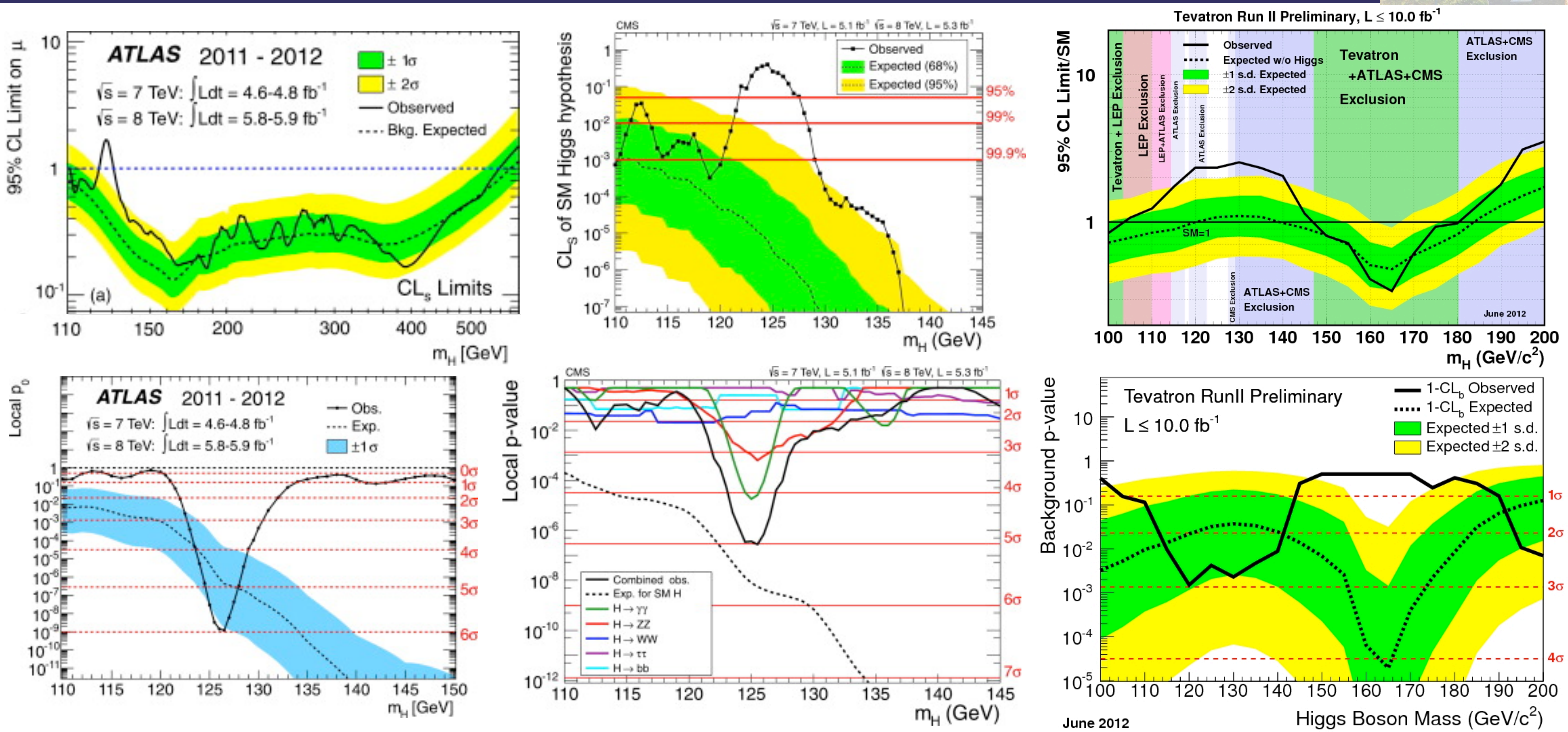
Measurements of the Interplay between the Top quark and the Higgs boson at Tevatron and LHC

21st September 2012

Sarah Boutle
University of Virginia
On behalf of the ATLAS, CDF, CMS and D0 collaborations

Higgs News

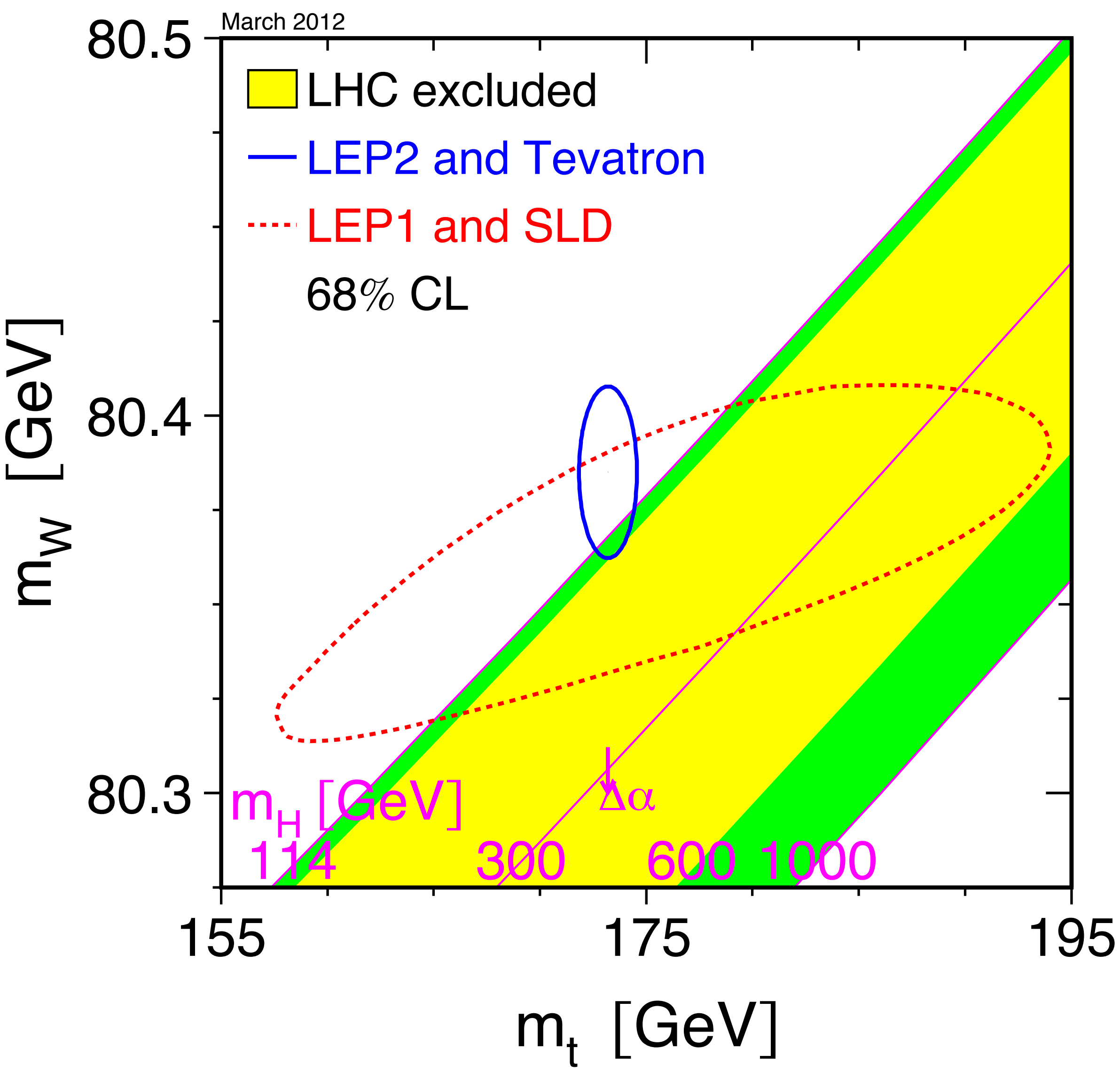


- Higgs-like boson with M~125 GeV observed in several channels at several experiments
- CMS, ATLAS: > 5σ when considering γγ, ZZ, WW; see larger excess than SM expectation in these channels
- Same excess not yet seen in fermionic channels but still accommodate SM-Higgs expectation
- CDF, D0: combining bb channels searches, 2.9σ excess is observed over mass range of 115-135 GeV.

What we know: there is something! **Big question: What is it?**

Top-Higgs Interplay

- **Top quark may play a significant role in understanding EWSB**
  - Large mass means large coupling to SM Higgs
    - Top Yukawa coupling to Higgs predicted ~1
  - Role evident from M_W-M_t constraints on M_H
  - Top quark could play a role in EWSB beyond that of the Higgs mechanism of the SM



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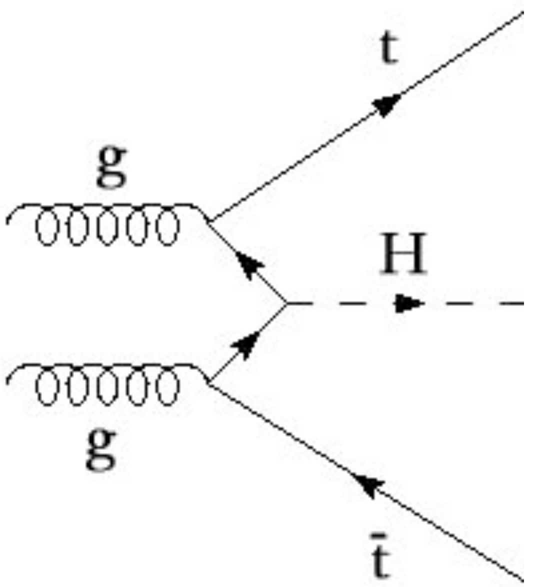
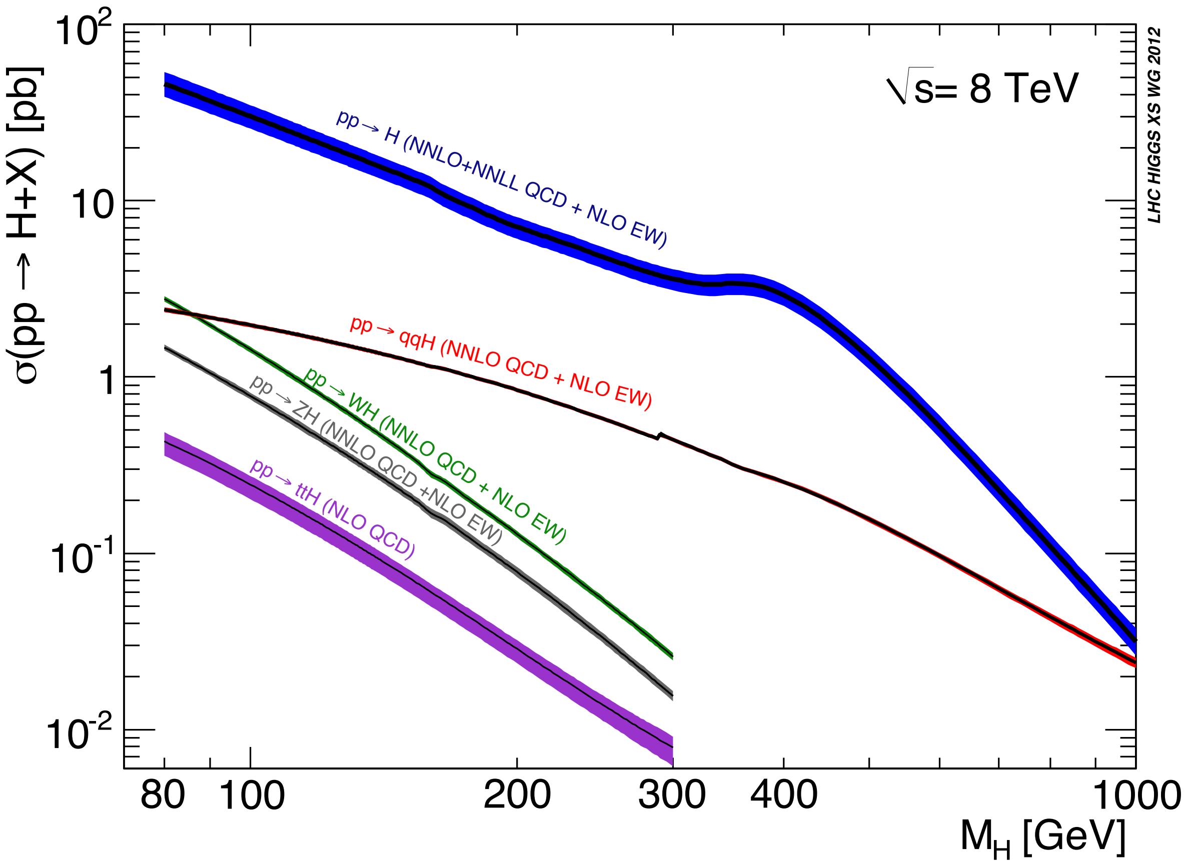


- **Top quark is essential for characterizing this new boson**
    - If it is the SM Higgs: need to see fermionic couplings
    - Fermionic couplings are among the least understood aspects of this new boson: accessible through ttH production
    - ttH: only production mode directly sensitive to top-Higgs Yukawa coupling: cross section proportional to coupling^2
    - Can access ttH, H→anything given enough lumi
    - Foremost is ttH, H→bb



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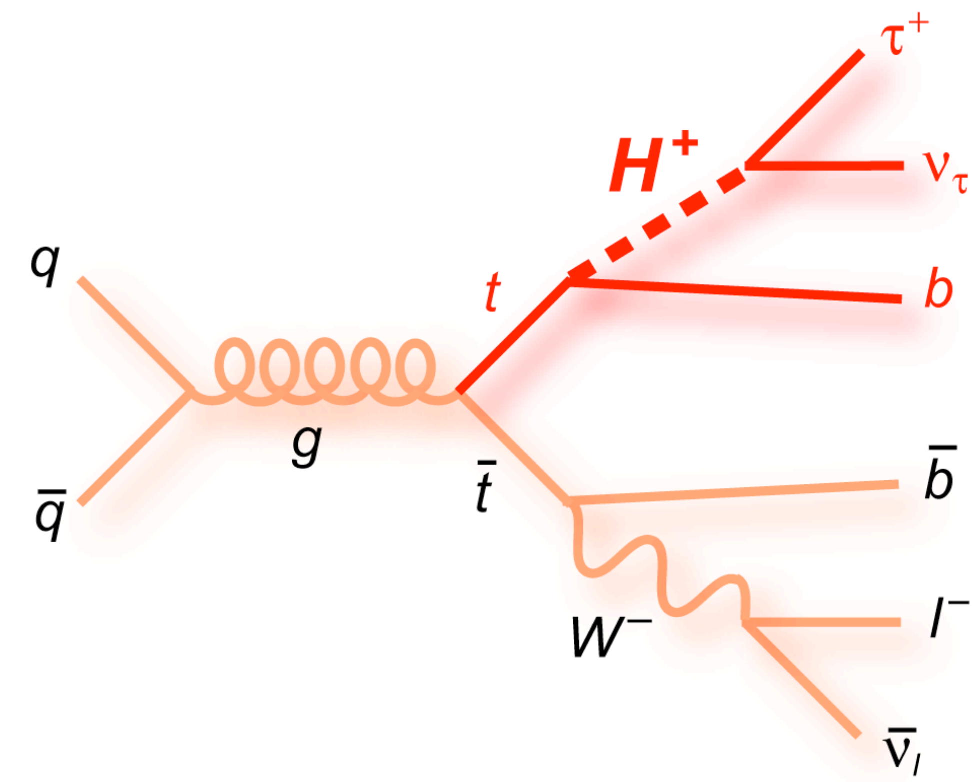
- **Sensitivity to non-SM Higgs as well, eg. $t \to H^{\pm}b$**



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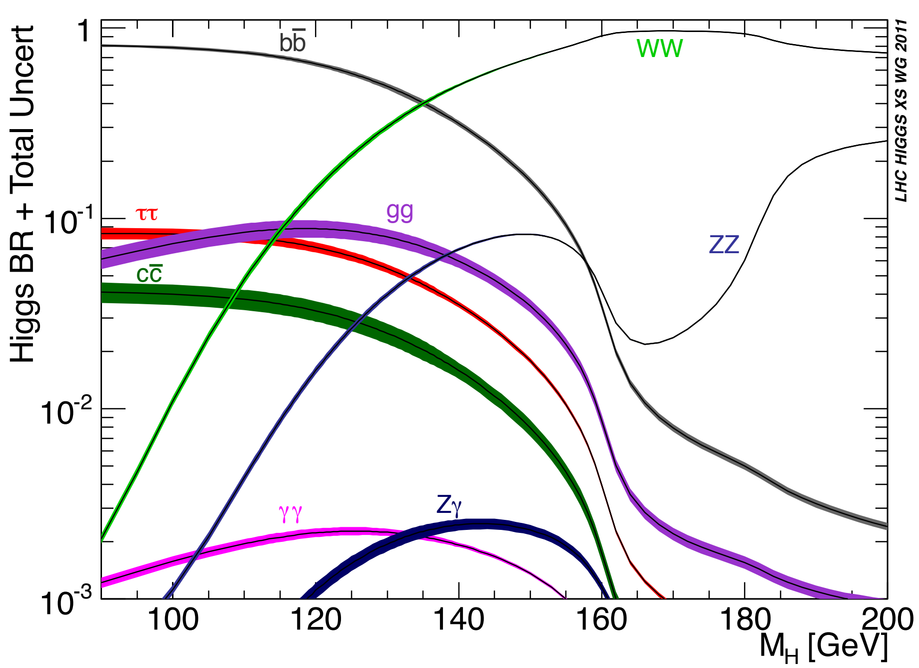
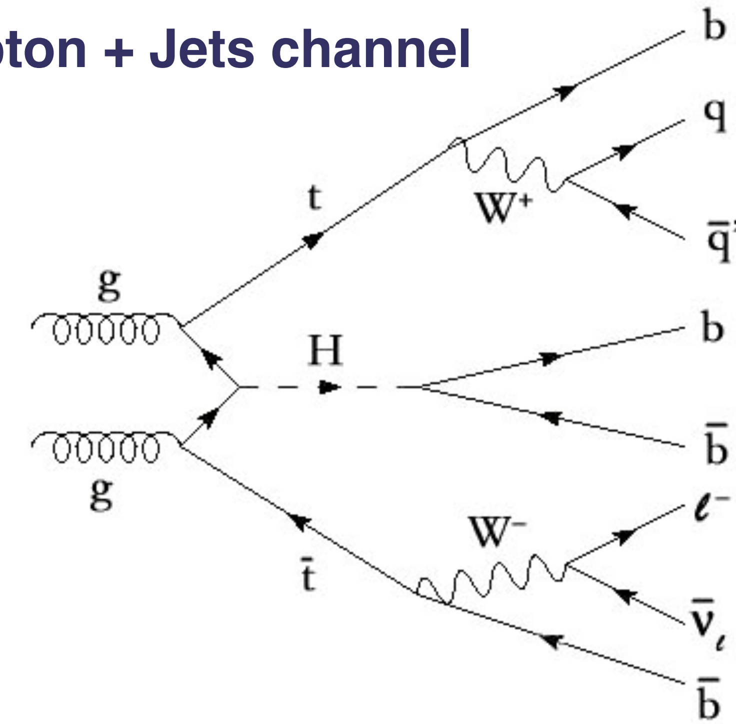
Direct Searches for ttH Production

- **Virtues**
  - Access to all Higgs decay modes
    - Focus initially on bb
  - Rich, characteristic signature
    - Top quarks are quite distinctive
  - Heavy recoil system against Higgs: “simple” final state

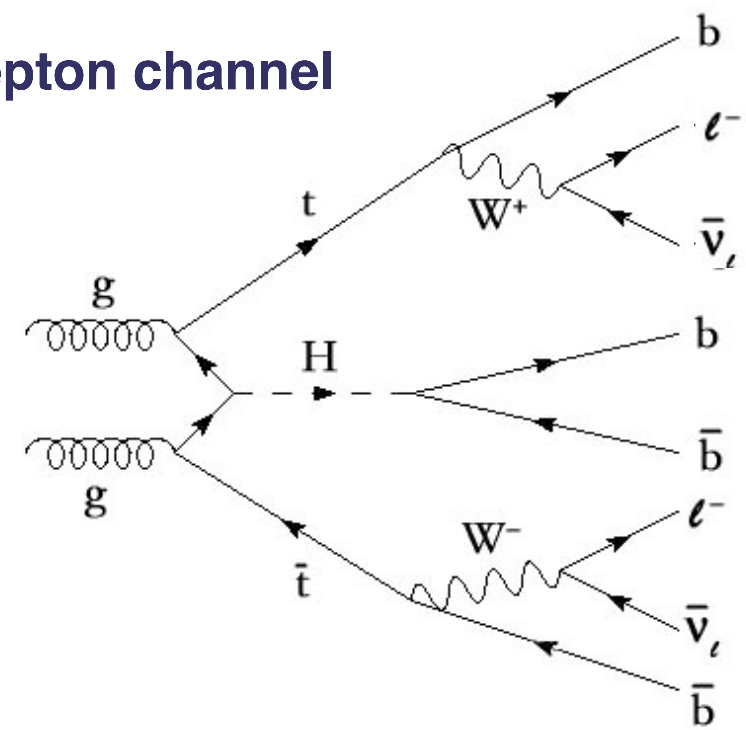
- **Challenges**
  - Need to measure background from tt+X production
  - Low production cross section
  - Very busy events
  - Heavy recoil system against Higgs: hard to distinguish



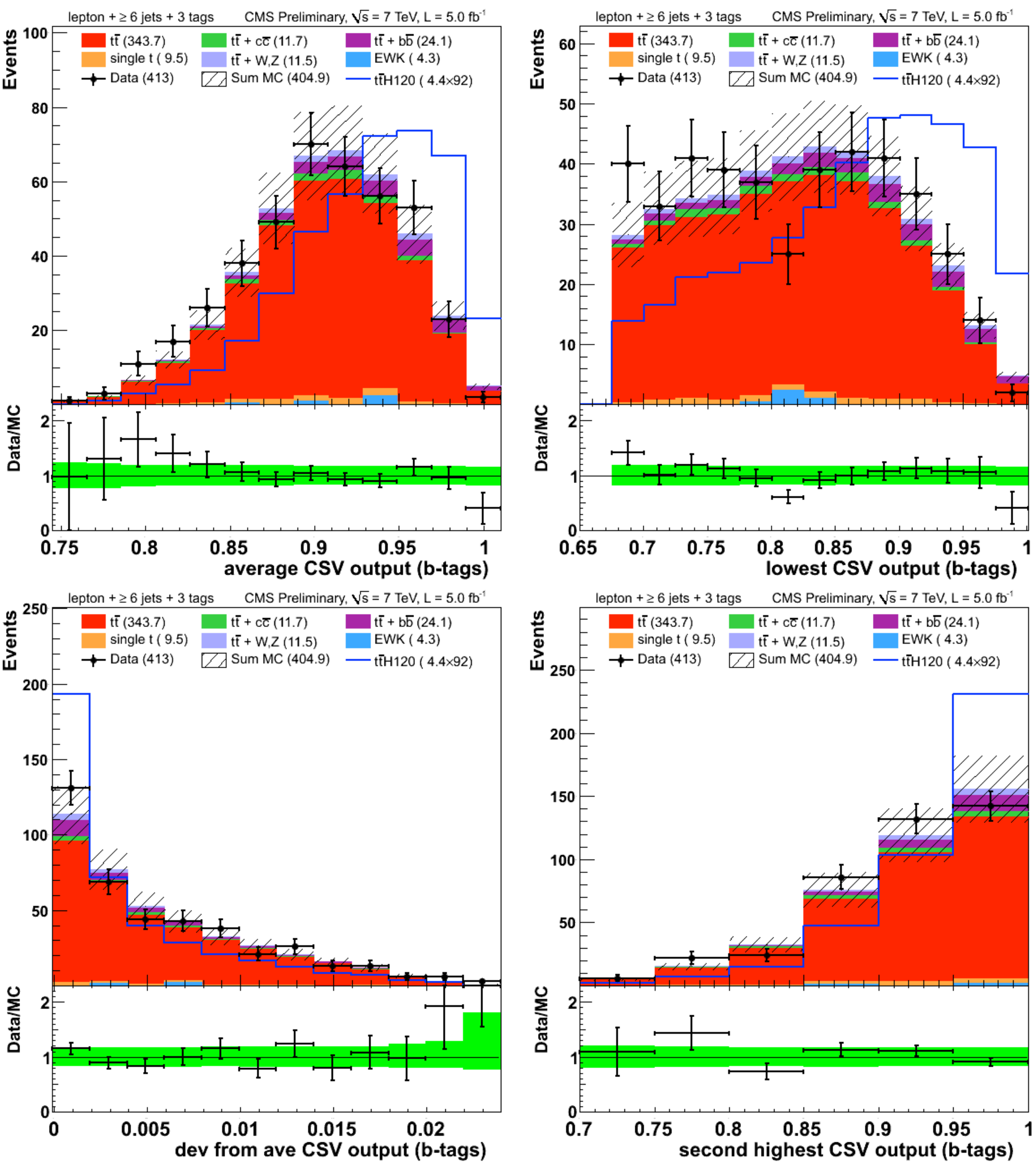
Lepton + Jets channel



Dilepton channel



CMS ttH Search



“Before Fit” normalizations and errors

- **Start from tt-enriched sample:**
  - [Lepton plus jets] 1 isolated lepton (30 GeV), at least 3 jets (40GeV) plus 1 jet (30GeV) and 2 b-tags
- **Divide into 7 categories:**
  - 4 jets (3, ≥ 4 tags)
  - 5 jets (3, ≥ 4 tags)
  - 6 jets (2, 3, ≥ 4 tags)

5 fb^{-1}
7TeV data

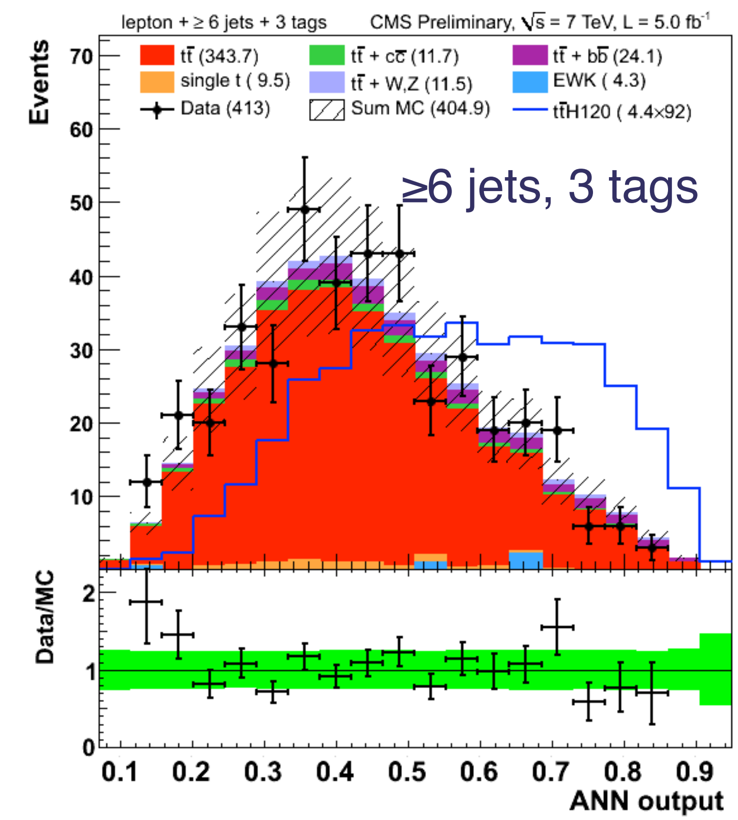
- **Main backgrounds:**
  - tt+jets (MADGRAPH+PYTHIA)
  - ttW, ttZ (MADGRAPH+PYTHIA)
  - W+jets, Drell-Yan (MADGRAPH+PYTHIA)
  - single-t (POWHEG+PYTHIA)
  - diboson (PYTHIA)
- **Signal:** ttH with H→anything (PYTHIA)
- **Train ANN:** 10 variables depending on category (eg. 6j3t)

av. b-tag disc. value for tag jets
lowest CSV (tags)
sum of devs from av. CSV (tags)
second highest CSV (tags)
av. ΔR for all tagged jet pairs
h3
sphericity
av. mjj for all untagged jet pairs
h2
mass (lepton, jet, MET)

CMS ttH Search

Expected event yields in each Lepton plus jets category in 5 fb^{-1}

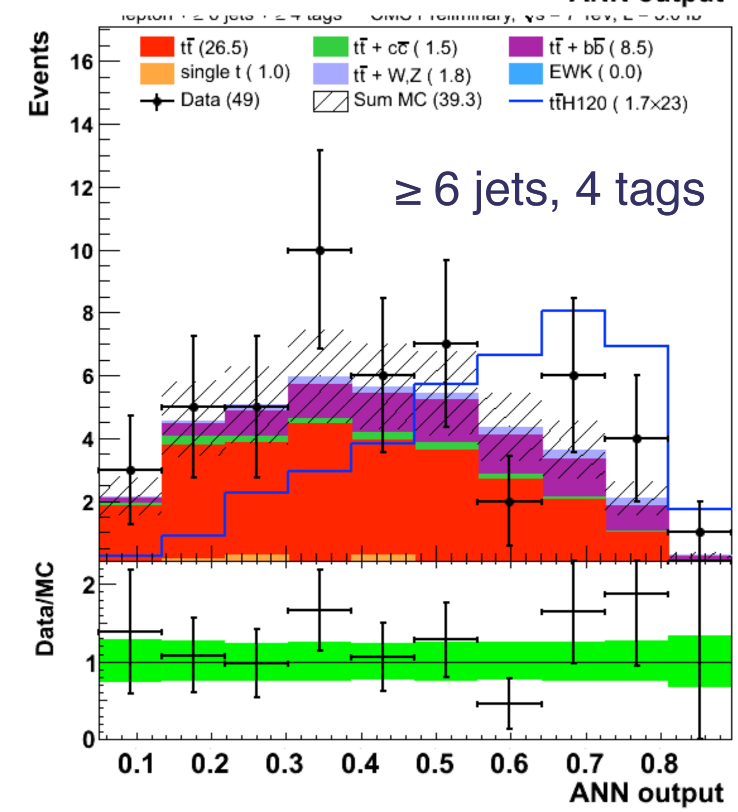
Category	signal (M=120) H→anything	background	S/√B
≥ 6 jets, 2 tags	6.3	2255.8	0.13
4 jets, 3 tags	3.5	1041.6	0.11
5 jets, 3 tags	4.7	666.7	0.18
≥ 6 jets, 3 tags	4.4	404.9	0.22
4 jets, ≥ 4 tags	0.5	20.0	0.11
5 jets, ≥ 4 tags	1.2	31.8	0.21
≥ 6 jets, ≥ 4 tags	1.7	39.3	0.27



- **Included also, the dilepton channel**
  - μμ, ee, eμ channels
  - Require 1 tight muon/electron (20 GeV) and 1 loose muon/electron (10,15 GeV), at least 2 jets (30GeV) and 2 b-tags

Expected event yields in each Dilepton category in 5 fb^{-1}

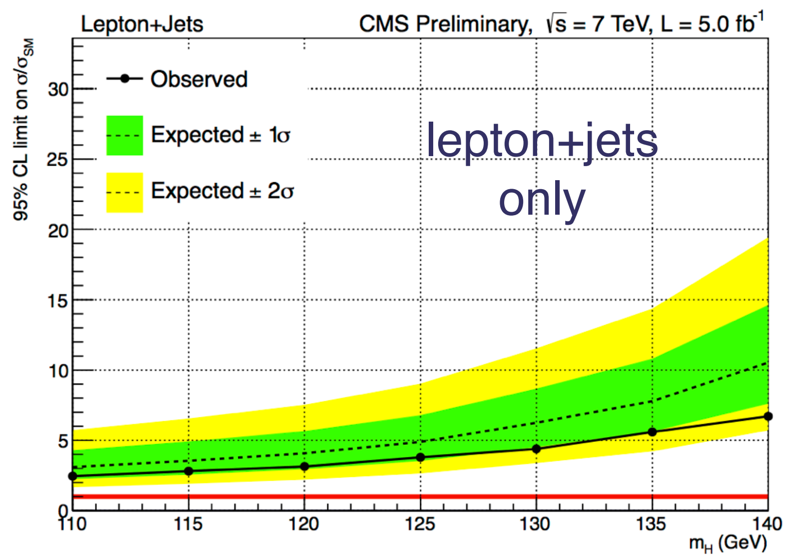
Category	signal (M=120) H→anything	background	S/√B
2 jets, 2 tags	0.7	4306.0	0.01
≥ 3 jets, ≥ 3 tags	2.9	167.6	0.22

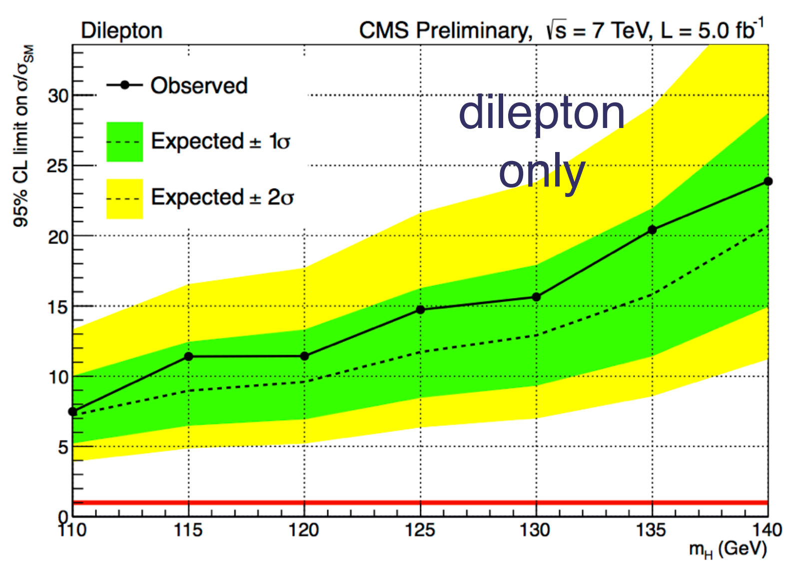


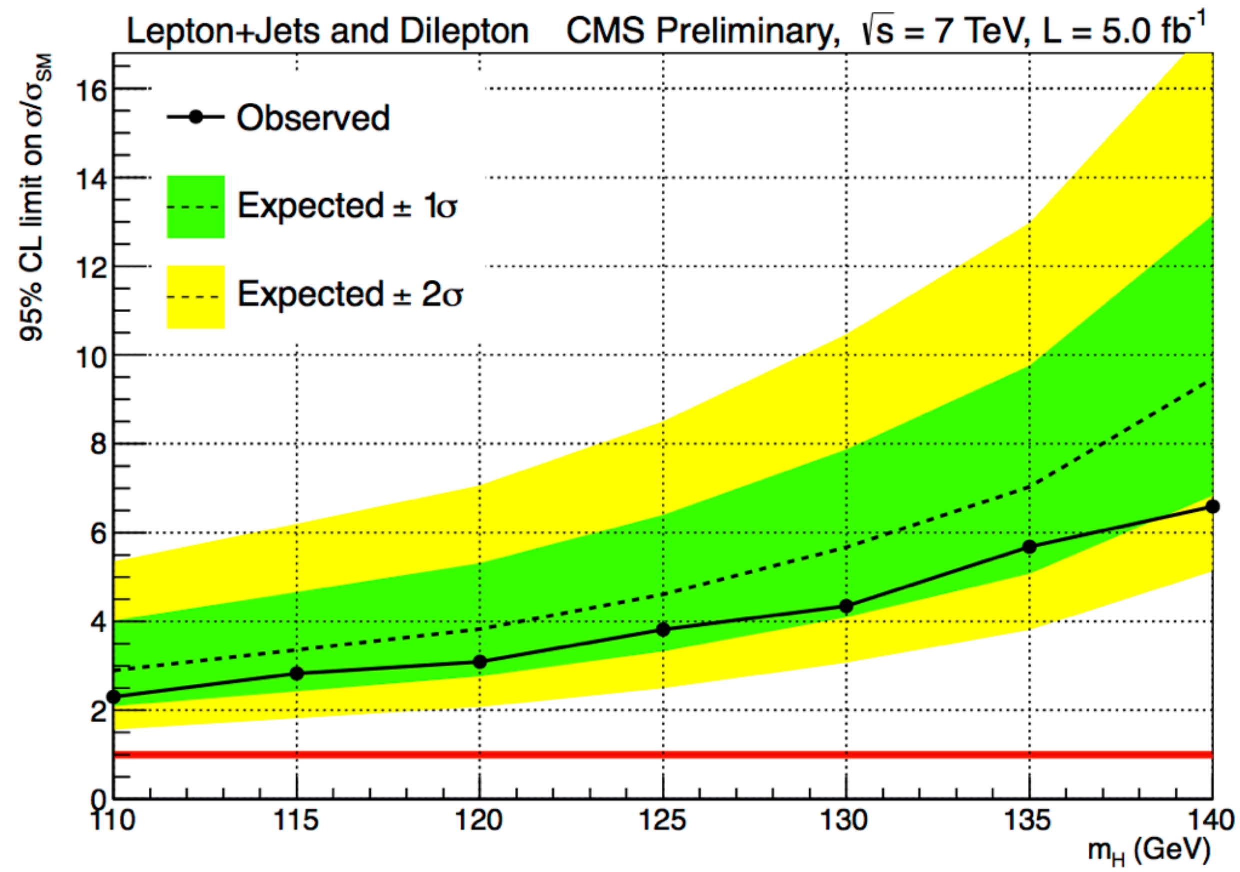
CMS ttH Search

At Higg's mass 125 GeV

- expect to set a limit of 4.6 x σ_{SM}
- observed upper limit: 3.8 x σ_{SM}







Source	Rate	Shape?	Notes
Luminosity	2.2%	No	All signal and backgrounds
Lepton ID/Trig	1.8%	No	All signal and backgrounds
Pileup	1%	No	All signal and backgrounds
Jet Energy Resolution	1.5%	No	All signal and backgrounds
Jet Energy Scale	0-66%	Yes	All signal and backgrounds
QCD Scale ($t\bar{t}H$)	12.5%	No	Scale uncertainty for NLO $t\bar{t}H$ prediction
QCD Scale ($t\bar{t}$)	2-12%	No	Scale uncertainty for NLO $t\bar{t}$, $t\bar{t}V$, and single top predictions
QCD Scale (V)	1.2-1.3%	No	Scale uncertainty for NNLO W and Z prediction
QCD Scale (VV)	3.5%	No	Scale uncertainty for NLO diboson prediction
pdf (gg)	9%	No	Pdf uncertainty for gg initiated processes ($t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$)
pdf ($q\bar{q}$)	4.2-7%	No	Pdf uncertainty for $q\bar{q}$ initiated processes ($t\bar{t}V$, W, Z)
pdf (qg)	4.6%	No	Pdf uncertainty for qg initiated processes (single top)
Factorization scale ($t\bar{t}$)	0-20%	Yes	Uncorrelated between $t\bar{t}$+jets/$b\bar{b}$/$c\bar{c}$; varies by jet bin
Factorization scale (V)	20-60%	No	Varies by jet bin
b-Tag SF (b/c)	0-15.2%	Yes	All signal and backgrounds
b-Tag SF (mistag)	0-10.6%	Yes	All signal and backgrounds

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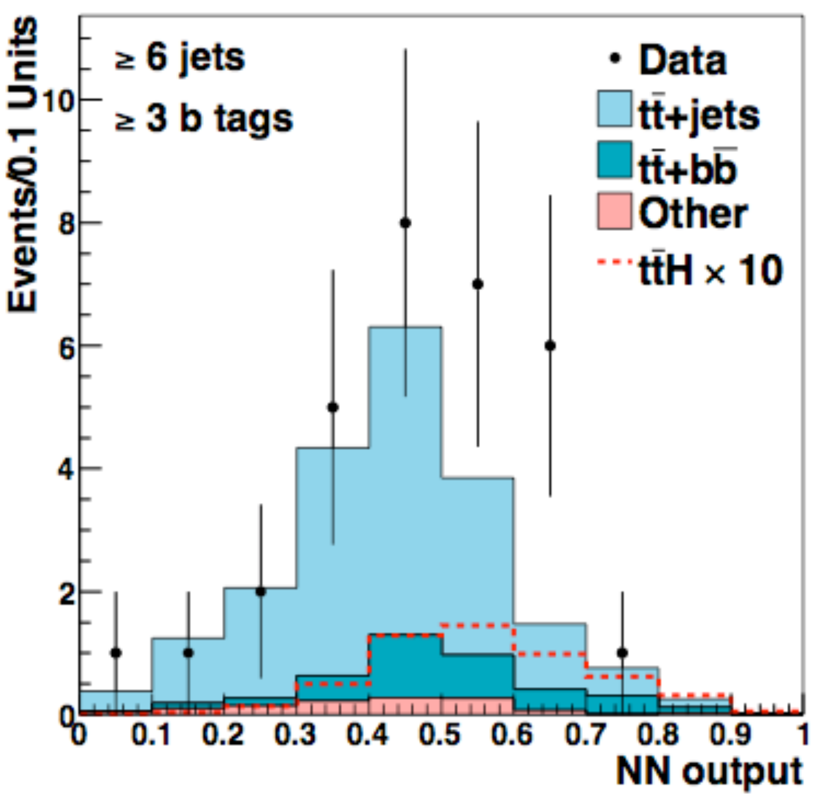
CDF ttH Search

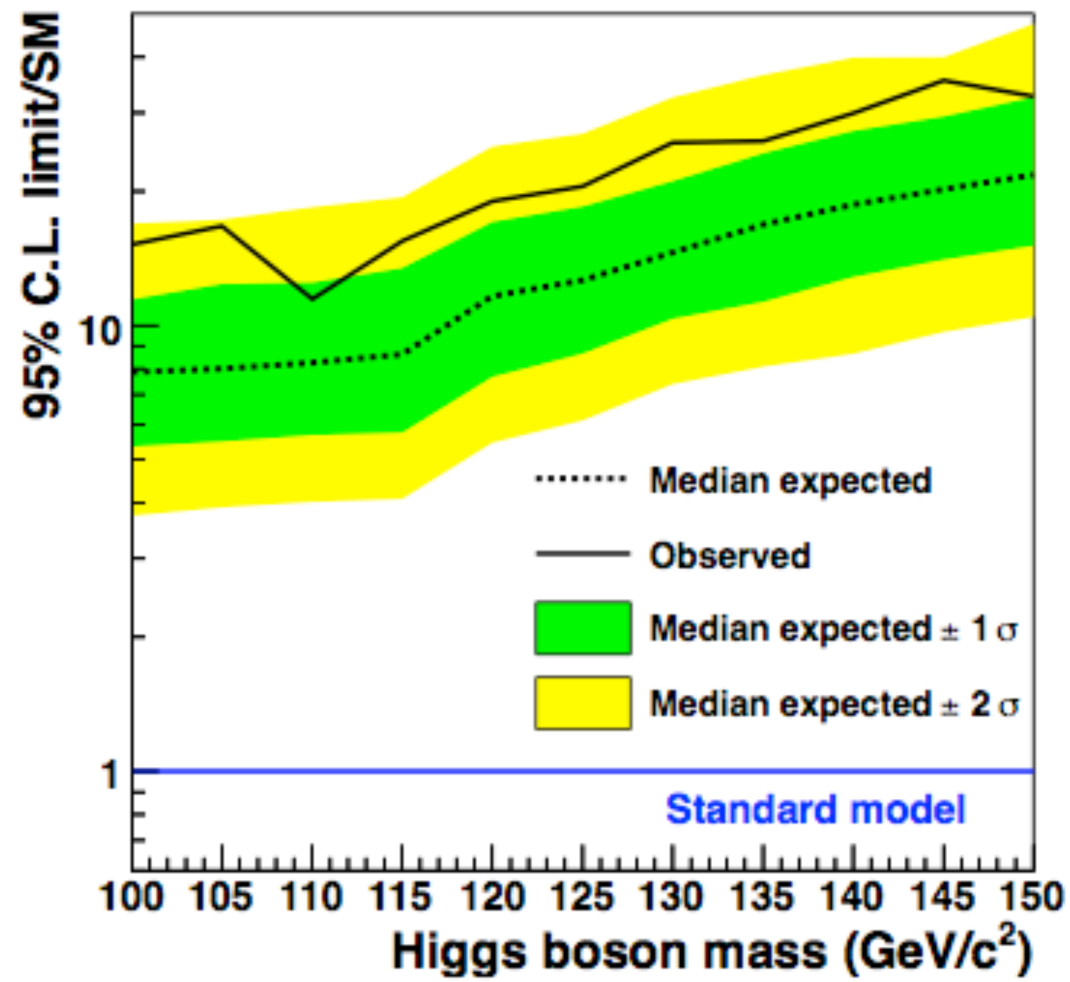
- **Also took the MVA approach**
- **Start from tt-enriched sample:**
  - [Lepton plus jets] 1 lepton (20 GeV), at least 4 jets (20GeV) and 2 b-tags, MET
- **Divide into categories:**
  - 4 jets (2, ≥ 3 tags)
  - 5 jets (2, ≥ 3 tags)
  - ≥ 6 jets (2, ≥ 3 tags)
- **Train NN to discriminate ttH from tt using 18 inputs, including:**
  - Dijet mass of leading untagged jets
  - HT, lead jet ET, MET
  - Minimum DR between b jet....

9.45 fb^{-1}
1.96 TeV data

At Higg's mass 125 GeV
- expect to set a limit of 12.6 x σ_{SM}
- observed upper limit: 20.5 x σ_{SM}



Most sensitive category:
≥ 6 jets ≥ 3 tags

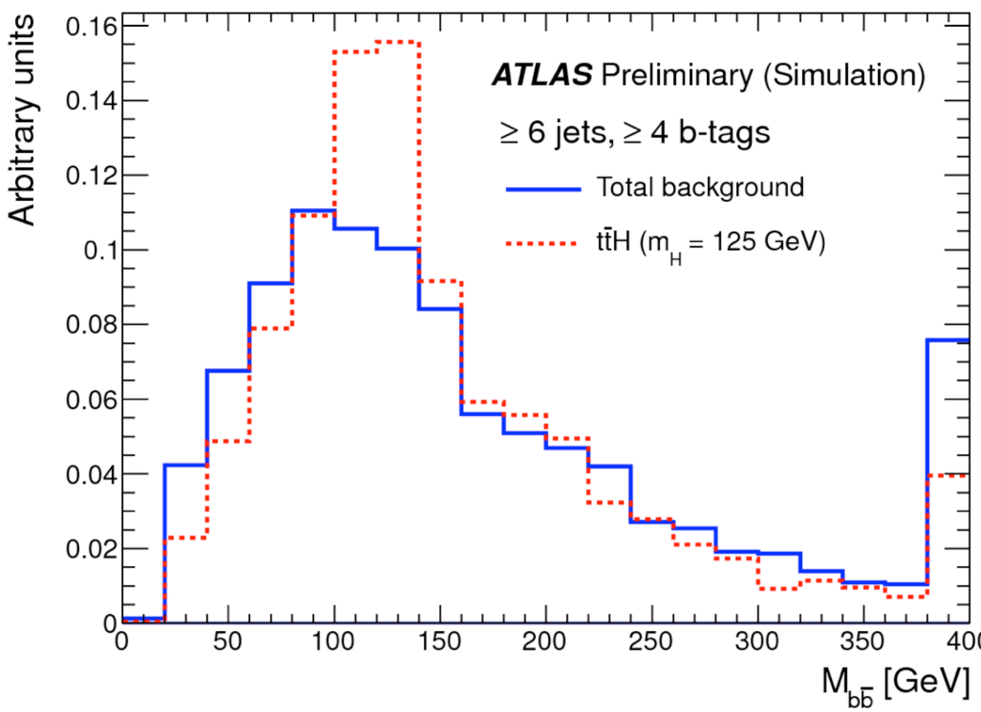


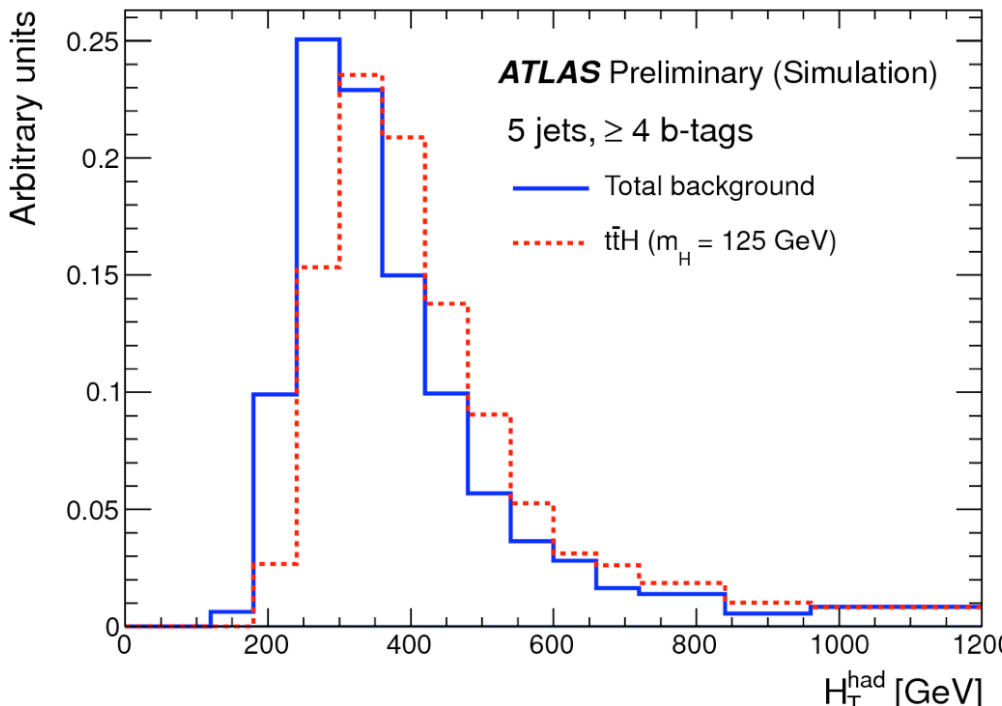
ATLAS ttH search

- **Event selection:**
  - [Lepton plus jets] 1 isolated electron/muon (25/20 GeV), at least 4 jets (25GeV), MET and MT cuts for QCD bkg removal
- **Divide into 9 categories:**

Signal region categories	Background dominated categories
• 5 jets (3, ≥ 4 tags) • ≥ 6 jets (3, ≥ 4 tags)	• 4 jets (0,1,≥ 2 tags) • 5 jets (2 tags) • ≥ 6 jets (2 tags)

- **Main backgrounds:**
  - tt+jets (ALPGEN+HERWIG)
  - ttW, ttZ (MADGRAPH+PYTHIA)
  - Drell-Yan (ALPGEN+HERWIG)
  - W+jets normalization: data-derived, shape: (ALPGEN+HERWIG)
  - single-t (MC@NLO+HERWIG/AcerMC+PYTHIA)
  - diboson (HERWIG)
  - Multijet: Data-derived model
- **Signal:** ttH with H→bb (PYTHIA)
- **Employ two discriminanting variables:**
  - In ≥ 6 jet events, use kinematic fit to reconstruct tt system from selected object. Reconstruct m_{bb} with remaining jets.
  - In all other categories, use H_T (scalar sum of jet p_Ts)





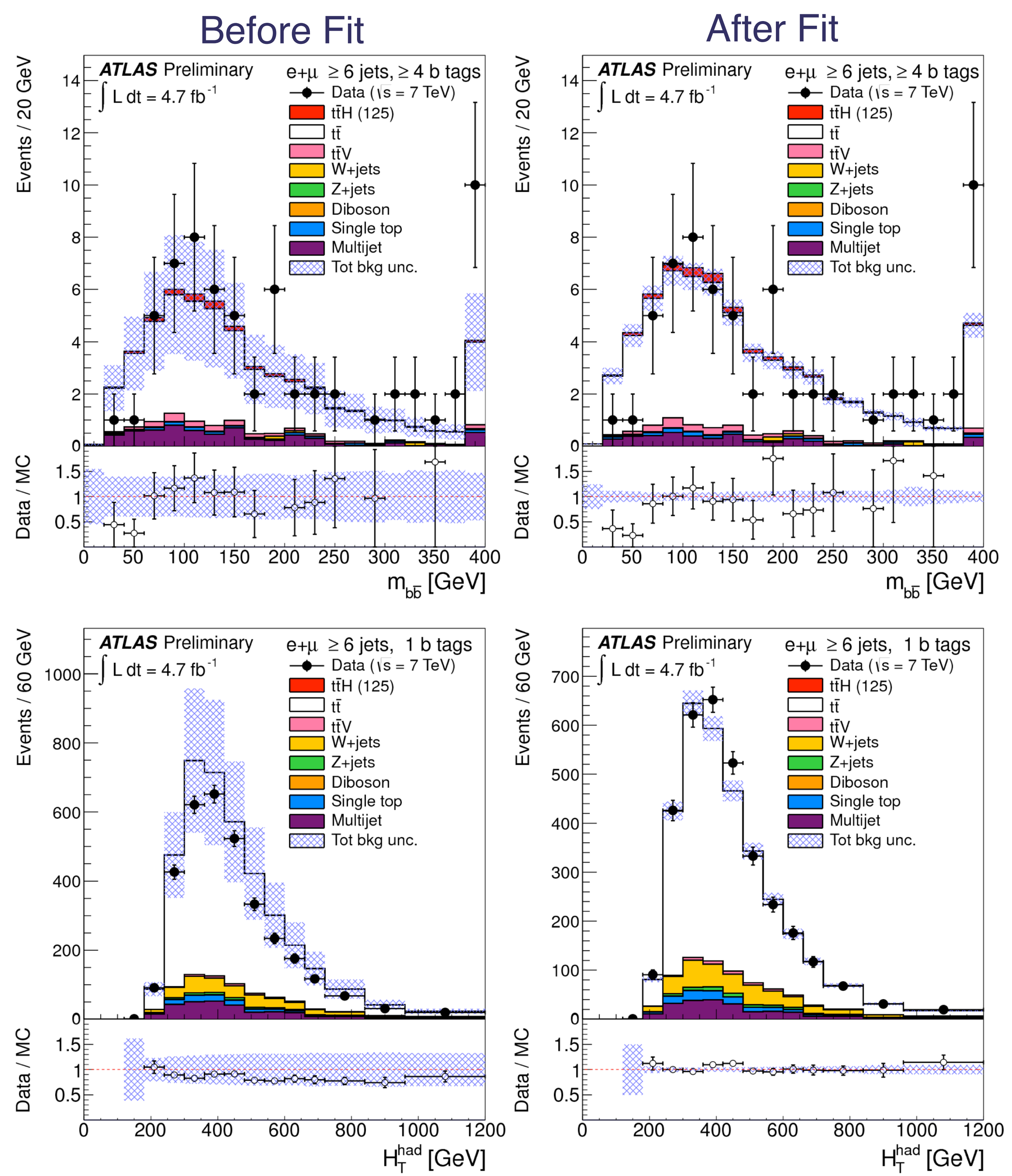
4.7 fb^{-1}
7TeV data

ATLAS ttH search

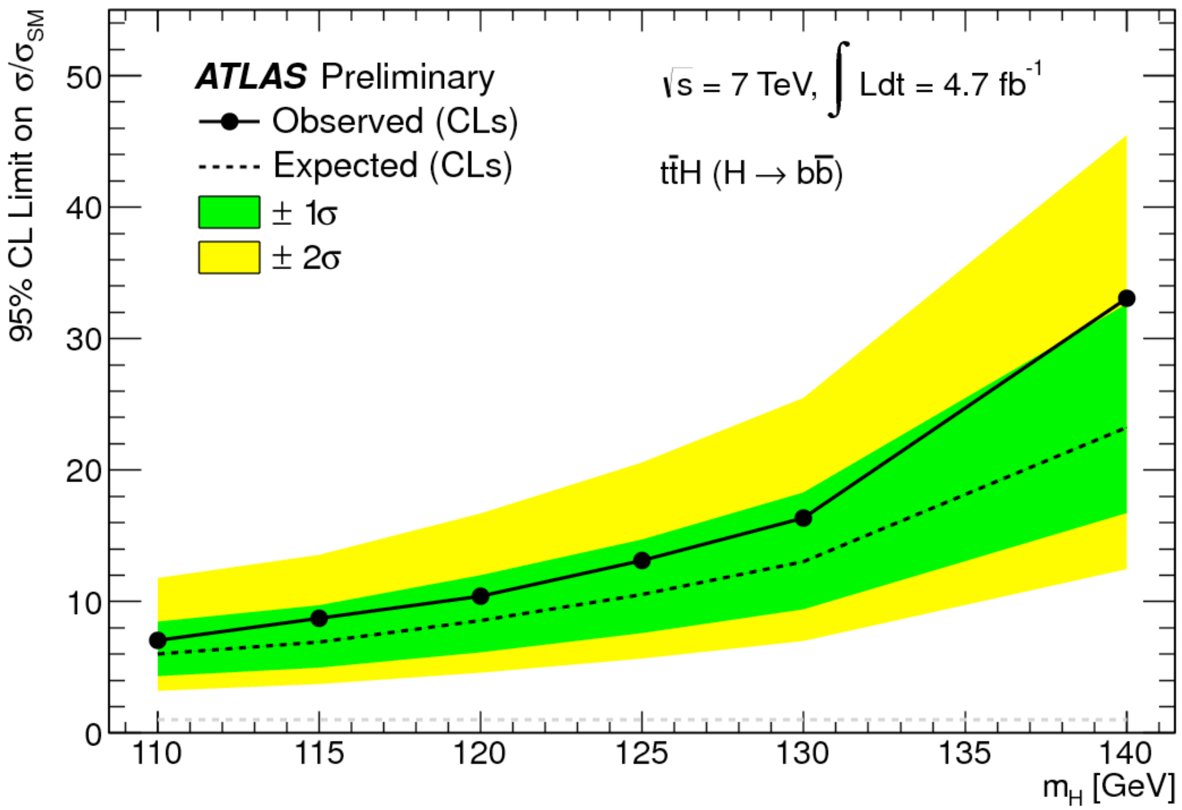
- **Perform simultaneous fit to the background-dominant + signal topologies:**
  - Improves background prediction
  - Reduces uncertainties, resulting in better search sensitivity
  - Use additional categories to validate background modelling (5 jets, 0 or 1 tags and 6 jets, 0 or 1 tags)

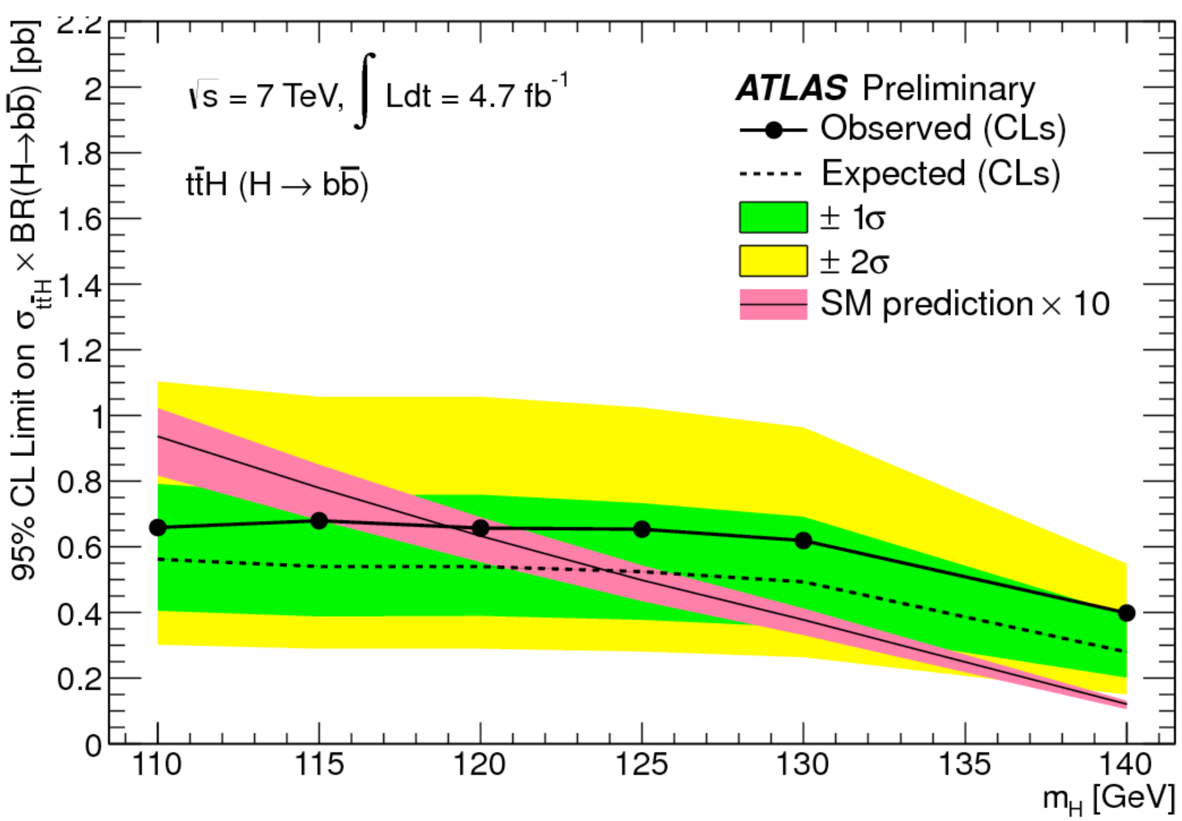
Category	signal (M=125) H→ bb	background	S/√B
4 jets, 0 tags	0.20	40200	0.001
4 jets, 1 tag	1.1	21240	0.008
4 jets, ≥ 2 tags	3.0	15040	0.02
5 jets, 2 tags	2.7	6640	0.03
≥ 6 jets, 2 tags	3.4	3360	0.06
5 jets, 3 tags	2.3	915	0.08
5 jets, ≥ 4 tags	0.74	45	0.11
≥ 6 jets, 3 tags	4.0	634	0.16
≥ 6 jets, ≥ 4 tags	2.2	62	0.28

Yields after the fit



ATLAS ttH search





At Higg's mass 125 GeV

- expect to set a limit of 10.5 x σ_{SM}
- observed upper limit: 13.1 x σ_{SM}

Also set upper limits on absolute

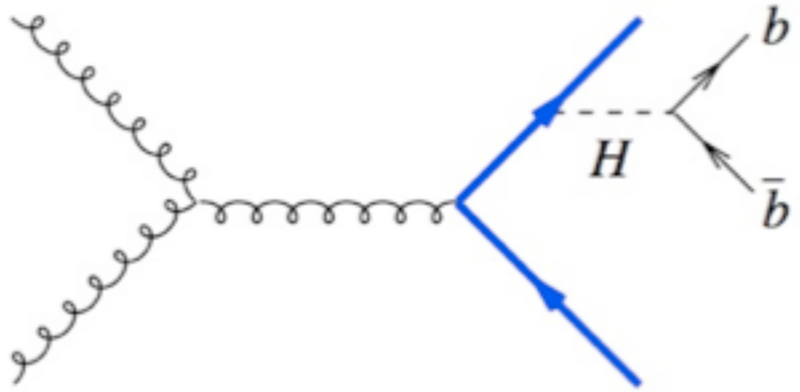
σ_{SM} x BR(H→bb)

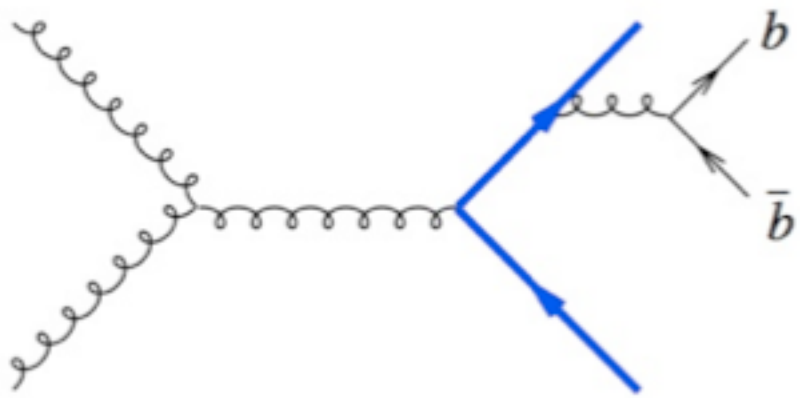
Systematic uncertainty	Status	Components
Luminosity	N	1
Lepton ID+reco+trigger	N	1
Jet vertex fraction efficiency	N	1
Jet energy scale	SN	16
Jet energy resolution	N	1
b-tagging efficiency	SN	9
c-tagging efficiency	SN	5
Light jet-tagging efficiency	SN	1
$t\bar{t}$ cross section	N	1
$t\bar{t}V$ cross section	N	1
Single top cross section	N	1
Dibosons cross section	N	1
V+jets normalisation	N	3
Multijet normalisation	N	7
W+heavy-flavour fractions	SN	4
$t\bar{t}$ modelling	SN	3
$t\bar{t}$+heavy-flavour fractions	SN	1
$t\bar{t}H$ modelling	N	1

Significant Challenge: Backgrounds

- **Most challenging background is ttbb**
  - Irreducible: has the same signature as ttH
  - ttbb NLO calculations are available
    - these suffer from large scale uncertainties due to presence of two very different energy scales: m_t and jet p_T threshold in tt and jj
  - Absolute cross section difficult to measure due to small cross section

- **Can measure ratio ttbb/ttjj**
  - Many experimental uncertainties cancel
  - Expected to have a reduced dependence on scale
    - Good test of NLO QCD





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CMS ttbb/ttjj Measurement

University of Virginia

- **Exploit difference in b-jet multiplicity between ttbb and ttjj**
- **Event selection**
  - Trigger on ee/μμ and eμ events
  - 2 isolated leptons (20 GeV), opposite sign
  - m_{ll} > 12 GeV
  - Z-veto (15 GeV around Z-mass)
  - MET > 30 GeV (ee /μμ channels only)
  - ≥4 jets with 30 GeV
  - ≥2 b-tagged jets (≥ 4 for ttbb sample)

5 fb^{-1}
7TeV data

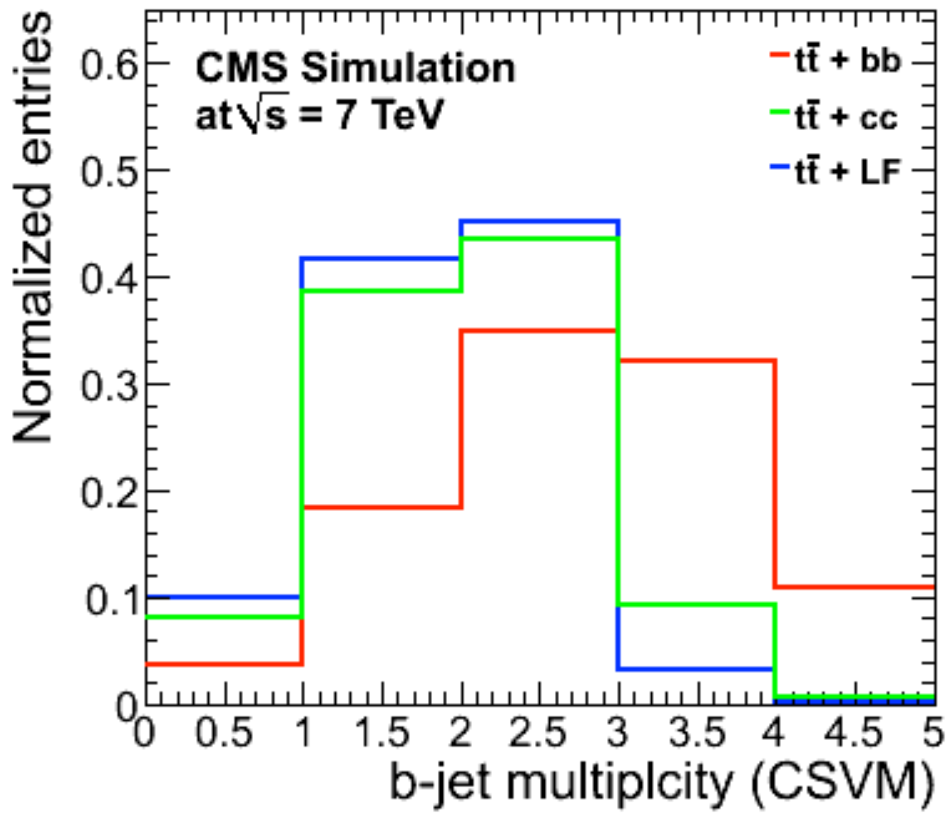
- **Analysis strategy**
  - Fit b-jet multiplicity
  - Correct for acceptance to visible phase space

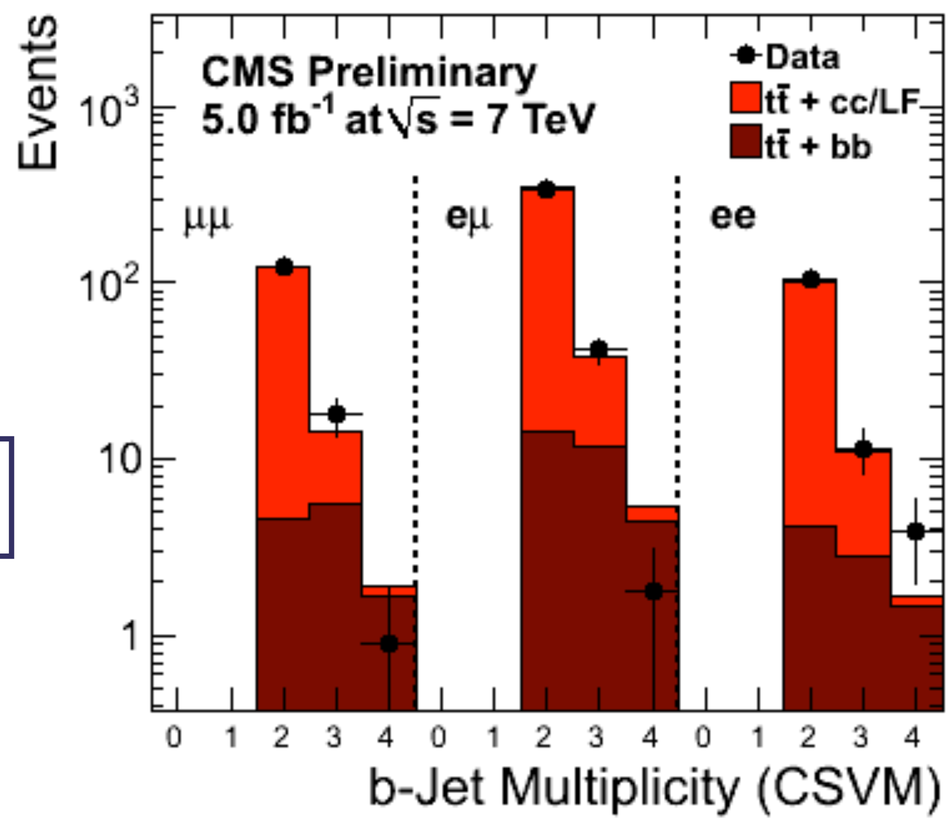
$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = R \times \epsilon_{t\bar{t}jj}/\epsilon_{t\bar{t}b\bar{b}}$$

ratio of events (reconstructed) — correction to visible phase space

•**Final result:** $\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(stat.) \pm 0.9(sys.)\%$

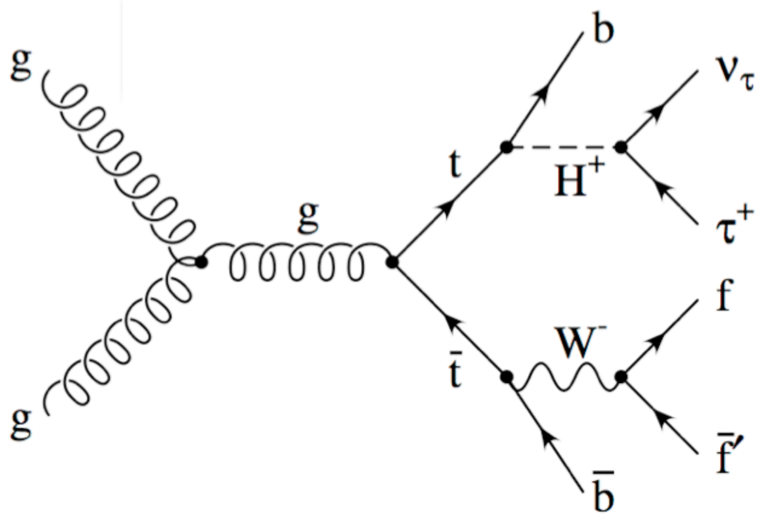
- **Prediction:** 1.2% (MADGRAPH) and 1.3% (POWHEG)
  - NLO analytical calculation in progress

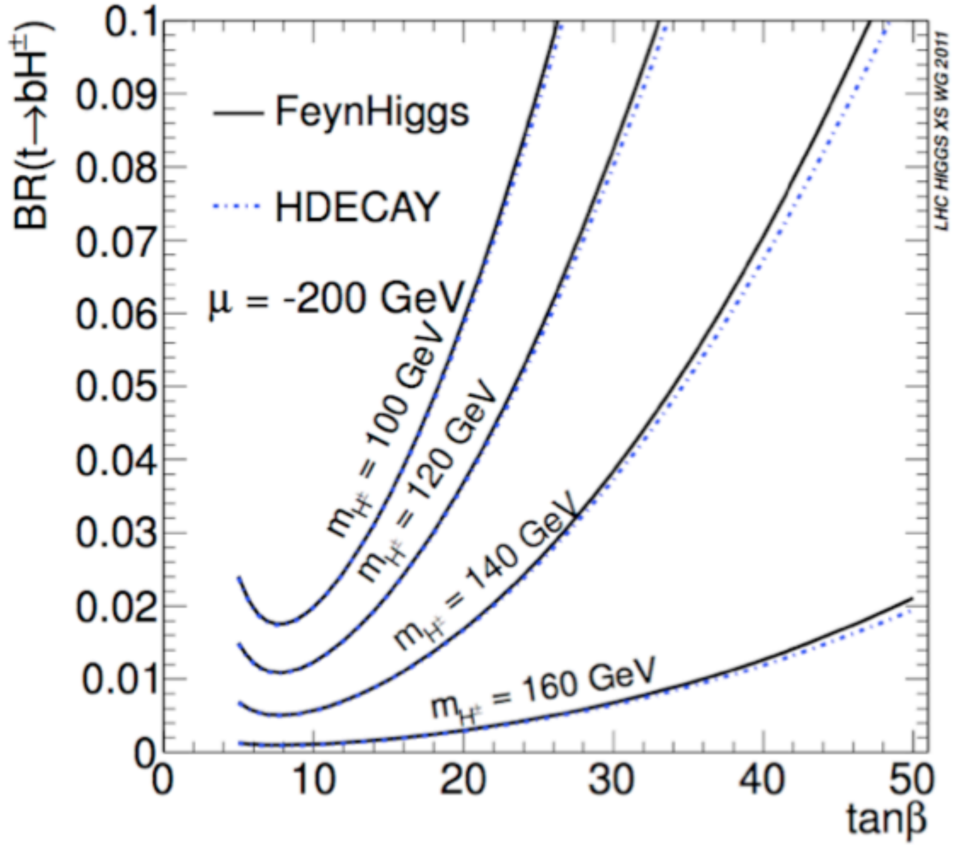


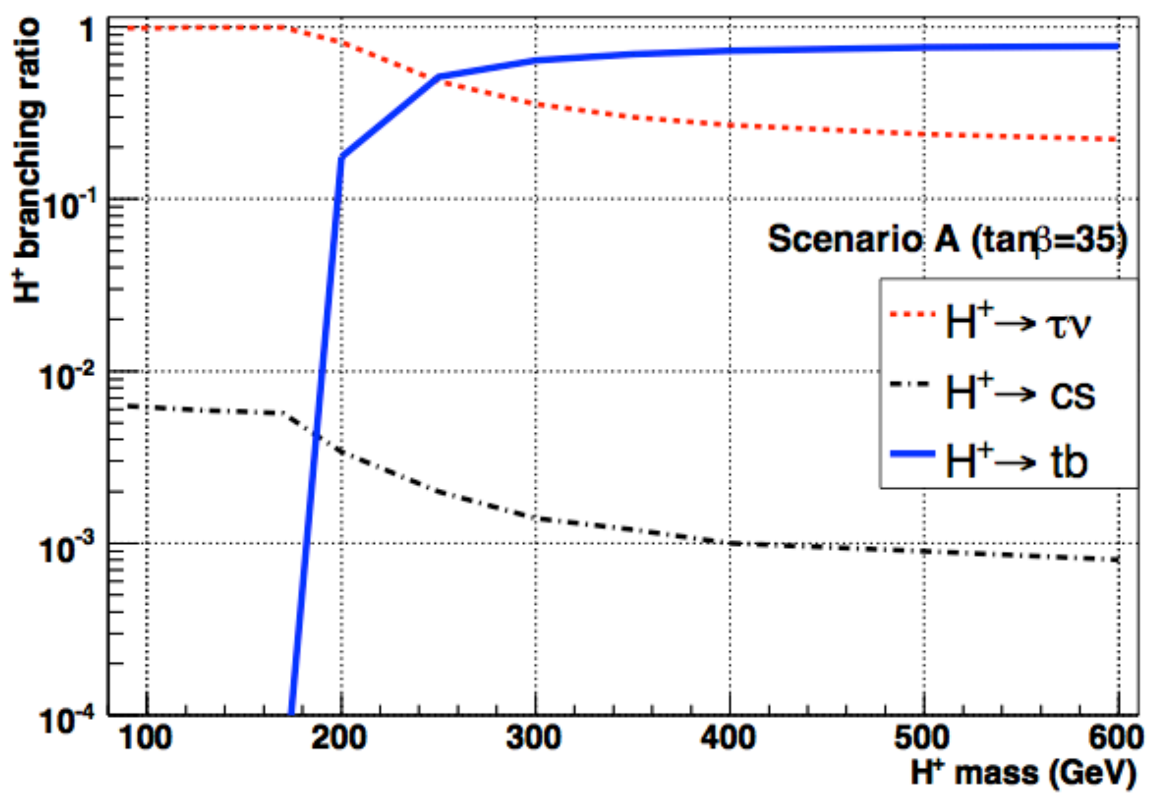


Direct Search for Charged Higgs

- We can look in top events for evidence of MSSM charged Higgs through $t \rightarrow H^{\pm} b$
- In standard model, tt events are dominated by Wb final states
- The presence of a light Higgs would result in a different distribution of tt final states than expected in SM
- For low Higgs mass and high tan β, the dominant decay mode $H^{\pm} \rightarrow \tau\nu$
- All assuming $BR(H^{\pm} \rightarrow \tau\nu) = 1$
- Results presented for $BR(t \rightarrow H^{\pm} b)$ as function of tan β and Higgs mass
- In these analyses, consider $M_H < M_{top}$

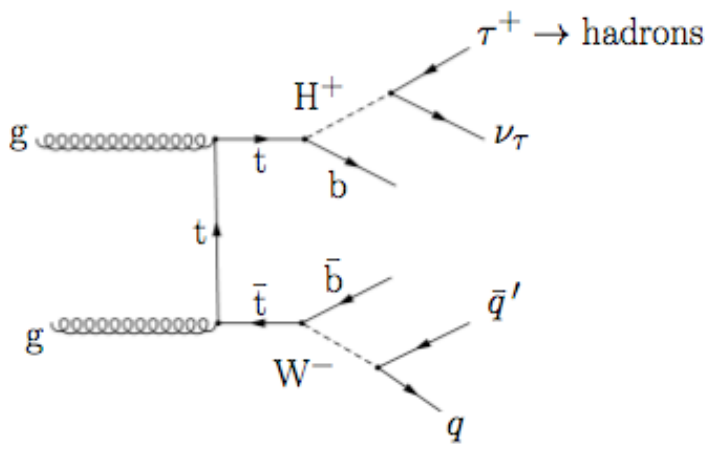






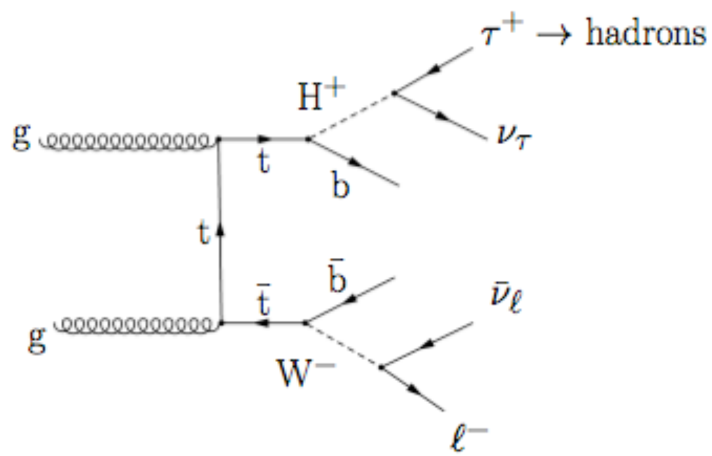
CMS Search

τ_h + jets



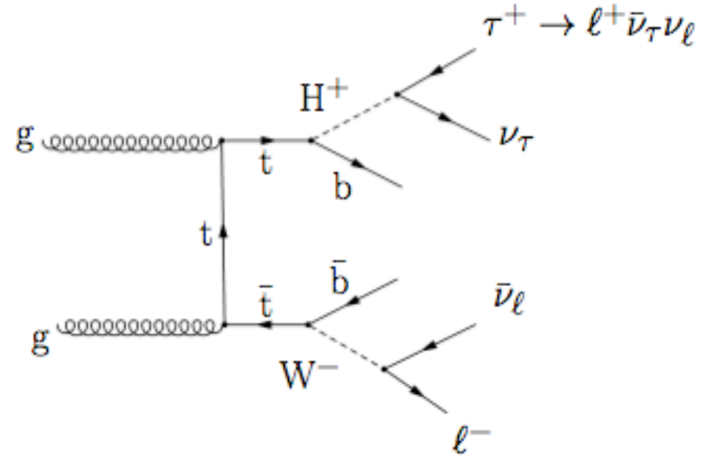
1 isolated hadronic tau
0 isolated leptons
Large missing ET
≥ 3 jets
≥ 1 b jet

τ_h + e/μ



1 isolated hadronic tau
1 isolated op. sign lep
Large missing ET
≥ 2 jets
≥ 1 b jet

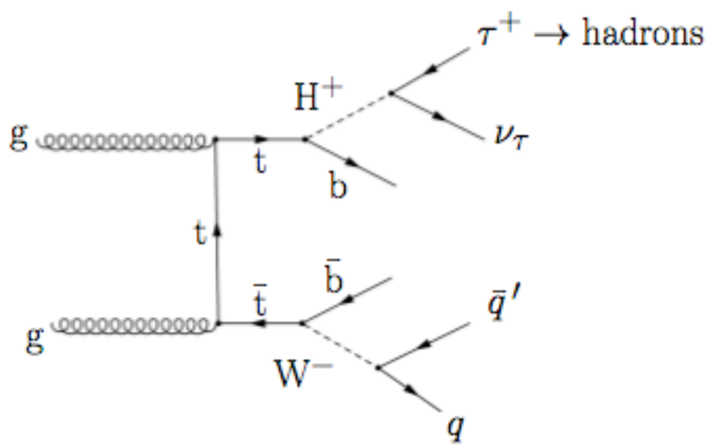
e+μ

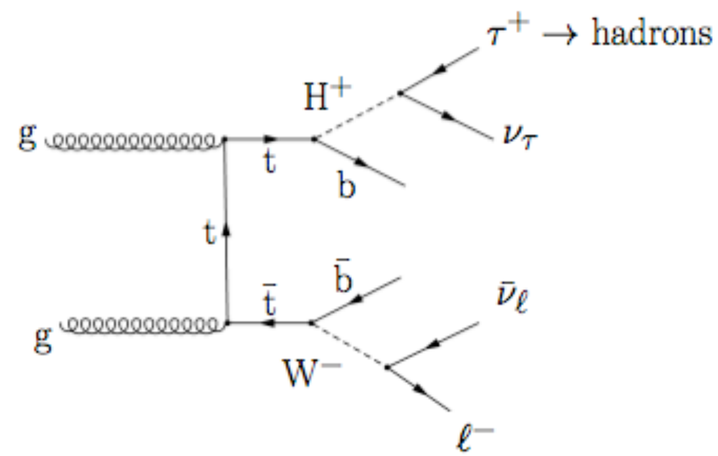


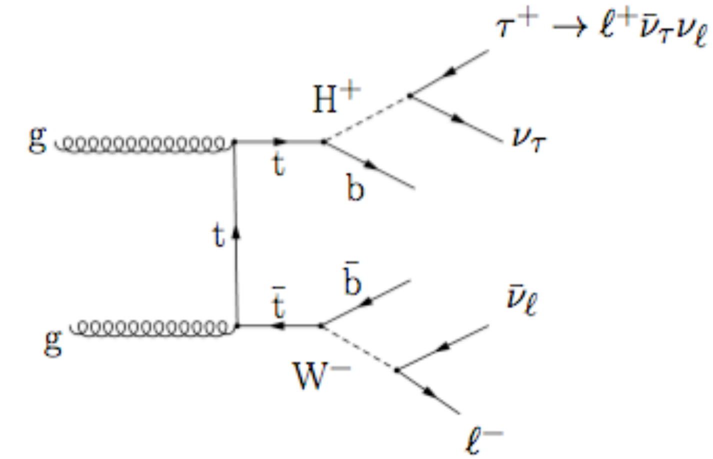
1 isolated muon
1 isolated electron
≥ 2 jets
Opposite sign
$m_{e\mu}$ > 12 GeV

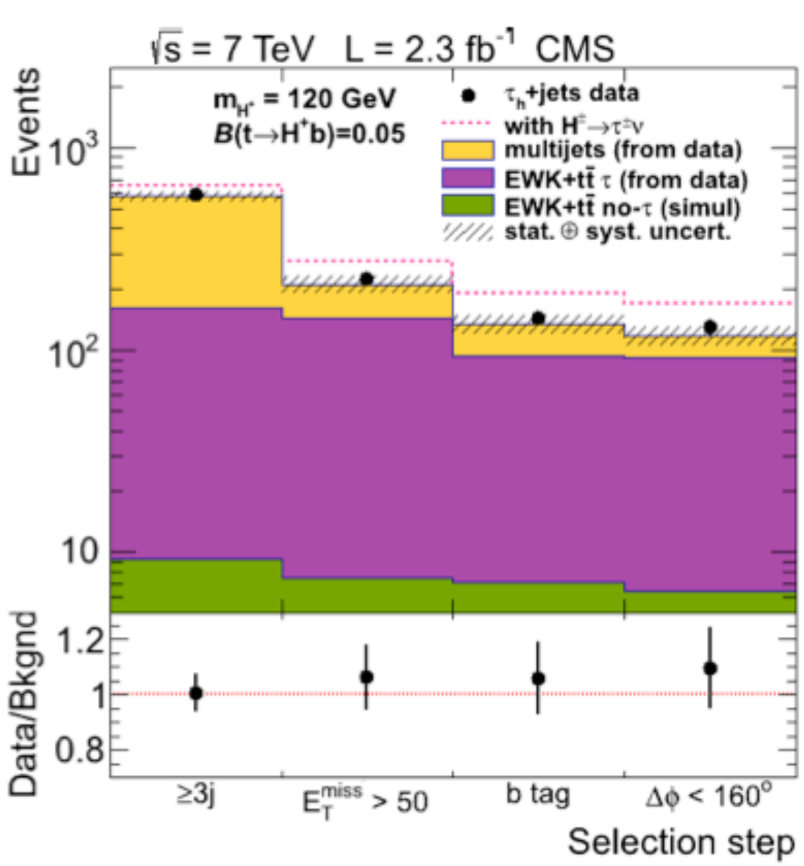
CMS Search

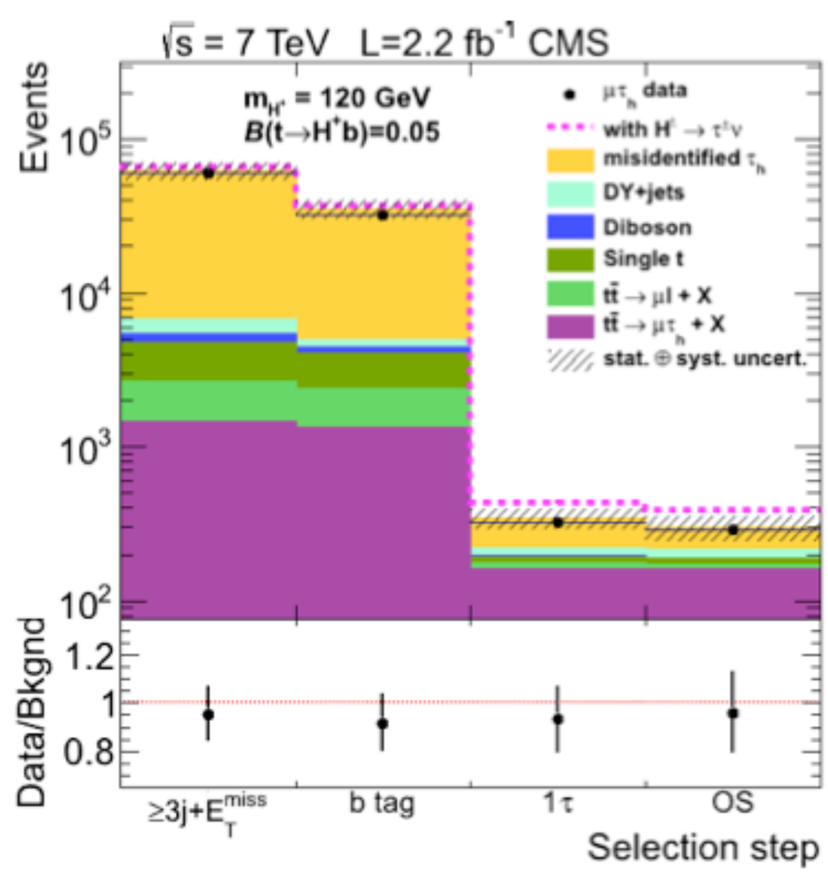
τ_h + jets	τ_h + e/μ	e+μ

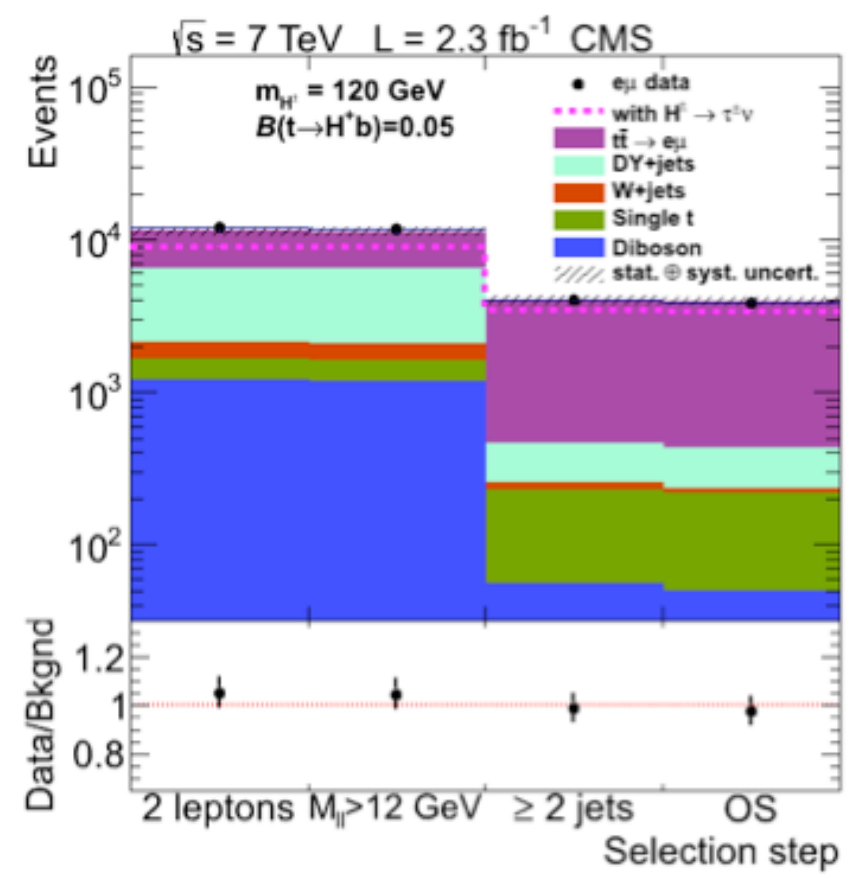




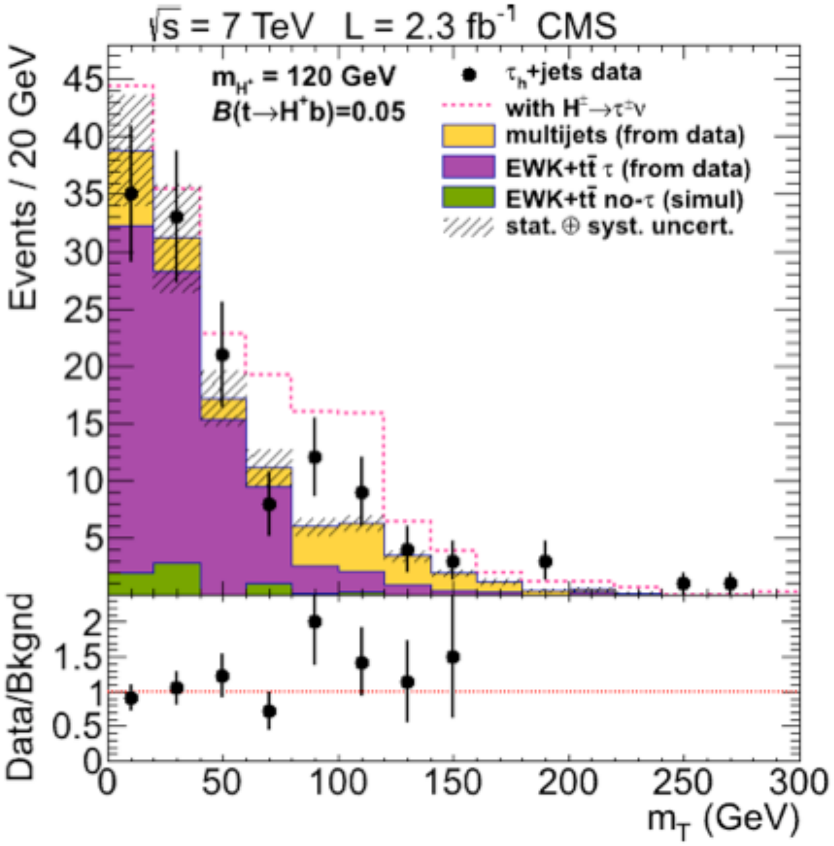








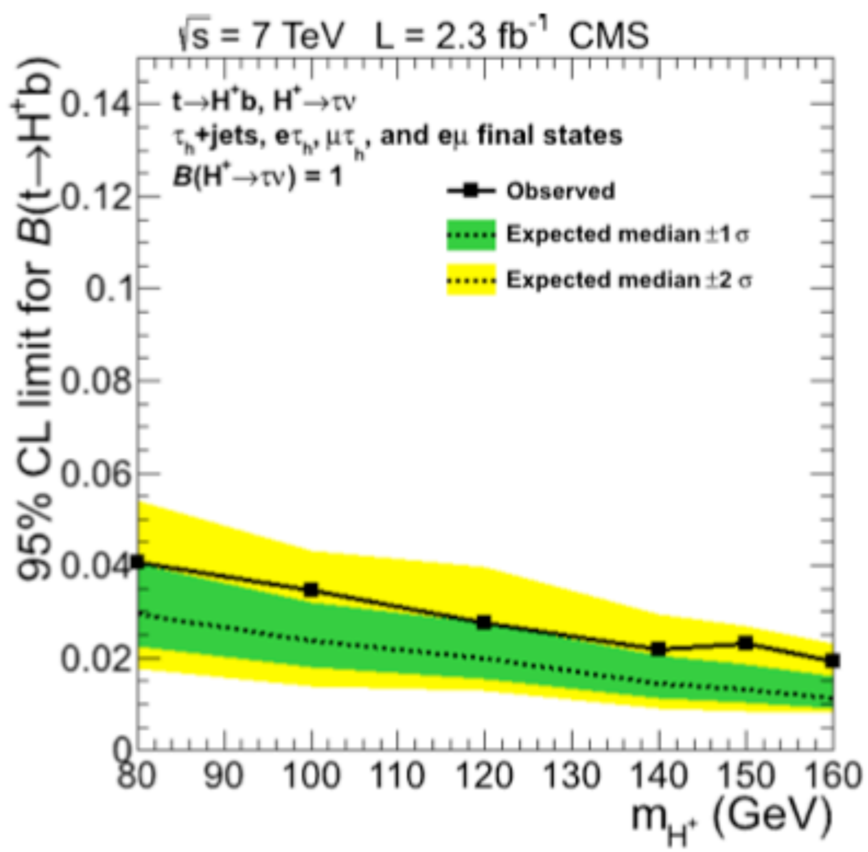
CMS Search

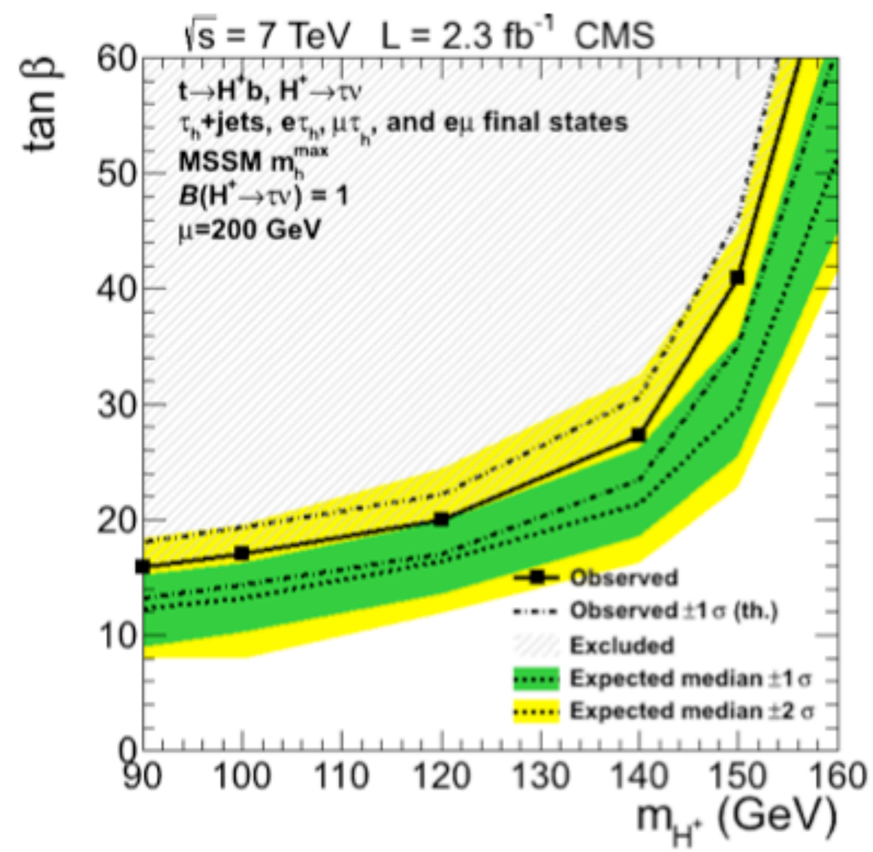


$m_T = \sqrt{(2 \times E_T^{\tau\text{-jet}} \times E_T^{miss} \times (1-\cos\Delta\Phi))}$

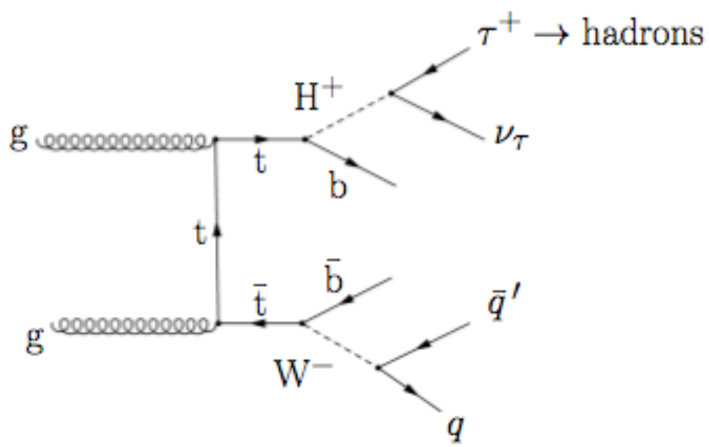
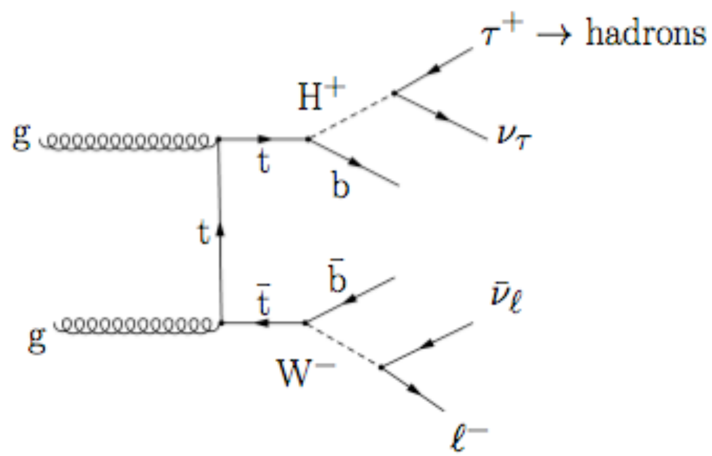
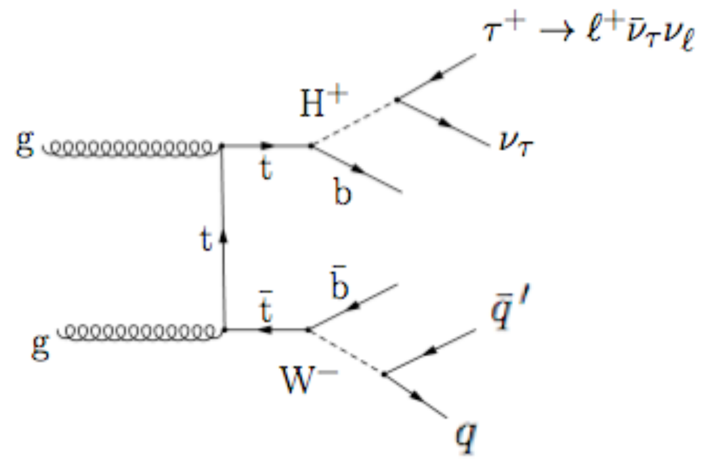
- For the τ_h + e/μ, and e+μ channels, only event counting is used to extract the final limits
- The τ_h + jets analysis extracts the possible signal using the m_T in a binned maximum-likelihood fit
- Limits show combination of all channels

τ_h + μ and τ_h + jets are the most sensitive channels



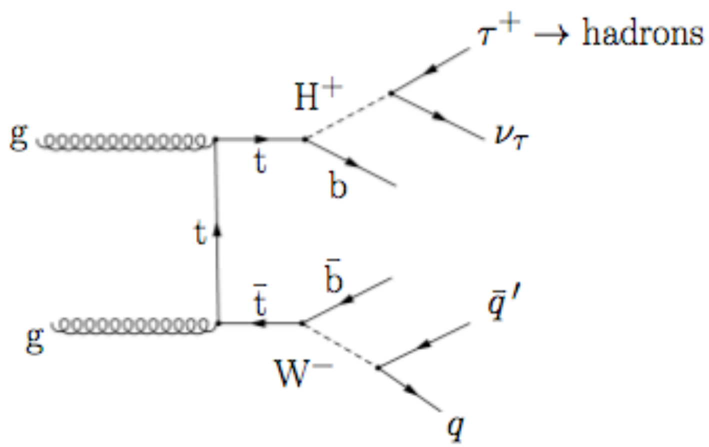


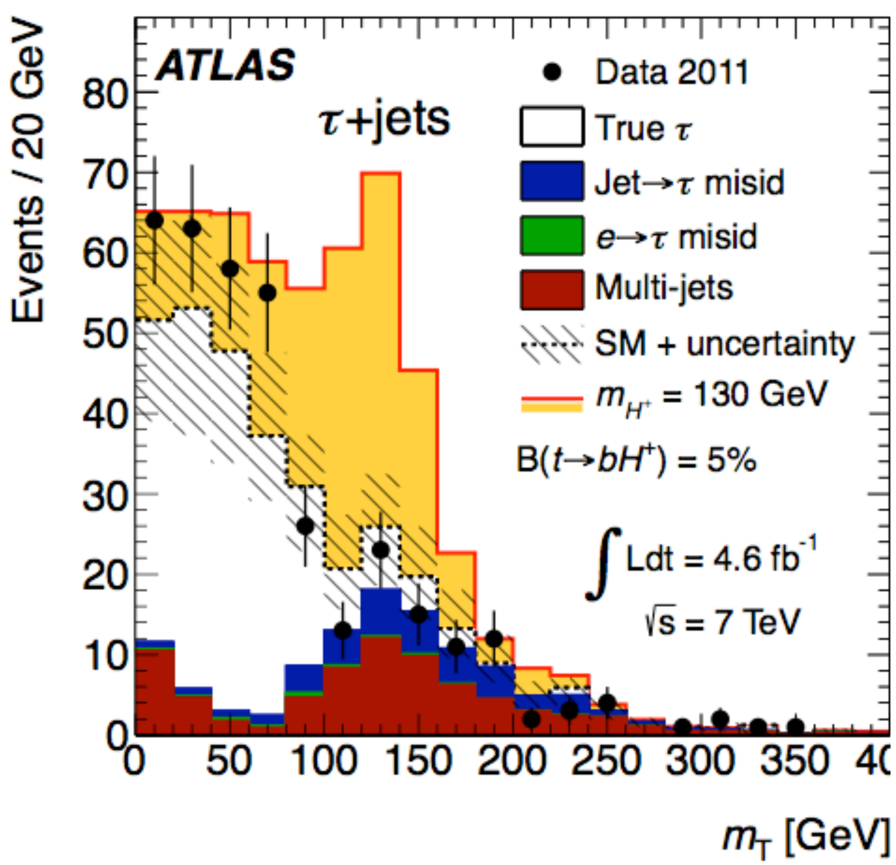
ATLAS Search

τ_h + jets	τ_h + e/μ	e/μ+jets
		
1 isolated hadronic tau 0 isolated leptons Large missing ET ≥ N jets	1 isolated hadronic tau 1 isolated op. sign lep ≥ 2 jets ≥ b jet	1 isolated muon/electron missing ET ≥ 4 jets ≥ 2 b jet cos θ* < -0.4

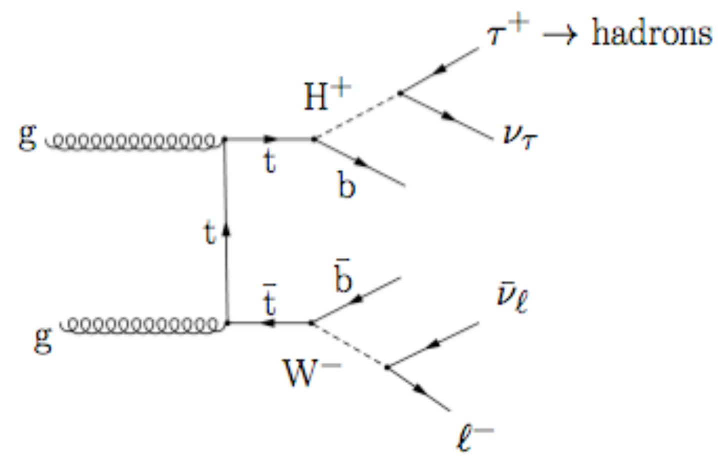
ATLAS Search

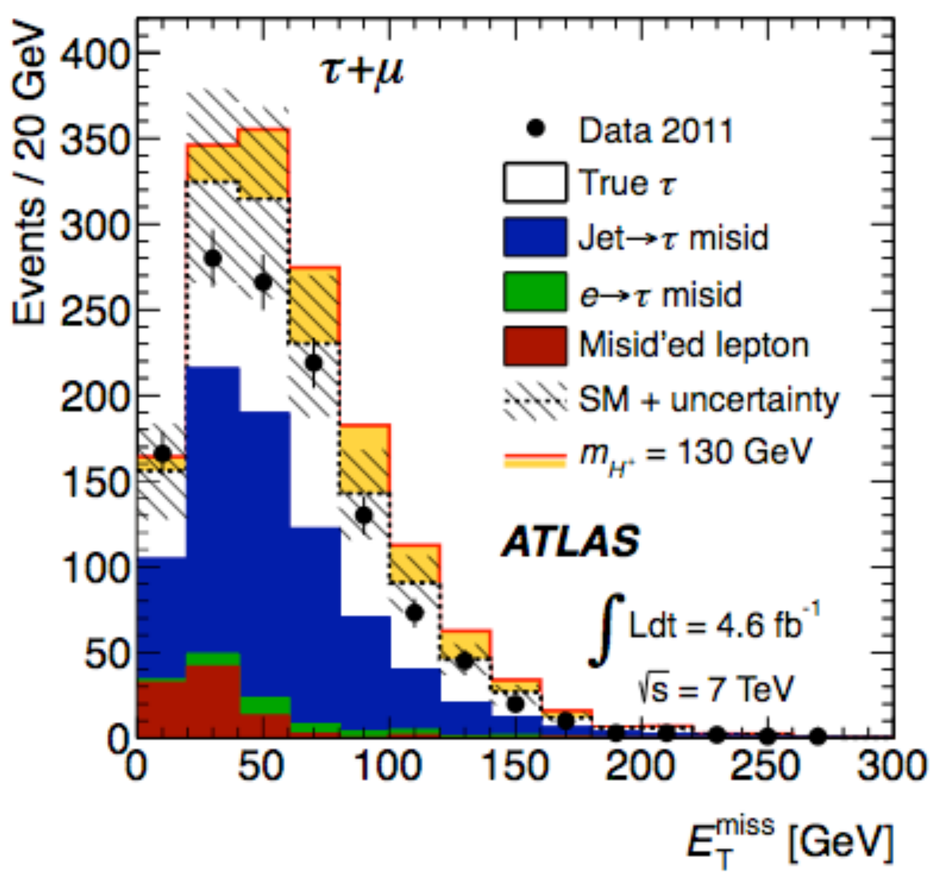
τh + jets



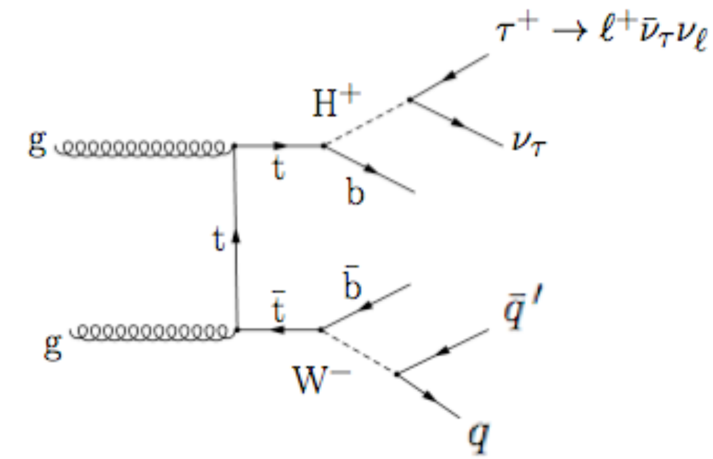


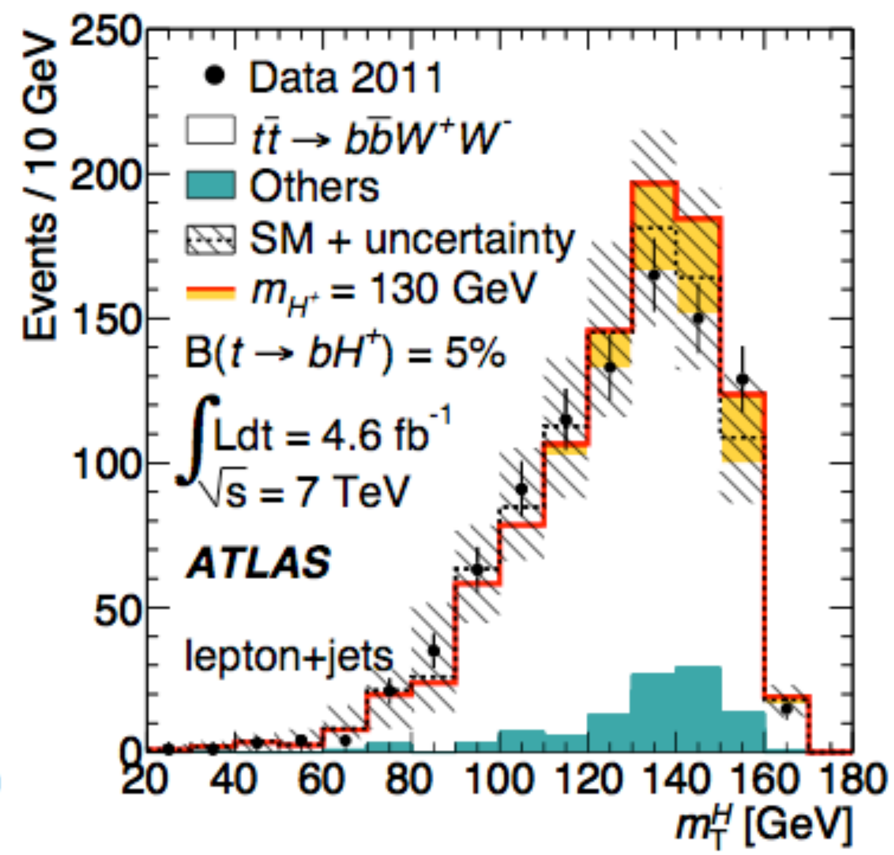
τh + e/μ



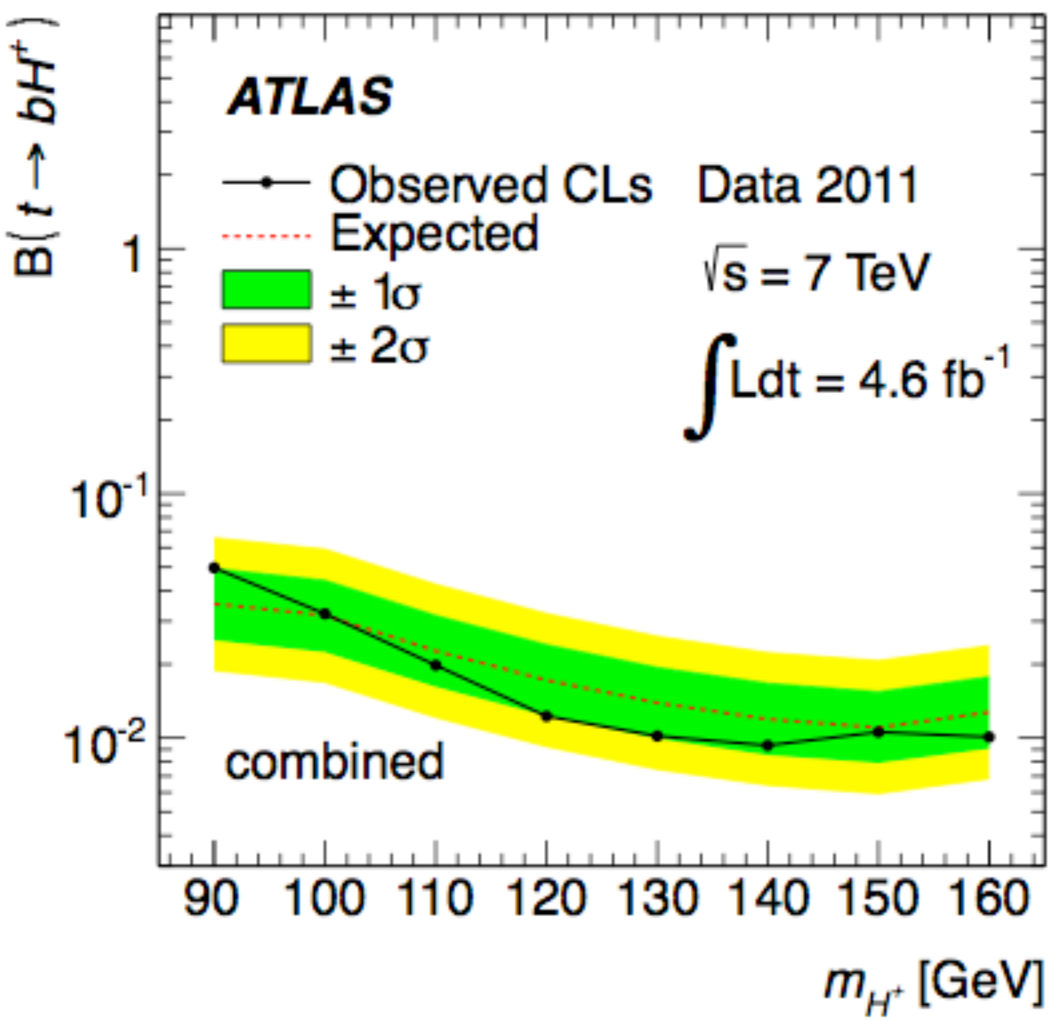


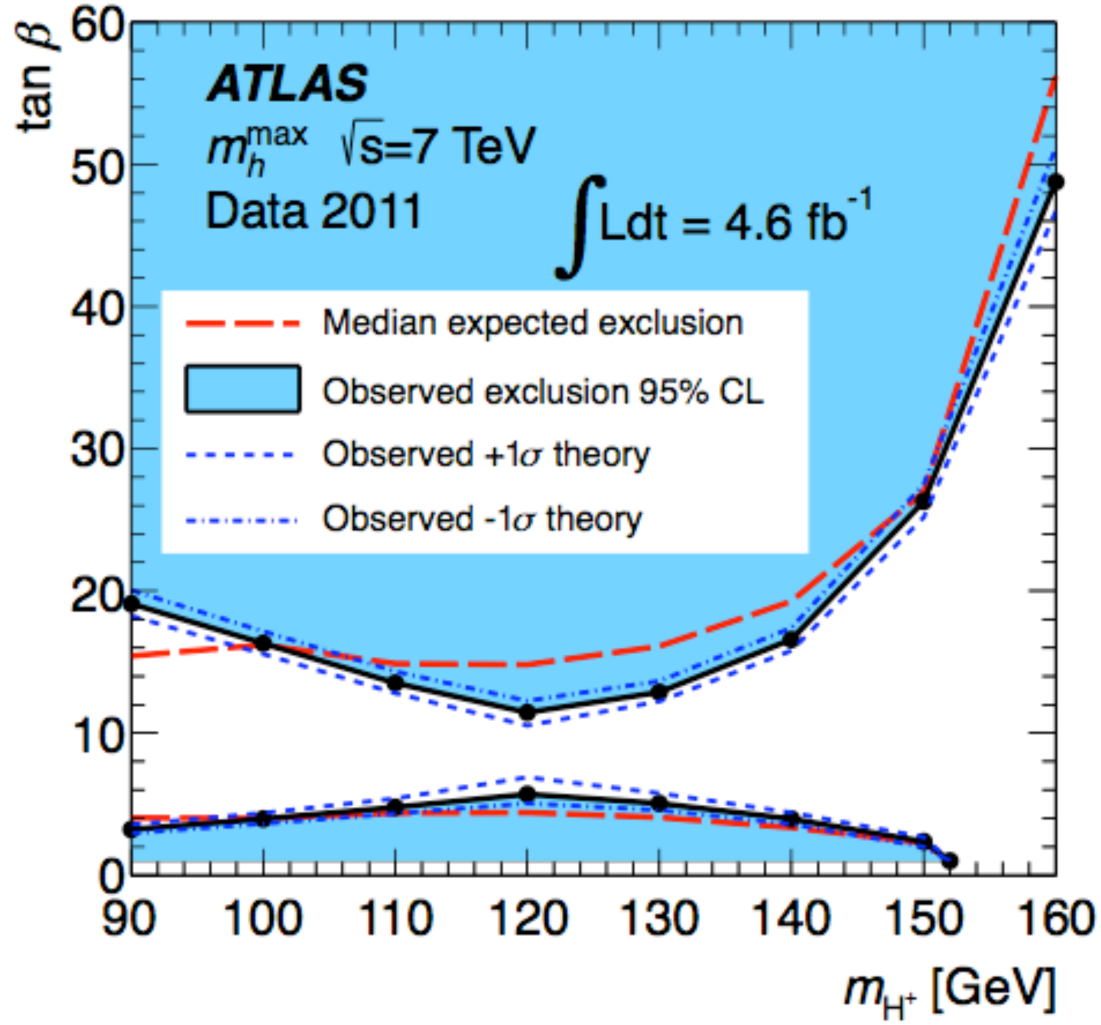
e/μ+jets





ATLAS Search





- Significant constraints on BR ($t \rightarrow H^{\pm}b$) by CMS and ATLAS:
  - Upper limit of 2-3% for a $H^{\pm}$ mass 80-160 GeV for CMS
  - 1-5% over $H^{\pm}$ mass 90-160 GeV for ATLAS

- Both exclude a large region of $m_{H^{\pm}}$ - tanβ parameter space

Summary

- Characterization of the new Higgs-like boson is a primary goal for current and future colliders
- The production of this Higgs-like boson in association with top quarks is a useful opportunity for study of the top-Higgs Yukawa coupling
- Direct searches for ttH production w/ H->bb have been undertaken by CMS, ATLAS and CDF. With enough integrated luminosity these searches will soon have SM sensitivity
- The challenges to these searches posed by the tt+jets, and specifically the tt+bb, background processes are being measured at the LHC. Need to make further progress on the theoretical description of this background
- Studies of top quark decay can provide insight into extended Higgs sectors present in some beyond-the-SM scenarios

ATLAS-CMS ttH analyses: comparison

	ATLAS	CMS: LJ channel
electron/muon	$p_T > 25/20$ GeV, $\lvert\eta\rvert < 2.5$	$p_T > 30$ GeV, $\lvert\eta\rvert < 2.5/2.1$
jet cuts	anti-kt R=0.4, $p_T > 25$GeV, $\lvert\eta\rvert < 2.5$	anti-kt R=0.5, p_T (jet 1,2,3) > 40GeV, p_T (jet 4,5,6) > 30GeV $\lvert\eta\rvert < 2.4$
additional cuts	$E_T^{miss} > 35$ GeV $M_T > 30$GeV (electrons) $E_T^{miss} + M_T > 60$GeV (muons)	no E_T^{miss} cut
signal	H→bb	H→anything
analysis strategy	fit m_{bb} in best signal categories fit H_T in background categories	MVA
categories	4 jets (0,1,≥ 2 tags) 5 jets (2, 3, ≥ 4 tags) ≥ 6 jets (2, 3, ≥ 4 tags)	4 jets (3, ≥ 4 tags) 5 jets (3, ≥ 4 tags) ≥ 6 jets (2, 3, ≥ 4 tags)