Search for SM Higgs Boson in H→bb at the LHC

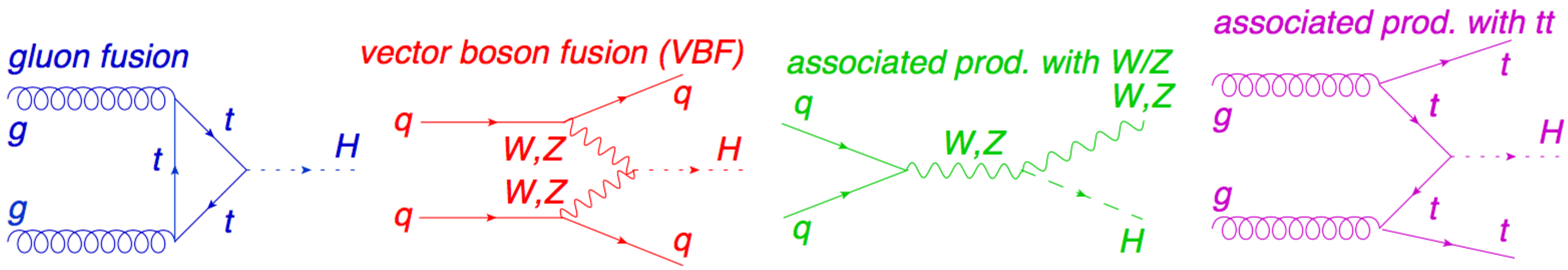
Second MCTP Spring Symposium on Higgs Boson Physics

April 16-20, 2012

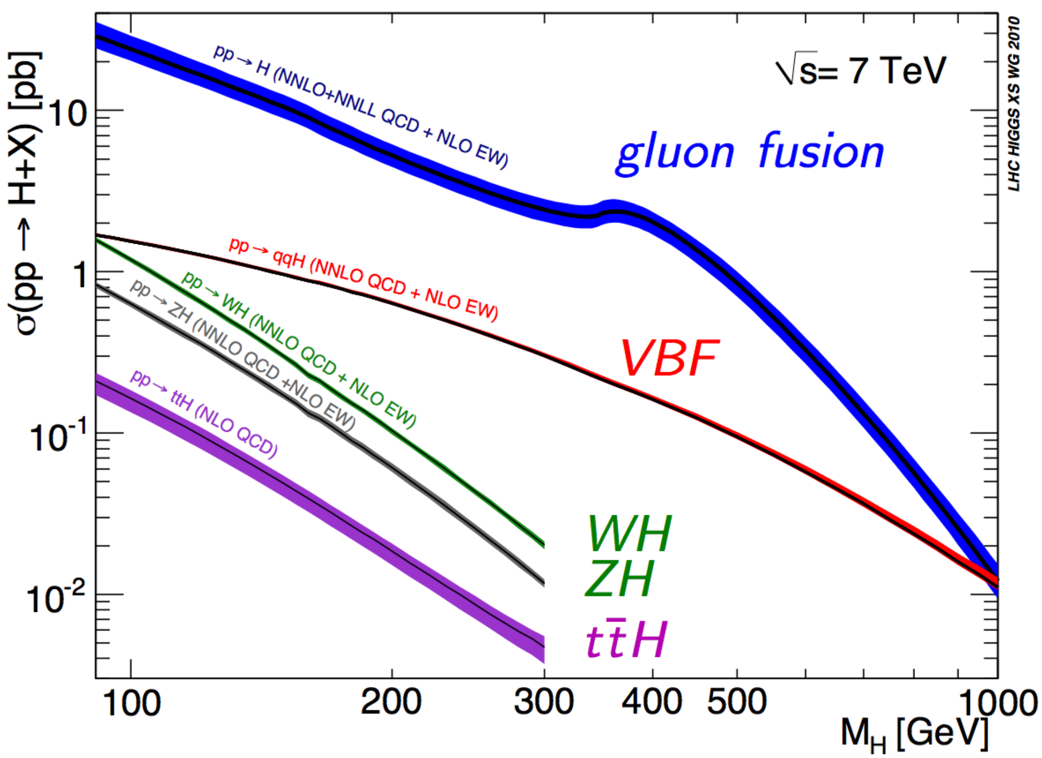
Song-Ming Wang
Academia Sinica

On behalf of the ATLAS and CMS Collaborations

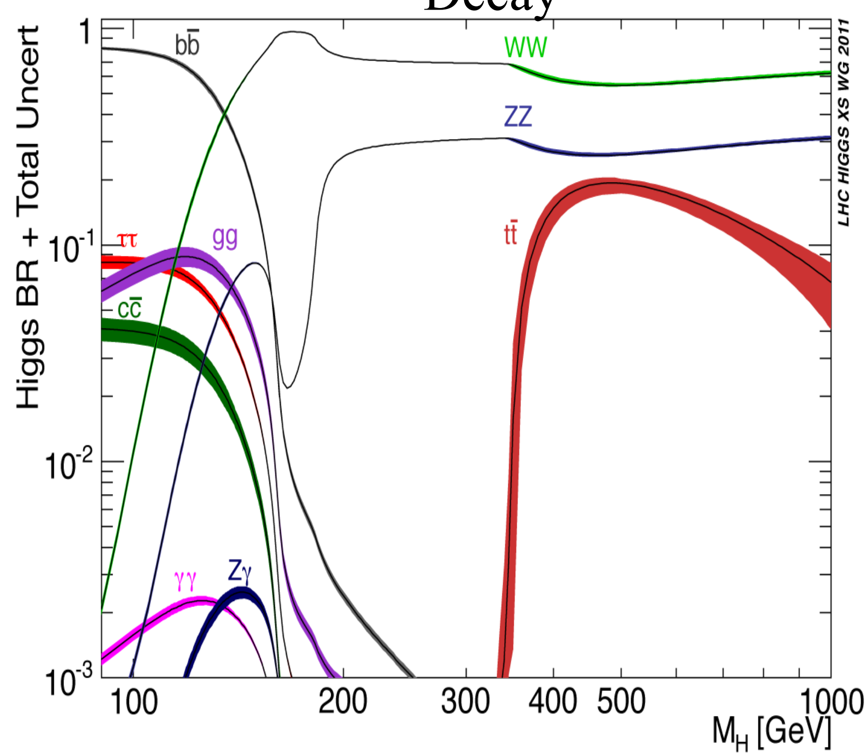
Introduction



Production

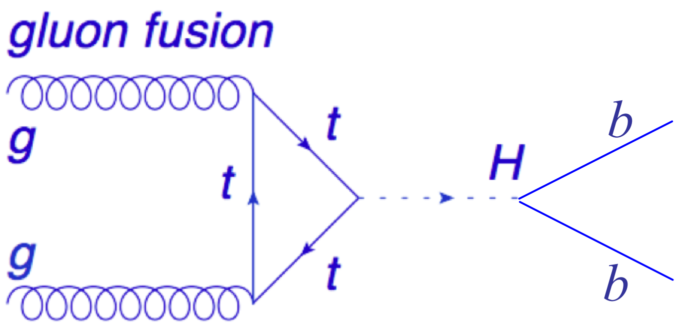


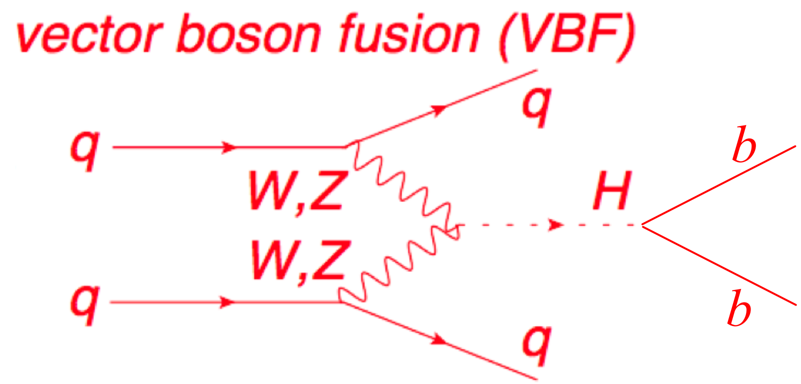
Decay



H→bb has highest decay BR at low mass (m_H < ~135 GeV)

Search for Low Mass Higgs Boson



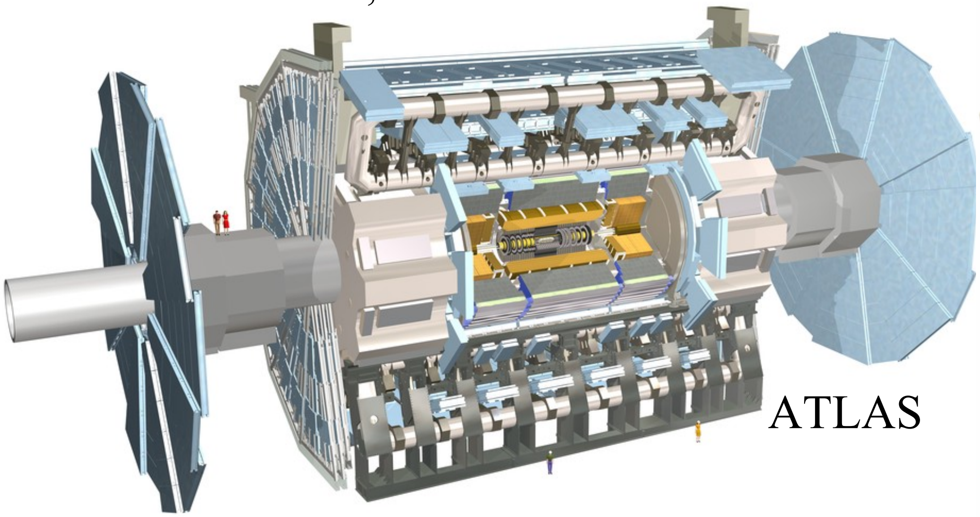


- $\sigma(m_H = 120\ \text{GeV}) \sim 17$ pb
- $\sigma(m_H = 120\ \text{GeV}) \sim 1.3$ pb

- Search in bb or qqbb final state will encounter huge multi-jet background
- Higgs production in association with W or Z
  - 3rd and 4th highest production rate ($\sigma(WH) \sim 0.66$ pb, $\sigma(ZH) \sim 0.36$ pb @ $m_H = 120$ GeV)
  - Final states with leptonic decays of W and Z can help to reduce contribution from multi-jet background

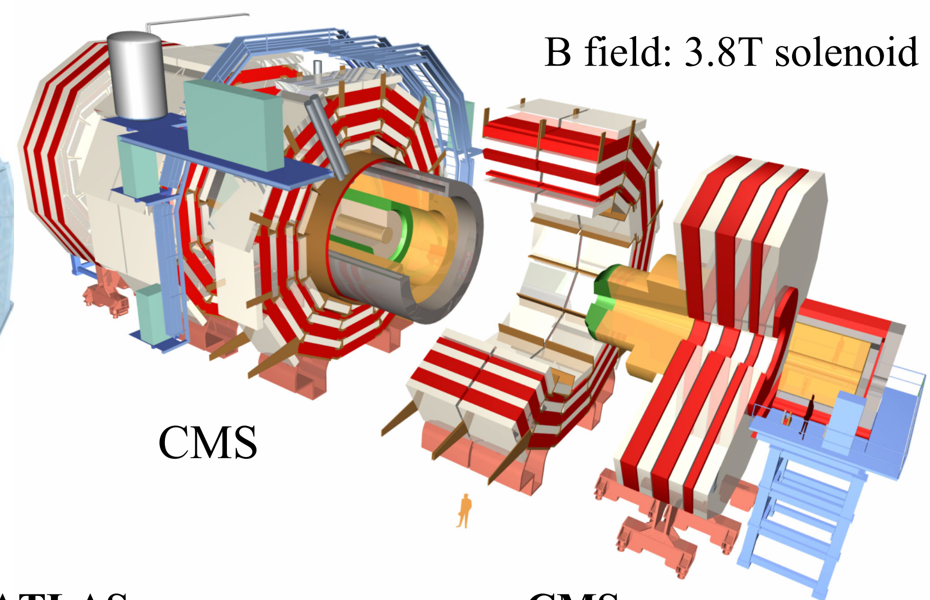
Detectors

B field: 2T solenoid, 4T toroid



ATLAS

B field: 3.8T solenoid

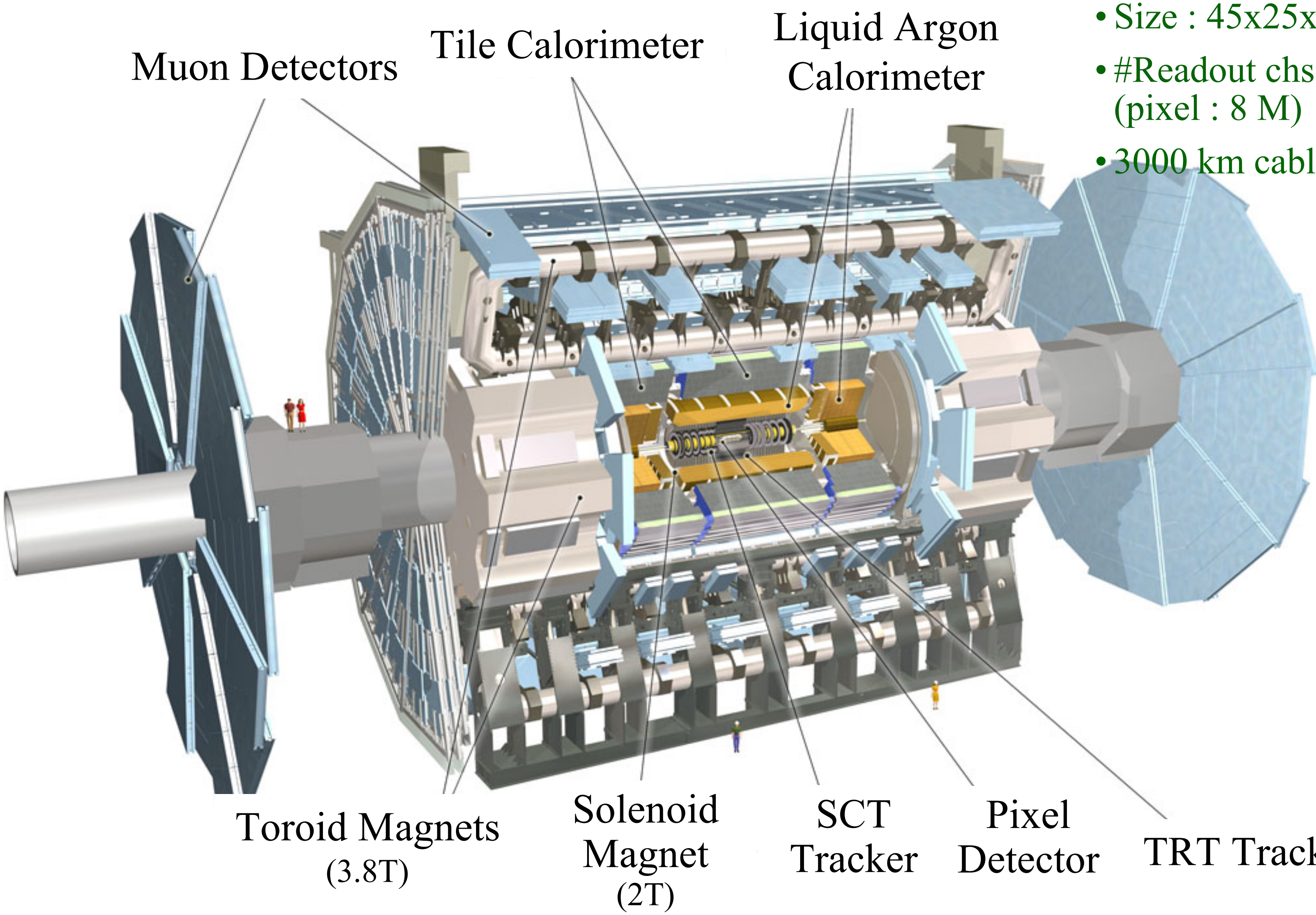


CMS

	ATLAS	**CMS**
Inner tracker : $\|\eta\|$ coverage	2.5	2.5
$\sigma(P_T)/P_T$ at P_T=100 GeV	3.8%	1.5%
EM calorimeter: $\|\eta\|$ coverage	3.2	3.0
$\sigma(E)/E$	$10\%/\sqrt{E}+0.7\%$	$3\%/\sqrt{E}+0.5\%$
HAD calorimeter: $\|\eta\|$ coverage	4.9	5.2
$\sigma(E)/E$ (EM+HAD combined)	$50\%/\sqrt{E}+3\%$	$85\%/\sqrt{E}+7\%$
Muon system: $\|\eta\|$ coverage	2.7	2.4
$\sigma(P_T)/P_T$ at P_T=1 TeV (standalone)	12% ($\|\eta\|<1.5$)	15-40% (depend on η range)

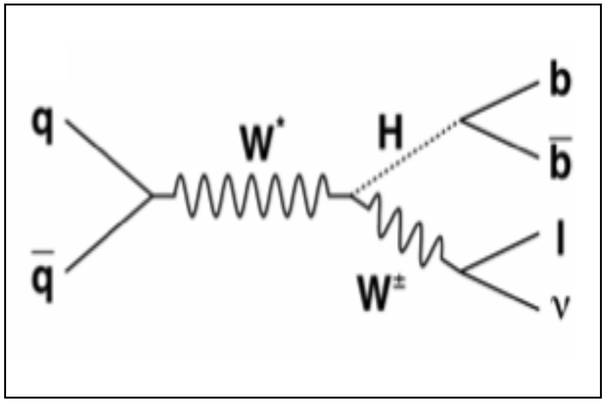
A Toroidal LHC ApparatuS (ATLAS) DETECTOR

- Weight : 7000 ton (same as Eiffel tower)
- Size : 45x25x25 m^3
- #Readout chs. : 8.8 M (pixel : 8 M)
- 3000 km cables

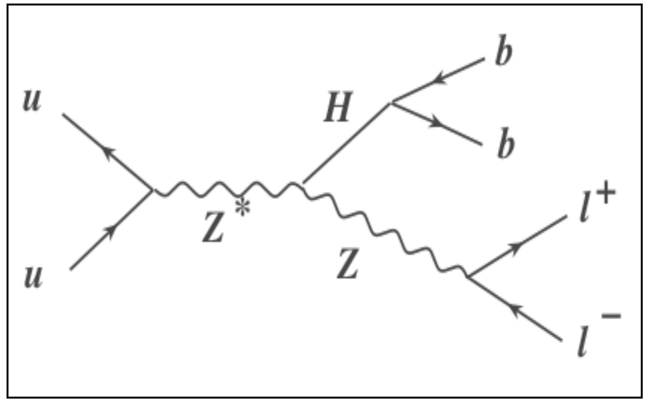


Search for Higgs Boson in Associated Production

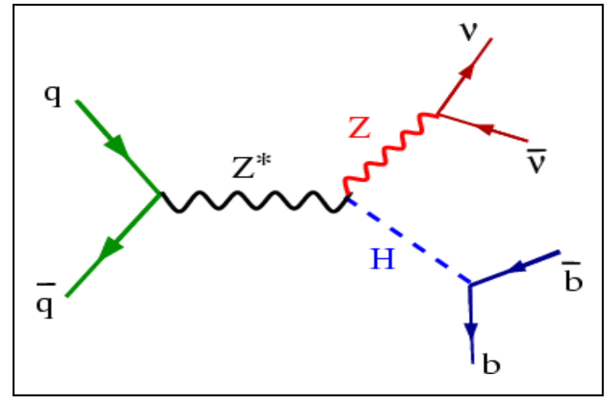
WH $\rightarrow$ $l\nu$ bb



ZH $\rightarrow$ l^+l^- bb



ZH $\rightarrow$ νν bb



WH (lνbb)

- 1 high p_T lepton
  - e or μ
- Missing Transverse Energy (E_T^{miss})
- 2 b jets

ZH (llbb)

- 2 high p_T leptons
  - e^+e^- or $\mu^+\mu^-$
  - Z resonance peak
- small E_T^{miss}
- 2 b jets

ZH (ννbb)

- 0 lepton
- Large E_T^{miss}
- 2 b jets

- CMS : Phys. Lett. B 710 (2012) 284-306
- ATLAS : ATLAS-CONF-2012-015

Background Sources

Main Physics Background

•Top quark production (ttbar, single top)

•Z + jets (Z + light-flavor (LF) jets, Z + heavy-flavor (HF) jets)

•Diboson (WW, WZ, ZZ)

•W + jets (W + LF jets, W + HF jets)

•QCD multi-jet

} only for WH(lνbb) and ZH(ννbb) searches

Other Sources

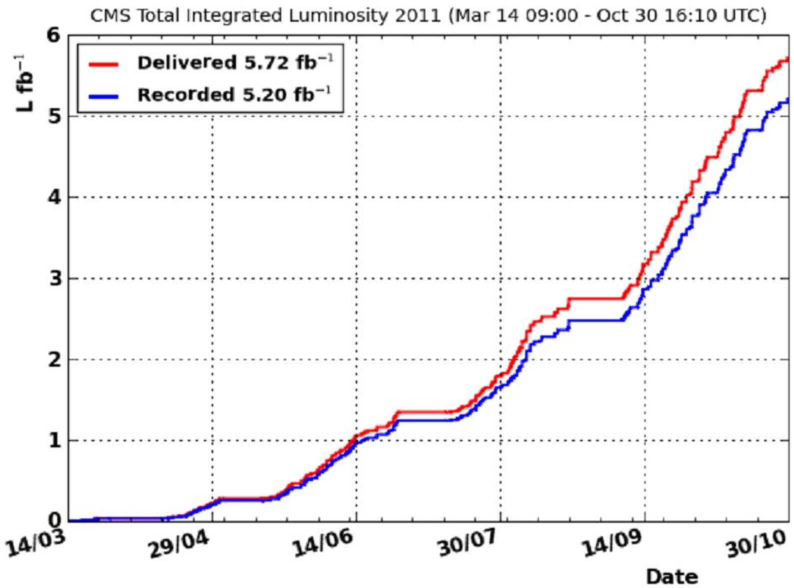
•Extra jets from pile-up

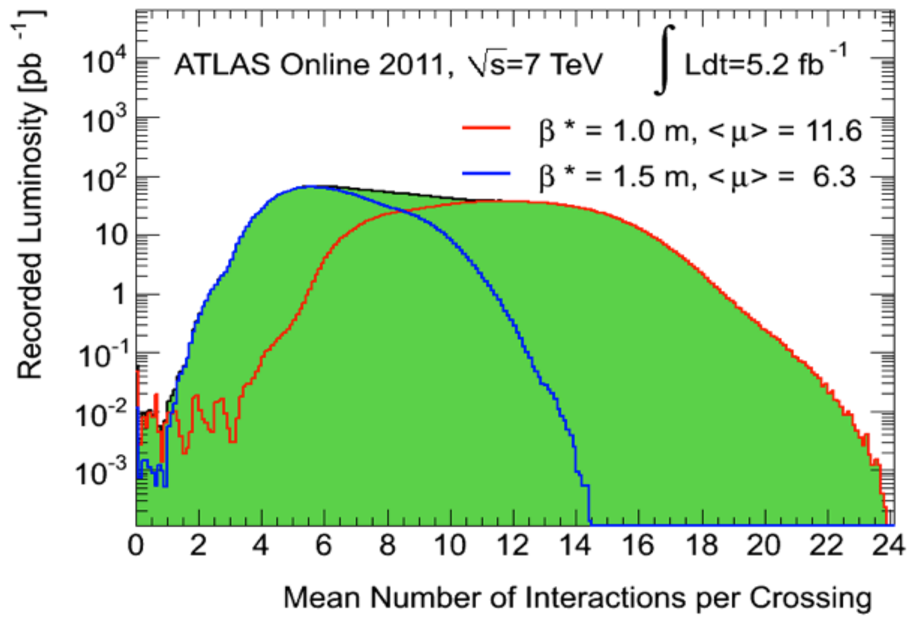
•Fake large E_T^{miss} sources

- •Noise in calorimeter
- •Beam gas, beam halo

Data Samples

•Perform searches on data samples with $\int L=4.7\ fb^{-1}$ at $\sqrt{s}=7$ TeV, collected in 2011





•Average number of interactions per p-p bunch crossing is ~10

Triggers to collect data samples :

• **WH(lνbb)** : single e/μ triggers (efficiency ~90-100%)

• **ZH(llbb)** : single or double e/μ triggers (efficiency ~95-100%)

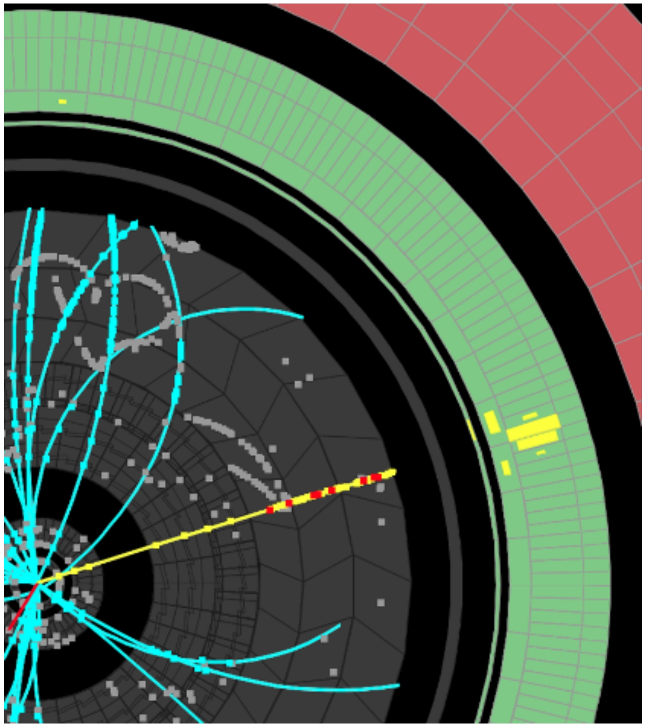
Efficiency measured w.r.t. offline selections

•**ZH(ννbb)** :

•CMS : E_T^{miss} and E_T^{miss}+jet triggers (efficiency ~98% at E_T^{miss}(offline)=160 GeV)

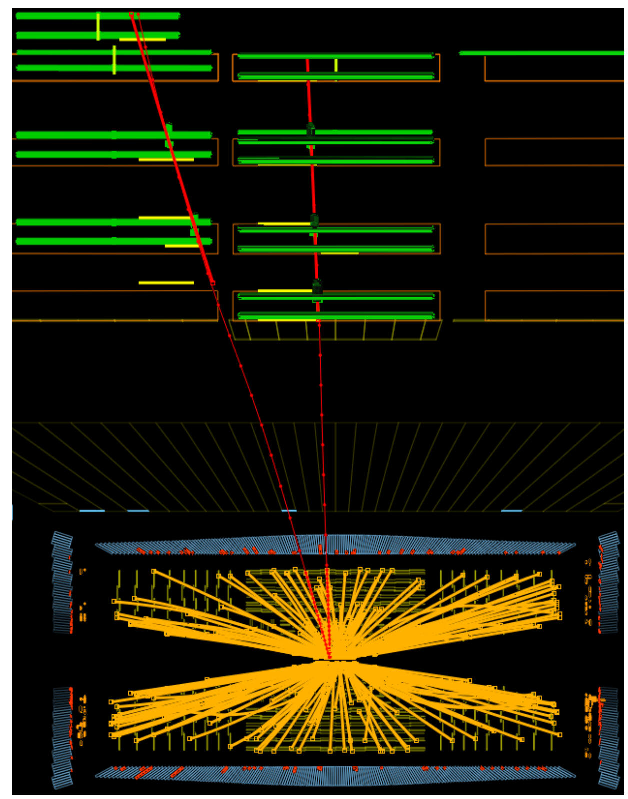
•ATLAS: E_T^{miss} trigger (efficiency ~50% at E_T^{miss}(offline)=120 GeV, 100% at E_T^{miss}(offline)=170 GeV)

Physics Objects Reconstruction



Electron

- Inner detector track from primary vertex matched to energy cluster in electromagnetic calorimeter
- $|\eta|<2.5$
- Pt>~20-30 GeV, isolated

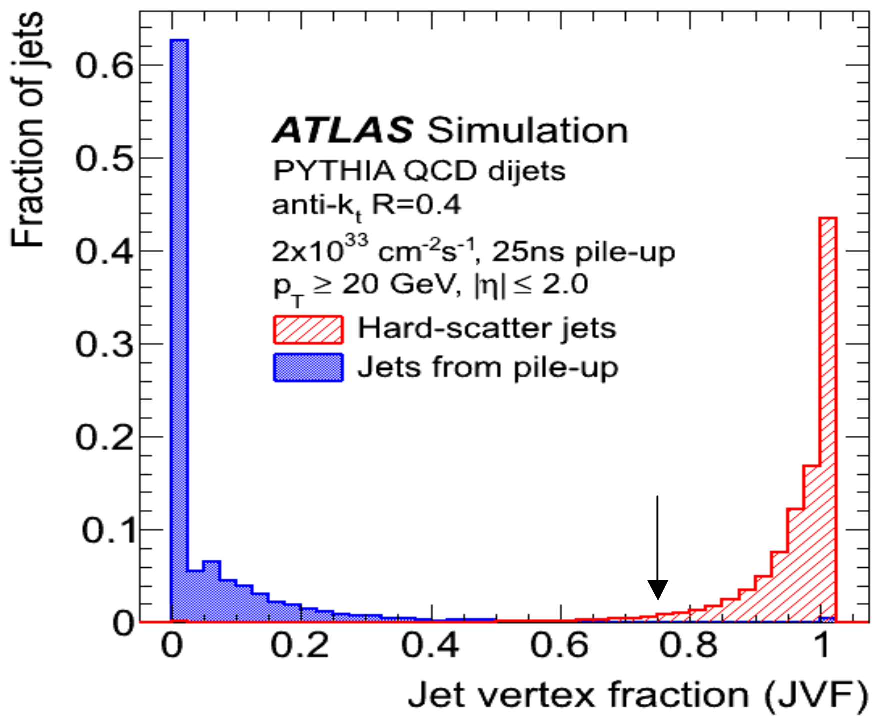


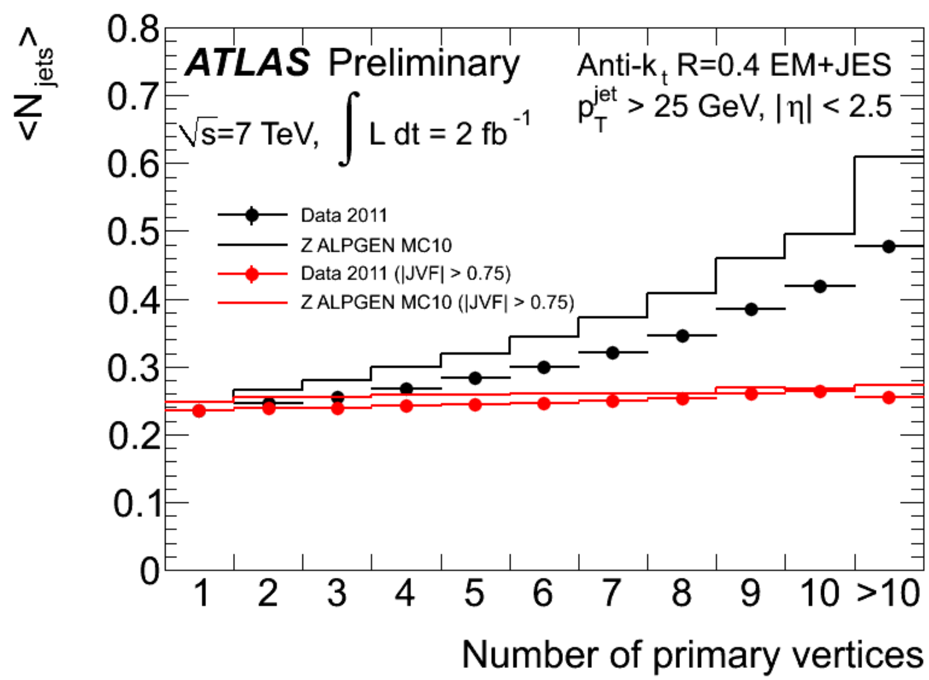
Muon

- Inner detector track from primary vertex matched to track in muon system
- $|\eta|<2.5$
- Pt>~20-25 GeV, isolated

Jets

- Reconstructed using anti-kt algorithm (cone size: 0.5 (CMS), 0.4 (ATLAS))
- Minimum Pt(jet)>~20-30 GeV, |η|<2.5
- Subtract extra energy from pile-up
- Remove extra jets coming from pile-up interactions (not from the main hard interaction)





JVF: fraction of momentum of tracks associated to the jet from main primary vertex

Missing Transverse Energy (E_T^{miss})

CMS

$\vec{E}_T^{miss}$: negative vector sum of transverse momentum of all particle flow objects in event

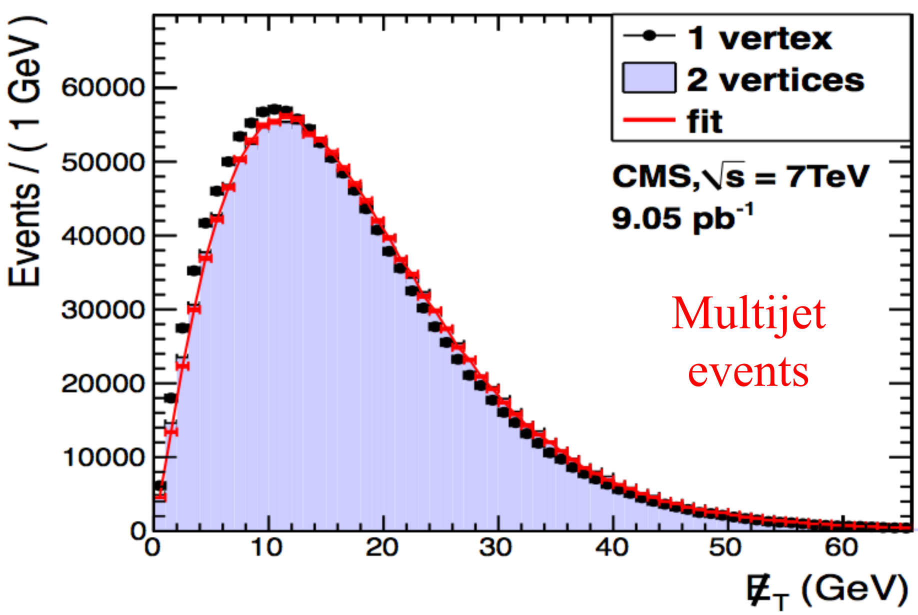
ATLAS

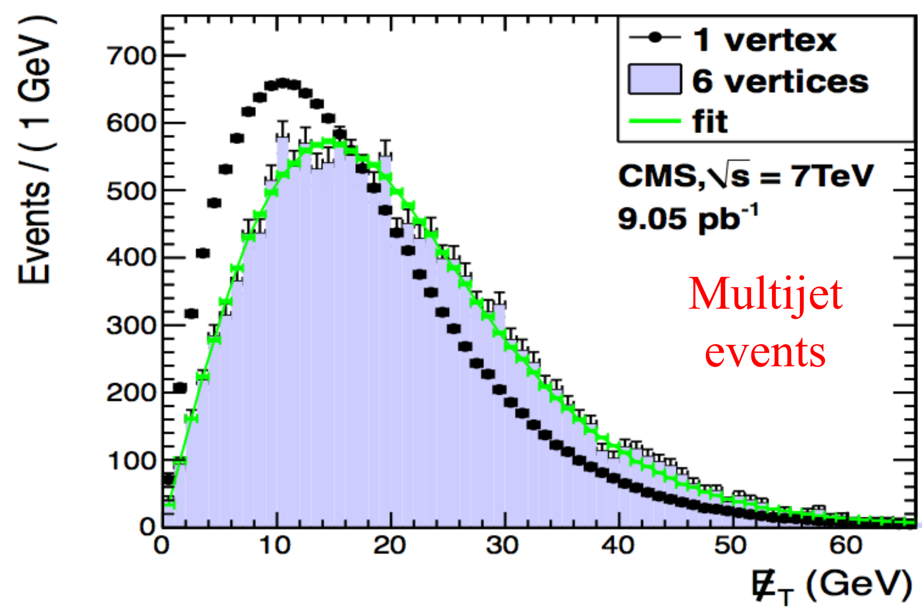
$\vec{E}_T^{miss}$: negative vector sum of cluster transverse energy in calorimeter.

- Correct cluster energy if associate to physics objects (e, μ, τ, γ)

Pile-up Effect:

- Additional interactions in bunch crossing can degrade E_T^{miss} resolution





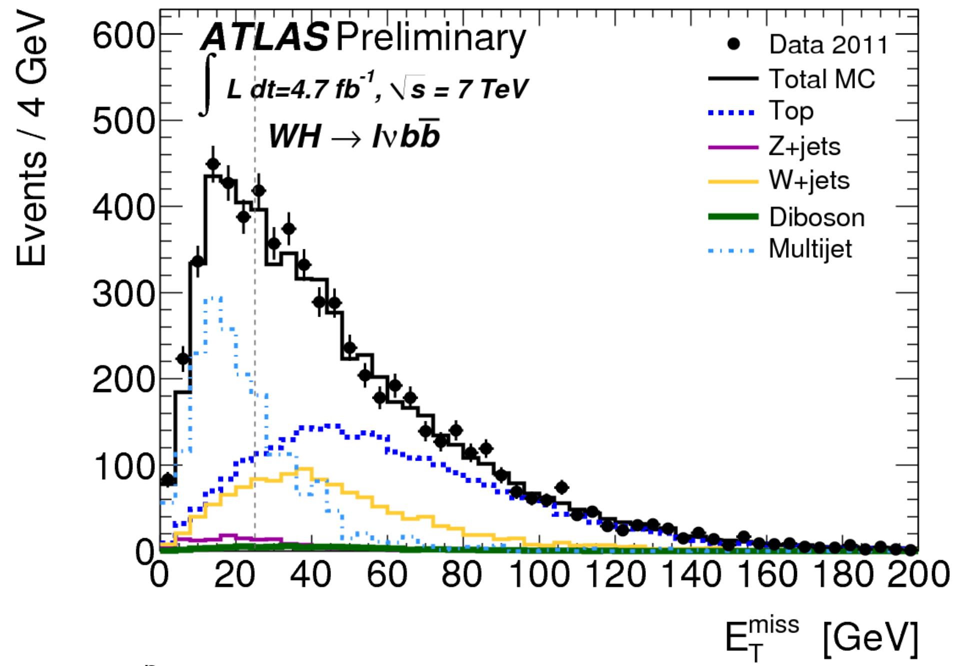
- E_t^{miss} (from high p_T multi-jet events) broaden with increase in multiple interactions
- Simulation needs right pile-up profile as seen in data

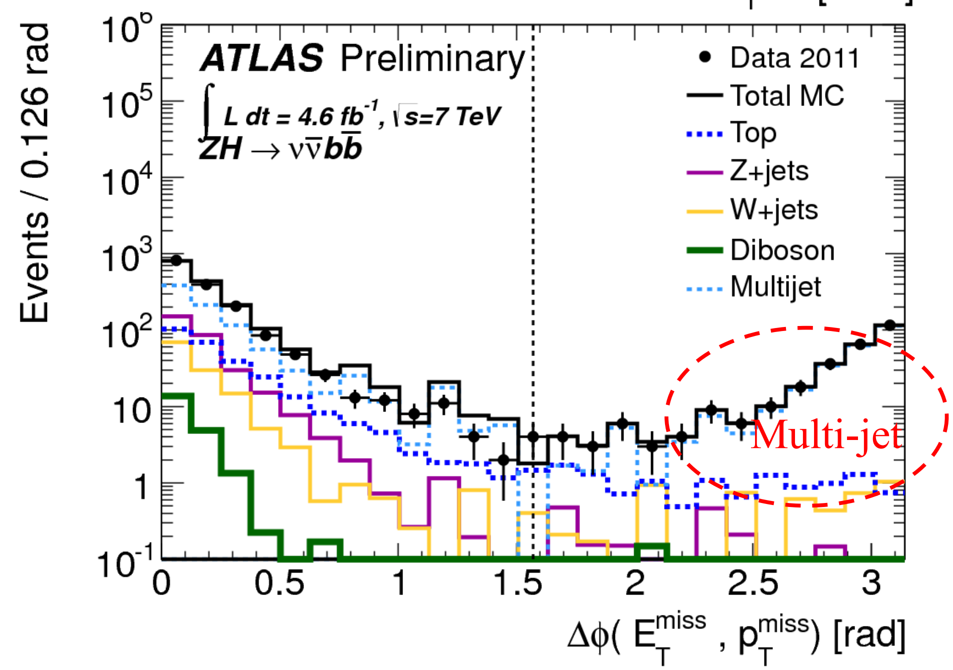
Missing Transverse Energy (E_T^{miss})

- Simulated events re-weighted to have pile-up profile matches data
- E_T^{miss} performance in simulation is under control for 2011 analyses

p_T^{miss} (ATLAS) :

- Alternative quantity to E_T^{miss}
  - Based on tracks
- $\vec{p}_T^{miss}$: negative vector sum p_T of tracks
- E_T^{miss} and p_T^{miss} point in same direction for events with real E_T^{miss}
  - Use correlation in directions of E_T^{miss} and p_T^{miss} to reduce multi-jet background
- Apply in ATLAS's ZH(ννbb) analysis to reduce QCD multi-jet background



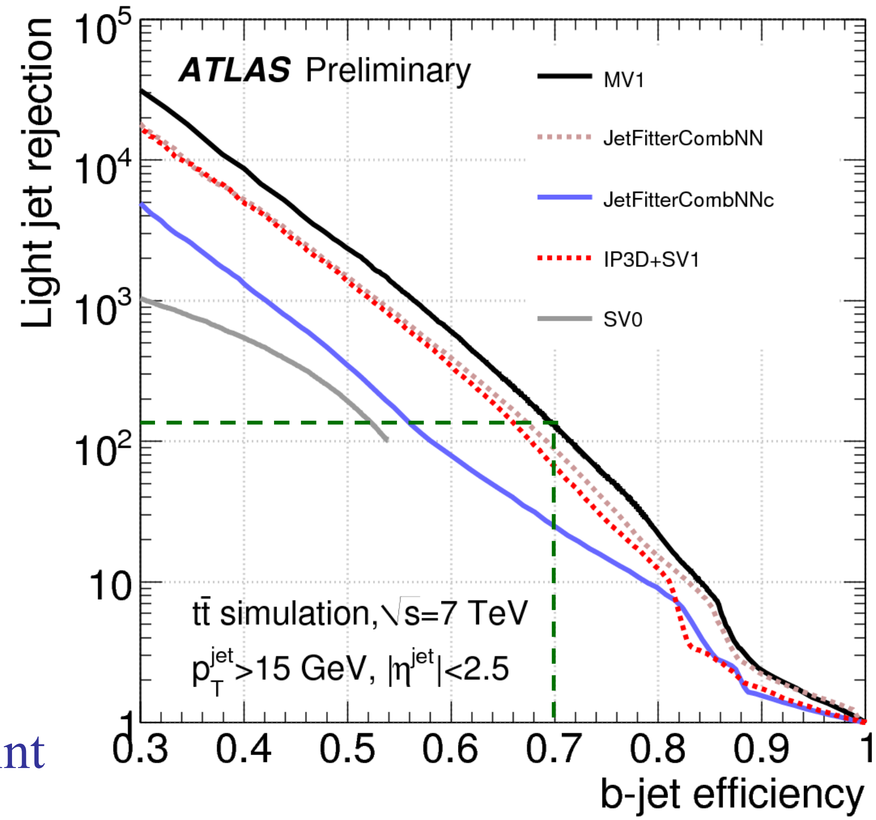


B-Jet Tagging

- b-jet : identified base on relatively long lifetime (cτ ~ 450 μm) of B hadron
- Construct single discriminant using information from track impact parameters and secondary vertices reconstructed in jet
  - to separate b-jet from light, c and gluon jets
- CMS :
  - apply b-tagging algorithm at several working points in Higgs search

	Eff(B) (%)	Reject C rate	Reject LF rate
"Loose" (CSV>0.244)	82	2.5	8.3
"Tight" (CSV>0.90)	50	17	670

- ATLAS :
  - apply b-tagging algorithm at 1 working point
  - Eff(B)=70%, reject C~5, reject LF~130



Event Selection

- CMS has two approaches :
  - "**BDT Analysis**"
    - Pre-select events with looser cuts and apply boosted-decision-tree (BDT) algorithm to further separate signal from background
    - Search for signal in the output of the BDT discriminant
  - "**Mjj Analysis**"
    - Apply tighter selection cuts and search for signal in the di-jet mass distribution (Mjj) of the $H \rightarrow bb$ candidates
- ATLAS employs the "**Mjj Analysis**" approach
- CMS performs search in 5 channels :
  - WH(eνbb), WH(μνbb), ZH(eebb), ZH(μμbb) and ZH(ννbb)
- ATLAS performs search in 3 channels :
  - WH(e/μνbb), ZH(ee/μμbb) and ZH(ννbb)

Event Selection (CMS)

channel	WH(lνbb)	ZH(llbb)	ZH(ννbb)
lepton	e or μ	e^+e^- or $\mu^+\mu^-$	0
Invariant mass (GeV)	-	$75<M(l^+l^-)<105$	-
E_T^{miss} (GeV)	>35 (only for electron)	-	>160
NJet	≥2 [=2]	≥2 [2-3]	≥2 [=2]
p_T(JJ) (GeV)	>150 [>160]	>100	>160
p_T(V) (GeV)	>150 [>160]	>100	-
Δφ(V,H) (rad)	- [>2.95]	- [>2.90]	- [>2.90]
B-tagging	medium,medium [tight,medium]	loose,loose [tight,medium]	medium,medium [tight,medium]
Δφ(E_T^{miss},Jet) (rad)	-	-	>0.5 [>1.5]

- "[ ]" : tighter thresholds use for "Mjj" analysis
- Events pass loose selection are used for "BDT" analysis
- Requiring significant boost in V and H (high pT(V) and p_T(JJ)) help to reduce background from W/Z+Jets

Event Selection (ATLAS)

channel	WH(lνbb)	ZH(llbb)	ZH(ννbb)
lepton	e or μ	ee or $\mu^+\mu^-$	0
Transverse or Invariant mass (GeV)	M_T>40	83<$M(l^+l^-)$<99	-
E_T^{miss} (GeV)	>25	<50	>120
p_T^{miss} (GeV)	-	-	>30
NJet	=2	≥2	=2
B-tagging	Exactly 2 b-tagged jets (@ Eff(b)=70%)		

- Addition cuts for ZH(ννbb) channel to suppress QCD multi-jet and W/Z+Jets
  - $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$ rad
  - ΔR(Jet1, Jet2) < 1.7 - 2.0
  - Δϕ(V,H) > 2.7-2.9 rad
  - $\Delta\phi(E_T^{miss}$, Jet) > 1.8 rad

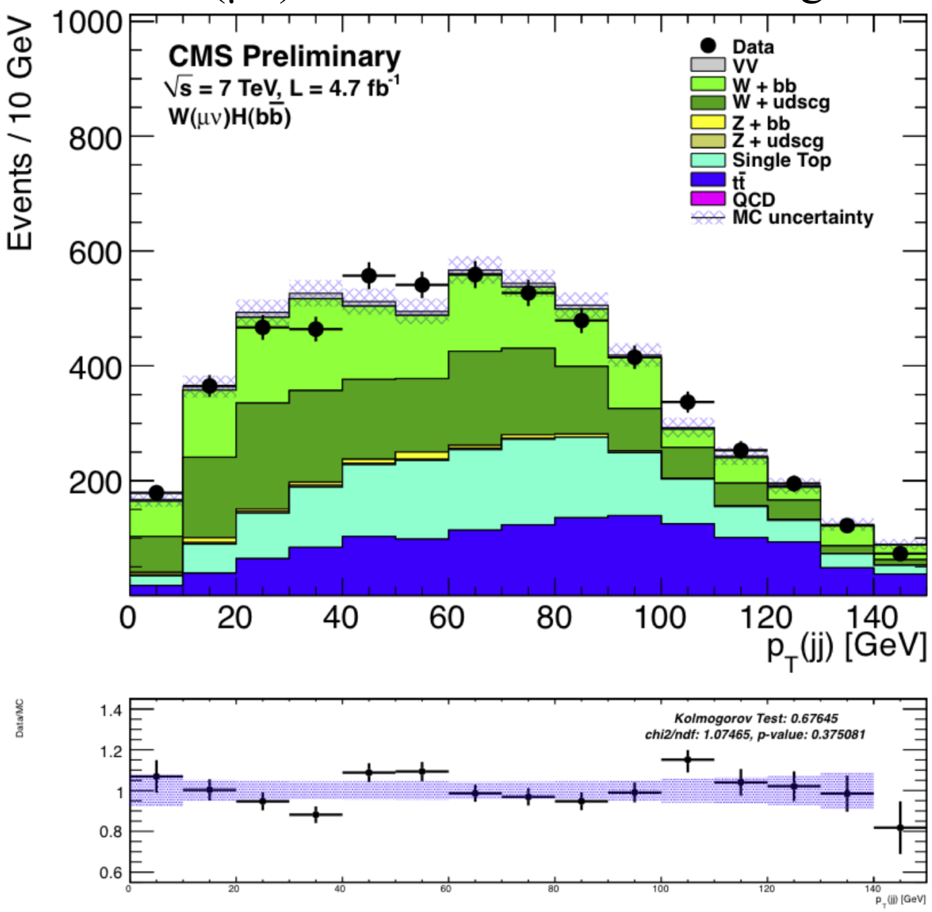
Event Selection (ATLAS)

- Search for H signal in 4 $p_T(V)$ bins and 3 E_T^{miss} bins :
- WH(lνbb), ZH(llbb) :
  - $p_T(V)$: <50 GeV, 50-100 GeV, 100-200 GeV, >200 GeV
- ZH(ννbb) :
  - E_T^{miss} : 120-160 GeV, 160-200 GeV, >200 GeV

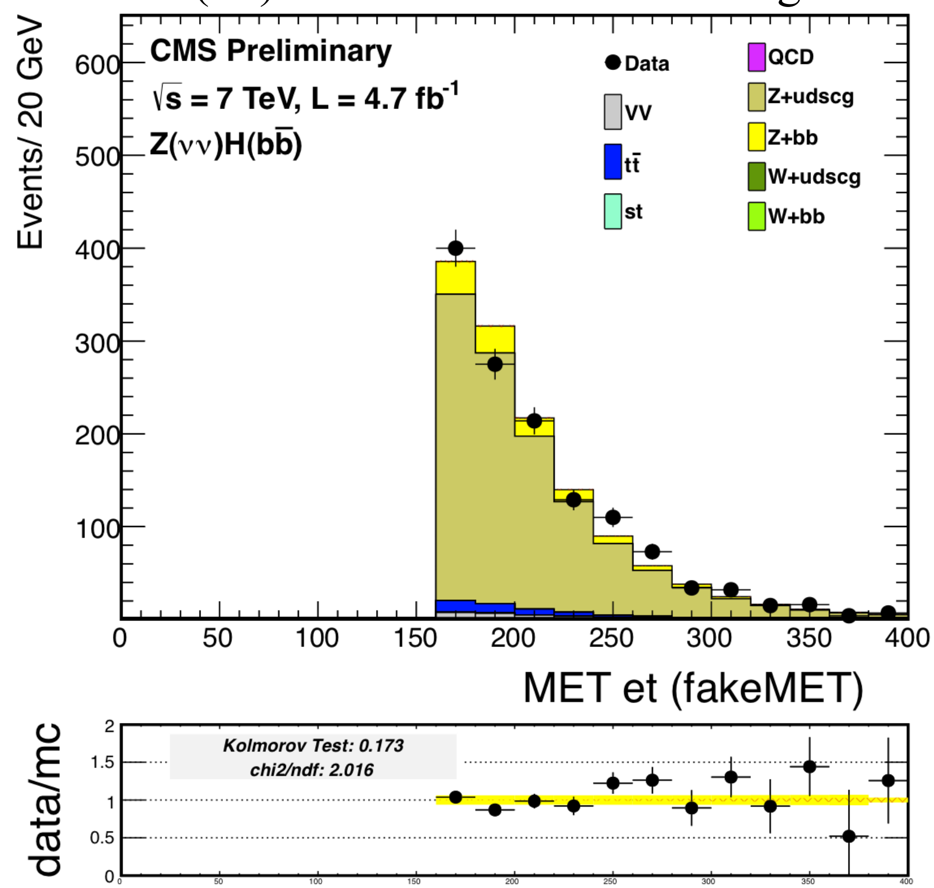
Background Estimation

- W+Jet, Z+Jet, Top, Diboson background contributions are estimated from simulation
- Corrections to background normalization are obtained from control regions with negligible signal contamination

W(μν)+HF enhanced Control Region



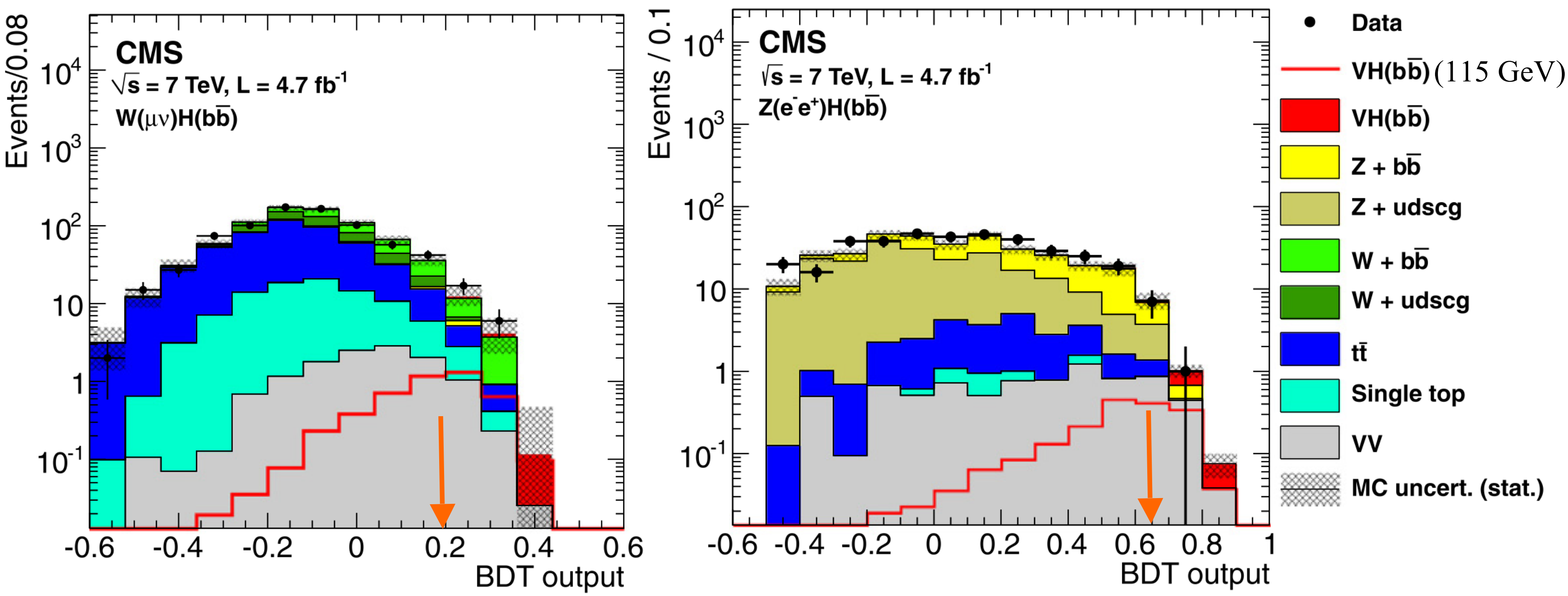
Z(νν)+LF enhanced Control Region



Multi-jet Background Estimation

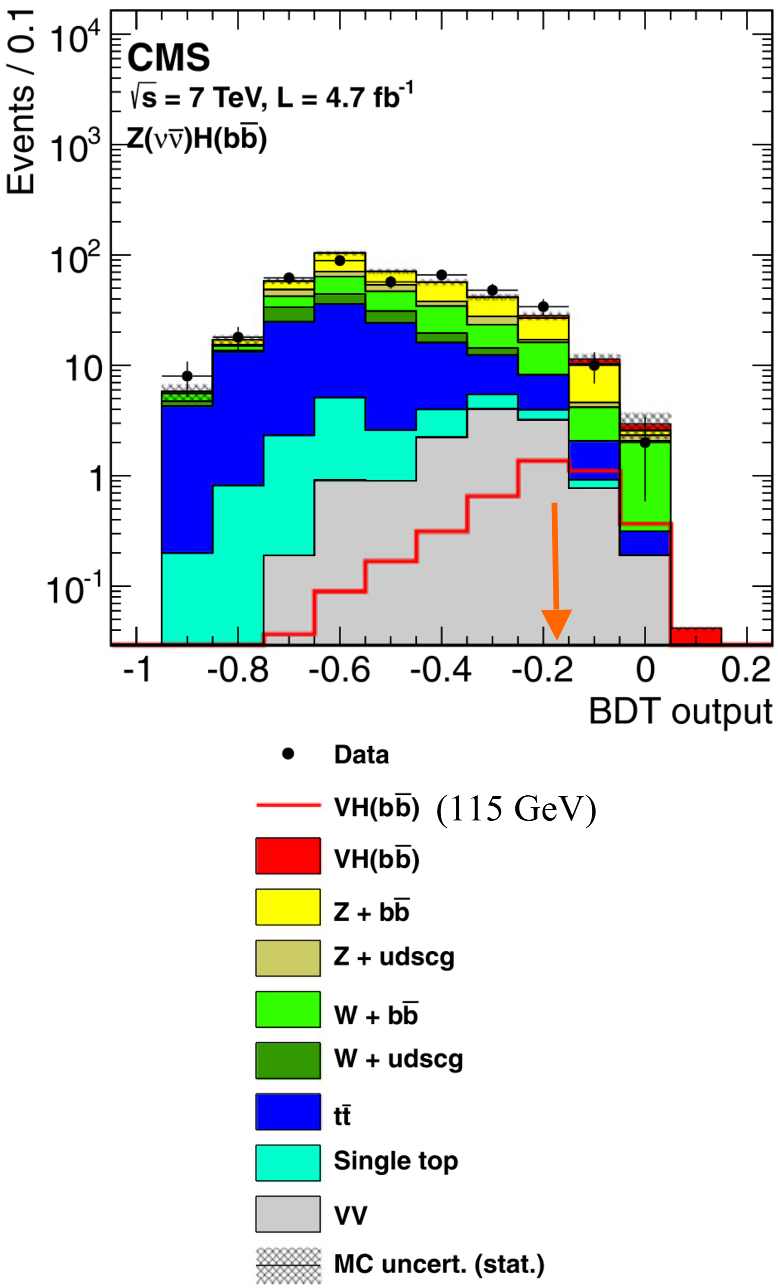
- QCD multi-jet background is estimated from data
- WH(lνbb) (ATLAS)
  - Obtain multi-jet template shape in events failing lepton identification
  - Determine normalization by fitting template to E_T^{miss} distribution of signal region (but loosening the E_T^{miss} and M_T cuts)
- ZH(ννbb) (CMS, ATLAS)
  - Use control regions defined by two un-correlated variables to estimate multi-jet background in signal region
    - CMS : sum of b-tagging discriminating weights vs $\Delta\phi(E_T^{miss}, \mathrm{Jet})$
    - ATLAS : $\Delta\phi(E_T^{miss}, p_T^{miss})$ vs $\Delta\phi(E_T^{miss}, \mathrm{Jet})$
  - Both CMS and ATLAS estimated negligible QCD multi-jet background in signal region of ZH(ννbb), not included in the limit calculation.

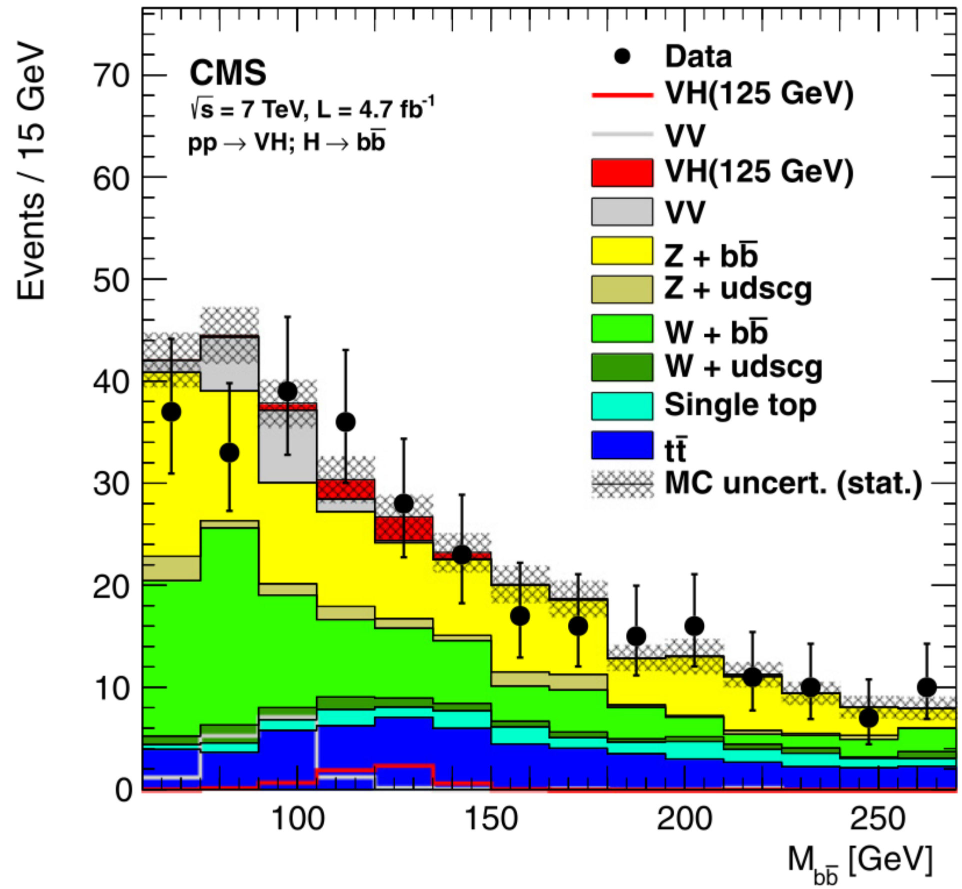
BDT Discriminant Output (CMS)



•Cut on BDT distribution to define signal region to search for Higgs signal

BDT Discriminant Output and Di-Jet Mass (CMS)

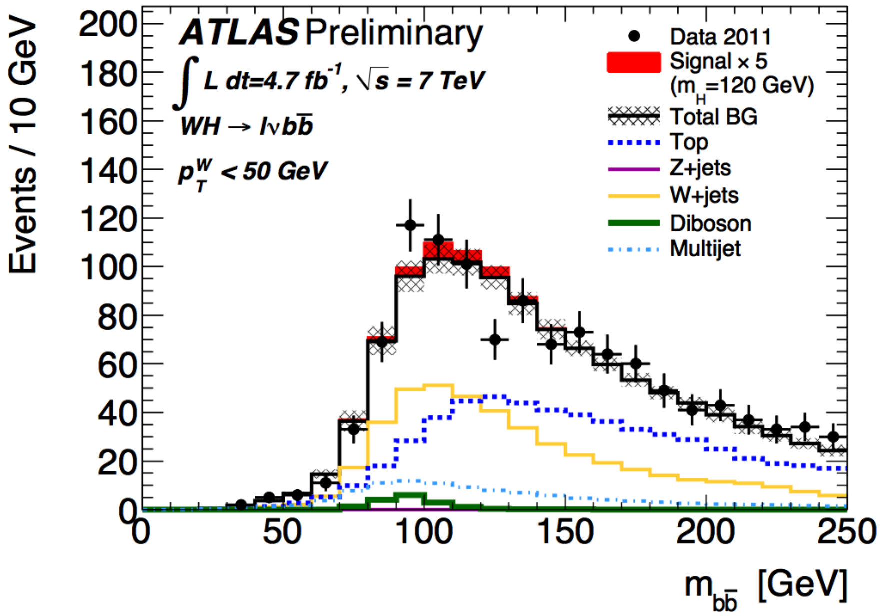




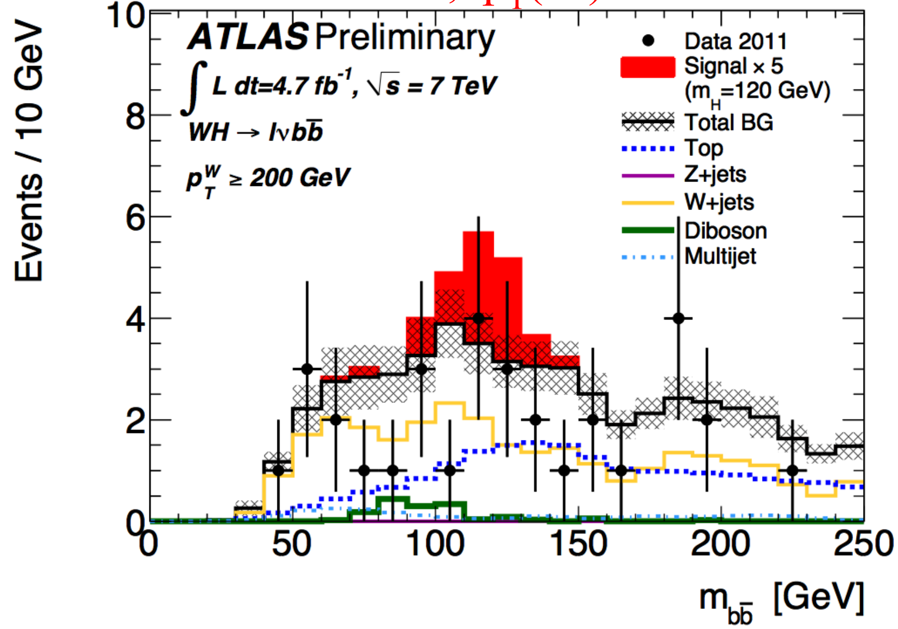
M_{bb} distribution for “MJJ” analysis

M_{bb} Distribution (ATLAS)

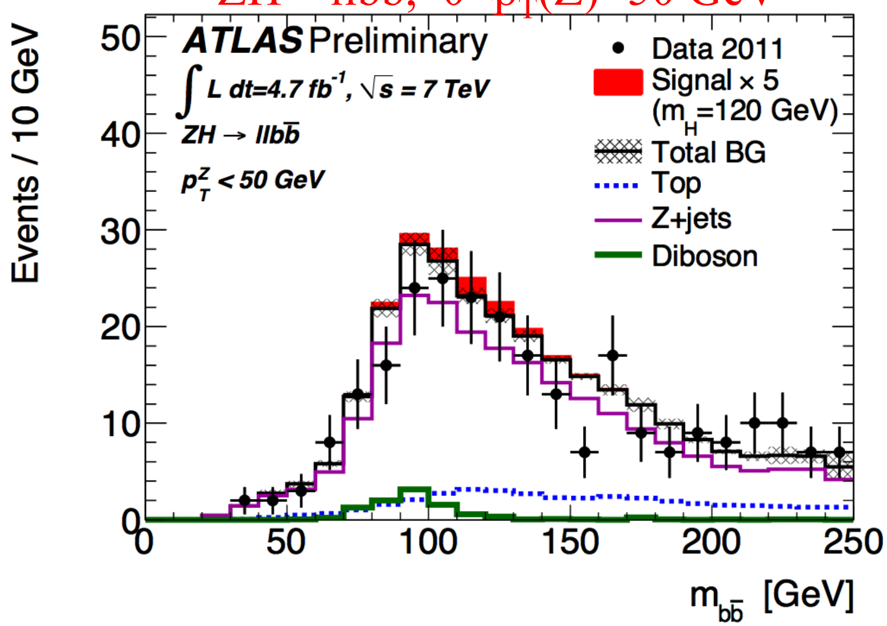
WH→lνbb, $0<p_T(W)<50$ GeV



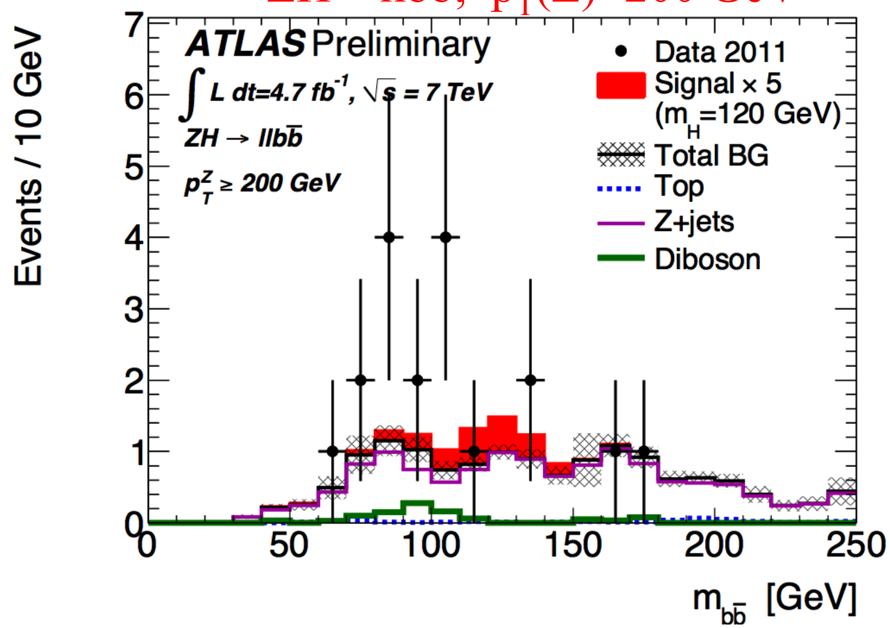
WH→lνbb, $p_T(W)>200$ GeV



ZH→llbb, $0<p_T(Z)<50$ GeV

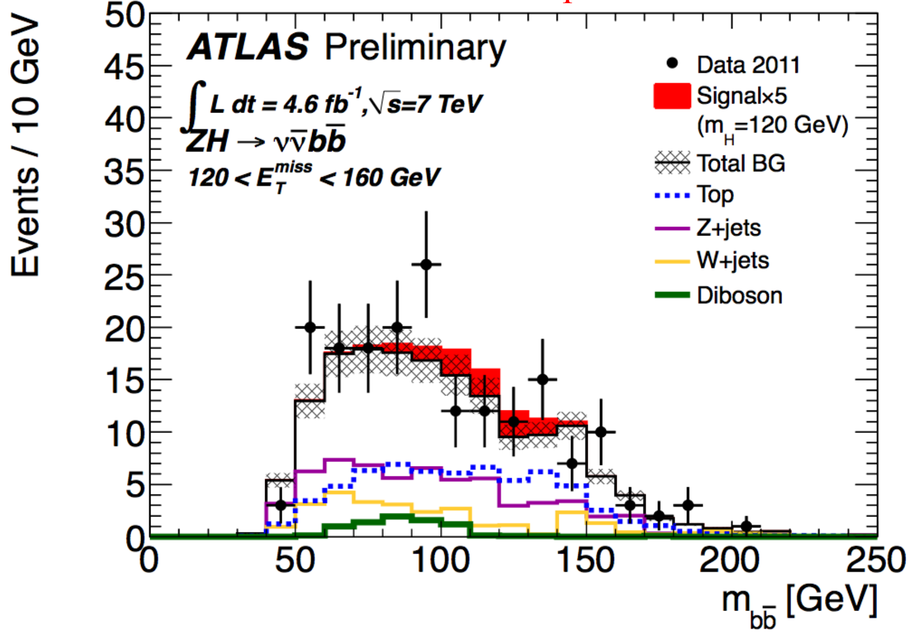


ZH→llbb, $p_T(Z)>200$ GeV

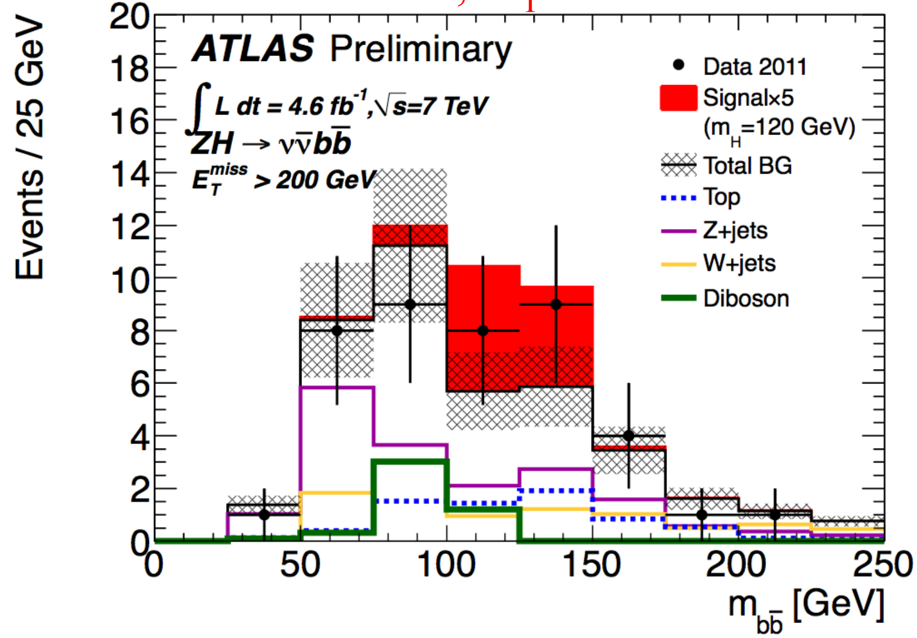


M_{bb} Distribution (ATLAS)

ZH→ννbb, $120<E_T^{miss}<160$ GeV



ZH→ννbb, $E_T^{miss}>200$ GeV



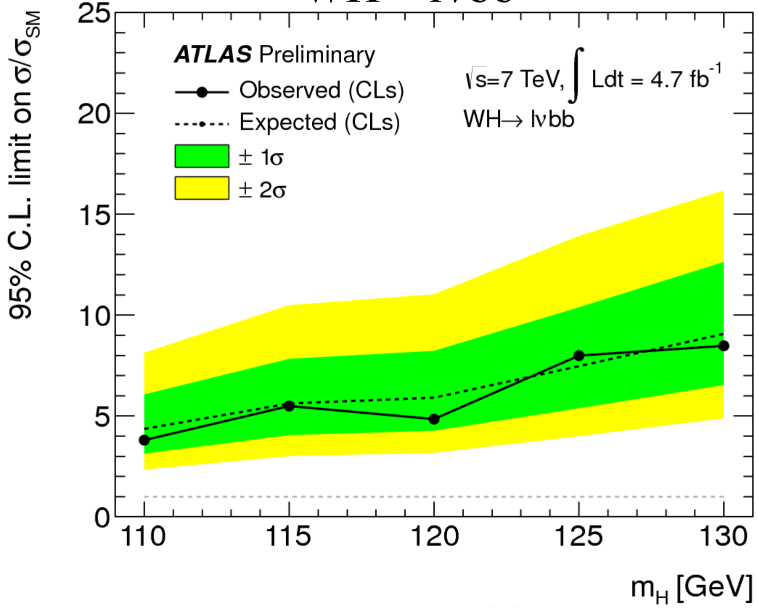
- **Better sensitivity at higher p_T^W , p_T^Z , E_T^{miss}**

Systematic Uncertainties

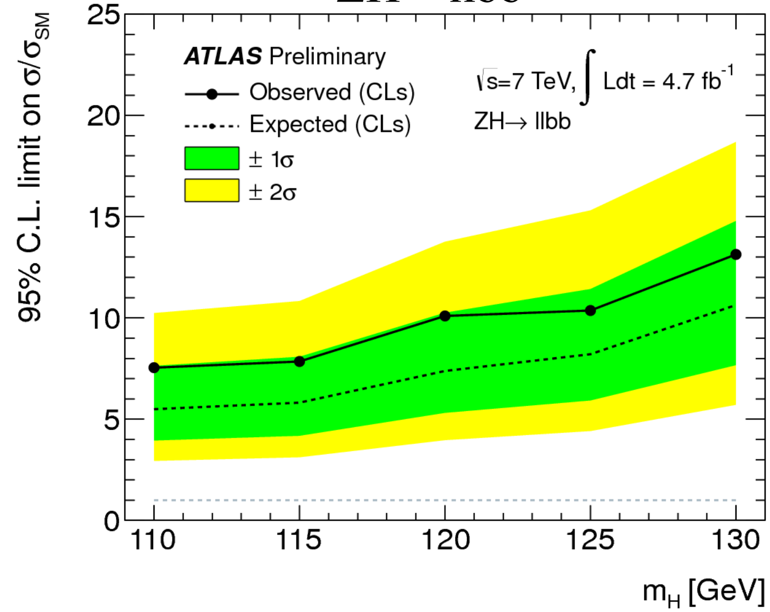
<table>
<tr><th></th><th>CMS (%)</th><th>ATLAS (%)</th></tr>
<tr><td>Luminosity</td><td>4.5</td><td>3.9</td></tr>
<tr><td>Lepton Efficiency</td><td>3 (include trigger, per lepton)</td><td>1-6</td></tr>
<tr><td>Trigger (ZH(ννbb))</td><td>2</td><td>5 ($120 < E_T^{miss} < 160$ GeV)</td></tr>
<tr><td>Jet Energy Scale</td><td>2-3</td><td rowspan="3">~2-17</td></tr>
<tr><td>Jet Energy Resolution</td><td>3-6</td></tr>
<tr><td>E_T^{miss}</td><td>3</td></tr>
<tr><td>B-Tagging</td><td>3-15</td><td>3-20</td></tr>
<tr><td>Signal cross section</td><td>6-14</td><td>5-13</td></tr>
<tr><td>Background estimation</td><td>10-35</td><td>3-24</td></tr>
</table>

Limits from Individual Channel (ATLAS)

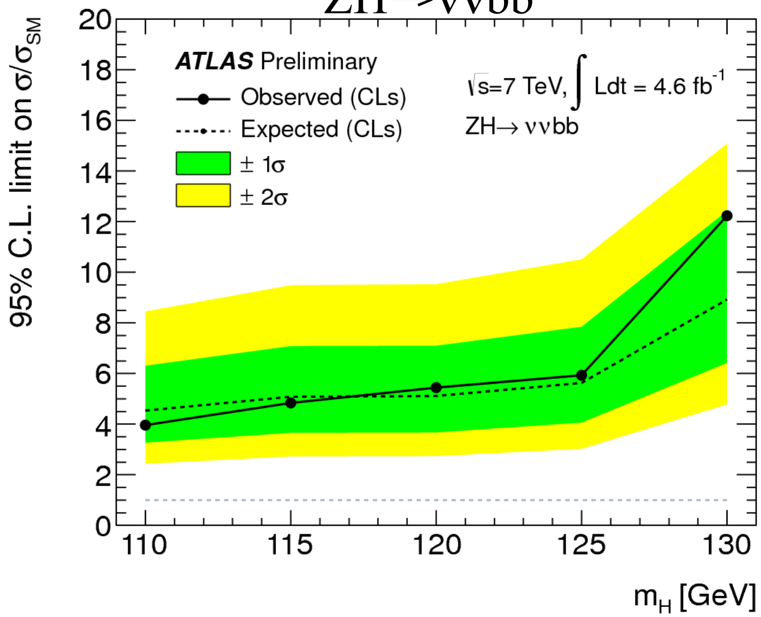
WH→lνbb



ZH→llbb

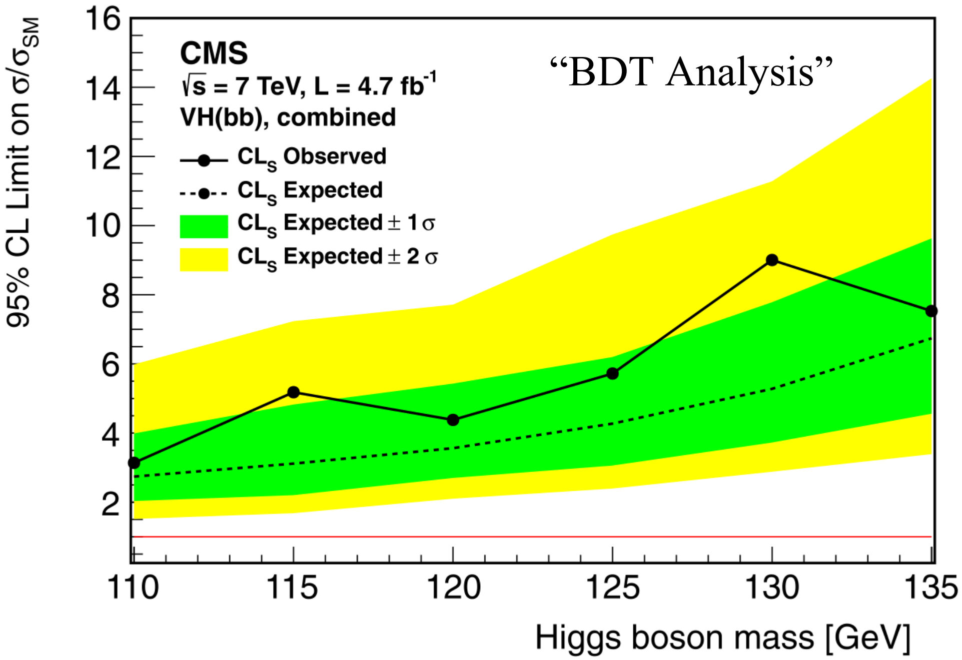


ZH→ννbb

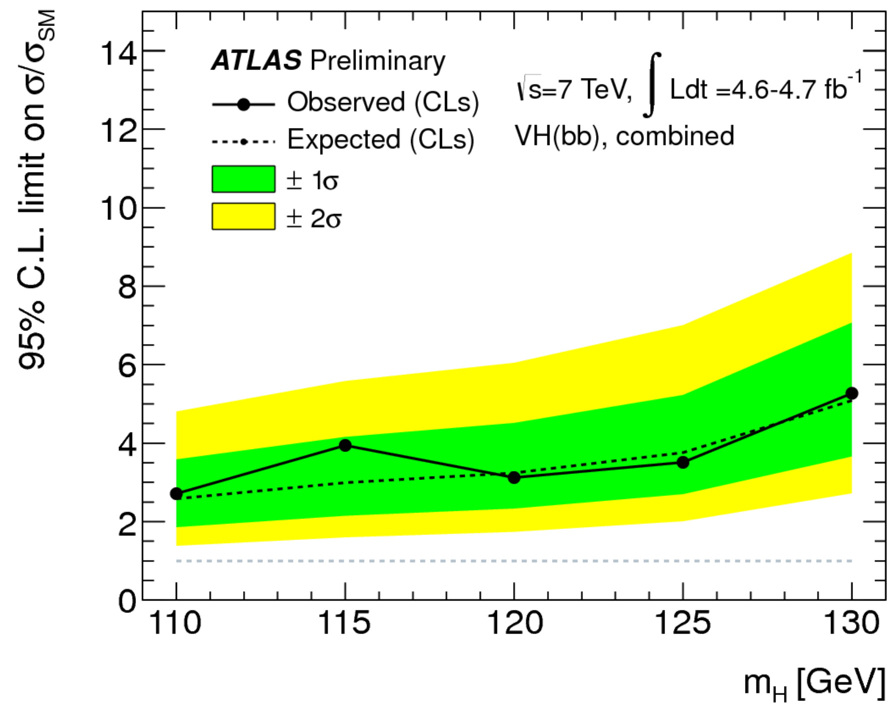


Combined Limits from All Channels (CMS, ATLAS)

CMS



ATLAS



Limits (σ/σ_{SM})

	m_H [GeV]	110	115	120	125	130	135
CMS	BDT Exp.	2.7	3.1	3.6	4.3	5.3	6.7
	BDT Obs.	3.1	5.2	4.4	5.7	9.0	7.5
ATLAS	Exp.	2.6	3.0	3.2	3.8	5.1	
	Obs.	2.7	3.9	3.1	3.5	5.3	

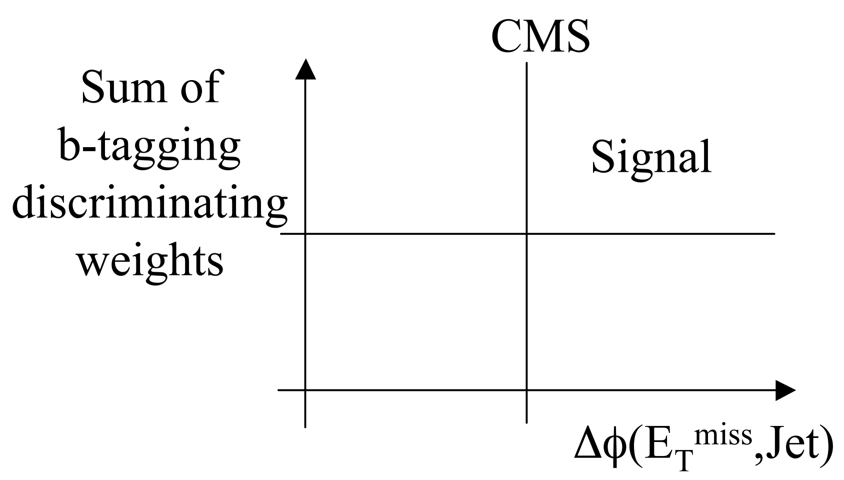
•CMS "MJJ analysis" is ~10% less sensitive than the "BDT analysis"

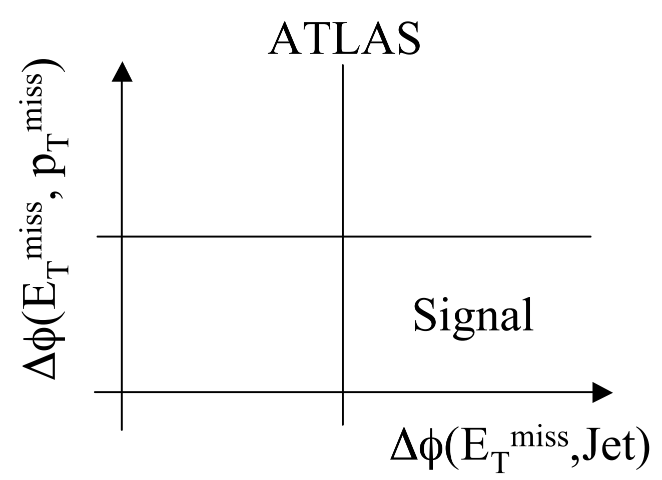
Summary

- CMS and ATLAS have searched for SM Higgs boson in the associated VH production via H→bb decay channel, using 5 fb^{-1} data sample
- No evidence of Higgs signal is observed
- Both experiments have similar search sensitivity for $110<M_H<130$ GeV
  - Expected limit :
    - CMS : 2.7 - 5.3 times the SM
    - ATLAS : 2.6 - 5.1 times the SM
  - Observed limit :
    - CMS : 3.1 - 9 times the SM
    - ATLAS : 2.7 - 5.3 times the SM
- Main systematic uncertainties are dominated by jet/E_T^{miss} reconstruction, b-tagging and background estimation
- Started taking data in 2012 at $\sqrt{s}$=8TeV, face new challenges (e.g. higher pile-up)
- If the Higgs boson is indeed light , H→bb will be an important channel to estimate the Higgs parameters

Multi-jet Background Estimation

- QCD multi-jet background is estimated from data
- WH(lνbb) (ATLAS)
  - Obtain multi-jet template shape in events failing lepton identification
  - Determine normalization by fitting template to E_T^{miss} distribution of signal region (but loosening the E_T^{miss} and M_T cuts)
- ZH(ννbb) (CMS, ATLAS)
  - Use control regions defined by two un-correlated variables to estimate multi-jet backgound in signal region





- Both CMS and ATLAS estimated negligible QCD multi-jet background in signal region of ZH(ννbb), not included in the limit calculation.