$t\bar{t}H$ at the LHC

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on behalf of ATLAS and CMS Collaborations

SISSA Trieste & INFN Udine

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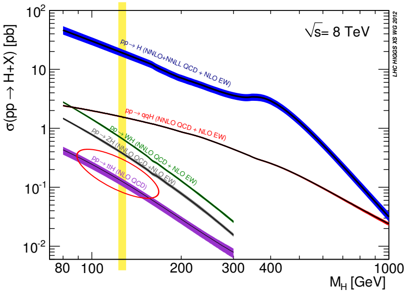
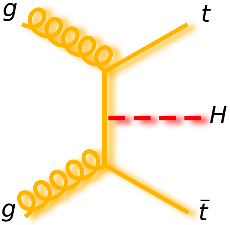
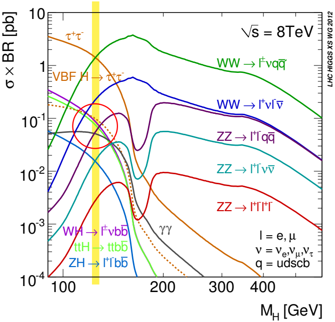




- Smallest Higgs production channel
- Allows direct y_t measurement: no loops, no no-BSM assumptions
- Thanks to $t\bar{t}$ signature, $H \to b\bar{b}$ can be looked at



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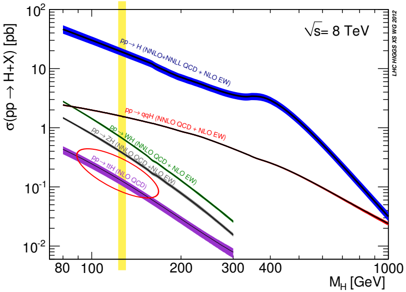

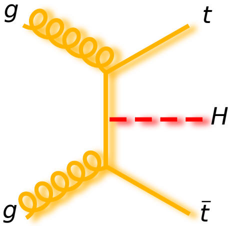

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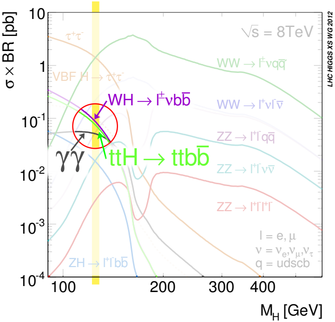
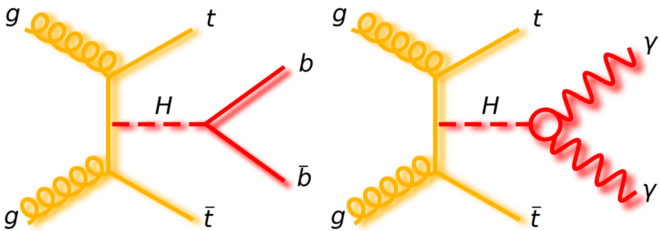


Public results by ATLAS and CMS

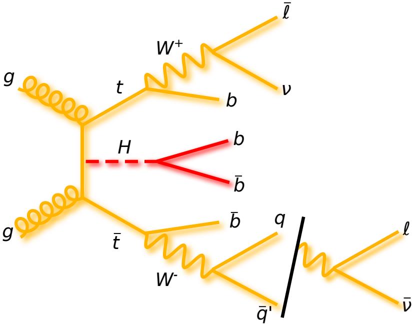
Exp.	Channel	7 TeV	8 TeV	Reference
ATLAS	$H \to b\bar{b}$	4.7 fb^{-1}	-	ATLAS-CONF-2012-135
CMS	$H \to b\bar{b}$	5.0 fb^{-1}	5.1 fb^{-1}	CERN-PH-EP-2013-027(*)
CMS	$H \to \gamma\gamma$	-	19.6 fb^{-1}	CMS-PAS-HIG-13-015

*: Preliminary result on 7 TeV only: CMS-PAS-HIG-12-025



Will concentrate more on $t\bar{t}H$ ($H \to b\bar{b}$)

Final State Topology

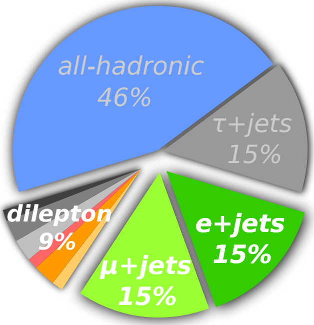


Best channel: $t\bar{t} \to \ell$+jets, $H \to b\bar{b}$

- 1 e or μ, $\not{E}_T$
- 4 b-jets from top's and Higgs
- 2 light (or c-) jets from W

CMS considers di-lepton as well

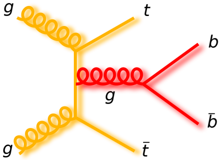
- opposite signed ee, $\mu\mu$ or $e\mu$, $\not{E}_T$
- 4 b-jets from tops and Higgs

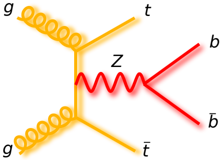


Background processes

Irreducible backgrounds:

- $t\bar{t} + b\bar{b}$
- $t\bar{t} + Z(\to b\bar{b})$





Other important backgrounds:

- $t\bar{t} + c\bar{c}$, $t\bar{t} + Z(\to c\bar{c})$, $t\bar{t} + W(\to c\bar{s})$
- $t\bar{t}$+light jets with mis-tag
- single top, W+jets
- Z+jets, dibosons
- QCD multi-jet with fake leptons

Difficulties

- Low statistics (not much lower than other channels)
- Low S/B even after event selection
- Jet reco and b-tag performances & systematics
- Hard to find powerful discriminating fit variables

Expected yields for $\ell+\geq 6$ jets, ≥ 4 b-tags:

-	ATLAS (7 TeV)	CMS (8 TeV)
$t\bar{t}H$	2.2	2.5
$t\bar{t}$+jets	54	60
$t\bar{t}+V$	2.7	1.5

Event Pre-Selection

ATLAS, ℓ+jets:

- Single e or μ trigger
- 1 isolated e ($E_T > 25$ GeV, $|\eta| < 2.47$) or μ ($p_T > 20$ GeV, $|\eta| < 2.5$)
- $\not\!\!E_T$ >30 GeV & $m_T(W)$ >30 GeV (e+jets), $\not\!\!E_T$ >20 GeV & $\not\!\!E_T + m_T(W)$ >60 GeV (μ+jets)
- Jets: Anti-k_T 0.4, p_T >25 GeV, $|\eta|$ <2.5
- b-jets: MV1 algorithm, 70% b-tag eff.
- $\geq$ 4 jets

CMS, ℓ+jets:

- Single μ or e+jets trigger
- 1 isolated e ($E_T > 30$ GeV, $|\eta| < 2.5$) or μ ($p_T > 30$ GeV, $|\eta| < 2.1$)
- Jets: Anti-k_T 0.5, p_T >30 GeV, $|\eta| < 2.4$
- b-jets: CSV algorithm, 70% b-tag eff.
- $\geq$4 jets, 3 of them with $p_T > 40$ GeV

CMS, dilepton:

- Dilepton (ee, $\mu\mu$ or $e\mu$) trigger
- 1 isolated e ($E_T > 20$ GeV, $|\eta| < 2.5$) or μ ($p_T > 20$ GeV, $|\eta| < 2.1$)
- 1 e ($E_T > 20$ GeV, $|\eta| < 2.5$) or μ ($p_T > 20$ GeV, $|\eta| < 2.1$) with looser isolation
- $\geq$ 2 jets

- Leptons: tighter selection for CMS ℓ+jets, looser for dilepton
- Jets: harder cuts for CMS
- B-tagging: similar algorithms & efficiencies
- $\not\!\!E_T$ and $m_T(W)$ cuts: ATLAS only

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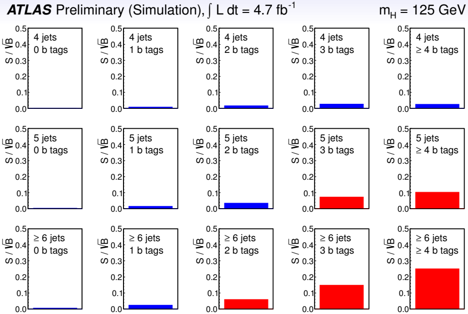
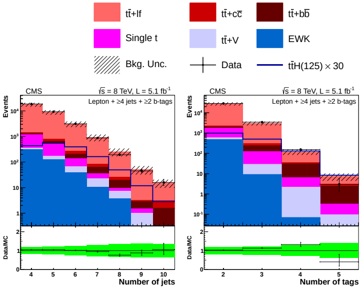
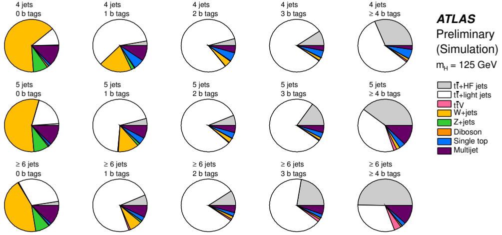
Divide et impera

Both ATLAS and CMS split according to N^{jet} & N^{btag}:

- To maximize statistical power
- To exploit the difference in N^{jet} & N^{btag} spectra for S and B
- To control the different sources of background



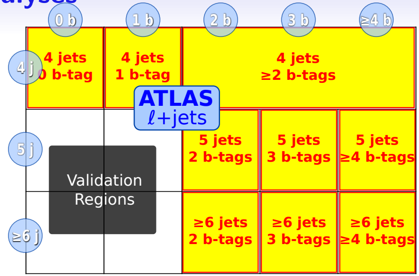




Regions used in the Analyses

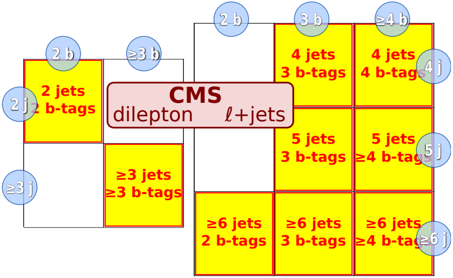
ATLAS:

- 9 regions used in ℓ+jets
- low N^{jet} and N^{tag} regions dominated by W+jets and $t\bar{t}$, help constrain systematics (b-tagging)



CMS:

- 7 regions used in ℓ+jets
- Regions with negligible expected signal excluded
- 2 regions in dilepton



Systematics

ATLAS: (S: shape - N: normalization)

Systematic uncertainty	Rate	Status	Components
Luminosity	1.4%	N	1
Lepton ID+reco+trigger	1.1%	N	1
Jet vertex fraction effciency	0.9-2.9%	N	1
Jet energy scale	2-15%	SN	16
Jet energy resolution	0-2%	N	1
b-tagging efficiency	13-36%	SN	9
c-tagging efficiency	0-19%	SN	5
Light jet-tagging efficiency	0-14%	SN	1
tt cross section	~10%	N	1
$t\bar{t}V$ cross section	30%	N	1
Single top cross section	~4%	N	1
Dibosons cross section	5%	N	1
V+jets normalisation	20-60%	N	3
Multijet normalisation	30-80%	N	7
W+heavy-flavour fractions	25-35%	SN	4
$t\bar{t}$ modelling	2-30%	SN	3
$t\bar{t}$+heavy-flavour fractions	50%	SN	1
$t\bar{t}H$ modelling	1.5-5%	N	1

LHC

Detector performance

Theoretical predictions

Data-driven backgrounds

Monte Carlo modelling

tt+bb/cc fraction

Alpgen parameter variations

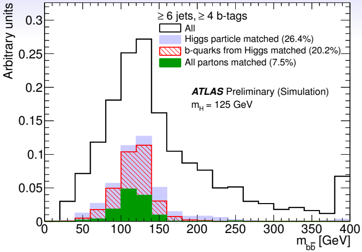
CMS:

Source	Rate Uncertainty	Shape
Luminosity (7 TeV)	2.2%	No
Luminosity (8 TeV)	4.4%	No
Lepton ID/Trig	4%	No
Pileup	1%	No
Additional Pileup Corr.	-	Yes
Jet Energy Resolution	1.5%	No
Jet Energy Scale	0-60%	Yes
b-Tag SF (b/c)	0-33.6%	Yes
b-Tag SF (mistag)	0-23.5%	Yes
MC Statistics	-	Yes
PDF (gg)	9%	No
PDF ($q\bar{q}$)	4.2-7%	No
PDF (qg)	4.6%	No
QCD Scale ($t\bar{t}H$)	15%	No
QCD Scale ($t\bar{t}$)	2-12%	No
QCD Scale (V)	1.2-1.3%	No
QCD Scale (VV)	3.5%	No
Madgraph Scale ($t\bar{t}$)	0-20%	Yes
Madgraph Scale (V)	20-60%	No
$t\bar{t} + bb$	50%	No

$t\bar{t}H$ system reconstruction

The idea:

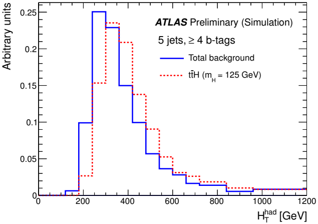
- Reconstruct $t\bar{t}$ system, by kinematic fit to assign jets:
  - with fixed m_t and m_W,
  - considering jet, lepton and $\not{E}_T$ resolutions
  - event-by-event Likelihood maximized
- Use the two highest MV1 weight jets not assigned to $t\bar{t}$ to reconstruct Higgs
- Take their invariant mass as fit variable

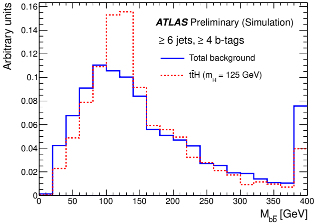


$\sim$20% Higgs reco. efficiency

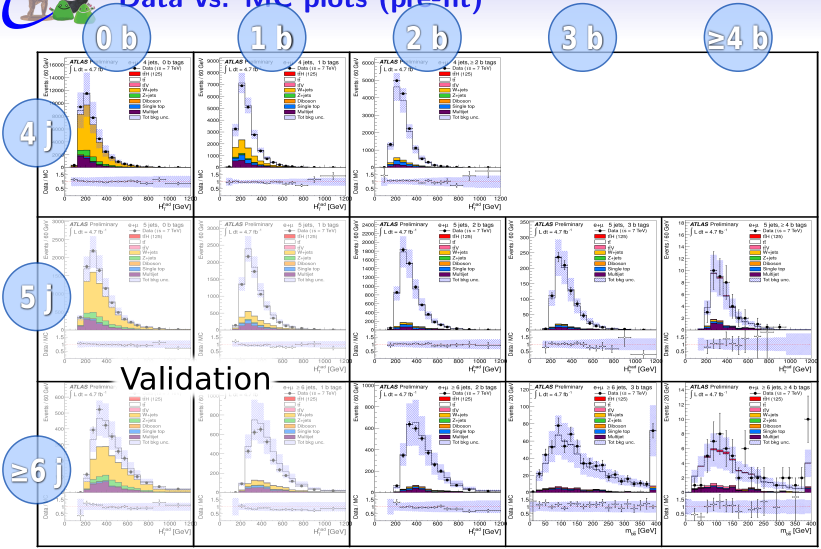
m_{bb} only in:
≥ 6 jets - 3 b-tags,
≥ 6 jets - ≥ 4 b-tags.

In other regions use:
$$H_T^{had} = \sum_{jets} p_T.$$

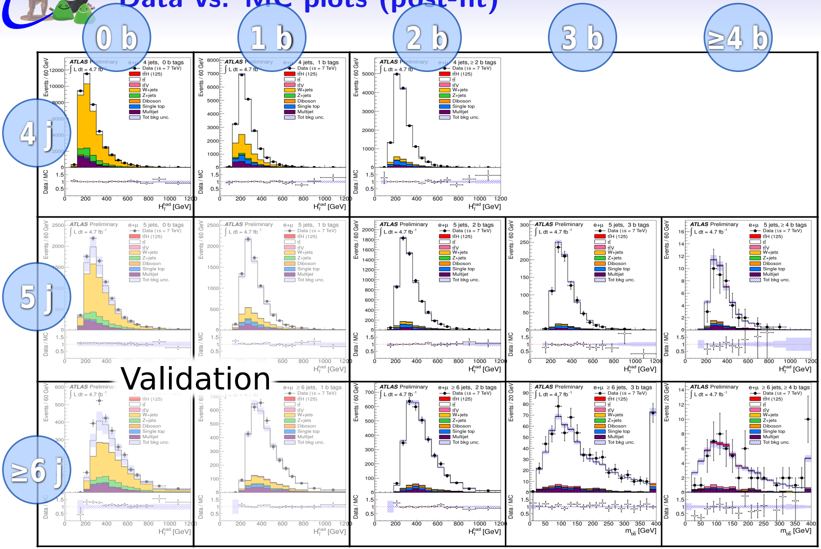




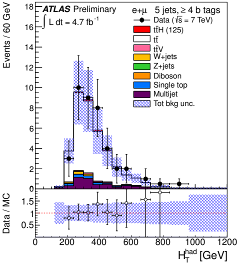
Data vs. MC plots (pre-fit)

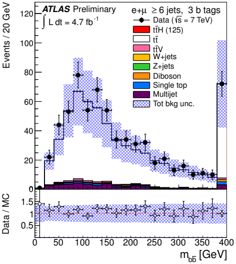


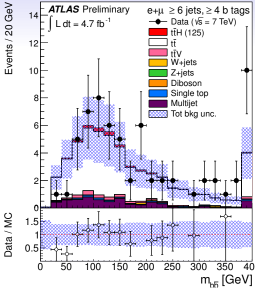
Data vs. MC plots (post-fit)



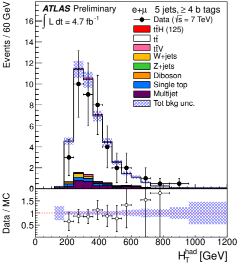
Zoom to Signal Region

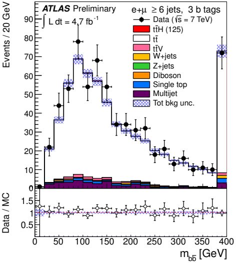


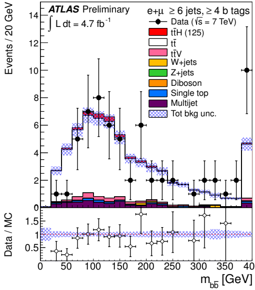




Bkg-only Fit







Neural Network Analysis

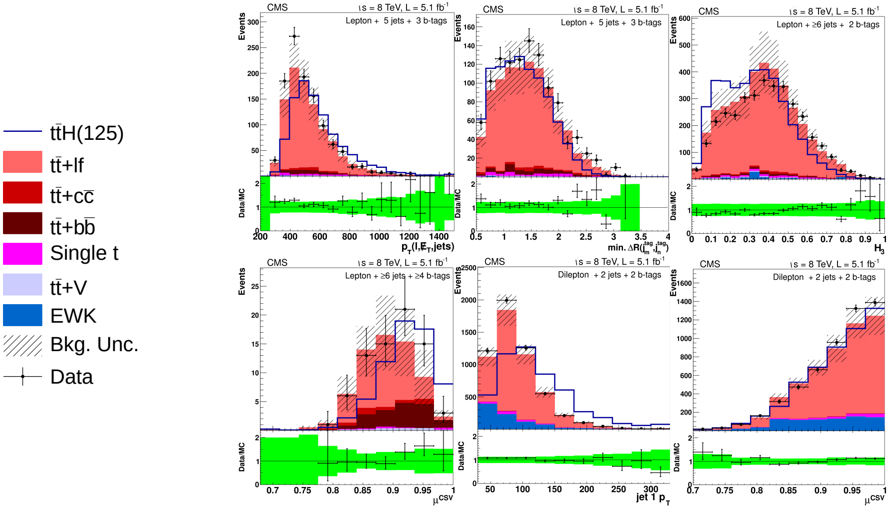
Multi-Variate approach:

- Combine several discriminating variables
- Build powerful output variable to discriminate $t\bar{t}H$ signal from background (mainly $t\bar{t}$+jets)
- Train a different Artificial Neural Network (ANN) in each region
- 10 variables per region in ℓ+jets
- 5 and 6 variables in dilepton regions

★ = best variable
✓ = used variable

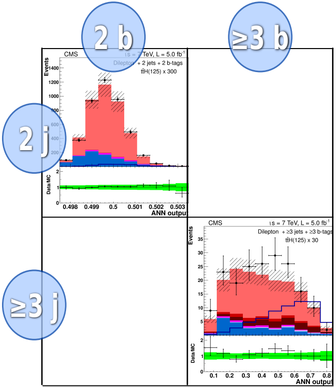
	Lepton+Jets							Dilepton		
Jets	≥6	4	5	≥6	4	5	≥6	2	≥3	
Tags	2	3	3	3	4	≥4	≥4	2	≥3	
Jet 1 p_T		✓	✓		✓			★	✓	Basic kinematic properties
Jet 2 p_T		✓	✓							
Jet 3 p_T	✓	✓	✓			✓				
Jet 4 p_T	✓	✓	✓			✓				
N_{jets}									✓	
$p_T(\ell, E_T^{miss}, jets)$		★	✓		✓	✓		✓	✓	
$M(\ell, E_T^{miss}, jets)$	✓	✓		✓	✓		✓			
Average $M((j_m^{untag}, j_n^{untag}))$	✓			✓						Di-jet masses
$M((j_m^{tag}, j_n^{tag})_{closest})$							✓			
$M((j_m^{tag}, j_n^{tag})_{best})$							✓			
Average $\Delta R(j_m^{tag}, j_n^{tag})$				✓	✓	✓	✓			Event shape variables
Minimum $\Delta R(j_m^{tag}, j_n^{tag})$			✓					✓	✓	
$\Delta R(\ell, j_{closest})$						✓	✓	✓	✓	
Sphericity	✓			✓			✓			
Aplanarity	✓				✓					
H_0	✓									
H_1 (Fox-Wolfram	✓				✓					
H_2 momenta)				✓			✓			
H_3	★			✓			✓			
μ^{CSV}	✓	✓	★	★	★	★	★	✓	★	b-tag weight variables
$(\sigma_n^{CSV})^2$		✓	✓	✓	✓	✓				
Highest CSV value						✓				
2nd-highest CSV value		✓	✓	✓	✓	✓	✓			
Lowest CSV value		✓	✓	✓	✓	✓	✓			

Input Variable Plots

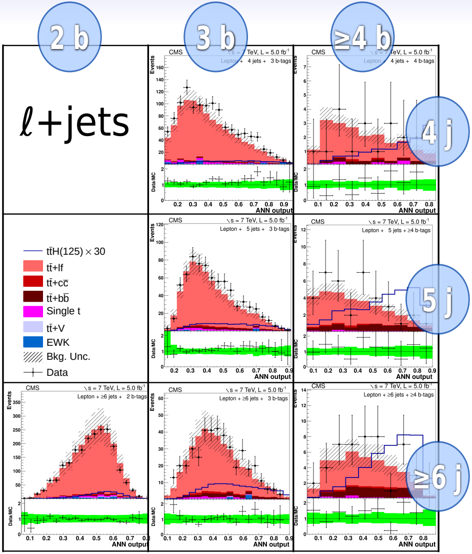


Data vs. MC plots - 7 TeV (pre-fit)

Dilepton

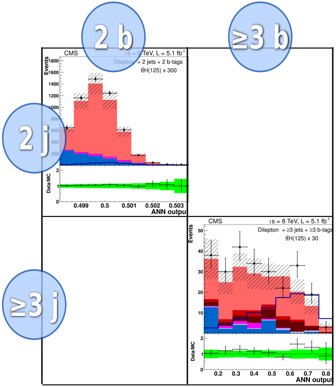


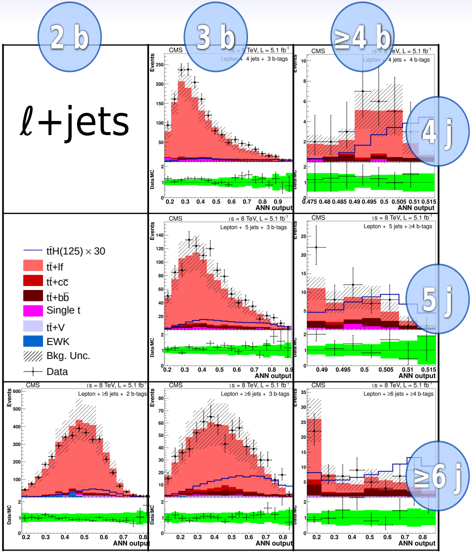
ℓ+jets



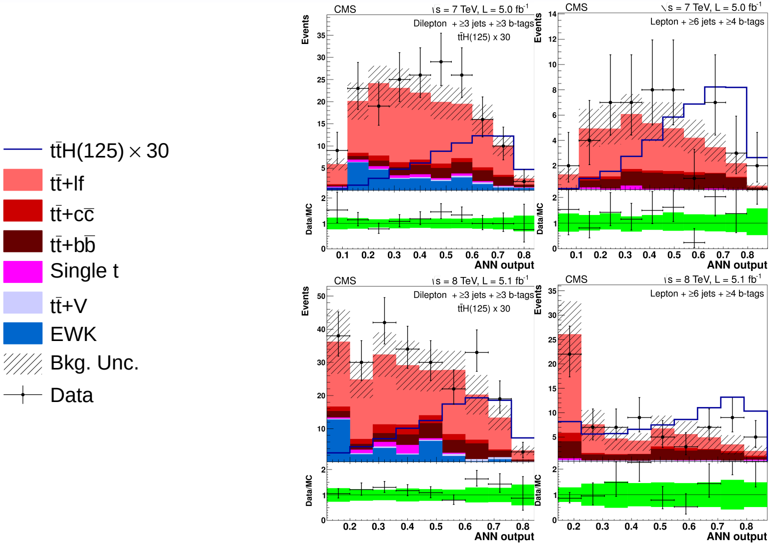
Data vs. MC plots - 8 TeV (pre-fit)

Dilepton

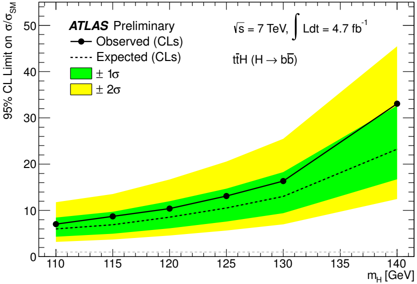


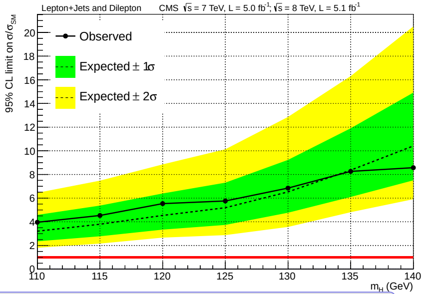


Zoom to signal regions



Fit and Limits



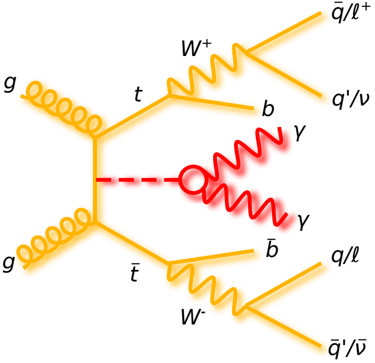


- For $m_H = 125$ GeV:
  - 13.1 × SM prediction excluded by ATLAS (expected limit = 10.5)
  - 5.8 × SM prediction excluded by CMS (expected limit = 5.2)
- Large degradation of sensitivity from systematics
- Significant improvement of CMS w.r.t. ATLAS:
  - dilep+ljets, 7+8 TeV combination
  - Multi-Variate discriminant
  - all Higgs decay channels considered as signal

Analysis Strategy

$t\bar{t}H$, $H \to \gamma\gamma$ channel:

- Low statistics is the main problem
- No combinatorial issues & much better Higgs mass resolution
- Relatively small background expected



Strategy in CMS analysis:

- Trying to select all the possible $t\bar{t}$ decays:
  - base selection 2 γ + jets + b-tag
  - "hadronic" selection: no lepton
  - "leptonic" selection: ≥ 1 e or μ
- Loose selection cuts to gain in statistics
- Background from $t\bar{t}$ or QCD + real or fake photons:
  - control sample obtained inverting one of the γ ID's
- Fit $m_{\gamma\gamma}$, like standard $H \to \gamma\gamma$
- Background fitted with exponential or polynomial (tested with control sample)

Event Selection & Background

Event Selection:

- Di-photon trigger
- Two isolated γ with $|\eta| < 2.5$:
  - 1^{st} γ: $p_T > 60$ GeV $\cdot m_{\gamma\gamma}/120$ GeV
  - 2^{nd} γ: $p_T > 25$ GeV
- At least one b-tagged jet (CSV 70% b-tag eff.)
- Hadronic channel:
  - ≥ 5 jets ($p_T > 25$ GeV, $|\eta| < 2.4$)
  - no lepton
- Leptonic channel:
  - ≥ 2 jets ($p_T > 25$ GeV, $|\eta| < 2.4$)
  - ≥ 1 isolated e (μ), $p_T > 20$ GeV, $|\eta| < 2.5$ (2.4)

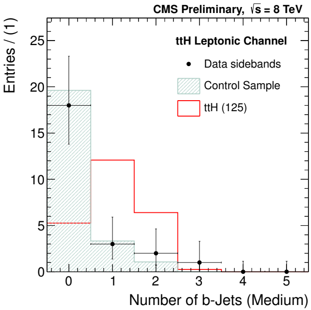
Contribution from other Higgs production processes!

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

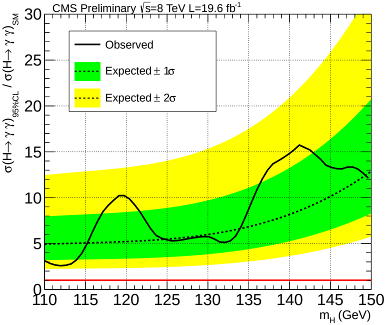
Control sample selection

Same as signal selection but:

- Single photon trigger
- Inverted ID cuts for one of the photons

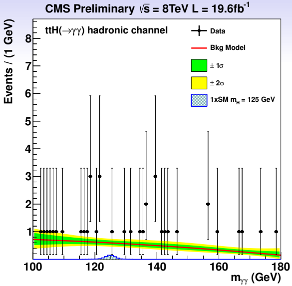


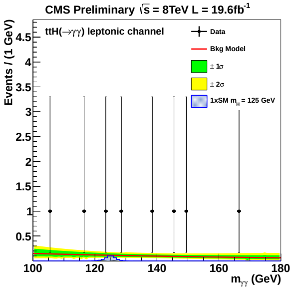
Fit and Results



- Better limit than $H \to b\bar{b}$
- Small effect of systematics

	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





Summary and Outlook

$t\bar{t}H$ results up to now:

- No observation of $t\bar{t}H$ yet
- $t\bar{t}H(H \to b\bar{b})$ limits from both ATLAS and CMS
- Analysis techniques and systematics treatment are key ingredients
- $t\bar{t}H(H \to \gamma\gamma)$ fresh results from CMS, competitive with $H \to b\bar{b}$

Still to come from LHC Run I data:

- Update from CMS on full data-set for $H \to b\bar{b}$
- Update from ATLAS with 8 TeV and dilepton included for $H \to b\bar{b}$
- More on $H \to \gamma\gamma$: 7 TeV from CMS, results from ATLAS
- Other decay channels might be sensitive with full data-set: $H \to WW, H \to \tau\tau$ ...