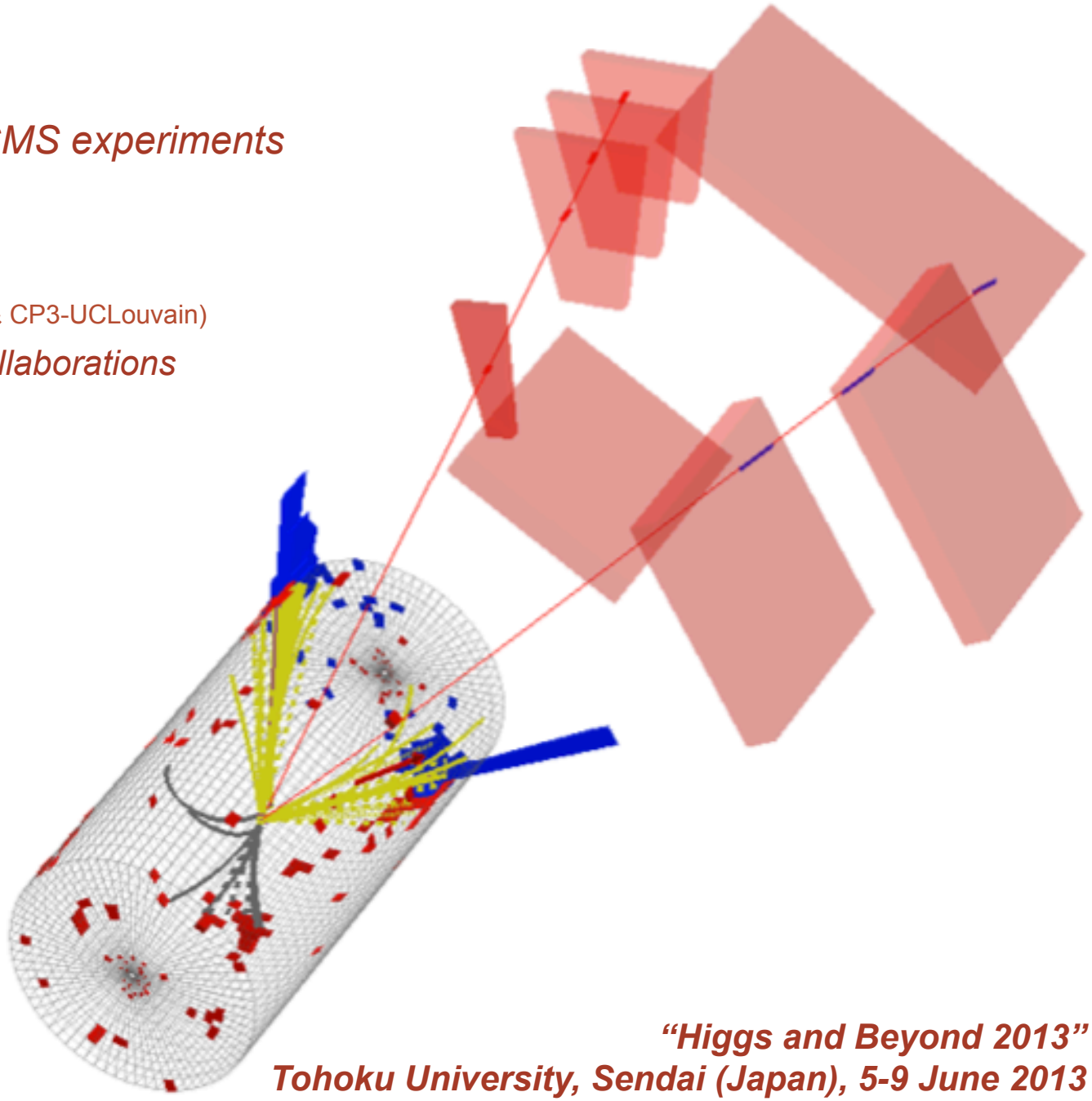
H→bb

results of the Atlas & CMS experiments

Tristan du Pree (FNRS & CP3-UCLouvain)

for the Atlas and CMS Collaborations

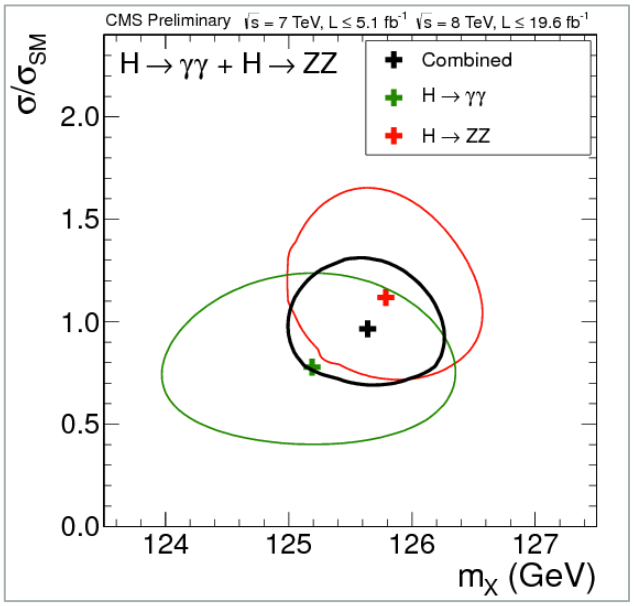


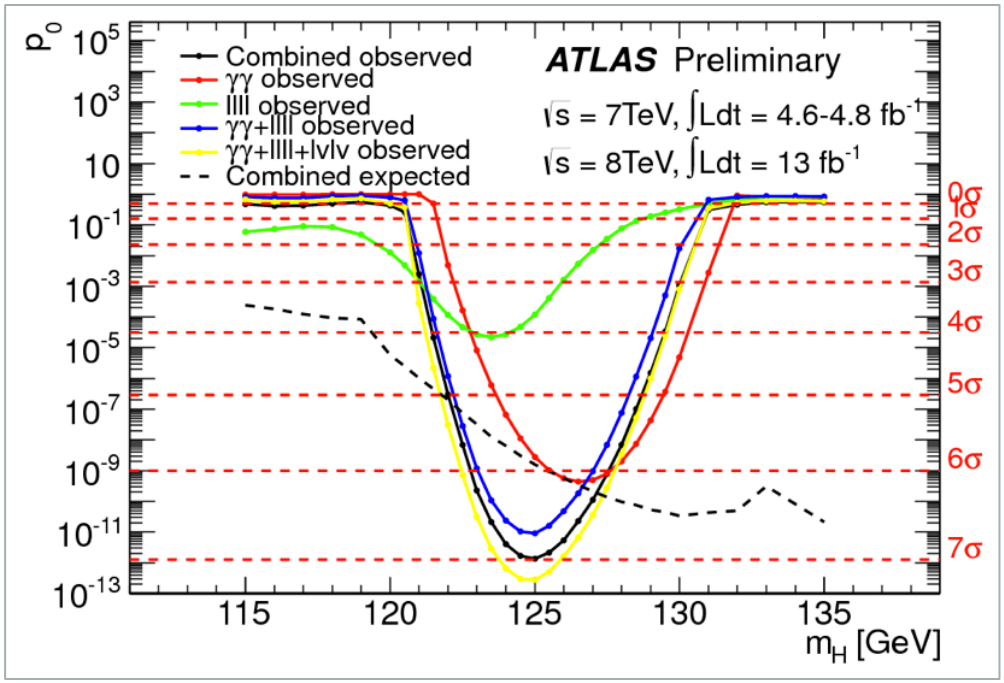
"Higgs and Beyond 2013"

Tohoku University, Sendai (Japan), 5-9 June 2013

Introduction

- **Studies of SM Higgs boson**
  - Searches & properties
  - Dominated by γγ, ZZ, WW

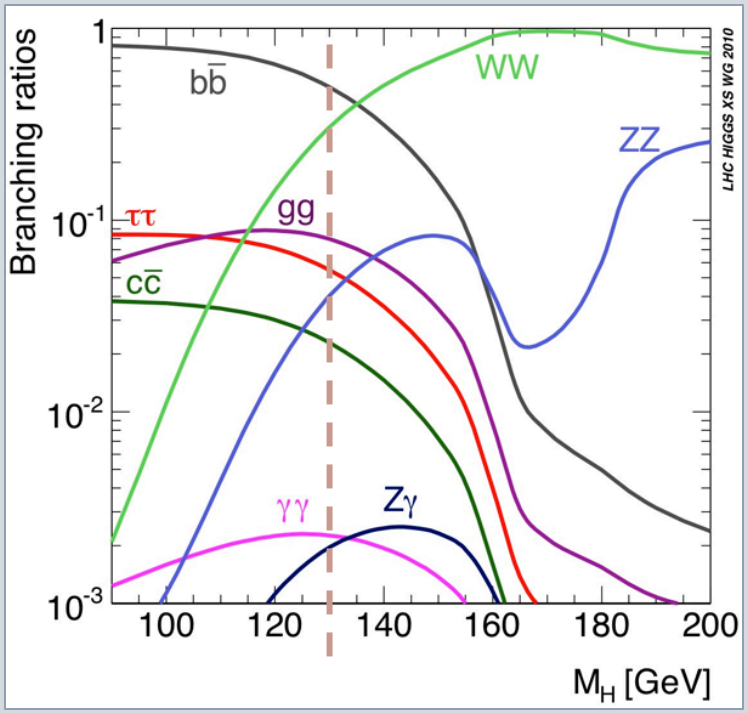




- **Less sensitivity in bb & ττ**
  - Test fermionic final states

Branching ratios

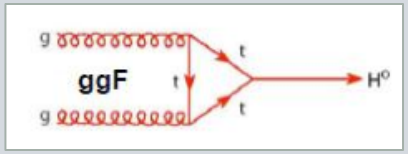
- **Branching ratios largest in bb final state**

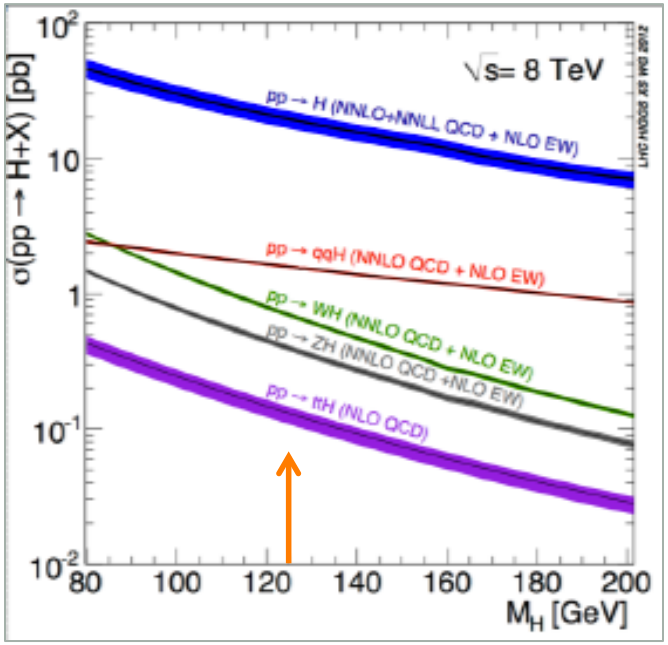


- At 125 GeV: **BR(H→bb) = (58 ± 2)%**
  - Test coupling to quarks

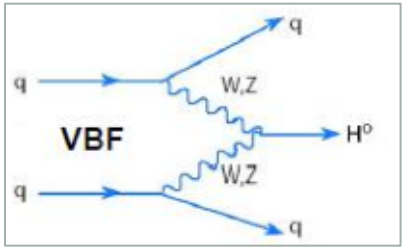
Production mechanisms

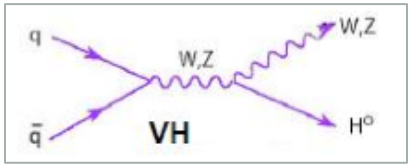
- **Search for H→bb not possible in dominant production mechanism**
  - Gluon fusion production: large multi-jet backgrounds
- **Search for H→bb in associated production**
  - No loops & suppress backgrounds

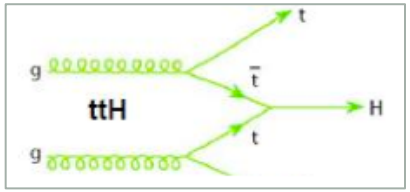




1. **VBF**
   - H→bb
     in association with quarks
2. **VH**
   - H→bb
     in association with W/Z
3. **ttH**
   - H→bb
     in association with tops



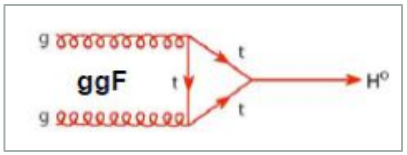


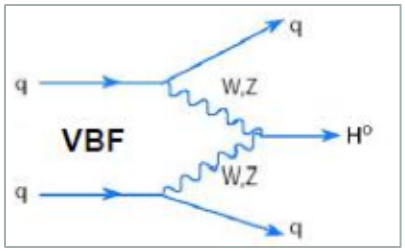


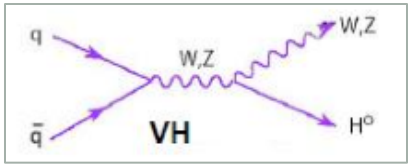
- **Let's discuss them by increasing sensitivity**

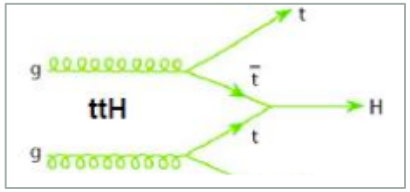
1★ ttH

More details on ttH tomorrow by Michele Pinamonti









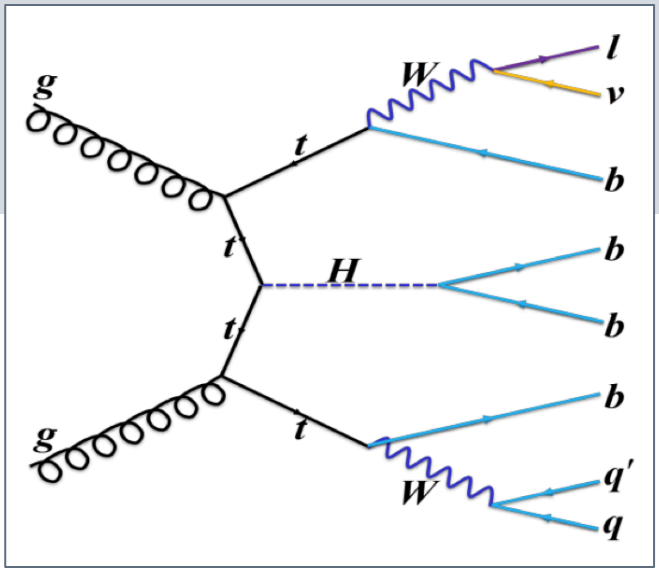
Smallest cross section

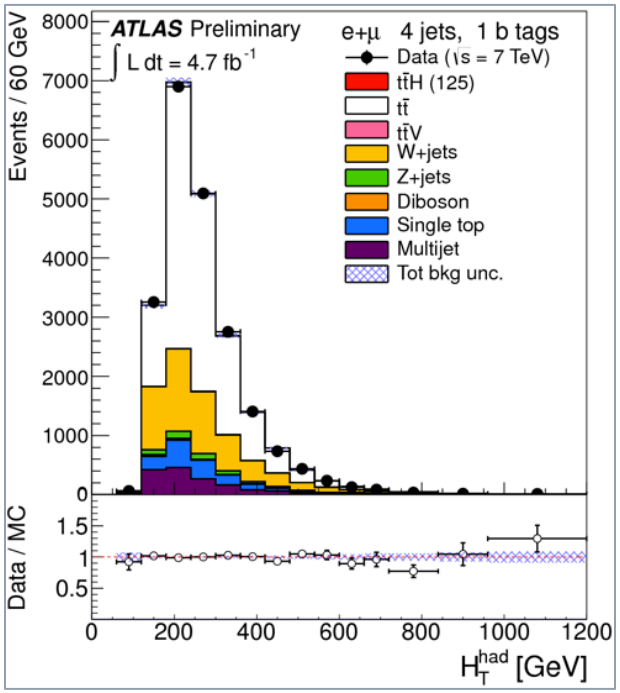
- **Probe directly ttH coupling**

ATLAS CONF-2012-135

Atlas ttH strategy

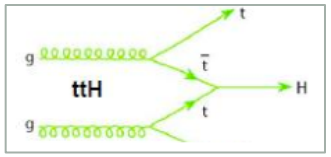
- Require **exactly one lepton**
  - Electron or muon
- **And at least 4 jets**





- **Main backgrounds:**
  - Multi-jets
    - Reduce with Missing-E_T & M_T
  - ttbar

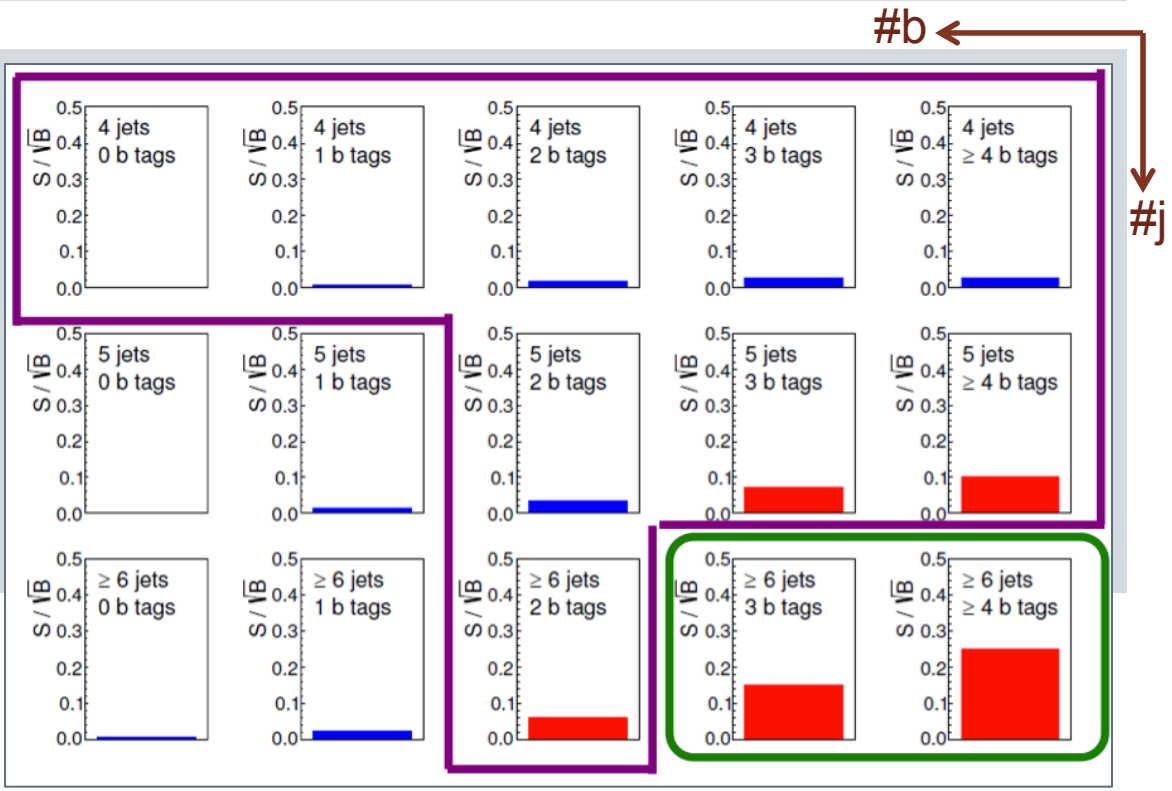
Categorization



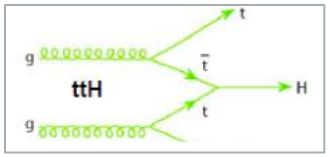
- **Event categorization in #jets and #b-tags**
  - Background description & signal sensitivity
  - 4j0b to >6j4b

Simultaneously fit all categories

- **H_T**
  - Previous slide
- **M(bb)**
  - Most signal-like bins: > 6j & 3/4b
  - Next slide

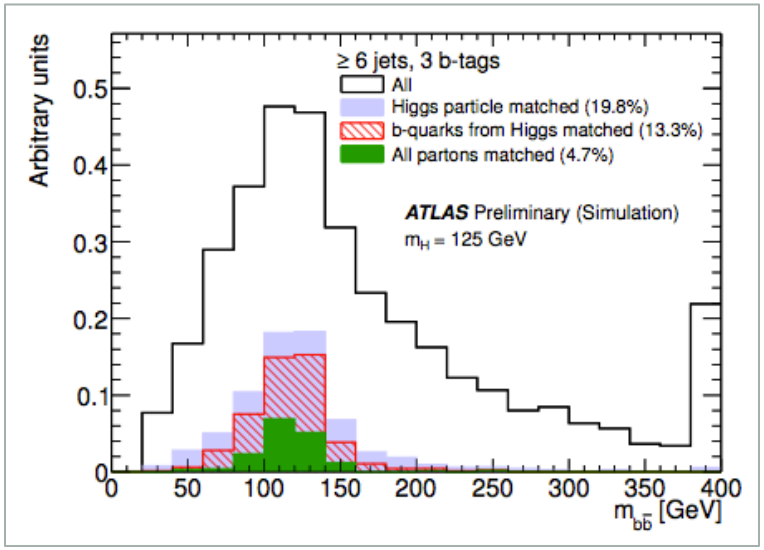


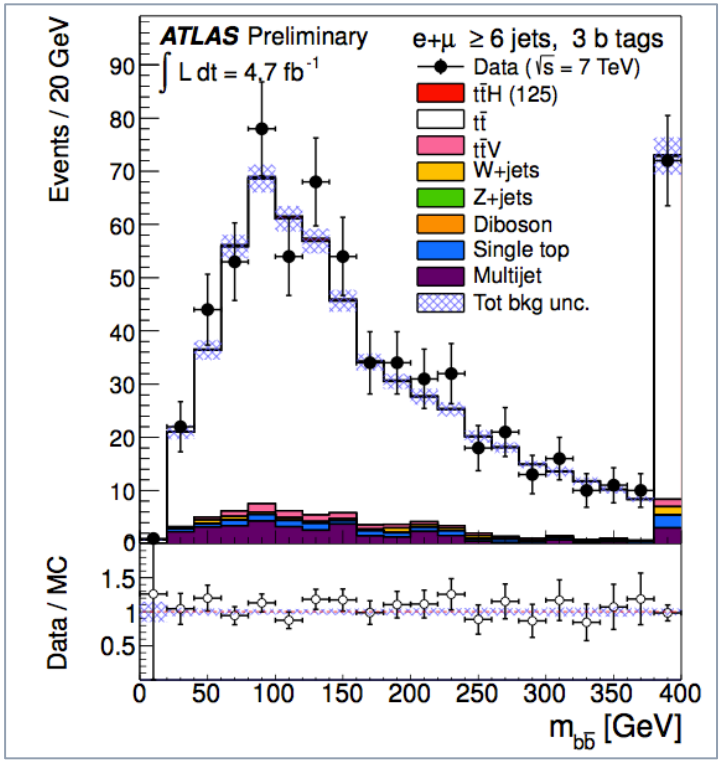
Kinematic fit



Kinematic Likelihood Fit

- Exploit kinematics in final states
  - Background: non-resonant bb
- Consider all (b-)jet permutations
- Constraints from W and top mass
  - Parton level

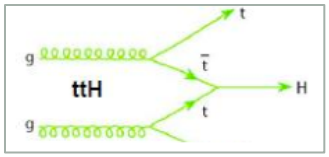




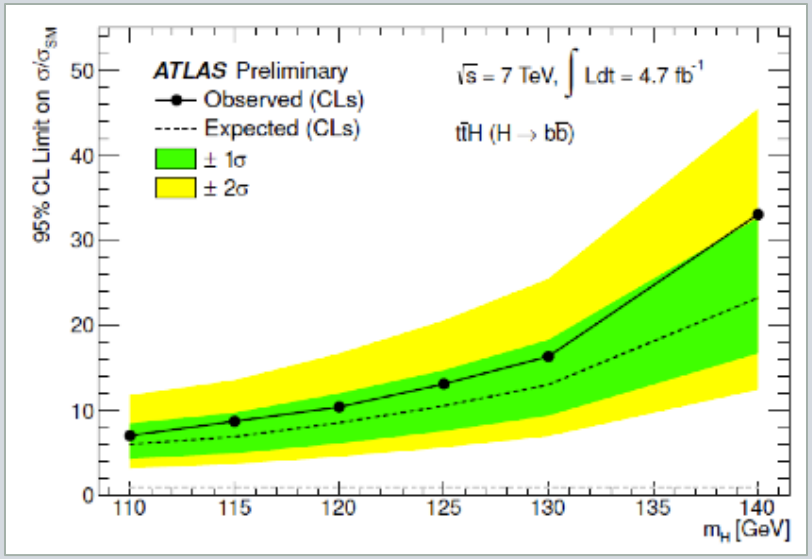
Unconstrained M(bb)

- **Use M(bb) to extract signal**

ttH result



Dataset: 4.7 fb^{-1} (at 7 TeV)



- **Main systematics**
  - tt+HF modelling
  - b/c-jet tag efficiencies
  - jet energy scale

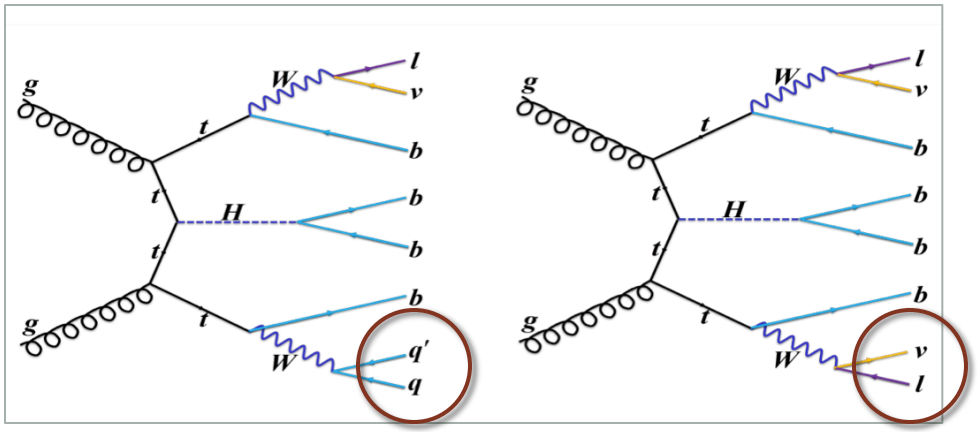
- **Limit: 13.1 obs (10.5 exp)**
  - 95% CL on σ/σ_{SM} for SM Higgs boson of m_H = 125 GeV

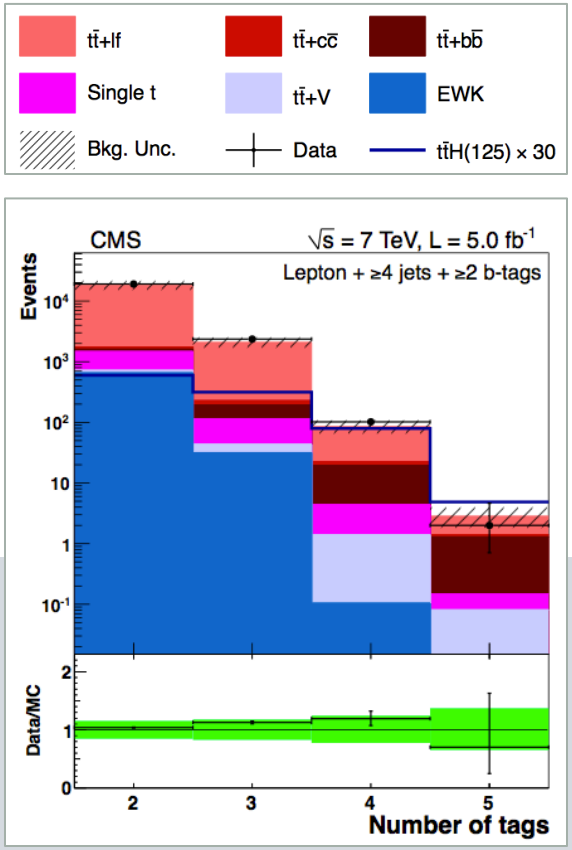
ATLAS CONF-2012-135

CMS HIG-12-035

ttH in CMS

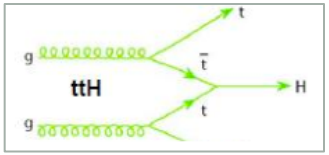
- **Semi-leptonic and di-leptonic top events**



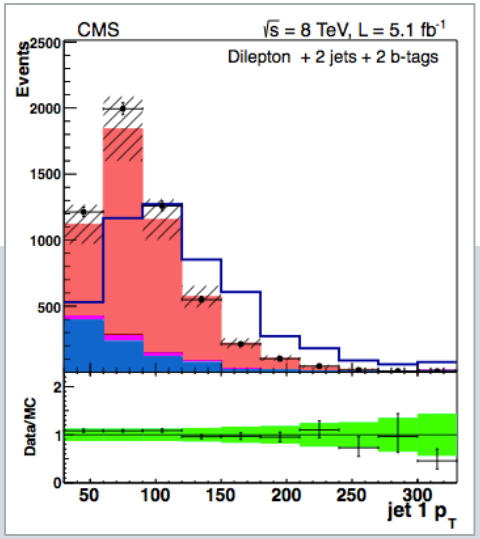


- **Categorize in #jet and #b-tag**
  - Single-lepton: 4j3b to 6j2b (7 bins)
  - Double-lepton: 2j2b and >3j3b (2 bins)
- **Use Artificial Neural Network (ANN)**

ANN

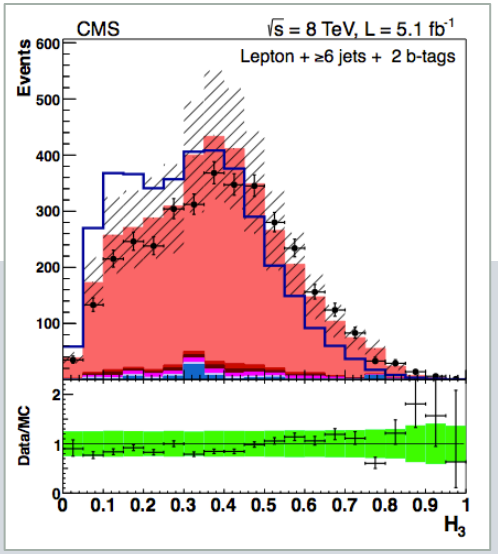


- **Input variables**
  - Total of 24 input variables
  - Category-dependent

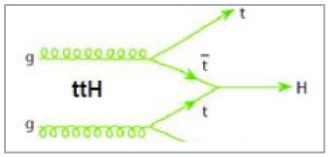


1. **Basic kinematics**
   - E.g. p_T of jets
2. **Kinematics of jet pairs**
   - E.g. M(bb)

3. **B-tag variables**
   - E.g. discriminant values
4. **Event shapes**
   - E.g. sphericity

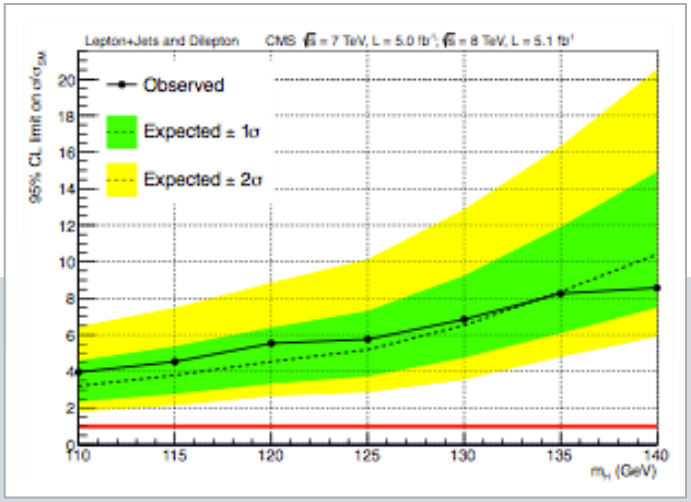


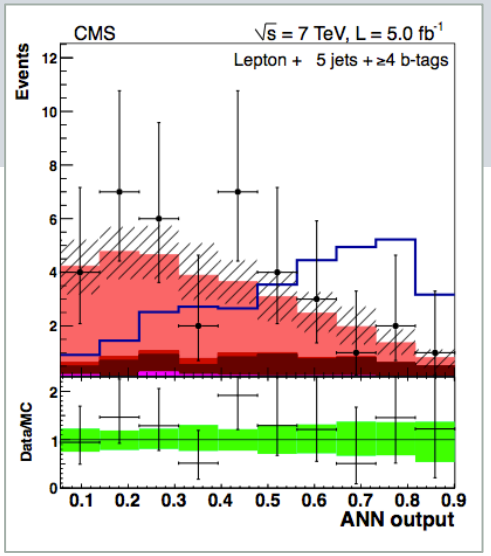
ttH result



Limit from ANN output distributions

- 27% better than single-best variable





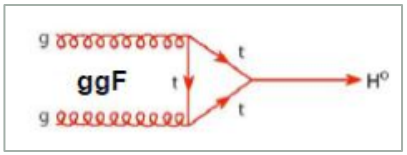
Dataset

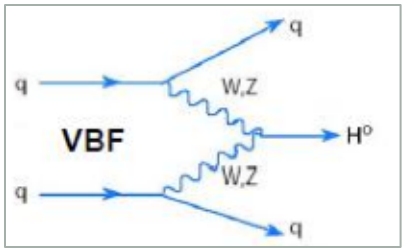
5.0 fb^{-1} (at 7 TeV)
+ 5.1 fb^{-1} (at 8 TeV)

- **Limit: 5.8 obs (5.2 exp)**
  - 95% CL on σ/σ_{SM} for SM Higgs of m_H = 125 GeV

CMS HIG-12-035
accepted by JHEP

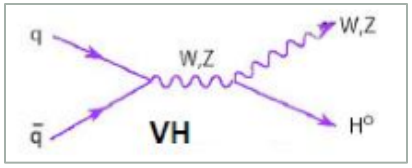
2★VBF

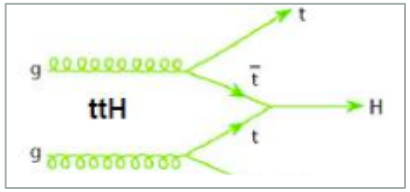




NEW! (LHCP)

- **Large cross section**
- **QCD backgrounds**

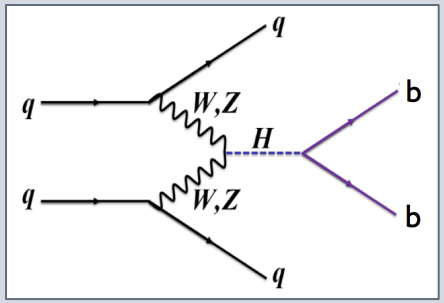




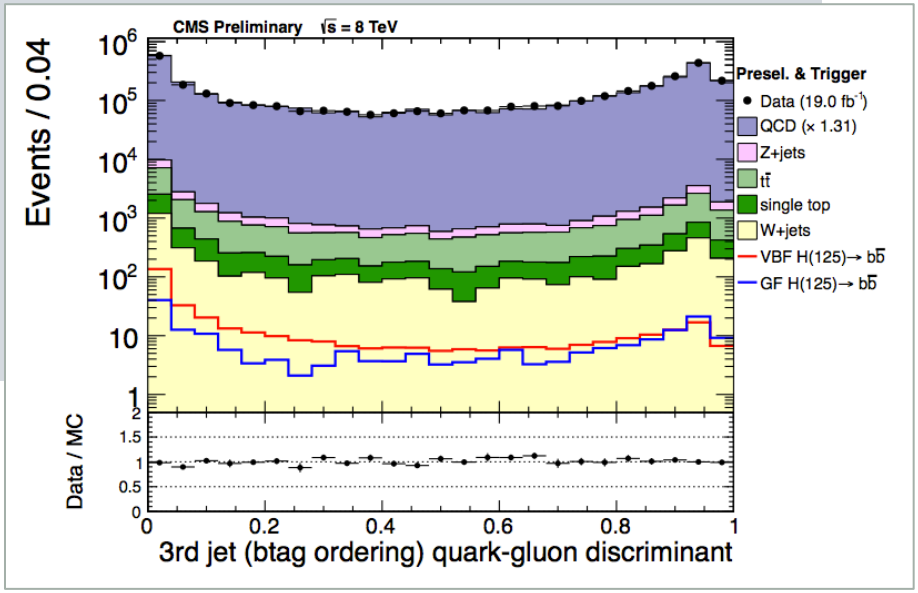
CMS HIG-13-011

VBF: CMS

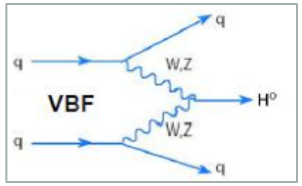
- **Fully hadronic final state**
  - QCD final state
    - 4 jets
  - VBF selection
    - Dedicated trigger
      - CMS L1 at 8 TeV: 3 jets, p_T >24, >44, >64 GeV
      - Only one of the two leading jets allowed to be forward



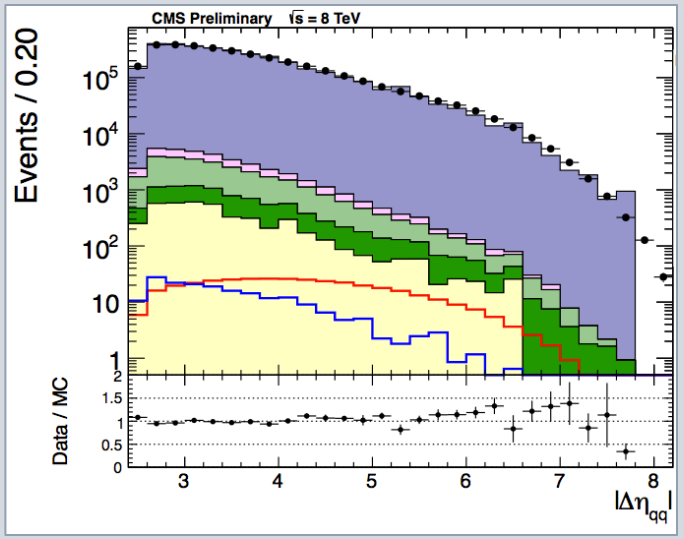
- **Quark/gluon-jet tagger**
  - Identify quarks up to |η|<4.7
- **Reconstruct VBF jet pair "qq"**
  1. Pair of least b-tagged jets
  2. Largest pseudorapidity separation



Discriminating variables



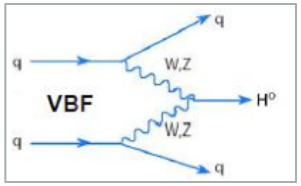
- **Discriminate VBF against QCD**
  1. Kinematics of qq pair
     - E.g. $\Delta\eta_{qq}$, m_{qq}
  2. B-tag discriminant values
  3. Quark/gluon discriminator
  4. Additional hadronic activity
     - H_T^{soft}: scalar sum of additional tracks
       - Track $p_T > 1$ GeV
       - Removing tracks from signal jets
       - Excluding region between b-tagged jets



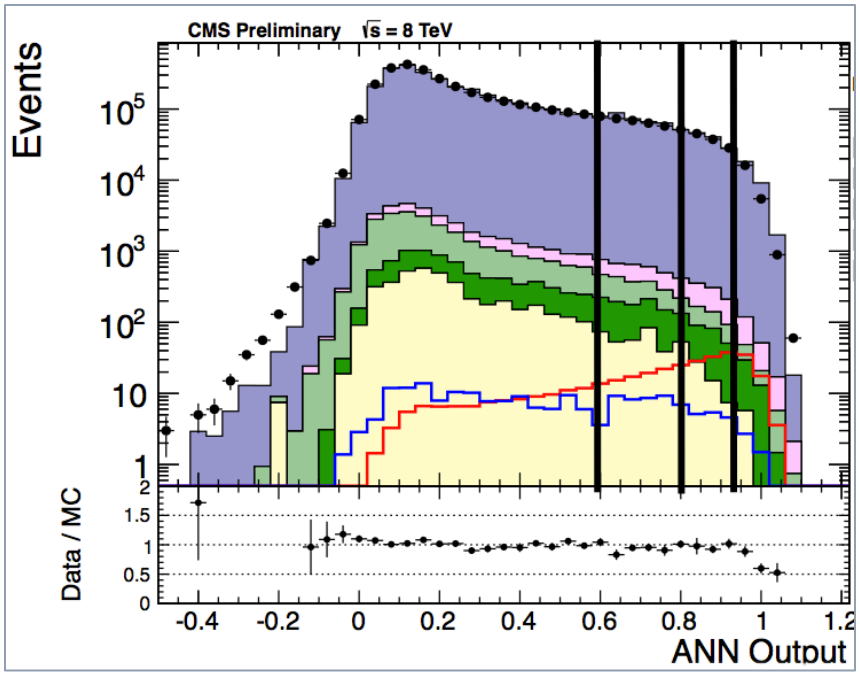
No kinematic information of b-tagged jets

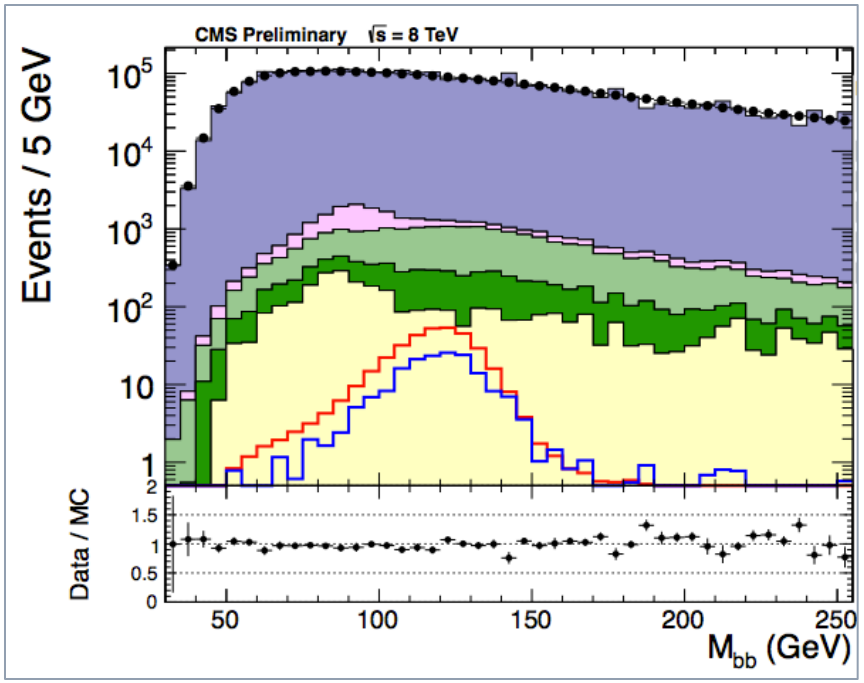
- Minimal correlation with M(bb)

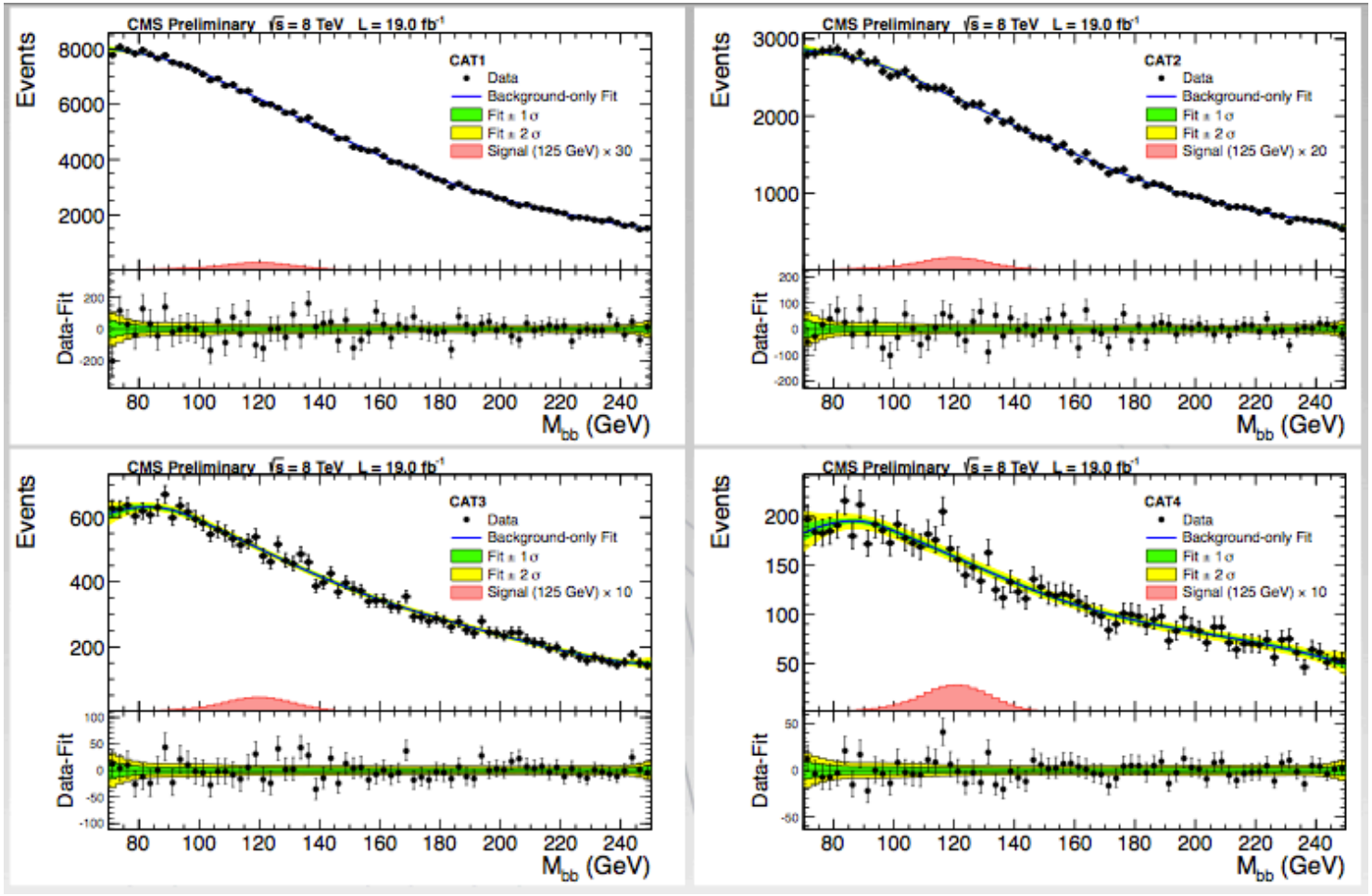
Categorization



- **Categorization according to neural net output**
  - Minimal correlation with M(bb)
- **Use M(bb) to extract signal**
  - Regression to improve resolution
    - See backup & VH
  - 4 categories

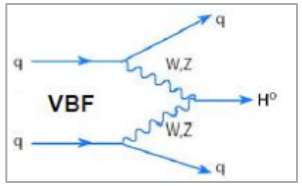




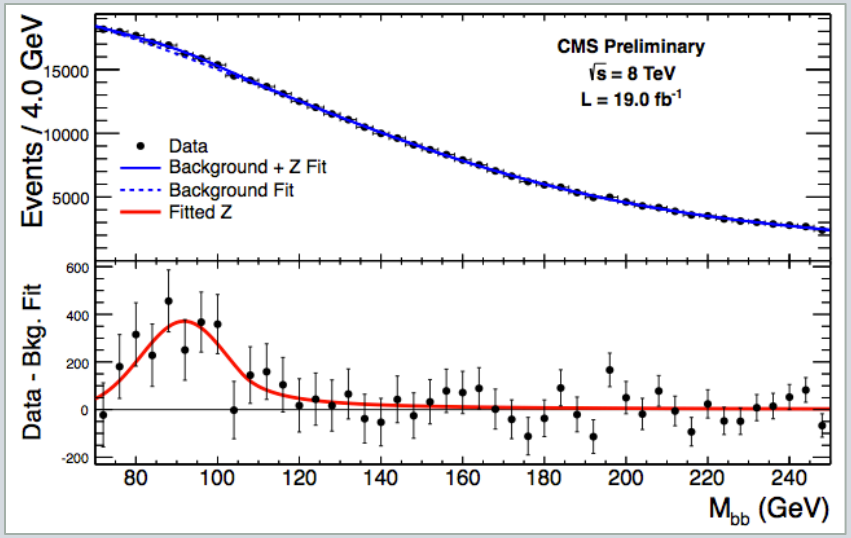


- **H→bb in VBF: Parameteric fit on top of falling spectrum**
  - 4 event categories
  - Describe m_{bb} spectrum of QCD background with 5^{th} degree polynomial

Control method

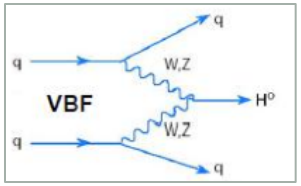


- **Fit of Z→bb peak to m(bb) distribution**
  - Looser event preselection
  - Same fitting procedure
    - Without systematics: 8.0σ obs (6.8σ exp)



  - After VBF Hbb pre-selection: 2.5σ
    - In agreement with expectations

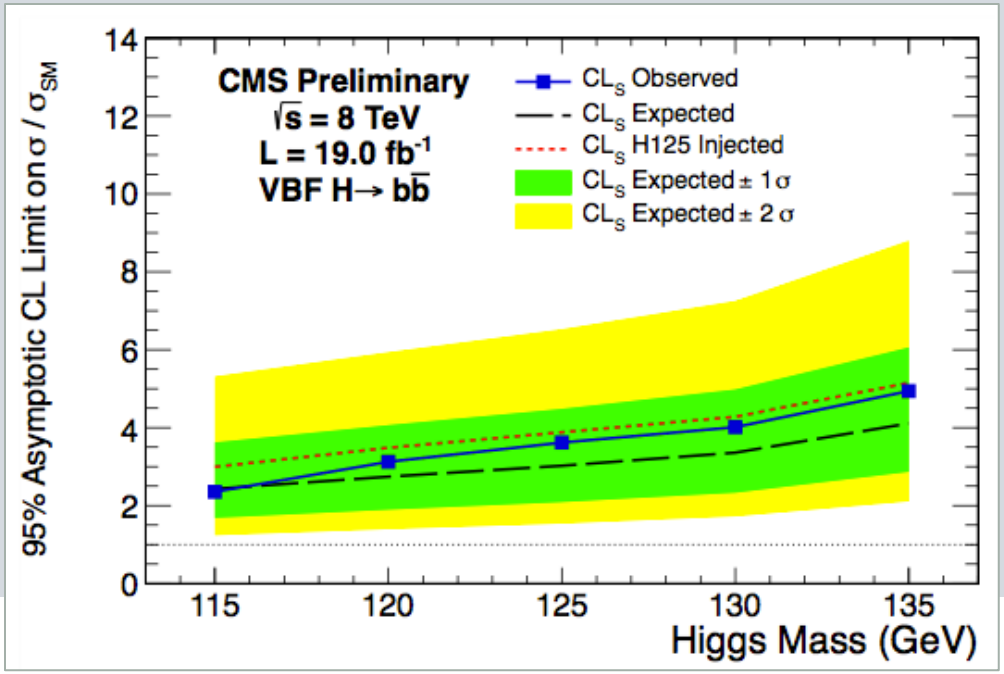
VBF result



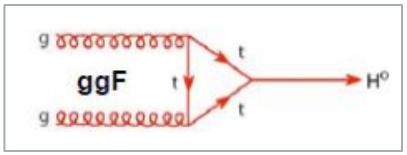
- **VBF recently added to H→bb results**
  - Complementing the VH and ttH searches

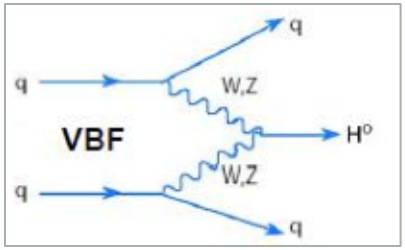
CMS HIG-13-011

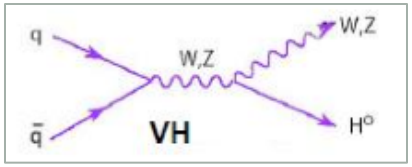
- **Limit at 125 GeV**
  - Observed: **3.6** x SM
  - Expected **3.0** x SM
- **Significance**
  - Observed: 0.5 σ
  - Expected: 0.7 σ
- **Best fit**
  - μ = 0.7±1.4

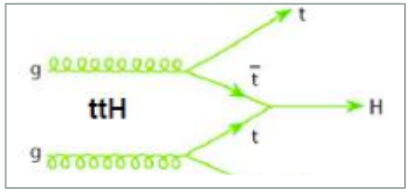


3★VH









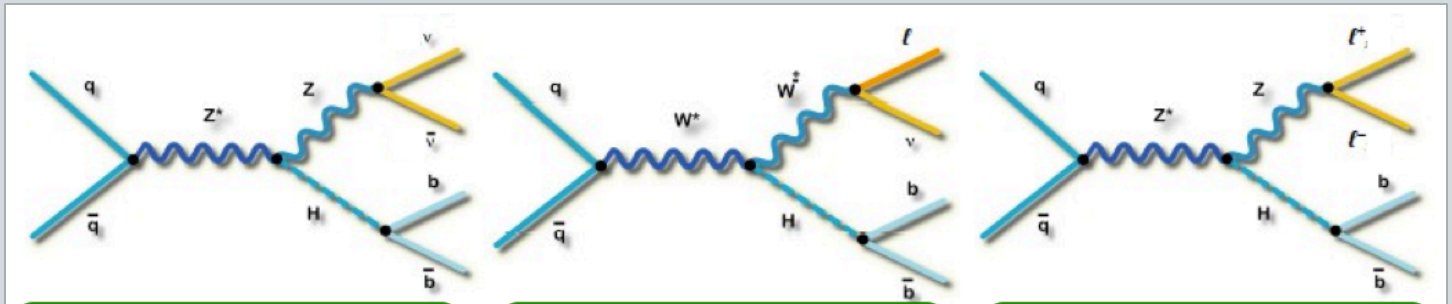
Best sensitivity for H→bb

- Intermediate cross section
- W/Z for signal identification

ATLAS CONF-2012-161

VH: Atlas

- **5 channels:**
  - Z(νν), W(eν), W(μν), Z(ee), Z(μμ)



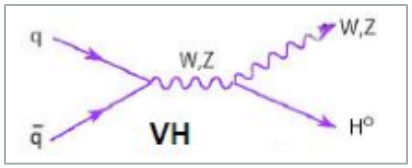
0-lepton
- no electrons or muons
- $E_T^{miss} > 120$ GeV

1-lepton
- exactly 1 high-p_T lepton
- $E_T^{miss} > 25$ GeV
- $40 < m_T^W < 120$ GeV

2-leptons
- exactly 2 high-p_T leptons
- opposite charge
- $E_T^{miss} < 60$ GeV
- $83 < m^Z < 99$ GeV

- In case of 3 jets: two leading-p_T b-tagged
- Extra topological requirements vary as function of vector boson boost

Strategy



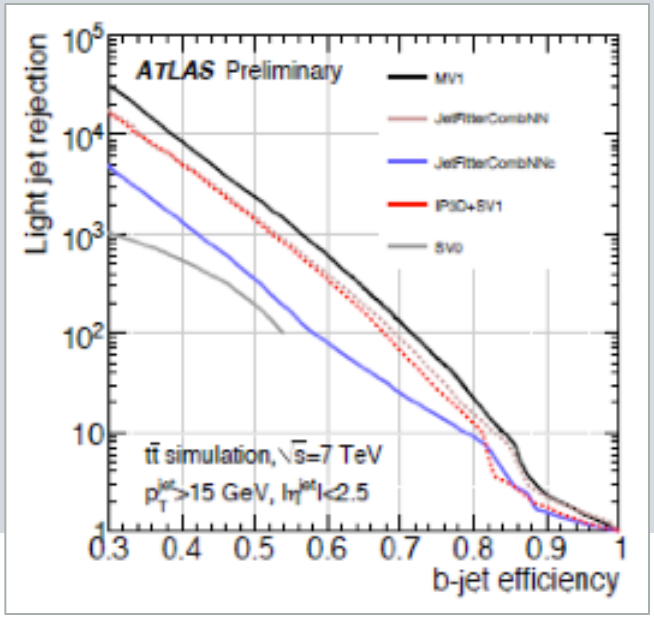
- **Binning as function of $p_T(V)$: increase sensitivity**

channel	bins (GeV)				
0 lepton (2/3j)			120-160	160-200	**>200**
1 lepton	0-50	50-100	100-150	150-200	**>200**
2 leptons	0-50	100-150	100-150	150-200	**>200**

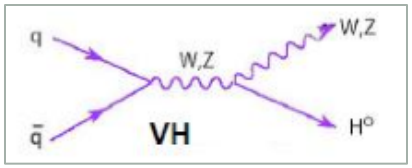
16 categories

B-tagging

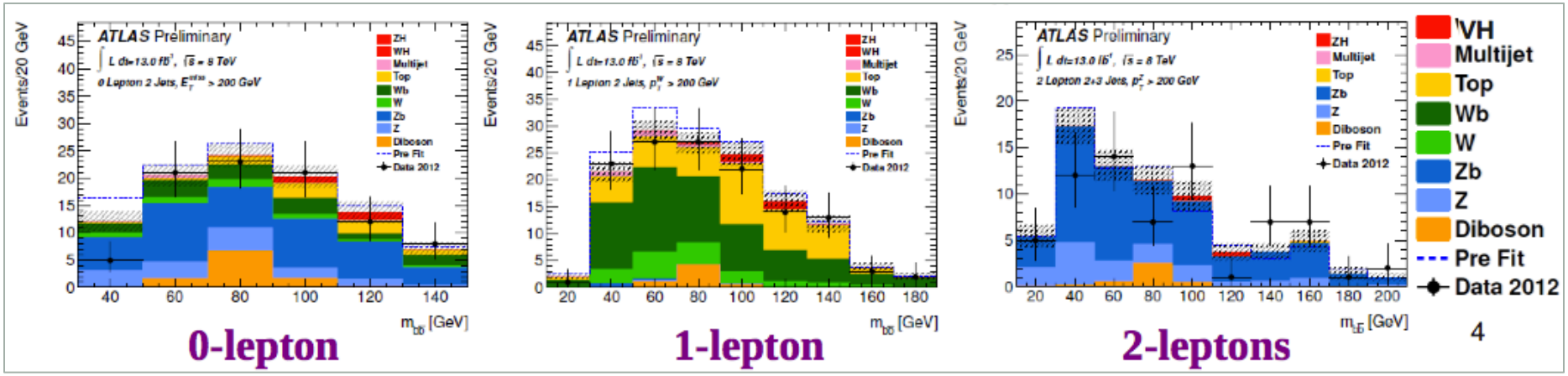
- **Neural Network using information from**
  - Secondary vertex
  - Tracks impact parameter
- **Performance**
  - 70% b-tag efficiency
  - 1% light-jet misidentification



Backgrounds

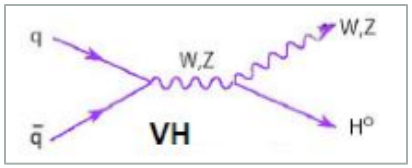


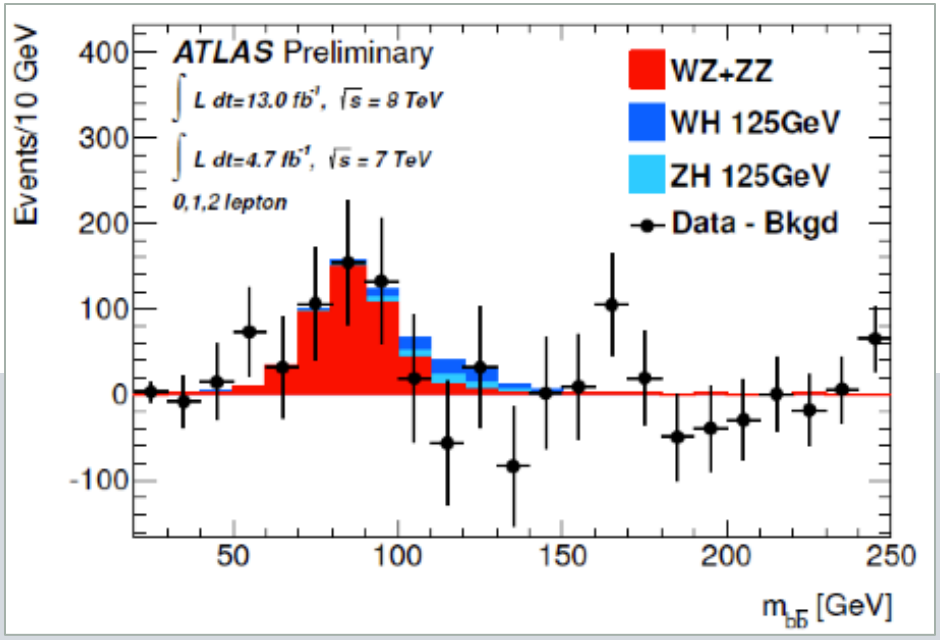
- **Data-derived multi-jet background**
- **Regions to control/normalize backgrounds**
  - **Top**: reverse top rejection criteria
    - 1-lepton: add 1/2 extra jets
    - 2-lepton: reverse cuts on m(ll) & missing E_T
  - **W+jets** & **Z+jets**: 0/1 b-tags



- **Final discriminant: invariant mass of pair of b-tagged jets**
  - Simultaneously fit all 16 categories + control regions

VH cross-check: VV

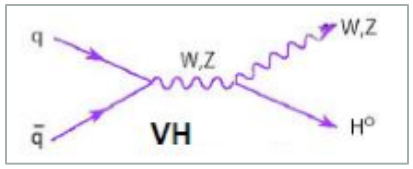


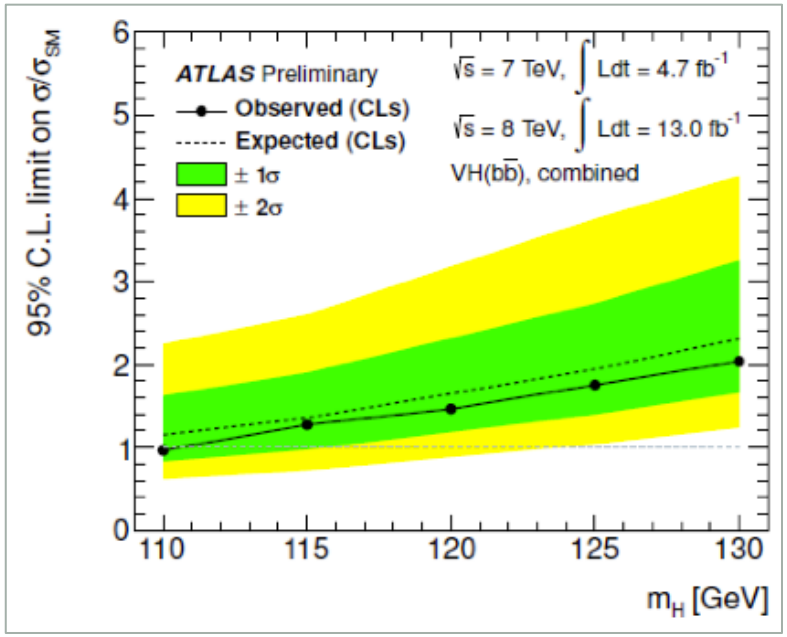


- **Cross check analysis: VZ diboson**
  - VH as background, VZ as signal
    - Data-MC subtracted

- **σ/σ_{SM} = 1.09 ± 0.20 (stat) ± 0.22 (syst)**
  - Significance of 4.0 σ

VH result





- **Main systematics**
  - b/c-tag efficiencies
  - jet energy scale/resolution
  - MC statistics
- **Constrained by fit to M(bb)**

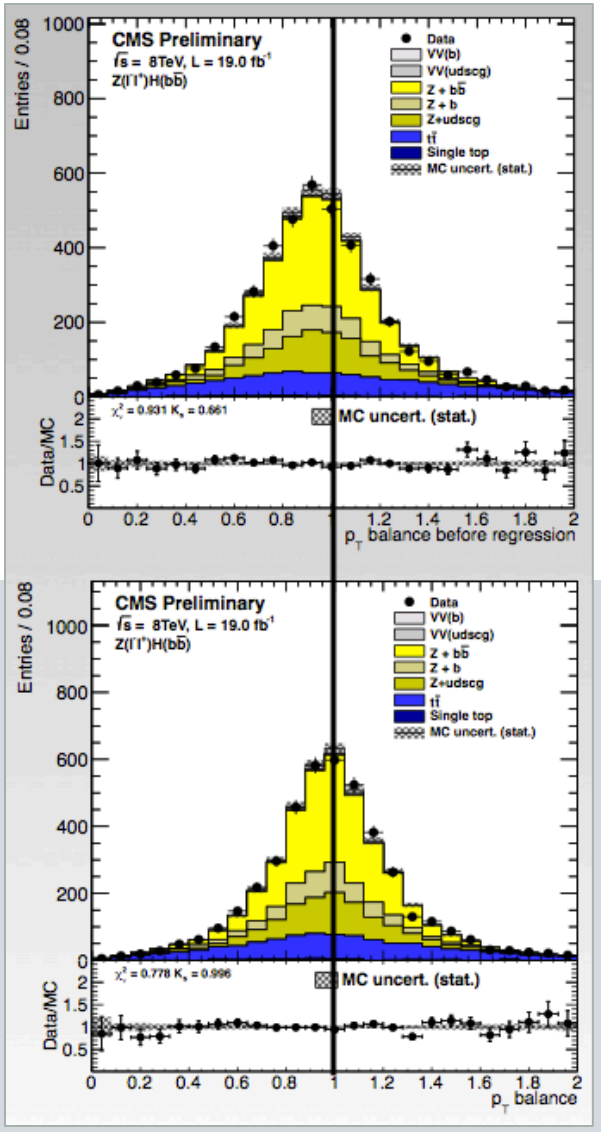
- **Limit on σ/σ_{SM}: 1.8 obs (1.9 exp)**
  - 95% CL for SM Higgs with m_H = 125 GeV

ATLAS CONF-2012-161

CMS VH strategy

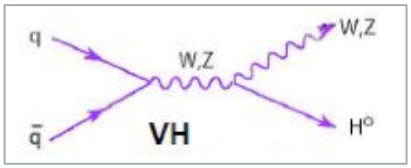
- **Di-jet selection in boosted regime**
  - Binning in $p_T(V)$
  - 6 modes: 2xZ(ll), Z(vv), 2xW(lv), **W(τv)**
    - W(τv): 8 TeV dataset
      - 1-prong hadronic

NEW! (LHCP)
CMS HIG-13-012

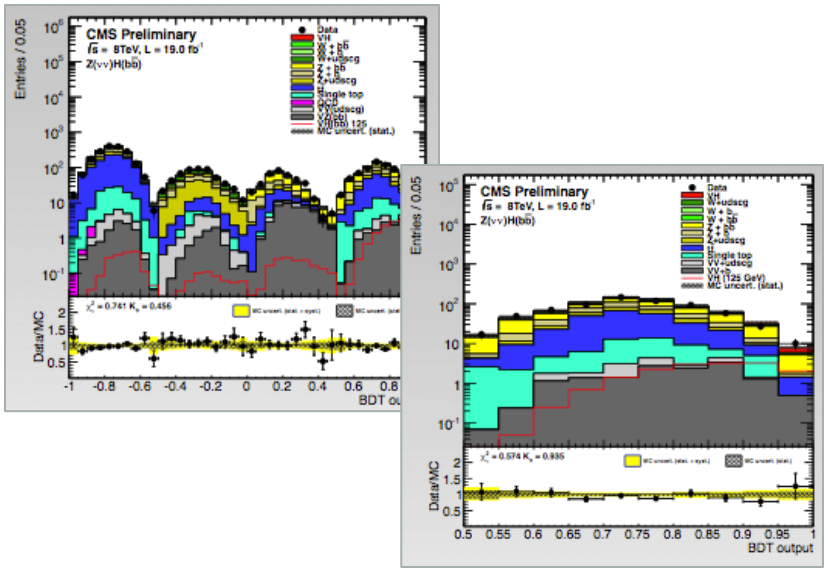


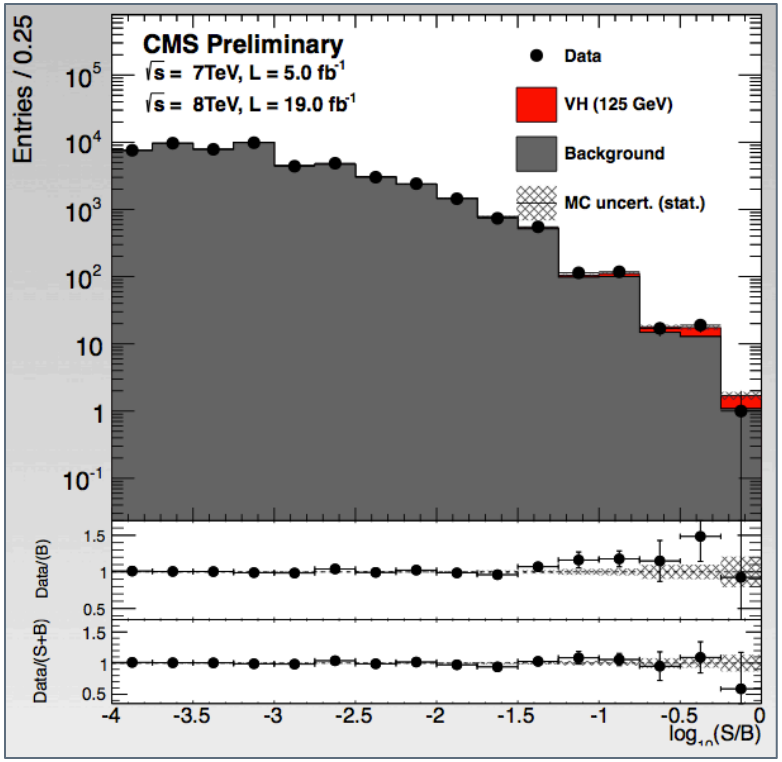
- **Boosted Decision Trees**
  - Signal & background:
    discriminate using BDT output
    - Input variables quite similar to ttH (see backup)
    - Dominant backgrounds (tt & V+jets) normalization from data
  - **Improve mass resolution** using BDT regression
    - Improvement validated on data

BDT Categories



- **14 BDT categories**
  - Wlν (6), Zνν (3), Zll (4), Wτν (1)

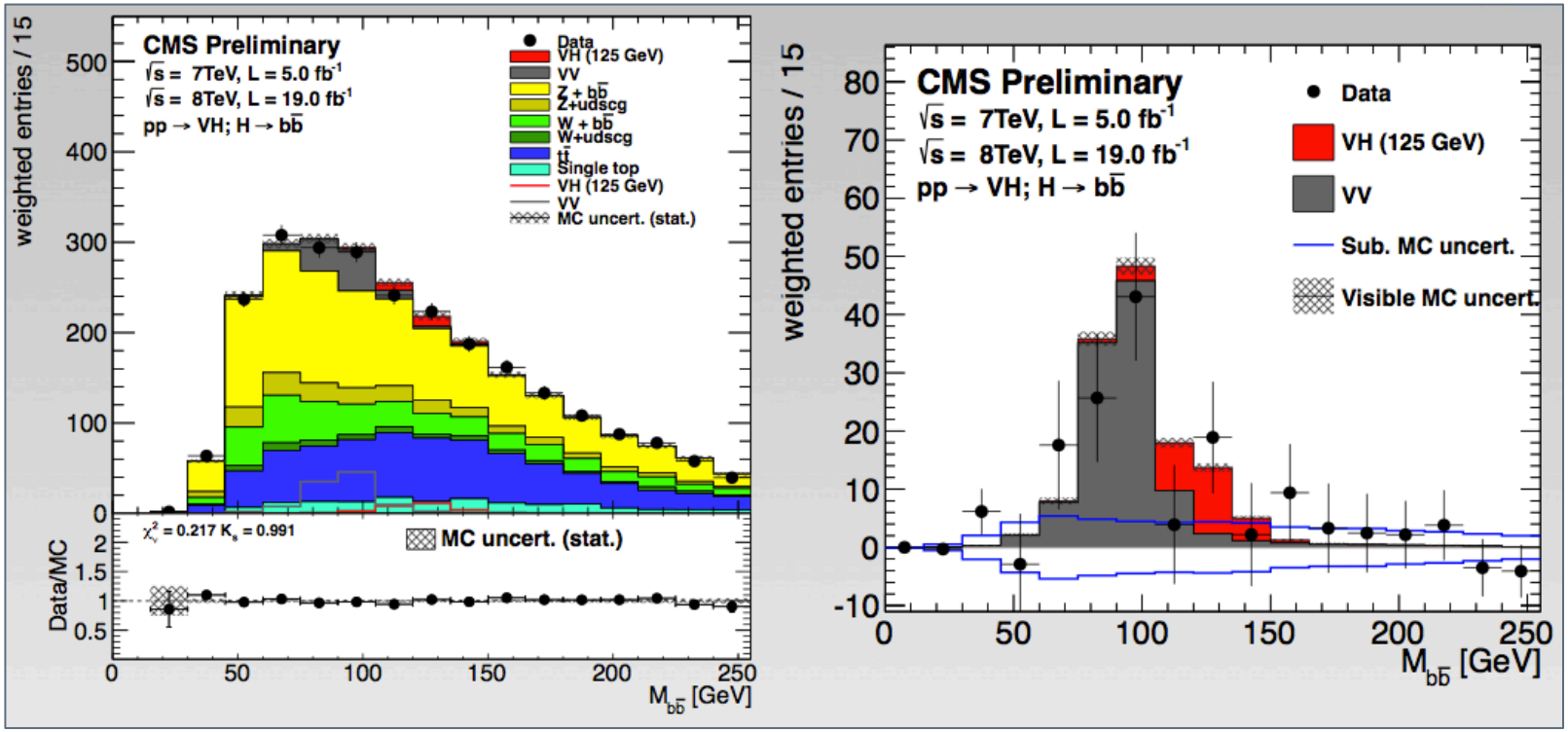




- **Enriched subsets**
  - tt, V+jets, VV, VH

- **Summarize BDT**
  - Sort bins in S/B

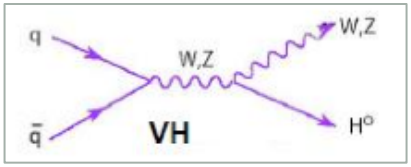
VH cross-check: VZ



- **Method validated on VZ(bb), using same technique**
  - Significance: 7.5σ obs (6.3σ exp)
  - Signal strength: $\mu = 1.19^{+0.27}_{-0.23}$

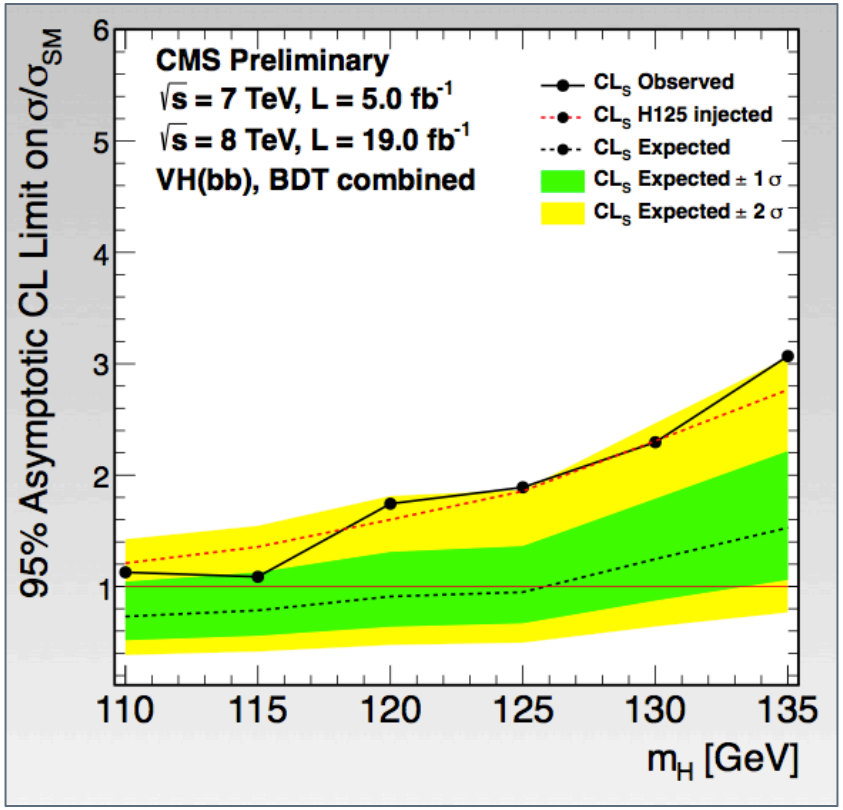
Figures from di-jet cross-check analysis

VH result



For m_H=125 GeV

- **Observed: 1.89xSM**
- **Expected: 0.95xSM**

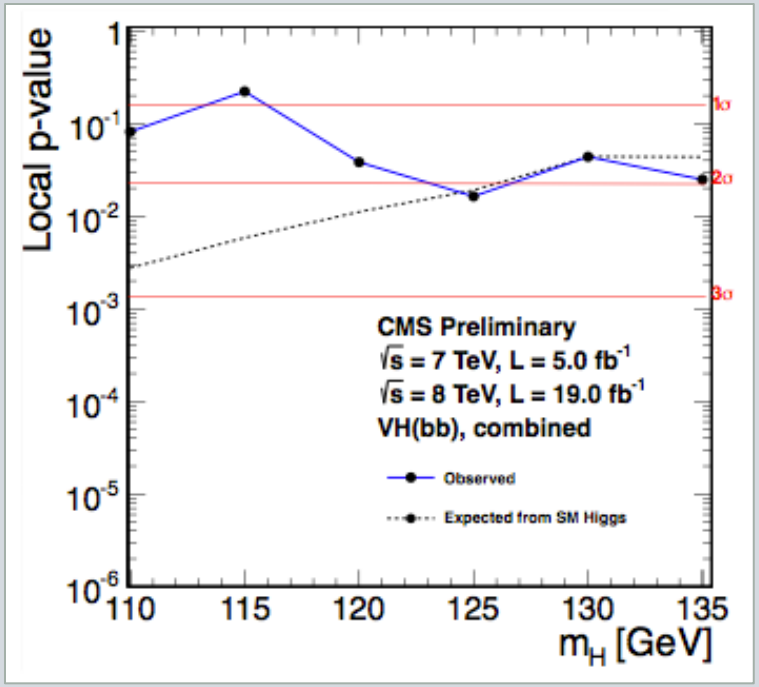


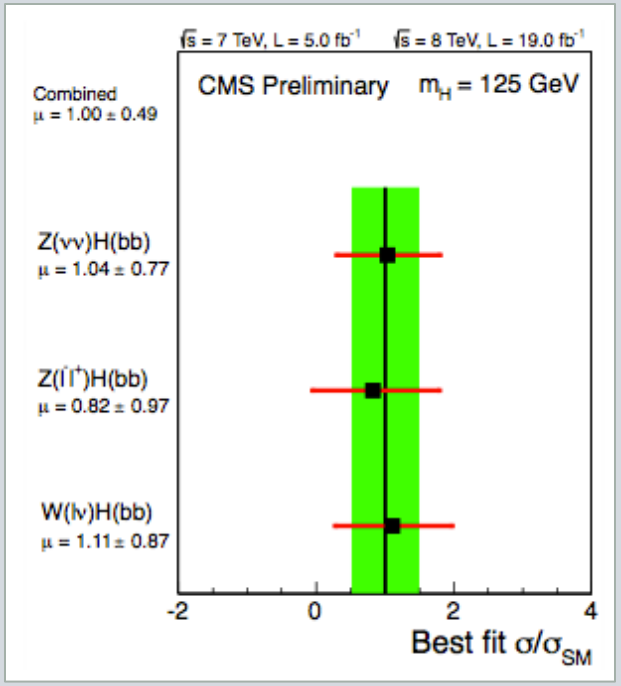
- Observation **agrees with expectation** for SM Higgs boson of 125 GeV

CMS HIG-13-012

Signal significance

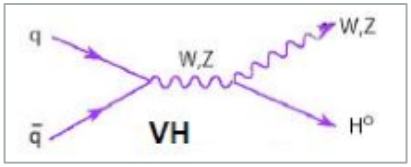
- **VH(bb) at 125 GeV**



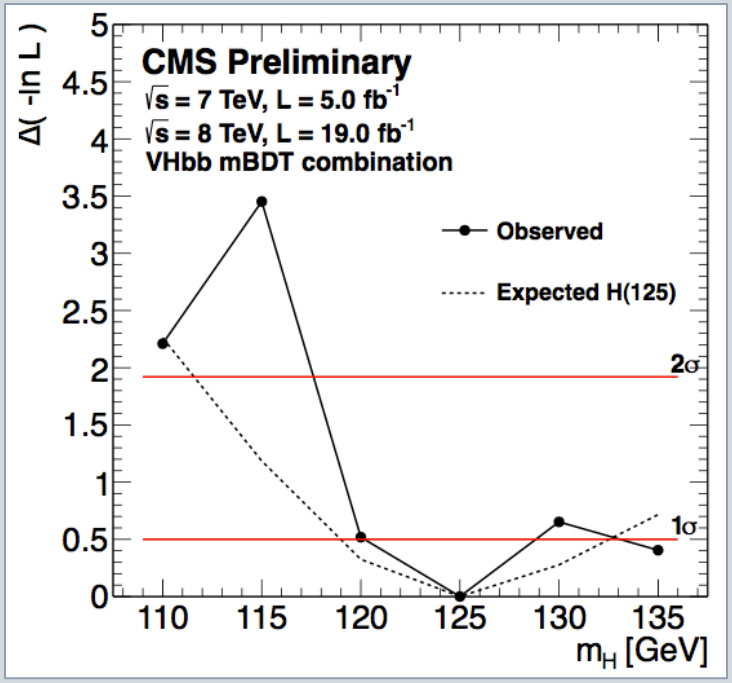


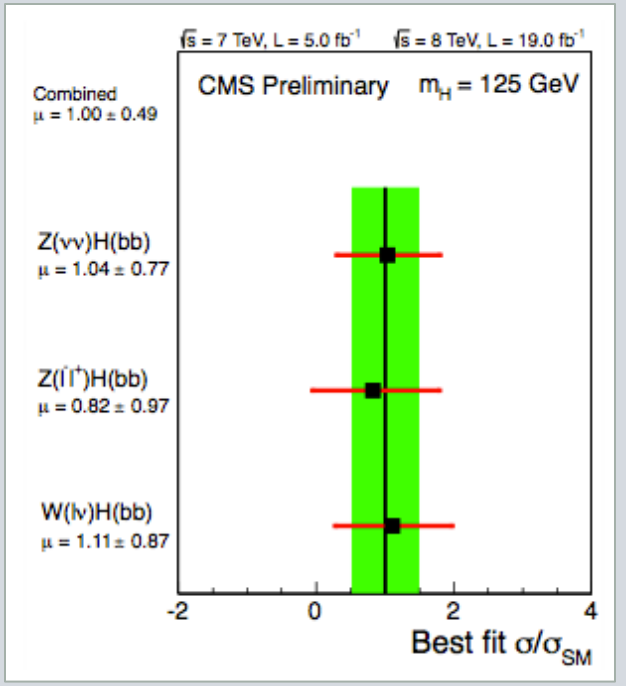
- **Significance: 2.1σ obs.** (2.1σ exp.)
- **Best fit: μ=1.0±0.5**

Significance



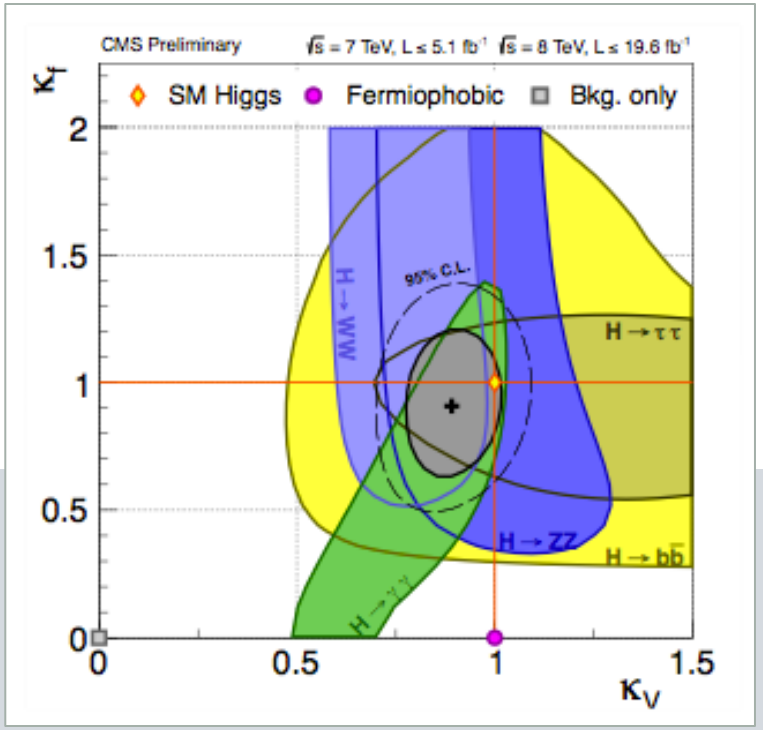
- **VH(bb) at 125 GeV**





- **Significance: 2.1σ obs** (2.1σ exp.)
- **Best fit: μ=1.0±0.5**

Couplings



- **Contribution of H→bb to coupling measurement**
  - See presentation on properties by Alessio Bonato

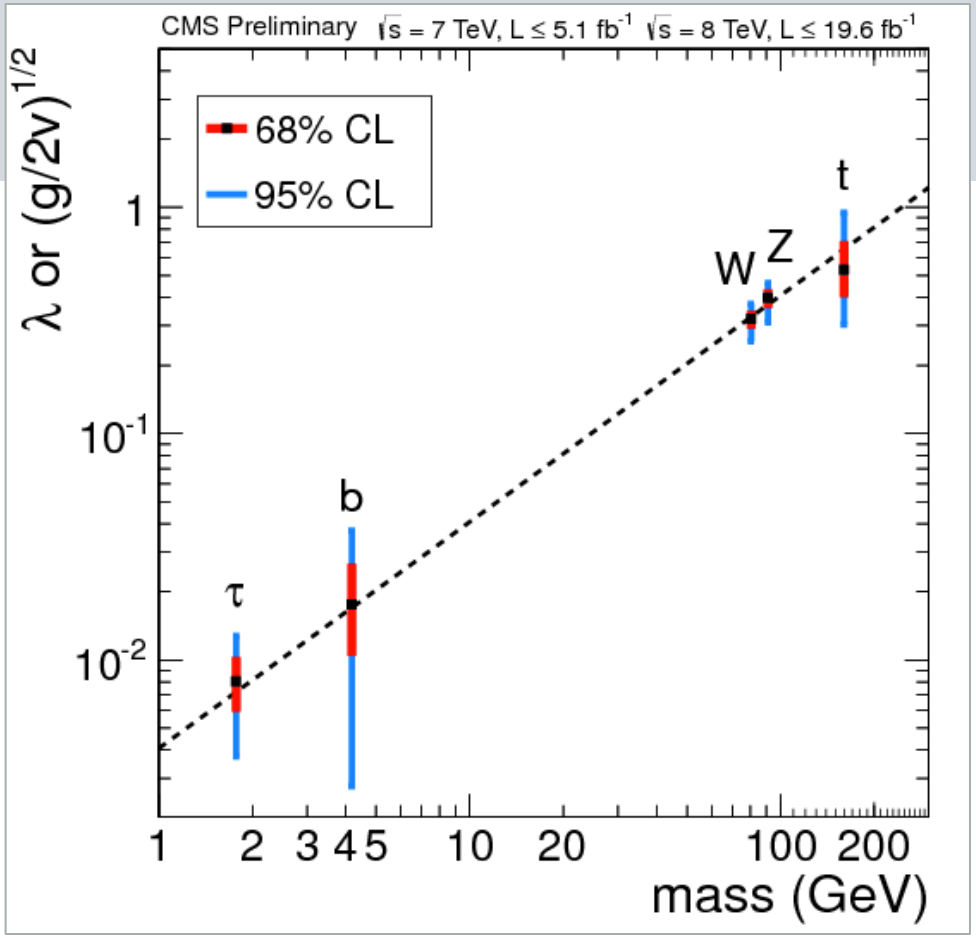
- **CMS: evidence for decay in fermion final states**
  - Combining H→ττ and VH(bb)
  - **3.4 sigma** (exp.&obs.)

CMS HIG-13-005

CMS HIG-13-005

Couplings

- **Mass vs coupling agrees with prediction**



Summary

Search for H→bb

- Results of Atlas & CMS
- Test of fermion final state
- Coupling to quarks

Challenging

- ggF: multi-jet backgrounds
- Study associated productions
  - No loops: ttH, VH, VBF

Prod.	Atlas limit obs. (exp.)	CMS limit obs. (exp.)
ggF	-	-
ttH	**13.1 (10.5)** [5 /fb]	**5.8 (5.2)** [5+5 /fb]
VBF	-	**3.6 (3.0)** [19 /fb]
VH	**1.8 (1.9)** [5+13 /fb]	**1.9 (1.0)** [5+19 /fb]

CMS: H→bb in VH with significance of 2.1σ (2.1σ exp.)

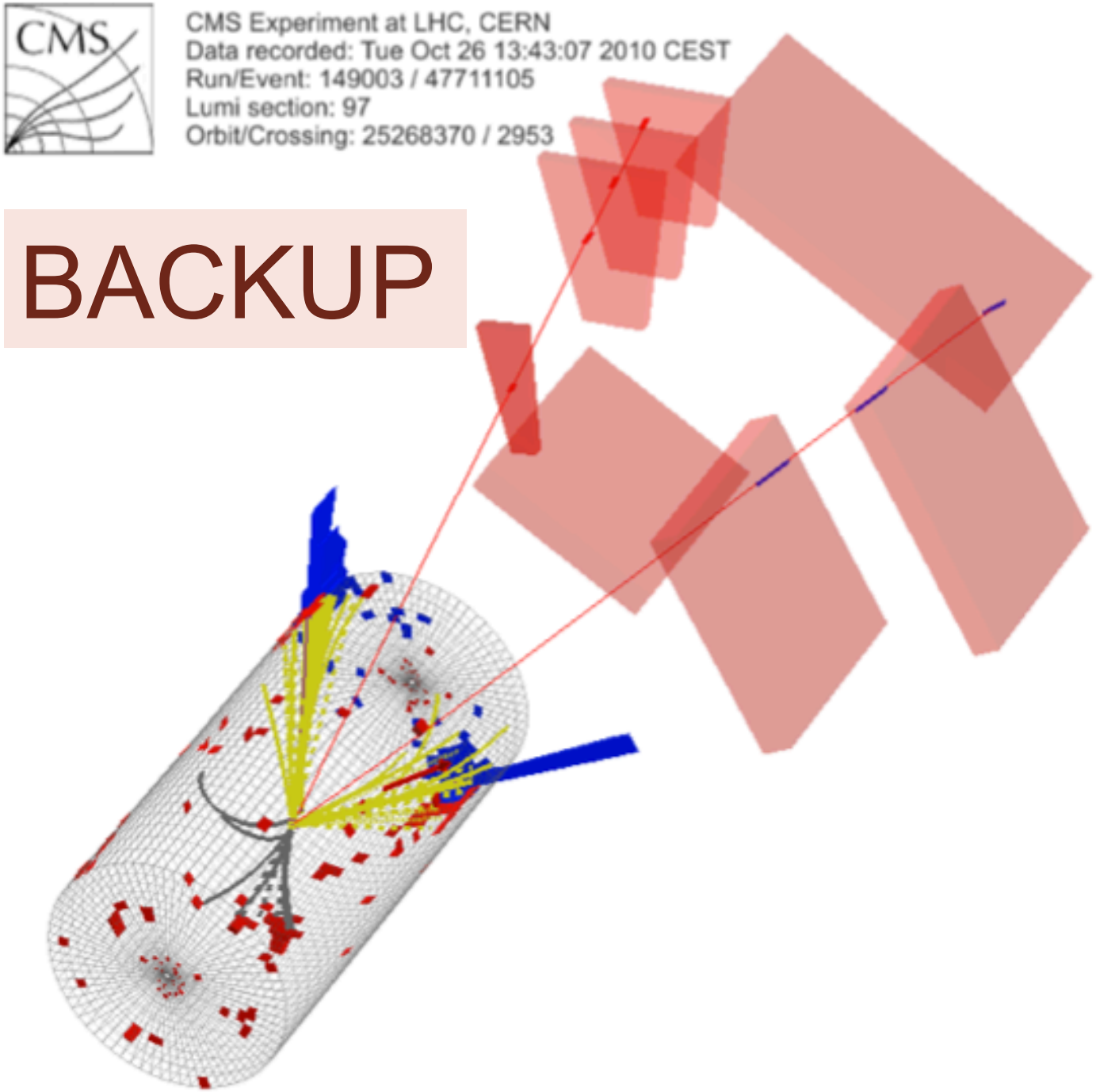
- **Large variety** of H→bb studies by Atlas and CMS
- H→bb **agrees with predictions** of SM Higgs boson

- **ttH**
  - ATLAS CONF-2012-135
  - CMS HIG-12-035
- **VBF**
  - CMS HIG-13-011
- **VH**
  - ATLAS CONF-2012-161
  - CMS HIG-13-012

Thank you for your attention

- **ttH**
  - ATLAS CONF-2012-135
  - CMS HIG-12-035
- **VBF**
  - CMS HIG-13-011
- **VH**
  - ATLAS CONF-2012-161
  - CMS HIG-13-012

…and see you at Shozankan!


CMS
CMS Experiment at LHC, CERN
Data recorded: Tue Oct 26 13:43:07 2010 CEST
Run/Event: 149003 / 47711105
Lumi section: 97
Orbit/Crossing: 25268370 / 2953

BACKUP

H→bb References

- **VH**
  - ATLAS CONF-2012-161
  - CMS HIG-13-012
- **VBF**
  - CMS HIG-13-011
- **ttH**
  - ATLAS CONF-2012-135
  - CMS HIG-12-035

- **Fermionic channels at LHCP:**
  - Atlas (D.Jamin): https://indico.cern.ch/getFile.py/access?contribId=295&sessionId=11&resId=0&materialId=slides&confId=210555
  - CMS (N.Mohr): https://indico.cern.ch/materialDisplay.py?contribId=296&sessionId=11&materialId=slides&confId=210555

CMS ttH

Table 4: The ANN inputs for the nine jet-tag categories in the 8 TeV $t\bar{t}H$ analysis in the lepton+jets and dilepton channels. The choice of inputs is optimized for each category. Definitions of the variables are given in the text. The best input variable for each jet-tag category is denoted by ★.

	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}									✓
$p_T(\ell, E_T^{miss}, jets)$		★	✓		✓	✓		✓	✓
$M(\ell, E_T^{miss}, jets)$	✓	✓		✓	✓		✓		
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		✓	✓	✓	✓	✓	✓		

CMS
ttH

Table 5: Summary of the systematic uncertainties considered on the inputs to the limit calculation. Except where noted, each row in this table will be treated as a single, independent nuisance parameter.

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 $t\bar{t}+b\bar{b}$.

CMS VBF (Yields)

Table 1: ANN output boundaries for the definition of preselected event categories.

Cat. 0	Cat. 1	Cat. 2	Cat. 3	Cat. 4
$ANN < 0.52$	$0.52 \leq ANN < 0.76$	$0.76 \leq ANN < 0.90$	$0.90 \leq ANN < 0.96$	$ANN \geq 0.96$

Table 2: Expected number of events in the m_{bb} interval $[70, 250\,\text{GeV}]$, in each ANN output category.

Sample/ANN range	< 0.52	$0.52 - 0.76$	$0.76 - 0.90$	$0.90 - 0.96$	> 0.96
QCD	1.9e+6	3.2e+5	1.1e+5	2.7e+4	8.7e+3
$Z + jets$	5531	1222	531	124	54
$t\bar{t}$	12730	1032	190	33	15
t	1839	383	128	25	10
$\bar{t}$	895	226	73	15	7
$W + jets$	2033	226	50	4	<1
VBF $M_H(125)$	66	79	84	49	33
GF $M_H(125)$	94	37	18	6	2

CMS VBF Systematics

Source	Uncertainty
Background fit	depending on the statistics of each category
Z+jets cross section	±20%
top cross section	±20%
Signal and Z peak position (JES)	±1.5%
Signal and Z resolution	±10%
Luminosity	±4.4%
Trigger efficiency	±5 – 8%
Signal acceptance due to JES	±10%
Signal acceptance due to JER	±2%
VBF cross section	±3%
VBF Monte Carlo acceptance	±10%
PDF	±5%
VBF ANN shape due to b-tag	±2%
VBF ANN shape due to quark-gluon discriminator	±2%
VBF ANN shape due to UE modeling	−8 – +2%
GF cross section	±15%
GF Monte Carlo acceptance	±50%
GF ANN shape	±50%

CMS VH Selection

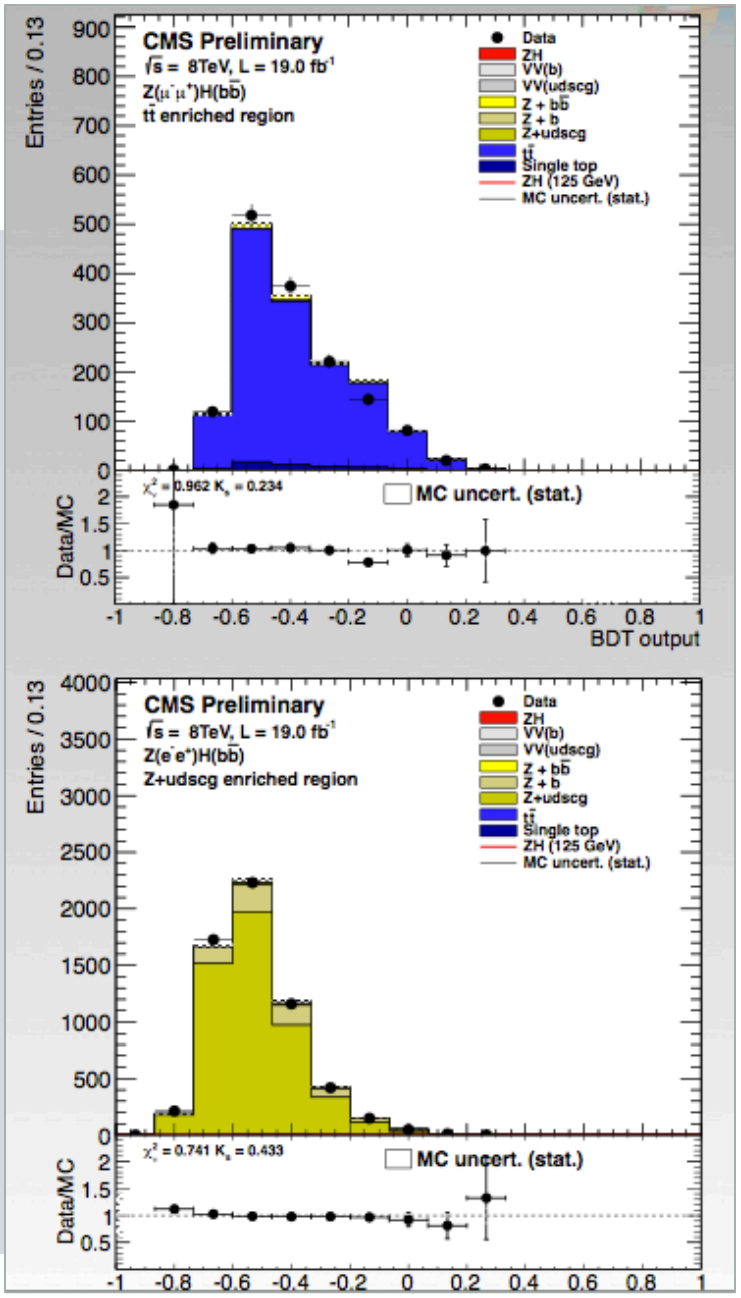
Variable	W($\ell\nu$)H	W($\tau\nu$)H	Z($\ell\ell$)H	Z($\nu\nu$)H
$m_{\ell\ell}$	–	–	$[75-105]$	–
$p_T(j_1)$	> 30	> 30	> 20	> 60
$p_T(j_2)$	> 30	> 30	> 20	> 30
p_T(jj)	> 100	> 120	–	> 100 (> 130,> 130)
m(jj)	< 250	< 250	$[40-250]$ (< 250)	< 250
p_T(V)	$100-130$ ($130-180$,> 180)	> 120	$[50-100]$ (> 100)	–
CSV_{max}	> 0.40	> 0.40	> 0.50 (> 0.244)	> 0.679
CSV_{min}	> 0.40	> 0.40	> 0.244	> 0.244
N_{aj}	–	–	–	< 2 (–,–)
N_{al}	$= 0$	$= 0$	–	$= 0$
E_T^{miss}	> 45	> 80	–	$[100-130]$ ($[130-170]$,> 170)
$\Delta\phi$(V,H)	–	–	–	> 2.0
$\Delta\phi(E_T^{miss}$,jet)	–	–	–	> 0.7 (> 0.7, > 0.5)
$\Delta\phi(E_T^{miss}, E_T^{miss(trks)})$	–	–	–	< 0.5
E_T^{miss} significance	–	–	–	> 3 (–,–)
$\Delta\phi(E_T^{miss},\ell)$	$< \pi/2$		–	–
$p_T(\tau)$	–	> 40	–	–
$p_T(track)$	–	> 20	–	–

CMS VH
BDT variables

Variable
$p_T(j)$: transverse momentum of each Higgs daughter
m(jj): dijet invariant mass
p_T(jj): dijet transverse momentum
p_T(V): vector boson transverse momentum (or E_T^{miss})
CSV_{max}: value of CSV for the Higgs daughter with largest CSV value
CSV_{min}: value of CSV for the Higgs daughter with second largest CSV value
$\Delta\phi$(V, H): azimuthal angle between V (or E_T^{miss}) and dijet
$\lvert\Delta\eta$(jj)$\rvert$: difference in η between Higgs daughters
ΔR(jj): distance in η–ϕ between Higgs daughters
N_{aj}: number of additional jets
$\Delta\theta_{pull}$: color pull angle [34]
$\Delta\phi(E_T^{miss}$, jet): azimuthal angle between E_T^{miss} and the closest jet (only for Z($\nu\nu$)H)
$maxCSV_{aj}$: maximum CSV of the additional jets in an event (only for Z($\nu\nu$)H and W($\ell\nu$)H)
$min\Delta R$(H, aj): mimimum distance between an additional jet and the Higgs candidate (only for Z($\nu\nu$)H and W($\ell\nu$)H)
Angular variables: HV system mass, Angle Z-Z*, Angle Z-l, Angle H-jet (only for Z($\ell\ell$)H)

CMS VH Control Regions

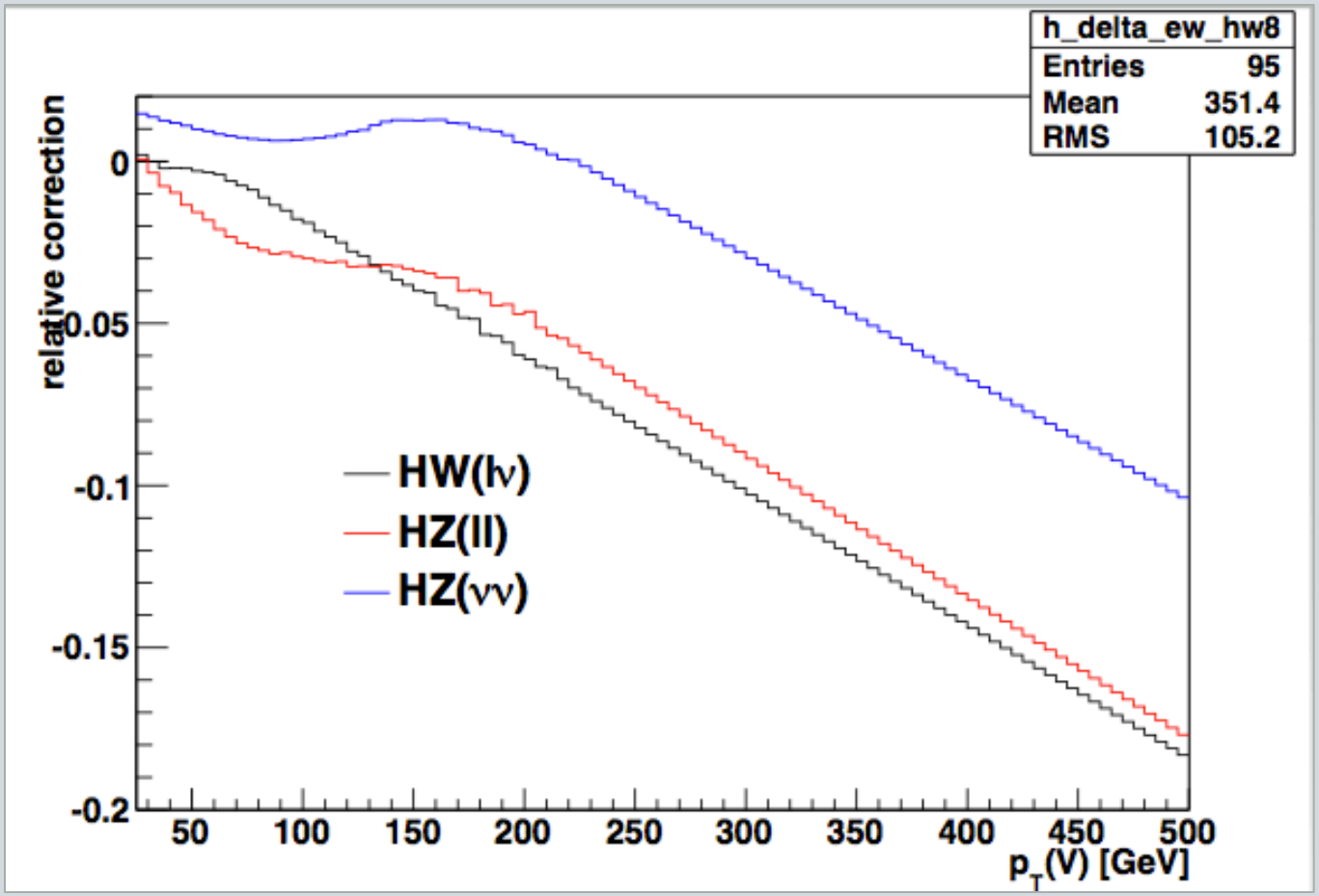
Process	W($\ell\nu$)H	Z($\ell\ell$)H	Z($\nu\nu$)H
Low p_T			
W0b	$1.03 \pm 0.01 \pm 0.05$	–	$0.83 \pm 0.02 \pm 0.04$
W1b	$2.22 \pm 0.25 \pm 0.20$	–	$2.30 \pm 0.21 \pm 0.11$
W2b	$1.58 \pm 0.26 \pm 0.24$	–	$0.85 \pm 0.24 \pm 0.14$
Z0b	–	$1.11 \pm 0.04 \pm 0.06$	$1.24 \pm 0.03 \pm 0.09$
Z1b	–	$1.59 \pm 0.07 \pm 0.08$	$2.06 \pm 0.06 \pm 0.09$
Z2b	–	$0.98 \pm 0.10 \pm 0.08$	$1.25 \pm 0.05 \pm 0.11$
$t\bar{t}$	$1.03 \pm 0.01 \pm 0.04$	$1.10 \pm 0.05 \pm 0.06$	$1.01 \pm 0.02 \pm 0.04$
Intermediate p_T			
W0b	$1.02 \pm 0.01 \pm 0.07$	–	$0.93 \pm 0.02 \pm 0.04$
W1b	$2.90 \pm 0.26 \pm 0.20$	–	$2.08 \pm 0.20 \pm 0.12$
W2b	$1.30 \pm 0.23 \pm 0.14$	–	$0.75 \pm 0.26 \pm 0.11$
Z0b	–	–	$1.19 \pm 0.03 \pm 0.07$
Z1b	–	–	$2.30 \pm 0.07 \pm 0.08$
Z2b	–	–	$1.11 \pm 0.06 \pm 0.12$
$t\bar{t}$	$1.02 \pm 0.01 \pm 0.15$	–	$0.99 \pm 0.02 \pm 0.03$
High p_T			
W0b	$1.04 \pm 0.01 \pm 0.07$	–	$0.93 \pm 0.02 \pm 0.03$
W1b	$2.46 \pm 0.33 \pm 0.22$	–	$2.12 \pm 0.22 \pm 0.10$
W2b	$0.77 \pm 0.25 \pm 0.08$	–	$0.71 \pm 0.25 \pm 0.15$
Z0b	–	$1.11 \pm 0.04 \pm 0.06$	$1.17 \pm 0.02 \pm 0.08$
Z1b	–	$1.59 \pm 0.07 \pm 0.08$	$2.13 \pm 0.05 \pm 0.07$
Z2b	–	$0.98 \pm 0.10 \pm 0.08$	$1.12 \pm 0.04 \pm 0.10$
$t\bar{t}$	$1.00 \pm 0.01 \pm 0.11$	$1.10 \pm 0.05 \pm 0.06$	$0.99 \pm 0.02 \pm 0.03$



CMS VH Systematics

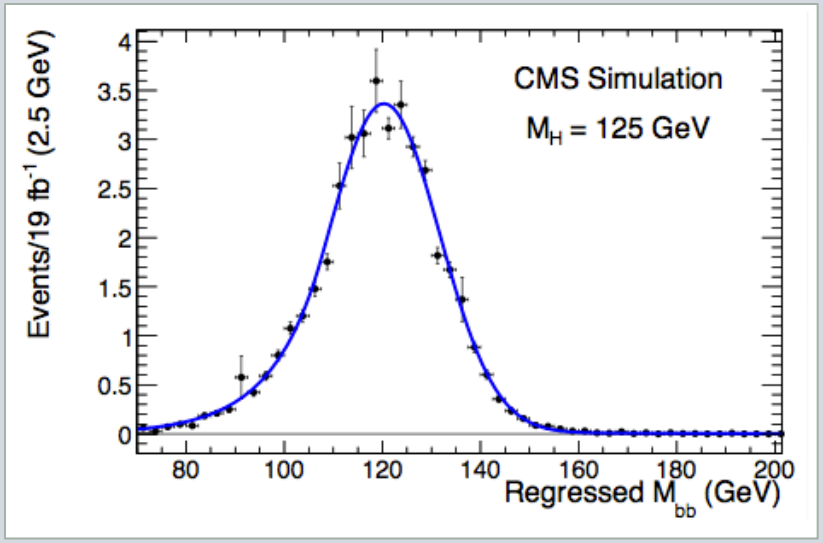
Source	Type	Yield uncertainty Range	Impact on expected significance
Luminosity	normalization	2.2-4.4%	$< -0.1\%$
Lepton efficiency and trigger (per lepton)	normalization	3%	$< -0.1\%$
$Z(\nu\nu)H$ triggers	shape	3%	$< -0.1\%$
Jet energy scale	shape	2–3%	-0.5%
Jet energy resolution	shape	3–6%	-0.7%
Missing transverse energy	shape	3%	-0.2%
b-tagging	shape	3–15%	-2.1%
Signal cross section (scale and PDF)	normalization	4%	-0.3%
Signal cross section (p_T boost, EWK/QCD)	normalization	2% / 5%	-0.3%
Signal Monte Carlo statistics	shape	1-5%	-3.6%
Backgrounds (data estimate)	normlization	$\approx 10\%$	-5.2%
Single-top (simulation estimate)	normalization	15–30%	-0.5%
Dibosons (simulation estimate)	normalization	30%	-0.5%
MC modeling (V+jets and $t\bar{t}$)	shape	10%	-1.1%

VH: NLO EW


h_delta_ew_hw8
Entries 95
Mean 351.4
RMS 105.2
relative correction
0
-0.05
-0.1
-0.15
-0.2
HW(lν)
HZ(ll)
HZ(νν)
50
100
150
200
250
300
350
400
450
500
p_T(V) [GeV]

Mbb

- **Regressed Mbb in VBF**



tion about the jet properties and structure. The inputs include (i) the CSV b-tagging output and variables containing information about a secondary vertex when present; (ii) the jet-energy fractions carried by charged hadrons, neutral hadrons, photons, electrons, or muons; (iii) the jet p_T, η and p_T distribution of its components; (iv) the event missing energy and azimuthal direction relative to the jet; (v) the event FastJet-ρ. The target of the regression is the p_T of the associated particle-level jet, clustered from all stable particles, excluding neutrinos.

VBF

- **Quark/gluon discriminator input variables**

lowing internal jet composition and structure observables, based on the PFJet constituents: (i) the jet constituents major quadratic mean (RMS) in the $\eta\phi$ plane, (ii) the jet constituents minor RMS in the $\eta\phi$ plane, (iii) the jet asymmetry pull [24], (iv) the jet particle multiplicity, and (v) the maximum energy fraction carried by a jet constituent. The pull and RMS variables are calculated weighing each jet constituent with its squared transverse momentum.

Atlas VH

- **Table of cuts**

Table 1: The basic event selection of the three channels. The details of the cuts on the individual objects are summarised in the text.

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_{\mathrm{T}}^{1} > 45$ GeV $p_{\mathrm{T}}^{2} > 20$ GeV + ≤ 1 extra jets	2 b-tags $p_{\mathrm{T}}^{1} > 45$ GeV $p_{\mathrm{T}}^{2} > 20$ GeV + 0 extra jets	2 b-tags $p_{\mathrm{T}}^{1} > 45$ GeV $p_{\mathrm{T}}^{2} > 20$ GeV -
Missing E_T	$E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$ $\mathrm{Min}[\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})] > 1.5$ $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, b\bar{b}) > 2.8$	-	$E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV
Vector Boson	-	$m_{\mathrm{T}}^{W} < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

Table 2: Further topological cuts for the three channels in separate p_{T}^{V} intervals.

0-lepton channel					
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	120-160		160-200		>200
$\Delta R(b,\bar{b})$	0.7-1.9		0.7-1.7		<1.5
1-lepton channel					
p_{T}^{W} (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b,\bar{b})$	>0.7			0.7-1.6	<1.4
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	> 25				> 50
m_{T}^{W} (GeV)	> 40			-	
2-lepton channel					
p_{T}^{Z} (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b,\bar{b})$	>0.7			0.7-1.8	<1.6

Atlas VH

- **SFs**

Table 3: Rescaling factors obtained from a fit to the data for the V+ light and c-jet backgrounds. The error includes statistical and systematic uncertainties. The numbers for $Z + c$ are not expected to match between years; see text for details.

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
$Z + c$	1.99 ± 0.51	0.71 ± 0.23
Z+ light	0.91 ± 0.12	0.98 ± 0.11
$W + c$	1.04 ± 0.23	1.04 ± 0.24
W+ light	1.03 ± 0.08	1.01 ± 0.14

Table 7: Rescaling factors obtained from the fit to the data for the $V + b$ and top backgrounds. The error includes statistical and systematic uncertainties.

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
Top	1.10 ± 0.14	1.29 ± 0.16
$Z + b$	1.22 ± 0.20	1.11 ± 0.15
$W + b$	1.19 ± 0.23	0.79 ± 0.20

Atlas VH

- **Syst**

Table 4: A summary of the size of the components of the systematic uncertainty on the total estimated background after all cuts for the three channels of the $\sqrt{s} = 8$ TeV analysis. The uncertainties are shown as a percentage and grouped together into broad categories and are averaged over all p_{T}^{V} bins in each category. The total error is worked out by adding the individual components together in quadrature in each p_{T}^{V} bin and then averaging.

Uncertainty [%]	0 lepton	1 lepton	2 leptons
b-tagging	6.5	6.0	6.9
c-tagging	7.3	6.4	3.6
light tagging	2.1	2.2	2.8
Jet/Pile-up/$E_{\mathrm{T}}^{\mathrm{miss}}$	20	7.0	5.4
Lepton	0.0	2.1	1.8
Top modelling	2.7	4.1	0.5
W modelling	1.8	5.4	0.0
Z modelling	2.8	0.1	4.7
Diboson	0.8	0.3	0.5
Multijet	0.6	2.6	0.0
Luminosity	3.6	3.6	3.6
Statistical	8.3	3.6	6.6
Total	25	15	14

Atlas VH

- **Syst**

Table 5: A summary of the size of the components of the systematic uncertainty on the signal with $m_H = 125$ GeV for the three channels of the $\sqrt{s} = 8$ TeV analysis. The dominant signal is shown for the 1 lepton and 2 lepton channels, while for the 0 lepton channel both ZH and WH signals are listed. The uncertainties are shown as a percentage, grouped together into broad categories and are calculated by summing in quadrature within each p_{T}^V bin and then averaging over all p_{T}^V bins in a channel.

Uncertainty [%]	0 lepton		1 lepton	2 leptons
	ZH	WH	WH	ZH
b-tagging	8.9	9.0	8.8	8.6
Jet/Pile-up/$E_{\mathrm{T}}^{\mathrm{miss}}$	19	25	6.7	4.2
Lepton	0.0	0.0	2.1	1.8
~~$H \to b\bar{b}$ BR~~	3.3	3.3	3.3	3.3
VH p_T-dependence	5.3	8.1	7.6	5.0
~~VH theory PDF~~	3.5	3.5	3.5	3.5
VH theory scale	1.6	0.4	0.4	1.6
Statistical	4.9	18	4.1	2.6
Luminosity	3.6	3.6	3.6	3.6
Total	24	34	16	13

Atlas VH

- **Yields**

Table 6: The expected numbers of signal and background events for the $\sqrt{s} = 8$ TeV data after the profile likelihood fit, as well as the observed number of events, are shown. The expected number of signal events are shown for WH and ZH production separately for $m_H = 125$ GeV. The quoted error on the total background represents one standard deviation of the profiled nuisance parameters incorporating both the systematic and statistical uncertainties.

	0-lepton, 2 jet			0-lepton, 3 jet			1-lepton					2-lepton				
Bin	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]						p_{T}^{W} [GeV]					p_{T}^{Z} [GeV]				
	120-160	160-200	>200	120-160	160-200	>200	0-50	50-100	100-150	150-200	> 200	0-50	50-100	100-150	150-200	>200
ZH	2.9	2.1	2.6	0.8	0.8	1.1	0.3	0.4	0.1	0.0	0.0	4.7	6.8	4.0	1.5	1.4
WH	0.8	0.4	0.4	0.2	0.2	0.2	10.6	12.9	7.5	3.6	3.6	0.0	0.0	0.0	0.0	0.0
Top	89	25	8	92	25	10	1440	2276	1120	147	43	230	310	84	3	0
$W + c$,light	30	10	5	9	3	2	580	585	209	36	17	0	0	0	0	0
$W + b$	35	13	13	8	3	2	770	778	288	77	64	0	0	0	0	0
$Z + c$,light	35	14	14	8	5	8	17	17	4	1	0	201	230	91	12	15
$Z + b$	144	51	43	41	22	16	50	63	13	5	1	1010	1180	469	75	51
Diboson	23	11	10	4	4	3	53	59	23	13	7	37	39	16	6	4
Multijet	3	1	1	1	1	0	890	522	68	14	3	12	3	0	0	0
Total Bkg.	361	127	98	164	63	42	3810	4310	1730	297	138	1500	1770	665	97	72
	± 29	± 11	± 12	± 13	± 8	± 5	± 150	± 86	± 90	± 27	± 14	± 90	± 110	± 47	± 12	± 12
Data	342	131	90	175	65	32	3821	4301	1697	297	132	1485	1773	657	100	69

Atlas ttH

- **Yields**

	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

Table 1: Table summarising post-fit event yields under the signal-plus-background hypothesis (assuming SM cross sections and branching ratios, and $m_H = 125$ GeV) for signal, backgrounds and data in each of the topologies considered, corresponding to the combined e+jets and μ+jets channels. The quoted uncertainties are the sum in quadrature of statistical and total systematic uncertainties on the yields, computed taking into account correlations among nuisance parameters and among processes.

Atlas ttH

- **Norm.unc.**

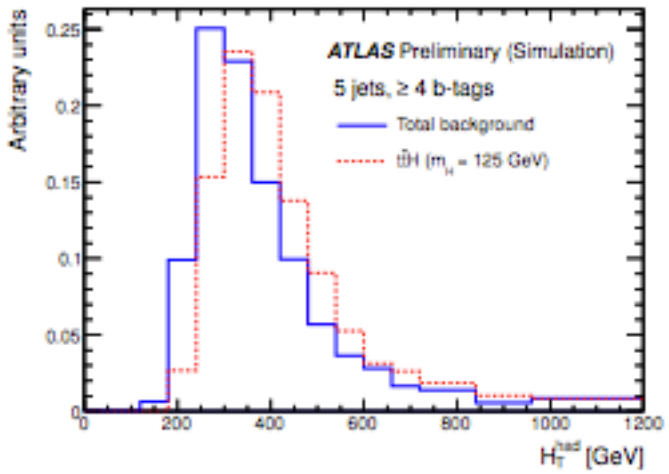
≥ 6 jets, ≥ 4 b tags

	$t\bar{t}H(125)$	$t\bar{t}$	W+jets	Z+jets	Single top	Diboson	$t\bar{t}V$	Multijet
Luminosity	+1.4/-1.4	+1.4/-1.4	+1.4/-1.4	+1.4/-1.4	+1.4/-1.4	+1.4/-1.4	+1.4/-1.4	–
Lepton ID+reco+trigger	+1.1/-1.1	+1.1/-1.1	+1.1/-1.1	+1.3/-1.3	+1.1/-1.1	+1.1/-1.1	+1.1/-1.1	–
Jet vertex fraction efficiency	+1.8/-1.3	+1.9/-1.4	+1.9/-1.7	+2.1/-2.1	+1.9/-1.4	+1.2/-0.9	+1.9/-1.4	–
Jet energy scale	+5.9/-6.1	+7.1/-8.0	–	+18.5/-19.1	+7.1/-8.0	+18.5/-19.1	+7.1/-8.0	–
Jet energy resolution	+0.9/-0.9	+0.6/-0.6	+8.5/-8.5	+35.9/-35.9	+6.1/-6.1	+5.9/-5.9	+1.6/-1.6	–
b-tagging efficiency	+12.8/-14.0	+9.9/-10.5	+9.7/-10.9	+6.8/-7.7	+10.4/-11.2	+13.0/-14.2	+10.5/-11.2	–
c-tagging efficiency	+3.5/-3.5	+11.8/-12.3	+11.6/-12.4	+9.2/-10.0	+10.6/-11.3	+7.0/-8.0	+11.3/-12.1	–
Light jet-tagging efficiency	+1.0/-1.0	+8.8/-9.3	+9.2/-10.2	+24.0/-28.3	+6.6/-7.0	+2.1/-2.5	+3.2/-3.3	–
$t\bar{t}$ cross section	–	+3.0/-3.2	–	–	–	–	–	–
$t\bar{t}V$ cross section	–	–	–	–	–	–	+29.4/-29.4	–
Single top cross section	–	–	–	–	+4.7/-3.7	–	–	–
Diboson cross section	–	–	–	–	–	+4.9/-4.9	–	–
V+jets normalisation	–	–	+32.1/-32.1	+32.1/-32.1	–	–	–	–
Multijet normalisation	–	–	–	–	–	–	–	+60.3/-60.3
W+heavy-flavour fractions	–	–	+26.3/-26.1	–	–	–	–	–
$t\bar{t}$ modeling	–	+6.3/-8.8	–	–	–	–	–	–
$t\bar{t}$+heavy-flavour fractions	–	+11.1/-11.1	–	–	–	–	–	–
$t\bar{t}H$ modeling	+1.3/-1.5	–	–	–	–	–	–	–
Total	+6.6/-6.9	+13.8/-16.0	+38.5/-38.4	+54.3/-56.1	+11.0/-11.1	+19.2/-19.9	+30.2/-30.4	+60.2/-60.2

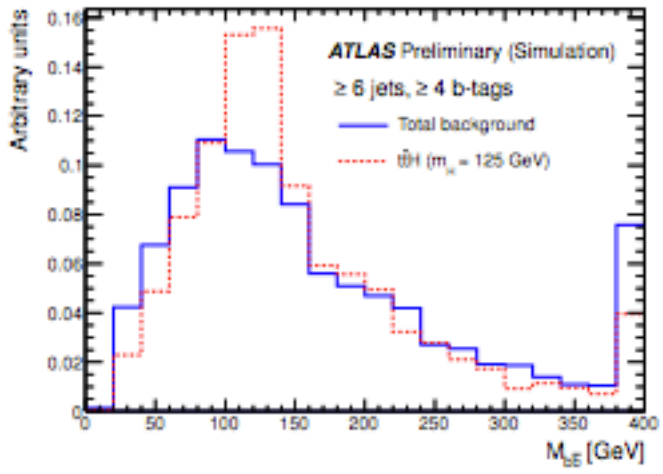
Table 12: Table summarising the overall normalisation uncertainties (expressed in %) in signal and each of the background processes for each of the systematic uncertainties considered, after fitting the nuisance parameters to data under the signal-plus-background hypothesis (assuming m_H = 125 GeV). The total uncertainty can be different from the sum in quadrature of individual sources due to the correlations between them. The selection presented here is the combined e+jets and μ+jets channels with ≥ 6 jets and ≥ 4 b tags.

Atlas ttH

- **Discriminating variables**



(a)

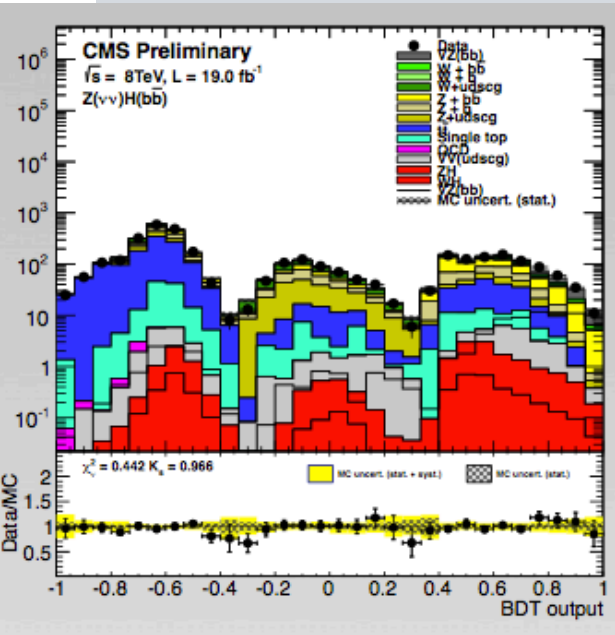


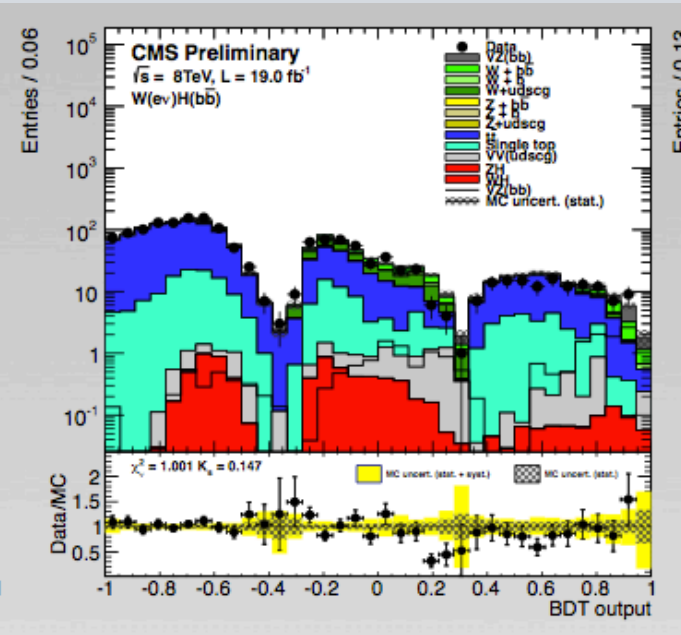
(b)

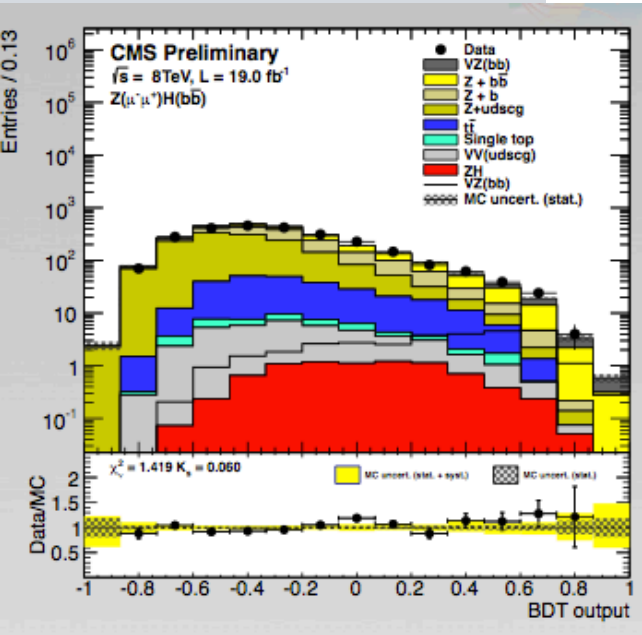
Figure 4: Comparison of (a) the H_T^{had} distribution and (b) the $m_{b\bar{b}}$ distribution between $t\bar{t}H$ signal with m_H = 125 GeV (dashed red histogram) and total background (solid blue histogram) in the combined e+jets and μ+jets channels. In the case of H_T^{had} the selection used is 5 jets of which ≥ 4 jets are b tagged, while in the case of $m_{b\bar{b}}$ the selection used is ≥ 6 jets of which ≥ 4 jets are b tagged. Both distributions are normalised to unity in order to better compare the shapes between signal and background. The last bin in the figures contains the overflow.

CMS VH

- VV BDT


CMS Preliminary
√s = 8TeV, L = 19.0 fb-1
Z(νν)H(bb̄)
Data
VZ(bb̄)
W + bb̄
W + b
W+udscg
Z + bb̄
Z + b
Z+udscg
tt̄
Single top
QCD
VV(udscg)
ZH
WH
VZ(bb̄)
MC uncert. (stat.)
χ² = 0.442 K_s = 0.966
MC uncert. (stat. + syst.)
MC uncert. (stat.)
Data/MC
BDT output


CMS Preliminary
√s = 8TeV, L = 19.0 fb-1
W(eν)H(bb̄)
Entries / 0.06
Data
VZ(bb̄)
MC uncert. (stat.)
χ² = 1.001 K_s = 0.147
MC uncert. (stat. + syst.)
MC uncert. (stat.)
Data/MC
BDT output


CMS Preliminary
√s = 8TeV, L = 19.0 fb-1
Z(μ⁻μ⁺)H(bb̄)
Entries / 0.13
Data
VZ(bb̄)
Z + bb̄
Z + b
Z+udscg
tt̄
Single top
VV(udscg)
ZH
VZ(bb̄)
MC uncert. (stat.)
χ² = 1.419 K_s = 0.060
MC uncert. (stat. + syst.)
MC uncert. (stat.)
Data/MC
BDT output