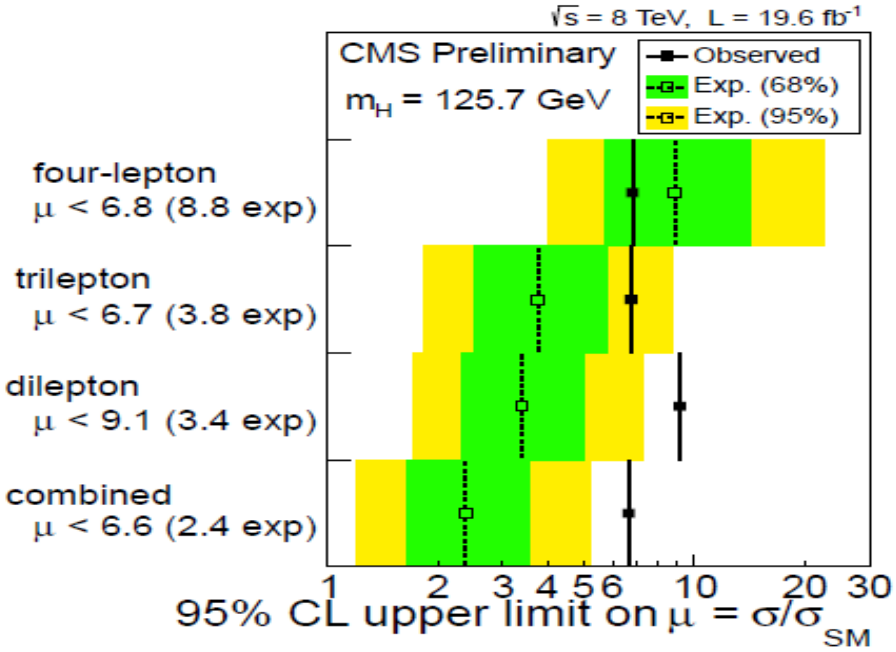
CMS at 8TeV, 19.6 fb-1

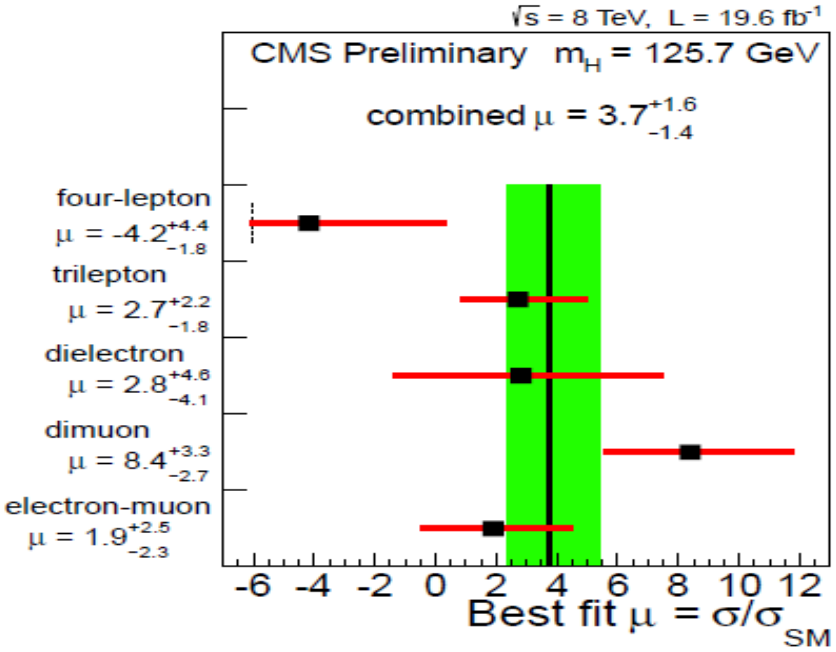
- Analysis strategy :
  - Di/tri-lepton channels: fit of BDTs constructed from various quantities related to leptons, jets, E_T^{miss}, H_T^{miss} etc…
  - Quadri-lepton channel: fit of NJet (lower sensitivity, lack of statistic in control regions).
- Backgrounds determination from data :
  - Dibosons : normalizations taken from control regions (b-tag veto + inversion of Z mass veto).
  - Background from non-prompt leptons (charge mis-reconstruction) : control region defined by inverting the lepton MVA selection, reweighted according to the fake rate.
  - ttbar+V backgrounds taken from simulation.



Results

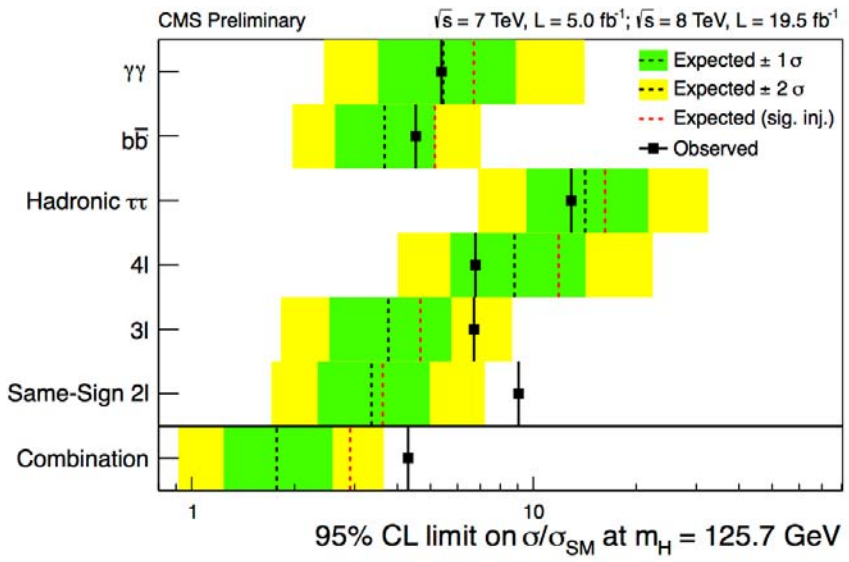
- Interpretation done for a Higgs mass of 125.7 GeV (no Higgs mass reconstruction possible).
- Combination of the yields and distributions of all channels.
- Excess observed for the di-muon channel.

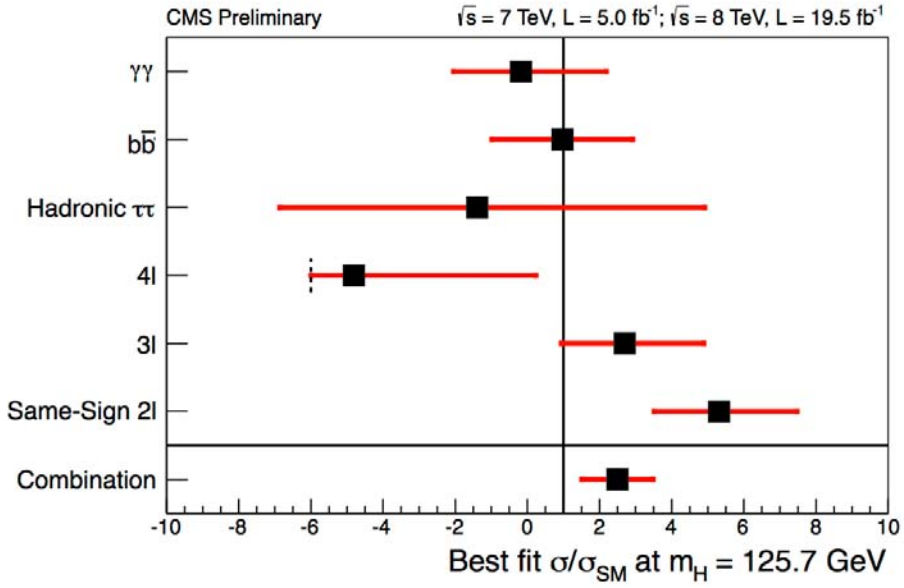




CMS combination

- Combination of all CMS 8TeV results + ttH(H→bb) at 7TeV.
- Same approach/tools as for the global Higgs combination.
- Correlations :
  - Statistically uncorrelated,
  - Experimental uncertainties taken as correlated (but b-tagging at 7TeV),
  - Theoretical uncertainties taken as correlated.





Conclusions

- Measuring the Top-Higgs coupling through the search for ttbarH events at the LHC.
- No evidence of ttbarH events is observed and 95% exclusion limits are calculated.
- Despite the difficulties (very challenging channel), **precisions of ttbarH analyses at the LHC are beyond expectations**.
- Best sensitivity from same sign dilepton, combinations significantly improve the sensitivity.
- Very encouraging for the future runs of the LHC.

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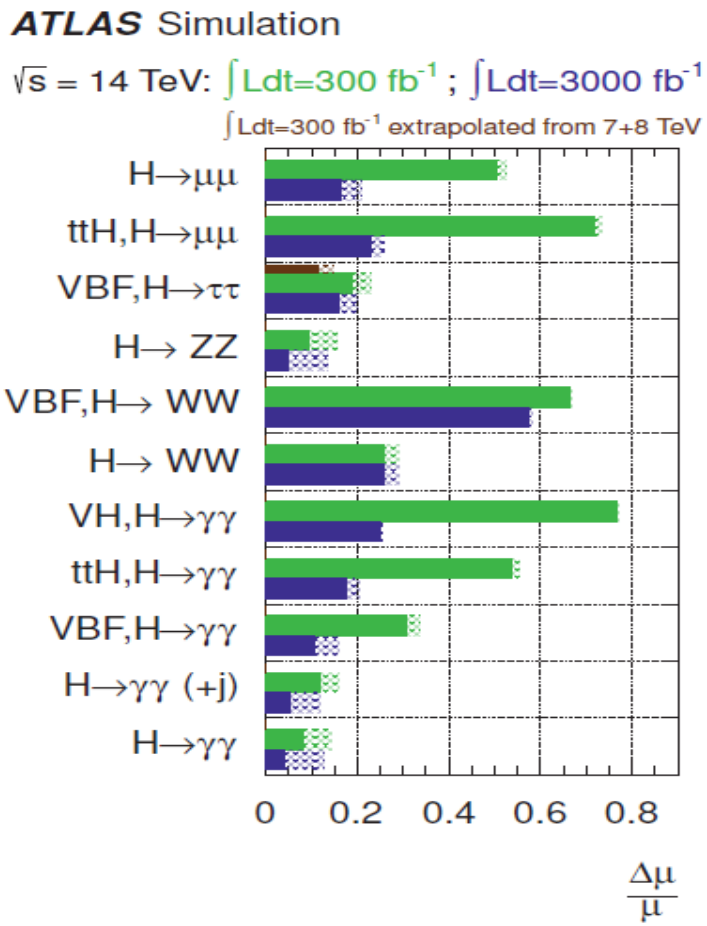


Backups

BDT input variables H->bb CMS

PAS HIG-13-019

Variable	Description
abs $\Delta\eta$ (leptonic top, bb)	Delta-R between the leptonic top reconstructed by the best Higgs mass algorithm and the b-jet pair chosen by the algorithm
abs $\Delta\eta$ (hadronic top, bb)	Delta-R between the hadronic top reconstructed by the best Higgs mass algorithm and the b-jet pair chosen by the algorithm
aplanarity	Event shape variable equal to $\frac{3}{2}(\lambda_3)$, where λ_3 is the third eigenvalue of the sphericity tensor as described in [31].
ave CSV (tags/non-tags)	Average b-tag discriminant value for b-tagged/non-b-tagged jets
ave ΔR(tag,tag)	Average ΔR between b-tagged jets
best Higgs boson mass	A minimum-chi-squared fit to event kinematics is used to select two b-tagged jets as top-decay products. Of the remaining b-tags, the invariant mass of the two with highest E_t is saved.
best ΔR(b,b)	The ΔR between the two b-jets chosen by the best Higgs boson mass algorithm
closest tagged dijet mass	The invariant mass of the two b-tagged jets that are closest in ΔR
dev from ave CSV (tags)	The square of the difference between the b-tag discriminant value of a given b-tagged jet and the average b-tag discriminant value among b-tagged jets, summed over all b-tagged jets
highest CSV (tags)	Highest b-tag discriminant value among b-tagged jets
H_0, H_1, H_2, H_3	The first few Fox-Wolfram moments [32] (event shape variables)
HT	Scalar sum of transverse momentum for all jets with $p_T > 30$ GeV/c
$\sum p_T$(jets,leptons,MET)	The sum of the p_T of all jets, leptons, and MET
$\sum p_T$(jets,leptons)	The sum of the p_T of all jets, leptons
jet 1, 2, 3, 4 p_T	The transverse momentum of a given jet, where the jet numbers correspond to rank by p_T
lowest CSV (tags)	Lowest b-tag discriminant value among b-tagged jets
mass(lepton,jet,MET)	The invariant mass of the 4-vector sum of all jets, leptons, and MET
mass(lepton,closest tag)	The invariant mass of the lepton and the closest b-tagged jet in ΔR (LJ channel)
max $\Delta\eta$ (jet, ave jet η)	max difference between jet eta and avg deta between jets
max $\Delta\eta$ (tag, ave jet η)	max difference between tag eta and avg deta between jets
max $\Delta\eta$ (tag, ave tag η)	max difference between tag eta and avg deta between tags
median inv. mass (tag pairs)	median invariant mass of all combinations of b-tag pairs
M3	The invariant mass of the 3-jet system with the largest transverse momentum.
MHT	Vector sum of transverse momentum for all jets with $p_T > 30$ GeV/c
MET	Missing transverse energy
min ΔR(lepton,jet)	The ΔR between the lepton and the closest jet (LJ channel)
HiggsLike dijet mass(2)	the invariant mass of a jet pair(at least one is b-tagged) ordered in closeness to a Higgs boson mass (DIL channel)
number of HiggsLike dijet 15	number of jet pairs(at least one is b-tagged) whose invariant mass is within 15 GeV window of a Higgs boson mass (DIL channel)
min ΔR(tag,tag)	The ΔR between the two closest b-tagged jets
min ΔR(jet,jet)	The ΔR between the two closest jets
$\sqrt{\Delta\eta(t^{lep}, bb) \times \Delta\eta(t^{had}, bb)}$	square root of the product of abs $\Delta\eta$ (leptonic top, bb) and abs $\Delta\eta$ (hadronic top, bb)
second-highest CSV (tags)	Second-highest b-tag discriminant value among b-tagged jets
sphericity	Event shape variable equal to $\frac{3}{2}(\lambda_2 + \lambda_3)$, where λ_2 and λ_3 are the second and third eigenvalues of the sphericity tensor as described in [31]
(Σ jet p_T)/(Σ jet E)	The ratio of the sum of the transverse momentum of all jets and the sum of the energy of all jets
tagged dijet mass closest to 125	The invariant mass of the b-tagged pair closest to 125 GeV/c^2
$t\bar{t}b\bar{b}$/$t\bar{t}H$ BDT	BDT used to discriminate between $t\bar{t}b\bar{b}$ and $t\bar{t}H$ in the LJ $\geq$ 6 jets, $\geq$ 4 tags, $\geq$6 jets + 3 tags, and 5 jets + $\geq$4 tags categories. See text for description and table 15 for list of variables.

BDT input variables H->bb CMS

PAS HIG-13-019

	4 jets, 3 b-tags	4 jets, 4 b-tags
	jet 1 p_T jet 2 p_T jet 3 p_T jet 4 p_T M3 $\sum p_T$(jets,lepton,MET) HT lowest CSV (tags) MHT MET	jet 1 p_T jet 2 p_T jet 4 p_T HT $\sum p_T$(jets,lepton,MET) M3 ave CSV (tags) second-highest CSV (tags) third-highest CSV (tags) lowest CSV (tags)
	5 jets, 3 b-tags	5 jets, $\geq$ 4 b-tags
	jet 1 p_T jet 2 p_T jet 3 p_T jet 4 p_T $\sum p_T$(jets,lepton,MET) (Σ jet p_T)/(Σ jet E) HT ave CSV (tags) third-highest CSV (tags) fourth-highest CSV (jets)	max $\Delta\eta$ (tag, ave jet η) $\sum p_T$(jets,lepton,MET) (Σ jet p_T)/(Σ jet E) ave ΔR(tag,tag) ave CSV (tags) dev from ave CSV (tags) second-highest CSV (tags) third-highest CSV (tags) lowest CSV (tags) ttbb/ttH BDT
$\geq$ 6 jets, 2 tags	$\geq$ 6 jets, 3 tags	$\geq$ 6 jets, $\geq$ 4 tags
$\sum p_T$(jets,lepton,MET) HT mass(lepton,closest tag) max $\Delta\eta$ (jet, ave jet η) min ΔR(lepton,jet) H_2 sphericity (Σ jet p_T)/(Σ jet E) third-highest CSV (jets) fourth-highest CSV (jets)	H_0 sphericity (Σ jet p_T)/(Σ jet E) max $\Delta\eta$ (jet, ave jet η) $\sum p_T$(jets,lepton,MET) ave CSV (tags) second-highest CSV (tags) third-highest CSV (tags) fourth-highest CSV (jets) ttbb/ttH BDT	(Σ jet p_T)/(Σ jet E) ave ΔR(tag,tag) product($\Delta\eta$(leptonic top, bb), $\Delta\eta$(hadronic top, bb)) closest tag mass max $\Delta\eta$ (tag, ave tag η) ave CSV (tags) third-highest CSV (tags) fourth-highest CSV (tags) best Higgs boson mass ttbb/ttH BDT

Table 14: BDT variables used in each analysis category of the lepton + jets channel.

BDT input variables H->bb CMS

PAS HIG-13-019

5 jets, $\geq$ 4 tags	$\geq$ 6 jets, 3 tags	$\geq$ 6 jets, $\geq$ 4 tags
ave ΔR(tag,tag)	tagged dijet mass closest to 125	H_3
max $\Delta\eta$ (tag, ave tag η)	(Σ jet p_T)/(Σ jet E)	ave ΔR(tag,tag)
(Σ jet p_T)/(Σ jet E)	$\sqrt{\Delta\eta(t^{lep},bb)\times\Delta\eta(t^{had},bb)}$	closest tagged dijet mass
tagged dijet mass closest to 125	H_1	sphericity
H_1	H_3	max $\Delta\eta$ (tag, ave jet η)
H_3	M3	max $\Delta\eta$ (tag, ave tag η)
$\sum p_T$(jets,lepton,MET)	max $\Delta\eta$ (tag, ave tag η)	mass(lepton,jet,MET)
fourth-highest CSV (tags)	max $\Delta\eta$ (tag, ave jet η)	(Σ jet p_T)/(Σ jet E)
aplanarity	max $\Delta\eta$ (jet, ave jet η)	abs $\Delta\eta$ (leptonic top, bb)
MET	abs $\Delta\eta$ (hadronic top, bb)	abs $\Delta\eta$ (hadronic top, bb)
	abs $\Delta\eta$ (leptonic top, bb)	$\sqrt{\Delta\eta(t^{lep},bb)\times\Delta\eta(t^{had},bb)}$
	sphericity	ave CSV (tags)
	aplanarity	best ΔR(b,b)
	min ΔR(tag,tag)	best Higgs boson mass
	jet 3 p_T	median inv. mass (tag pairs)

Table 15: List of variables used as inputs to the ttbb/ttH BDTs.

3 jets, 2 b-tags	$\geq$4 jets, 2 b-tags	$\geq$3 jets, $\geq$3 b-tags
ave CSV (tags)	ave CSV (non-tags)	ave CSV (tags)
min ΔR(jet,jet)	min ΔR(jet,jet)	min ΔR(jet,jet)
$\sum p_T$(jets,leptons)	$\sum p_T$(jets,leptons)	$\sum p_T$(jets,leptons)
ave CSV (non-tags)	Number of jets	Number of HiggsLike dijet 15
	HiggsLike dijet mass	HiggsLike dijet mass
	HiggsLike dijet mass2	HiggsLike dijet mass2

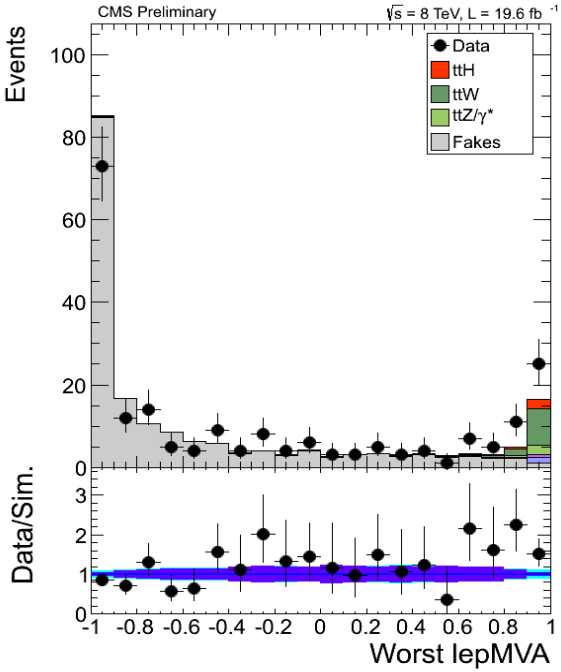
Table 16: BDT variables used in each analysis category of the dilepton channel. Descriptions of the variables can be found in Table 13.

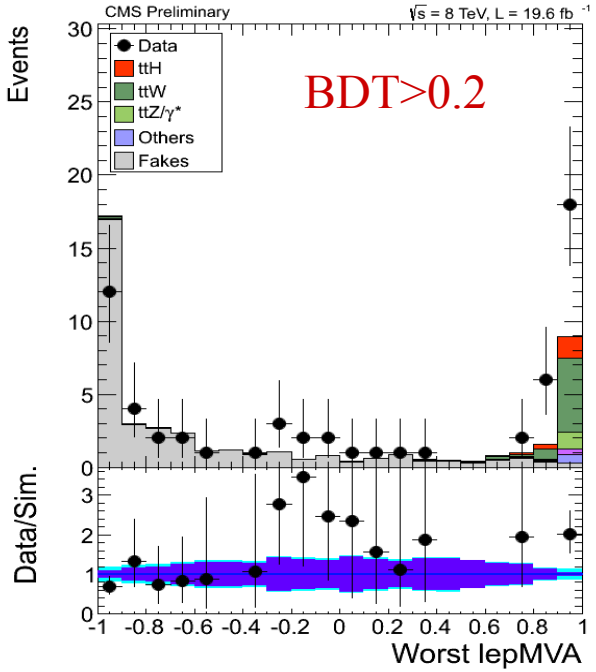
Variable	Description
Tau1Pt	The p_T of the more energetic τ
Tau2Pt	The p_T of the less energetic τ
Tau1Eta	The $\lvert\eta\rvert$ of the more energetic τ
Tau1IsolationMVA2Raw	The HPS MVA2 score of the more energetic τ
Tau2IsolationMVA2Raw	The HPS MVA2 score of the less energetic τ
DitauVisibleMass	The reconstructed visible mass from the τ-pair
DeltaRTau1Lepton	The distance between the more energetic τ and the lepton
Tau1DecayMode	The decay mode of the more energetic τ
Tau2DecayMode	The decay mode of the less energetic τ
LeadingJetPt	The leading jet p_T, excluding jets from the selected τ

Table 17: Event variables used for the MVA training of the tau channel and their descriptions.

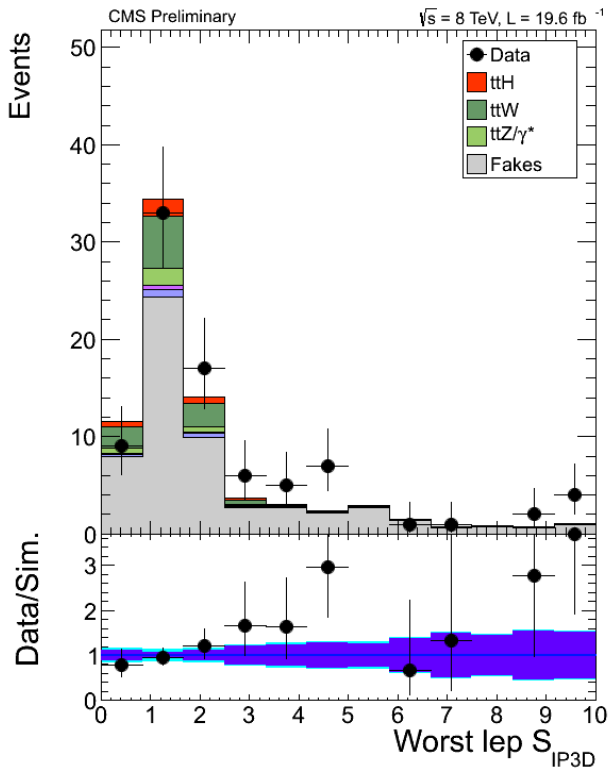
Same-sign di-muon excess

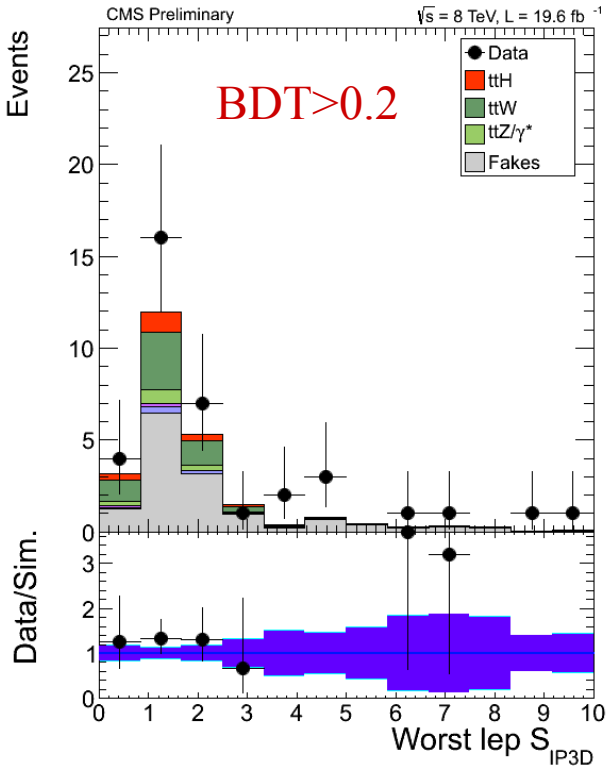
- Unlikely to come from underestimated background :
  - Consistent yields between ee and emu channels,
  - Muon charge mis-reconstruction would have to be 10 times > electron charge mis-reconstruction to explain the excess.
  - Multiple checks in distributions, in control regions (looser lepton MVA selection) = no obvious background missing.
  - Cut based analyses (worse sensitivities) lead to consistent results.



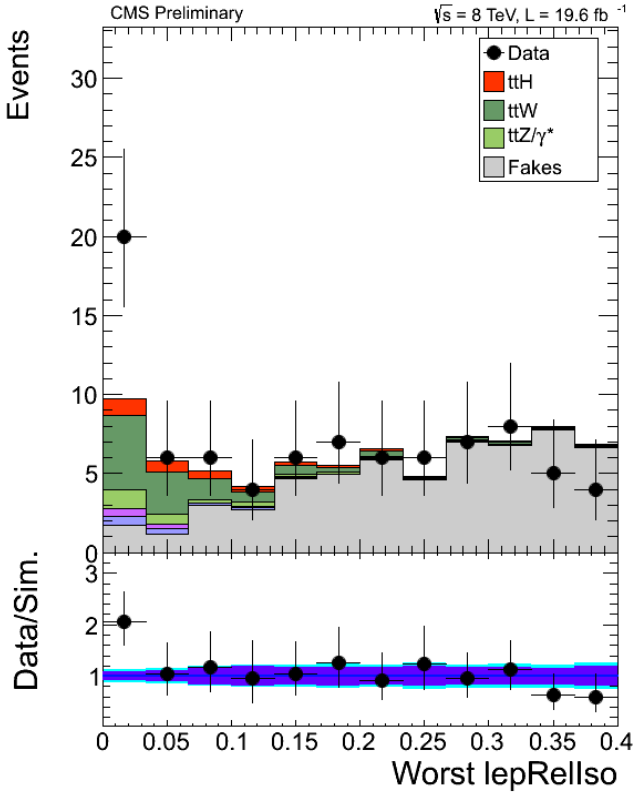


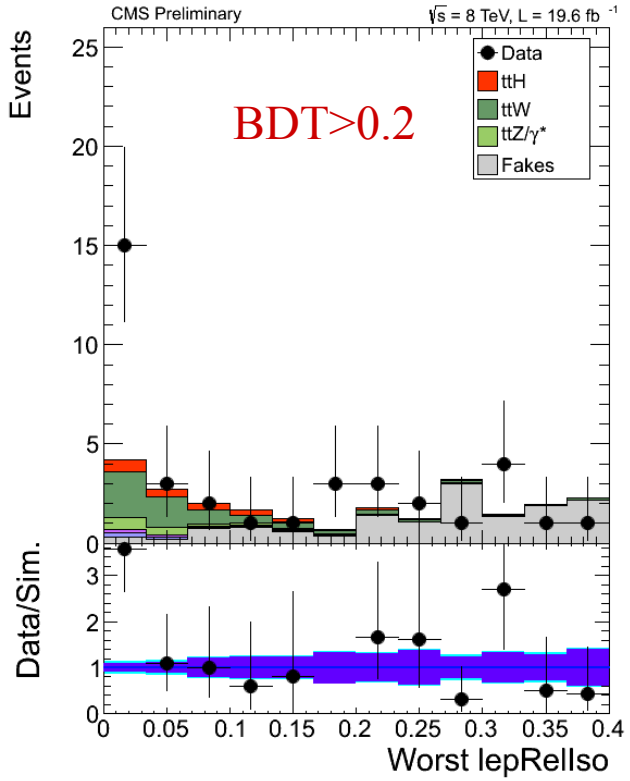
Same-sign di-muon excess



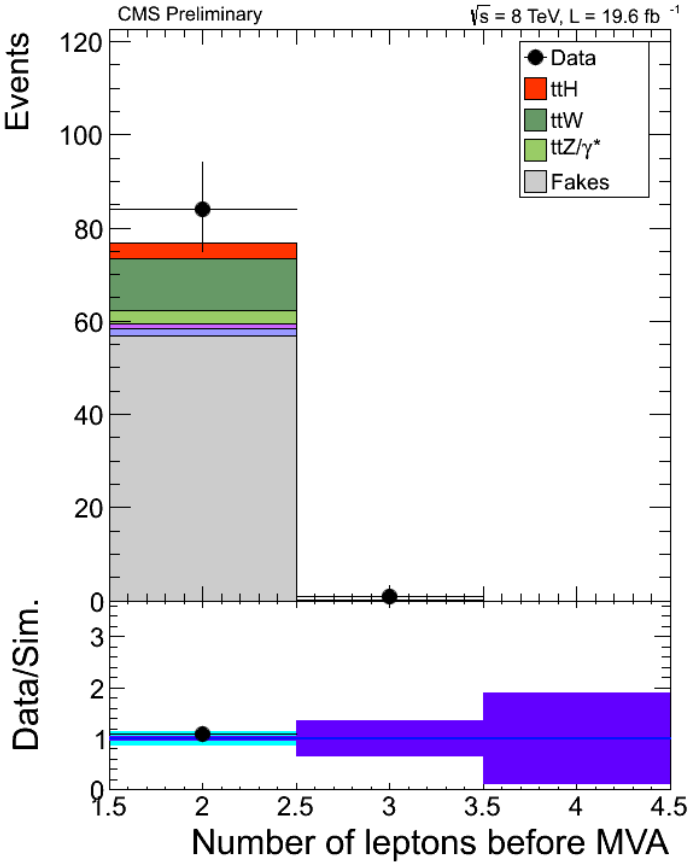


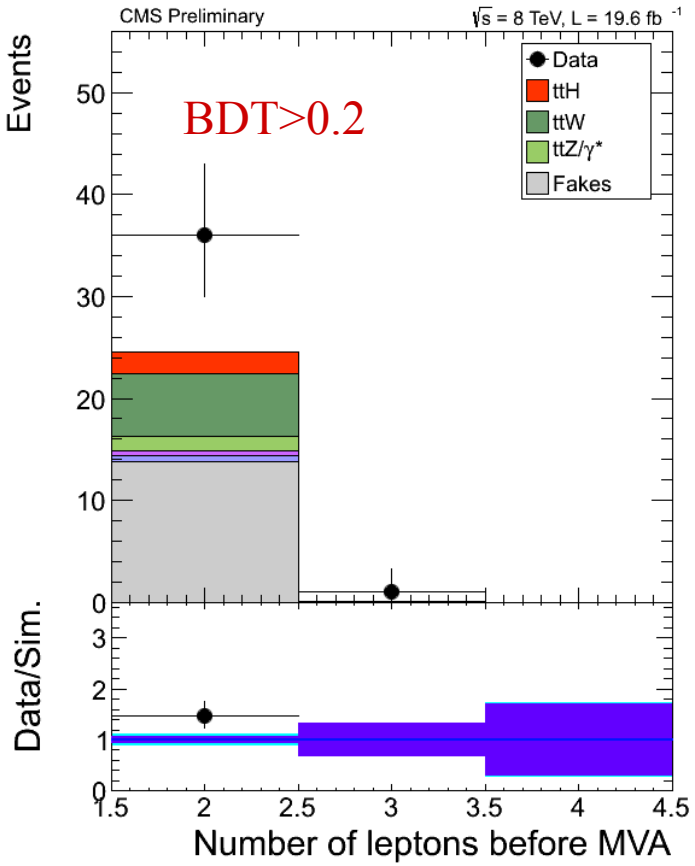
Same-sign di-muon excess



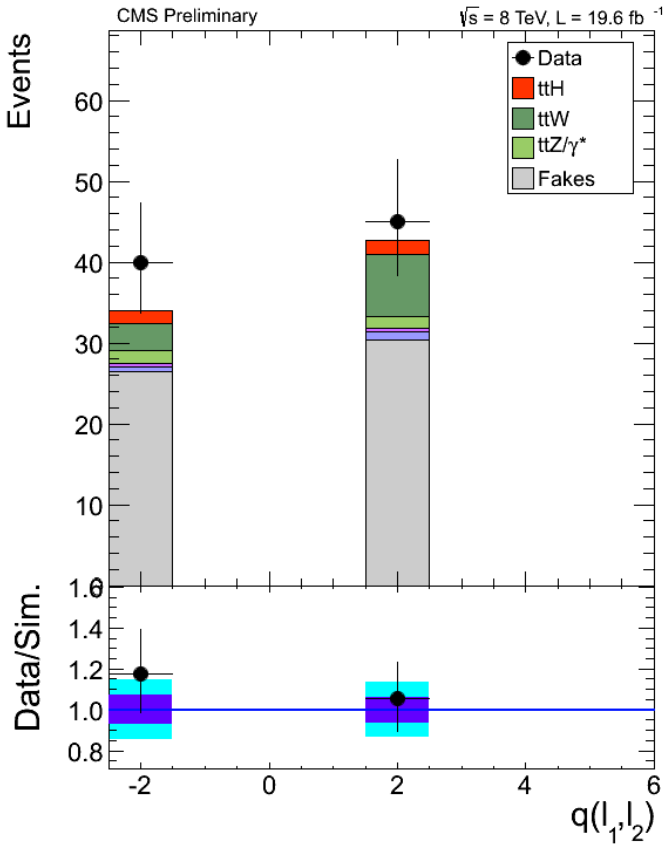


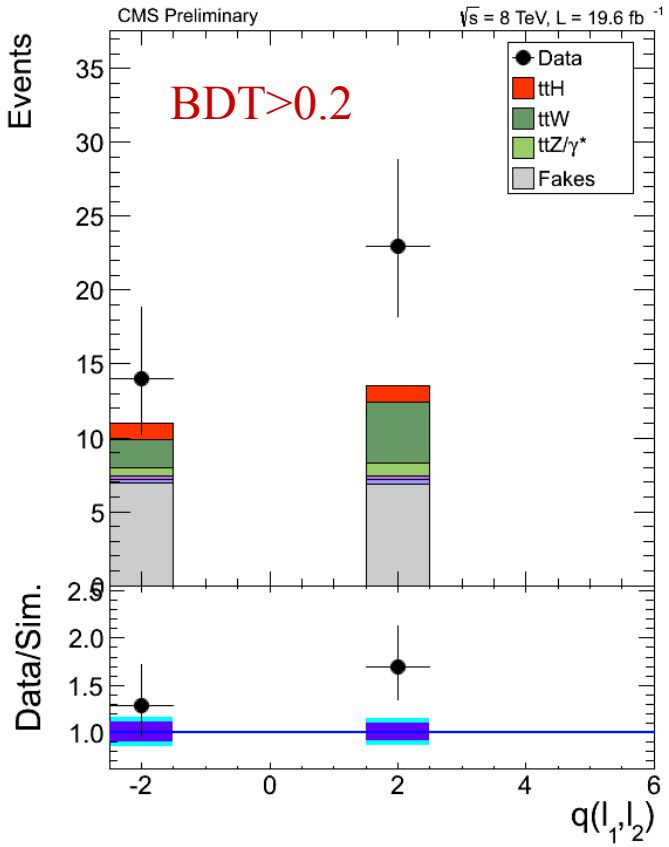
Same-sign di-muon excess



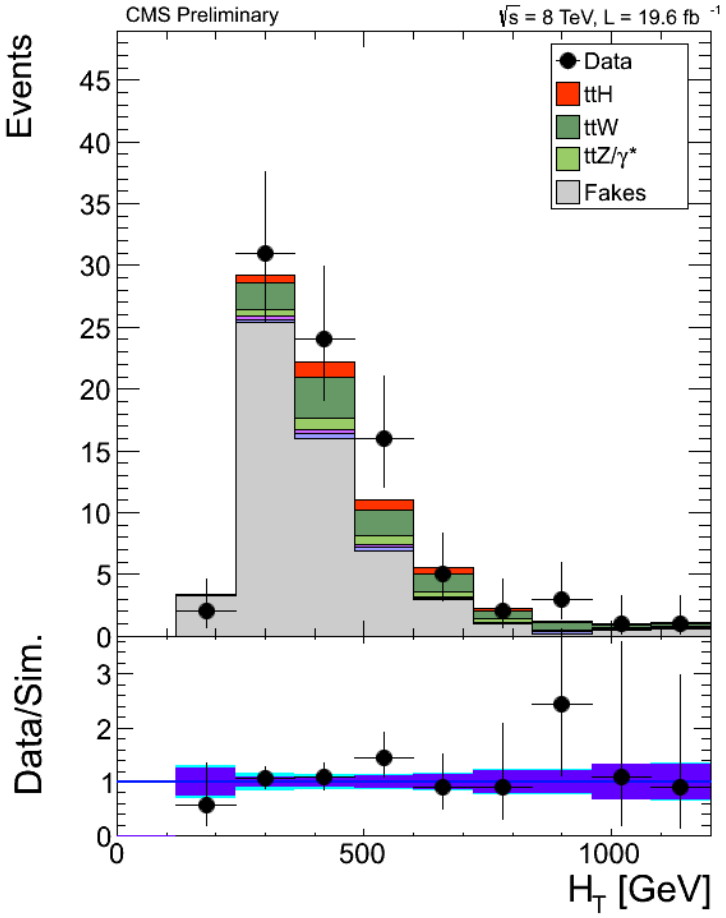


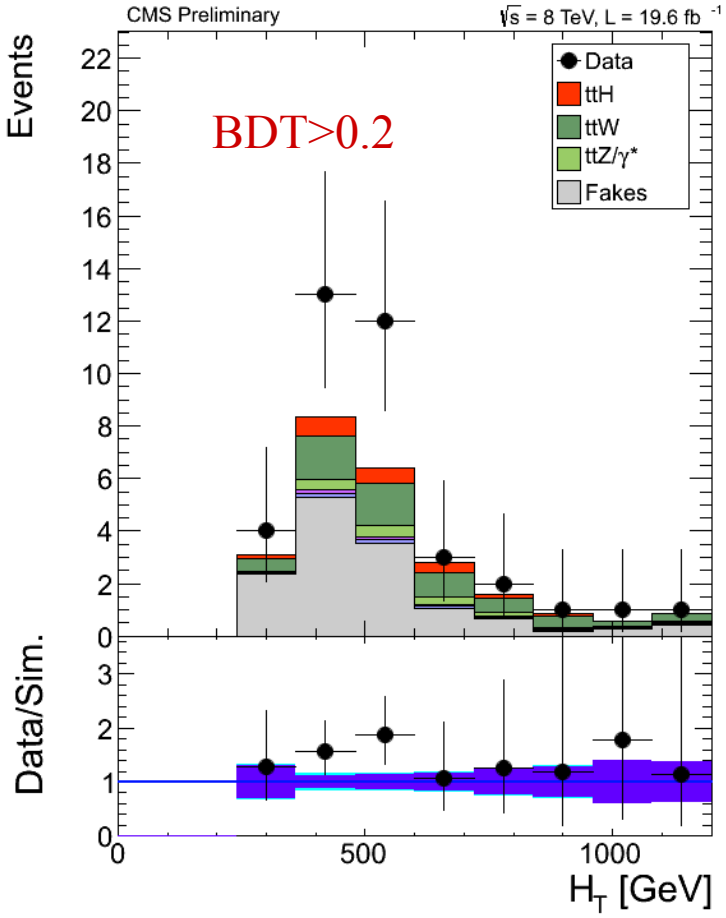
Same-sign di-muon excess





Same-sign di-muon excess





Multi-lepton BDT

- Same-sign dilepton :
  - the pT and |η | of the trailing lepton,
  - the minimal angular separation between the trailing lepton and the closest jet,
  - the transverse mass of the leading lepton
  - and E_T^{miss} , H_T , H_T^{miss}
- Tri-lepton :
  - the multiplicity of hadronic jets, the pT of the jet with the highest b-tagging discriminant value,
  - HT , the fraction of HT from jets and leptons within |η | < 1.2,
  - the maximum of the |η | values of the three leptons,
  - the minimal ΔR separation between any pair of opposite-sign leptons,
  - the mass of the best candidate hadronically-decaying top quark reconstructed from the jets in the event.
- Quadri-lepton : no BDT, multiplicity of hadronic jets.