Searches for the SM BEH boson decaying into a pair of *b* quarks at the LHC

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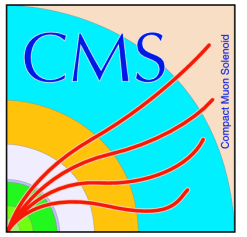
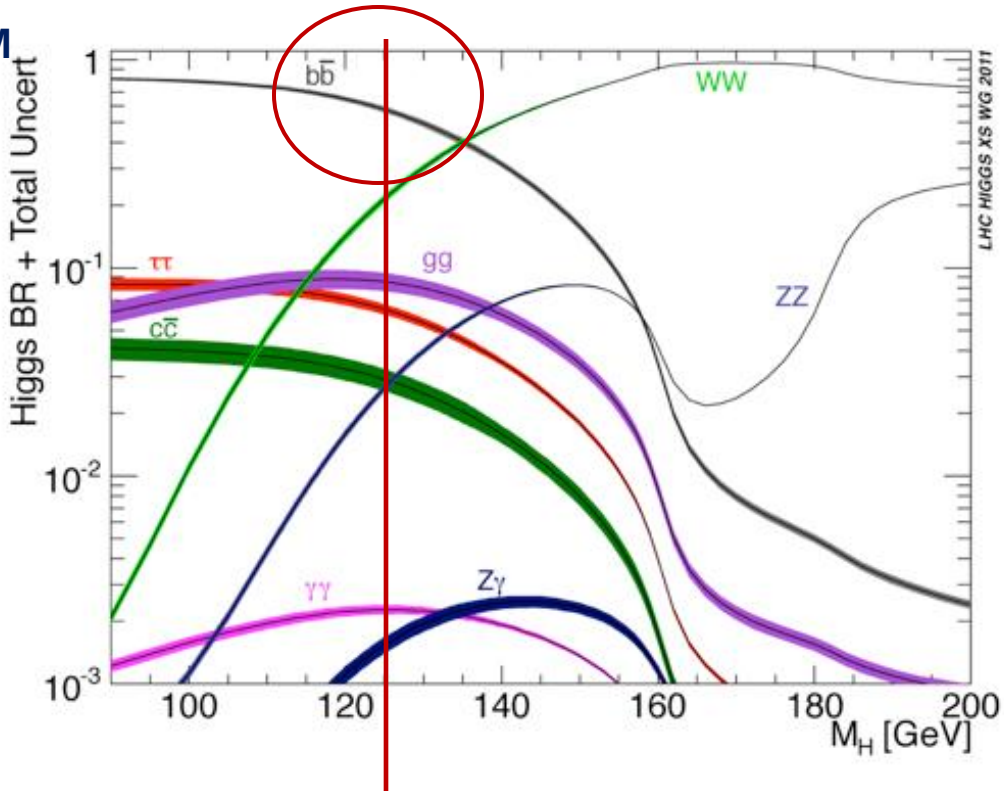
LHC France – Annecy – April 2013



H→ bb: introduction

- **2012 → ATLAS & CMS: Observation of a new BEH-like particle with a mass around 125 GeV decaying into a pair of bosons:**
  - **High resolution channels: H→ ZZ, H→WW and H→γγ**
- **Test the compatibility with the SM BEH boson:**
  - **Look at fermionic decays:**
  - **Largest BR for a *bb* decay:**
    - **BR($H \to b\bar{b}$) =(57.7±1.9)%**
    - BR($H \to \tau^+\tau^-$) =(6.3±0.4)%
    - BR($H \to c\bar{c}$) = (2.9±0.4)%
    - BR($H \to \mu^+\mu^-$) = (0.022±0.001)%



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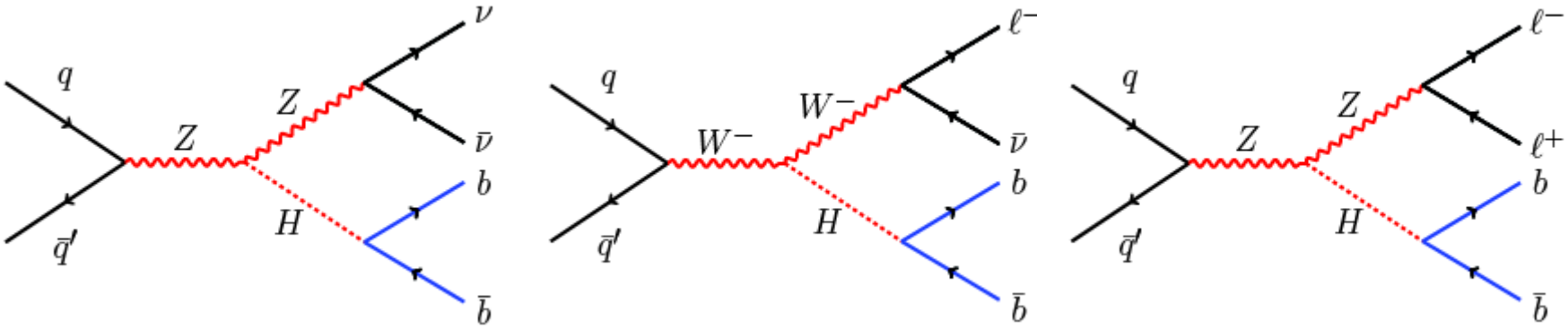
  - **HUGE background coming essentially from the high p_T *b*-jet production, and the multi-jets production**

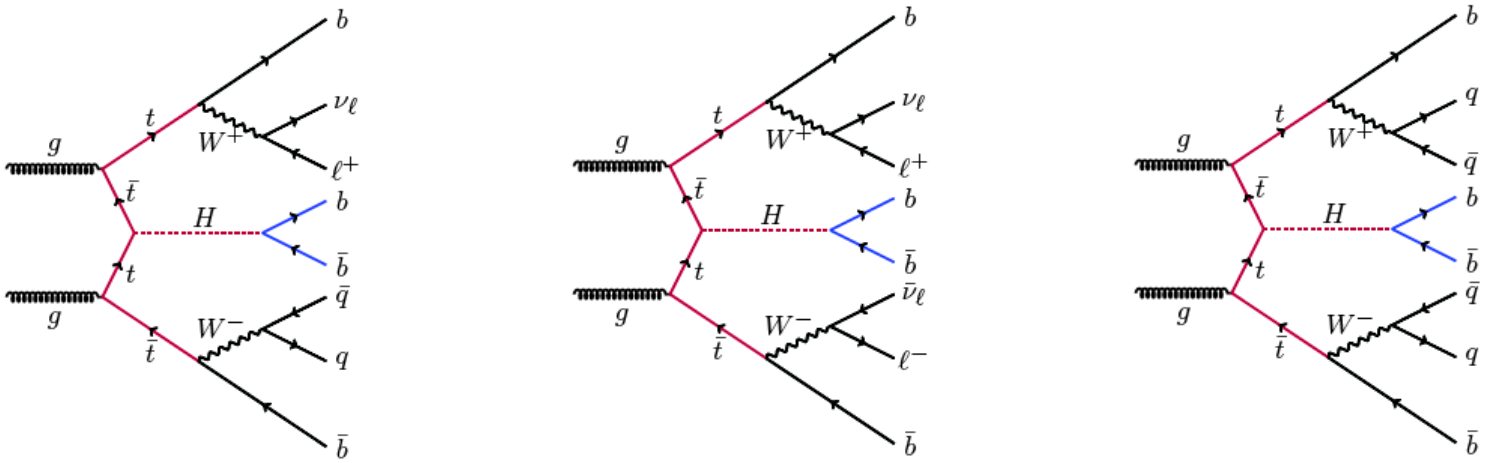
Challenge: improve the analyses strategies to get the best discrimination between signal & BG

ATLAS and CMS searches for the H→bb

Associated production with a vector boson



Associated production with a pair of top quarks



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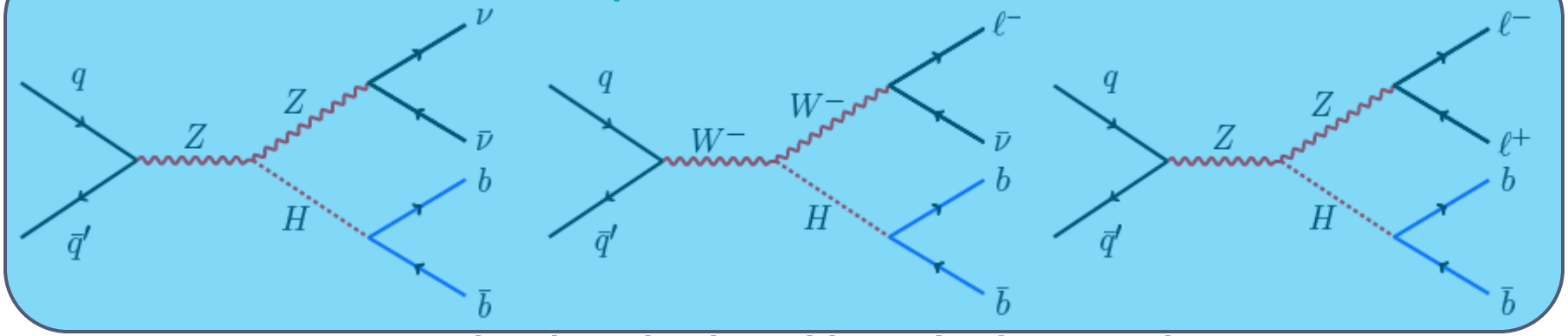
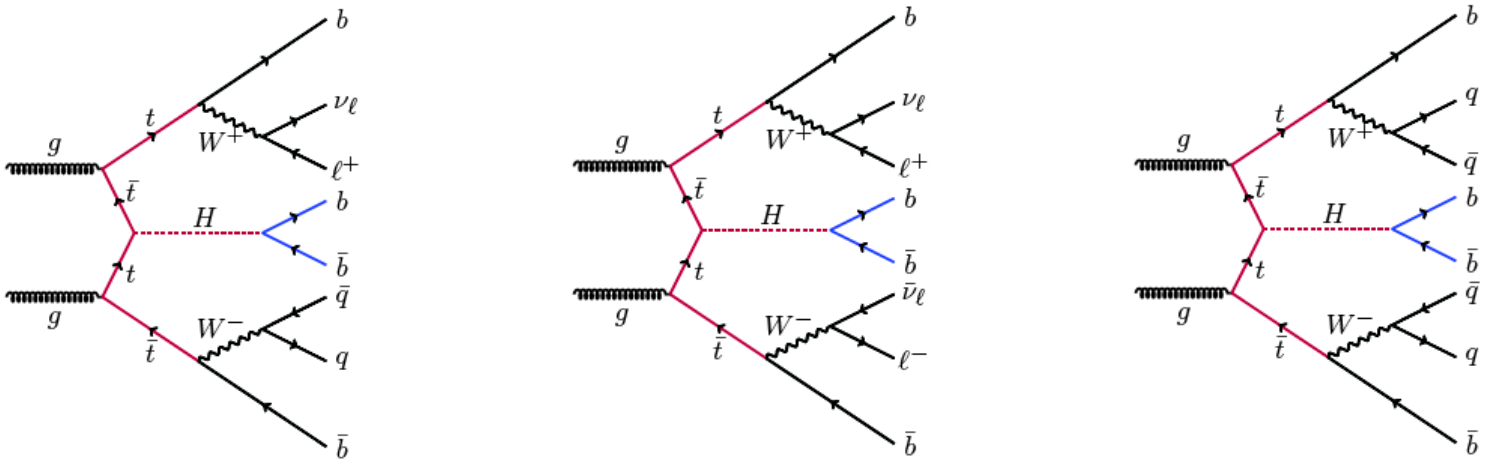


Associated production with a pair of top quarks



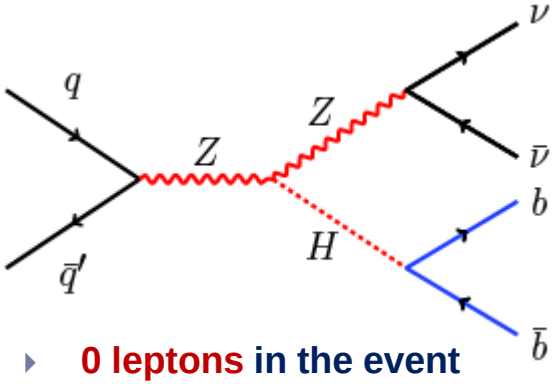
VH→Vbb: channels

- Profit from the best reconstructed objects:
  - CMS: particle flow reconstruction, PU jet discrimination
  - ATLAS: improved b-jet energy
- **Strategy:** require boosted V, boosted H and 2 *b*-tags

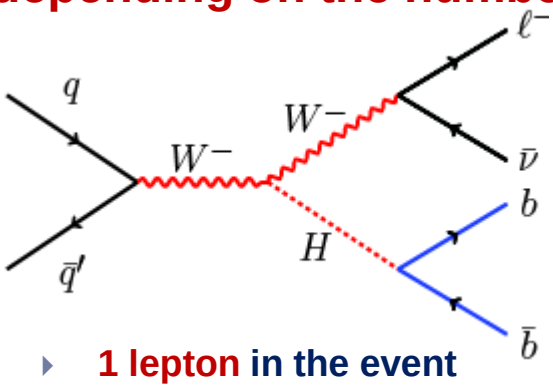
- ATLAS-CONF-2012-161
  - 5fb^{-1} @ 7 TeV & 13 fb^{-1} @ 8TeV
- CMS-PAS-HIG-12-044
  - 5fb^{-1} @ 7 TeV & 12 fb^{-1} @ 8TeV

Final states with {0,1,2} leptons, *b*-tagged jets and missing E_T

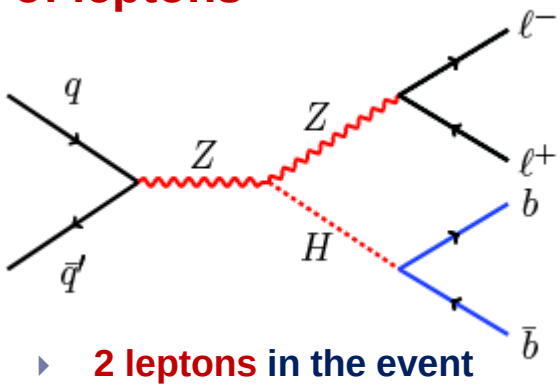
3 channels depending on the number of leptons



- **0 leptons** in the event
- + High E_T^{miss}



- **1 lepton** in the event
- + E_T^{miss}



- **2 leptons** in the event
- + low E_T^{miss}
- Cut on the Z mass

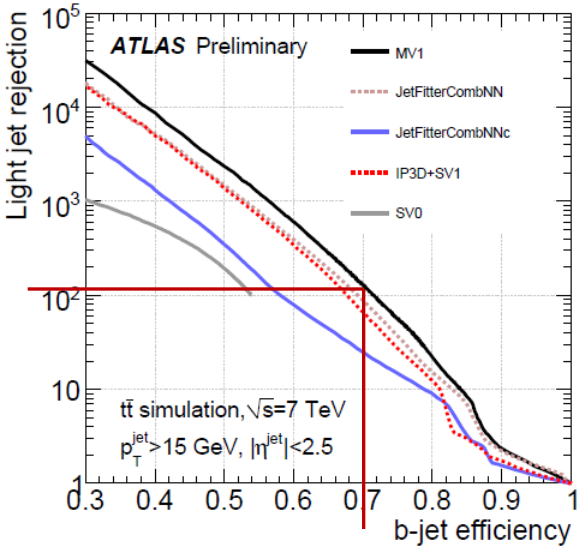
+ 2 *b*-tagged jets
ATLAS : The MV1 tagger
CMS: The CSV tagger

b-jet identification : Key ingredient

See talk by Y. Nagai

MV1 tagger:

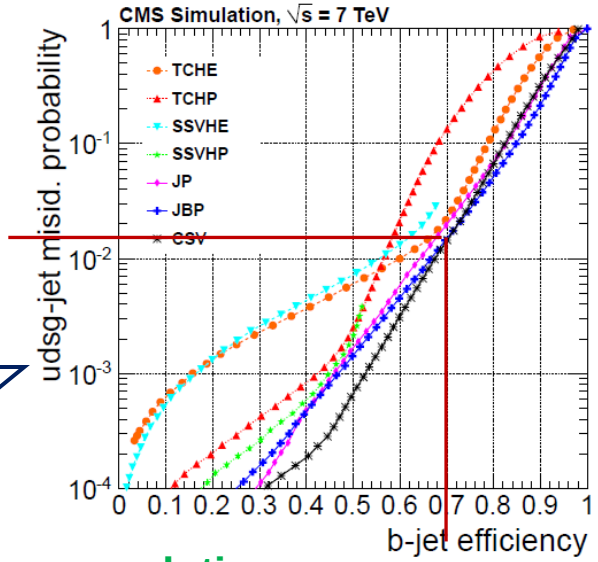
- Neural network built on outputs of advanced algorithms (IP and SV)
- **70% *b*-tagging efficiency working point**
- **~0.7% mistag rate for light jets**



See talk by C. Collard

CSV tagger:

- Combined Secondary Vertex algorithm→ SV + IP taggers
- **70% *b*-tagging efficiency working point**
- **~ 2% mistag rate for light jets**



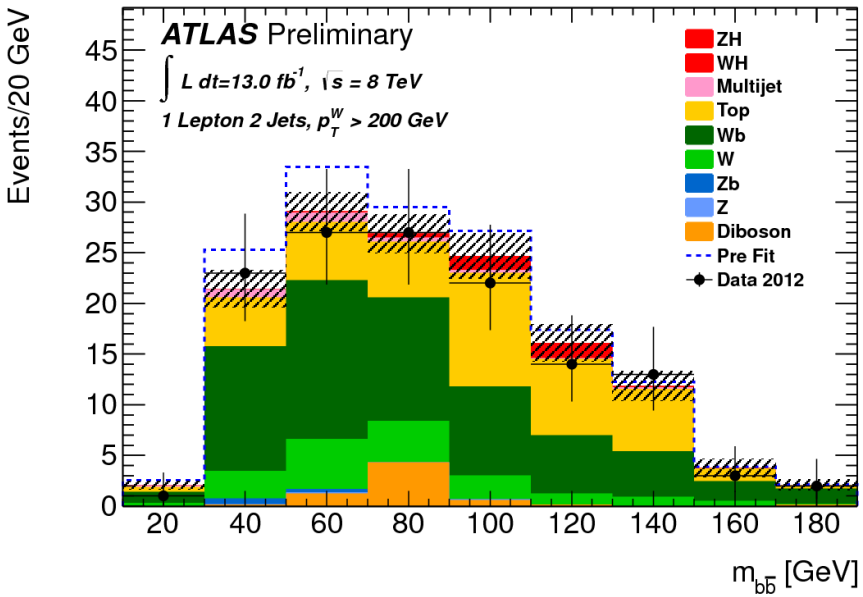
Improved *b*-jet energy

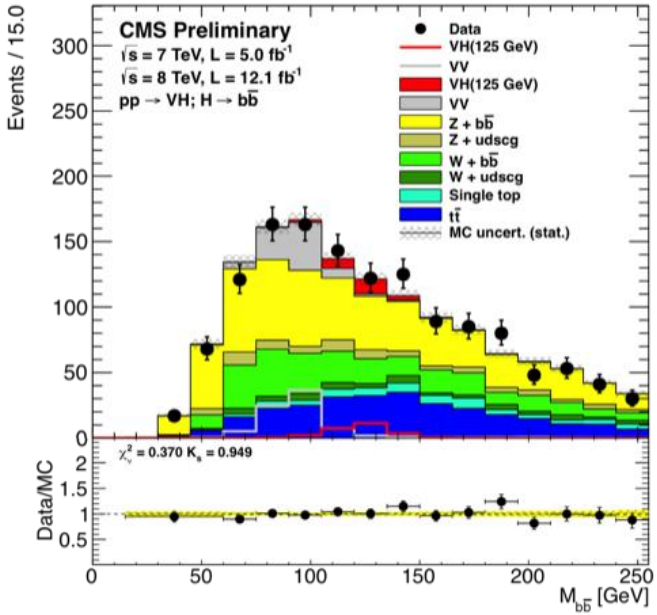
improved di-*b*-jets mass resolution

- → **Adding soft lepton p_T**
- → **Average mass resolution is ~ 16%**
- → **Regression techniques → new correction for the *b*-jet energy**
- → **Average mass resolution ~ 10%**

VH→Vbb: Background treatment

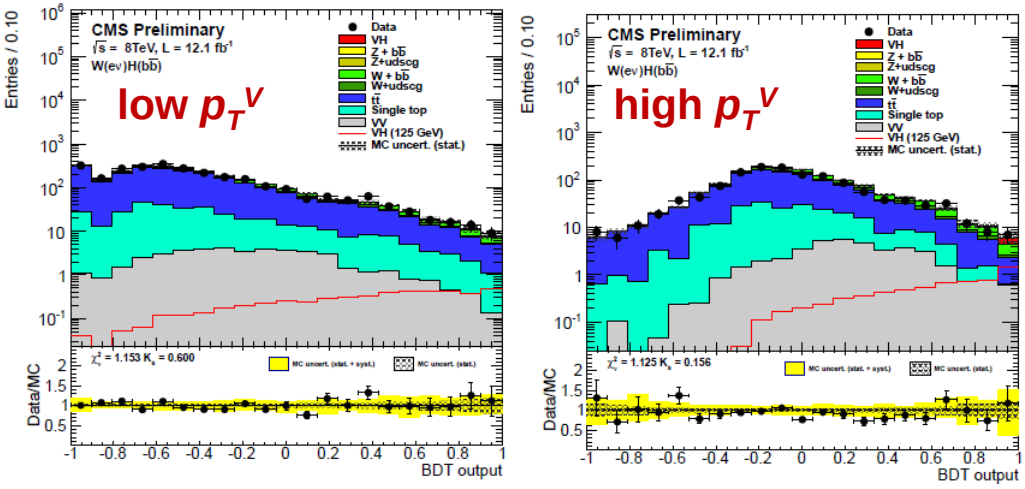
- **Main bkg processes:**
  - **W+jets, Z+jets, tt, single top**
  - **ATLAS+CMS: shape from simulation and normalization from data**
    - **ATLAS & CMS: normalization from data/MC scale factors from data control regions**
  - **ATLAS: multi-jets bkg estimated from data driven method**

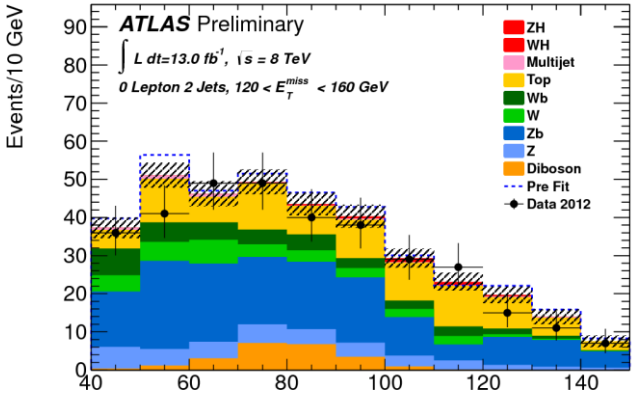


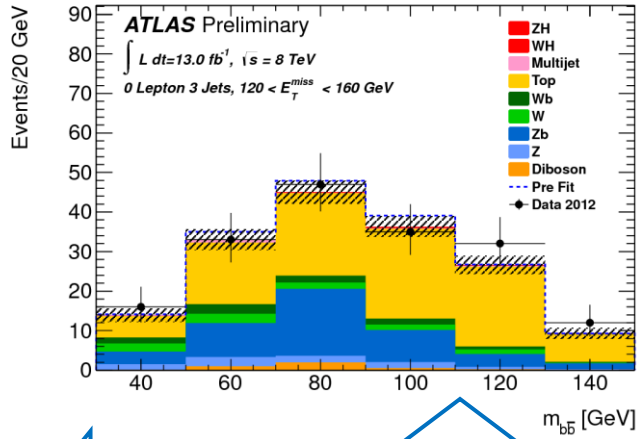


VH→Vbb: Signal extraction

- **Shape analysis discriminator:**
  - **ATLAS: profile likelihood fit based on M_{bb}**
  - **CMS: signal and bkg fit to the shape of the BDT output**
- **Improve the sensitivity of the analysis:**
  - **Split the analysis into separate regions:**
  - **ATLAS : 0-leptons events → six categories in jet multiplicity (2 or 3jets) and in missing E_T, 1 or 2 leptons: 5 categories in the p_T of the vector boson**
  - **CMS : split each channel into low or high p_T^V,looser b-tagging requirement in the high p_T^V**







CMS W(ev)H

ATLAS Z(vv)H

VH→Vbb: Systematic Uncertainties

ATLAS

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

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

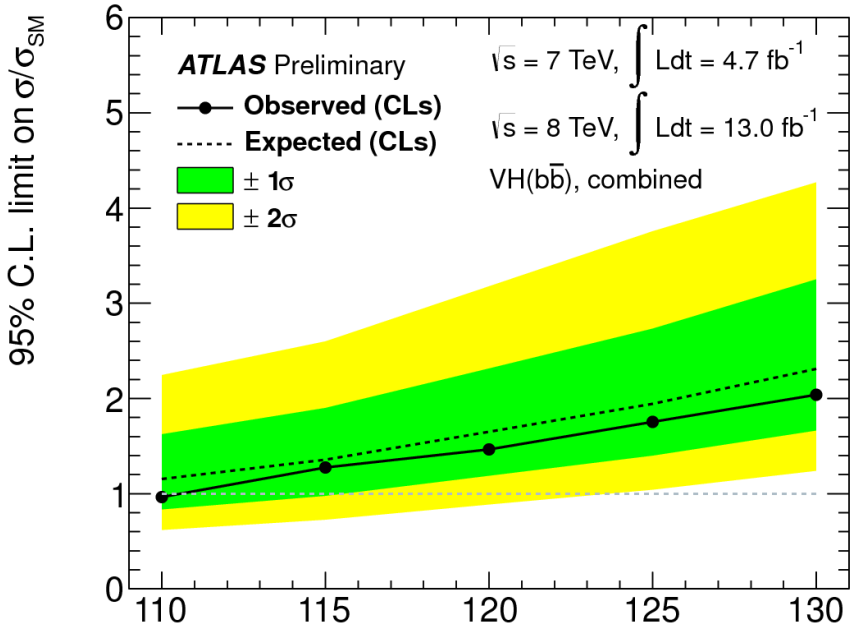
CMS

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%

- CMS & ATLAS main sources of systematics:
  - b-tagging (ATLAS,CMS)
  - JES (ATLAS)
  - Signal cross section uncertainty (CMS & ATLAS)

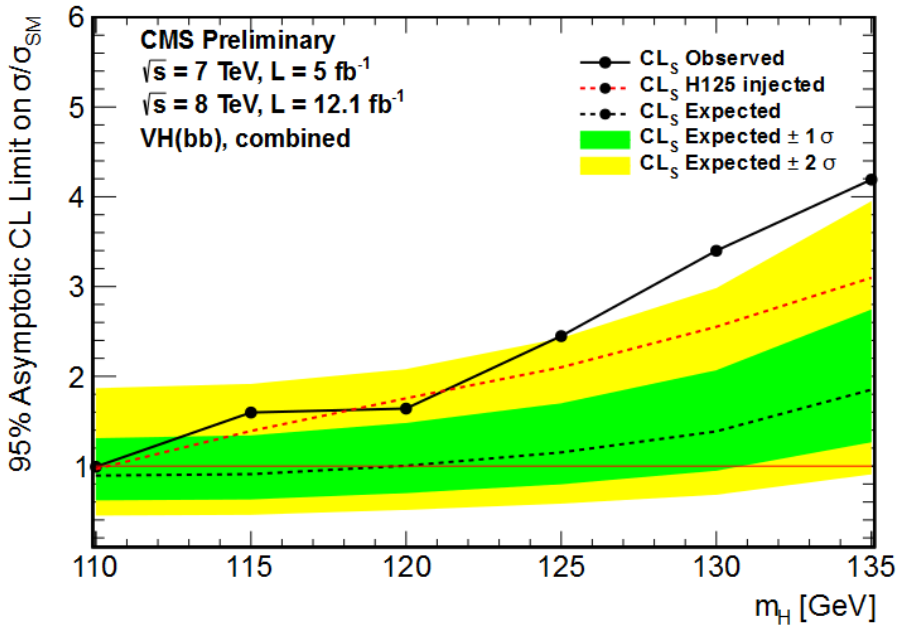
VH→Vbb: Results

- **Observed (expected) limit of 1.8 (1.9) x SM at 125 GeV**



- **μ = -0.4 ± 0.7 (stat) ± 0.8 (syst)**

- **Observed (expected) limit of 2.5 (1.2) x SM at 125 GeV**

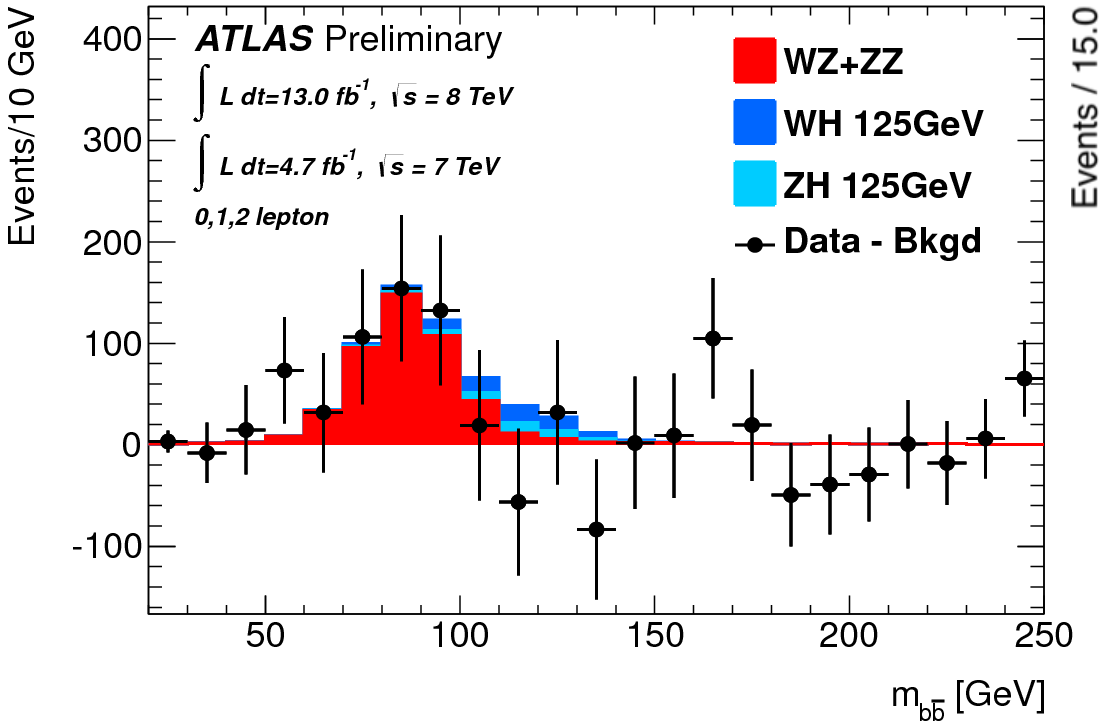


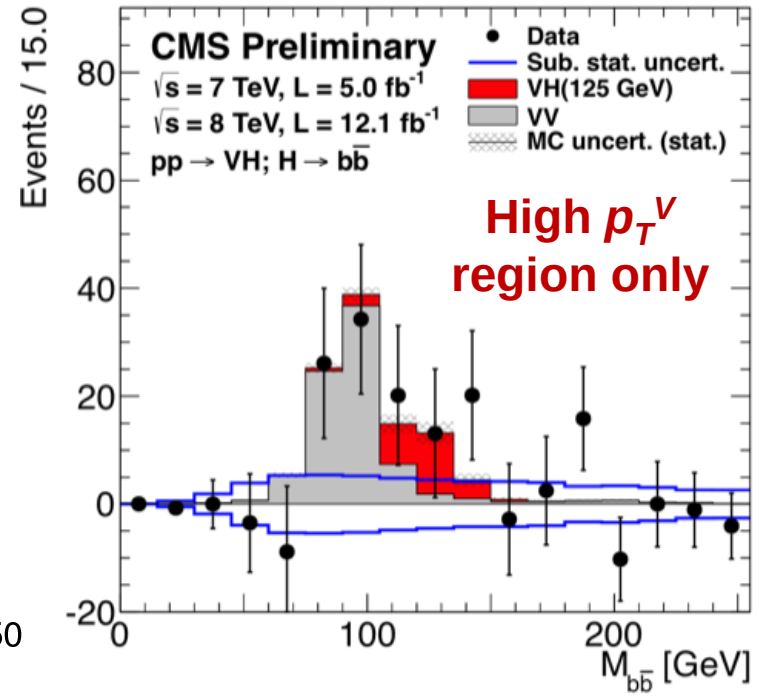
- **μ = $1.3^{+0.7}_{-0.6}$, 2.2σ (2.1σ) excess**

Small excess compatible with a SM Higgs

VH→Vbb: M_{bb} distribution cross check

M_{bb} distributions after subtracting all the background except the di-boson process and the SM Higgs from WH and ZH associated production



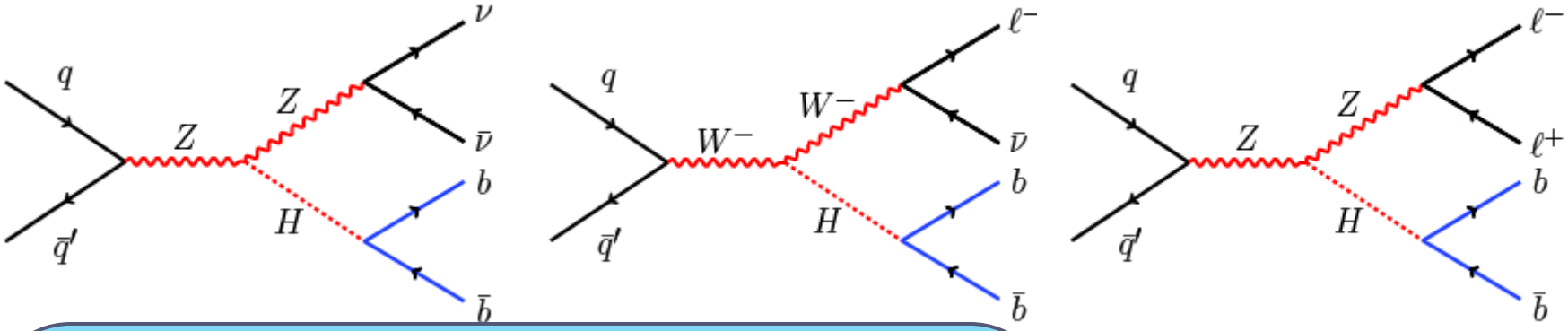


Combined lepton channels,
Combined 2011 and half 2012 LHC data

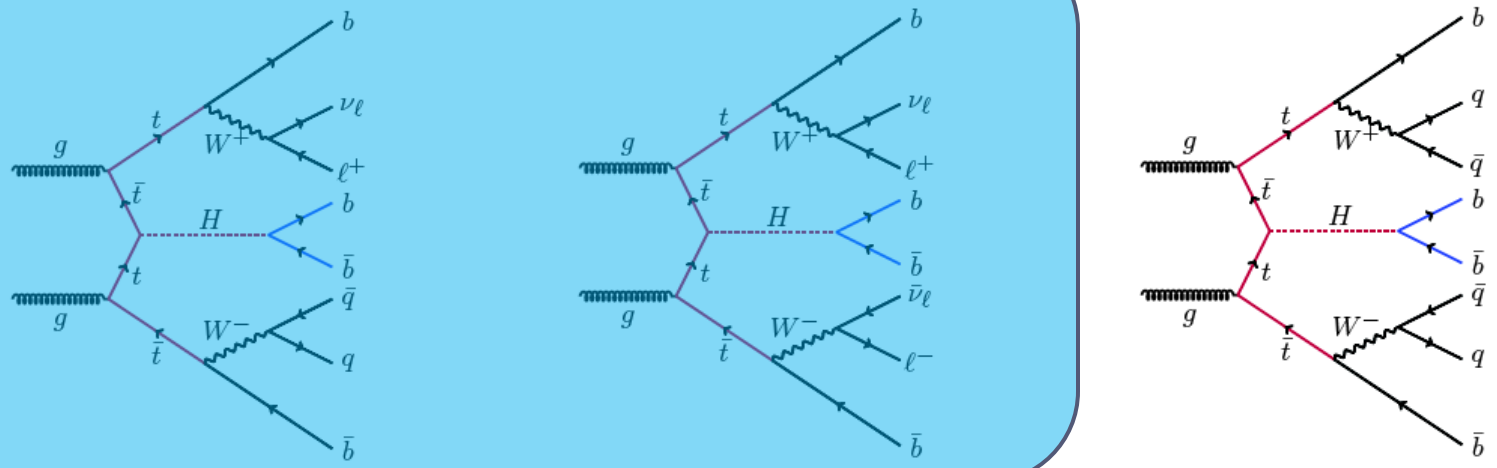
VH→Vbb and ttH→ttbb

ATLAS and CMS searches for the H→bb:

Associated production with a vector boson



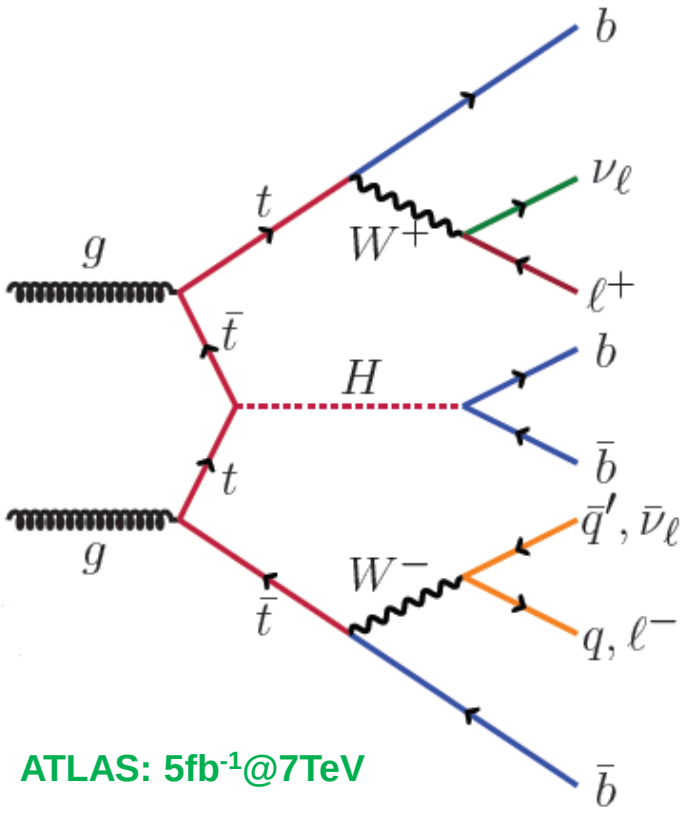
Associated production with a pair of top quarks



ttH→ttbb : Introduction

- Directly probe top-Higgs Yukawa coupling
  - The largest coupling
  - Help understanding the EWSB
  - Direct measurement via tt+H
- top→Wb
- 3 decay channels depending on the W decay
  - Lepton+jets (CMS & ATLAS)
    - $ttH \rightarrow Wb\ Wb\ bb \rightarrow \ell\nu b\ jjb\ bb$
  - Di-lepton channel (CMS)
    - $ttH \rightarrow Wb\ Wb\ bb \rightarrow \ell\nu b\ \ell\nu b\ bb$
  - All hadronic channel: (ongoing)
    - $ttH \rightarrow Wb\ Wb\ bb \rightarrow jjb\ jjb\ bb$

Busy channels, large combinatorial background, huge *tt* background

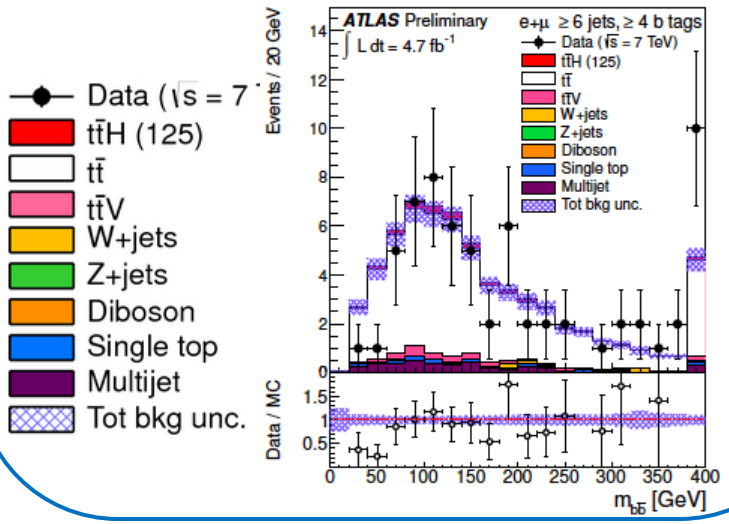


- **ATLAS: 5fb^{-1}@7TeV**
  - **ATLAS-CONF-2012-135**
- **CMS: 5fb^{-1}@7TeV+ 5fb^{-1}@8TeV**
  - **CMS-HIG-12-035 ; CERN-PH-EP-2013-027**

ttH→ttbb: Analysis Strategy

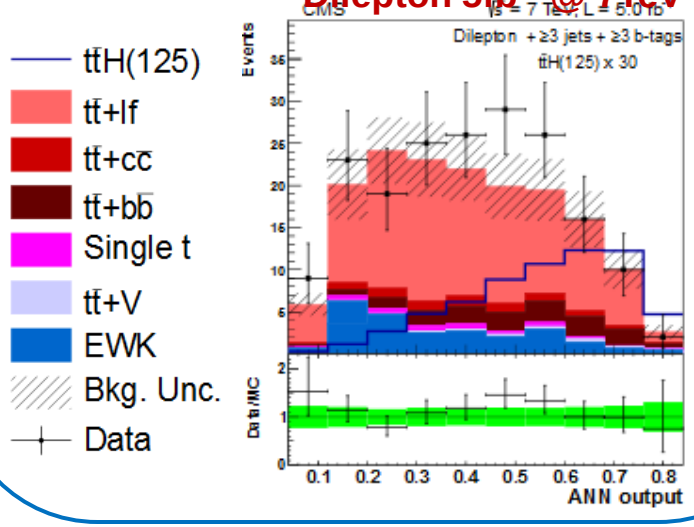
Different categories depending on the jet and *b*-tagged jet multiplicities

- **15 categories:**
  - **Njets (=4,=5,>=6) nbtags(=0,=1,=2,=3,>=4)**
- **Shape discriminator:**
  - **M_{bb} for njets>=6&nbtags>=3**
  - **H_T = Σ p_T jet for the rest of the categories**



- **Artificial neural network for the signal and bkg discrimination:**
  - **Separate ANN are used for different jet and *b*-tagged jet categories,**
  - **Input variables: object kinematics, event shape, discriminant output from the b-tagging algorithm**

Dilepton 5fb^{-1} @ 7TeV



ttH→ttbb: Systematic uncertainties

Source	Rate Uncertainty
Luminosity (7 TeV)	2.2%
Luminosity (8 TeV)	4.4%
Lepton ID/Trig	4%
Pileup	1%
Additional Pileup Corr.	–
Jet Energy Resolution	1.5%
Jet Energy Scale	0–60%
b-Tag SF (b/c)	0–33.6%
b-Tag SF (mistag)	0–23.5%
MC Statistics	–
PDF (gg)	9%
PDF ($q\bar{q}$)	4.2–7%
PDF (qg)	4.6%
QCD Scale ($t\bar{t}H$)	15%
QCD Scale ($t\bar{t}$)	2–12%
QCD Scale (V)	1.2–1.3%
QCD Scale (VV)	3.5%
Madgraph Scale ($t\bar{t}$)	0–20%
Madgraph Scale (V)	20–60%
$t\bar{t}+b\bar{b}$	50%

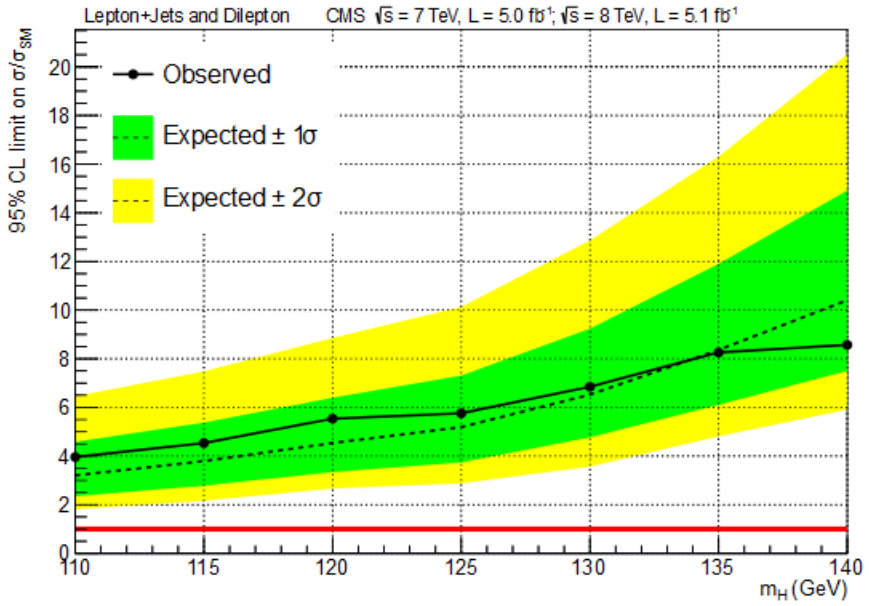
	$t\bar{t}H(125)$	$t\bar{t}$
Luminosity	+1.8/-1.8	+1.8/-1.8
Lepton ID+reco+trigger	+1.3/-1.3	+1.3/-1.3
Jet vertex fraction efficiency	+2.4/-1.7	+2.5/-1.9
Jet energy scale	+9.6/-9.9	+13.5/-15.2
Jet energy resolution	+1.0/-1.0	+0.7/-0.7
b-tagging efficiency	+30.4/-34.8	+22.9/-25.2
c-tagging efficiency	+5.0/-5.0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

- **Biggest experimental systematics for ATLAS & CMS:**
  - **JES**
  - **b-tagging**

Big uncertainties on the tt modeling and the heavy flavor fraction of the extra jets in the tt+extra jets

ttH→ttbb: Results

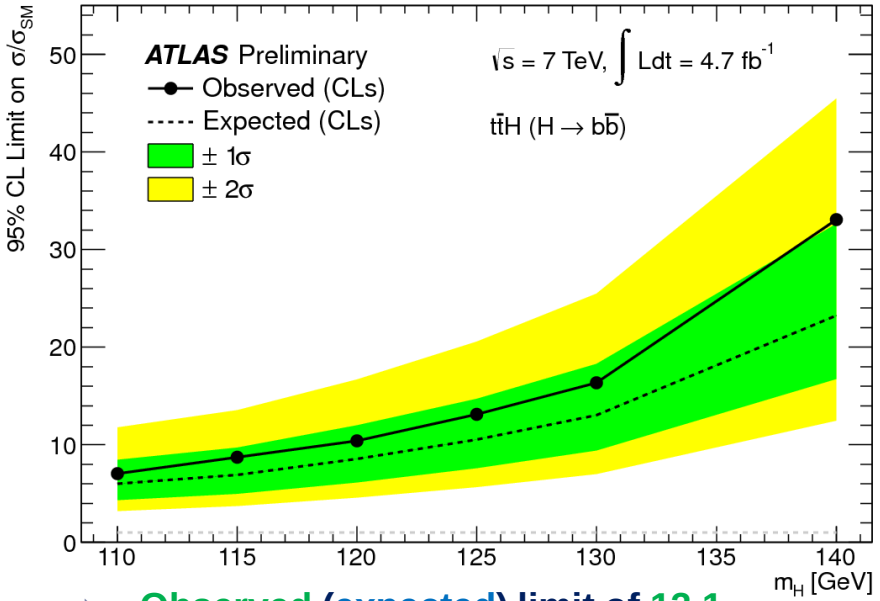
Lepton+jets channel
+ di-lepton channel
5fb^{-1}@7TeV+ 5fb^{-1}@8TeV



- **Observed (expected) limit of 5.8 (5.2) x SM at 125 GeV**

Lepton+jets channel

5fb^{-1}@7TeV



- **Observed (expected) limit of 13.1 (10.5) x SM at 125 GeV**

No significant excess is observed.

Summary

- **Looking to fermionic decays is crucial to determine the true nature of the newly discovered scalar boson!**
- VH→Vbb:
  - 3 channels studied @LHC: Z(ll)H, Z(vv)H, W(lv)H
- ttH→ttbb
  - 2 channels studied @LHC: lepton+jets and di-lepton

Associated production	ATLAS Observed	ATLAS Expected	CMS Observed	CMS Expected
VH→Vbb	5 fb^{-1} @ 7 TeV & 13 fb^{-1} @ 8TeV		5 fb^{-1} @ 7 TeV & 13 fb^{-1} @ 8TeV	
	1.8xSM	1.9xSM	2.5xSM	1.2xSM
ttH→ttbb	5 fb^{-1} @ 7 TeV		5 fb^{-1} @ 7 TeV & 5 fb^{-1} @ 8TeV	
	13.1xSM	10.5xSM	5.8xSM	5.2xSM

- No significant excess has been observed in any of the *H→bb* studied channels.
  - CMS: 2.2 σ excess in VH compatible with a SM Higgs
- All analysis are incorporating all 2012 @ 8 TeV dataset!
  - New MVA analysis, new updates and results soon, keep tuned!

Back Up

VH→Vbb: ATLAS event selection

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

Object and event selection in the three channels

Topological cuts for the three channels in separate p_T^V regions

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

VH→Vbb: CMS BDT inputs

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]

Input variables used for the BDT training

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

Selection criteria for the variables in the three channels used in the BDT training

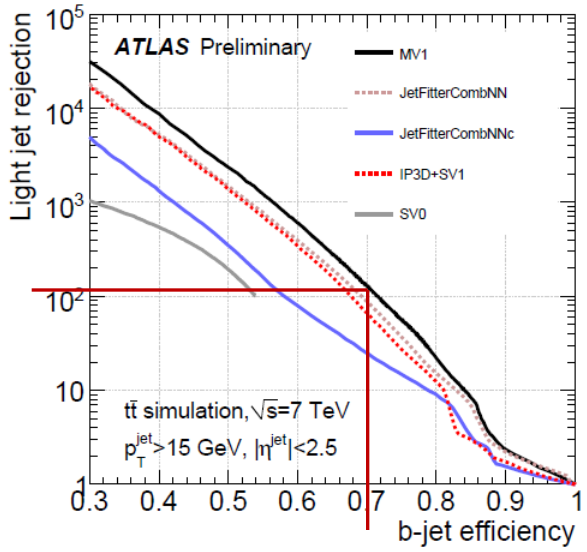
b-jet identification : Key ingredient

ATLAS
- ATLAS-CONF-2012-100
- ATLAS-CONF-2012-097
- ATLAS-CONF-2012-043
- ATLAS-CONF-2012-040

CMS
- CMS-BTV-12-001
- CMS-PAS-BTV-11-004
- CMS-PAS-BTV-11-003

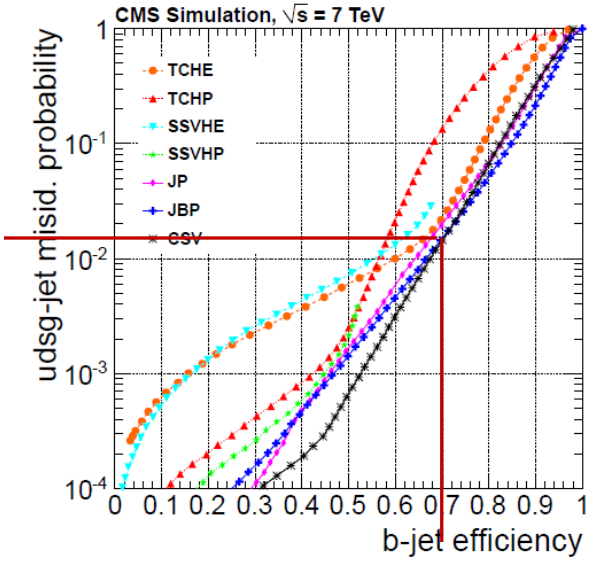
MV1 tagger:

- Neural network built on outputs of advanced algorithms (IP and SV)
- **70% b-tagging efficiency working point**
- **~0.7% mistag rate for light jets**



CSV tagger:

- Combined Secondary Vertex algorithm→ SV + IP taggers
- **70% b-tagging efficiency working point**
- **~ 2% mistag rate for light jets**



VH→Vbb: Categories

- Improve the sensitivity of the analysis:
  - Split the analysis into separate regions:
  - **ATLAS :**
    - **0-leptons events** → six categories in jet multiplicity (2 or 3jets) and in missing E_T ($120<E_T^{miss}<160$ GeV, $160 < E_T^{miss}< 200$ GeV and $E_T^{miss}>200$ GeV)
    - **1 or 2 leptons:** 5 categories in the p_T of the vector boson: $p_T^V \leq 50$ GeV, $50 < p_T^V \leq 100$ GeV, $100< p_T^V \leq 150$ GeV, $150< p_T^V \leq 200$ and $p_T^V > 200$GeV
  - **CMS :** split each channel into low or high p_T^V
    - 0-leptons events: $130 < p_T^V < 170$ GeV and $p_T^V > 170$GeV
    - 1-lepton events : $120 < p_T^V < 170$ GeV and $p_T^V > 170$ GeV
    - 2-leptons region : $50 < p_T^V < 100$ GeV and $p_T^V > 100$ GeV

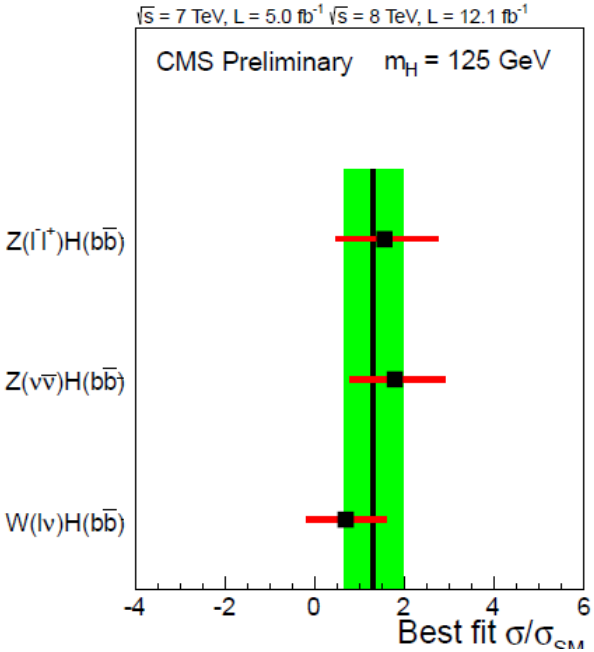
VH→Vbb:

CMS :

observed and expected limits for different Higgs mass

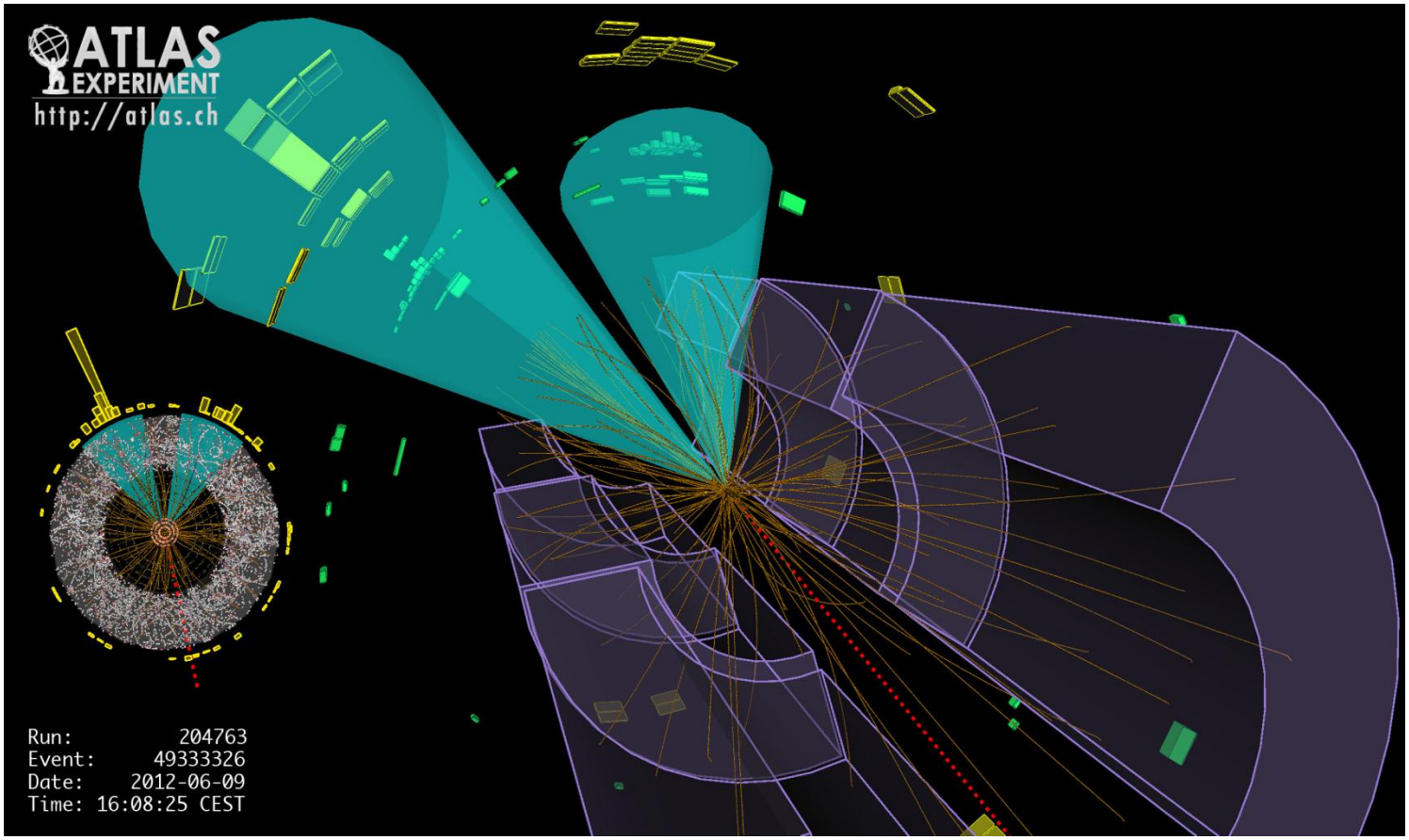
m_H(GeV)	110	115	120	125	130	135
Exp.	0.89	0.91	1.00	1.15	1.39	1.85
Obs.	0.99	1.60	1.64	2.45	3.40	4.19

The most likely value of the production cross section for a 125 GeV Higgs boson, relative to the standard model cross section, for each mode and for all modes combined



ATLAS: 0-lepton Higgs candidate

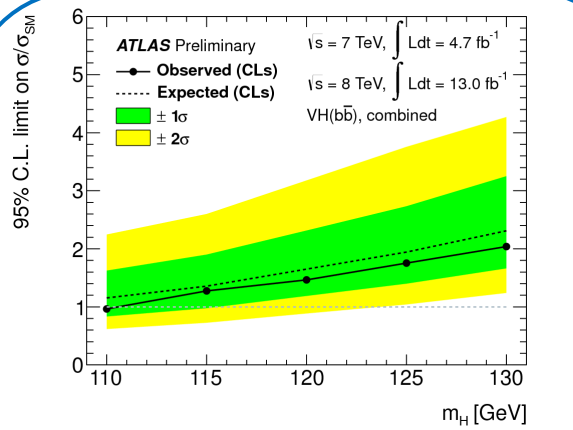
The event contains two identified *b-jets with transverse momenta of 193 GeV and 78 GeV, respectively, with an invariant mass* of 123 GeV. The missing energy in the transverse plane is 271 GeV.

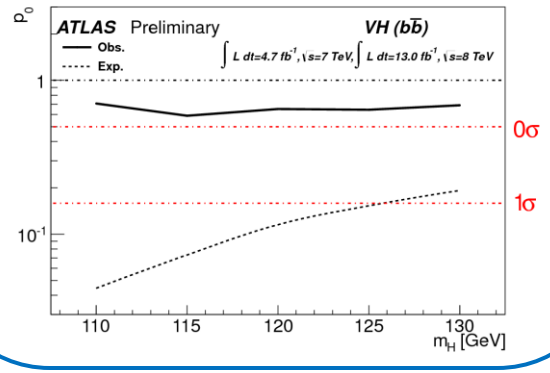


VH→Vbb: Results

- **Observed (expected) limit of 1.8 (1.9) x SM at 125 GeV**
- **μ = -0.4 ± 0.7 (stat) ± 0.8 (syst)**

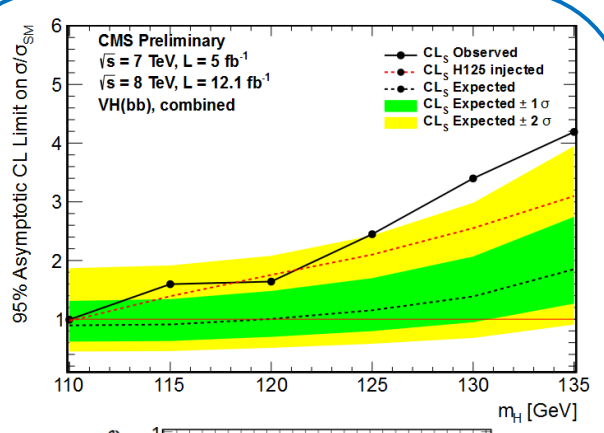
- **Observed (expected) limit of 2.5 (1.2) x SM at 125 GeV**
- **$\mu = 1.3^{+0.7}_{-0.6}$, 2.2σ (2.1σ) excess**

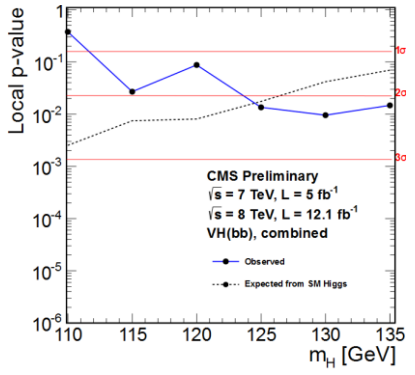




Small excess compatible with a SM Higgs

Not enough significant





ttH→ttbb: Event Selection

Final states with leptons, missing E_T, jets and *b*-tagged jets

- **Trigger:**
  - ATLAS: l+jets : single lepton trigger, e p_T >20 (22) GeV, μ p_T>18 GeV
  - CMS: l+jets: single lepton trigger: μ pT > 24 GeV , e pt > 24 GeV and 3 jets pT > 30 GeV (2012) e pT > 27 GeV. veto on second loose lepton for lepton+jets. Dilepton : 2 lepton pT > 17 and 8 GeV(1 tight and 1 loose lepton)
- **Offline lepton:**
  - ATLAS: l+jets: exactly one isolated lepton (μ :|η| < 2.5, tight pT > 20 GeV or e: |η| < 2.47 pT > 25 GeV)
  - CMS: l+jets: exactly one isolated lepton(tight μ : |η| < 2.1, tight pT > 30 GeV, or tight e: |η| < 2.5, tight pT > 30 GeV) Dilepton: one tight μ + one loose (|η| < 2.4, pT > 10 GeV) or one tight e + 1 loose (loose pT > 10 GeV)
- **Jets:**
  - CMS: anti-k_t 0.5, |η| < 2.4,
    - **L+jets: ≥ 3 jets pT > 40 GeV and 4 pT > 30 ,**
    - **Dilepton: ≥ 2 jets pT > 30 GeV**
  - ATLAS: anti-k_t 0.4, |η| < 2.5
    - **>= 4 jets with pT > 25**
- **B-tagging:**
  - CMS: CSV :working point: 70% b-jet, 20% c-jet,~ 2% light jets
  - ATLAS: MV1: working point: 70% b-jet, 20% c-jet, <1% light jets