VH→bb: Experimental Review

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Outline

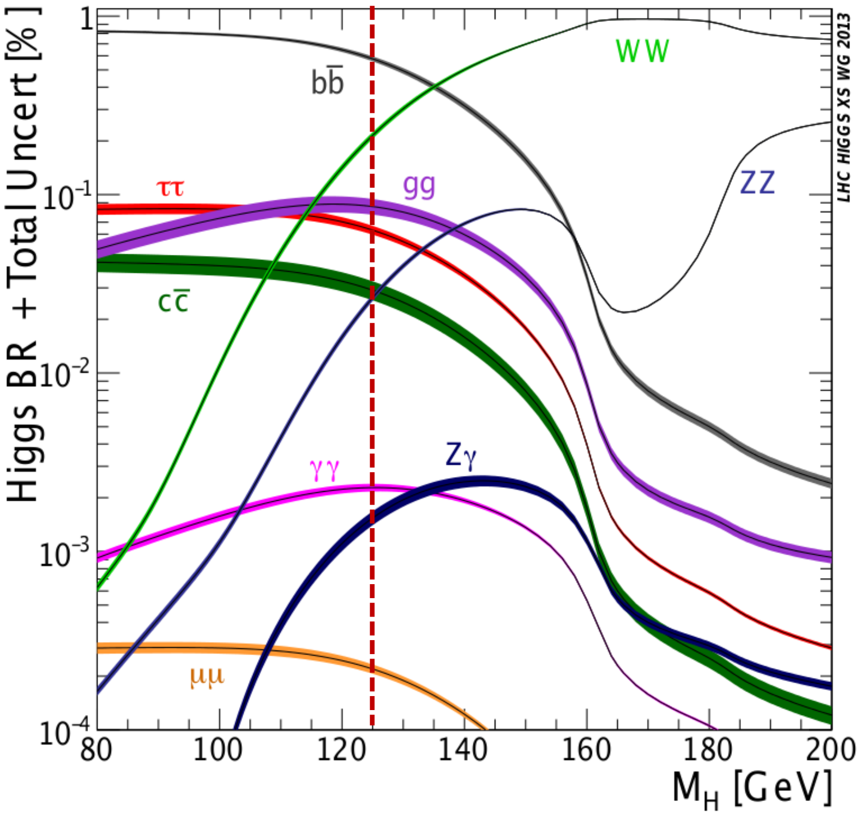
- Quickly, why (V)H→bb?

- Search for VH(H→bb) at the LHC
  - ATLAS (4.7 fb^{-1} @7 TeV and 20.3 fb^{-1} @8 TeV)
    - ATLAS-CONF-2013-079
  - CMS (5.1 fb^{-1} @7 TeV and 18.9 fb^{-1} @8 TeV)
    - arXiv:1310.3687v1
  - ATLAS and CMS Strategies (commonalities)
  - ATLAS and CMS Strategies (particularities)
  - VZ(Z→bb) results
  - results

- D0 spin results with VH(H→bb)
  - 9.5–9.7 fb^{-1}
  - testing $J^P = 2^+$ with graviton like coupling (Randall-Sundrum model)
  - D0 Note 6387-CONF

Why VH(H→bb)?

- A Higgs boson is discovered at the LHC
  - is it The SM Higgs Boson?
  - coupling to fermions yet to be established
- H→bb: highest branching ratio at m_H=125 GeV (58%)
  - especially important at the LHC for coupling measurements precision
    - total width not directly measurable



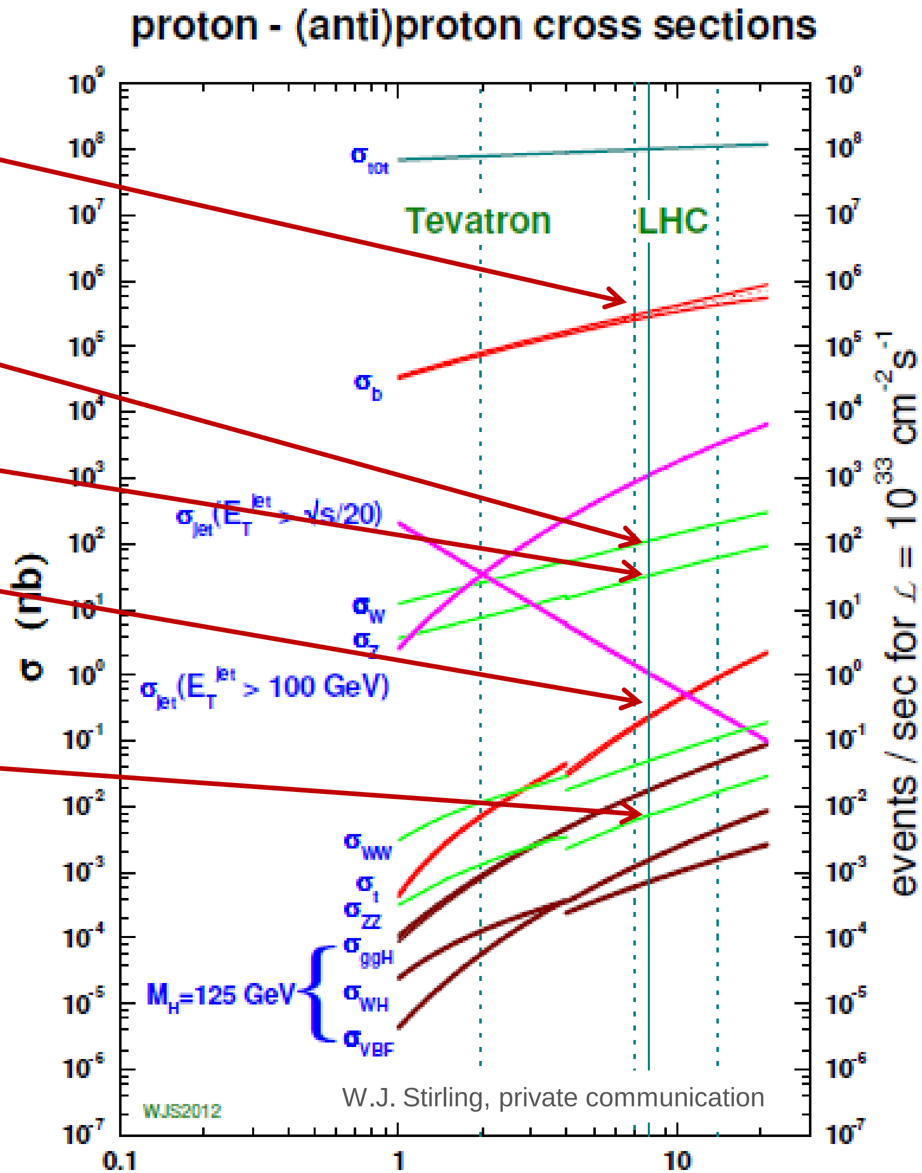
- gg→H→bb impossible to extract from large QCD background
  - additional signature needed
  - VH associated production in this talk

VH→bb @LHC - Backgrounds

Huge QCD (with HF) background
➢ heavily reduced due to the vector boson selection

@ 8 TeV

- $\sigma(WX) = 1.2 \times 10^5 \times \sigma(WH)$
- $\sigma(ZX) = 7 \times 10^4 \times \sigma(ZH)$
- $\sigma(top) = 275 \times \sigma(VH)$
- $\sigma(WZ) = 28 \times \sigma(WH)$
- $\sigma(ZZ) = 16 \times \sigma(ZH)$



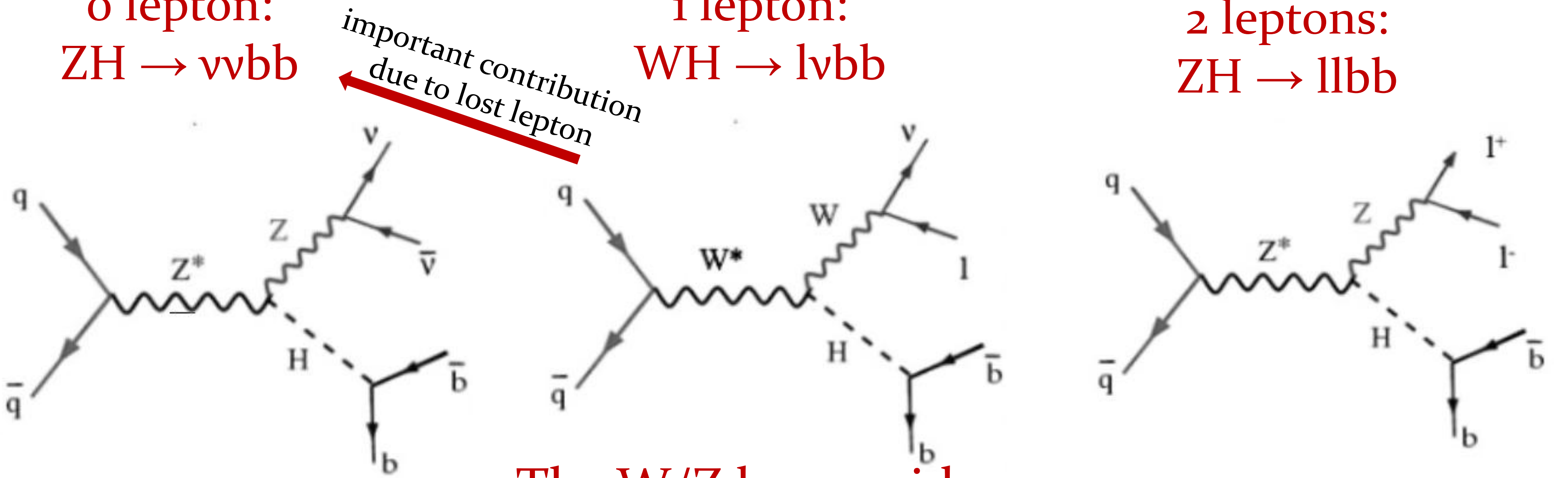
Large backgrounds including large irreducible backgrounds

VH→bb @LHC – Selection Overview

0 lepton:
ZH → ννbb

1 lepton:
WH → lνbb

2 leptons:
ZH → llbb



The W/Z boson side

0 lepton	1 lepton	2 leptons
No leptons High E_T^{miss} E_T^{miss} cleaning	Exactly one high-pT lepton High E_T^{miss} mT(W) cuts (ATLAS)	2 high-pT leptons Z boson mass window Low E_T^{miss} (ATLAS)

The Higgs boson side

- 2 high pT b-tagged jets
- DR(b,b) cuts (ATLAS)
- m(b,b) loose cuts (CMS)
- High pT(jj) (CMS)

VH→bb @LHC - Analysis Strategy

- Reconstruct the "transverse" V (W,Z) boson
- Reconstruct the Higgs candidate using two b-jets
- Divide into several pT(V) regions to take advantage of the higher signal purity at high boost

Not for 0-lepton (→ 0-90, 90-120)

pTV range in GeV

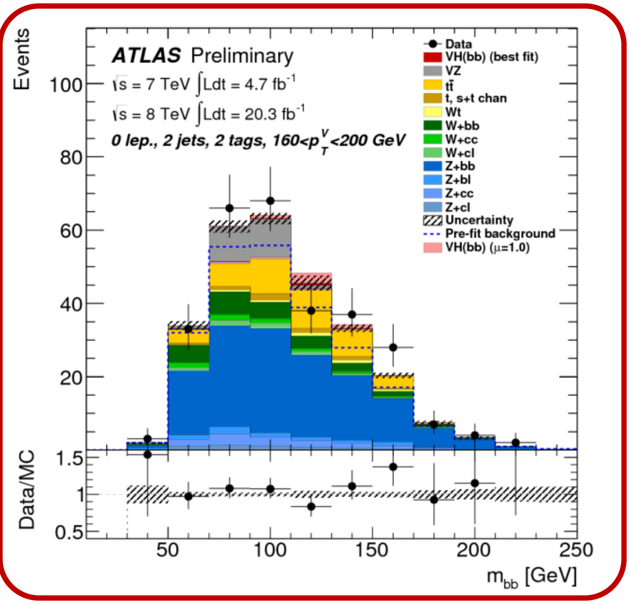
ATLAS	0-90	90-120	120-160	160-200	>200
CMS - Wlν	-	100-130	130-180	>180	
CMS - Wτν	-	>120			
CMS - Zll	-	50-100	>100		
CMS - Zνν	-	100-130	130-170	>170	

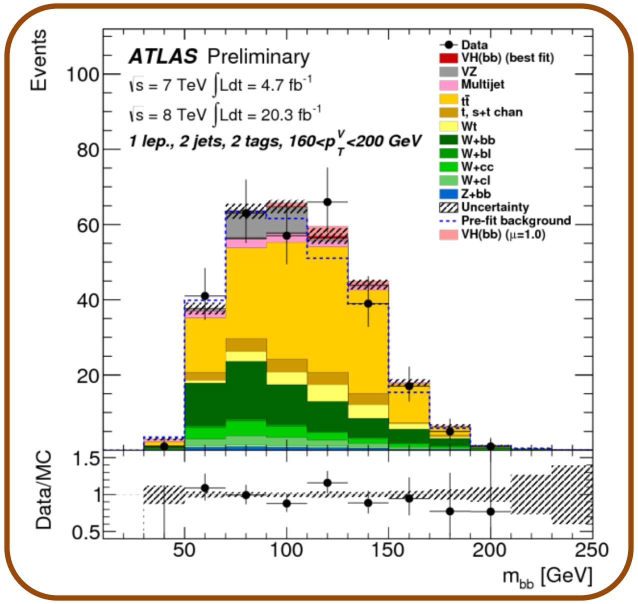
- Fit performed simultaneously in all channels and pT(V) bins
  - ATLAS: cut-based analysis with m_{bb} as final discriminant
  - CMS: Multivariate analysis with the BDT output as final discriminant

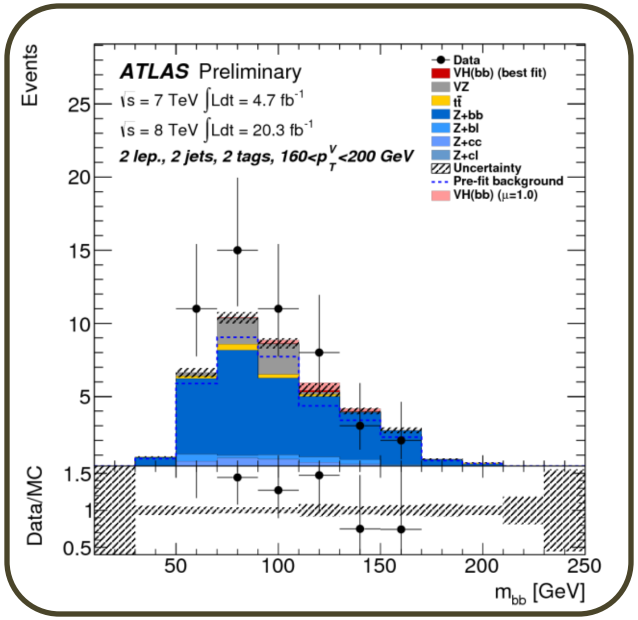
VH→bb @ATLAS - Strategy

Cut-based analysis + simultaneous m_{bb} fit in several signal and control regions

	2 b-tags			1 b-tag	
	2 jets	3 jets	e-μ	2 jets	3 jets
0-lepton (x 3 pTV bins)	mbb shape	mbb shape	-	norm	norm
1-lepton (x 5 pTV bins)	mbb shape	mbb shape	-	norm	norm
2-lepton (x 5 pTV bins)	mbb shape	mbb shape	norm	norm	norm



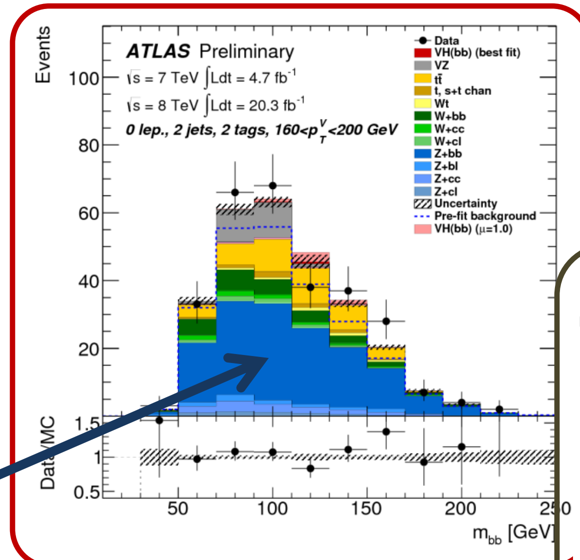


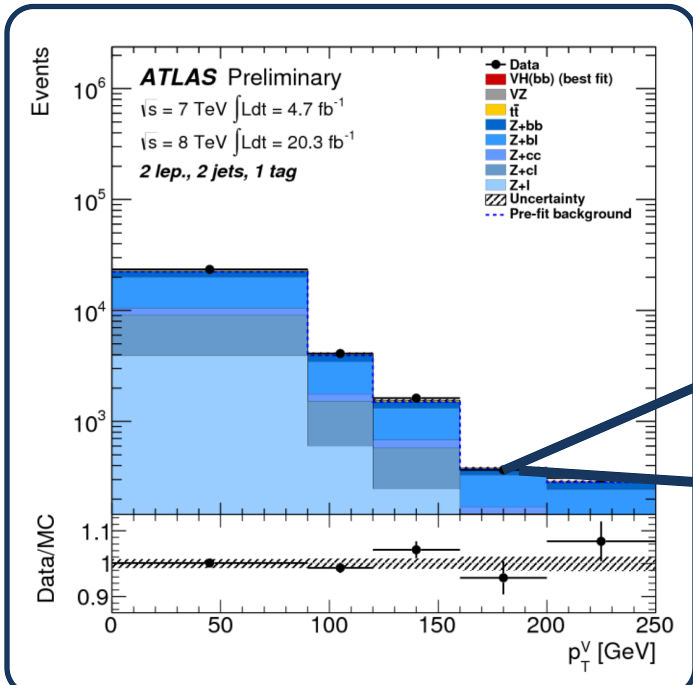


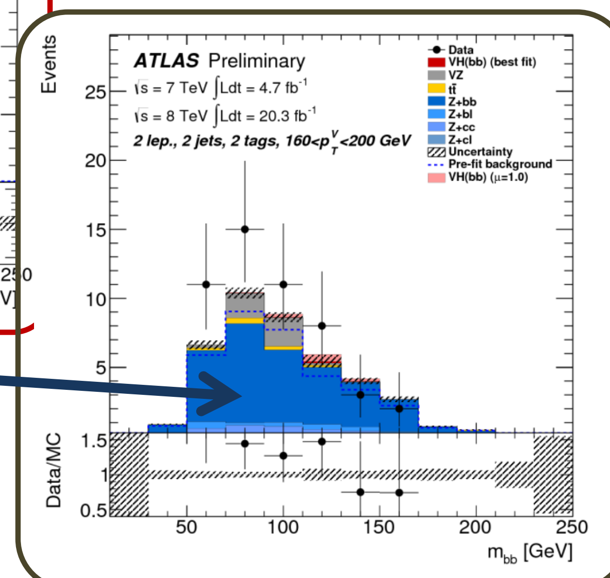
VH→bb @ATLAS - Strategy

Z+jets constrained in e.g. 2lep-2jets-1tag

	2 tags			1 tag	
	2 jets	3 jets	e-μ	2 jets	3 jets
0-lepton (x 3 pTV bins)	mbb shape	mbb shape	-	norm	norm
1-lepton (x 5 pTV bins)	mbb shape	mbb shape	-	norm	norm
2-lepton (x 5 pTV bins)	mbb shape	mbb shape	norm	norm	norm



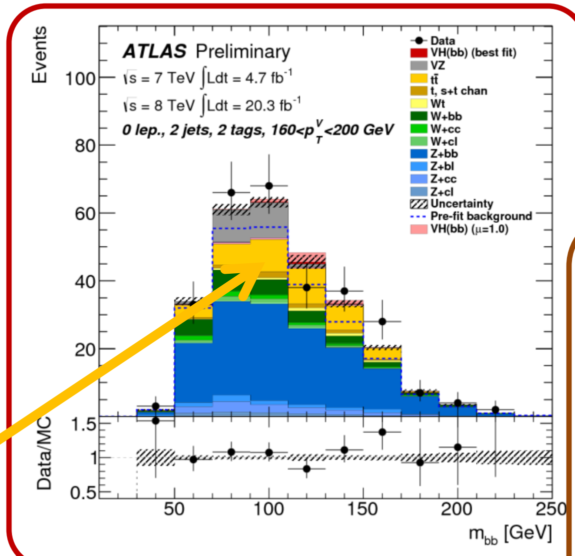


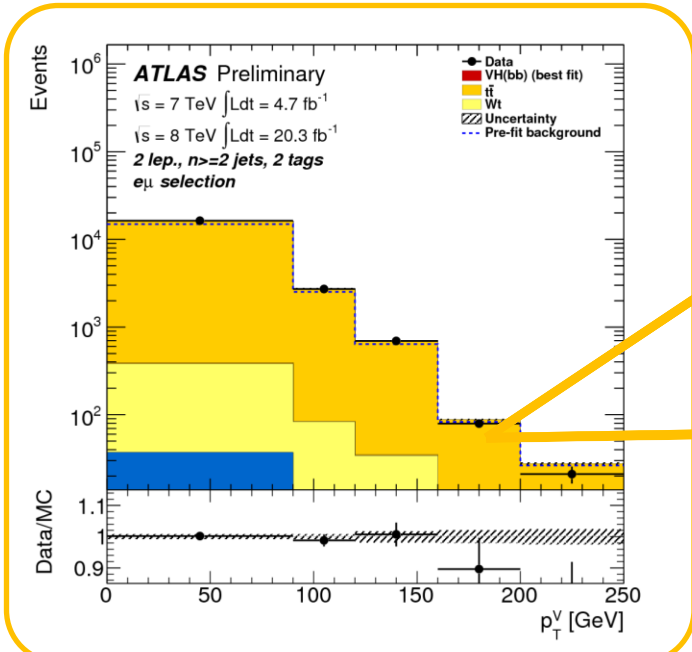


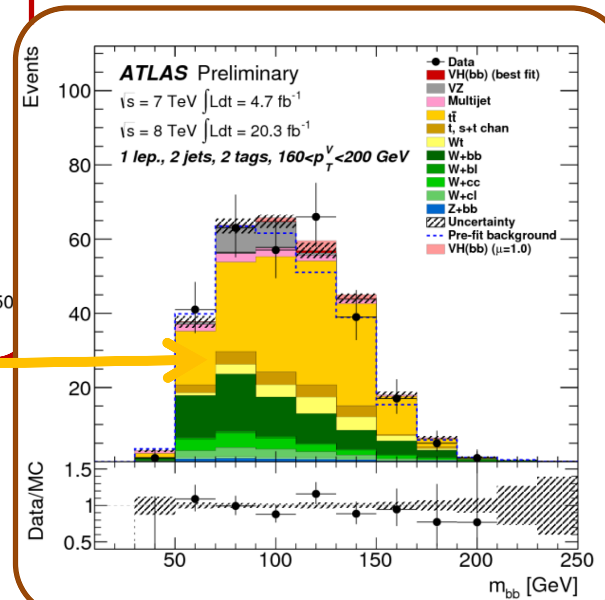
VH→bb @ATLAS - Strategy

ttbar constrained in e.g. eμ-2tag

	2 tags			1 tag	
	2 jets	3 jets	e-μ	2 jets	3 jets
0-lepton (x 3 pTV bins)	mbb shape	mbb shape	-	norm	norm
1-lepton (x 5 pTV bins)	mbb shape	mbb shape	-	norm	norm
2-lepton (x 5 pTV bins)	mbb shape	mbb shape	norm	norm	norm







VH→bb @ATLAS - Strategy

W+jets constrained in e.g. 1lep-2jet-1tag

	2 tags			1 tag	
	2 jets	3 jets	e-μ	2 jets	3 jets
0-lepton (x 3 pTV bins)	mbb shape	mbb shape	-	norm	norm
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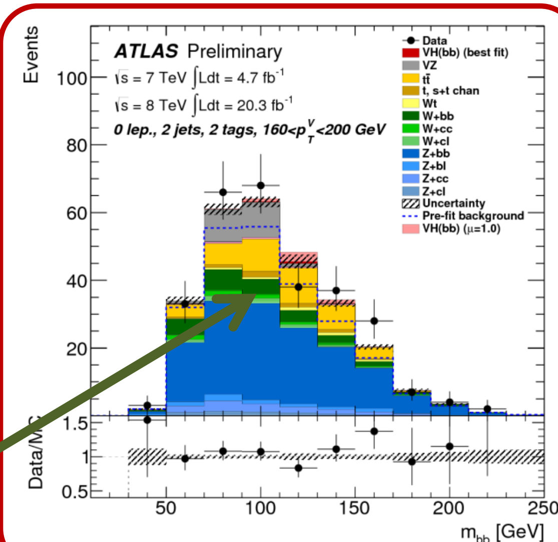
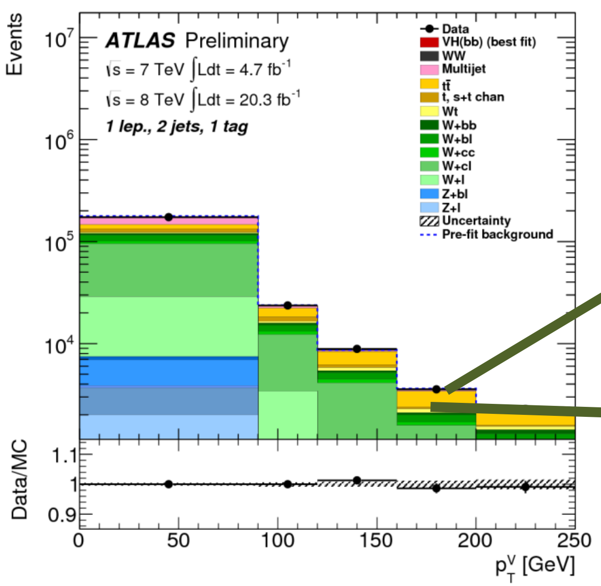
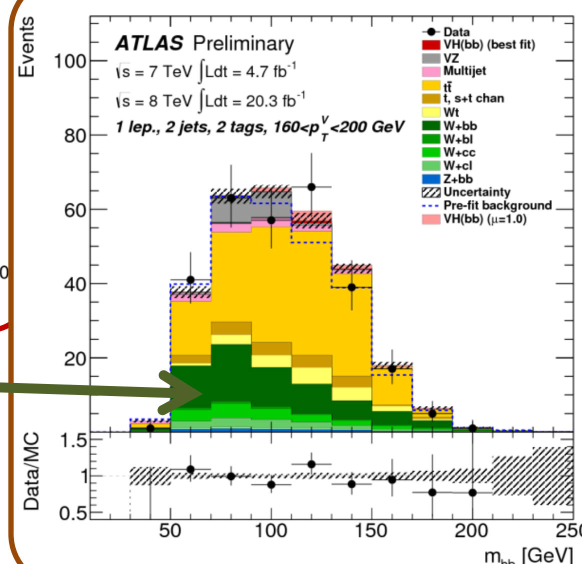
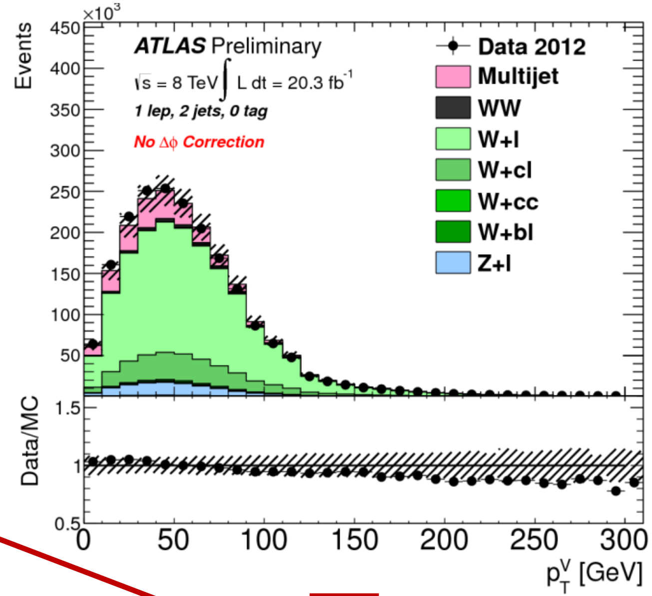


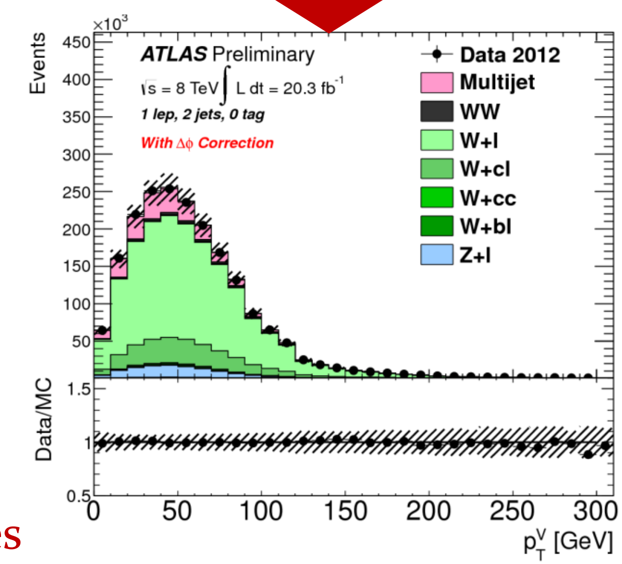




VH→bb @ATLAS (Bkg Modeling)

- Bkg norm from fit
  - but need to control the migrations between different regions: njets/ntags, pTV and m_{bb} bins
- Systematics (corrections when needed) are derived for each Bkg
  - e.g. Δφ(j,j) correction for V+jets
  - ➢ improves pTV as well as other variables





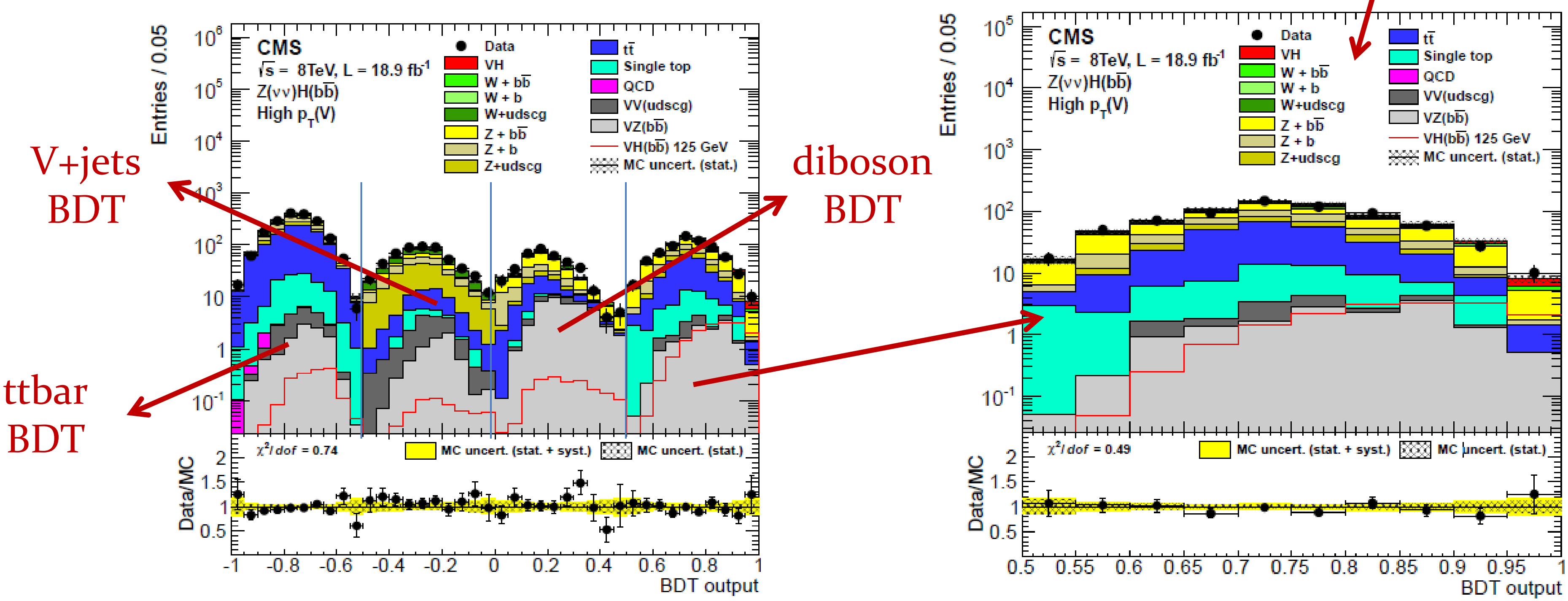
	mbb	Δφ(j,j)	pTV	3-to-2-jets	HF composition
W+jets	MC	data	data	MC	MC
Z+jets	data	data	data	MC	MC
tt	MC	-	data	MC	-
Single top	MC	-	MC	MC	-
diboson	MC	-	MC	MC	-
multijet	data	-	data	free	-

More important with shrinking experimental uncertainties

VH→bb @CMS - Strategy

- Use BDT with several kinematic, btag and topology variables to separate the signal from backgrounds
  - specific BDTs to separate specific backgrounds (top, V+jets, diboson)
  - classify events in different background region
  - final BDT in signal region to select signal
  - merge the 4 BDT outputs in one distribution
- Fit a total of 14 distributions in all channels and pTV bins

Zoom on signal BDT



VH→bb @CMS - Strategy

- Use BDT with several kinematic, btag and topology variable to separate the signal from background
  - specific BDTs to separate specific backgrounds (top, V+jets, diboson)
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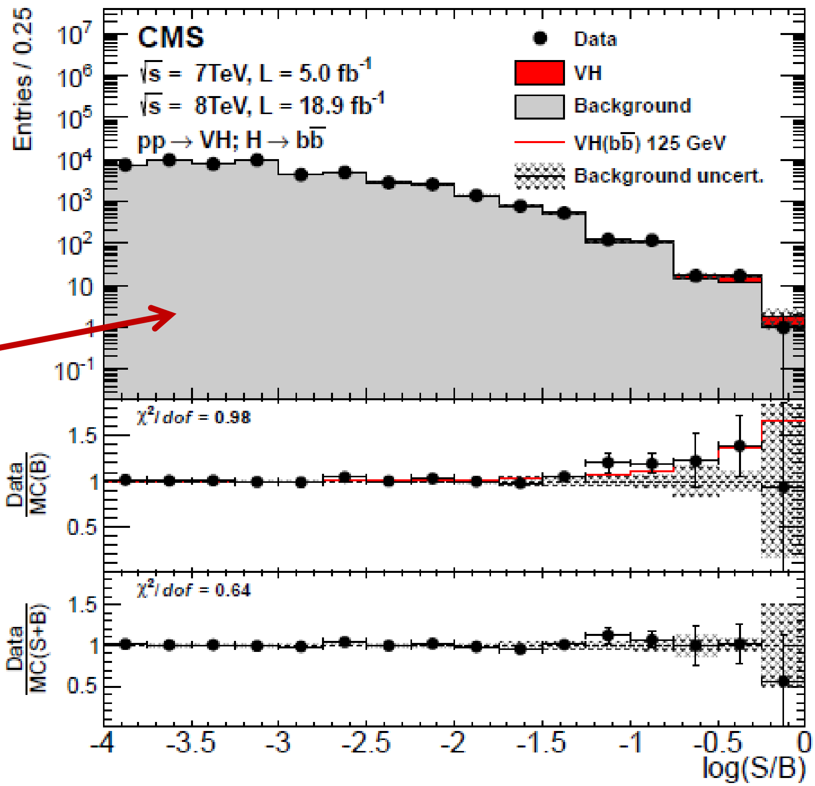
  - final BDT in signal region to select signal
  - merge the 4 BDT output in one distribution

- Fit a total of 14 distributions in all channels and pTV bins

Easier to visualize

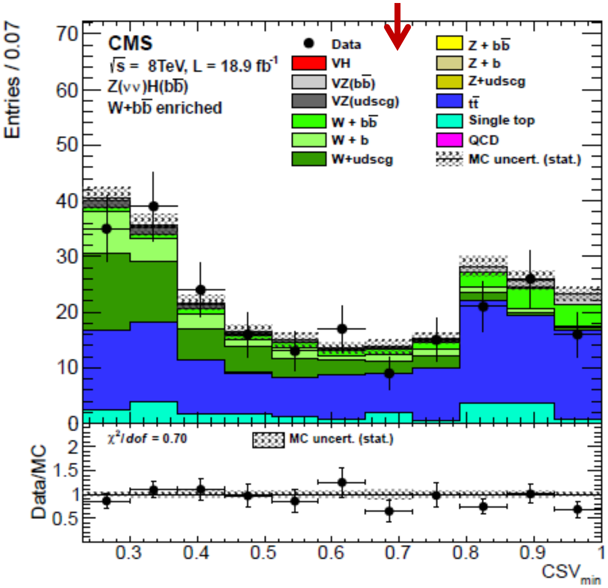
Merged BDT outputs in a single distribution

Bins ordered according to S/B

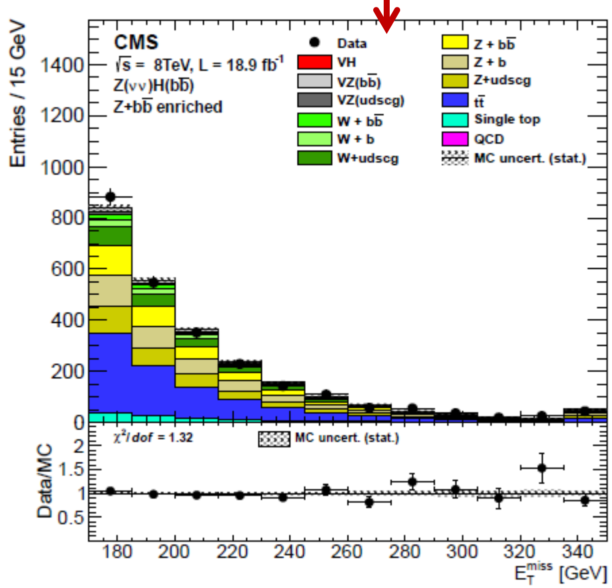


- Prior to the final fit the bkg norm is extracted from different control regions
  - fit the btag weight (CSVmax) variable independently for each channel
  - modeling and scale factors validated using additional variables
  - results used as input to the final fit

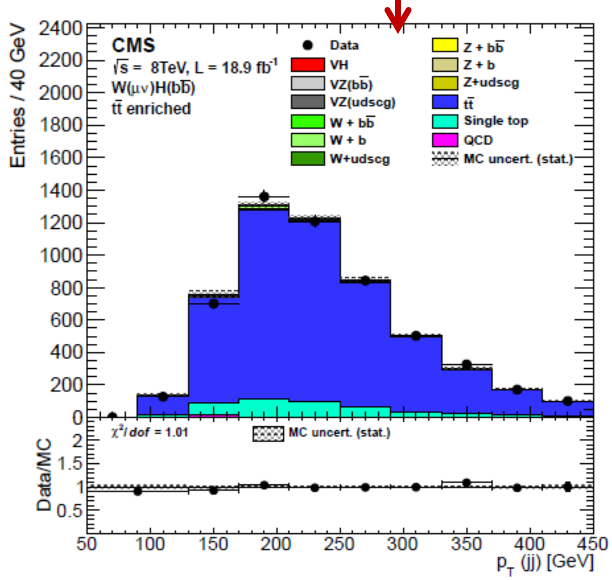
Wbb region
Low njets + high btag
M(jj) veto



Zbb region
Low njets + high btag
M(jj) veto

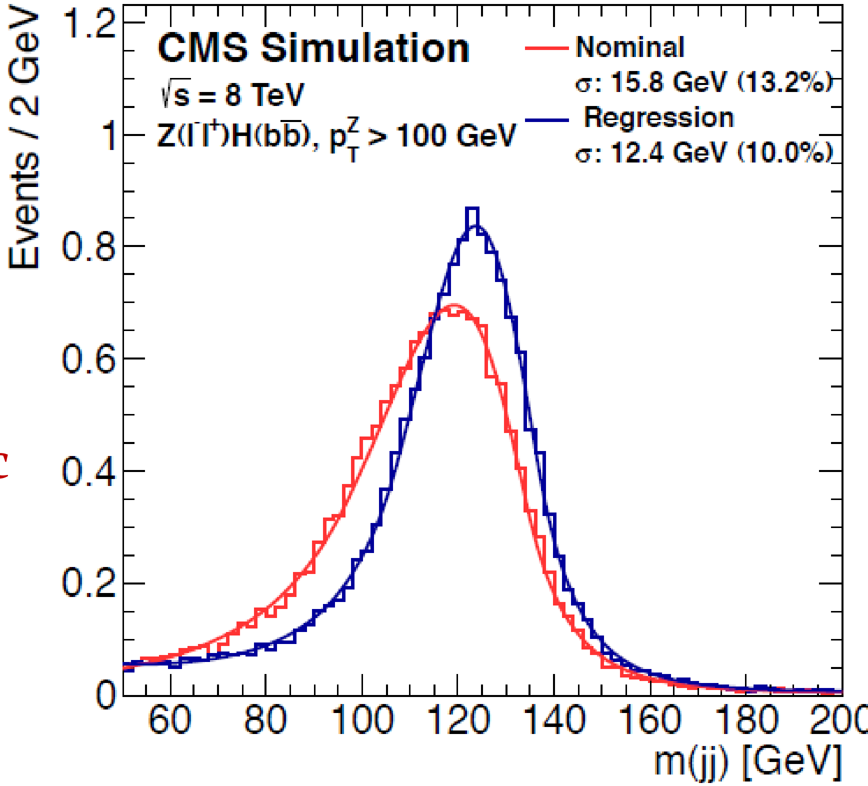


ttbar region
High Njets + High btag



VH→bb @CMS - b-jet Regression

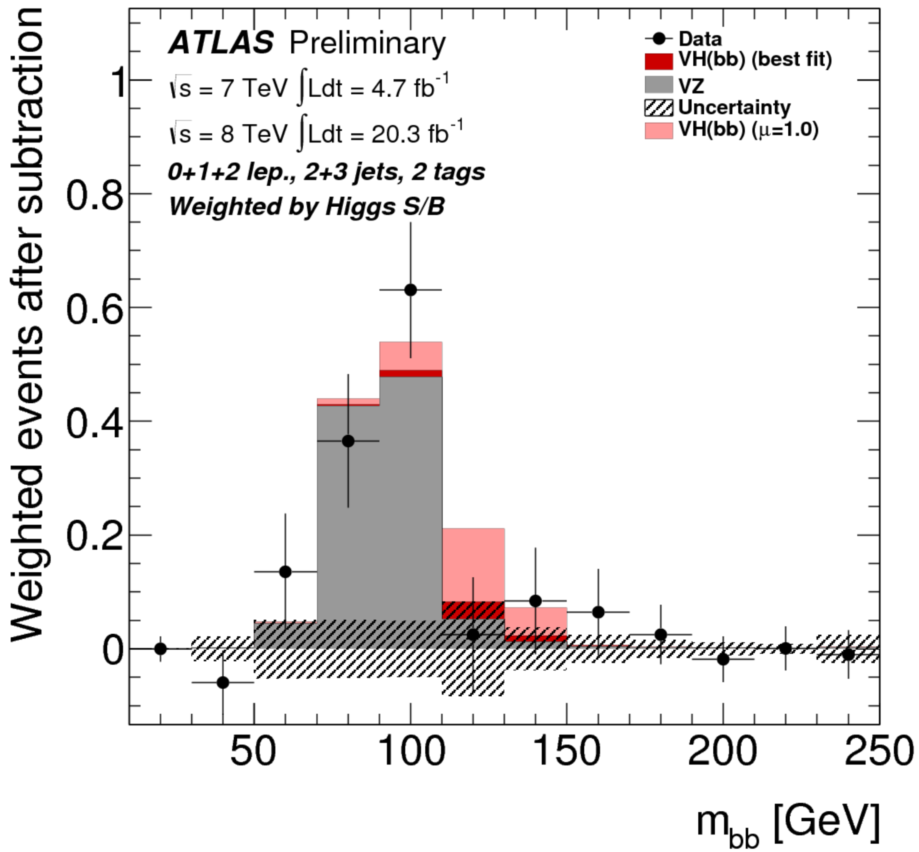
- Improving b-jets energy (m_{bb}) resolution using a multivariate regression technique
- BDT including:
  - jet-substructure variables
  - tracks and vertex in jet variables
  - soft-lepton variables (for semi-leptonic decays)
  - Event kinematics (ETmiss) variables in case of ZH→llbb

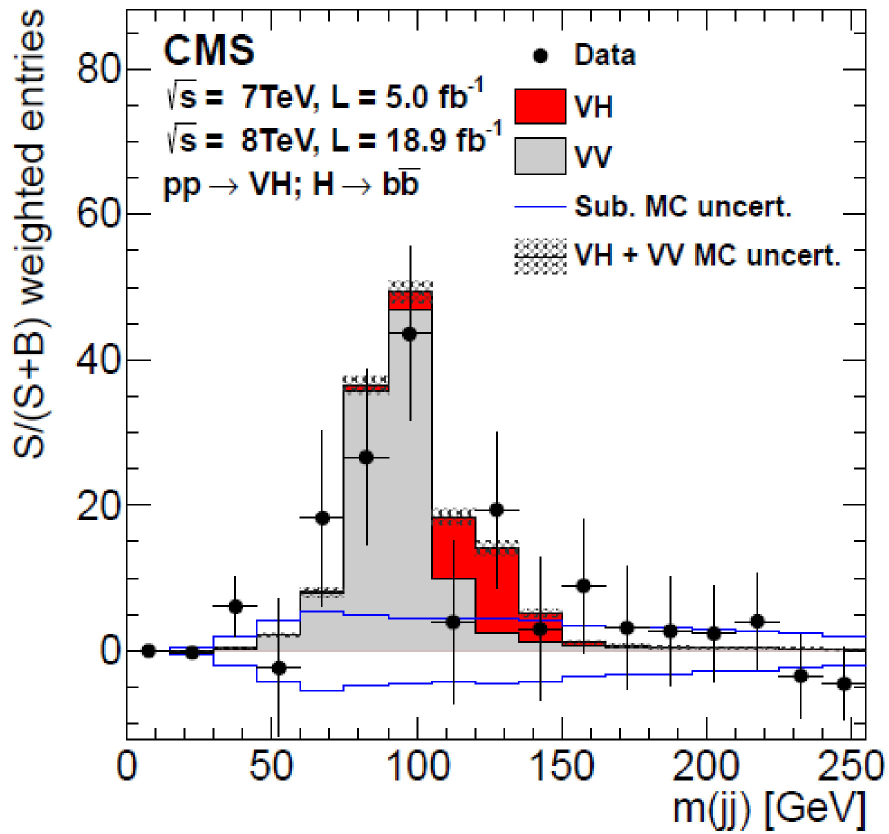


- Improve m_{bb} resolution by 15%
- Improve analysis sensitivity by 10%-20%

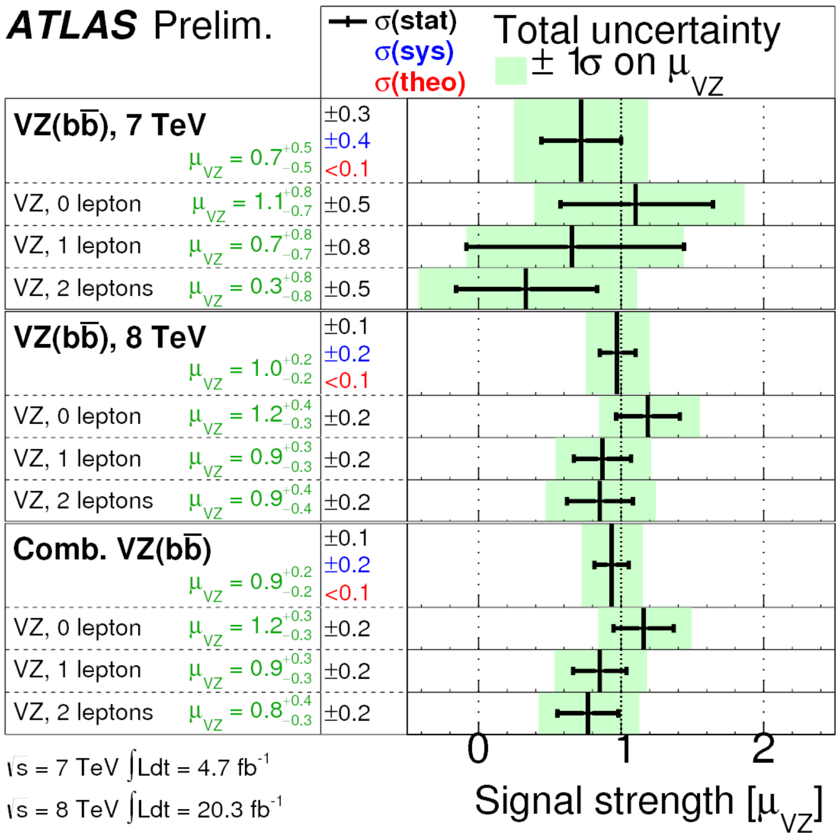
VH(Z)→bb @LHC - Results

- Validation of the VH analyses using VZ events
  - nice peak at the Z mass





- Fit performed for VZ in a similar way as for ZH
  - extracted signal strength compatible with SM



ATLAS

4.8σ (expected 5.1σ)

$\mu_{VZ} = 0.9 \pm 0.2$

CMS

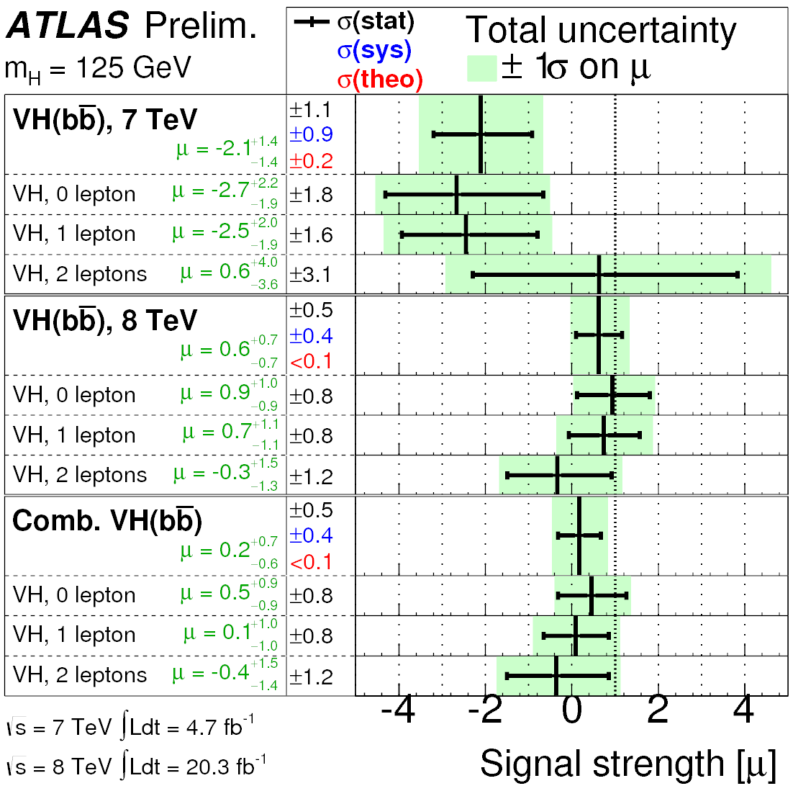
7.5σ (expected 6.3σ)

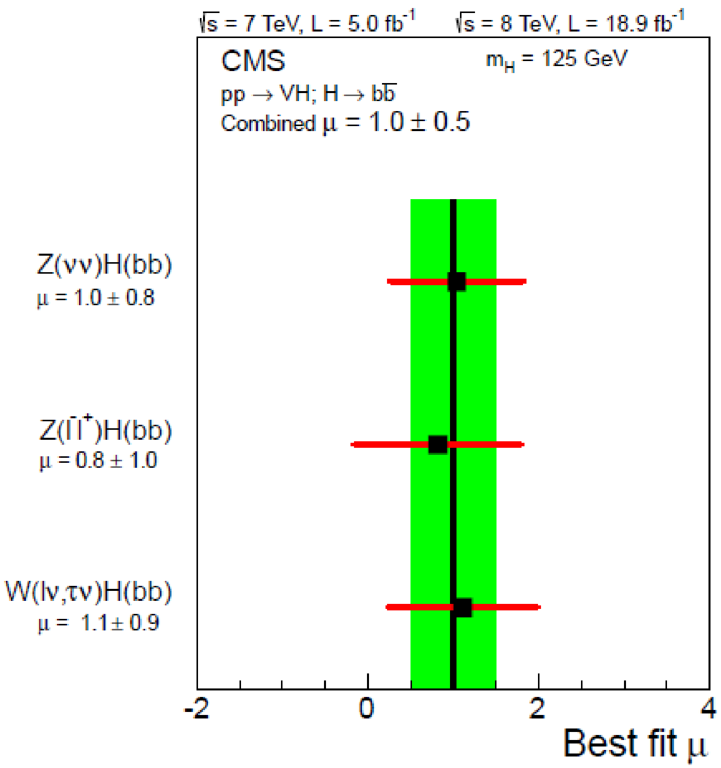
$\mu_{VZ} = 1.19^{+0.28}_{-0.23}$

VH→bb @LHC - Results

ATLAS m_H=125 GeV
$\mu=0.2^{+0.7}_{-0.6}$

CMS m_H=125 GeV
$\mu=1.0\pm0.5$





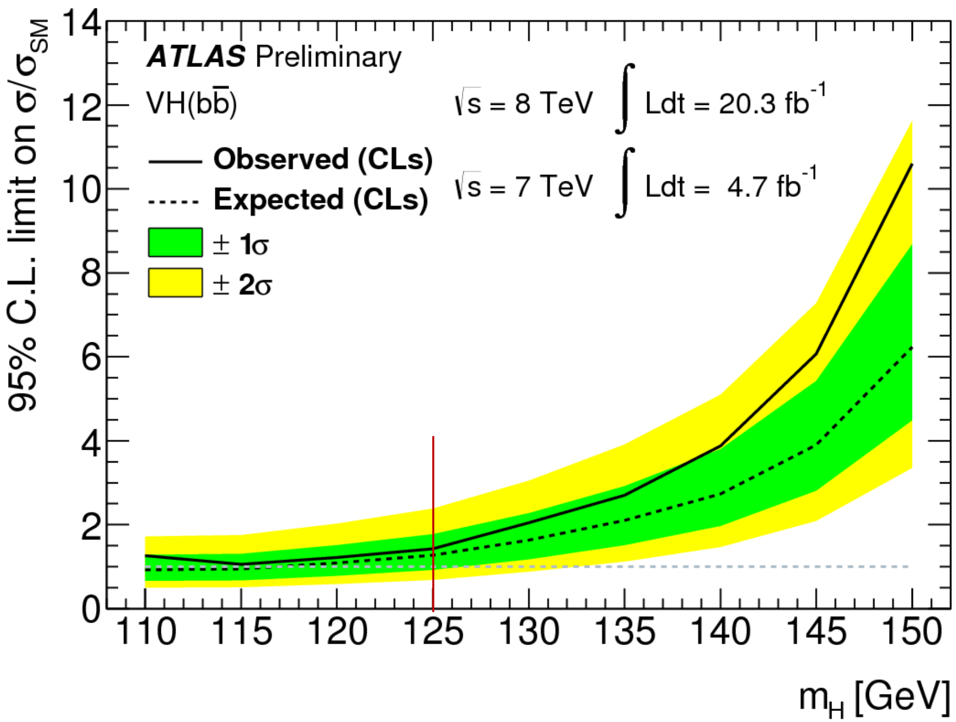
Both results compatible with the presence of a SM Higgs boson

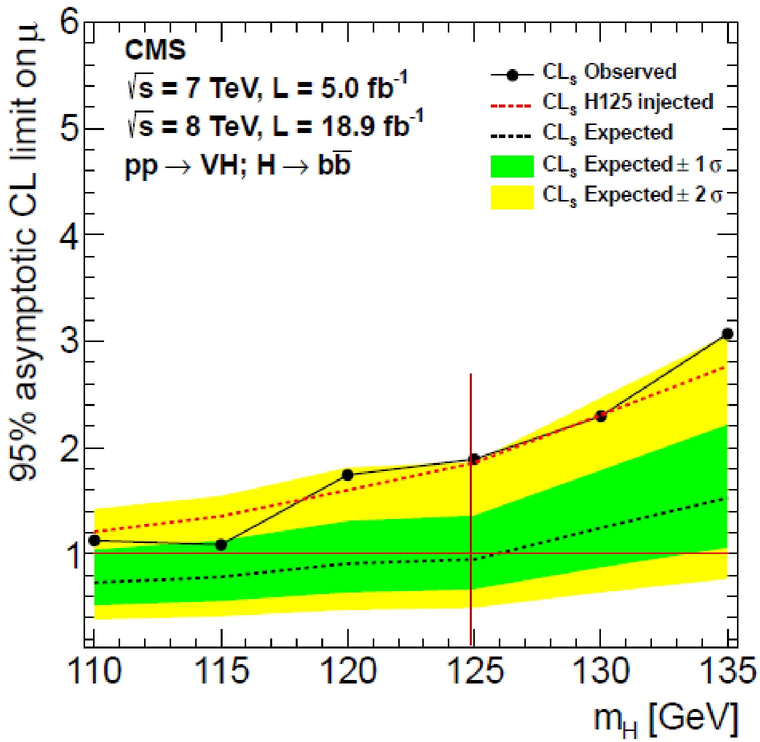
Compatible results for W and Z associated production

VH→bb @LHC - Results

ATLAS m_H=125 GeV
Expected Limit: 1.3
Observed Limit: 1.4

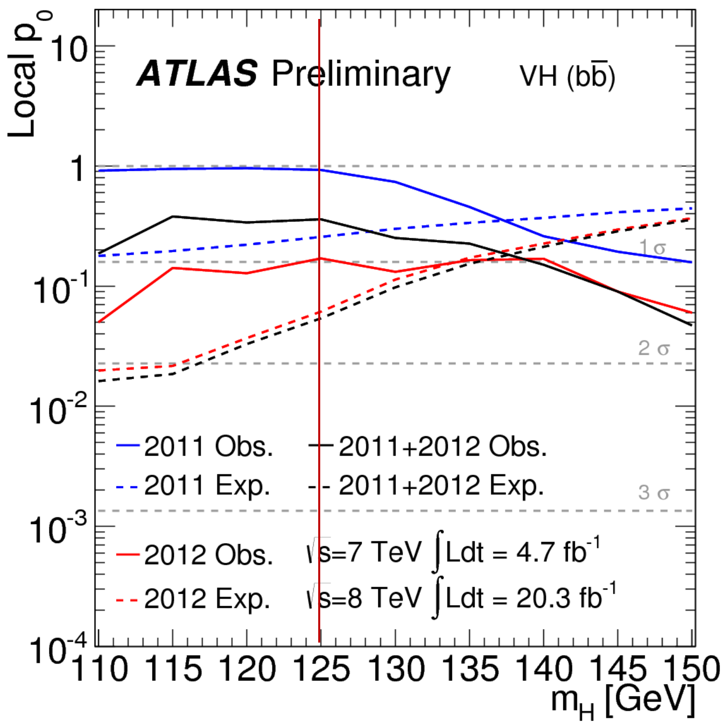
CMS m_H=125 GeV
Expected Limit: 0.95
Observed Limit: 1.89



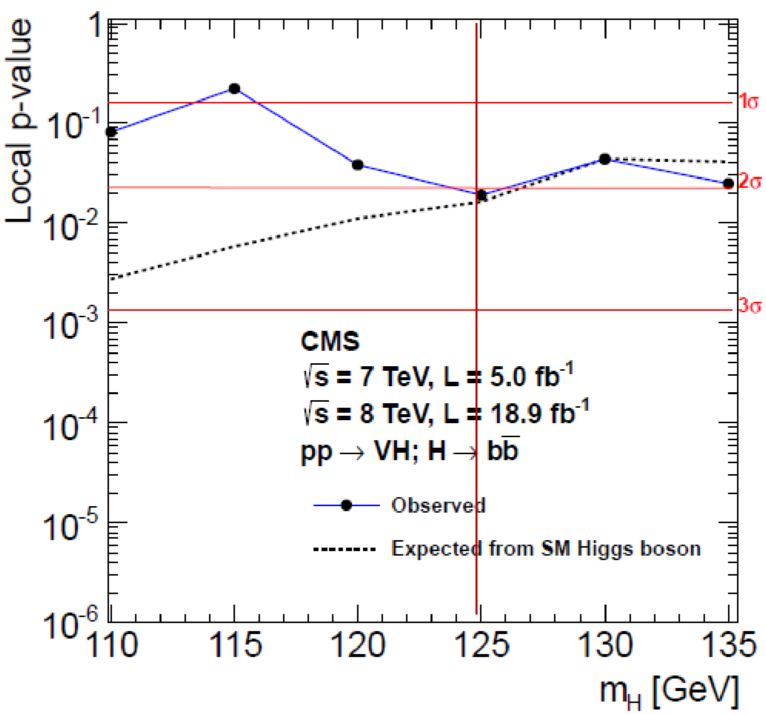


VH→bb @LHC - Results

ATLAS m_H=125 GeV
Expected Limit: 1.3
Observed Limit: 1.4
No significant excess
SM Higgs probability: 0.36
(expected 1.6σ)

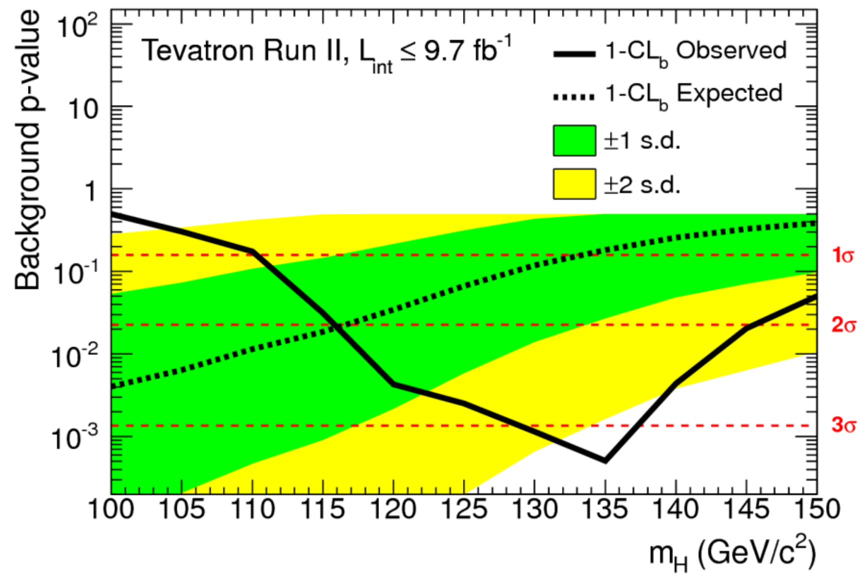


CMS m_H=125 GeV
Expected Limit: 0.95
Observed Limit: 1.89
2.1 sigma excess
(expected 2.1σ)



VH→bb Spin @D0 - Introduction

- Evidence @Tevatron for the presence of H→bb

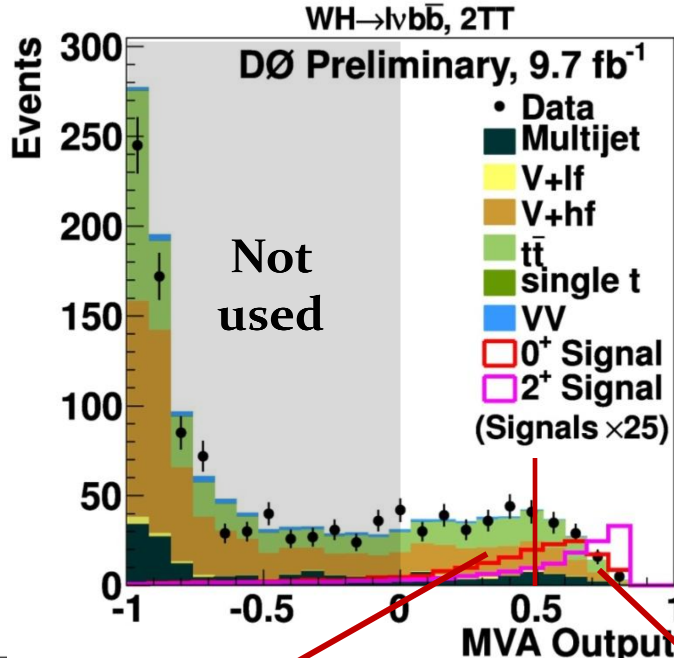


- First test of Higgs boson spin and parity in H→bb channels
  - ATLAS(CMS) excluded a 2^+ Higgs boson in bosonic decay channels
- Testing the 2^+ hypothesis with a graviton like coupling (Randall-Sundrum model)

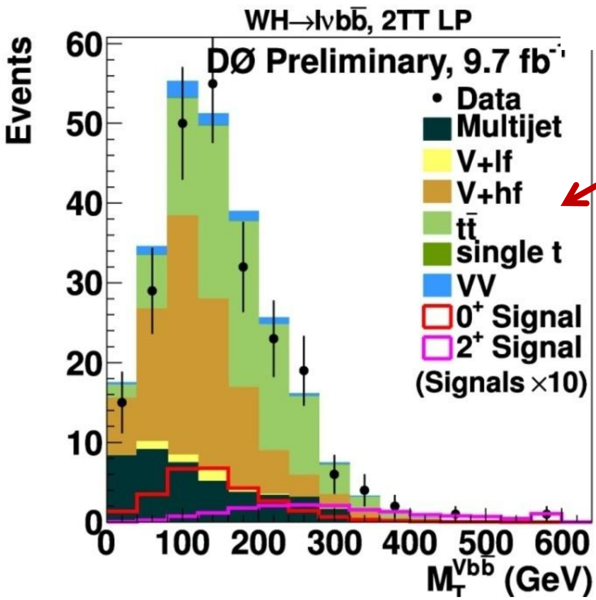
- Analysis based on D0 results for VH→bb searches
  - ➢ $\mu=1.23^{+1.24}_{-1.17}$
- Assumptions:
  - 2^+ production cross section and BR equal to SM
    - ➢ test 2+ hypothesis
  - or mixture of 2^+ and 0^+ with a total corresponding to SM σ.BR
    - ➢ set a lower limit on the 2^+ fraction

VH→bb Spin @D0 - Strategy

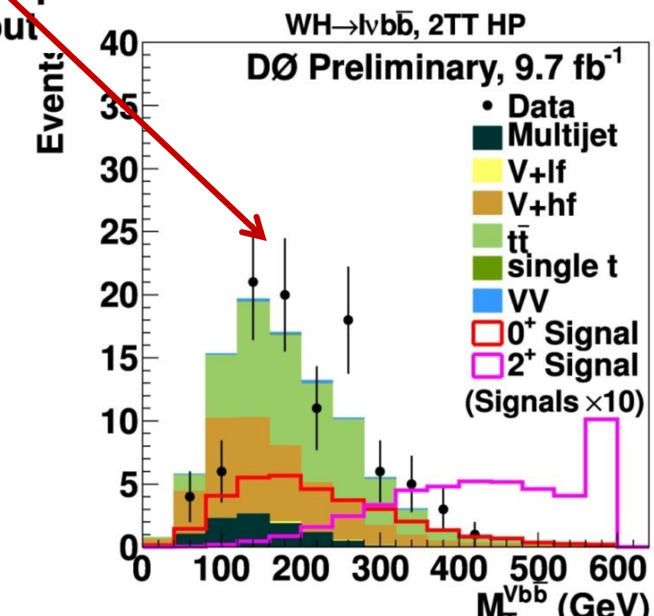
MVA output(or m_{bb}) from search analysis used to discriminate SM backgrounds



Fit the (transverse) mass of the VH system in different regions to test the 0+ and 2+ hypotheses

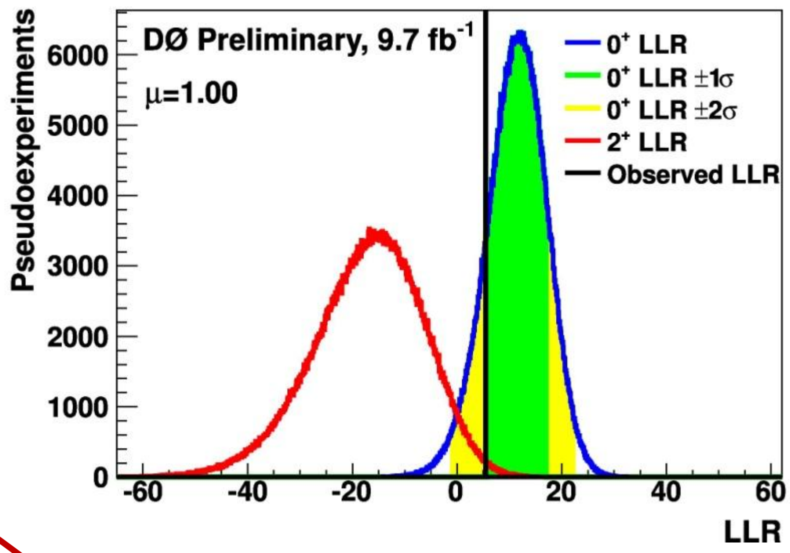


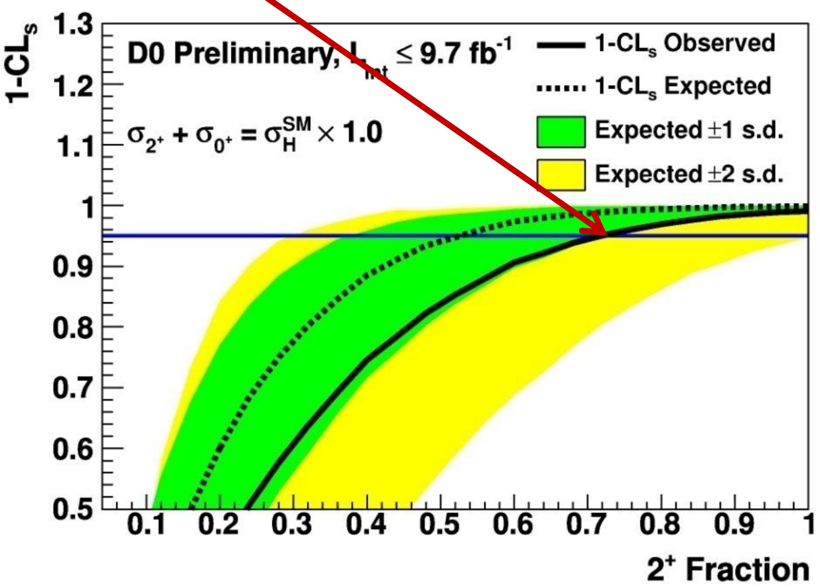
Divide to low and high signal purity region

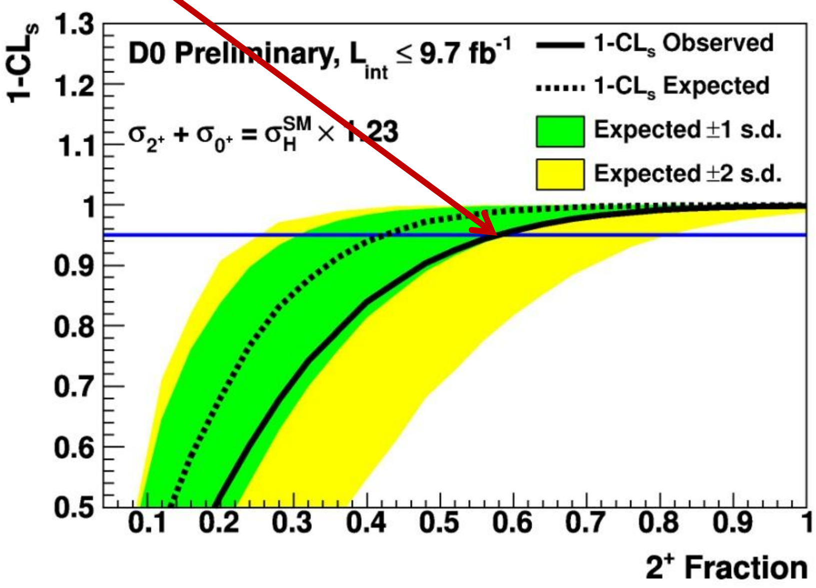


VH→bb Spin @D0 - Results

- CLs method with log likelihood ratio (LLR) as test statistics
- 2^+ excluded at better than 99% CL
- Fraction of 2^+ is lower than 0.57 (0.71) for μ=1.23 (1.00) @95% CL







Conclusion

- No doubt that $H \to ff$ and particularly $H \to bb$ represent one of the most important programs for the LHC in the near future
- VH channels are the most sensitive for $H \to bb$ searches
- ATLAS and CMS latest results presented with the full 2011 and 2012 datasets
  - CMS: observed (expected) limit of 1.89 (0.95) @95% CL for m_H=125 GeV
    - Local significance of 2.1 s.d.
  - ATLAS: observed (expected) limit of 1.4 (1.3) @95% CL for m_H=125 GeV
    - No significant excess observed with signal p-value=0.36
- D0 presented the first spin-parity analysis using $H \to bb$ channels
  - fraction of $J^P=2^+$ > 0.57 (0.71) excluded for μ=1.23 (1.00) @95% CL
- Run II data will be conclusive about $(V)H \to bb$ @LHC
  - More importantly, enhanced precision on the Higgs coupling and constraint on the decay width

Extra Slides

VH→bb @ATLAS - 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 $p_{\mathrm{T}}^{\mathrm{jet}_1} > 45$ GeV $p_{\mathrm{T}}^{\mathrm{jet}_2} > 20$ GeV $+ \leq 1$ extra jets		
Missing E_T	$E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV $\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$ $\min[\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})] > 1.5$ $\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, b\bar{b}) > 2.8$	$E_{\mathrm{T}}^{\mathrm{miss}} > 25$ Gev	$E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV
Vector Boson	-	$m_{\mathrm{T}}^{W} < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

	p_{T}^{V} [GeV]	0-90	90-120	120-160	160-200	>200
All Channels	$\Delta R(b, \bar{b})$	0.7-3.4	0.7-3.0	0.7-2.3	0.7-1.8	<1.4
1-lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>25				>50
	m_{T}^{W} [GeV]	40-120			<120	

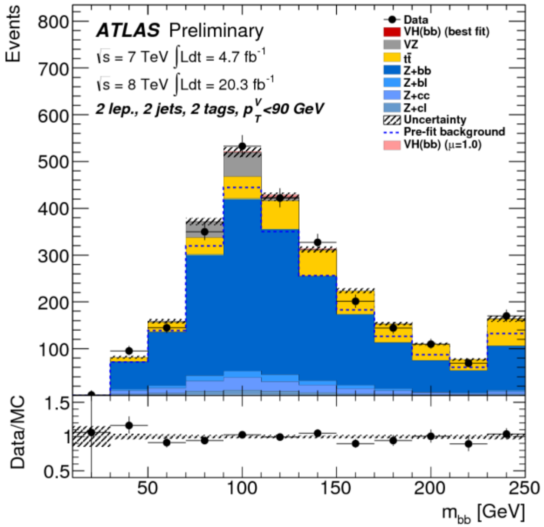
VH→bb @CMS - Selection

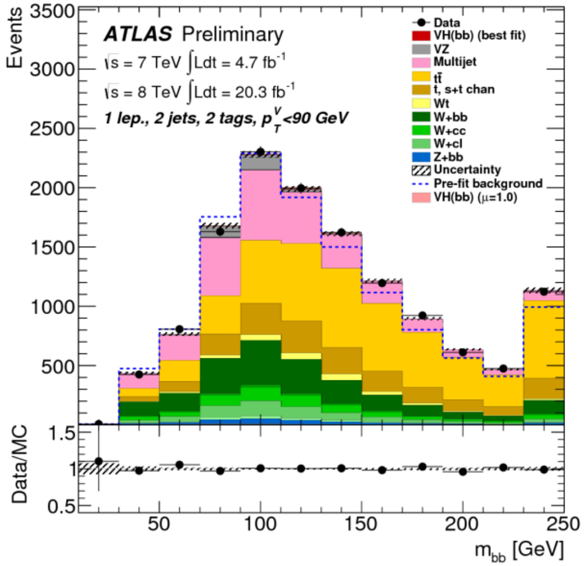
Variable	W($\ell\nu$)H	W($\tau\nu$)H	Z($\ell\ell$)H	Z($\nu\nu$)H
p_T(V)	[100–130] [130–180] [>180]	[>120]	[50–100] [>100]	[100–130] [130–170] [>170]
$m_{\ell\ell}$	–	–	[75–105]	–
$p_T(j_1)$	>30	>30	>20	>60
$p_T(j_2)$	>30	>30	>20	>30
p_T(jj)	>100	>120	–	[>100] [>130] [>130]
m(jj)	<250	<250	[40–250] [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

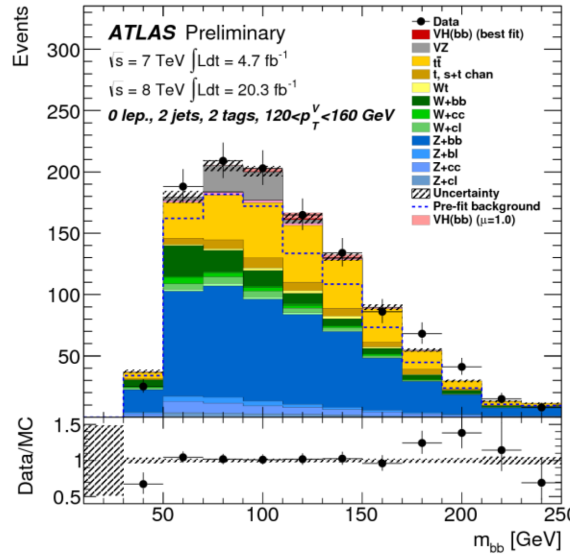
VH→bb @ATLAS – m(bb)

	Z→ll	W→lν	Z→νν

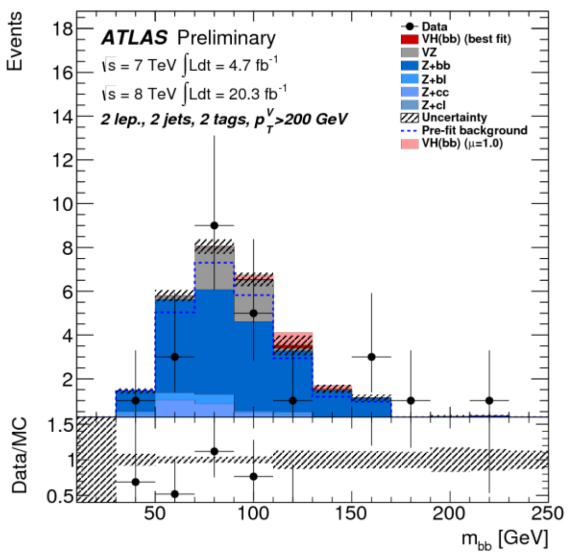
Low pTB

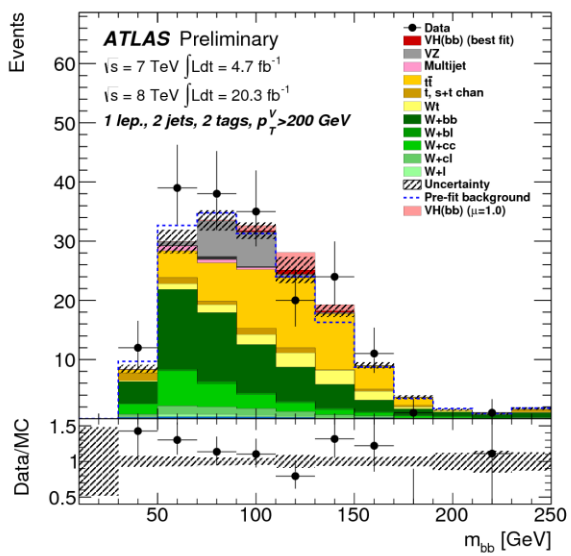


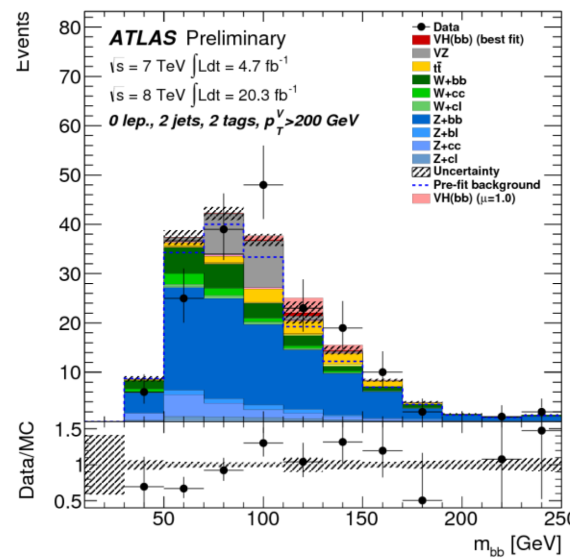




High pTB





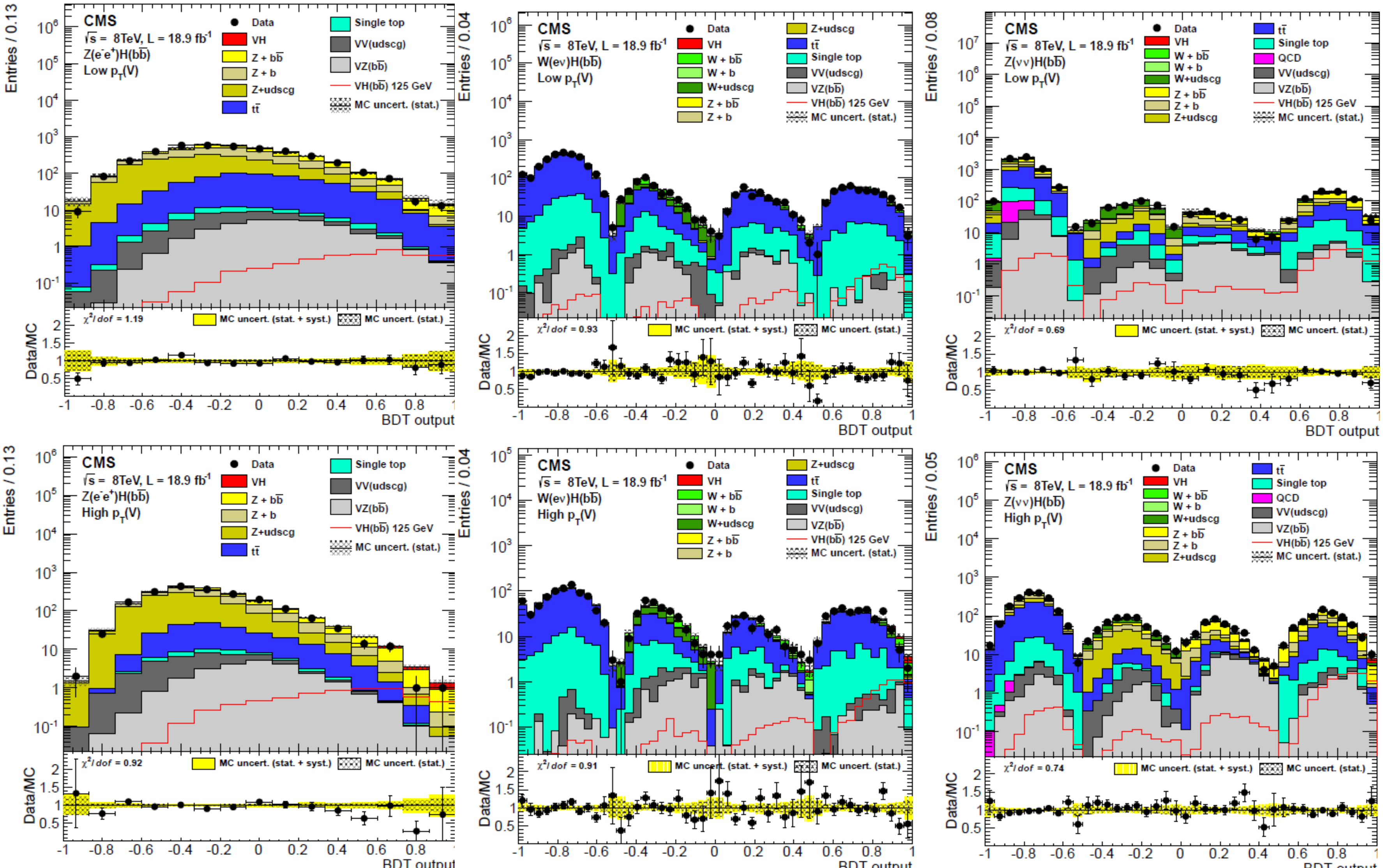


VH→bb @CMS – BDT Output

Z→ee | W→eν | Z→νν

Low pTB

High pTB

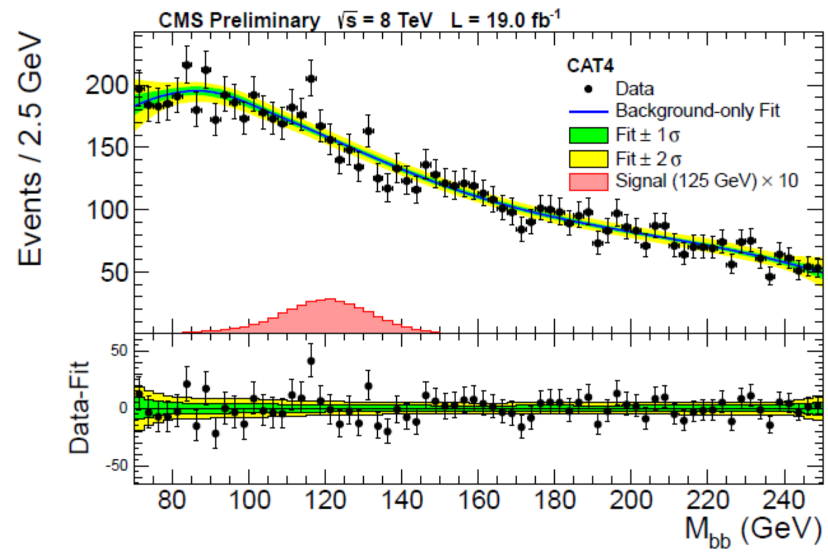


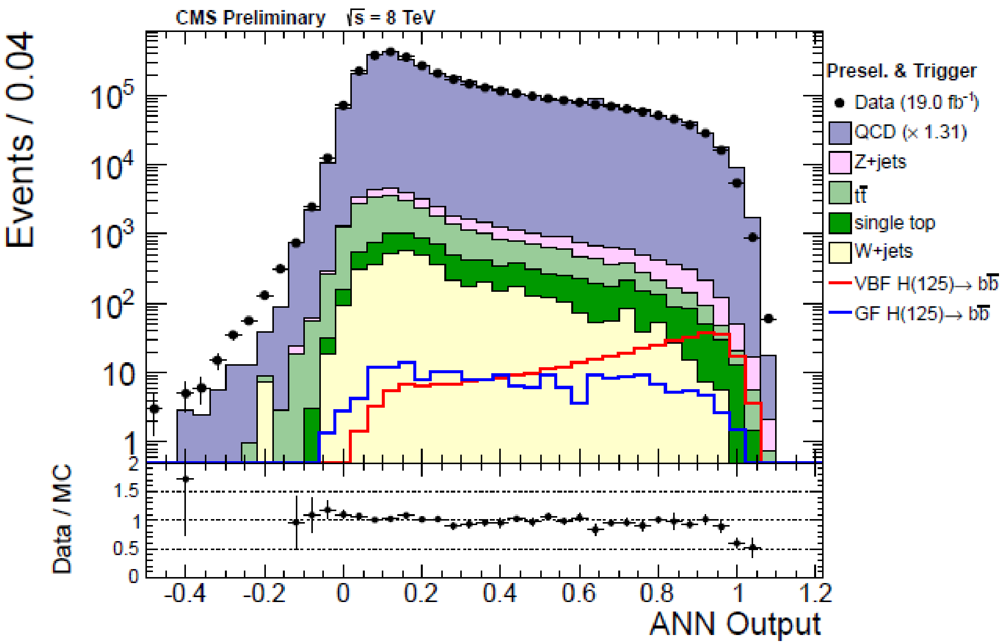
VH→bb @CMS - Systematics

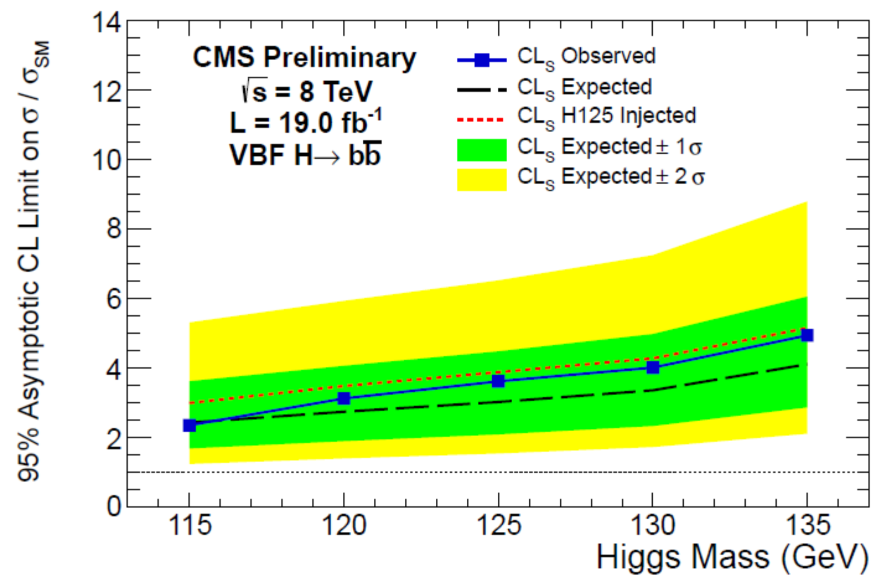
Source	Type	Event yield uncertainty range (%)	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
Luminosity	norm.	2.2–2.6	<2	<0.1
Lepton efficiency and trigger (per lepton)	norm.	3	<2	<0.1
$Z(\nu\nu)H$ triggers	shape	3	<2	<0.1
Jet energy scale	shape	2–3	5.0	0.5
Jet energy resolution	shape	3–6	5.9	0.7
Missing transverse energy	shape	3	3.2	0.2
b-tagging	shape	3–15	10.2	2.1
Signal cross section (scale and PDF)	norm.	4	3.9	0.3
Signal cross section (p_T boost, EW/QCD)	norm.	2/5	3.9	0.3
Monte Carlo statistics	shape	1–5	13.3	3.6
Backgrounds (data estimate)	norm.	10	15.9	5.2
Single top quark (simulation estimate)	norm.	15	5.0	0.5
Dibosons (simulation estimate)	norm.	15	5.0	0.5
MC modeling (V+jets and $t\bar{t}$)	shape	10	7.4	1.1

VBF H→bb @CMS

- Select VBF topology + 2 btags
- Separate background using a NN
  - bb-kinemtics not used in the NN
- Fit bb-invariant mass in NN-bins







H Width Through Interferometry

- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ mass difference due to interference of non-resonant Higgs contribution
  - Sensitive to the Higgs boson width
  - Indirect measurement of the Higgs boson width at the LHC
  - Need very accurate Higgs mass measurements
  - Probably allows to have a an upper limit