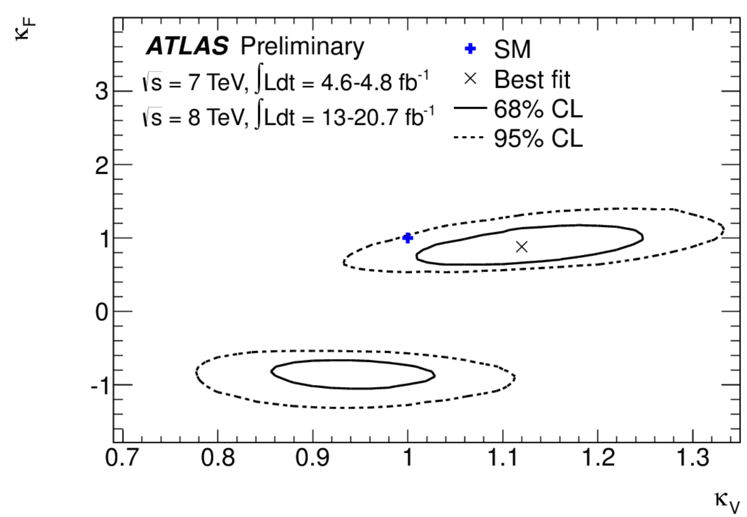
top Higgs associated production at LHC

Lorenzo Feligioni

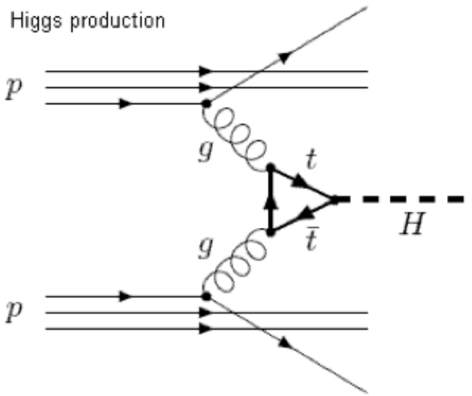
Higgs couplings

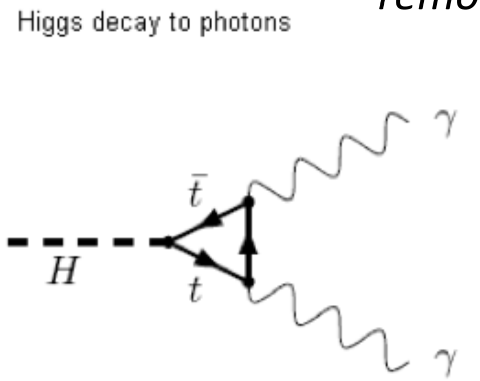
- After the discovery of the new boson the focus is shifted on the measure of its properties.
- No direct measure of the top-Higgs Yukawa coupling accessible yet
  - Indirect constraints by one loop contributions in different Higgs production and decay channels

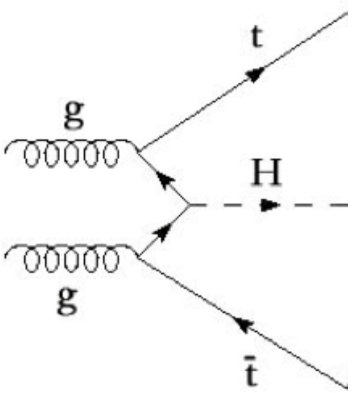
ATLAS-CONF-2013-034



Need to measure fermion couplings to remove degeneracy





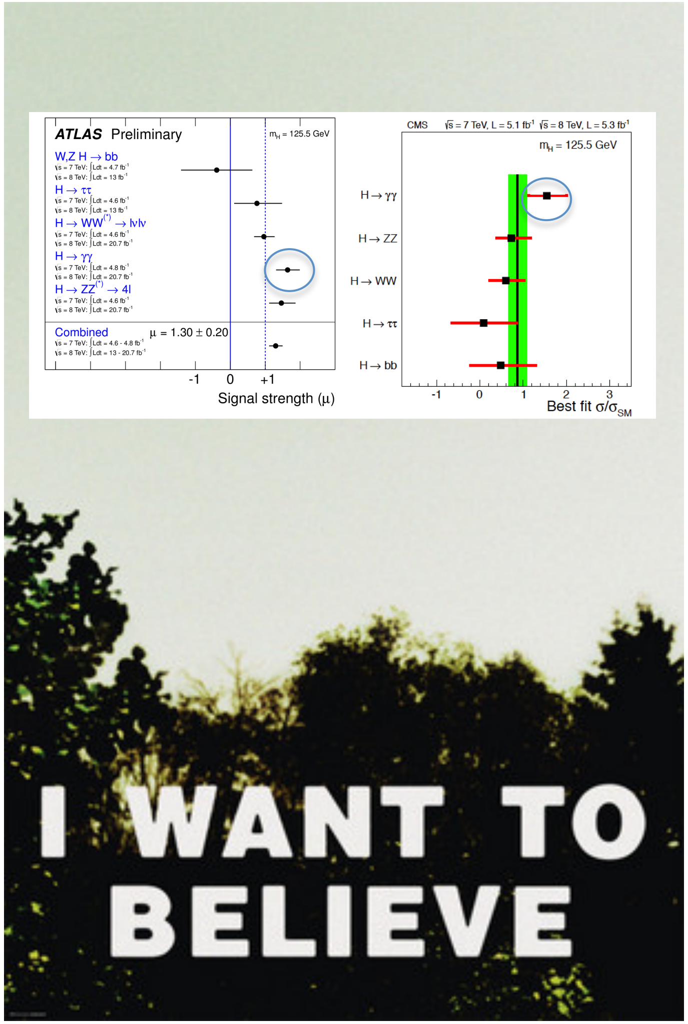


Higgs couplings

ATLAS-CONF-2013-034

arXiv:1207.7235

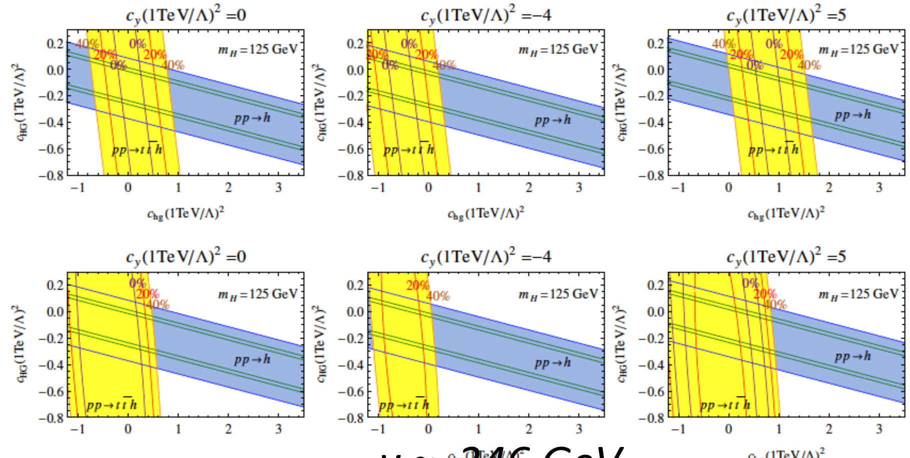
- After the discovery of the new boson the focus is shifted on the measure of its properties.
- No direct measure of the top-Higgs Yukawa coupling accessible yet
  - Indirect constraints by one loop contributions in different Higgs production and decay channels
- Latest results from ATLAS and CMS show no significant deviation from SM expectation in terms of couplings.
  - ATLAS measure combined signal strength among all SM channels
    - μ=1.30 ± 0.13 (stat) ± 0.14 (syst)



New physics in the ttH sector

arXiv:1205.1065

- Effective field theory provides a model independent parameterization of the potential deviations from the SM.
  - Dimension 6 operators which modify the contributions from top loop are already constrained by Higgs production measurements
  - Higgs production by gluon fusion only constraints a linear combination and cannot discriminate among them.
  - ttH production can independently constrain the chromomagnetic operator O_{hg}



$$\sigma(gg \to h) = \sigma(gg \to h)_{SM}\left(1 + \frac{c_{HG}}{\Lambda^2}\frac{6\pi v^2}{\alpha_s}\right) \qquad \sigma(pp \to t\bar{t}h) = \sigma(pp \to t\bar{t}h)_{SM}\left(1 - c_y\frac{v^2}{\Lambda^2}\right)^2$$

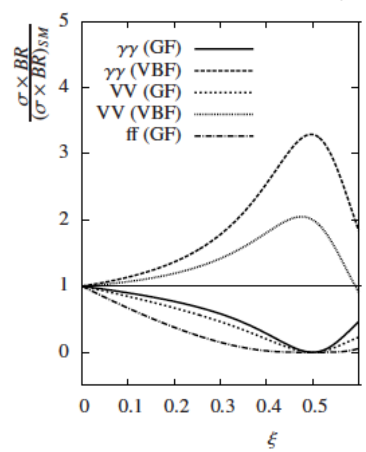
$$\xi = \frac{v^2}{f^2},$$

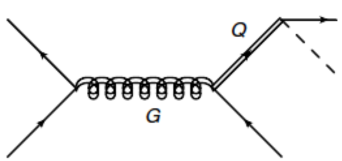
$v \approx$ 246 GeV

f :decay constant of composite sector

- New Higgs productions in composite models
  - Single production of new vector-like quark in association with a SM quark mediated by the exchange of a in association of a heavy gluon and subsequent decay in Higgs boson [model $MCHM_5$]
    - Production cross section O(1-10)fb at 7,8 TeV and O(10-100)fb at 14 TeV
    - Signature that can be directly searched for

arXiv:1205.237

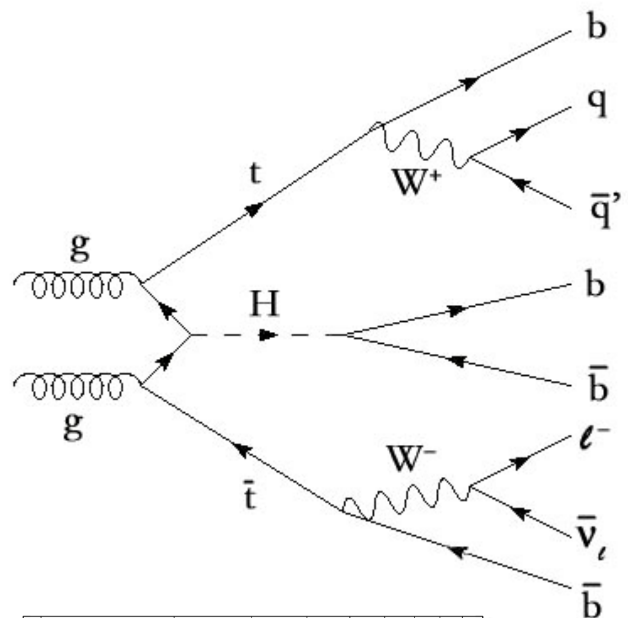


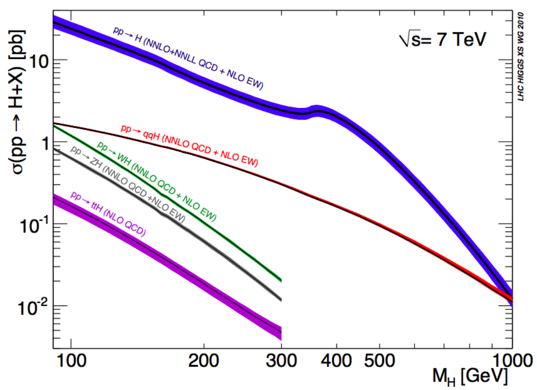


For SM Higgs
With m_H =125 GeV
➔ $0 \le \xi \le 0.4$

ttH production and signature

- Phenomenology:
  - Distinctive final state with high jet b-jet multiplicity
  - Lepton can be used for triggering
  - A priori many handles against backgrounds!
- Difficulties at analysis level:
  - Very busy events which are hard to reconstruct kinematically (large combinatorial background).
  - Low production cross section.
  - Huge background from tt+jets affected by large systematic uncertainties, both theoretical and experimental.

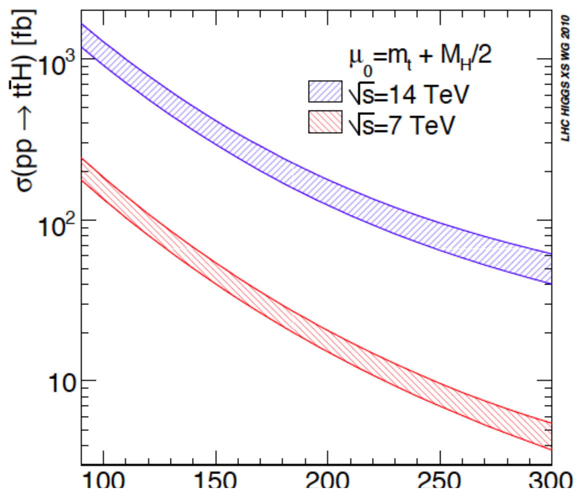


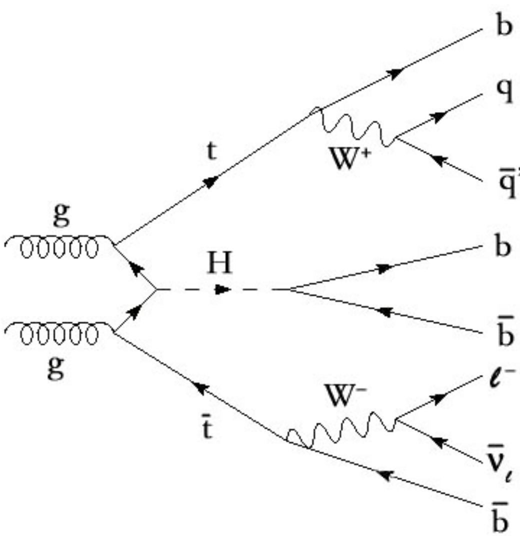


ttH production and signature

arXiv:1101.0593

- At the LHC, **σ**(ttH) known at NLO in QCD. For M_H=125 GeV:
  - √s=7 TeV: **σ**(ttH) = 86 fb
    - Uncertainties:
      - +3.3%/-9.3% (scale)
      - ±8.5% (PDF)
    - About 400 events in 2011 LHC data
  - √s=8 TeV: **σ**(ttH) = 130 fb
    - ~x1.5 wrt √s=7 TeV
  - √s=14 TeV: **σ**(ttH) = 611 fb
    - ~x7 wrt √s=7 TeV
- Most rate goes to H→bb channel
  - BR(H→bb)~0.58 for M_H=125 GeV
- Irreducible background ttbb LO σ~788 fb at √s=7 TeV but K-factor could be as large as 2 [arXiv:1001.4727]



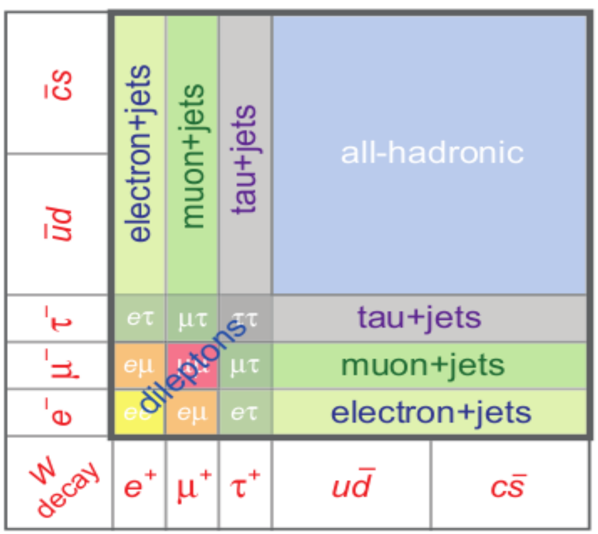


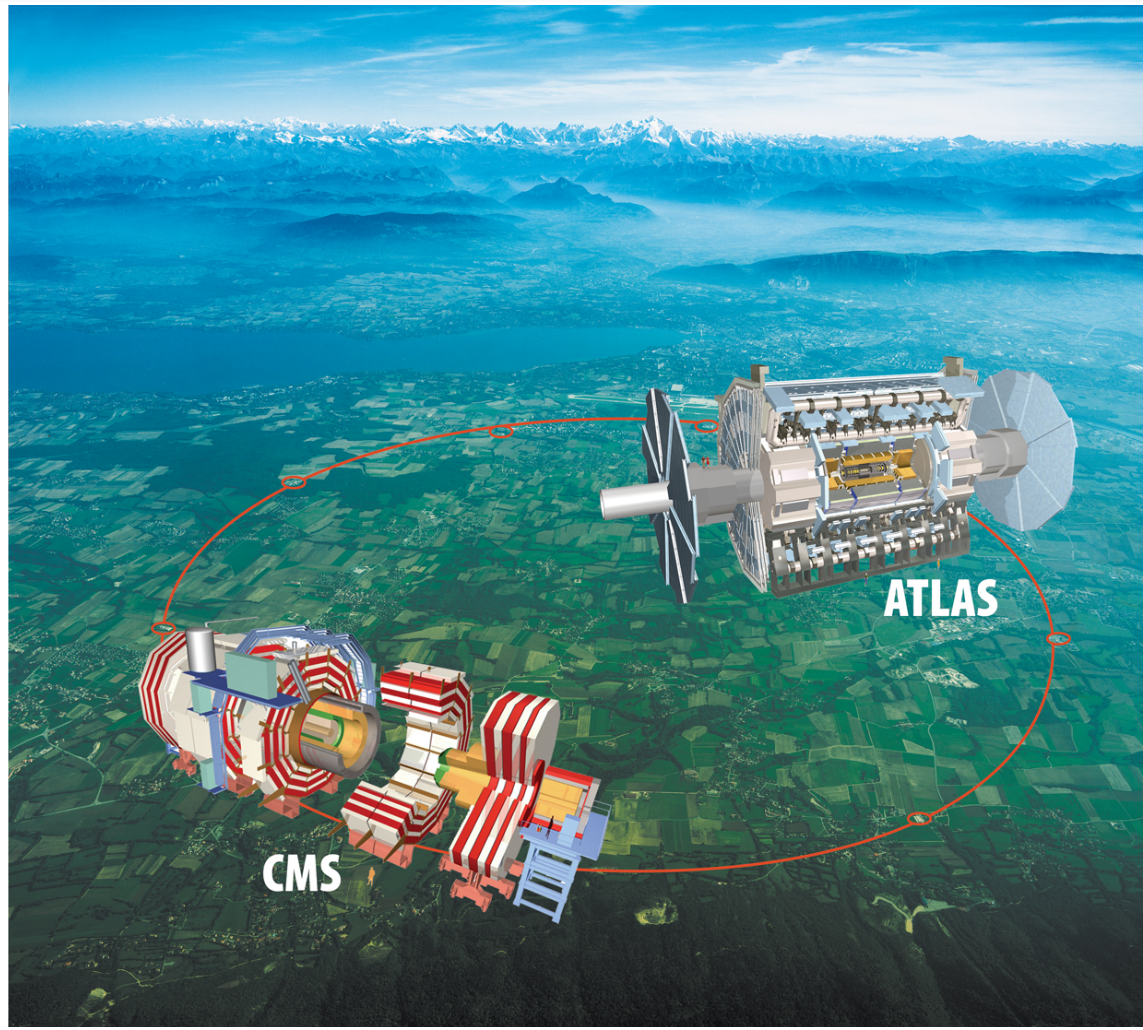
ttH@LHC

ttH(H→bb) analysis

– CMS
  - dilepton and lepton+jets final states
  - 5.0 fb-1 at 7 TeV and 5.1 at 8 TeV

– ATLAS
  - Letpon+jets only
  - 4.7 fb-1 at 7 TeV

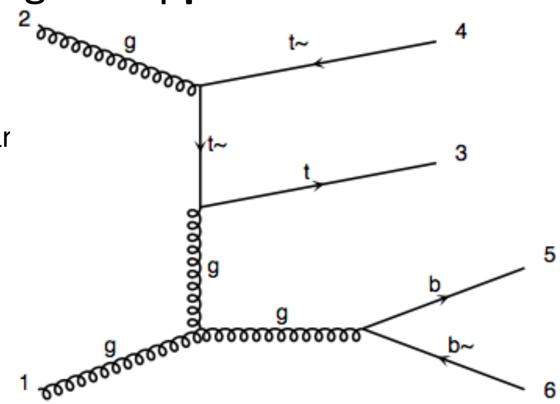


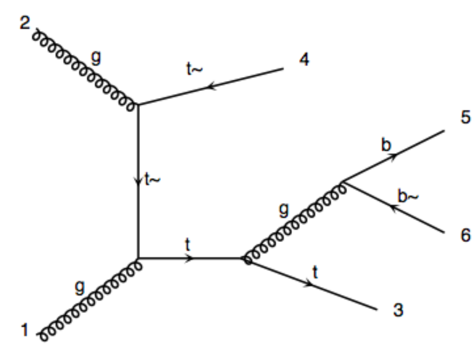


Signal and background modelling

- Signal:
  - **ttH:**
    - PYTHIA [ATLAS, CMS]: normalized to NLO cross section
- Backgrounds:
  - **tt+jets:**
    - ALPGEN+HERWIG [ATLAS]: normalized to approx NNLO cross section
      - Separate samples for tt+n light partons (n≤5), tt**b**b, and tt**c**c.
      - heavy-flavor overlap removal between ME and PS based on **Δ**R separ between heavy quarks.
    - MADGRAPH+PYTHIA [CMS]: Normalized to NLO cross section
  - **ttW, ttZ:**
    - MADGRAPH+PYTHIA [ATLAS, CMS]
  - **W/Z/γ*+jets:**
    - ALPGEN+HERWIG [ATLAS]: norm data driven
    - MADGRAPH+PYTHIA [CMS]: Normalized to NNLO
  - **Single top:**
    - MC@NLO+HERWIG/AcerMC+PYTHIA [ATLAS]
    - POWHEG+PYTHIA [CMS]: NNLO normalization
  - **Dibosons:**
    - HERWIG [ATLAS]: NLO normalization
    - POWHEG+PYTHIA [CMS]
  - **Multijets:**
    - normalization and shape data-driven [ATLAS]
    - Not considered in CMS

Challenging background: event at LO, tt**b**b has many diagrams
36 diags for g→tt**b**b,
7 diags for q**q**→tt**b**b



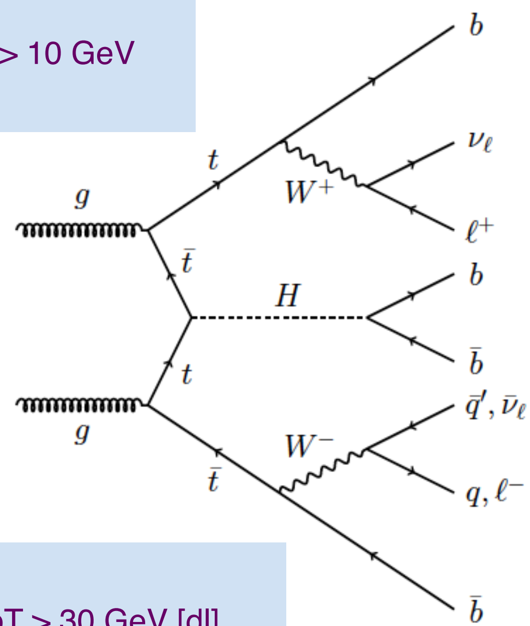


One slide on preselection

- **Electron offline selection:**
  - CMS: $|\eta| < 2.5$, tight pT > 30 GeV [l+j], 20 GeV [dl], loose pT > 10 GeV
  - ATLAS: : $|\eta| < 2.47$ pT > 25 GeV

- **Muon offline selection:**
  - CMS: tight $|\eta| < 2.1$, tight pT > 30 GeV [l+j], 20 GeV [dl], loose $|\eta| < 2.4$, pT > 10 GeV
  - ATLAS: : $|\eta| < 2.5$, tight pT > 20 GeV

- Trigger:
  - CMS
    - l+jets: μ isolated pT > 24 GeV , e pt > 24 GeV and 3 jets pT > 30 GeV (2012) e pT > 27 GeV.
      - veto on second loose lepton for lepton+jets
    - Dilepton 2 lepton pT > 17 and 8 GeV
      - dilepton 1 tight and 1 loose lepton
  - ATLAS:
    - μ pT >18 GeV and electron pT >20, 22 GeV



- **Jets**
  - CMS: ant-kt 0.5, $|\eta| < 2.4$, ≥ 3 jets pT > 40 GeV and 4 pT > 30 [l+j], , ≥ 2 jets pT > 30 GeV [dl]
  - ATLAS: ant-kt 0.4, $|\eta| < 2.5$, pT > 25

- **b-tagging**
  - CMS: working point: 70% b-jet, 20% c-jet, 2% light jets
  - ATLAS: working point: 70% b-jet, 20% c-jet, <1% light jets

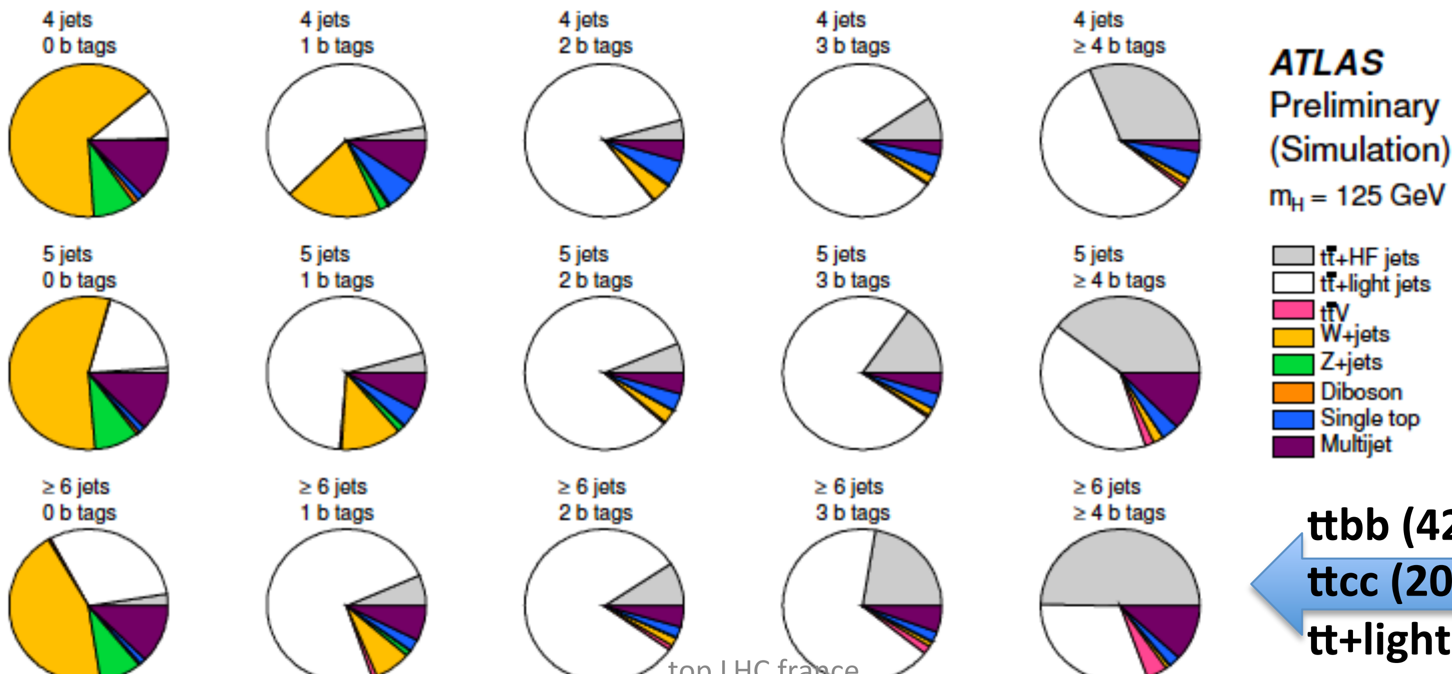
Expected Yields

ATLAS Background Region

cathegory	Signal	Bkgrd	S/√B
4 jets 0 tag	0.20	40200	0.001
4 jets 1 tag	1.1	21240	0.008
4 jets ≥ 2 tags	3.0	15040	0.02
5 jets 2 tags	2.7	6640	0.03
≥ 6 jets 2 tags	3.4	3360	0.06

ATLAS Signal Region

cathegory	Signal	Bkgrd	S/√B
5 jets 3 tags	2.3	915	0.08
5 jets ≥ 4 tags	0.74	45	0.11
≥ 6 jets 3 tags	4.0	634	0.16
≥ 6 jets ≥ 4 tags	2.2	62	0.28



ttbb (42%)
ttcc (20%)
tt+light (38%)

Expected Yields

CMS lepton+jets 7 TeV

cathegory	Signal	Bkgrd	S/√B
≥ 6 jets 2 tag	6.1	2230	0.13
4 jets 3 tag	2.7	1040	0.08
5 jets 3 tags	4.0	660	0.15
≥ 6 jets 3 tag	3.8	396	0.19
4 jets 4 b-tag	0.4	19.7	0.09
5 jets ≥ 4 b-tag	1.1	30.9	0.20
≥ 6 jets ≥ 4 b-tag	1.4	38	0.23

CMS lepton+jets 8 TeV

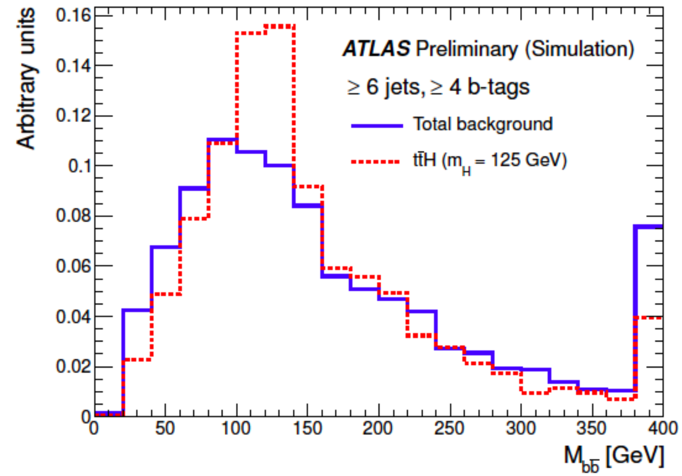
cathegory	Signal	Bkgrd	S/√B
≥ 6 jets 2 tag	11.7	3760	0.19
4 jets 3 tag	3.9	1440	0.10
5 jets 3 tags	6.1	1116	0.18
≥ 6 jets 3 tag	6.9	686	0.26
4 jets 4 b-tag	0.6	21.6	0.13
5 jets ≥ 4 b-tag	1.5	41	0.23
≥ 6 jets ≥ 4 b-tag	2.5	74	0.29

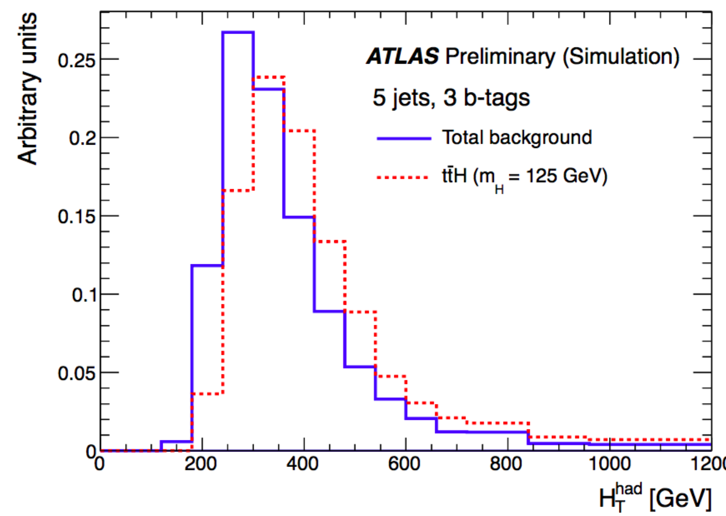
CMS dilepton 7+8 TeV

cathegory	Signal	Bkgrd	S/√B
2 jets 2 tags	0.5	4303	0.007
≥ 3 jets ≥ 3 tags	2.1	185	0.15
2 jets 2 tags	0.7	5406	0.03
≥ 3 jets ≥ 3 tags	3.3	251	0.21

Analysis strategy

- Categorize events as function of jet and b-tagged jet multiplicity
  - ATLAS:
    - For events with 6 jets or more and at least 3 b-tagged jets:
      - m_{bb} via constrained kinematic fit
      - Hadronic W resonance: $m_{jj} \sim M_W$
      - Leptonic W resonance: $m_{l\nu} \sim M_W$
      - Top quark resonances: $m_{jjb} \sim m_{l\nu b} \sim m_t$
      - m_{bb} built from the two b-jet candidates not assigned to the $t\bar{t}$ system
    - Rest of channels: $HT_{had} = \Sigma\, p_T$ jet
  - CMS:
    - Artificial neural networks are used in all categories of the analysis
    - Separated ANNs are trained for each jet-tag category
    - 24 input variables has been considered, the inputs are ranked and only 10 retained for each jet category





Analysis strategy

High combinatorial background

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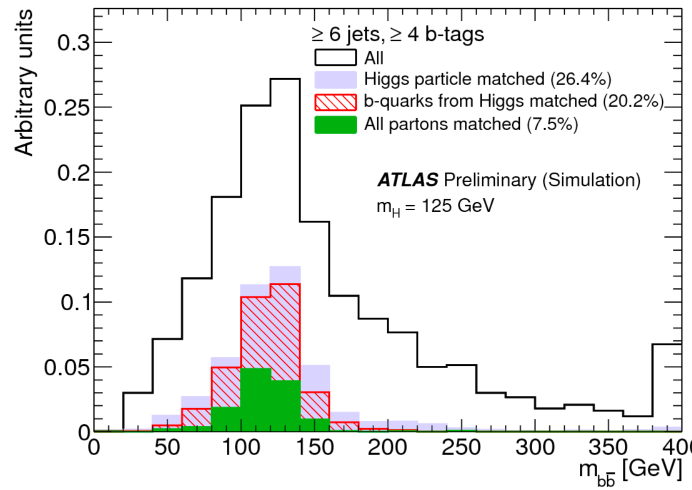

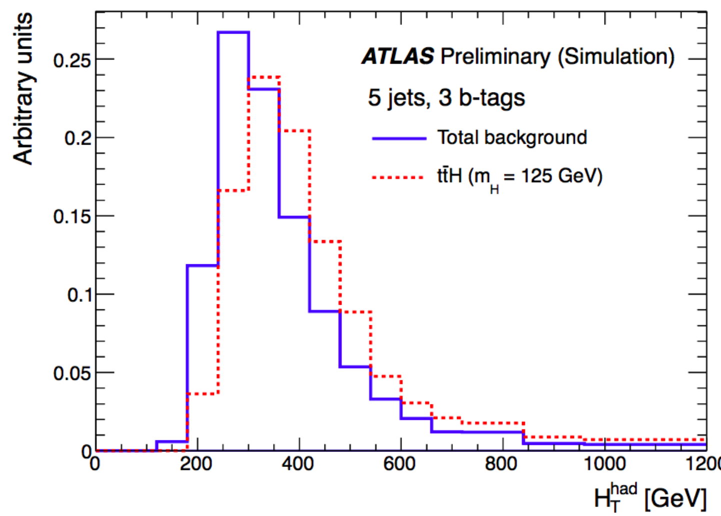

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CMS choice of variable for ANN in each jet category. Best discriminating variables are starred (★)

	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		✓	✓		✓			★	✓
Jet 2 p_T		✓	✓						
Jet 3 p_T	✓	✓	✓			✓			
Jet 4 p_T	✓	✓	✓			✓			
N_{jets}									✓
$p_T(\ell, E_T^{miss}, \text{jets})$		★	✓		✓	✓		✓	✓
$M(\ell, E_T^{miss}, \text{jets})$	✓	✓		✓	✓		✓		
Average $M((j_m^{untag}, j_n^{untag}))$	✓			✓					
$M((j_m^{tag}, j_n^{tag})_{closest})$							✓		
$M((j_m^{tag}, j_n^{tag})_{best})$							✓		
Average $\Delta R(j_m^{tag}, j_n^{tag})$				✓	✓	✓	✓		
Minimum $\Delta R(j_m^{tag}, j_n^{tag})$			✓					✓	✓
$\Delta R(\ell, j_{closest})$						✓	✓	✓	✓
Sphericity	✓			✓			✓		
Aplanarity	✓				✓				
H_0	✓								
H_1	✓				✓				
H_2				✓			✓		
H_3	★			✓			✓		
μ^{CSV}	✓	✓	★	★	★	★	★	✓	★
$(\sigma_n^{CSV})^2$		✓	✓	✓	✓	✓			
Highest CSV value						✓			
2^{nd}-highest CSV value		✓	✓	✓	✓	✓	✓		
Lowest CSV value		✓	✓	✓	✓	✓	✓		

Average b-tag weight is the best variable

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  - CMS:
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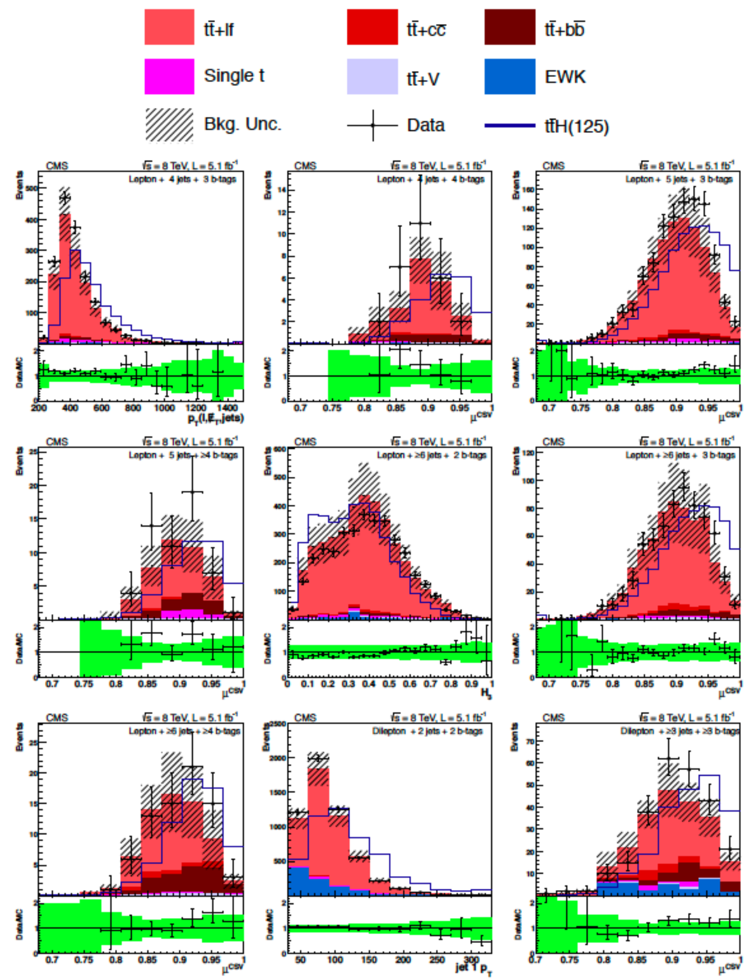
CMS best variables for each category



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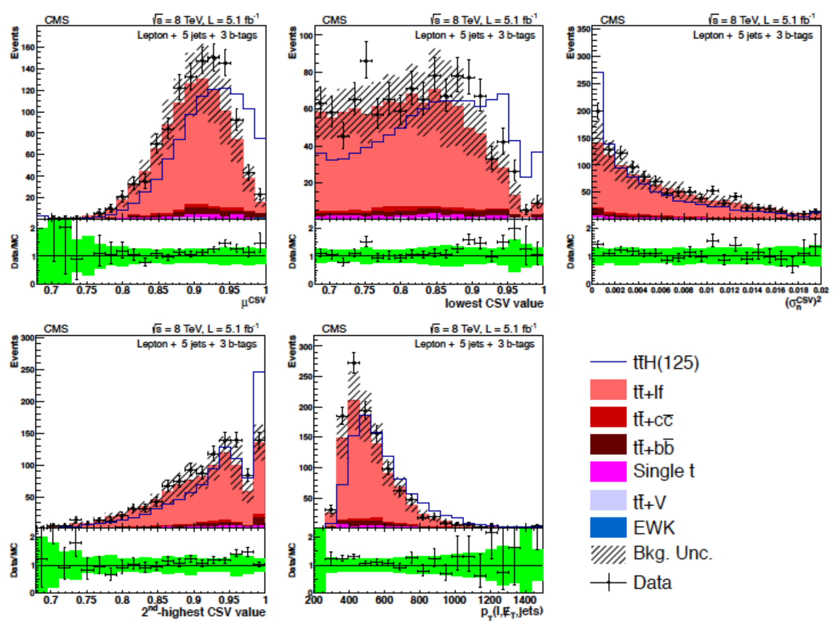
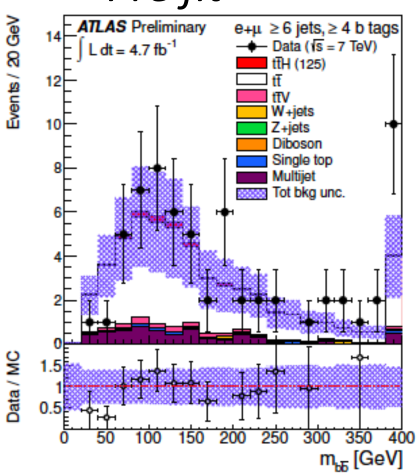
CMS best variables for the 5 jets
And 3 b-tags category



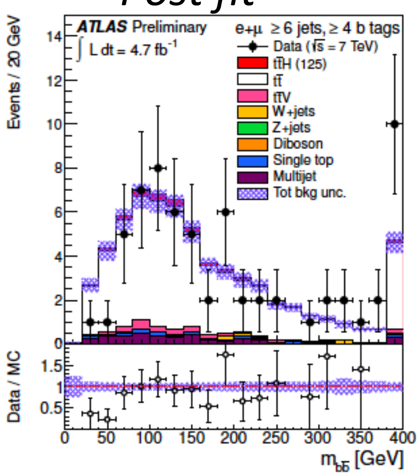
Systematic Uncertainties

- Many systematic uncertainties
  - From experiment
    - b-tagging performance
    - Jet energy scale
  - and theoretical ones:
    - Modeling of tt
    - Heavy flavor content of tt extra jets
- Can constrain some of them using nuisance parameter while extracting the limits

Pre fit



Post fit



ATLAS

	$t\bar{t}H(125)$	$t\bar{t}$
Luminosity	+1.8/-1.8	+1.8/-1.8
Lepton ID+reco+trigger	+1.3/-1.3	+1.3/-1.3
Jet vertex fraction efficiency	+2.4/-1.7	+2.5/-1.9
Jet energy scale	+9.6/-9.9	+13.5/-15.2
Jet energy resolution	+1.0/-1.0	+0.7/-0.7
b-tagging efficiency	+30.4/-34.8	+22.9/-25.2
c-tagging efficiency	+5.0/-5.0	+16.5/-17.3
Light jet-tagging efficiency	+1.3/-1.3	+11.4/-12.1
$t\bar{t}$ cross section	–	+9.9/-10.7
$t\bar{t}V$ cross section	–	–
Single top cross section	–	–
Diboson cross section	–	–
V+jets normalisation	–	–
Multijet normalisation	–	–
W+heavy-flavour fractions	–	–
$t\bar{t}$ modeling	–	+15.8/-20.2
$t\bar{t}$+heavy-flavour fractions	–	+25.9/-25.9
$t\bar{t}H$ modeling	+1.3/-1.5	–
Total	+32.5/-36.7	+46.3/-50.1

Systematic Uncertainties

CMS

Source	Rate Uncertainty	Shape	Remarks
Luminosity (7 TeV)	2.2%	No	All signal and backgrounds
Luminosity (8 TeV)	4.4%	No	All signal and backgrounds
Lepton ID/Trig	4%	No	All signal and backgrounds
Pileup	1%	No	All signal and backgrounds
Additional Pileup Corr.	–	Yes	All signal and backgrounds
Jet Energy Resolution	1.5%	No	All signal and backgrounds
Jet Energy Scale	0–60%	Yes	All signal and backgrounds
b-Tag SF (b/c)	0–33.6%	Yes	All signal and backgrounds
b-Tag SF (mistag)	0–23.5%	Yes	All signal and backgrounds
MC Statistics	–	Yes	All backgrounds
PDF (gg)	9%	No	For gg initiated processes ($t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$)
PDF ($q\bar{q}$)	4.2–7%	No	For $q\bar{q}$ initiated processes ($t\bar{t}W$, W, Z).
PDF (qg)	4.6%	No	For qg initiated processes (single top)
QCD Scale ($t\bar{t}H$)	15%	No	For NLO $t\bar{t}H$ prediction
QCD Scale ($t\bar{t}$)	2–12%	No	For NLO $t\bar{t}$ and single top predictions
QCD Scale (V)	1.2–1.3%	No	For NNLO W and Z prediction
QCD Scale (VV)	3.5%	No	For NLO diboson prediction
Madgraph Scale ($t\bar{t}$)	0–20%	Yes	$t\bar{t}$ + jets/$b\bar{b}$/$c\bar{c}$ uncorrelated. Varies by jet bin.
Madgraph Scale (V)	20–60%	No	Varies by jet bin.
$t\bar{t} + b\bar{b}$	50%	No	Only $t\bar{t} + b\bar{b}$.

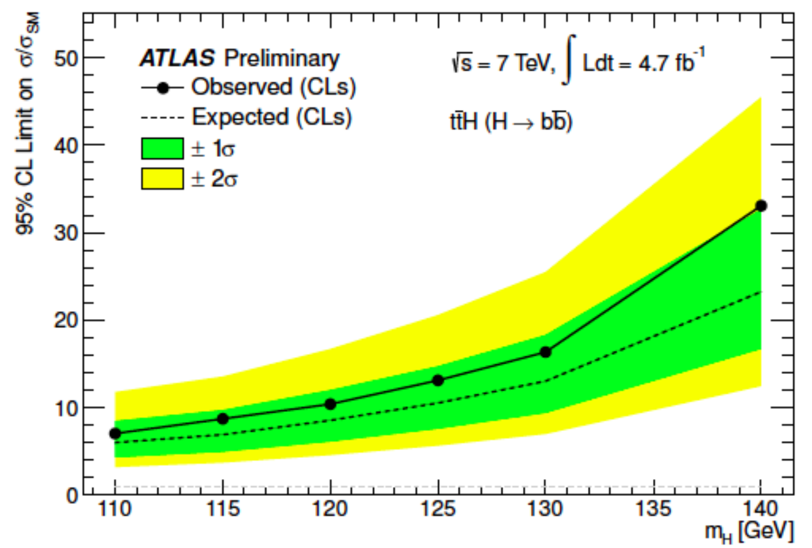
ATLAS

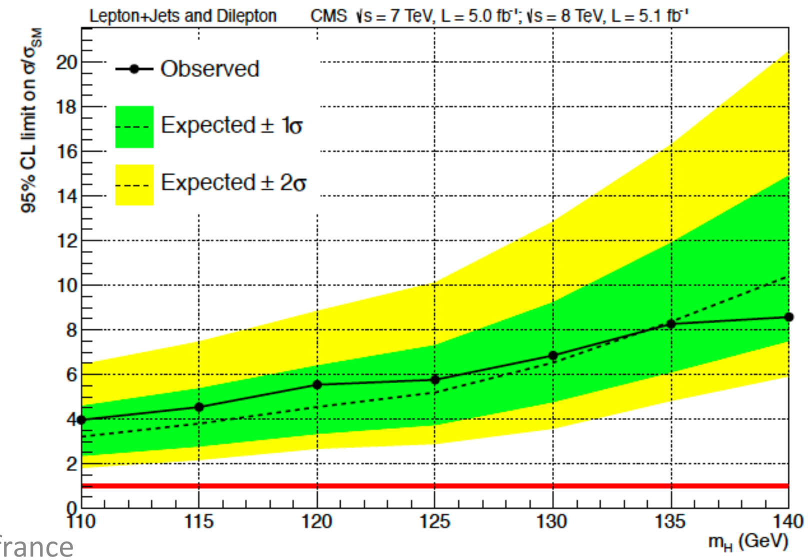
	$t\bar{t}H(125)$	$t\bar{t}$
Luminosity	+1.8/-1.8	+1.8/-1.8
Lepton ID+reco+trigger	+1.3/-1.3	+1.3/-1.3
Jet vertex fraction efficiency	+2.4/-1.7	+2.5/-1.9
Jet energy scale	+9.6/-9.9	+13.5/-15.2
Jet energy resolution	+1.0/-1.0	+0.7/-0.7
b-tagging efficiency	+30.4/-34.8	+22.9/-25.2
c-tagging efficiency	+5.0/-5.0	+16.5/-17.3
Light jet-tagging efficiency	+1.3/-1.3	+11.4/-12.1
$t\bar{t}$ cross section	–	+9.9/-10.7
$t\bar{t}V$ cross section	–	–
Single top cross section	–	–
Diboson cross section	–	–
V+jets normalisation	–	–
Multijet normalisation	–	–
W+heavy-flavour fractions	–	–
$t\bar{t}$ modeling	–	+15.8/-20.2
$t\bar{t}$+heavy-flavour fractions	–	+25.9/-25.9
$t\bar{t}H$ modeling	+1.3/-1.5	–
Total	+32.5/-36.7	+46.3/-50.1

- Both experiments suffer from
  - b-tagging
  - JES uncertainty
  - heavy flavor content in tt+jets
- Both experiments use systematic uncertainties as nuisance parameters to fit background shape, normalization or both

results

- Observed (expected) limit @ MH=125 GeV:
  - ATLAS 13.1xSM (10.5xSM)
    - Effect of systematic uncertainties is to degrade expected limit/SM by 72%
  - CMS results 5.8xSM (5.2xSM)
    - Larger dataset
    - Multi Variate Analysis
    - Dilepton channel added (5-10% more sensitivity)

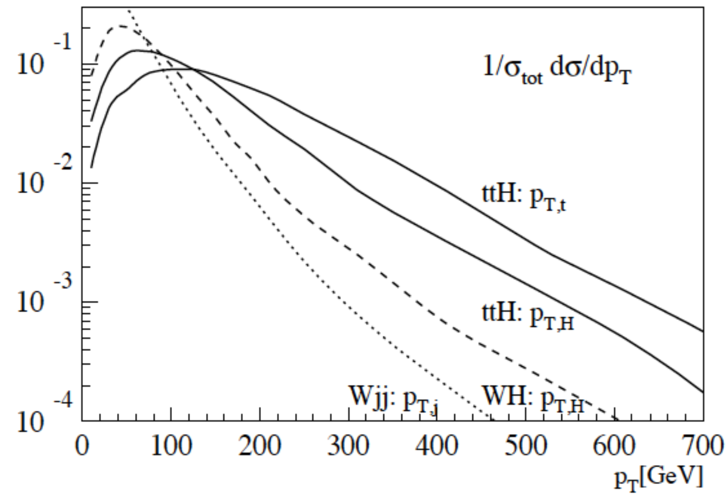




New energy frontier: boosted analysis

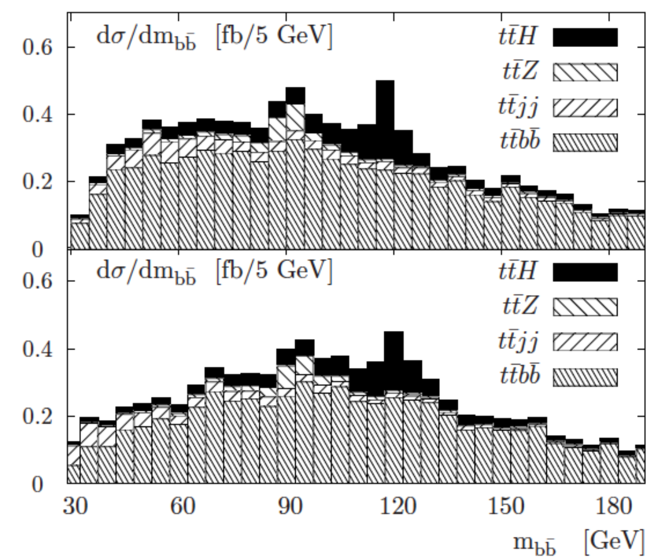
arXiv:1101.0593

- Boosted analysis analysis possible at 14 TeV
  - Top and Higgs carry sizeable momentum
- Selecting events with at least two high pT Cambridge/Aachen (C/A) jets with R=1.5
  - One high pT lepton for trigger
  - pT>200 GeV $|y^H|<2.5$
- Top tagger:
  - Look at dijet mass in the substructure compatible with W
  - Trijet compatible with top mass
- Higgs Tagger:
  - Order all pairs by modified Jade distance
  - Ask for two subjets to be b-tagged
- Third b-tagged jets away from the Higgs candidate



Sensistivity for 100 fb^{-1}

	S	B	S/B	$S/\sqrt{B}$
m_H = 115 GeV	120	380	1/3.2	6.2
120 GeV	100	380	1/3.8	5.1
130 GeV	51	330	1/6.5	2.8



Summary

- ATLAS CMS performed analysis using 2011 and partially 2012 dataset (CMS):
  - ATLAS observed (expected) limit @ MH=125 GeV 13.1xSM (10.5xSM)
  - CMS observed (expected) limit @ MH=125 GeV 5.8xSM (5.2xSM)
- Updates are foreseen with full datasets, MVA, more final states
- For 2015 after LS1 data taking analysers need to consider new conditions for trigger strategies since the lepton pT threshold will increase
  - lepton+jets, b-jet trigger
- Monte Carlo modeling will play a big role since analysis rely on profile likelihood to decrease the impact of systematics uncertainties
  - Usually constrained in high statistics background dominated regions
- Boosted regime could be an option for high luminosity