Higgs Search in $b\bar{b}$ Signatures at ATLAS and CMS

Beauty 2013 in Bologna, Italy

14th International Conference on B-physics at Hadron Machines

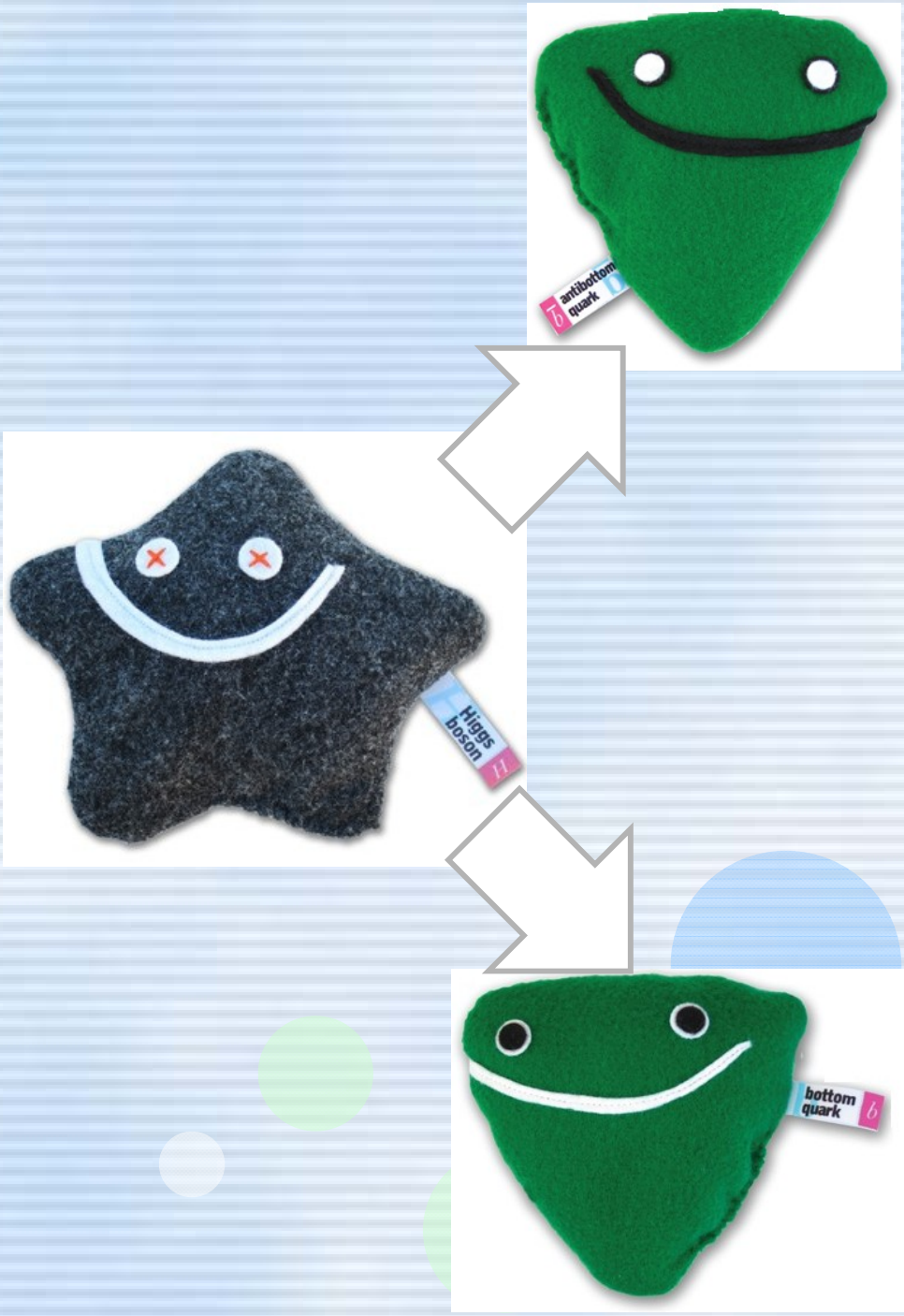
Yoshikazu Nagai

(CPPM, Aix-Marseille Université)

on behalf of the ATLAS & CMS Collaboration

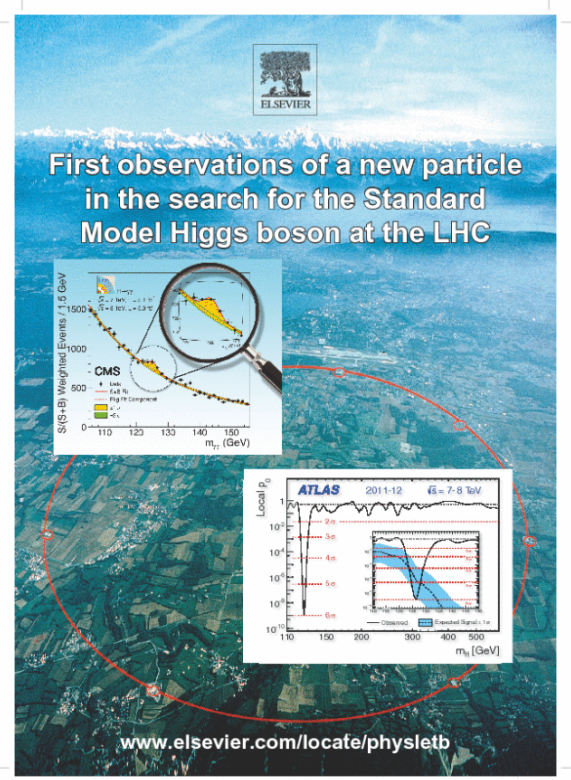
Talk Outline

- Introduction & Motivations
- H → bb analyses at the LHC
  - VH, H→bb
  - ttH, H→bb
- Summary



Higgs-like boson discovery

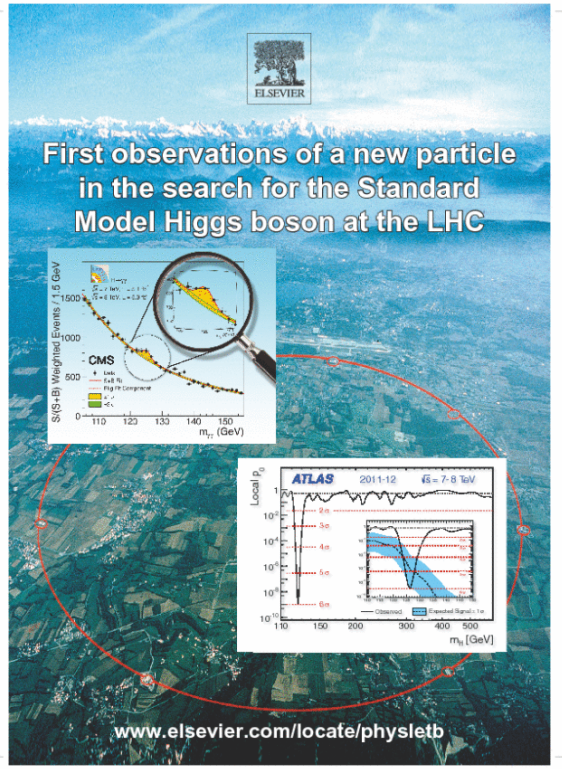
- July 4th 2012, new Higgs-like boson observation was announced by both ATLAS & CMS



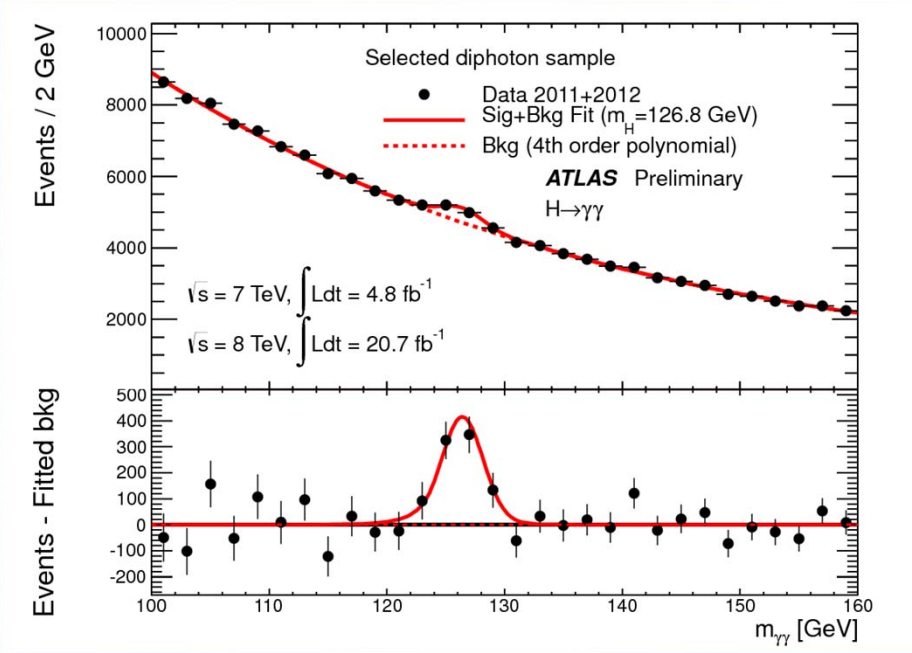
PLB 716(2012) 1-29

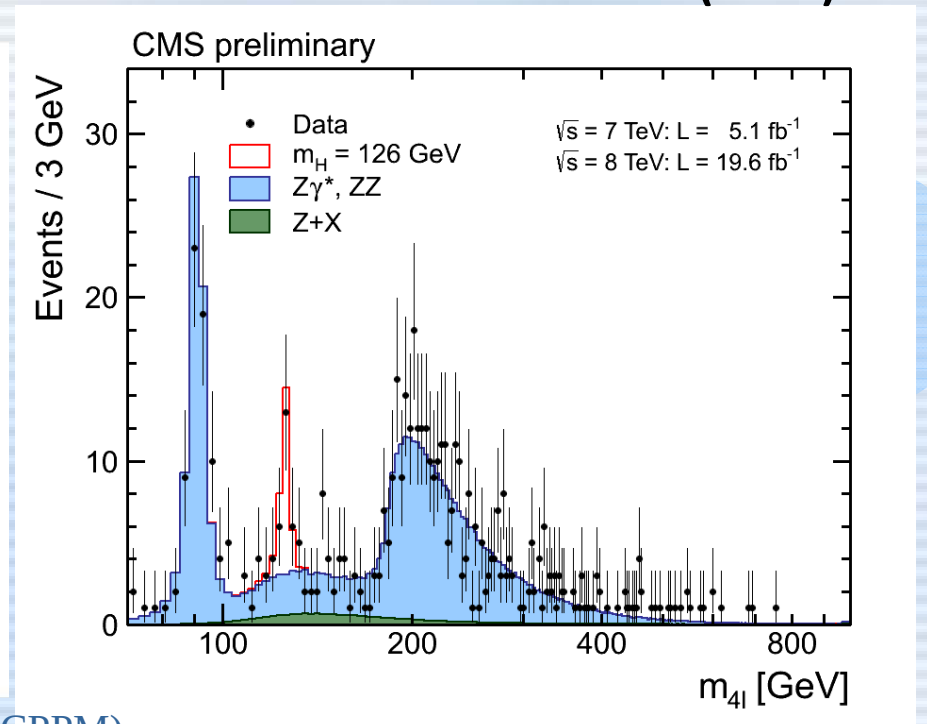
Higgs-like boson discovery

- July 4th 2012, new Higgs-like boson observation was announced by both ATLAS & CMS
- Recently, ATLAS & CMS updated Higgs search result with full dataset



PLB 716(2012) 1-29





Higgs-like boson discovery

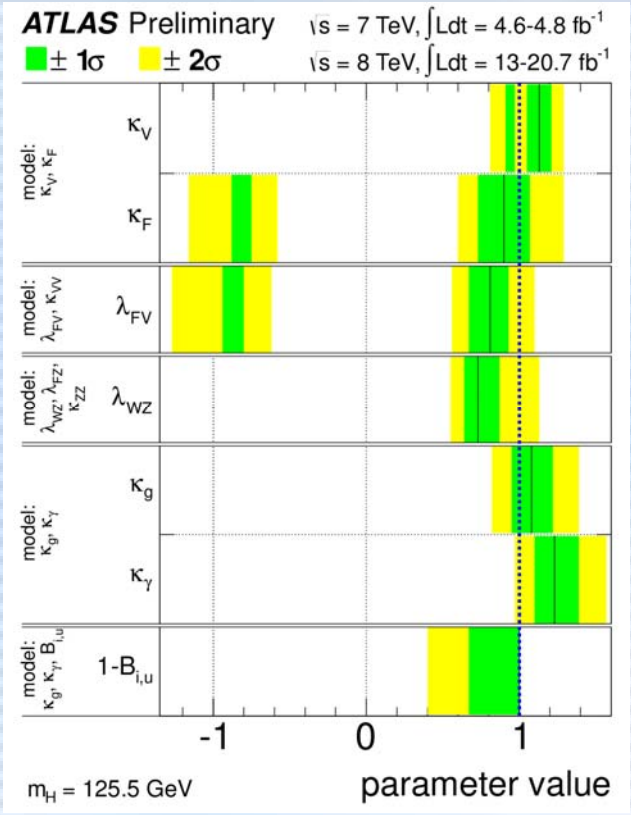
What is the next step?

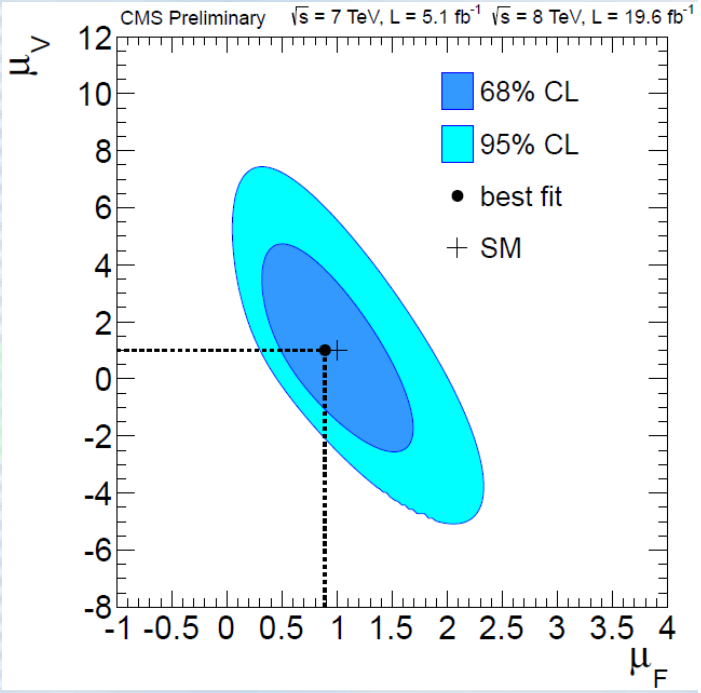
Confirm nature of new boson.
SM Higgs boson? Or something else?

Property measurement (mass, spin, CP, coupling) is ongoing mainly using bosonic decay modes ($H\to\gamma\gamma$, ZZ, WW)

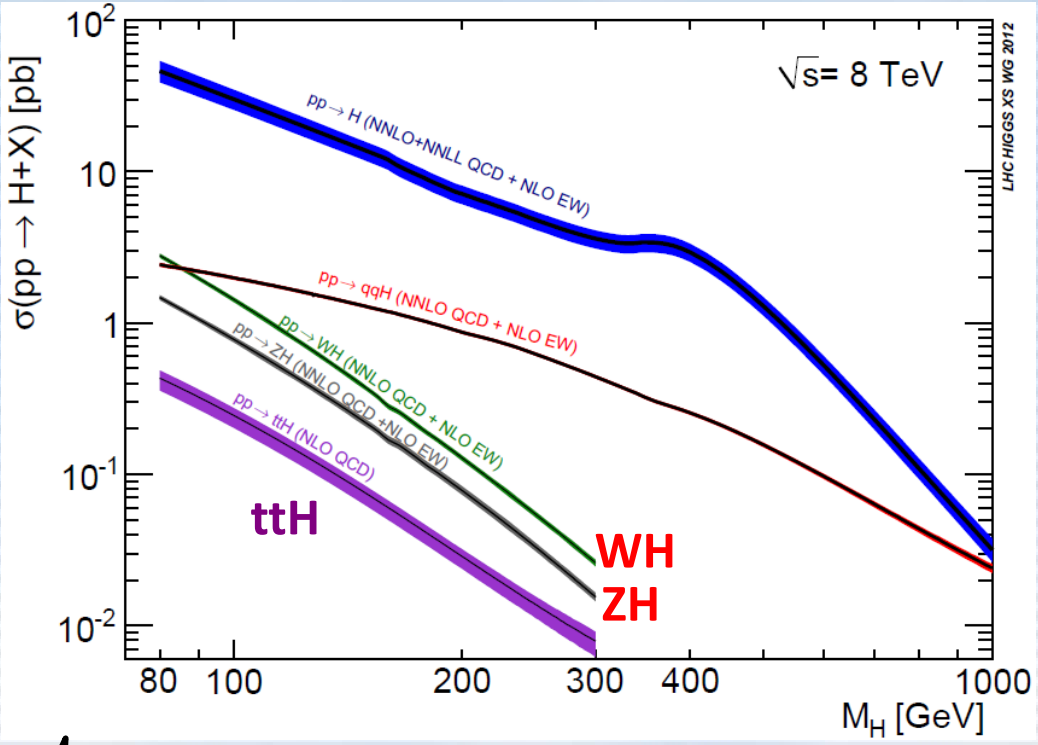
If the new boson is the SM Higgs,
it predominately decays to the b-quark pair.

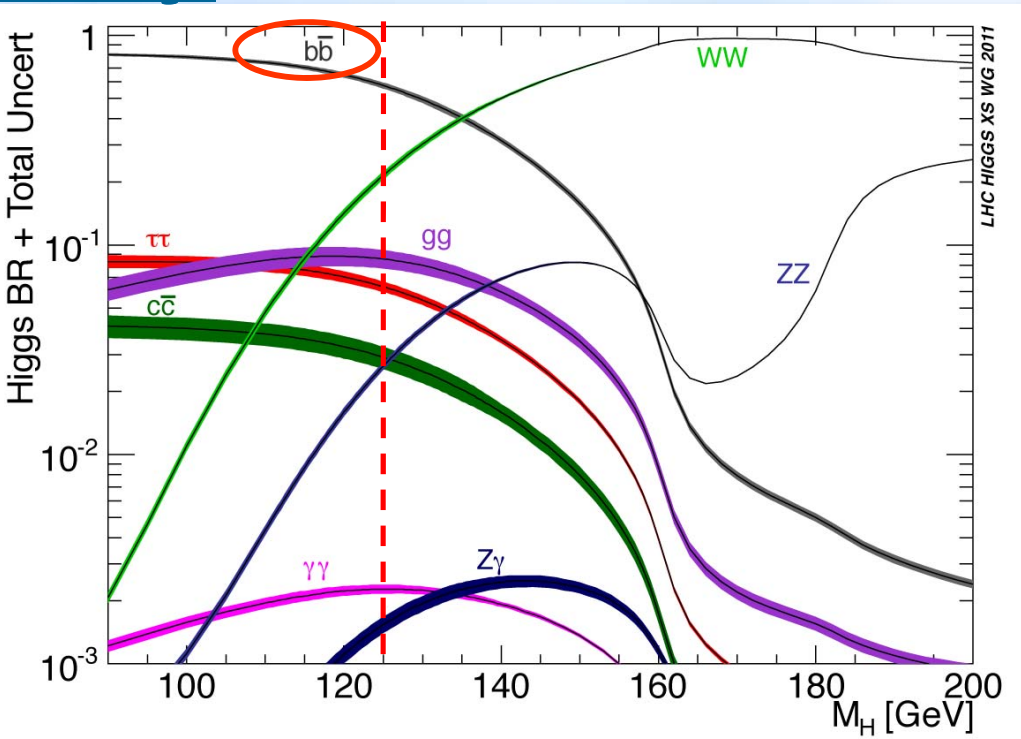
This talk focuses on $H\to bb$





Higgs Production & Decay





For m_H = 125 GeV

σ(WH) = 0.573 (0.697) pb for 7 TeV (for 8 TeV)

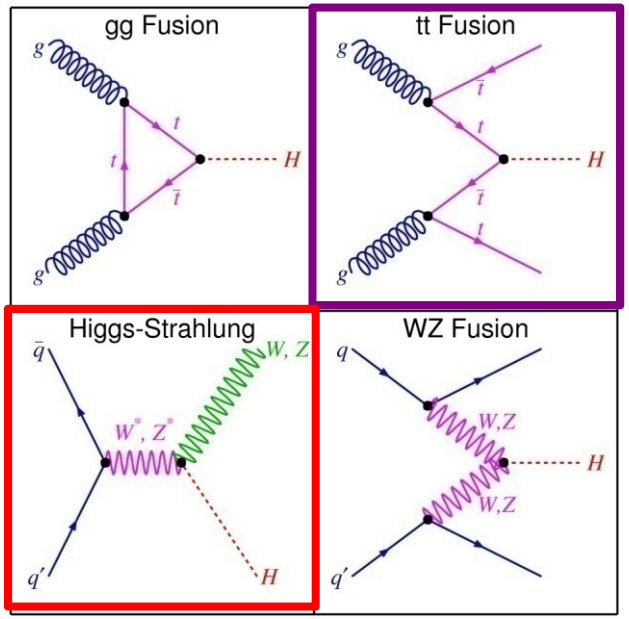
σ(ZH) = 0.316 (0.394) pb for 7 TeV (for 8 TeV)

σ(ttH) = 0.086 (0.130) pb for 7 TeV (for 8 TeV)

Br(H→bb) = 0.577

(LHC Higgs cross section working group)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

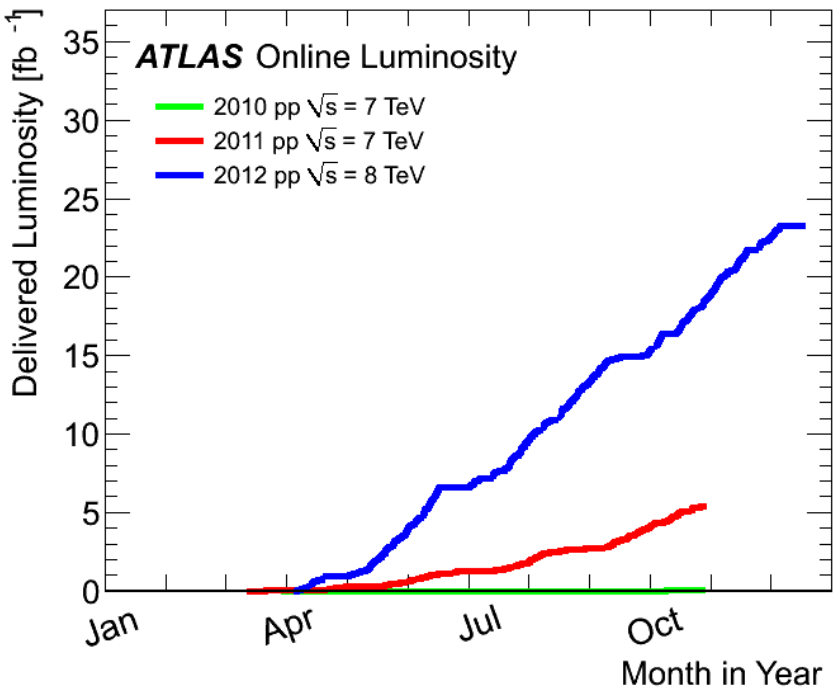


LHC and ATLAS/CMS

- proton-proton collisions at 7 TeV (2011) and 8 TeV (2012)
- The peak instantaneous luminosity at 8 TeV is 7.7 x 10^{33} cm^{-2} s^{-1}
- ATLAS & CMS are large general purpose detectors built on the LHC

Integrated Luminosity

- Both ATLAS and CMS recorded > 5.0 fb^{-1} (2011) and > 23 fb^{-1} (2012)
- In this talk, analyses use full dataset of 2011 and up to 13 fb^{-1} of 2012 dataset

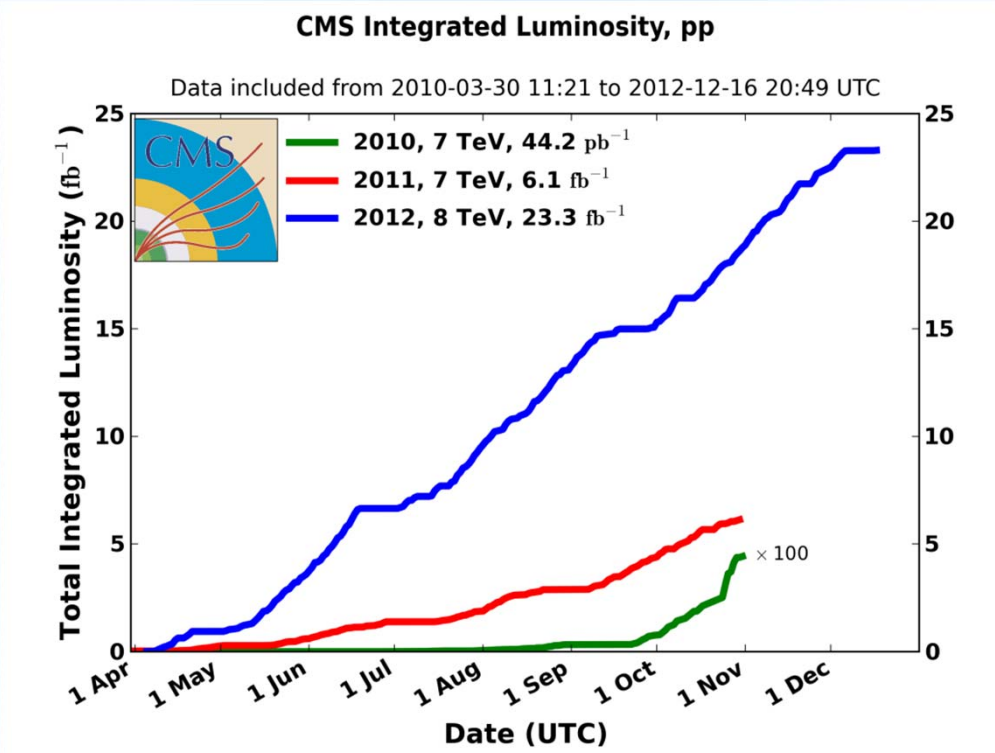


LHC and ATLAS/CMS

- proton-proton collisions at 7 TeV (2011) and 8 TeV (2012)
- The peak instantaneous luminosity at 8 TeV is 7.7 x 10^{33} cm^{-2} s^{-1}
- ATLAS & CMS are large general purpose detectors built on the LHC

Integrated Luminosity

- Both ATLAS and CMS recorded > 5.0 fb^{-1} (2011) and > 23 fb^{-1} (2012)
- In this talk, analyses use full dataset of 2011 and up to 13 fb^{-1} of 2012 dataset

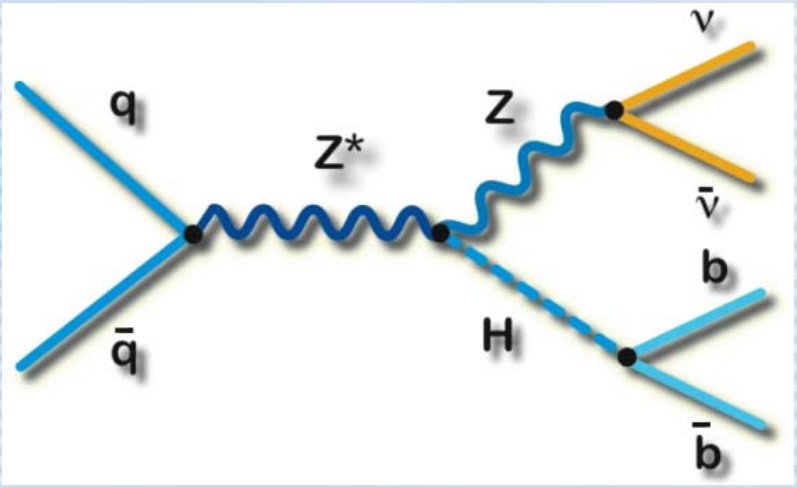


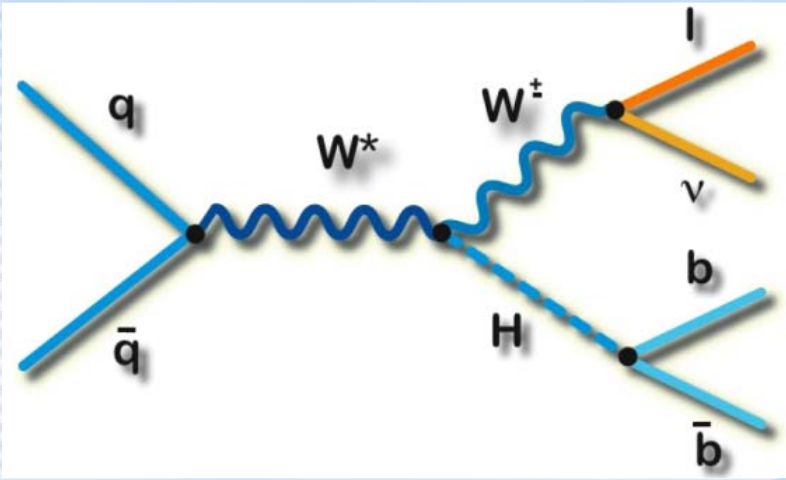
VH, H→bb Analyses

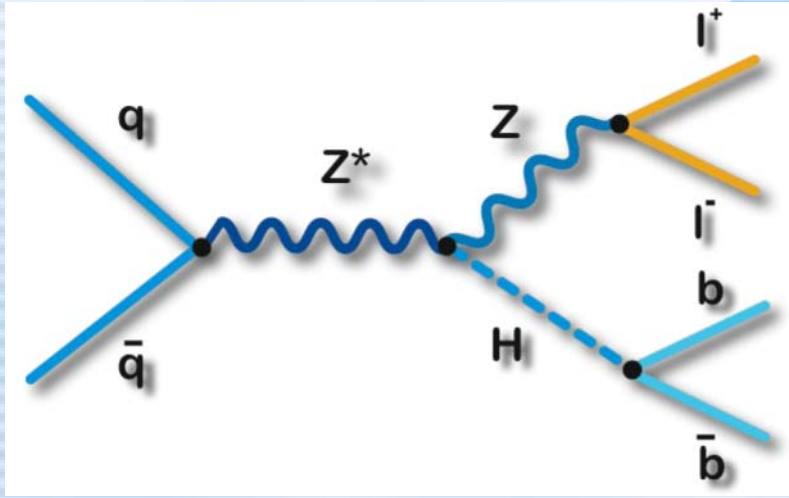
dataset:

4.7 fb-1 (2011, 7 TeV)
13.0 fb-1 (2012, 8 TeV)

5.0 fb-1 (2011, 7 TeV)
12.1 fb-1 (2012, 8 TeV)







Overview of Analysis

- H→bb has the largest BR at the low mass, but very large QCD multijet background

  → Focus on associated production with W or Z

  0-lepton (ZH→$\nu\nu$bb), 1-lepton (WH→lνbb), 2-lepton (ZH→llbb)

- Selection for the VH→Vbb analysis

  - Triggers: MET (ATLAS), MHT or MET + 2jets (CMS) for 0-lepton

    1 high-p_T electron or muon for 1-lepton

    1 or 2 high-p_T electrons or muons for 2-lepton

  - Jets: Antikt R=0.4 jets, $p_{T1}(p_{T2}) > 45\ (20)$ GeV & $|\eta| < 2.5$ (ATLAS)

    Antikt R=0.5 jets with particle flow, $p_T > 30$ GeV & $|\eta| < 2.5$ (CMS)

  - b-tag: two b-tagged jets (ATLAS, CMS)

  - V boson: MET > 120 GeV (ATLAS), MET > 130 GeV (CMS) for 0-lepton

    1 high-p_T tight electron or muon for 1-lepton

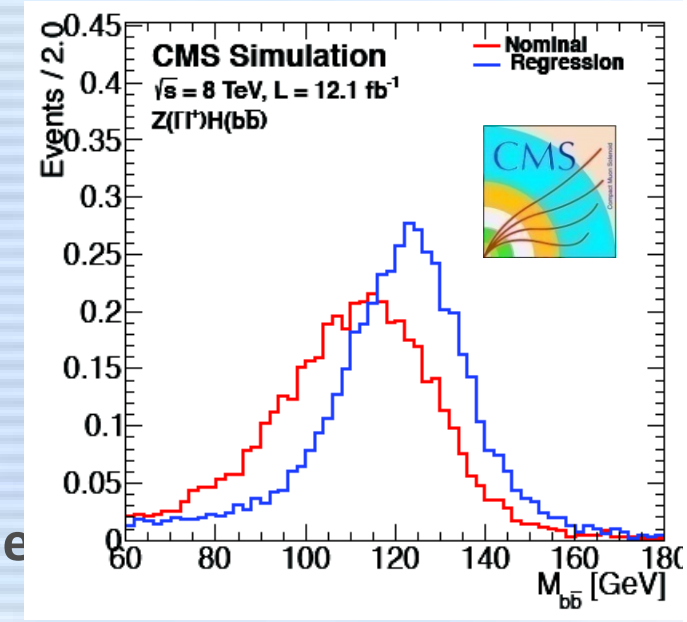
    2 high-p_T electrons or muons with looser criteria for 2-lepton

- Main backgrounds: V+jets, top, Diboson

Overview of Analysis (cont.)

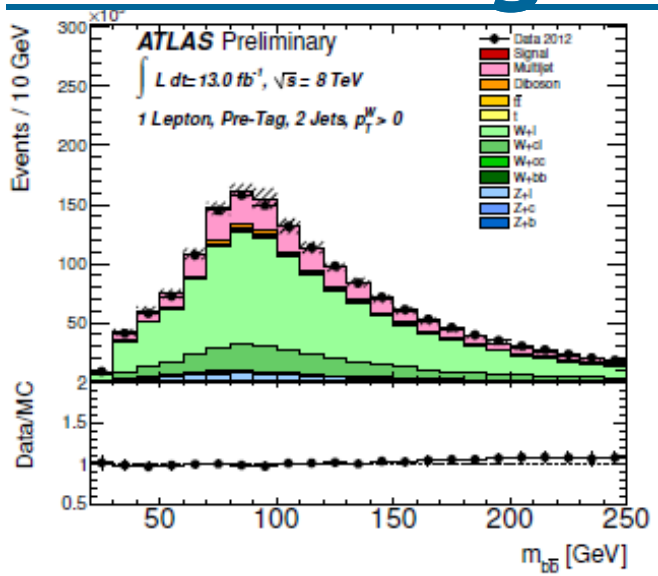
- Sub-divided into several $p_T(V)$ signal regions to maximize sensitivity
- b-jet energy corrected by including soft lepton p_T
- Final result with invariant mass of b-jets (m_{bb})

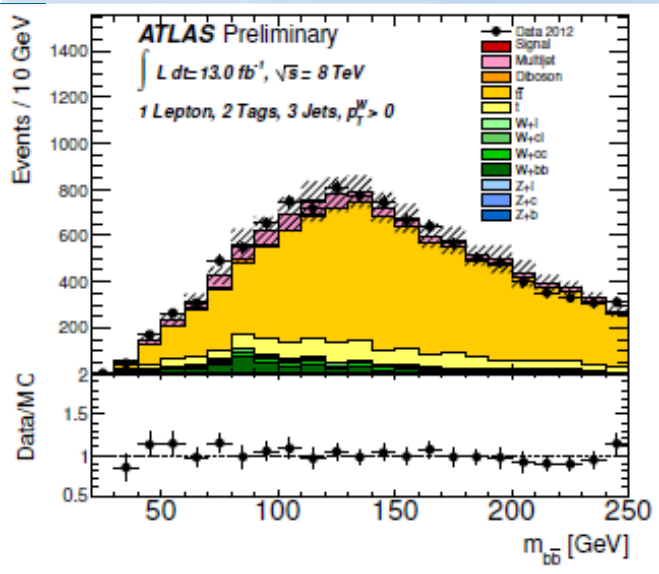
- Categorized into low & high $p_T(V)$ signal regions
- b-jet energy regression with Boosted Decision Tree
- Limit extracted from BDT discriminator



0-lepton (ZH→νν̄bb) channel						
ATLAS	E_T^{miss} (GeV)	120-160	160-200	>200		
CMS	E_T^{miss} (GeV)	130-170	>170			
1-lepton (WH→lνbb) channel						
ATLAS	p_T^W (GeV)	0-50	50-100	100-150	150-200	>200
CMS	p_T^W (GeV)	--	120-170	>170		
2-lepton (ZH→llbb) channel						
ATLAS	p_T^Z (GeV)	0-50	50-100	100-150	150-200	>200
CMS	p_T^Z (GeV)	--	50-100	>100		

Control region



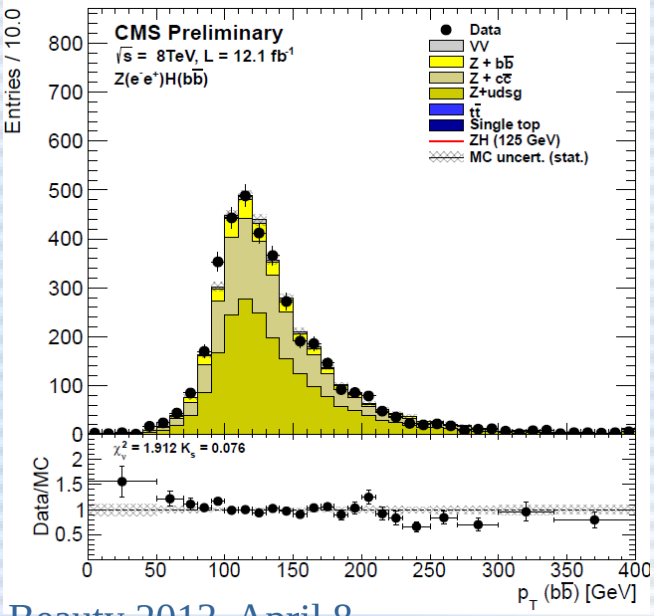


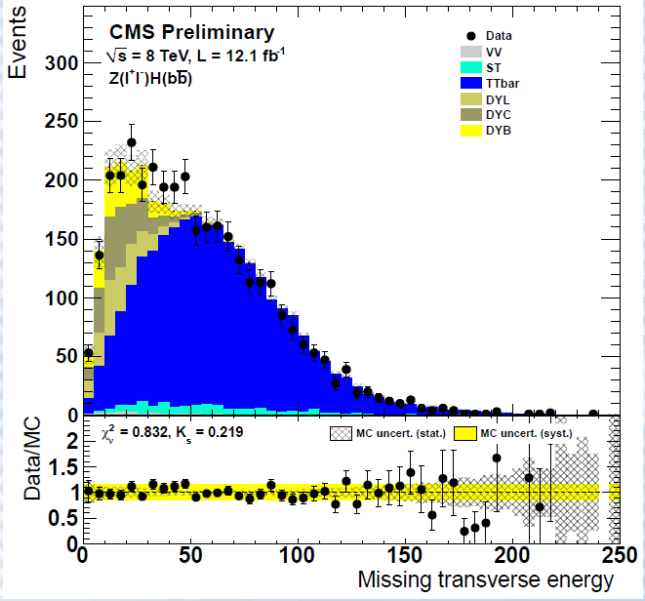
- **W/Z+jets** normalization from fits to the 0/1/2-tag control regions
- **W/Z+b, top** normalization from final fit

Typical control region definition

Top: Z mass veto in 2-lepton, additional jets in 1-lepton

V+light: b-jet veto **V+c/b**: m_{bb} sideband





Three control regions to determine data/MC scale factor

- **W/Z+jets (light/charm)**
- **W/Z + b**
- **top**

Systematic uncertainties

Background

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

Signal & Background

Source	Range
Luminosity	2.2-4.4%
Lepton efficiency and trigger (per lepton)	3%
$Z(\nu\nu)H$ triggers	3%
Jet energy scale	2–3%
Jet energy resolution	3–6%
Missing transverse energy	3%
b-tagging	3–15%
Signal cross section (scale and PDF)	4%
Signal cross section (p_{T} boost, EWK/QCD)	5–10% / 10%
Signal Monte Carlo statistics	1-5%
Backgrounds (data estimate)	≈ 10%
Single-top (simulation estimate)	15–30%
Dibosons (simulation estimate)	30%

Signal

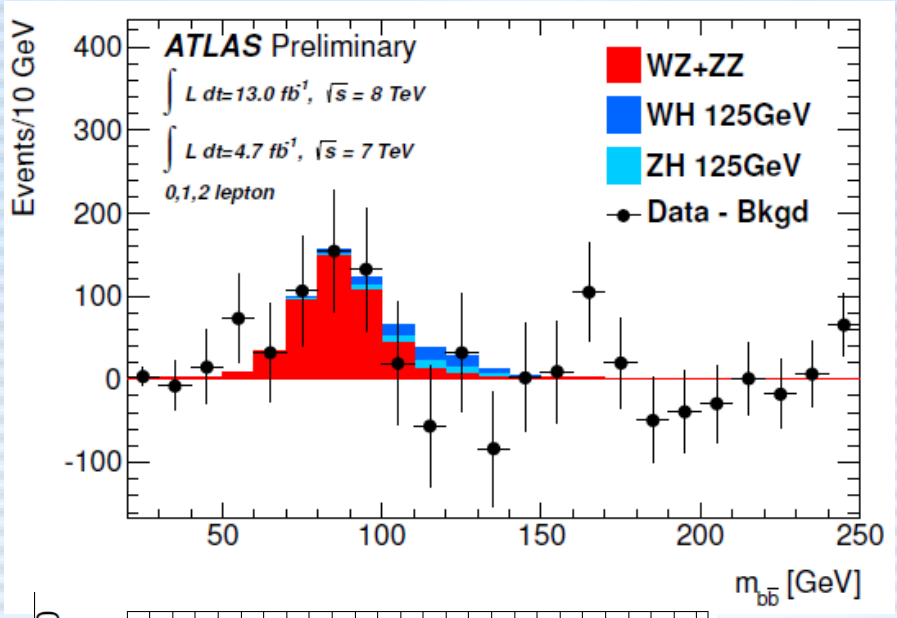
Uncertainty [%]	0 lepton		1 lepton	2 leptons
	ZH	WH	WH	ZH
b-tagging	8.9	9.0	8.8	8.6
Jet/Pile-up/$E_{\mathrm{T}}^{\mathrm{miss}}$	19	25	6.7	4.2
Lepton	0.0	0.0	2.1	1.8
$H \to bb$ BR	3.3	3.3	3.3	3.3
VH p_T-dependence	5.3	8.1	7.6	5.0
VH theory PDF	3.5	3.5	3.5	3.5
VH theory scale	1.6	0.4	0.4	1.6
Statistical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

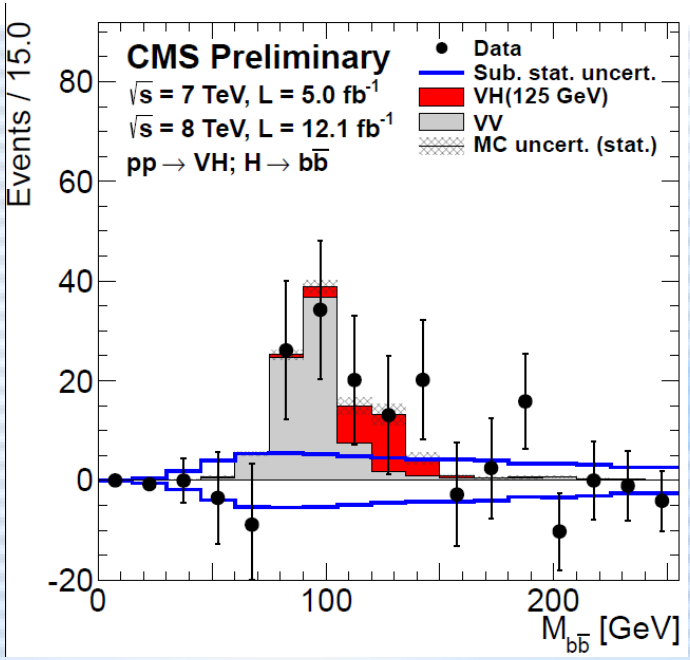
Main experimental systematics

- b-tagging (ATLAS, CMS)
- Jet/MET (ATLAS)
- MC statistics (ATLAS)

Background subtraction

Backgrounds are subtracted except diboson & Higgs signals





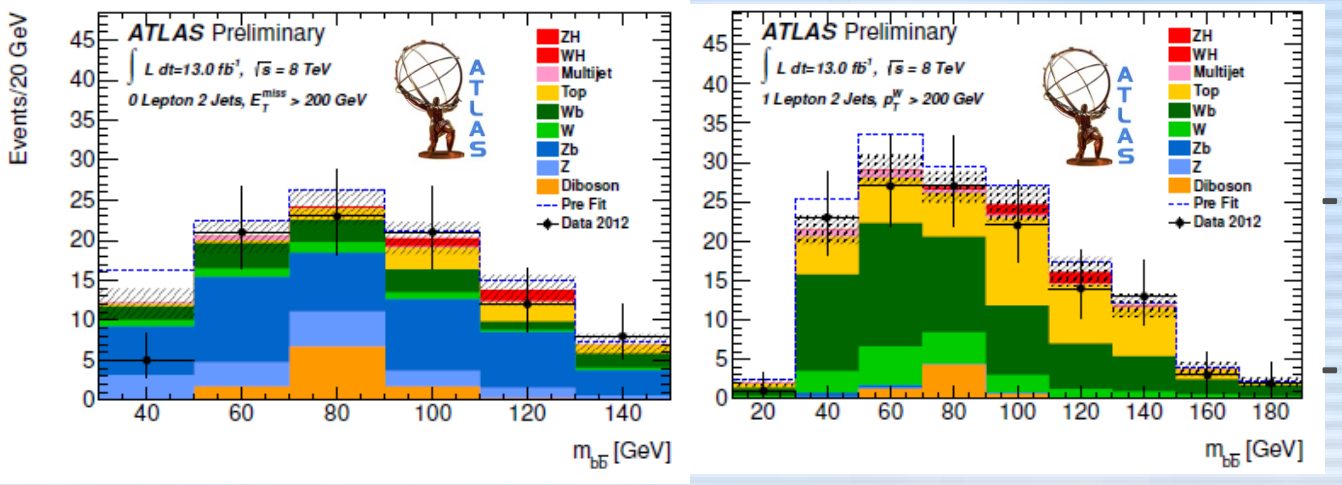
$\mu_D = 1.09 \pm 0.20(\text{stat.}) \pm 0.22(\text{syst.})$

Significance 4.0σ

Nice validation for H→bb search with well-known diboson VZ→Vbb signal

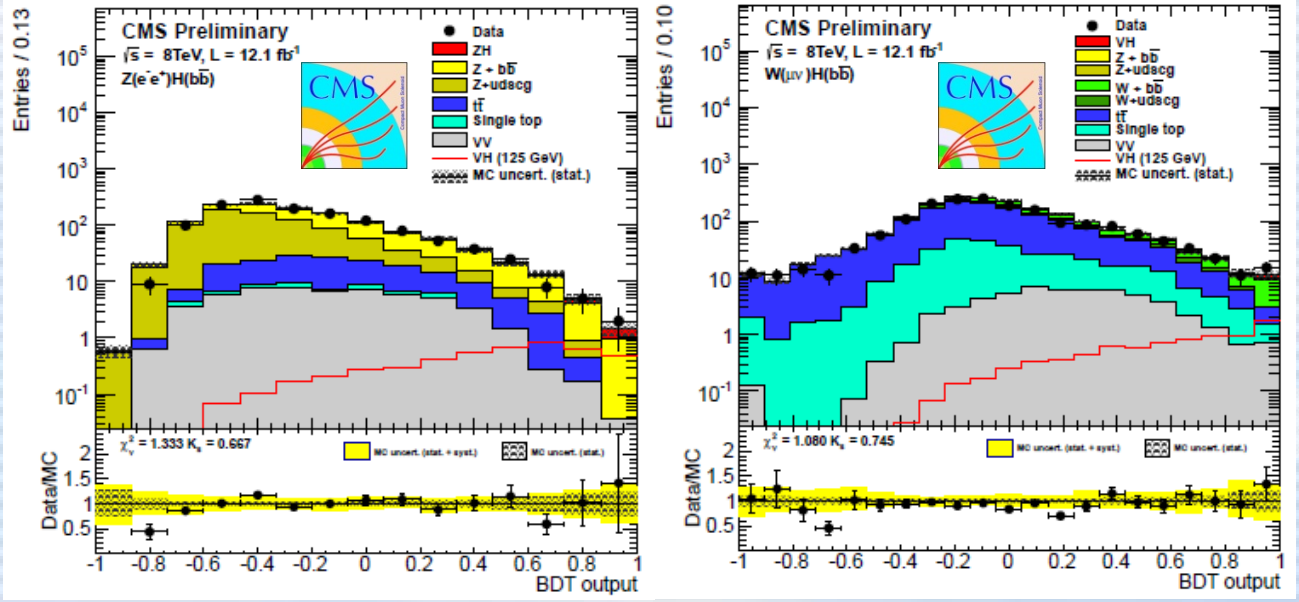
→ Clear diboson peak visible in both ATLAS and CMS result, good agreement with SM expectation

Final discriminant distribution



- 0-lepton: split by $p_T(V)$ and 2 or 3 jets
- 1, 2-lepton: split by $p_T(V)$ with 2 jets

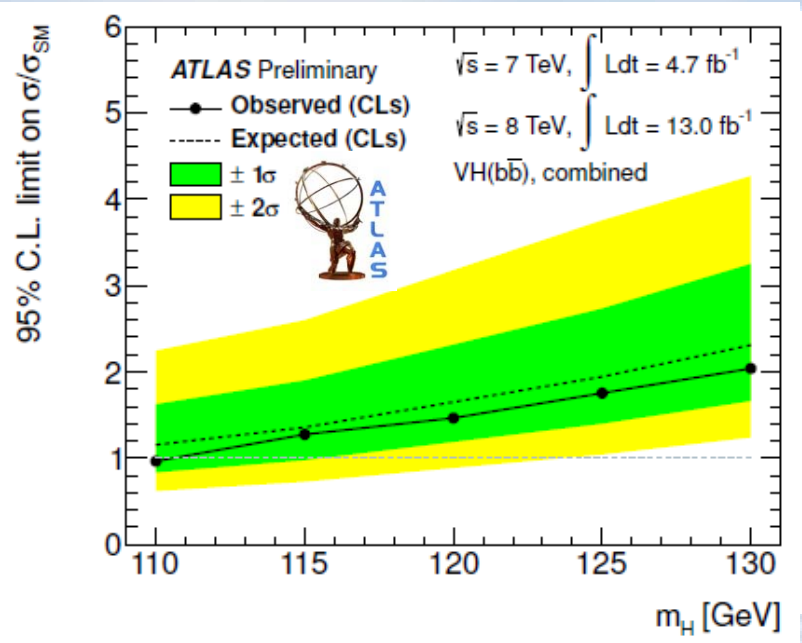
→ 16 signal regions in total

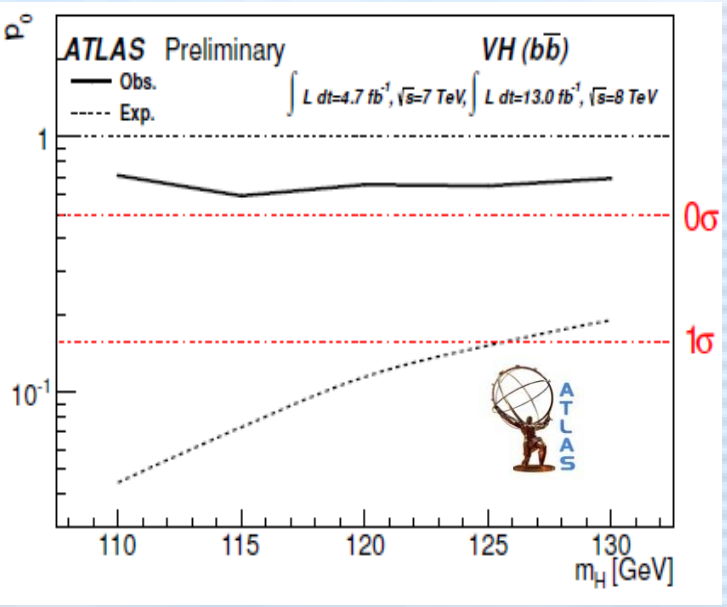


Split by low, high-$p_T(V)$ and lepton flavor

→ 10 signal regions in total

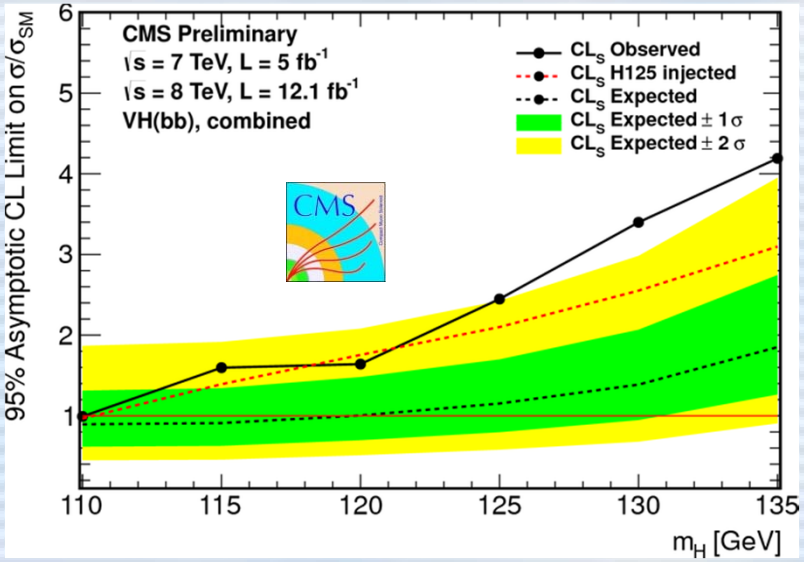
Result

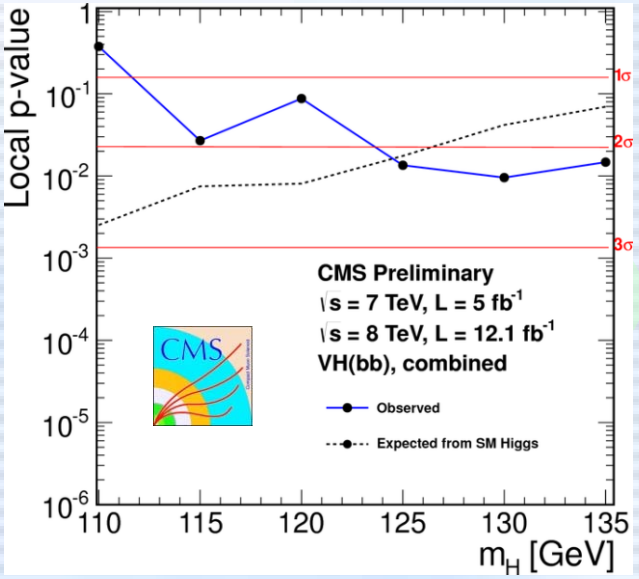


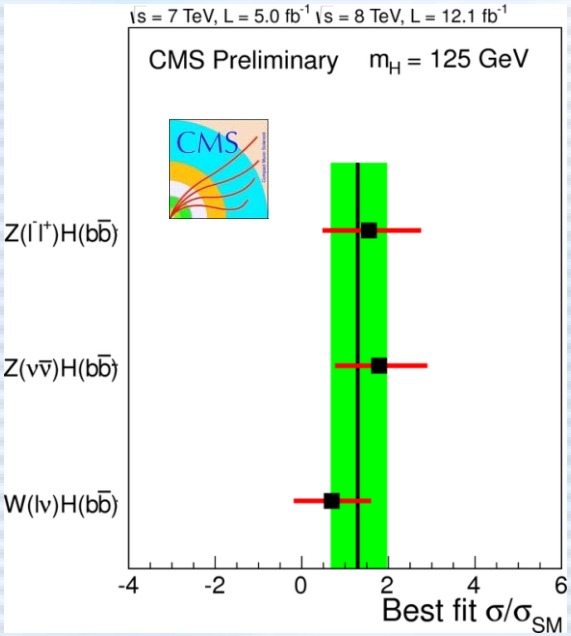


Obs. (Exp.) limit @125 GeV: 1.8 (1.9) x σ(SM) μ = -0.4±0.7(stat.)±0.8(syst.)

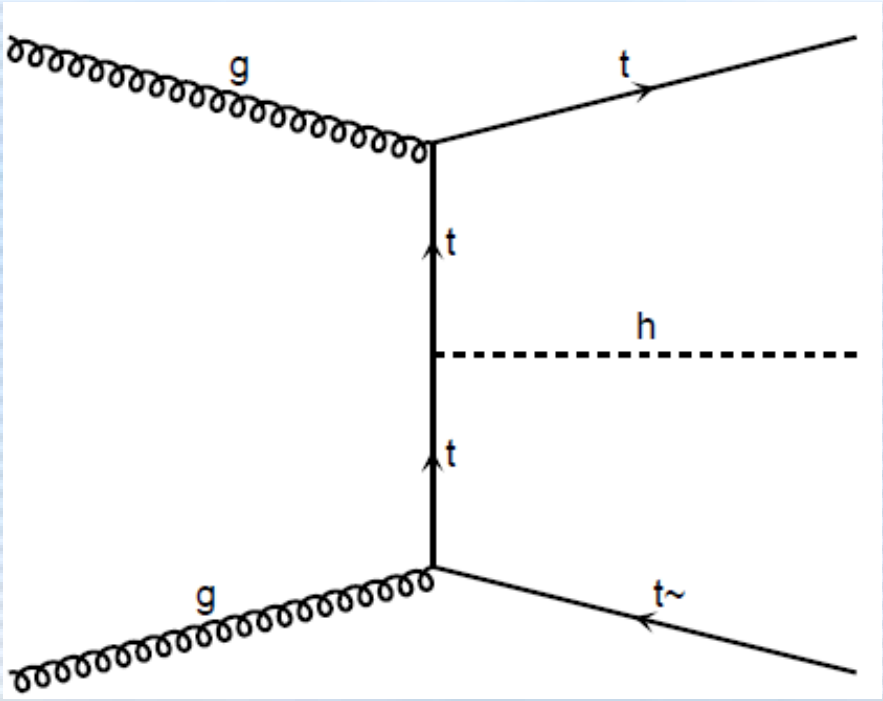
Obs. (Exp.) limit @125 GeV: 2.5 (1.2) x σ(SM) μ = 1.3 $^{+0.7}_{-0.6}$ 2.2σ (2.1σ) excess







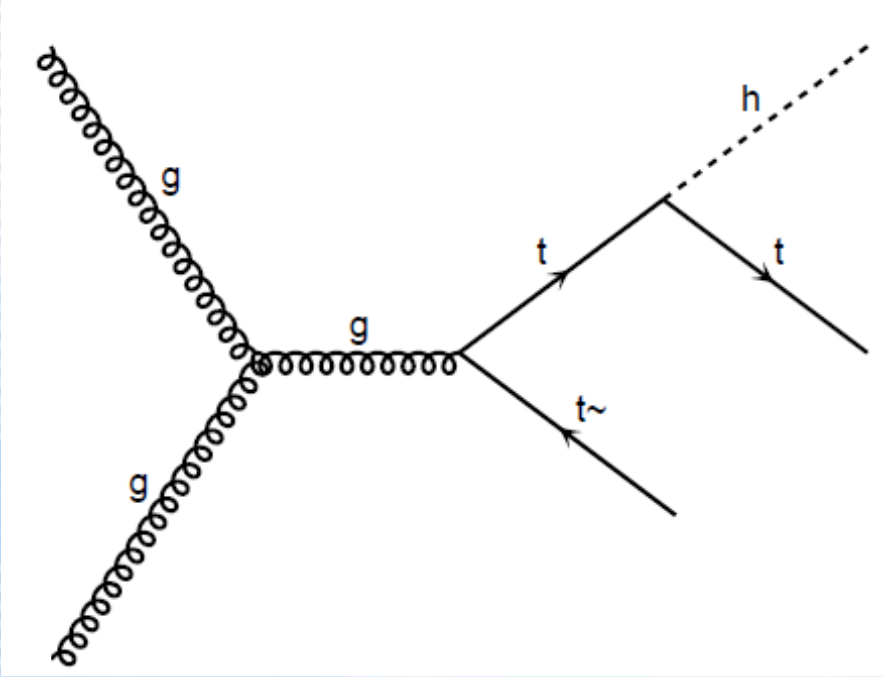
ttH, H→bb analyses



dataset:

4.7 fb-1 (2011, 7 TeV)

5.0 fb-1 (2011, 7 TeV)
5.1 fb-1 (2012, 8 TeV)



Overview of Analysis

- Important channel to test top-Higgs Yukawa coupling

  → Analyze 1-lepton (ATLAS, CMS) & di-lepton (CMS) top-pair decay channels

  → Total number of jets (b-jets) in final state: 4 or 6 jets (4-bjets)

  Selection for the ttH→ttbb analysis

  - Triggers: 1 high-p_T electron or muon for 1-lepton channel (ATLAS, CMS)

    any combination of electrons and muons for di-lepton channel (CMS)

- Main background: tt + jets
- Strategy: Categorize based on number of jets, b-tagged jets

- Define signal enriched region, background enriched region, and cross-check region based on jets and b-tagged jets multiplicity
- Analyze m_{bb} distribution (≥6 jets, ≥3 b-tagged jets) or $\Sigma(p_T^{jets})$ (others)
- Include background enriched regions in the fit to constrain uncertainty

- Low jet (b-jets) multiplicity region to determine background normalization, and define high multiplicity as signal region
- Analyze Artificial Neural Network (ANN) distribution to extract signal
- Include all Higgs decays, largest contribution from H→bb

Analysis Strategy (ATLAS)

Lepton + jets:

5 jets with 3 b-tags, ≥4 b-tags

≥6 jets with 3 b-tags, ≥ 4 b-tags

→ 4 signal regions in total

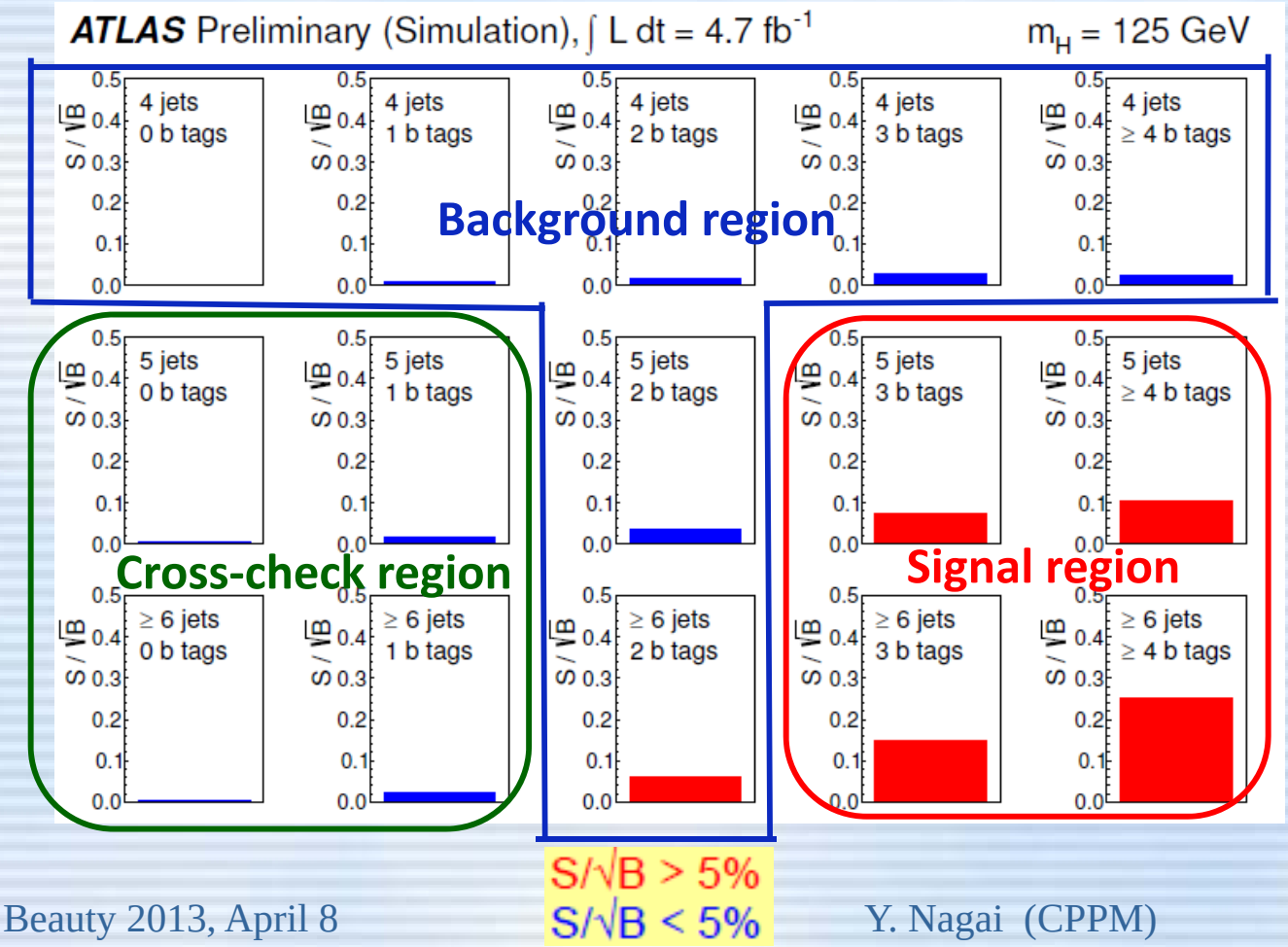
→ Background region is included into final fit together with signal region

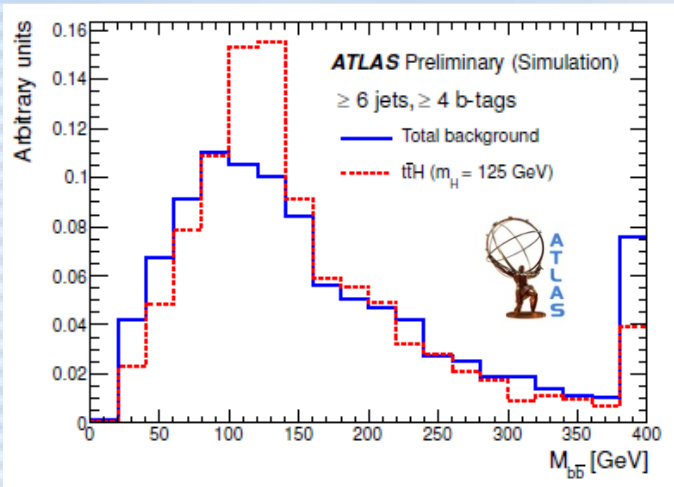
For ≥6 jets with ≥3 b-tags regions

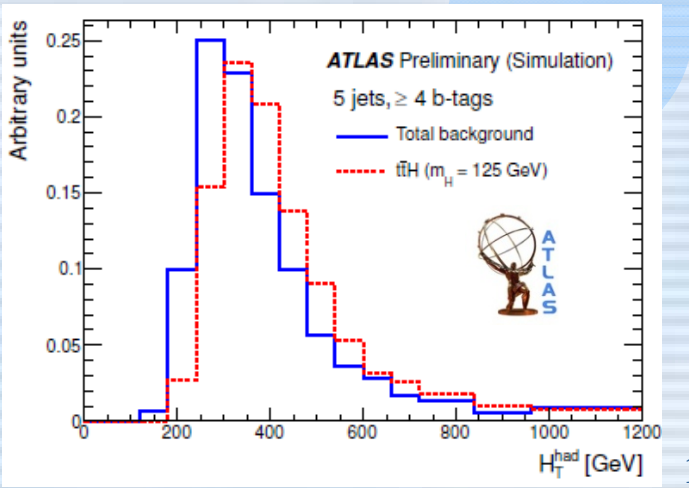
- Kinematic fit to reconstruct tt system
- Reconstruct m_{bb} using remaining 2 jets

For other regions

- Use H_T^{had} (scalar sum pT of jets)







Analysis Strategy (CMS)

Lepton + jets:

4 jets with 3 b-tags, 4 b-tags

5 jets with 3 b-tags, ≥4 b-tags

≥6 jets with 2 b-tags, 3 b-tags, ≥ 4 b-tags

→ 7 signal regions in total

Di-lepton:

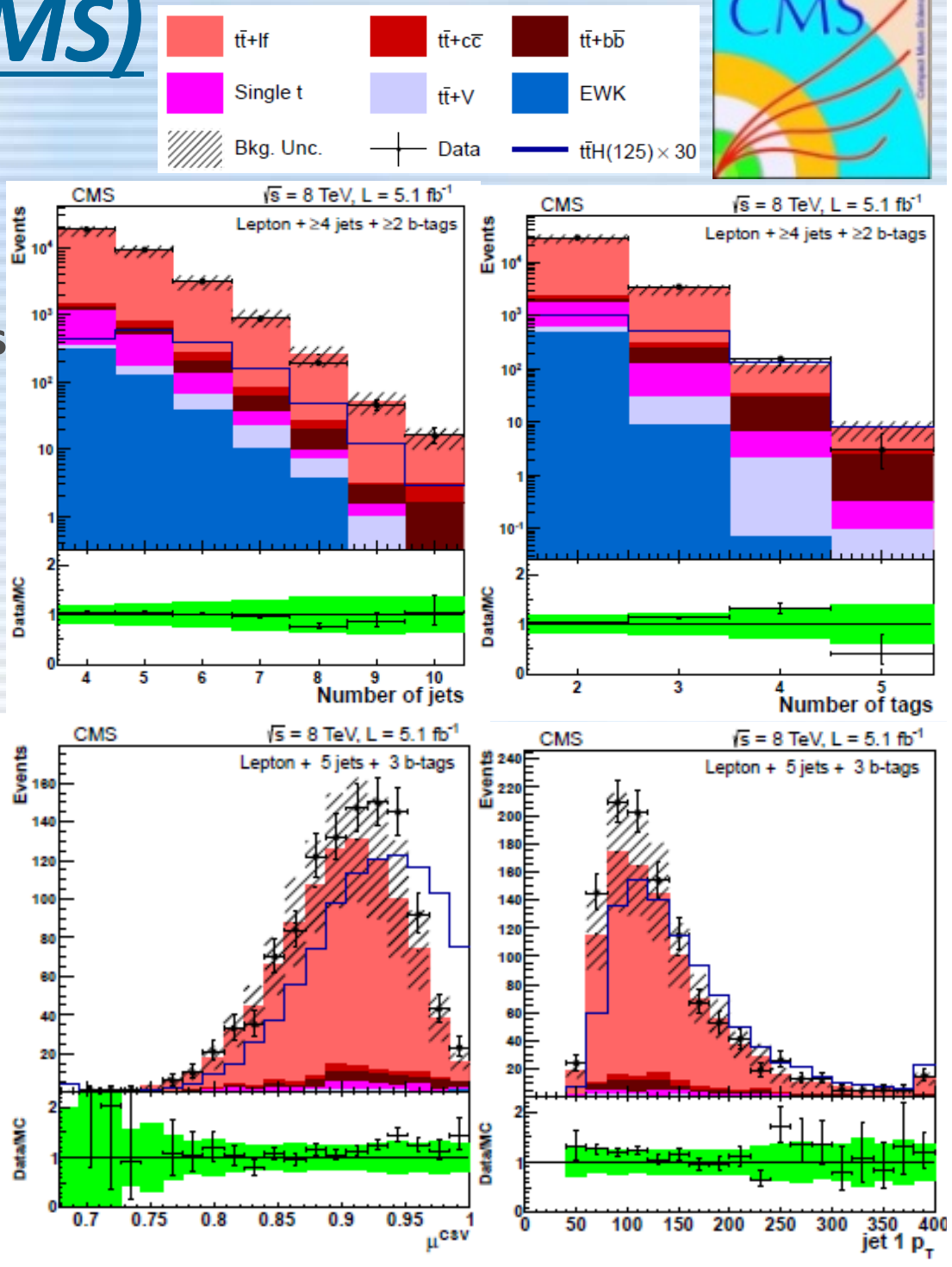
2 jets with 2 b-tags

≥3 jets with ≥3 b-tags

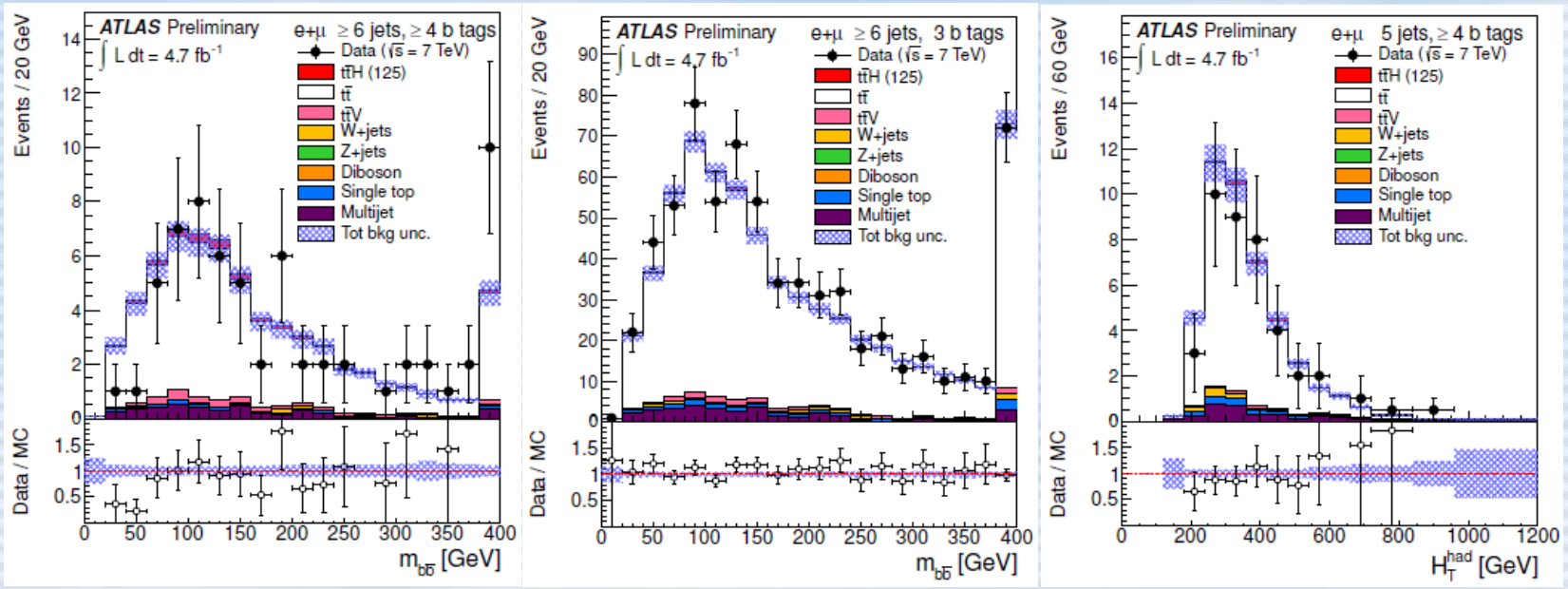
→ 2 signal regions in total

Construct ANN as discriminant variable

- Optimize set of inputs for each region

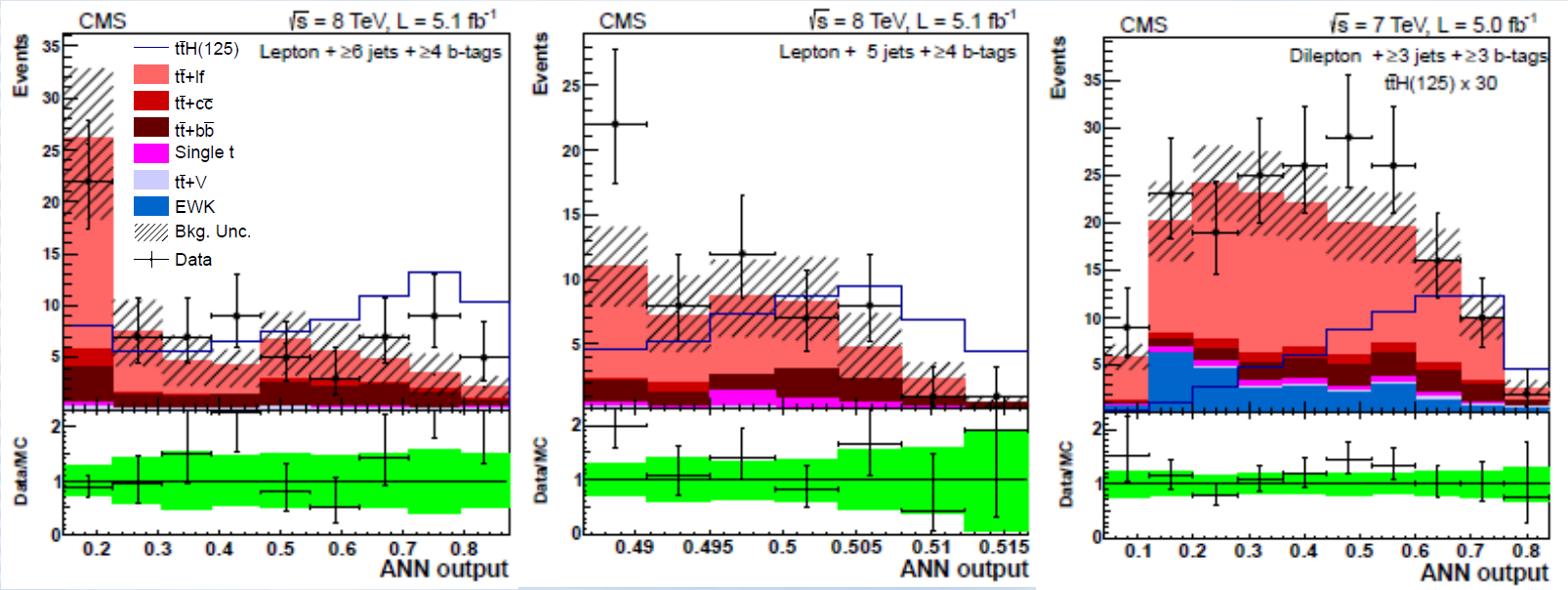


Final discriminant distribution

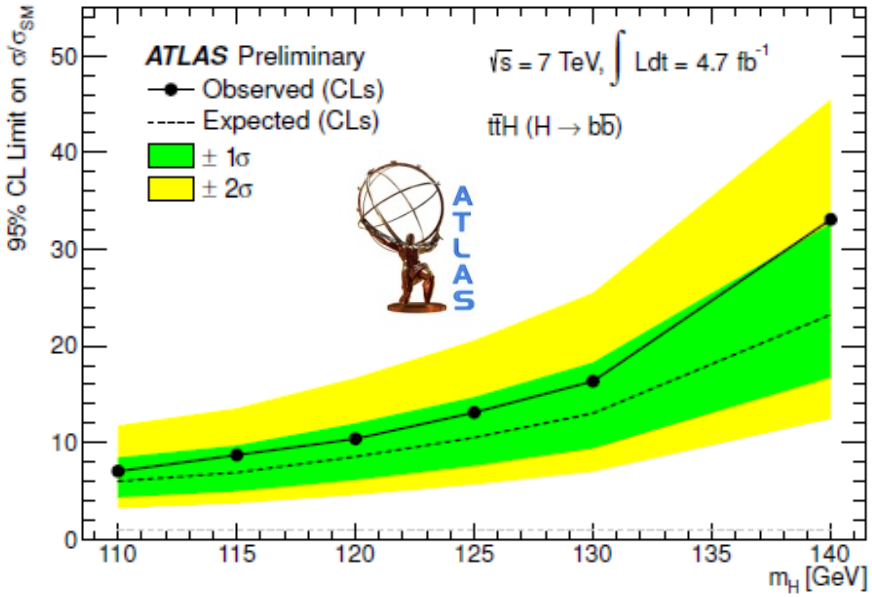


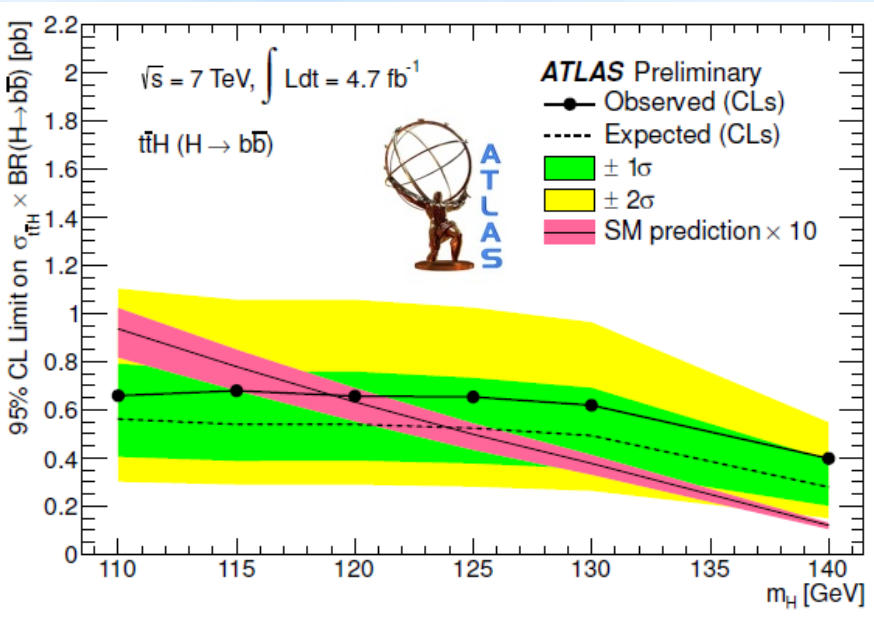
ATLAS: Post-fit final discriminant distributions

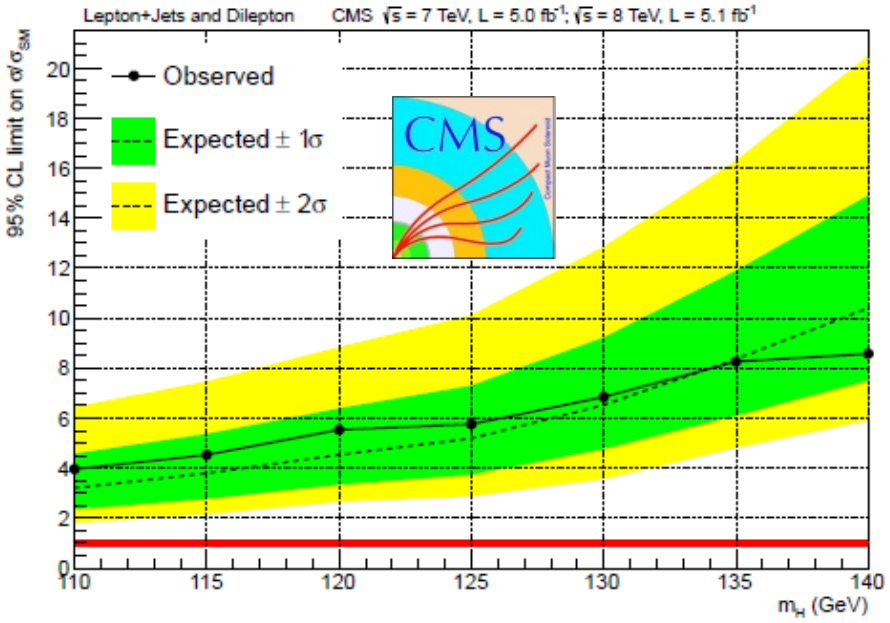
CMS: Final discriminant distributions after applying all scale factors



Result







Obs. (Exp.) limit @125 GeV

13.1 (10.5) x σ(SM)

Obs. (Exp.) limit @125 GeV

5.8 (5.2) x σ(SM)

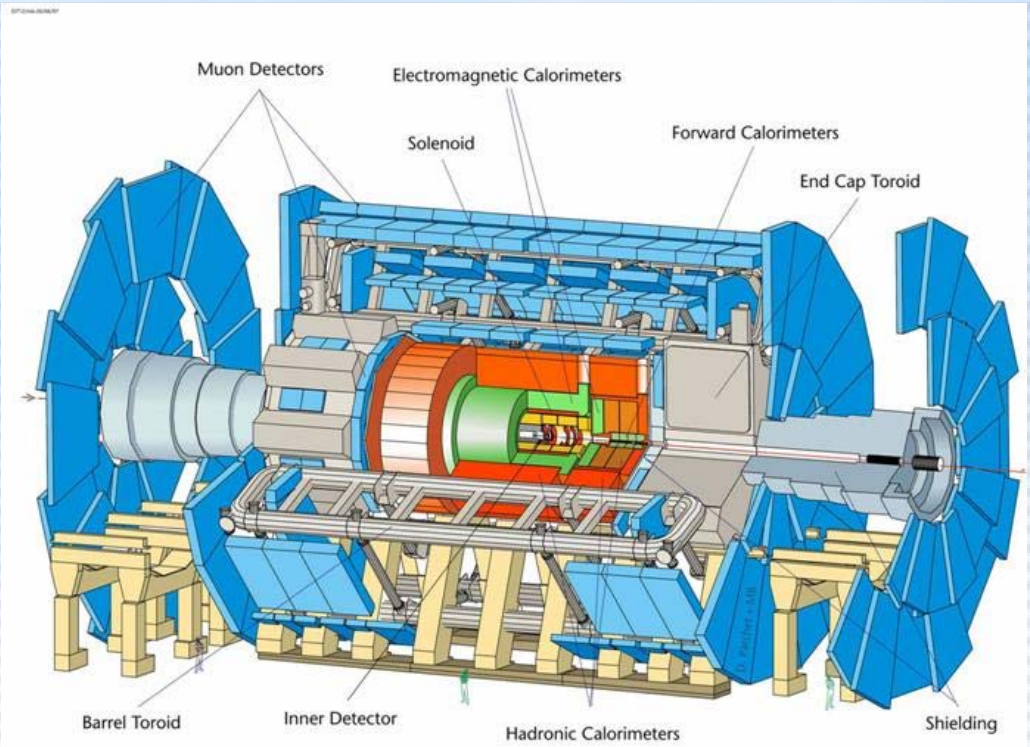
Summary

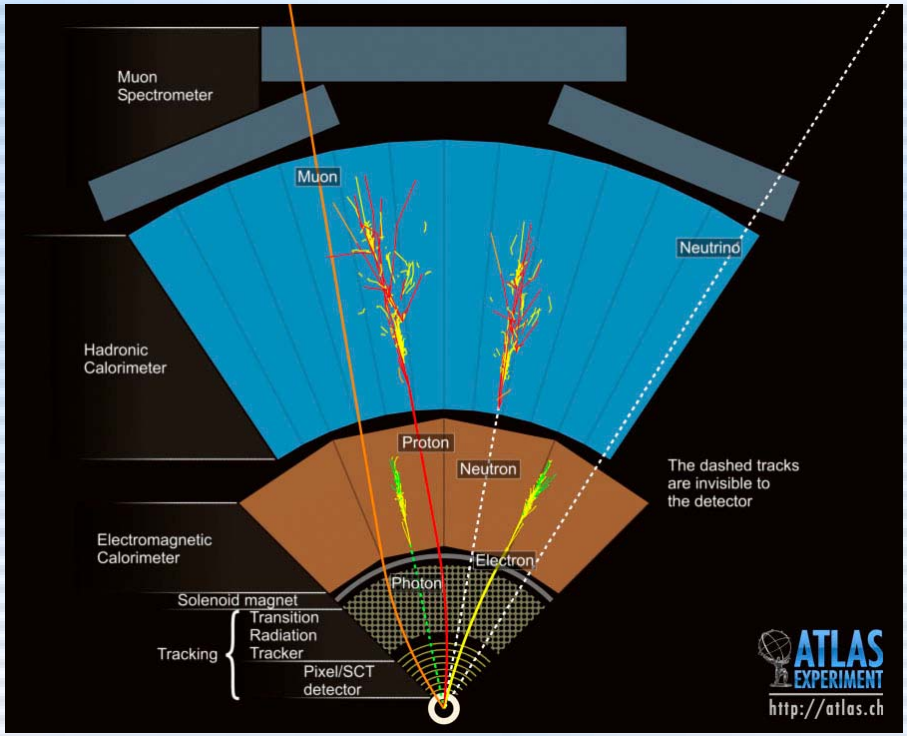
- ATLAS & CMS analyses search for the Higgs boson decaying to b-quark pair
  - **VZ→Vbb**: Observed SM diboson process with 4σ significance
  - **VH→Vbb**: Sensitivity @125 GeV is close to SM, CMS observed 2.2σ excess
  - **ttH→ttbb**: Observed (Expected) limit on σ_{ttH} x Br(H→bb) @125 GeV
    ATLAS: 13.1 (10.5) x σ(SM), CMS: 5.8 (5.2) x σ(SM)
- All H→bb analyses have yet to use full 2012 dataset
  - **Will increase significance of H→bb search**
- ATLAS & CMS are currently working to achieve further analysis improvements
  - **Will expect solid observation soon if the SM H→bb process exists**

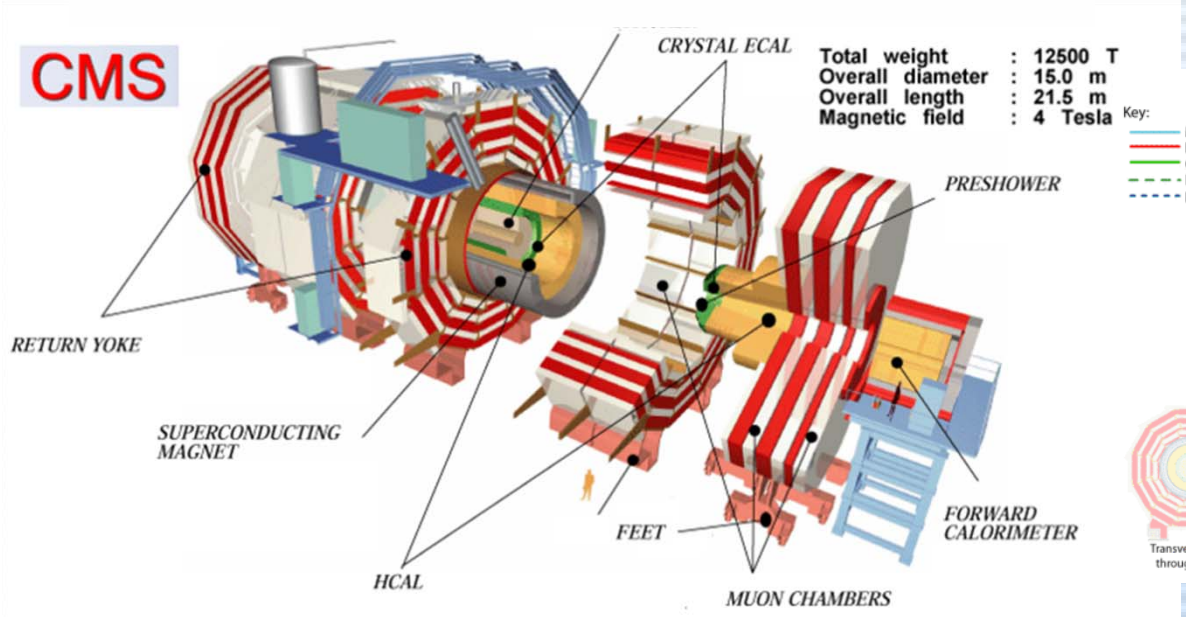
Stay tuned!!

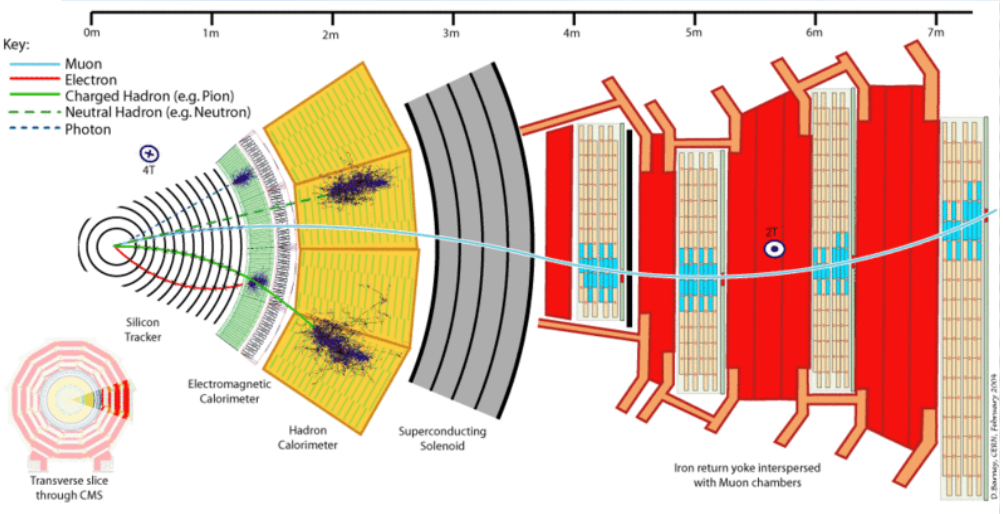
Backup

ATLAS & CMS detector

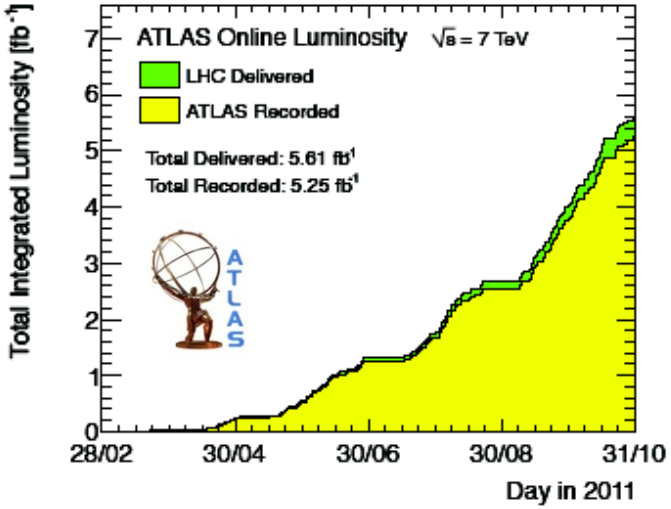


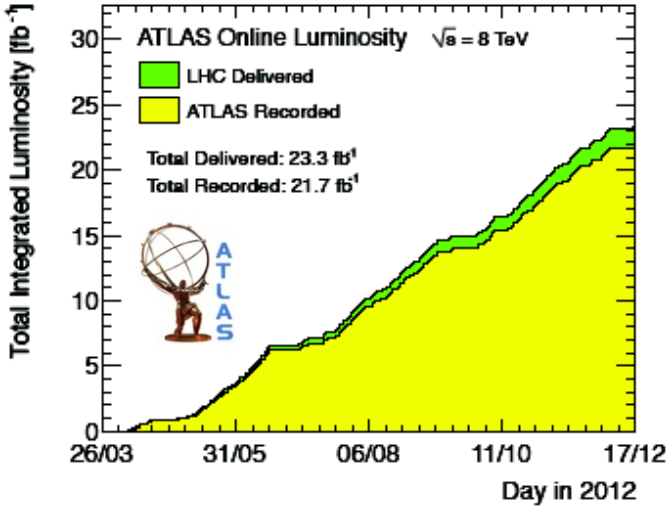


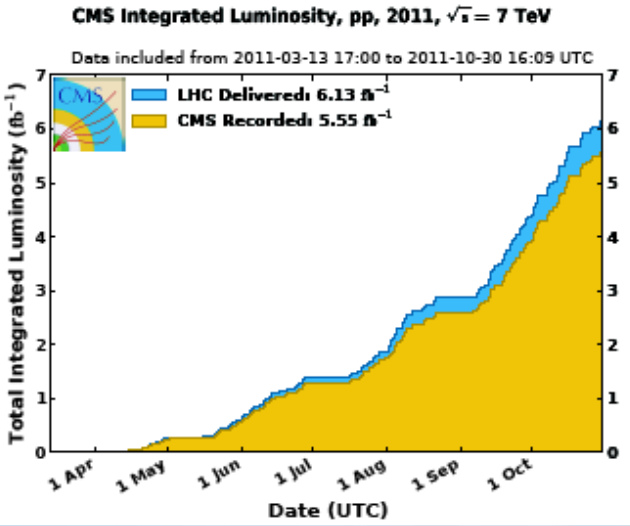


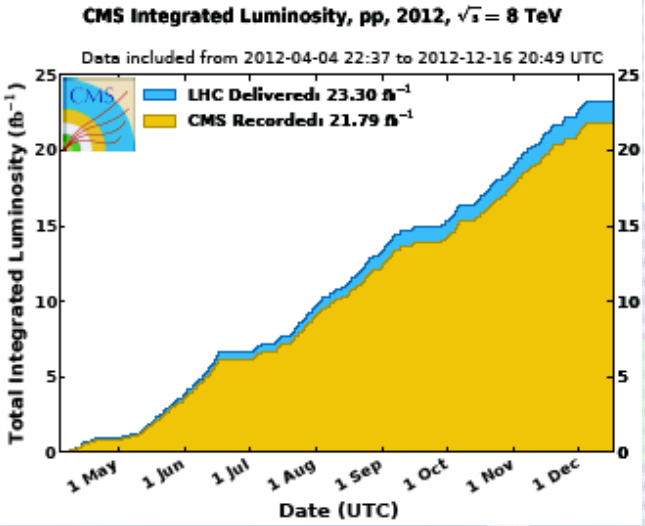


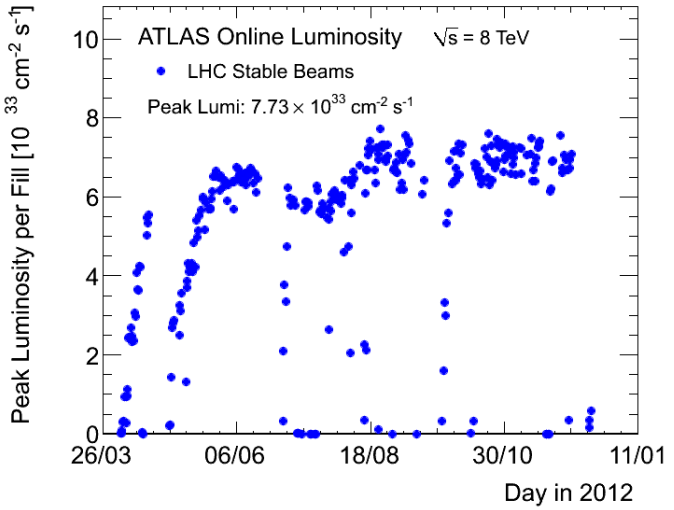
ATLAS & CMS Luminosity



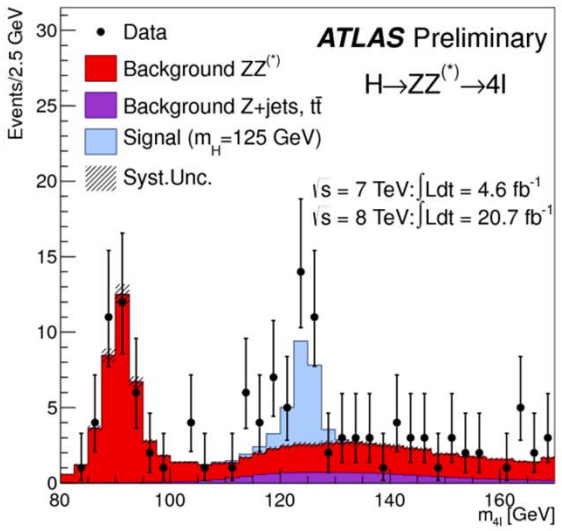


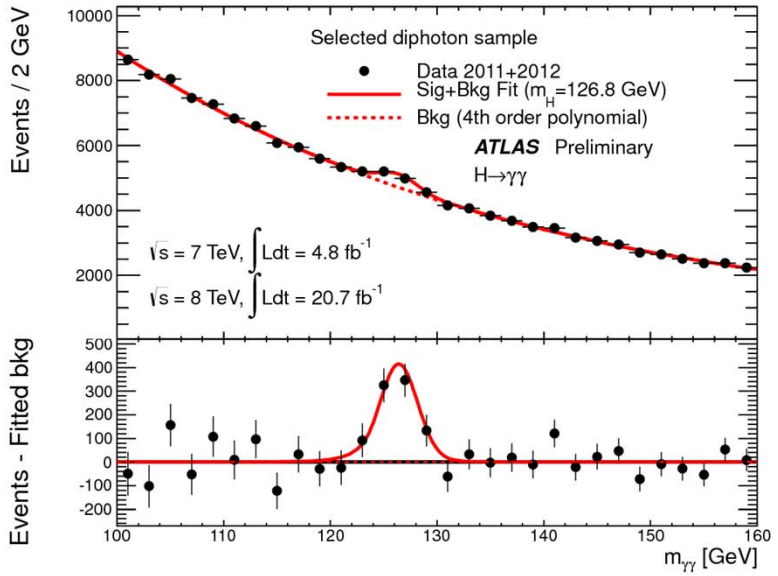


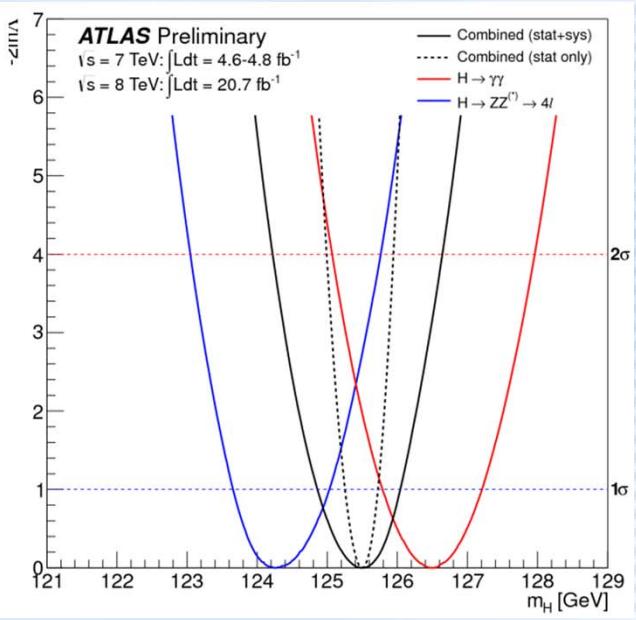




ATLAS & CMS Higgs mass measurement

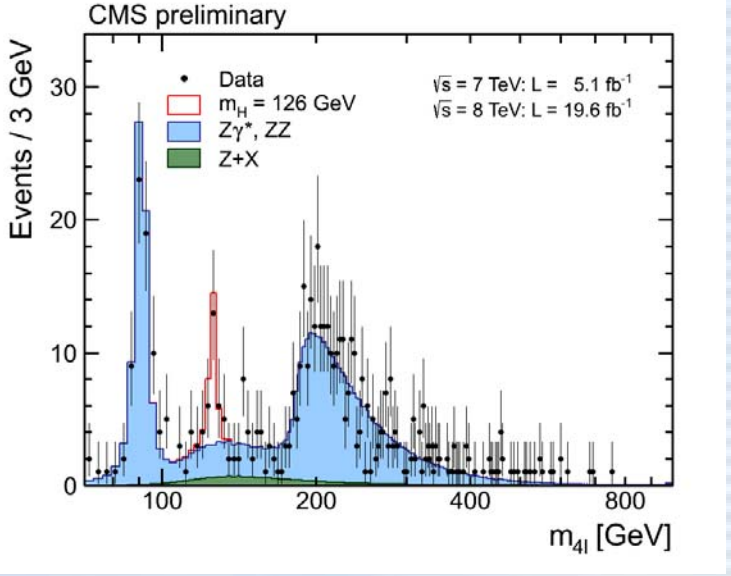


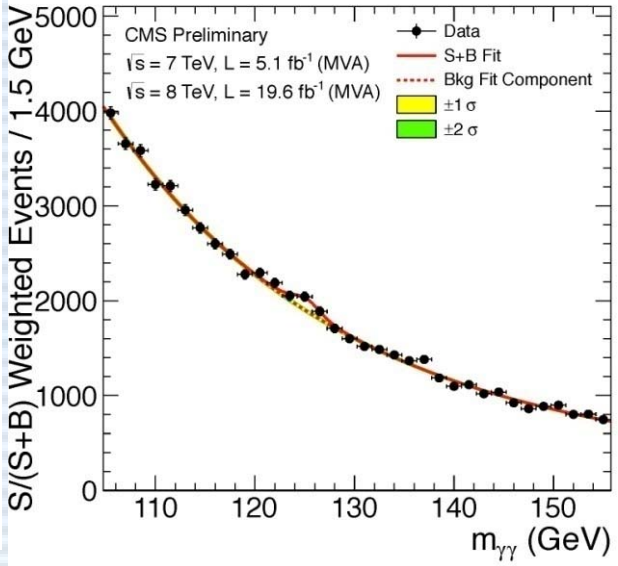


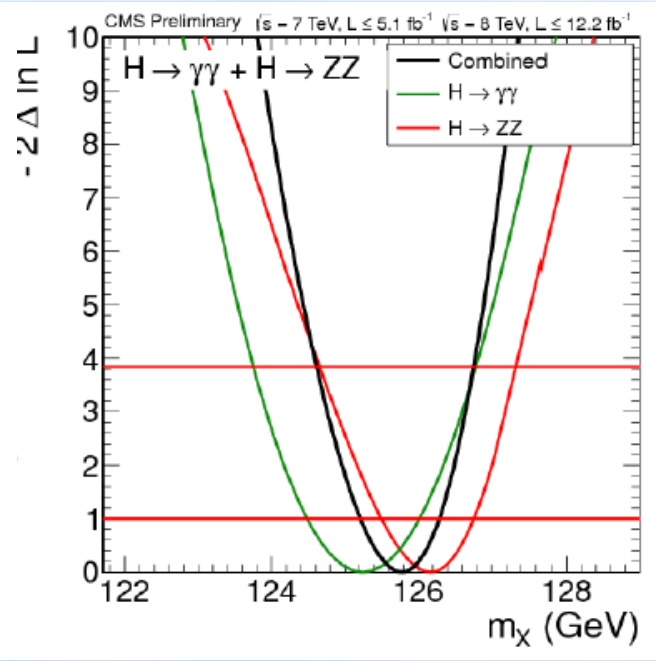


$m_H = 125.5 \pm 0.2(\text{stat.})^{+0.5}_{-0.6}$ (syst.) GeV

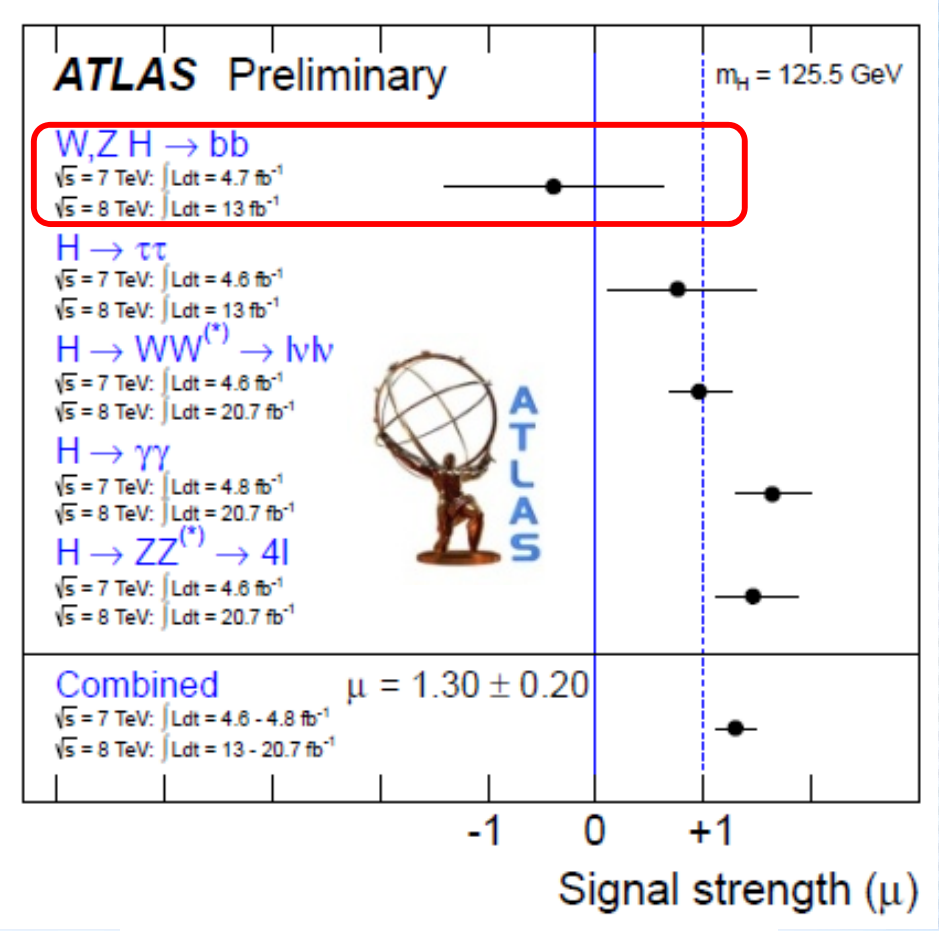
$m_H = 125.8 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.})$ GeV

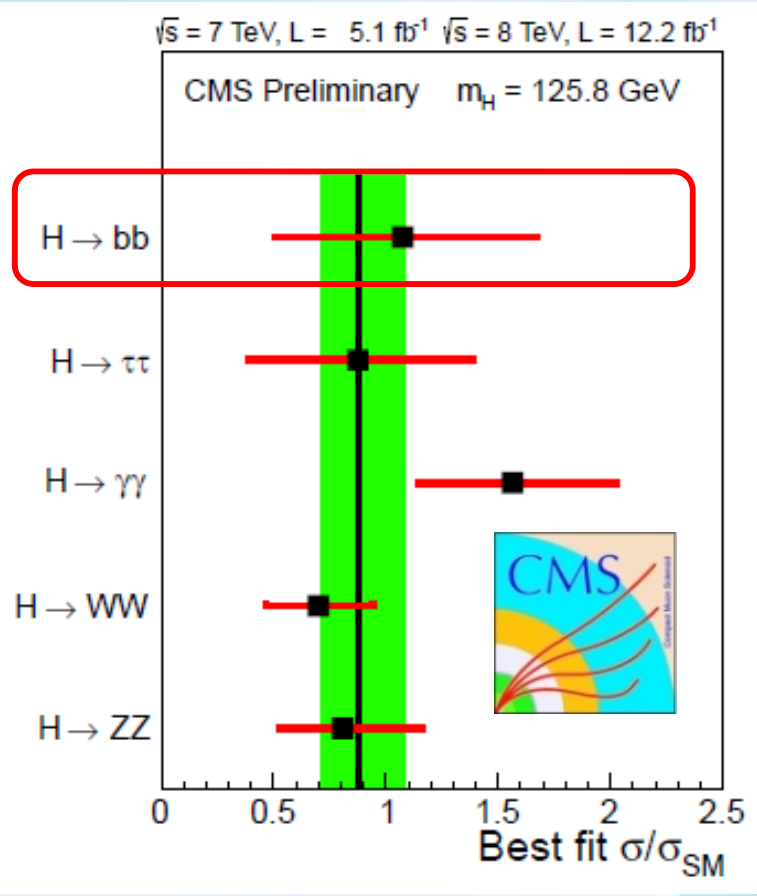






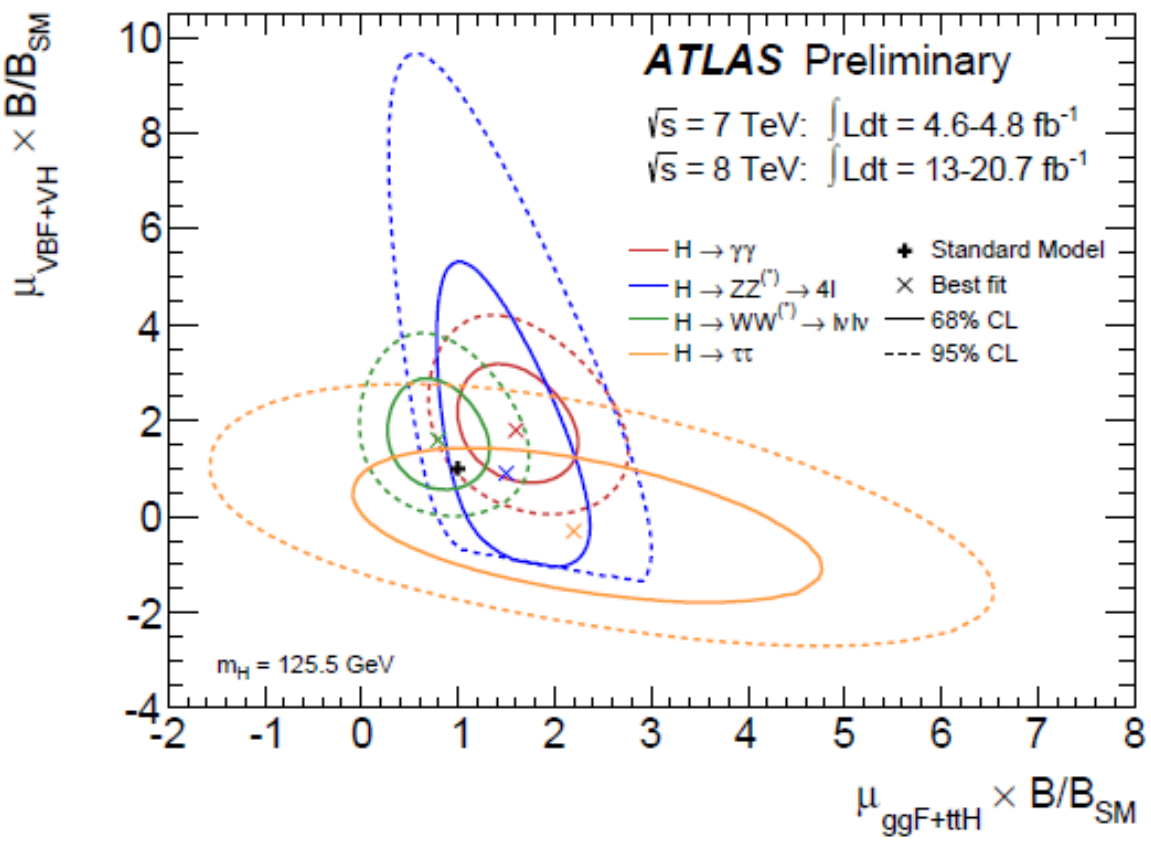
ATLAS & CMS signal strength

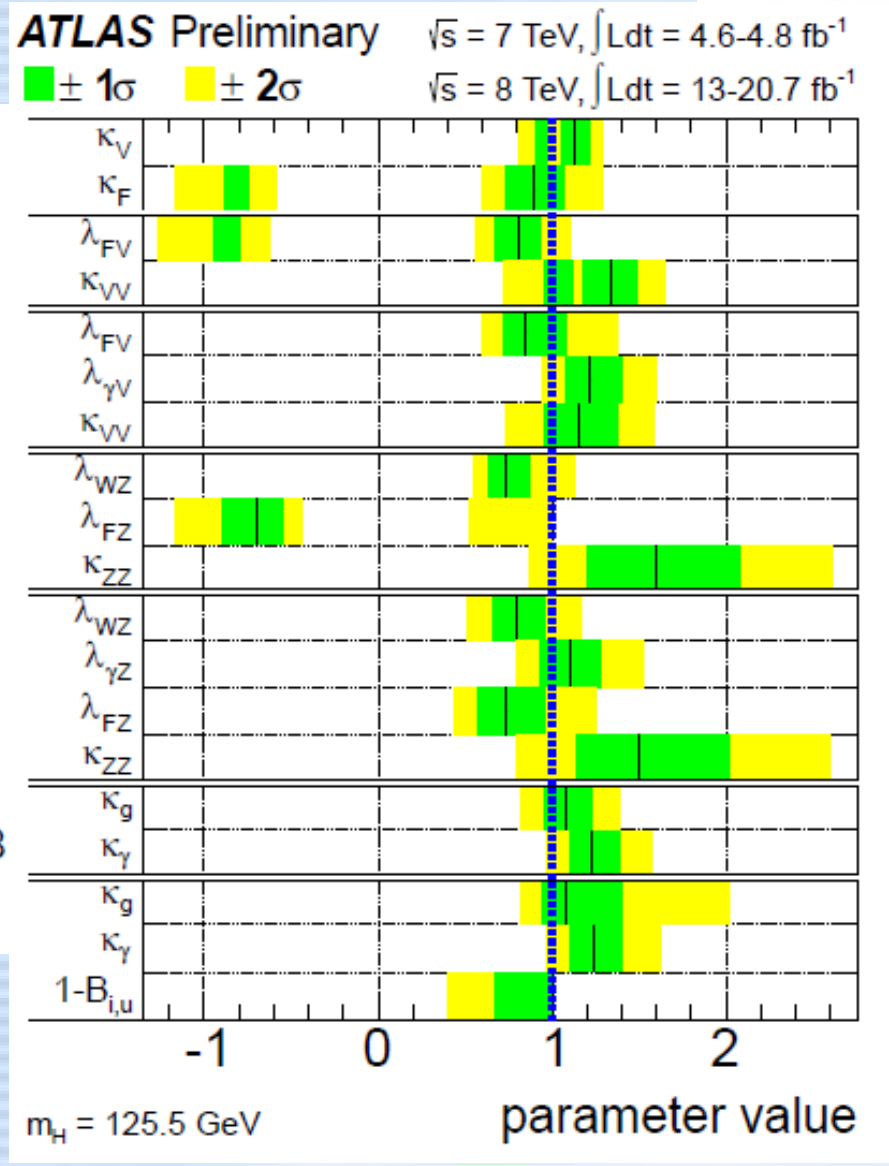




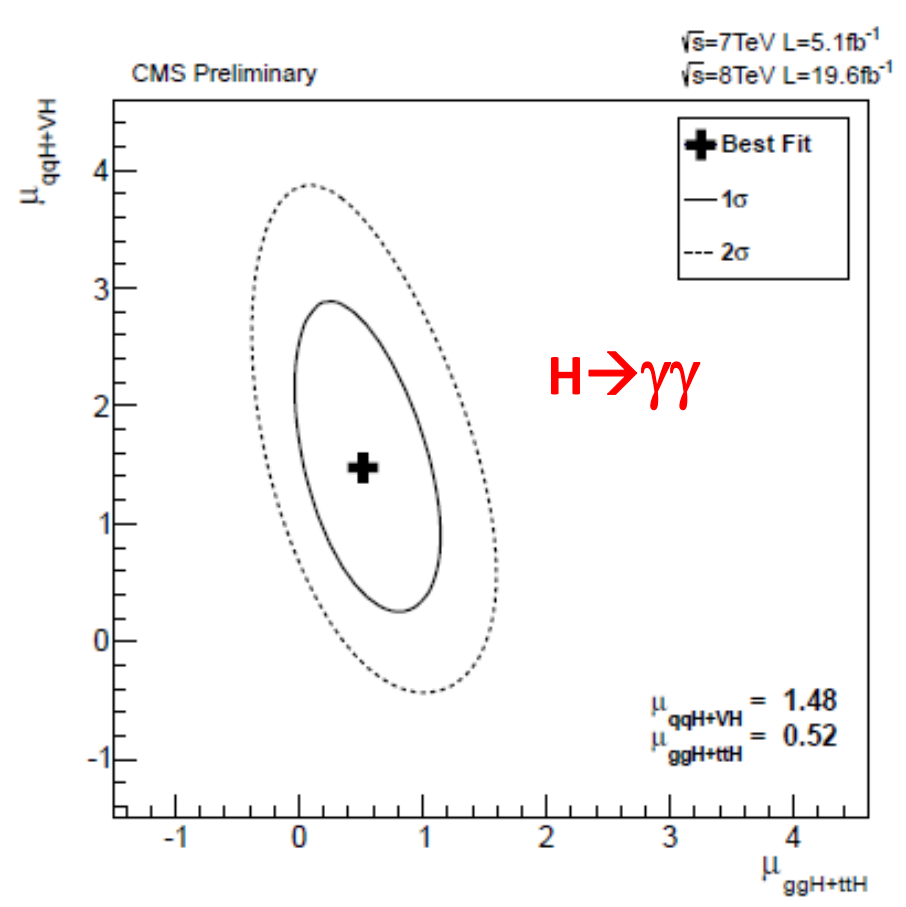
Higgs Boson Decay	μ (m_H=125.5 GeV)
$VH \to Vbb$	-0.4 ± 1.0
$H \to \tau\tau$	0.8 ± 0.7
$H \to WW^{(*)}$	1.0 ± 0.3
$H \to \gamma\gamma$	1.6 ± 0.3
$H \to ZZ^{(*)}$	1.5 ± 0.4
Combined	1.30 ± 0.20

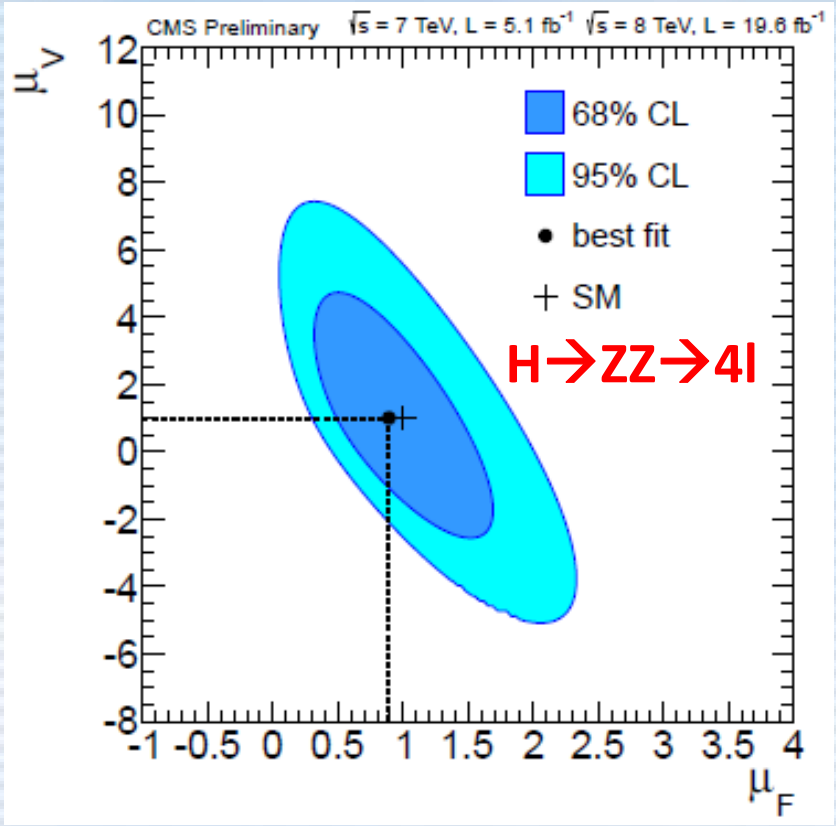
ATLAS coupling result





CMS spin & coupling result





H→ZZ→4l

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

b-tagging

Algorithm

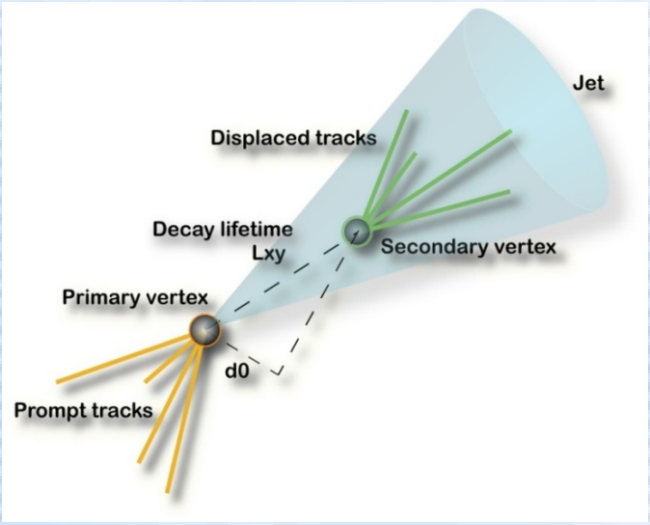
- ATLAS: **multivariate b-jet identification (MV1)**

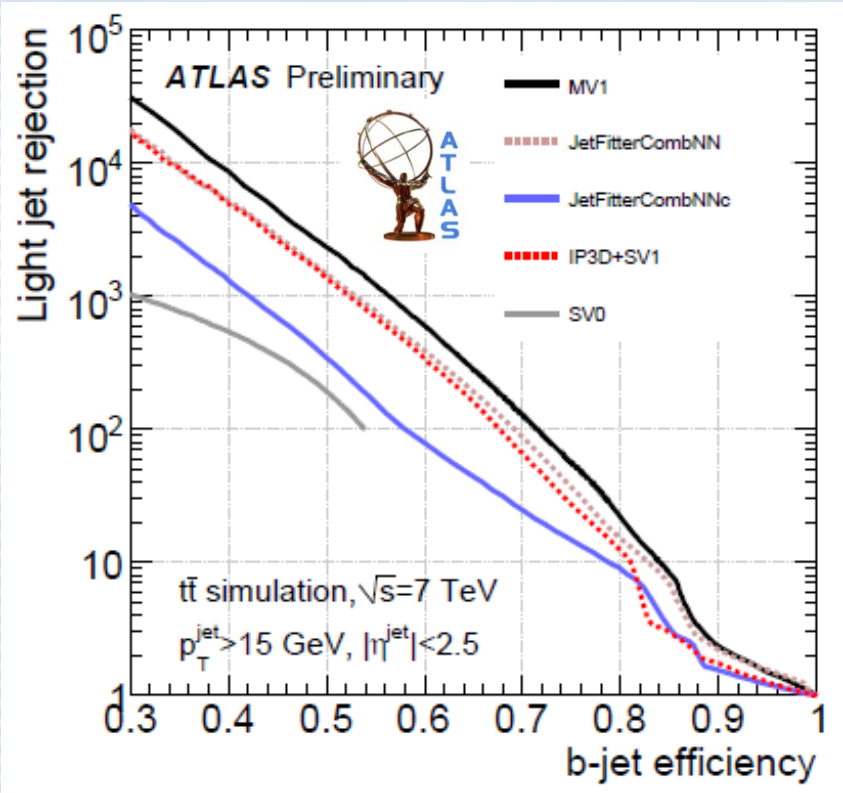
  Use 70% efficiency (0.7% fake rate)

- CMS: **Combined Secondary Vertex (CSV)**

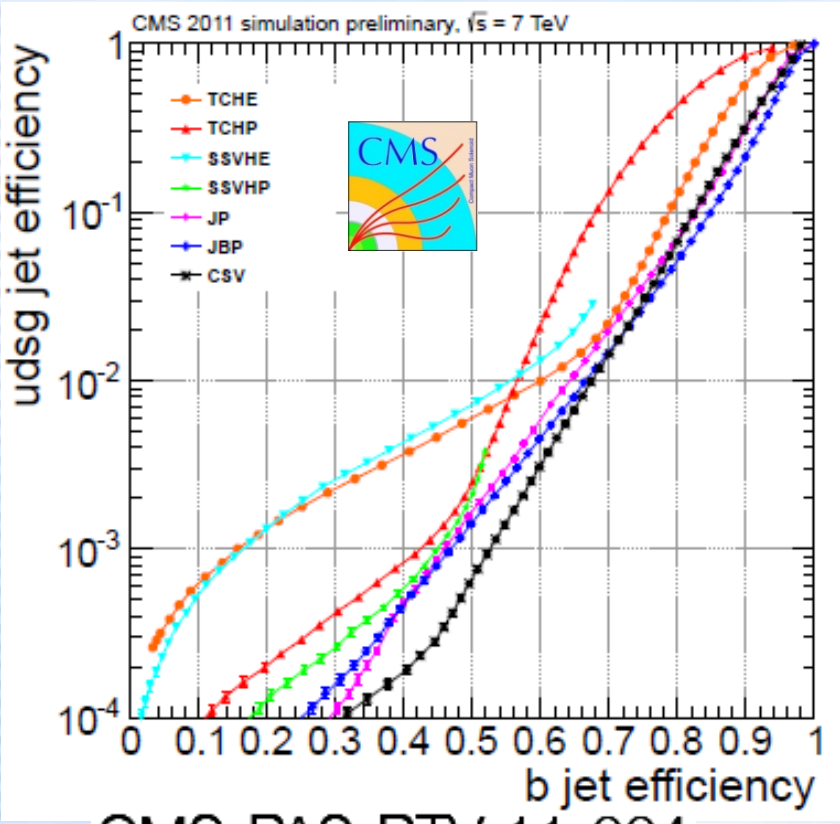
  Use several operation points

  (72% efficiency with 3% fake rate)



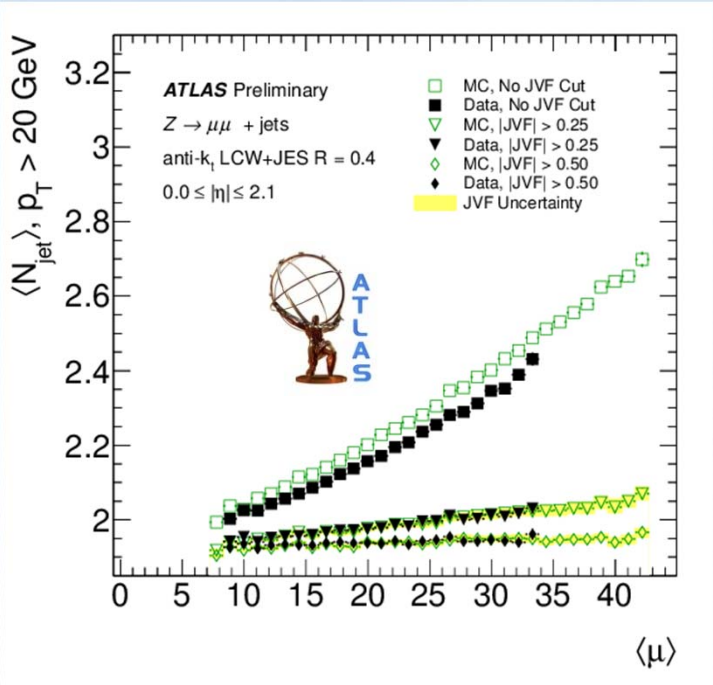


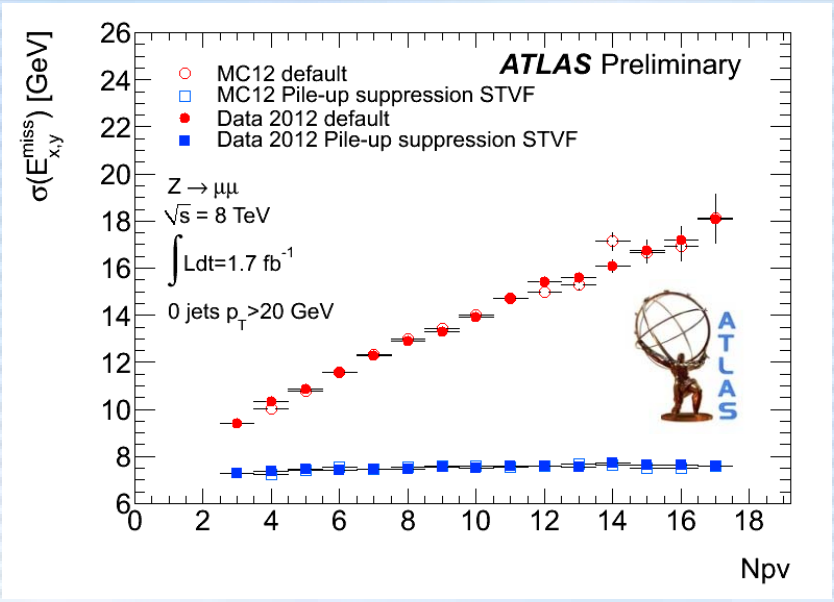
ATLAS-CONF-2012-043

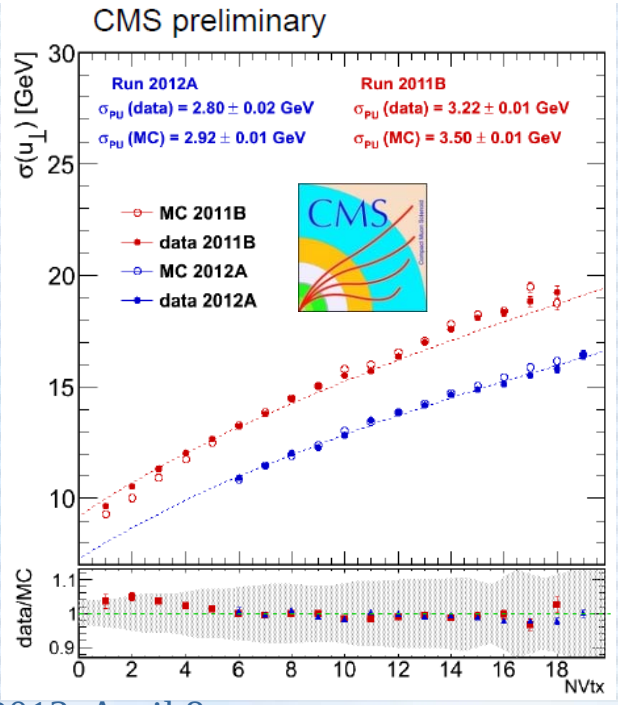


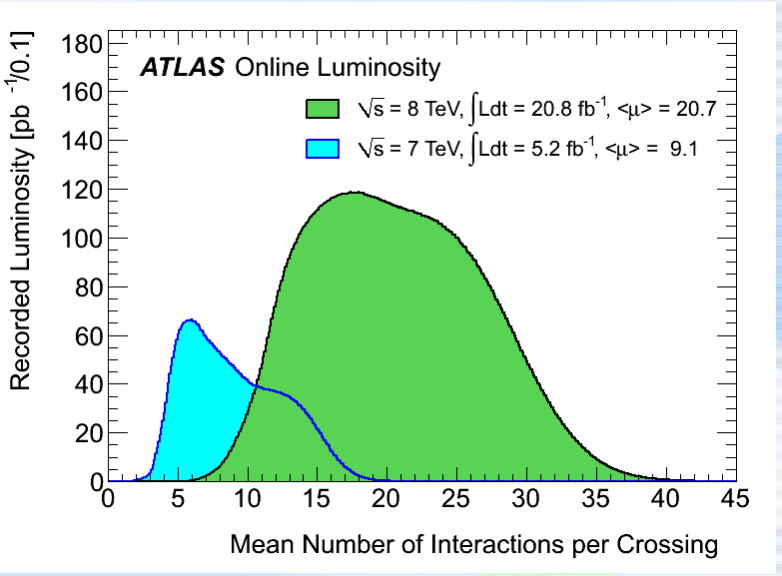
CMS-PAS-BTV-11-004

JET/MET performance









Categorization & Event selection (VH)

0-lepton channel			
E_T^{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
$\Delta R(b,b)$	>0.7			0.7-1.6	<1.4
E_T^{miss} (GeV)	> 25				> 50
m_T^W (GeV)	> 40			-	

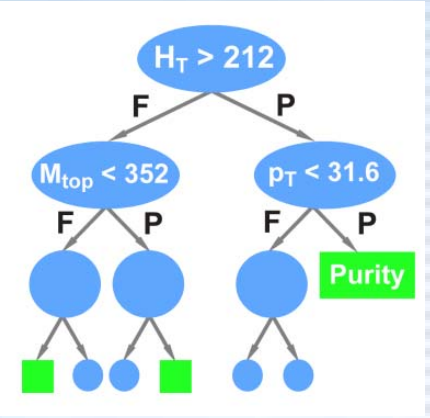
2-lepton channel					
p_T^Z (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b,\bar{b})$	>0.7			0.7-1.8	<1.6

Variable	W($\ell\nu$)H	Z($\ell\ell$)H	Z($\nu\nu$)H
$m_{\ell\ell}$	–	$[75-105]$	–
$p_T(j_1)$	>30	>20	>60
$p_T(j_2)$	>30	>20	>30
p_T(jj)	>120	–	>130
m(jj)	<250	$[80-150]$ (<250)	<250
p_T(V)	$[120-170]$ (>170)	$[50-100]$ (>100)	–
CSV_{max}	>0.40	>0.50 (>0.244)	>0.679
CSV_{min}	>0.40	>0.244	>0.244
CSV_{min}^{loose}	– (<0.40)	–	– (<0.244)
N_{al}	$=0$	–	$=0$
E_T^{miss}	>45 (elec)	–	$[130-170]$ (>170)
$\Delta\phi(E_T^{miss}, jet)$	–	–	>0.5
$\Delta\phi(E_T^{miss}, E_T^{miss(trks)})$	–	–	<0.5
$\Delta\phi$(V,H)	–	–	>2.0

Boosted Decision Tree (CMS, VH→Vbb)

BDT variables to construct final discriminant

Variable
p_{Tj}: 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
$\Delta\phi(E_T^{miss}$, jet): azimuthal angle between E_T^{miss} and the closest jet (only for Z($\nu\nu$)H)
$\Delta\theta_{pull}$: color pull angle [35]



Background Normalization (VH→Vbb)

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

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 6: Data/MC scale factors for each control region in each decay mode for the 2011 7 TeV and the 2012 8 TeV analyses. The errors include the statistical uncertainty from the fit, and a systematic uncertainty accounting for possible data/MC shape differences in the discriminating variables. Electron and muon samples in $Z(\ell\ell)H$ and $W(\ell\nu)H$ are fit simultaneously to determine average scale factors.

Process	$W(\ell\nu)H$	$W(\ell\nu)H$	$Z(\ell\ell)H$	$Z(\ell\ell)H$	$Z(\nu\nu)H$	$Z(\nu\nu)H$
Low p_T	7 TeV	8 TeV	7 TeV	8 TeV	7 TeV	8 TeV
W + udscg	$0.88 \pm 0.01 \pm 0.03$	$1.01 \pm 0.02 \pm 0.01$	–	–	$0.89 \pm 0.01 \pm 0.03$	$0.96 \pm 0.06 \pm 0.03$
$Wb\bar{b}$	$1.91 \pm 0.14 \pm 0.31$	$2.07 \pm 0.15 \pm 0.10$	–	–	$1.36 \pm 0.10 \pm 0.15$	$1.30 \pm 0.17 \pm 0.10$
Z + udscg	–	–	$1.11 \pm 0.03 \pm 0.11$	$1.10 \pm 0.02 \pm 0.06$	$0.87 \pm 0.01 \pm 0.03$	$1.15 \pm 0.07 \pm 0.03$
$Zb\bar{b}$	–	–	$0.98 \pm 0.05 \pm 0.12$	$1.08 \pm 0.04 \pm 0.08$	$0.96 \pm 0.02 \pm 0.03$	$1.12 \pm 0.10 \pm 0.04$
$t\bar{t}$	$0.93 \pm 0.02 \pm 0.05$	$1.07 \pm 0.01 \pm 0.01$	$1.03 \pm 0.04 \pm 0.11$	$1.01 \pm 0.02 \pm 0.06$	$0.97 \pm 0.02 \pm 0.04$	$1.05 \pm 0.07 \pm 0.03$
High p_T	7 TeV	8 TeV	7 TeV	8 TeV	7 TeV	8 TeV
W + udscg	$0.79 \pm 0.01 \pm 0.02$	$0.94 \pm 0.02 \pm 0.01$	–	–	$0.78 \pm 0.02 \pm 0.03$	$0.95 \pm 0.05 \pm 0.02$
$Wb\bar{b}$	$1.49 \pm 0.14 \pm 0.19$	$1.72 \pm 0.16 \pm 0.08$	–	–	$1.48 \pm 0.15 \pm 0.20$	$1.27 \pm 0.18 \pm 0.10$
Z + udscg	–	–	$1.11 \pm 0.03 \pm 0.11$	$1.10 \pm 0.02 \pm 0.06$	$0.97 \pm 0.02 \pm 0.04$	$1.04 \pm 0.07 \pm 0.02$
$Zb\bar{b}$	–	–	$0.98 \pm 0.05 \pm 0.12$	$1.08 \pm 0.04 \pm 0.08$	$1.08 \pm 0.09 \pm 0.06$	$1.15 \pm 0.10 \pm 0.04$
$t\bar{t}$	$0.84 \pm 0.02 \pm 0.03$	$0.99 \pm 0.01 \pm 0.01$	$1.03 \pm 0.04 \pm 0.11$	$1.01 \pm 0.02 \pm 0.06$	$0.97 \pm 0.02 \pm 0.04$	$1.03 \pm 0.07 \pm 0.03$

CMS ttH ANN input variables

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

ATLAS ttH systematic uncertainties

≥ 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	+1.8/-1.8	+1.8/-1.8	+1.8/-1.8	+1.8/-1.8	+1.8/-1.8	+1.8/-1.8	+1.8/-1.8	–
Lepton ID+reco+trigger	+1.3/-1.3	+1.3/-1.3	+1.3/-1.3	+1.5/-1.5	+1.3/-1.3	+1.3/-1.3	+1.3/-1.3	–
Jet vertex fraction efficiency	+2.4/-1.7	+2.5/-1.9	+2.5/-2.3	+2.7/-2.7	+2.5/-1.8	+1.6/-1.2	+2.5/-1.9	–
Jet energy scale	+9.6/-9.9	+13.5/-15.2	–	+27.4/-28.6	+13.5/-15.2	+27.4/-28.6	+13.5/-15.2	–
Jet energy resolution	+1.0/-1.0	+0.7/-0.7	+9.9/-9.9	+41.7/-41.7	+7.1/-7.1	+6.9/-6.9	+1.9/-1.9	–
b-tagging efficiency	+30.4/-34.8	+22.9/-25.2	+29.7/-35.6	+22.5/-28.0	+26.2/-29.7	+34.0/-38.4	+26.0/-29.0	–
c-tagging efficiency	+5.0/-5.0	+16.5/-17.3	+16.3/-17.5	+12.7/-14.0	+15.0/-16.0	+9.8/-11.5	+16.0/-17.2	–
Light jet-tagging efficiency	+1.3/-1.3	+11.4/-12.1	+12.0/-13.2	+31.1/-36.7	+8.5/-9.1	+2.7/-3.2	+4.2/-4.3	–
$t\bar{t}$ cross section	–	+9.9/-10.7	–	–	–	–	–	–
$t\bar{t}V$ cross section	–	–	–	–	–	–	+30.0/-30.0	–
Single top cross section	–	–	–	–	+4.7/-3.7	–	–	–
Diboson cross section	–	–	–	–	–	+5.0/-5.0	–	–
V+jets normalisation	–	–	+58.8/-58.8	+58.8/-58.8	–	–	–	–
Multijet normalisation	–	–	–	–	–	–	–	+82.8/-82.8
W+heavy-flavour fractions	–	–	+35.2/-35.0	–	–	–	–	–
$t\bar{t}$ 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	+78.0/-80.8	+87.1/-91.4	+35.3/-39.1	+45.7/-50.2	+45.2/-47.9	+82.8/-82.8

Table 8: Table summarising the overall normalisation uncertainties (expressed in %) in signal and each of the background processes for each of the systematic uncertainties considered, prior to fitting the nuisance parameters to data. The selection presented here is the combined e+jets and μ+jets channels with ≥ 6 jets and ≥ 4 b tags.

CMS ttH systematic uncertainties

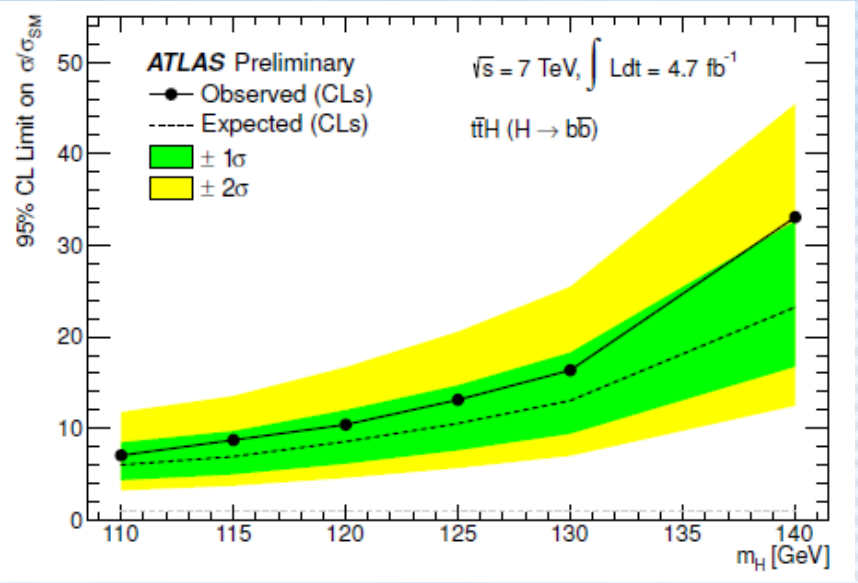
Table 5: Summary of the systematic uncertainties considered on the inputs to the limit calculation. Except where noted, each row in this table will be treated as a single, independent nuisance parameter.

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

ATLAS ttH result

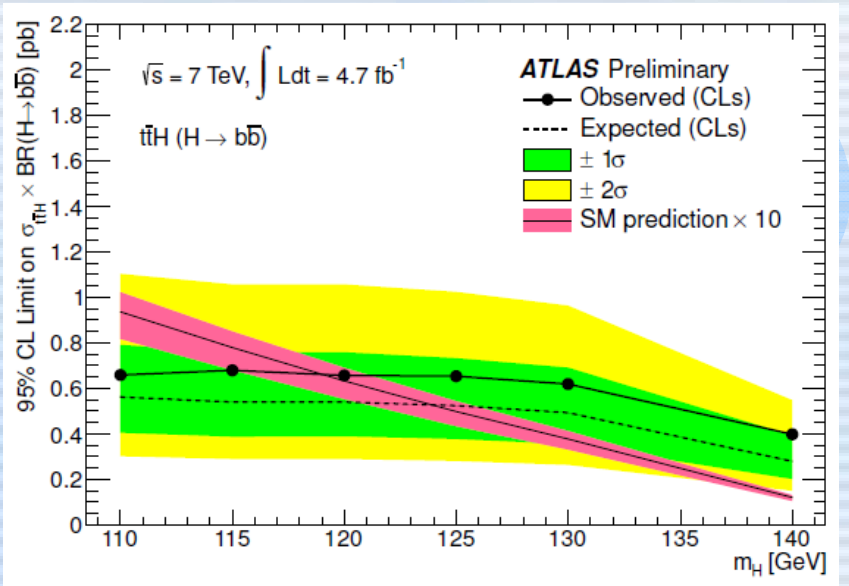
m_H (GeV)	observed	-2 s.d.	-1 s.d.	median	+1 s.d.	+2 s.d.	stat only
110	7.0	3.2	4.3	6.0	8.5	11.8	3.5
115	8.7	3.7	5.0	6.9	9.7	13.6	4.0
120	10.4	4.6	6.2	8.5	12.0	16.7	4.9
125	13.1	5.7	7.6	10.5	14.7	20.6	6.1
130	16.4	7.0	9.4	13.0	18.3	25.5	7.8
140	33.0	12.5	16.7	23.2	32.7	45.5	14.2

Table 3: Observed and expected (median, for the background-only hypothesis) 95% CL upper limits on $\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$ relative to the SM prediction, σ/σ_{SM}, as functions of m_H. The last column corresponds to the median upper limit with all systematic uncertainties removed.



m_H (GeV)	observed	-2 s.d.	-1 s.d.	median	+1 s.d.	+2 s.d.	stat only
110	0.66	0.30	0.41	0.56	0.79	1.10	0.36
115	0.68	0.29	0.39	0.54	0.76	1.06	0.34
120	0.66	0.29	0.39	0.54	0.76	1.06	0.34
125	0.65	0.28	0.38	0.53	0.73	1.03	0.34
130	0.62	0.26	0.36	0.49	0.69	0.96	0.32
140	0.40	0.15	0.20	0.28	0.39	0.55	0.19

Table 4: Observed and expected (median, for the background-only hypothesis) 95% CL upper limits on $\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$ (in pb), as functions of m_H. The last column corresponds to the median upper limit with all systematic uncertainties removed.



CMS ttH result

7 TeV Lepton+Jets and Dilepton				
		Expected		
m_H	Observed	Median	68% CL Range	95% CL Range
110 GeV	4.1	4.4	[3.3, 6.3]	[2.7, 8.7]
115 GeV	4.7	5.0	[3.7, 7.1]	[2.9, 10.0]
120 GeV	5.5	5.8	[4.3, 8.2]	[3.4, 11.4]
125 GeV	6.2	6.9	[5.2, 9.7]	[4.1, 13.6]
130 GeV	7.3	8.8	[6.5, 12.5]	[5.0, 17.3]
135 GeV	8.8	10.8	[7.9, 15.4]	[6.3, 21.3]
140 GeV	10.4	14.2	[10.2, 20.0]	[8.2, 27.8]

8 TeV Lepton+Jets and Dilepton				
		Expected		
m_H	Observed	Median	68% CL Range	95% CL Range
110 GeV	5.6	3.3	[2.4, 4.7]	[2.0, 6.9]
115 GeV	6.6	4.1	[3.0, 5.8]	[2.5, 8.1]
120 GeV	8.2	5.1	[3.8, 7.1]	[3.1, 10.0]
125 GeV	8.7	5.7	[4.3, 8.2]	[3.5, 11.3]
130 GeV	10.4	6.9	[5.2, 9.8]	[4.2, 13.9]
135 GeV	13.7	9.4	[7.1, 13.1]	[5.7, 18.3]
140 GeV	15.2	11.3	[8.5, 16.2]	[6.8, 22.5]

7 TeV + 8 TeV Lepton+Jets and Dilepton combined				
		Expected		
m_H	Observed	Median	68% CL Range	95% CL Range
110 GeV	4.0	3.2	[2.4, 4.6]	[1.8, 6.5]
115 GeV	4.5	3.8	[2.8, 5.4]	[2.2, 7.5]
120 GeV	5.5	4.5	[3.3, 6.4]	[2.7, 8.9]
125 GeV	5.8	5.2	[3.7, 7.3]	[2.9, 10.1]
130 GeV	6.8	6.5	[4.8, 9.2]	[3.6, 12.9]
135 GeV	8.3	8.4	[6.1, 11.9]	[4.8, 16.3]
140 GeV	8.6	10.4	[7.5, 14.9]	[5.9, 20.5]