Searches for the Higgs boson decaying into fermion pairs with the ATLAS detector

David Jamin
ACADEMIA SINICA.
On behalf of the ATLAS collaboration

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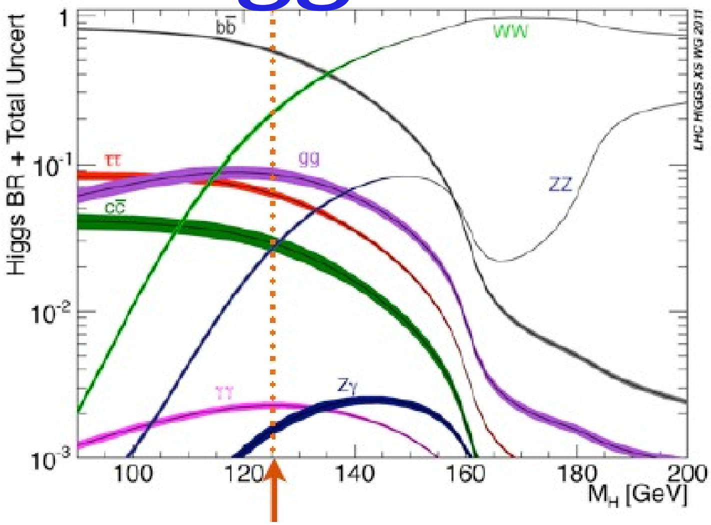
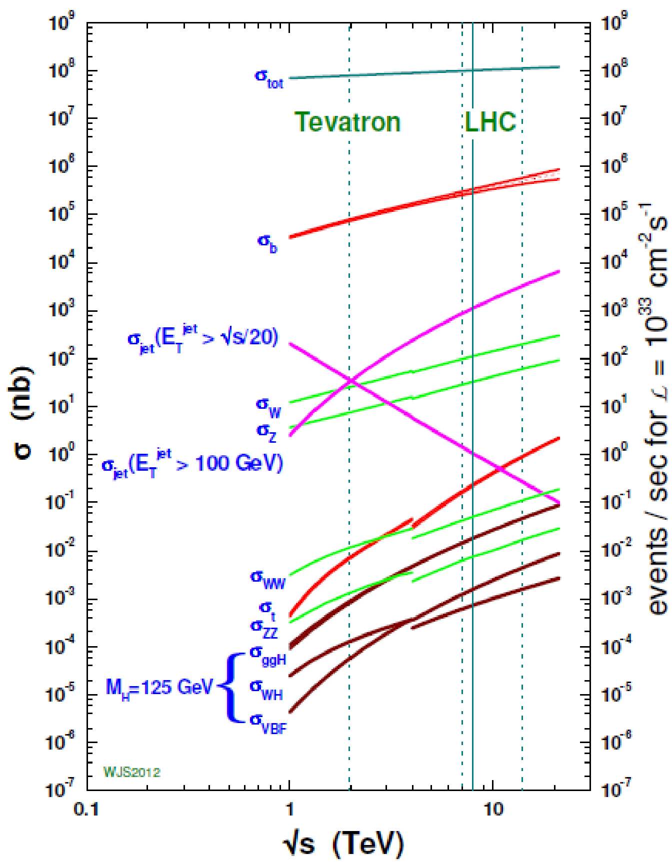
Higgs boson decays and production



proton - (anti)proton cross sections

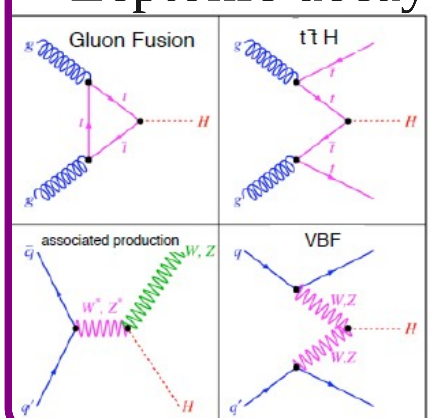


DECAYS :

- For a Higgs boson mass of 125 GeV considerable contributions from decays to fermions are expected :
  $BR(H \to bb) = (57.7 \pm 1.9)\%$
  $BR(H \to \tau\tau) = (6.3 \pm 0.4)\%$
  $BR(H \to \mu\mu) = (0.022 \pm 0.001)\%$
- Fermionic decays are important to probe SM Higgs boson hypothesis

PRODUCTION :

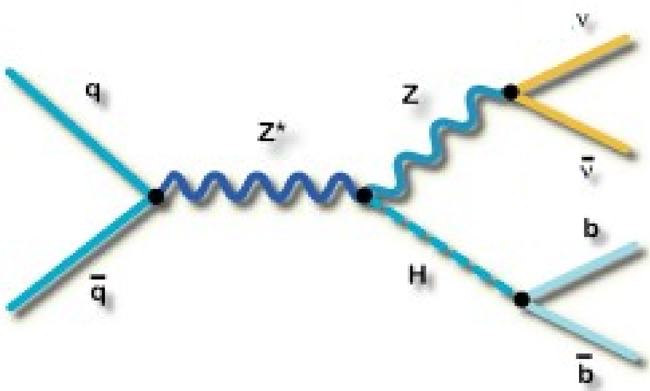
- Gluon fusion is the most important process of Higgs production.
- Because of huge multi-jet background, it cannot be used for quark decays.
- Leptonic decays can benefit of gluon fusion.

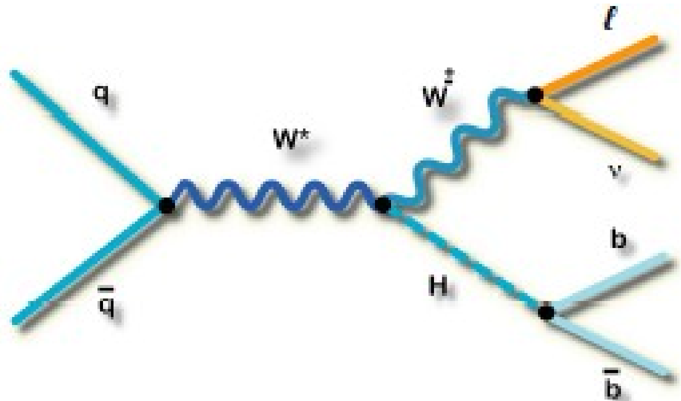


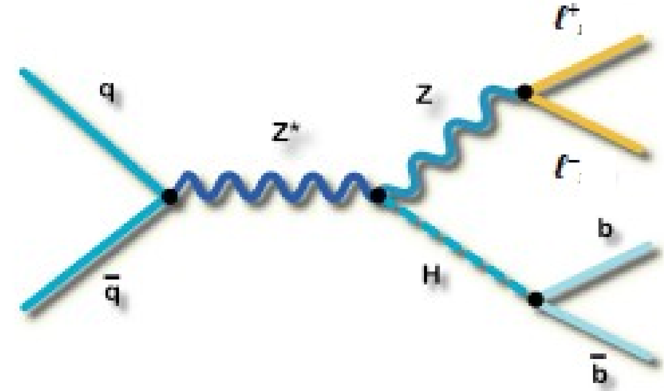
CHANNELS COVERED :

VH, $H \to bb$ (V = W or Z)
ttH, $H \to bb$
$H \to \tau^+\tau^-$
$H \to \mu^+\mu^-$

VH, H → bb selection



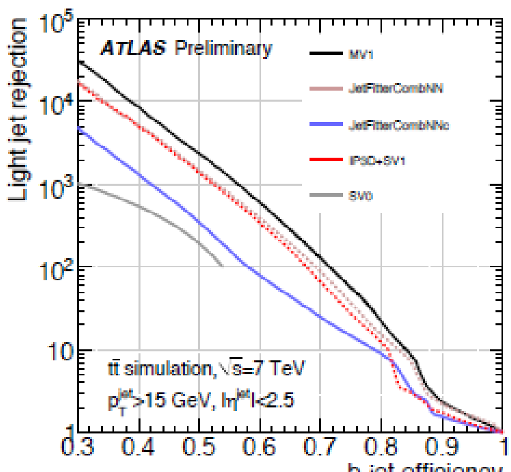




0-lepton
- no electrons or muons
- $E_T^{miss} > 120$ GeV

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

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



+ 2 or 3 jets with 2 b-tagged jets
- NN using information from :

→ secondary vertex,

→ tracks impact parameter.

- Performance :

→ 70% b-jet efficiency,

→ ~1% light-jet mis-identification.

ATLAS-CONF-2012-097
ATLAS-CONF-2012-043
ATLAS-CONF-2012-040
ATLAS-CONF-2011-102

VH, H→bb strategy

- Signal region splitted in p_T^V bins to increase sensitivity :

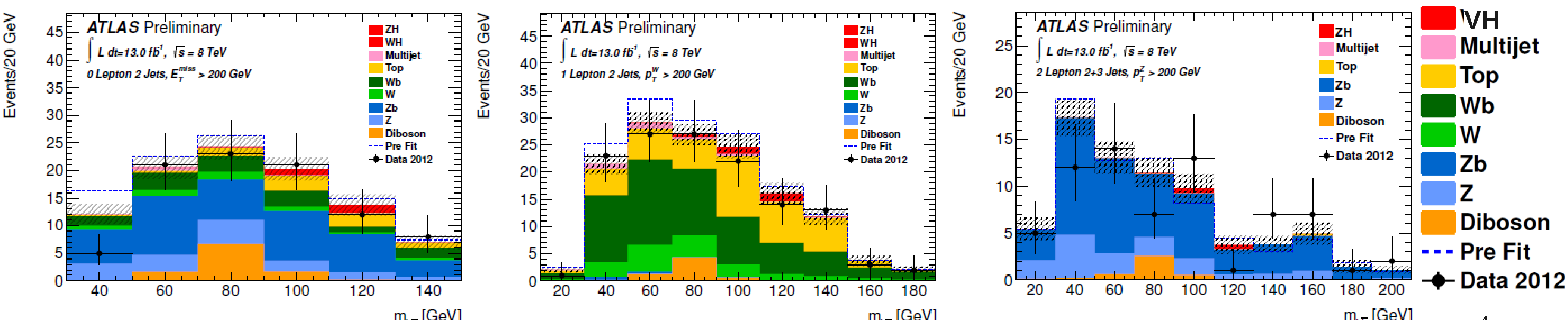
channel	bins (GeV)				
0-lepton (2/3 jets)			120-160	160-200	>200
1-lepton (2 jets)	0-50	50-100	100-150	150-200	>200
2-leptons (2 jets)	0-50	50-100	100-150	150-200	>200

- Data-driven multi-jet background.
- Different control regions to check / normalize simulated EW backgrounds :

→ top CR : adding extra jet (1-lepton) / reversing m_Z and E_T^{miss} cuts (2-leptons),

→ V+jets CR : define 0 and 1 b-tagged jet samples.

- Final discriminant : 2 b-tagged jets invariant mass m_{bb}

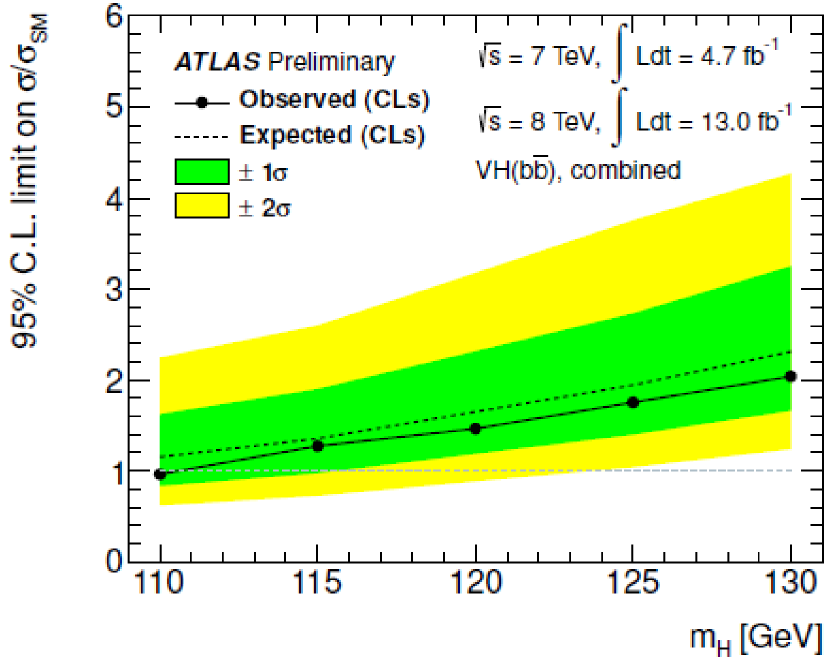


0-lepton Z+jets W+jets top

1-lepton W+jets top

2-leptons Z+jets

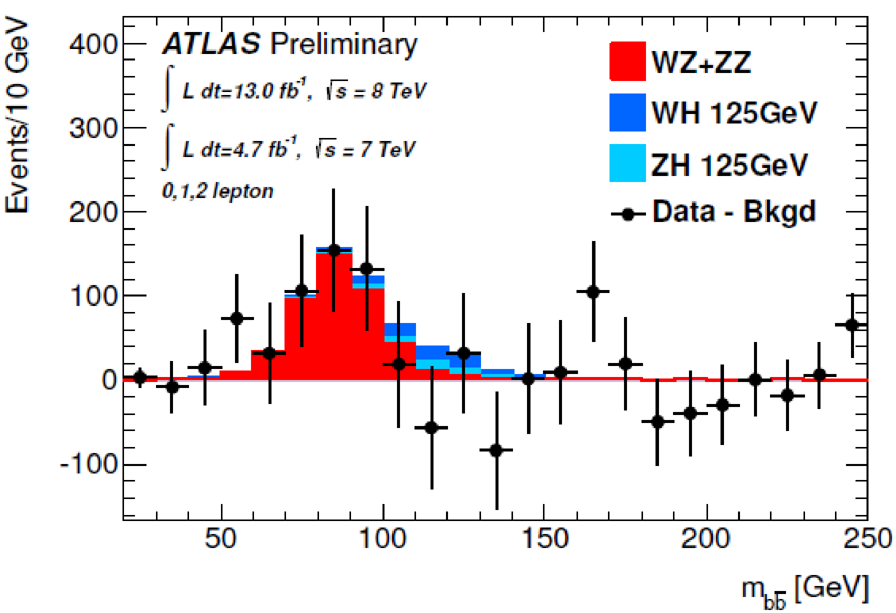
VH, H→bb limit and cross-check



- Main systematics :
  - b/c jet tagging efficiencies
  - jet energy scale and resolution
  - MC statistics

→ constrained by fitting m_{bb} to data

95% CL on SM Higgs for m_H = 125 GeV obs (exp) 1.8 (1.9)



- Cross-check analysis by searching VZ diboson

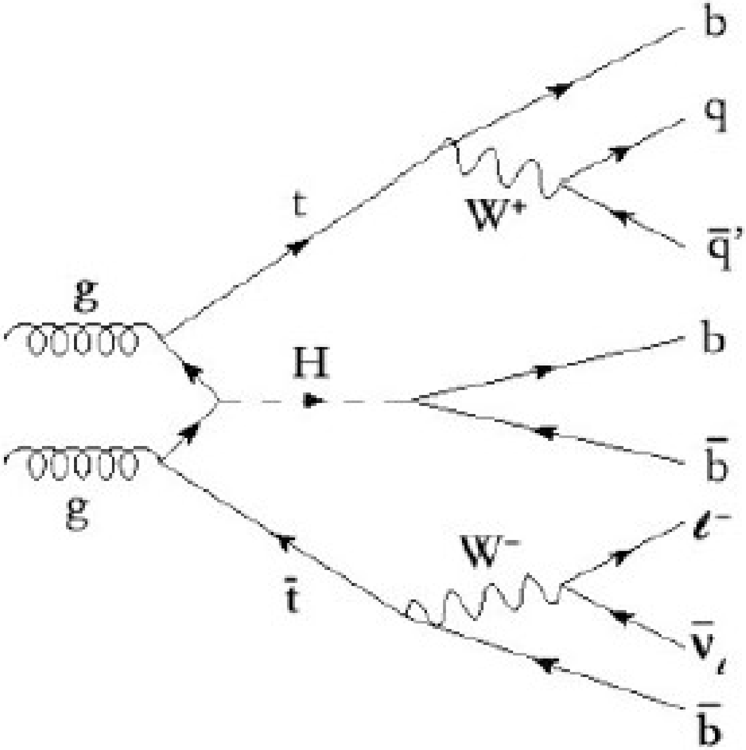
→ keep VH and VZ as signals

→ data-MC subtracted

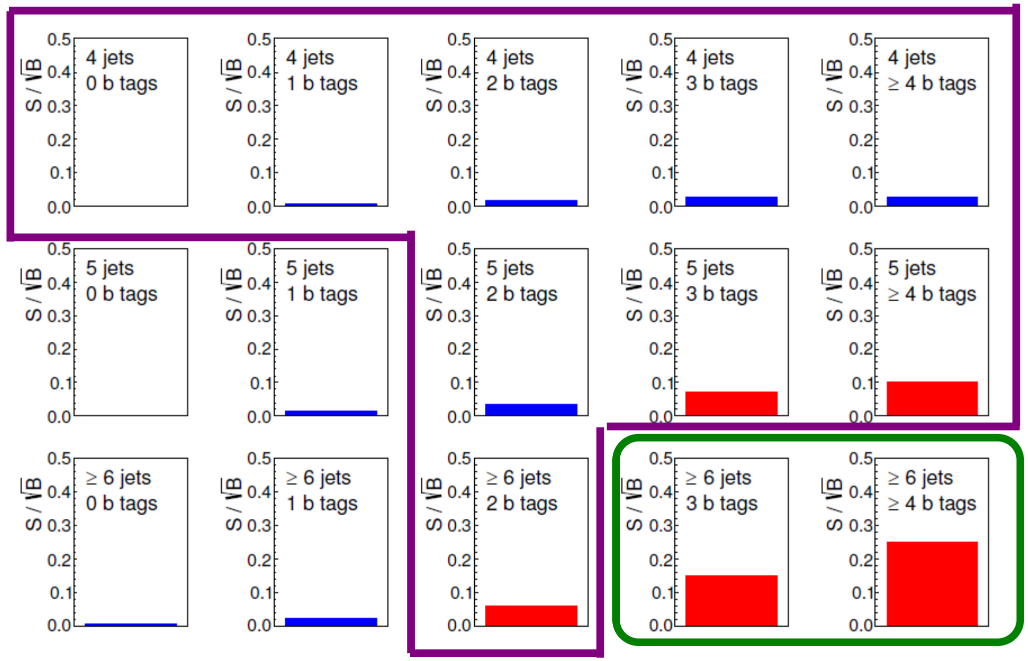
$\sigma/\sigma_{SM} = \mu_D = 1.09 \pm 0.20$ (stat) ± 0.22 (syst)

Significance of **4.0σ**

ttH, H→bb selection and strategy



- Exactly 1 e or μ.
- At least 4 jets.
- E_t^{miss} and m_T cut to reduce multi-jet background.
- **Control** and **signal** regions :

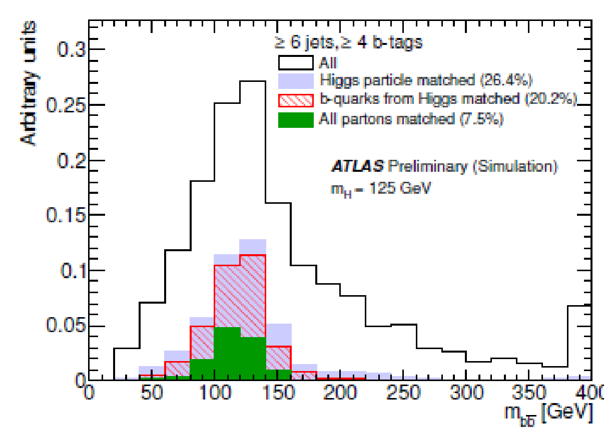


Final discriminant :

→ H_T

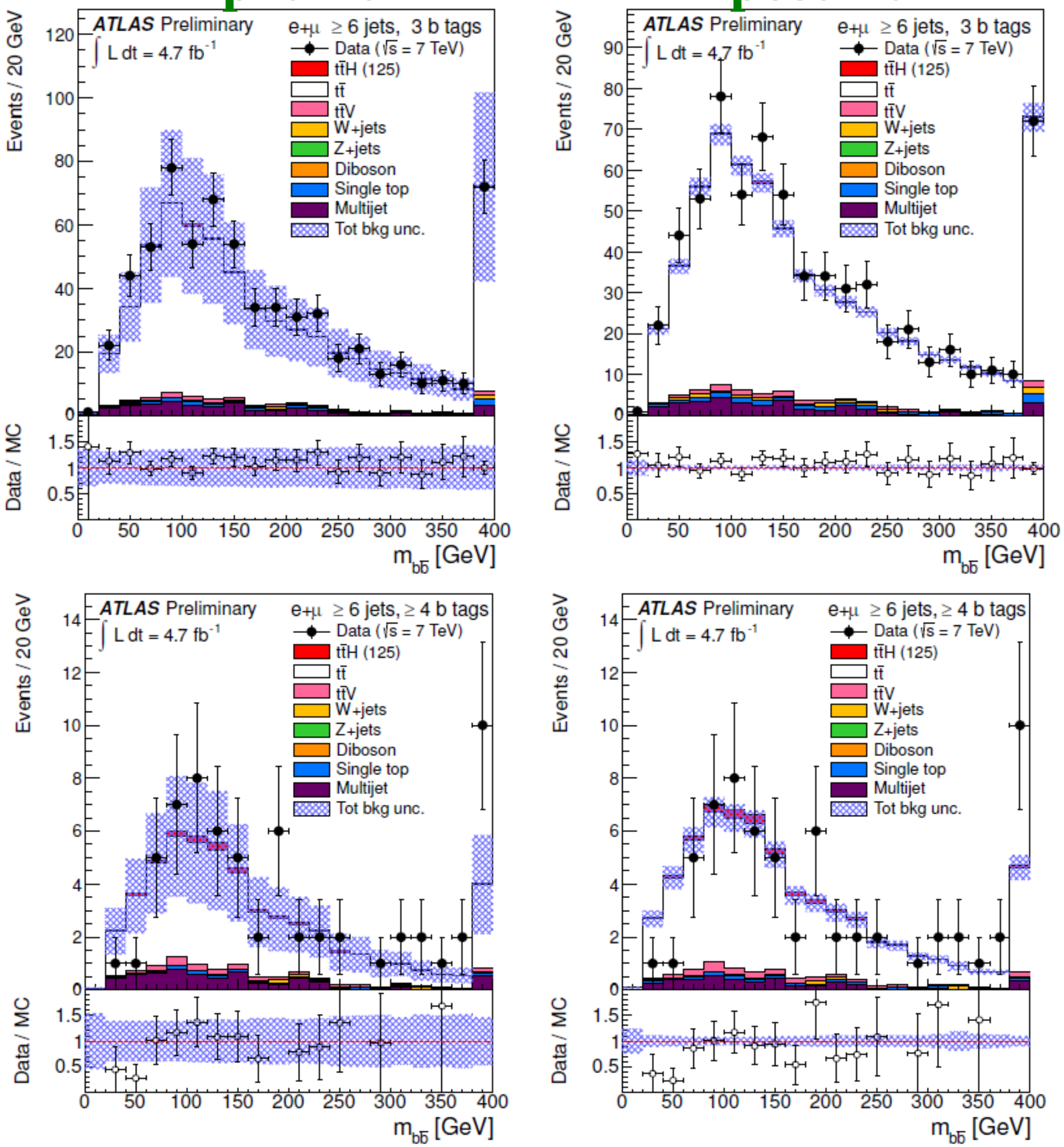
→ m_{bb}

- Use simultaneous fit on signal and control region :
  - → reconstruct W and top
  - → m_{bb} has no mass constraint



ttH, H → bb results

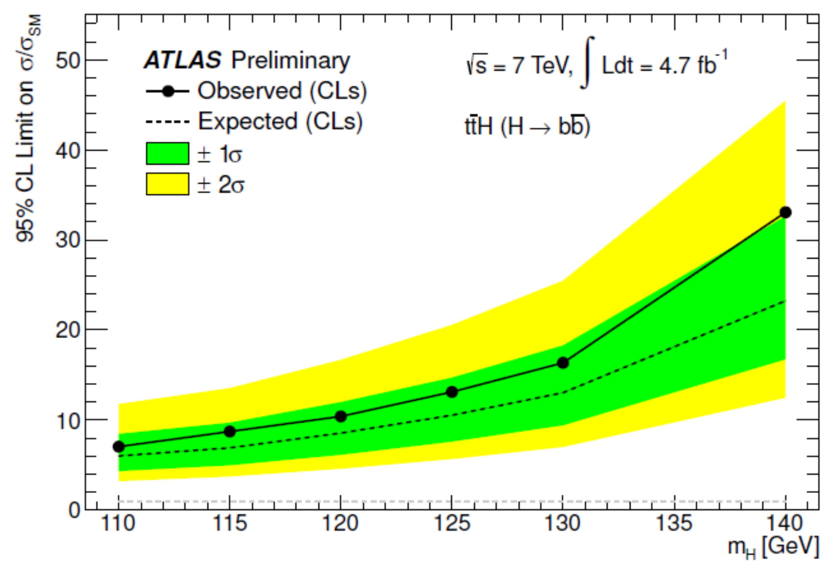
pre-fit post-fit



- kinematic likelihood fit :
  → improve background prediction
  → reduce systematics

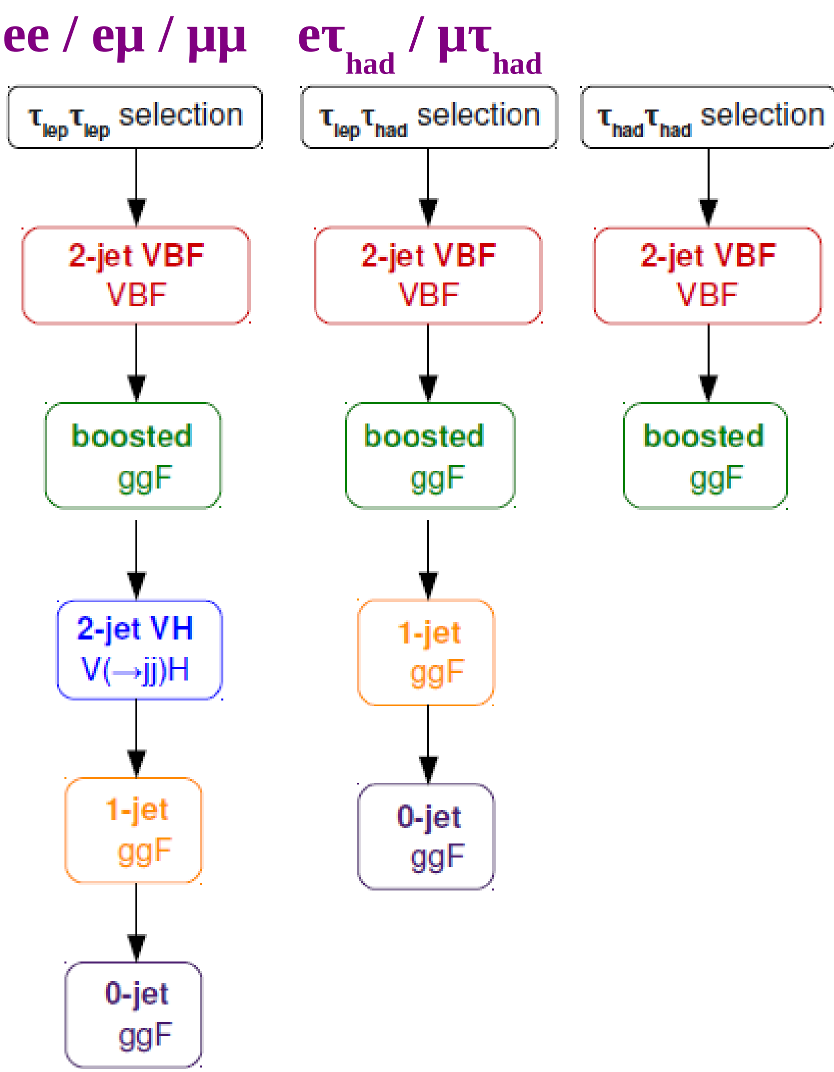
- tt : main background in signal region

- Main systematics :
  - tt+hf modeling
  - b/c jet tagging efficiencies
  - jet energy scale



95% CL on SM Higgs for m_H = 125 GeV obs (exp) : 13.1 (10.5)

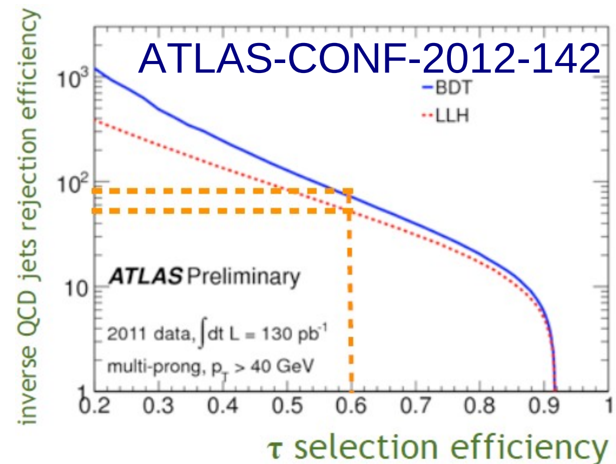
H → ττ selection and strategy



→ highest sensitivity from VBF and then boosted

- separate τ_{had} from jets with multivariate τ ID (Z → ττ main background)

→ select 60% of τ_{had} and few % of QCD jets.



- Final discriminant : $m_{\tau\tau}$

→ Missing Mass Calculator (MMC) derived from
- measured momenta
- real E_T^{miss} (from neutrinos in τ decays)
- simulated distribution of angle between visible and missing momenta

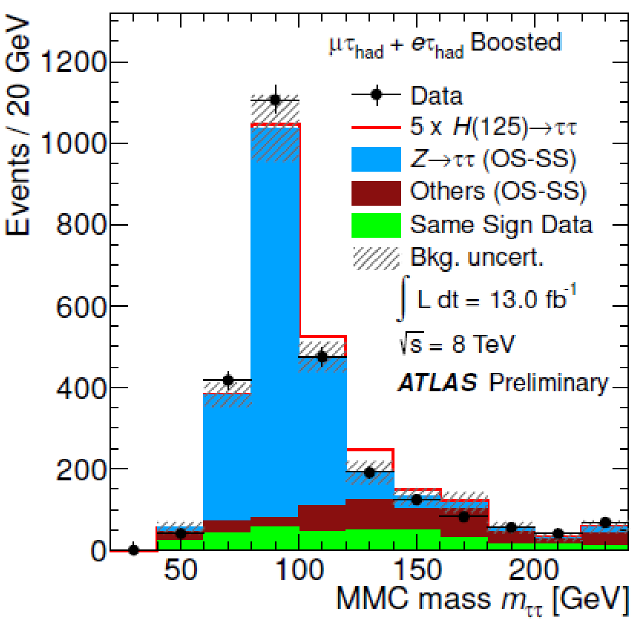
→ E_T^{miss} >20 GeV

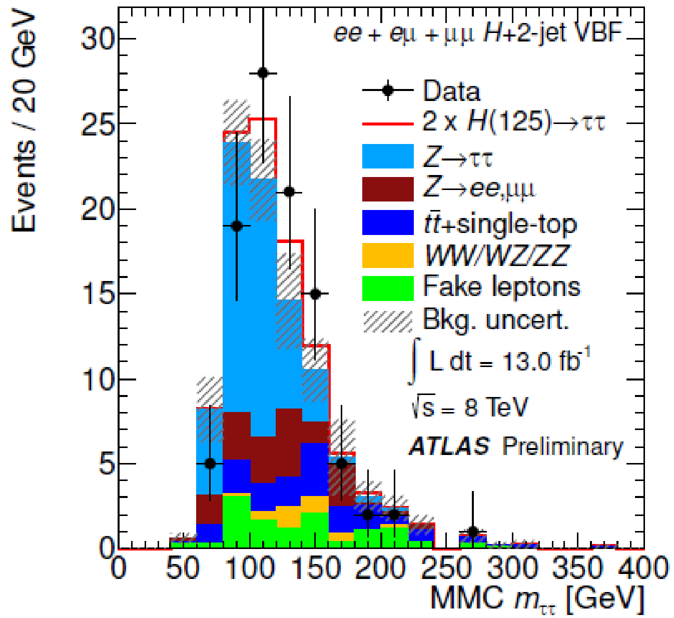
- Benefit from different Higgs productions :

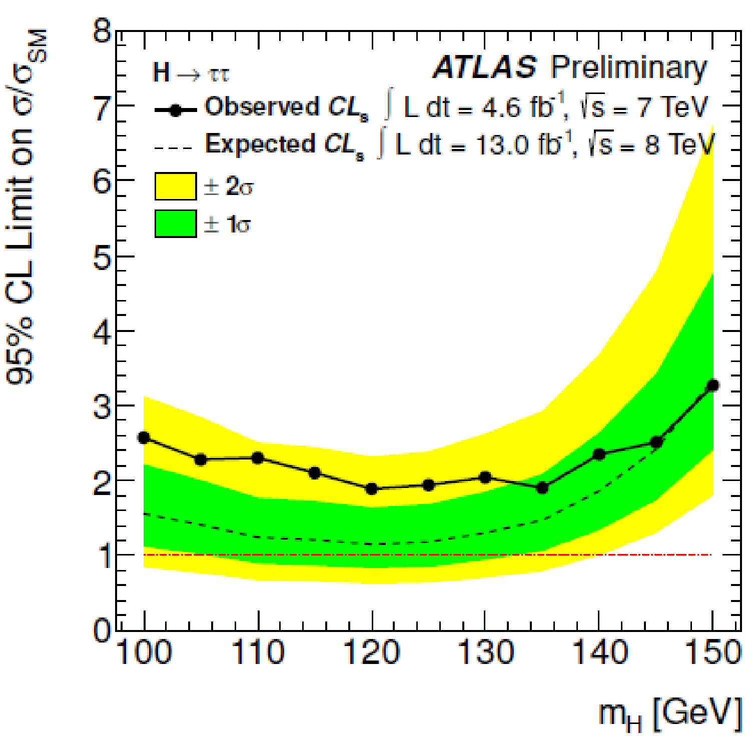
→ VBF : 2 forward jets
$\Delta\eta(jj)>3$ and Mjj > 400 GeV in leplep

→ boosted : $p_T^H = p_T(\tau_{vis}, \tau_{vis}, E_t^{miss}) > 100$ GeV

H → ττ results





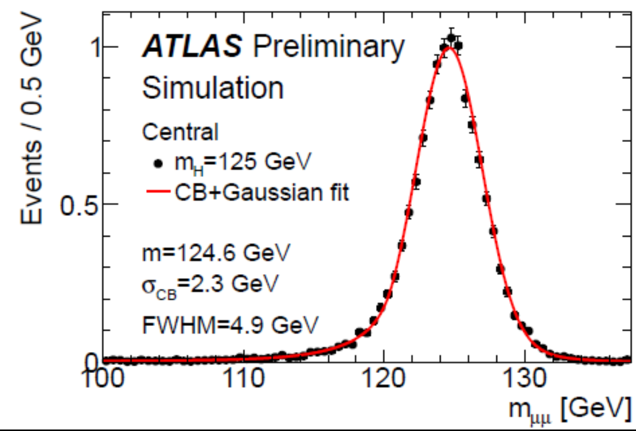


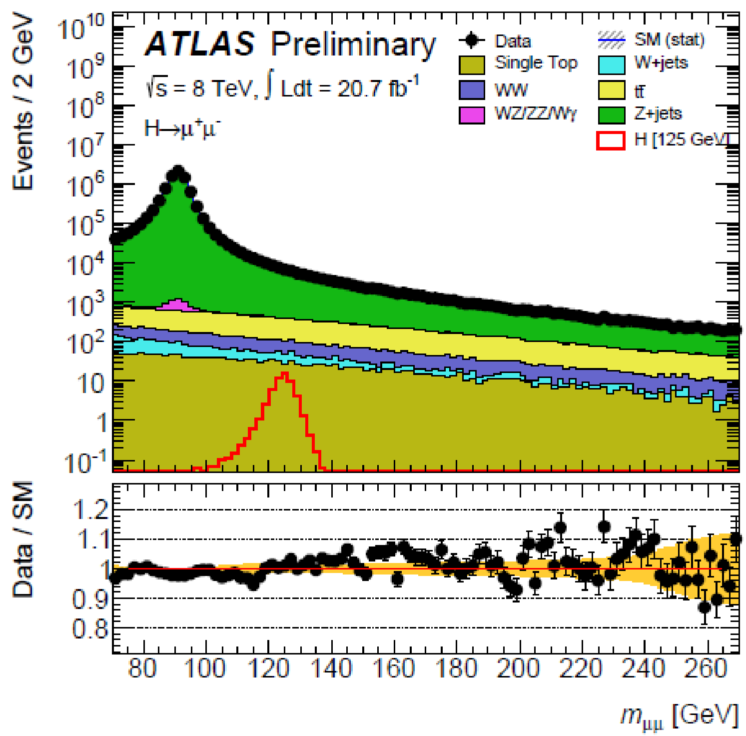
- Data-driven **Z → ττ** from embedding τ decays into Z → μμ data events.
- Data-driven **Multijet** from : Same Sign Data (lephad, hadhad) or Fake leptons estimate (leplep).
- Simulated :
  - **Z+jets**
  - **W+jets** (Others in lephad)
  - **top** (ttbar+single-top)
  - **diboson** (WW/WZ/ZZ)
  - → corrected to data from control region
- Main systematics :
  τ energy scale
  theoretical uncertainties

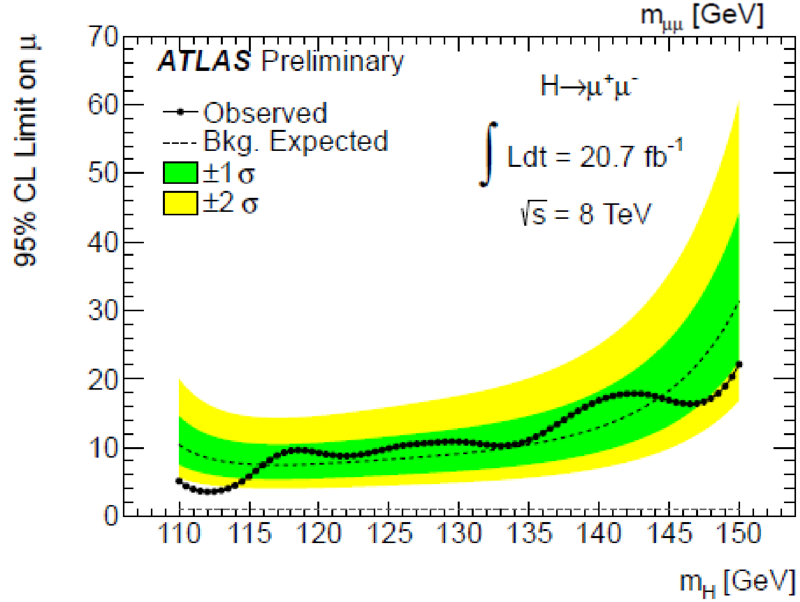
95% CL on SM Higgs for m_H = 125 GeV obs (exp) : 1.9 (1.2)

H → μμ

- Search for the rare SM Higgs boson decay H → μμ in mass range [110-150] GeV.
- Two opposite charged isolated μ with high transverse momenta.
- $p_T^{\mu\mu}$ > 15 GeV to suppress DY background → reversed cuts : control region
- 2 signal regions : barrel ($|\eta^{\mu 1}| < 1$ and $|\eta^{\mu 2}| < 1$) non-barrel ($|\eta^{\mu 1}| > 1$ or $|\eta^{\mu 2}| > 1$)
- Main background : $Z/\gamma^* \rightarrow \mu^+\mu^-$
- (+) $m_{\mu\mu}$ resolution of 2.3 in barrel
- (-) very low signal-to-background ratio







95% CL on SM Higgs for m_H = 125 GeV obs (exp) : 9.8 (8.2)

SUMMARY

- Higgs boson decays to fermions are very challenging final states
  → **large backgrounds and complex final states**
- Currently no significant excesses observed in the fermionic search channels.
- VH ($H \rightarrow bb$) and $H \rightarrow \tau\tau$ channels starts to become sensitive :

Analysis	Dataset	95% CL on SM Higgs for m_H = 125 GeV obs (exp)
VH, $H \rightarrow b\bar{b}$ (V = W or Z) ATLAS-CONF-2012-161	4.7 fb^{-1} (7 TeV collisions) 13 fb^{-1} (8 TeV collisions)	**1.8 (1.9)**
$H \rightarrow \tau^+\tau^-$ ATLAS-CONF-2012-160	4.6 fb^{-1} (7 TeV collisions) 13 fb^{-1} (8 TeV collisions)	**1.9 (1.2)**
$t\bar{t}H$, $H \rightarrow b\bar{b}$ ATLAS-CONF-2012-135	4.7 fb^{-1} (7 TeV collisions)	**13.1 (10.5)**
$H \rightarrow \mu^+\mu^-$ ATLAS-CONF-2013-010	20.7 fb^{-1} (8 TeV collisions)	**9.8 (8.2)**

NEXT

• Use full dataset accessible (21 fb^{-1}) :

VH ($H\rightarrow bb$), $H\rightarrow\tau\tau$ and ttH analysis on-going

• Analysis improvements to gain in sensitivity :

→ adding more final states in ttH with di-lepton final state

→ better understanding of flavour tagging and tau reconstruction.

→ use advanced techniques to control systematics and have better separation signal and background contributions :

- multivariate analysis
- use full information of b-tag weights

BACK-UP

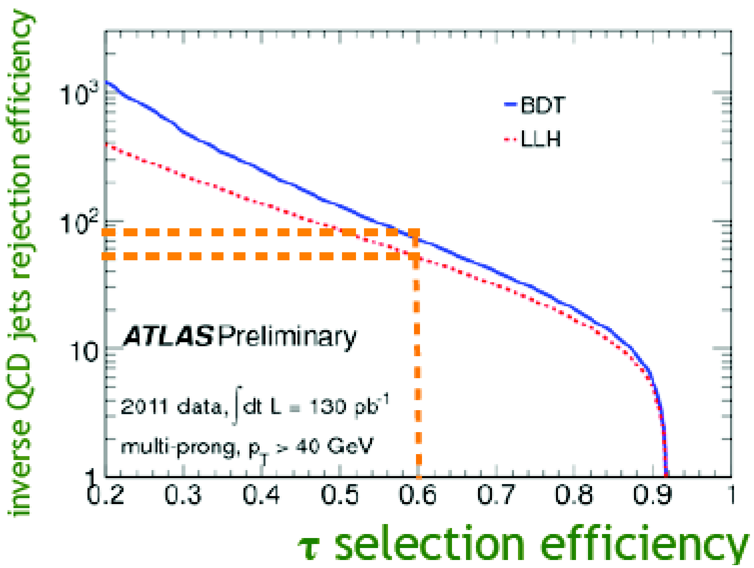
Identifying τ leptons

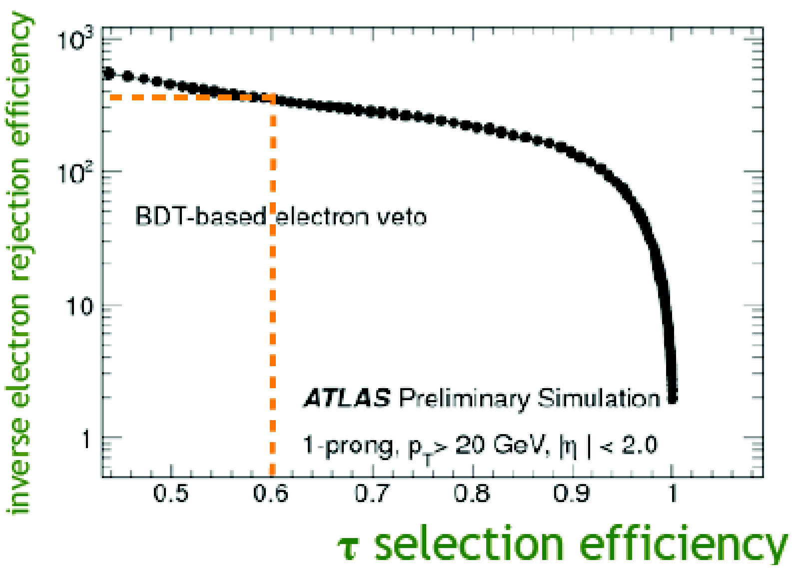
ATLAS-CONF-2012-142

- τ-leptons decay inside the LHC beam pipe
  - Leptonic decays: τ_{lep} $\tau \rightarrow e\bar{\nu}_e\nu_\tau$ (17.8%) $\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau$ (17.4%)
  - Hadronic decays: τ_{had} $\tau \rightarrow \mathrm{hadrons} + \nu_\tau$ (1-prong: 49.5%; 3-prong: 15.2%)

- Jets + tracks are used to form τ_{had} candidates; energy calibrated using MC, but energy scale determined using studies of isolated hadrons
- Cuts on boosted decision trees (BDT) and a log-likelihood (LLH) are used to reject electrons and QCD jets.

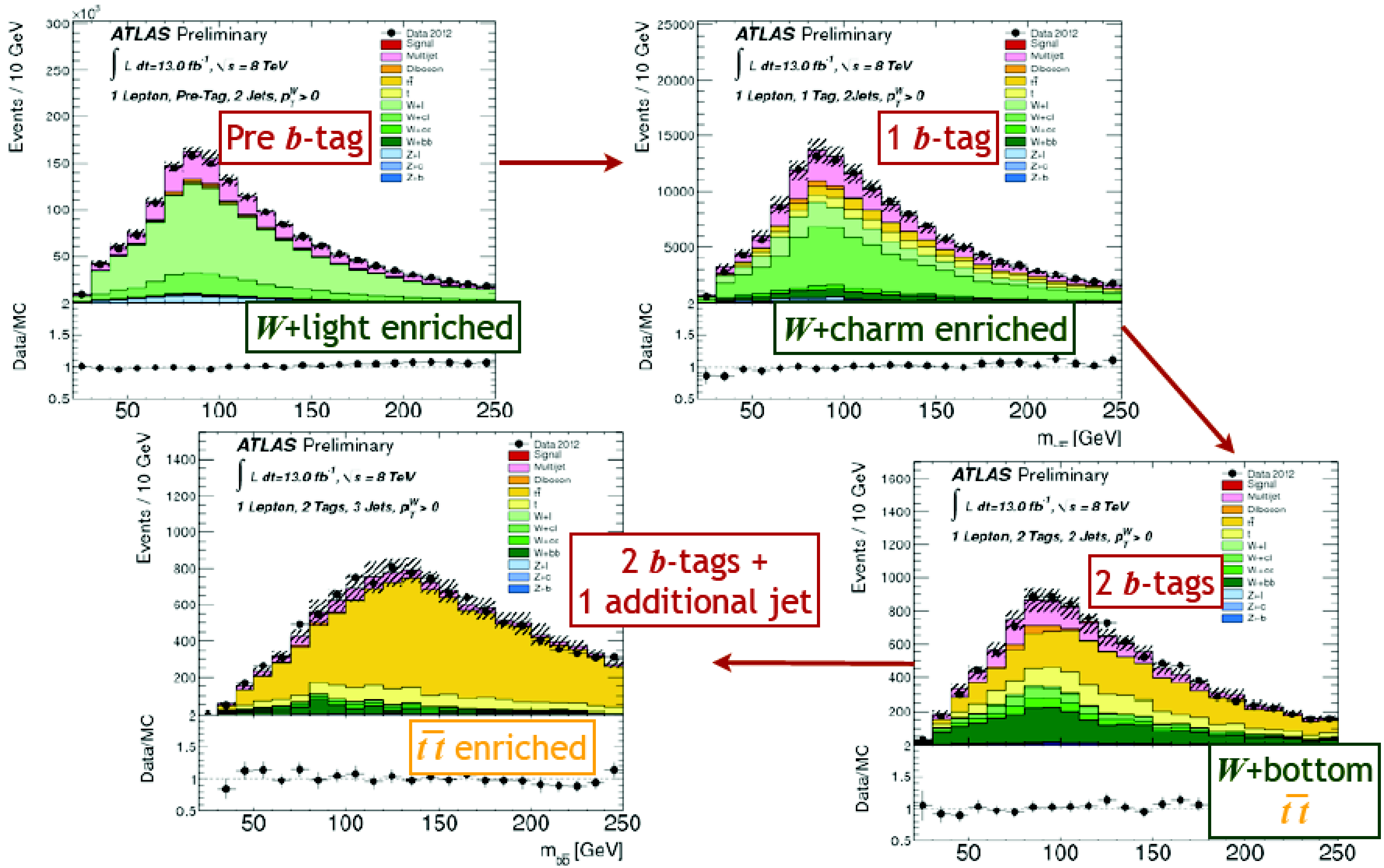
- Analyses presented here use 60% working point - selects 60% of τ_{had}
  - selects few% of QCD jets and <1% of electrons





$VH \rightarrow Vb\bar{b}$ BG Normalisation Fit

- example for 1-lepton; plots integrated over all $p_T^{\ell\nu}$ bins.



$VH \rightarrow Vb\bar{b}$ Systematics and Observed Events

Main uncertainties:

- b-/c-tagging
- jet energy scale & resolution
- MC statistics

Uncertainties on backgrounds

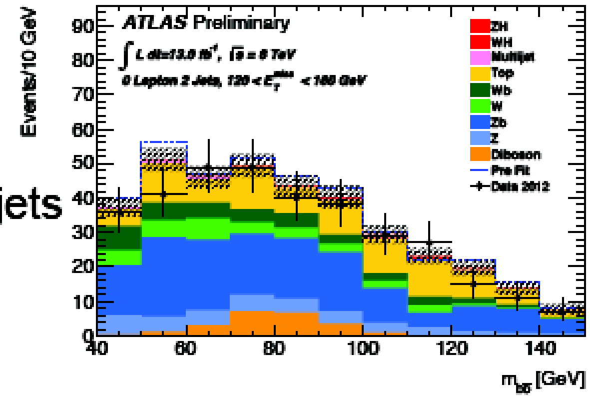
Uncertainty [%]	0 lepton	1 lepton	2 leptons
b-tagging	6.5	6.0	6.9
c-tagging	7.3	6.4	3.6
light tagging	2.1	2.2	2.8
Jet/Pile-up/$E_{\mathrm{T}}^{\mathrm{miss}}$	20	7.0	5.4
Lepton	0.0	2.1	1.8
Top modelling	2.7	4.1	0.5
W modelling	1.8	5.4	0.0
Z modelling	2.8	0.1	4.7
Diboson	0.8	0.3	0.5
Multijet	0.6	2.6	0.0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

	0-lepton, 2 jet			0-lepton, 3 jet			1-lepton					2-lepton				
Bin	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]						p_{T}^{W}[GeV]					p_{T}^{Z}[GeV]				
m_H=125 GeV	120-160	160-200	>200	120-160	160-200	>200	0-50	50-100	100-150	150-200	> 200	0-50	50-100	100-150	150-200	>200
ZH	2.9	2.1	2.6	0.8	0.8	1.1	0.3	0.4	0.1	0.0	0.0	4.7	6.8	4.0	1.5	1.4
WH	0.8	0.4	0.4	0.2	0.2	0.2	10.6	12.9	7.5	3.6	3.6	0.0	0.0	0.0	0.0	0.0
Top	89	25	8	92	25	10	1440	2276	1120	147	43	230	310	84	3	0
$W + c$,light	30	10	5	9	3	2	580	585	209	36	17	0	0	0	0	0
$W + b$	35	13	13	8	3	2	770	778	288	77	64	0	0	0	0	0
$Z + c$,light	35	14	14	8	5	8	17	17	4	1	0	201	230	91	12	15
$Z + b$	144	51	43	41	22	16	50	63	13	5	1	1010	1180	469	75	51
Diboson	23	11	10	4	4	3	53	59	23	13	7	37	39	16	6	4
Multijet	3	1	1	1	1	0	890	522	68	14	3	12	3	0	0	0
Total Bkg.	361	127	98	164	63	42	3810	4310	1730	297	138	1500	1770	665	97	72
	± 29	± 11	± 12	± 13	± 8	± 5	± 150	± 86	± 90	± 27	± 14	± 90	± 110	± 47	± 12	± 12
Data	342	131	90	175	65	32	3821	4301	1697	297	132	1485	1773	657	100	69

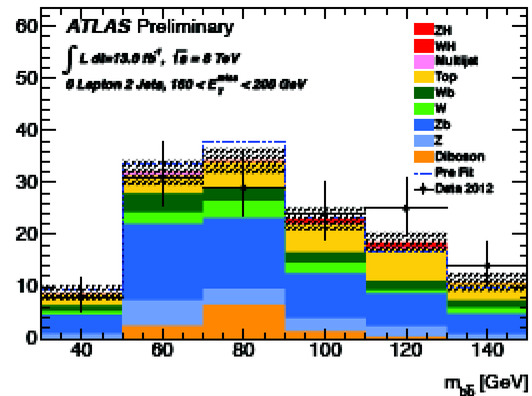
$VH \to Vb\bar{b}$, 0-lepton: m_{bb} distributions

$\sqrt{s} = 8$ TeV

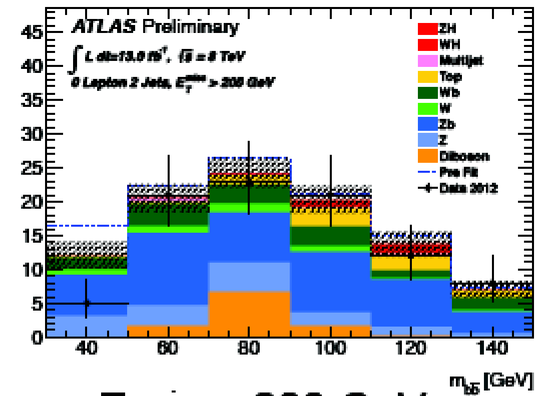
2 jets



120 < E_T^{miss} < 160 GeV

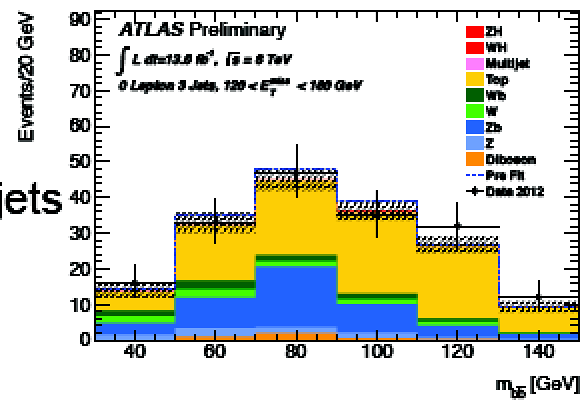


160 < E_T^{miss} < 200 GeV

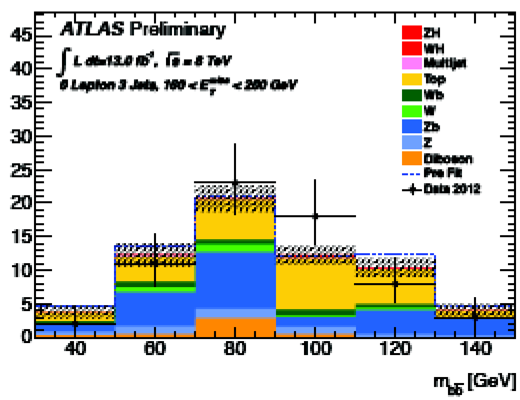


E_T^{miss} > 200 GeV

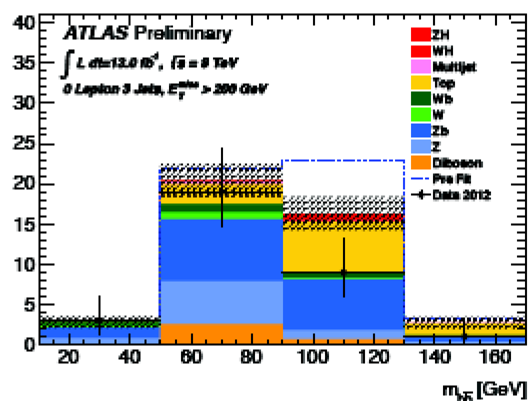
3 jets



120 < E_T^{miss} < 160 GeV



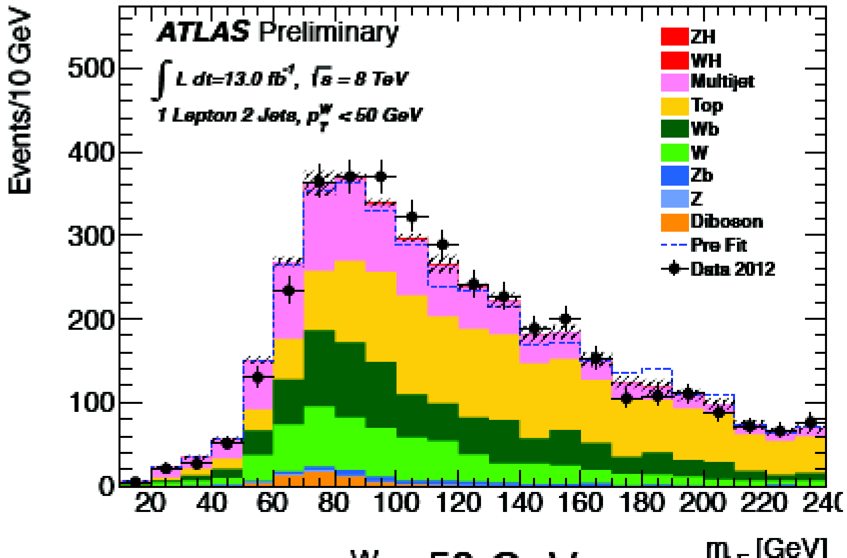
160 < E_T^{miss} < 200 GeV



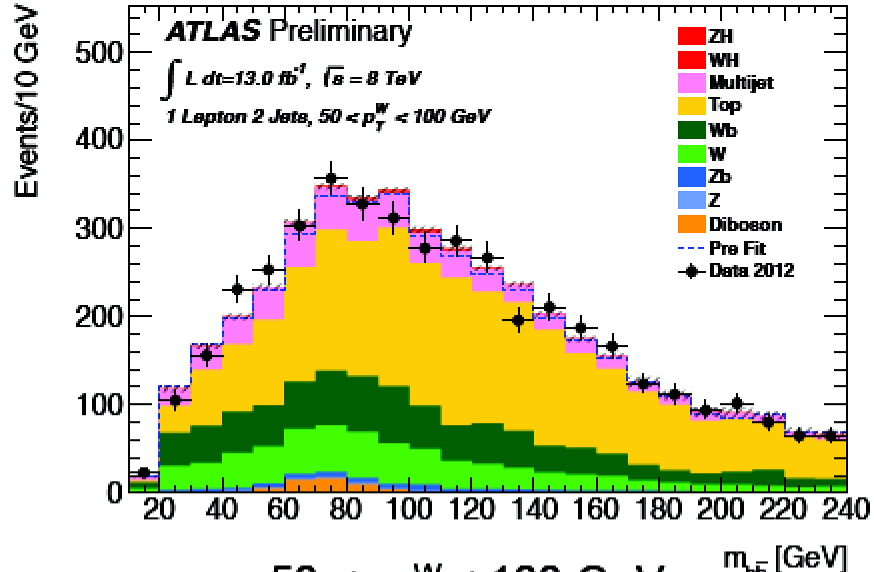
E_T^{miss} > 200 GeV

$VH \rightarrow Vb\bar{b}$, 1-lepton: m_{bb} distributions

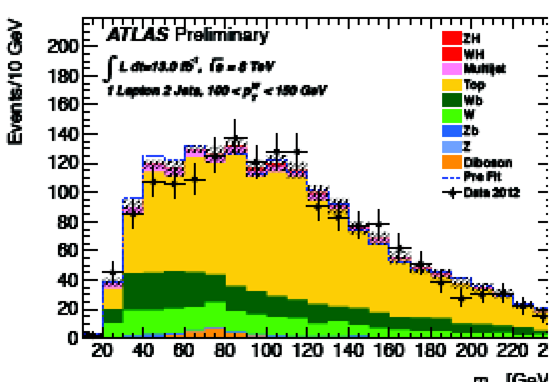
$\sqrt{s} = 8$ TeV



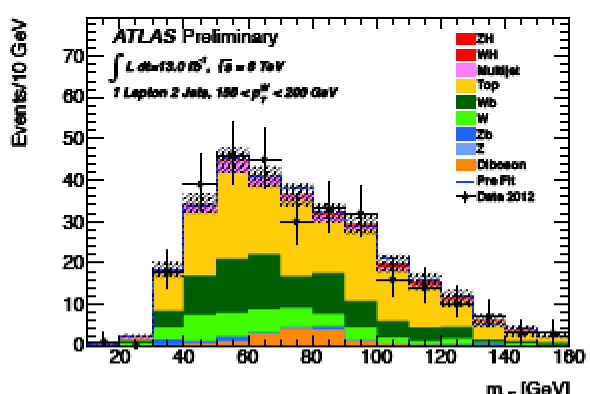
$p_T^W < 50$ GeV



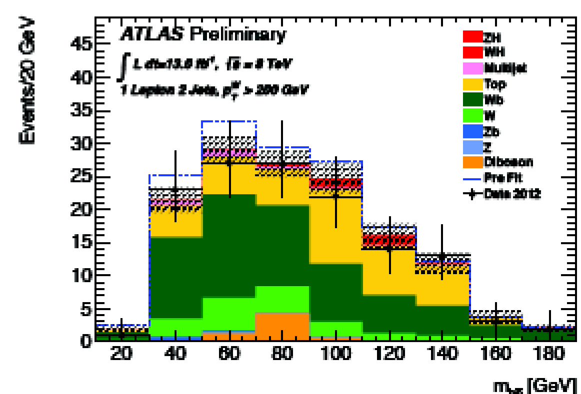
$50 < p_T^W < 100$ GeV



$100 < p_T^W < 100$ GeV



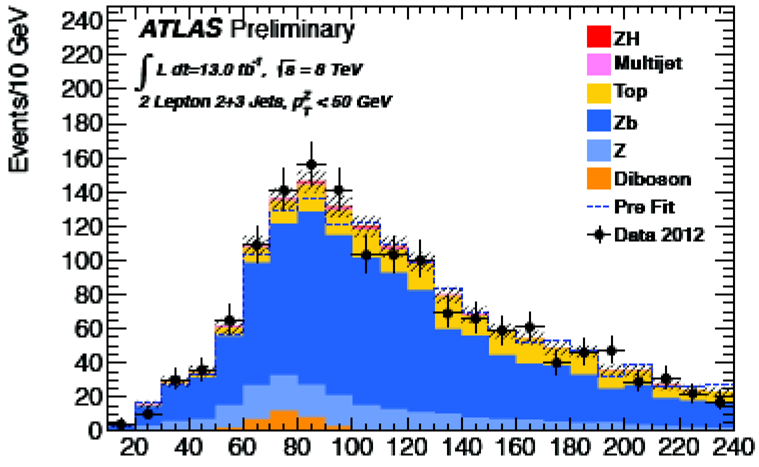
$150 < p_T^W < 200$ GeV



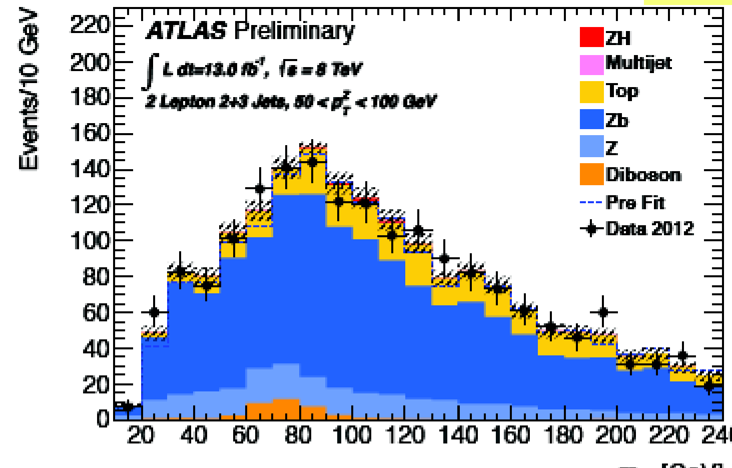
$p_T^W > 200$ GeV

$VH \rightarrow Vb\bar{b}$, 2-leptons: m_{bb} distributions

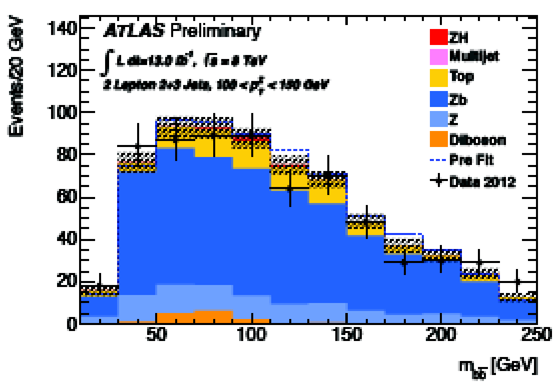
$\sqrt{s} = 8$ TeV



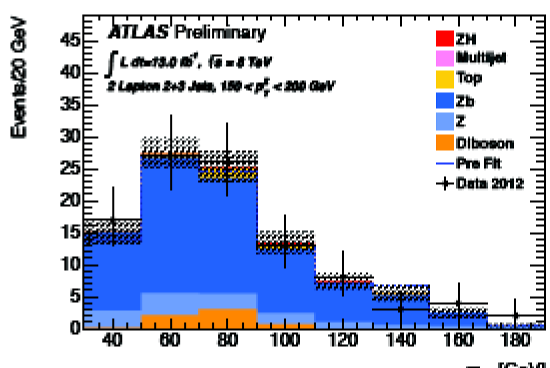
$p_T^Z < 50$ GeV



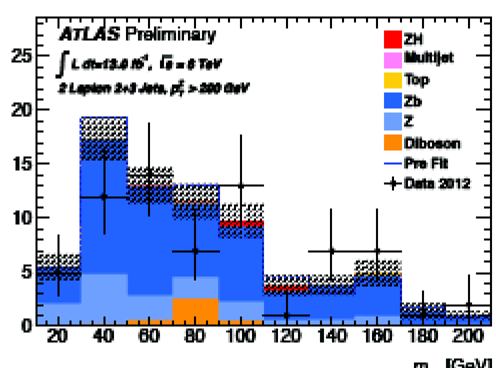
$50 < p_T^Z < 100$ GeV



$100 < p_T^Z < 150$ GeV



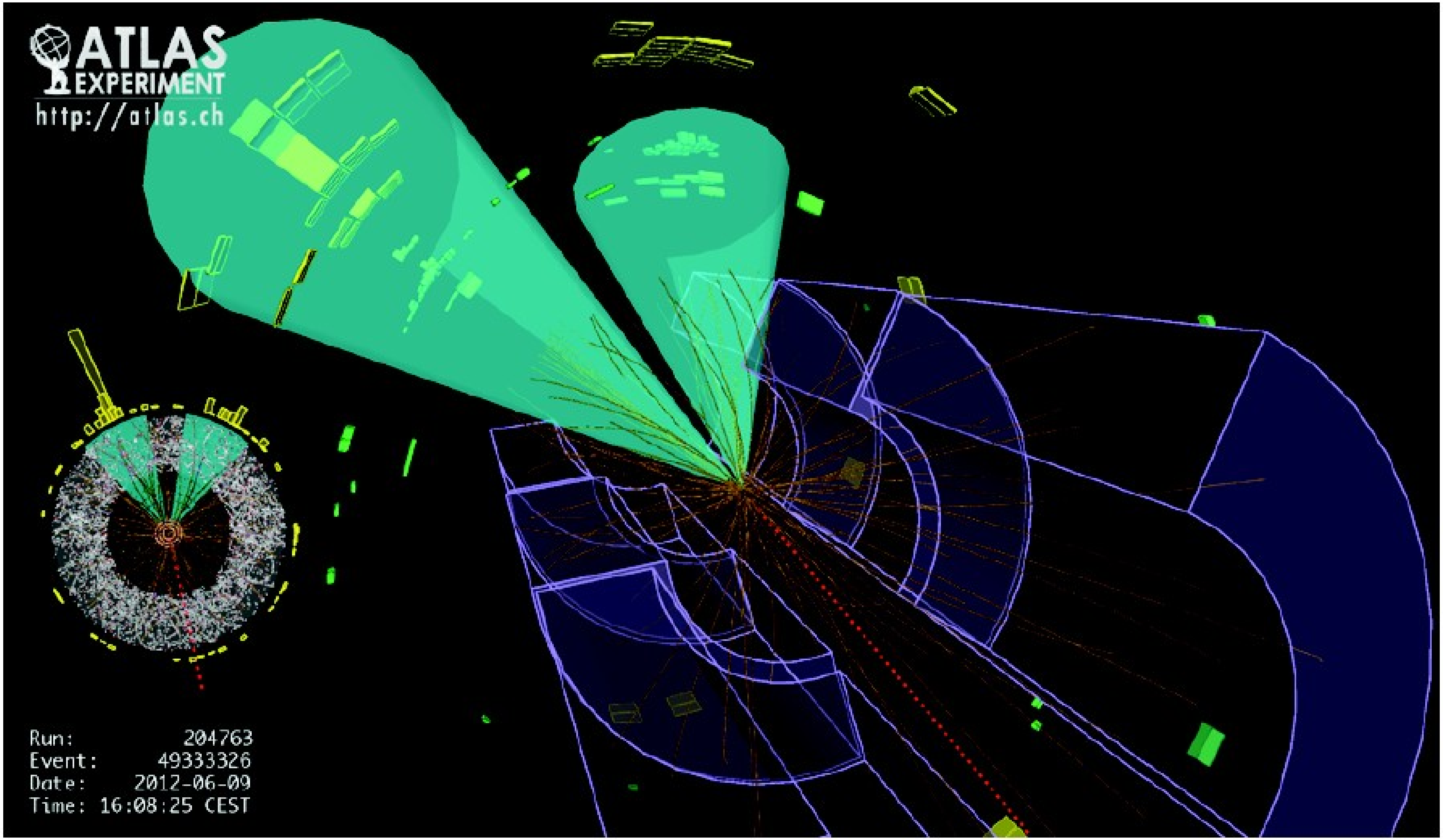
$150 < p_T^Z < 200$ GeV



$p_T^Z > 200$ GeV

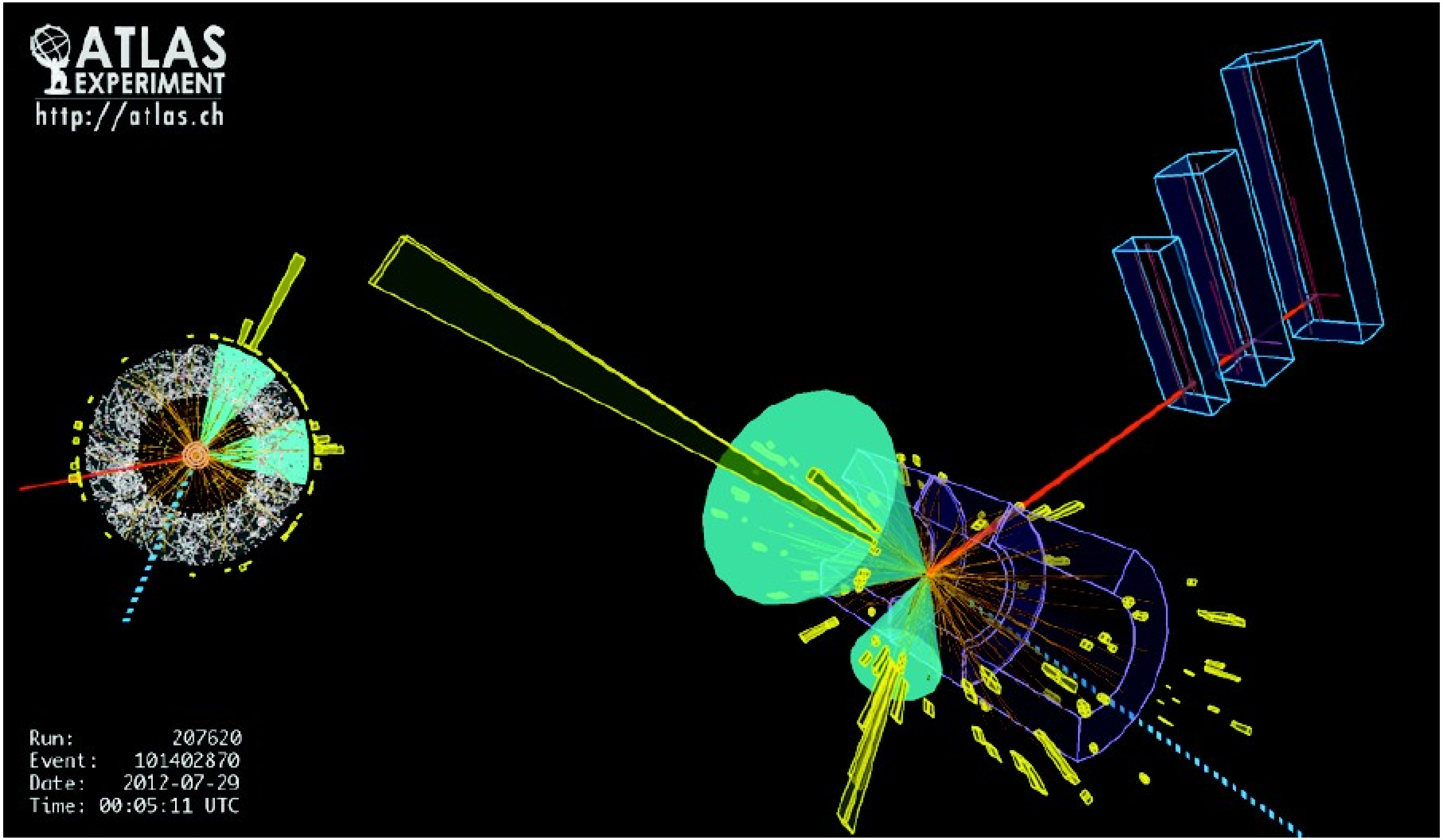
$ZH \to \nu\bar{\nu}\ b\bar{b}$ candidate event

- $m_{b\bar{b}}$ = 123 GeV E_T^{miss} = 271 GeV



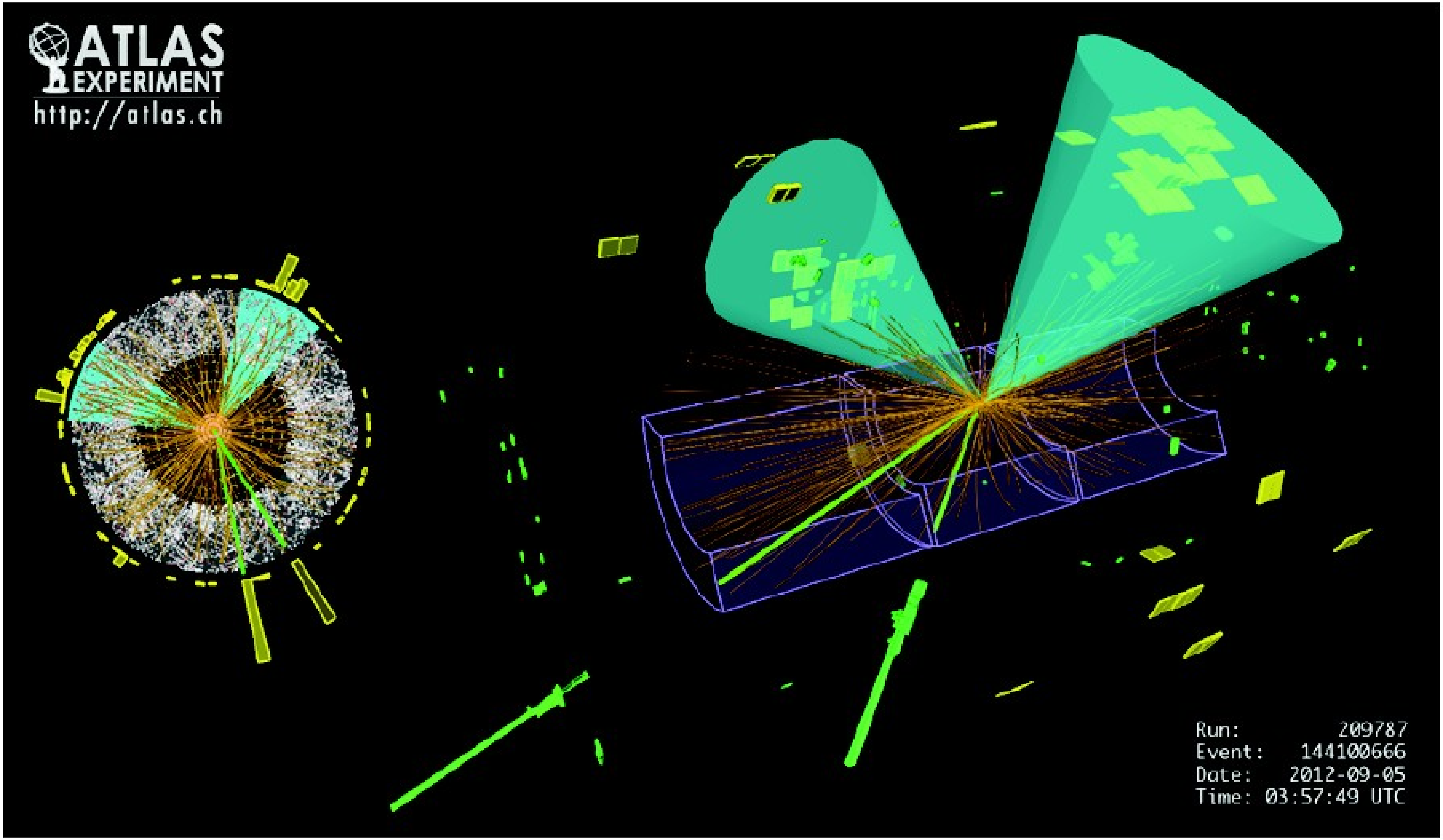
$WH \rightarrow \mu\nu\, b\bar{b}$ candidate event

- $m_{b\bar{b}}$ = 109 GeV, E_T^{miss} = 139 GeV



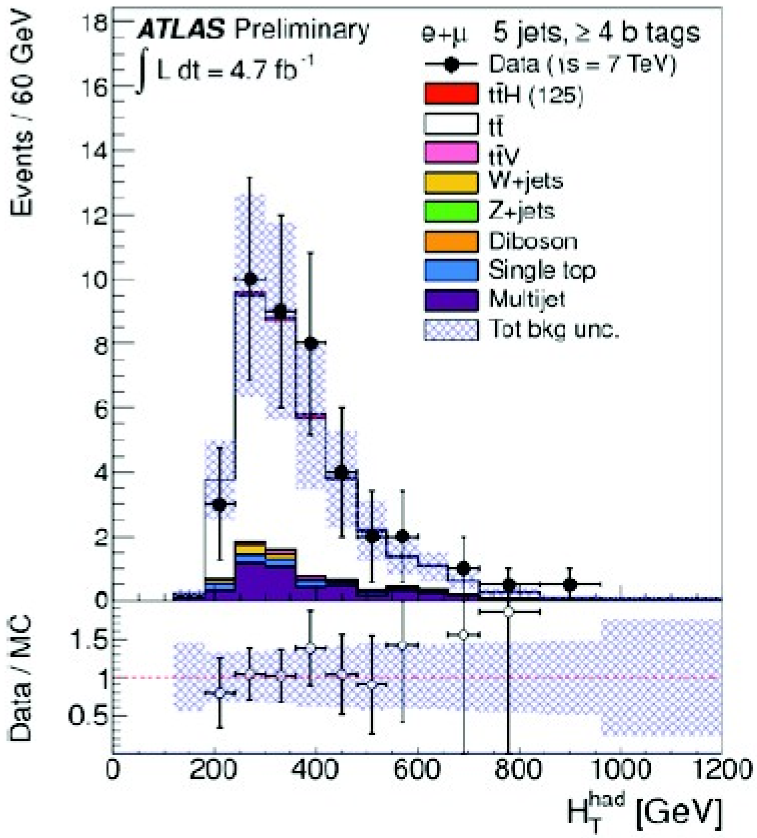
$ZH \rightarrow e^+e^- \, b\bar{b}$ candidate event

- $m_{b\bar{b}}$ = 122 GeV

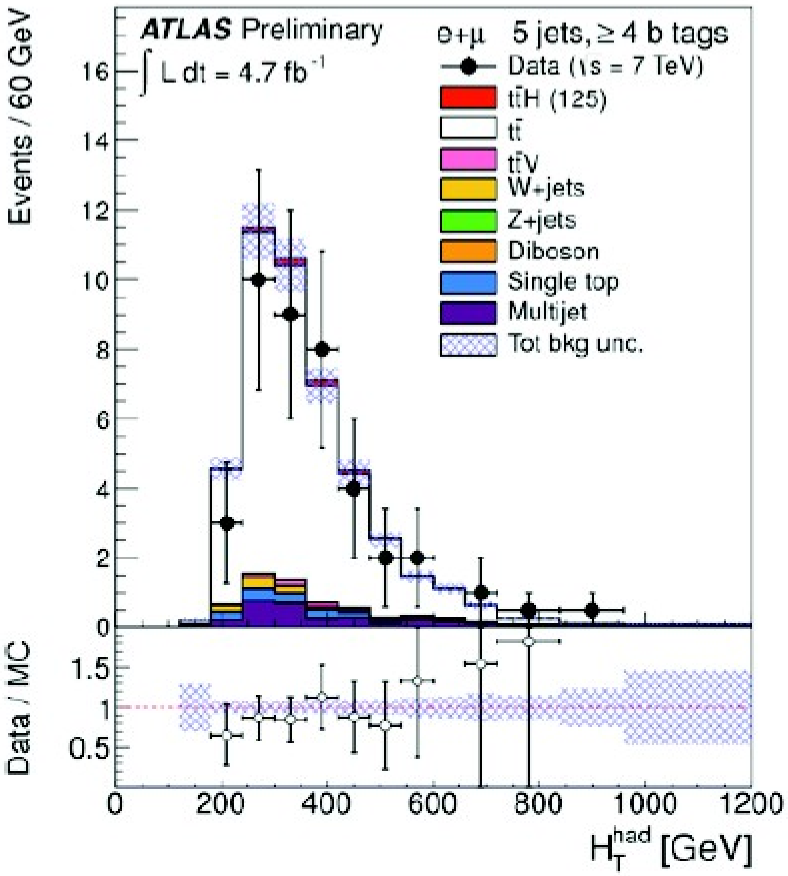


$t\bar{t}H, H \to b\bar{b}$: H_T^{had} distributions

Pre-Fit



Post-Fit



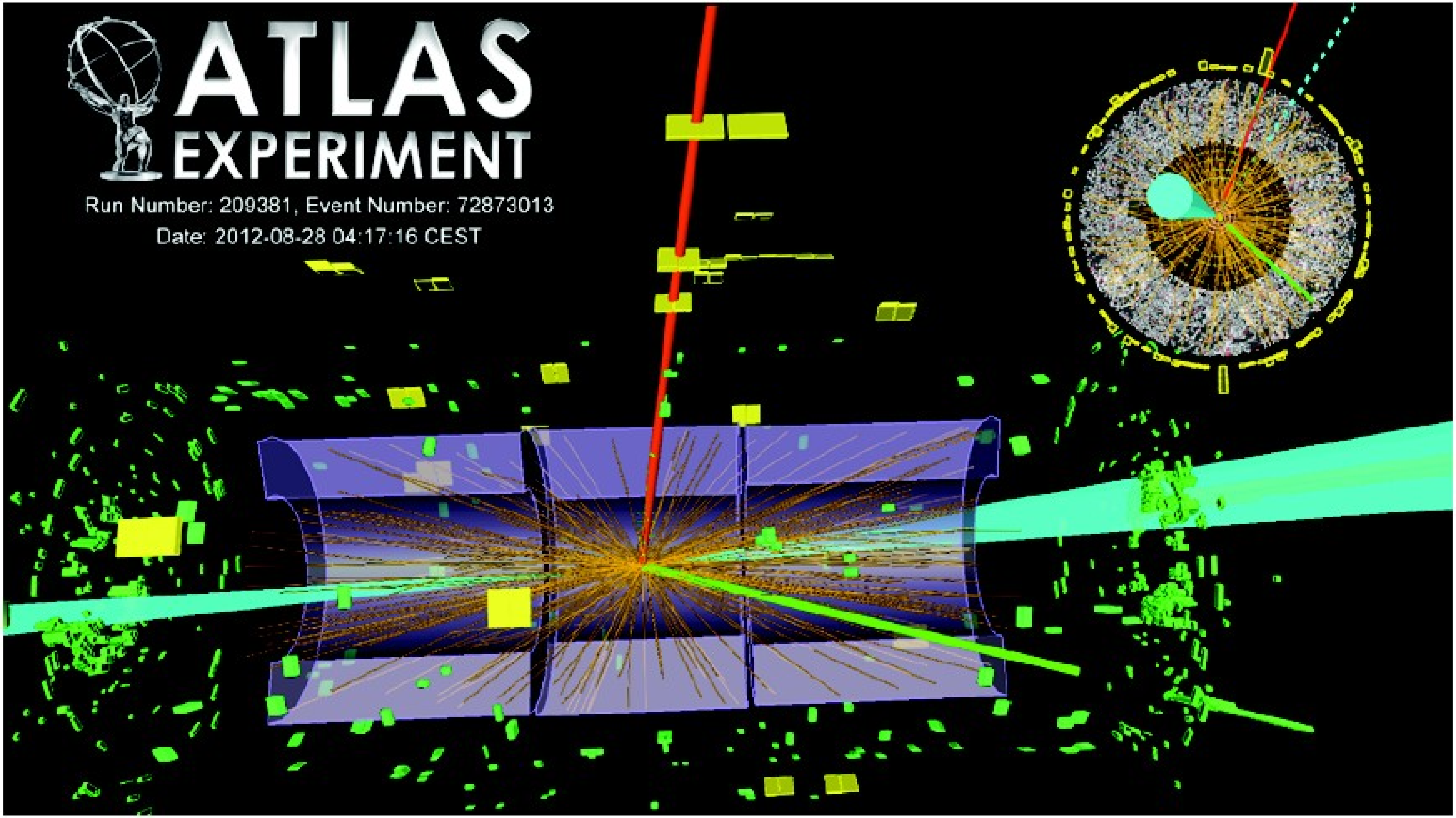
$H \rightarrow \tau^+\tau^-$ Systematics

Table 14: Summary of $Z \rightarrow \tau^+\tau^-$ background and signal systematic uncertainties by channel. The quoted ranges refer specifically to the 8 TeV dataset, but they are similar for the 7 TeV dataset. Uncertainties indicated with (S) are also applied bin-by-bin, and therefore affect the shape of the final distributions. Signal systematic uncertainties are derived from the sum of all signal production modes.

Uncertainty	$H \rightarrow \tau_{lep}\tau_{lep}$	$H \rightarrow \tau_{lep}\tau_{had}$	$H \rightarrow \tau_{had}\tau_{had}$
$Z \rightarrow \tau^+\tau^-$			
Embedding	1–4% (S)	2–4% (S)	1–4% (S)
Tau Energy Scale	–	4–15% (S)	3–8% (S)
Tau Identification	–	4–5%	1–2%
Trigger Efficiency	2–4%	2–5%	2–4%
Normalisation	5%	4% (non-VBF), 16% (VBF)	9–10%
Signal			
Jet Energy Scale	1–5% (S)	3–9% (S)	2–4% (S)
Tau Energy Scale	–	2–9% (S)	4–6% (S)
Tau Identification	–	4–5%	10%
Theory	8–28%	18–23%	3–20%
Trigger Efficiency	small	small	5%

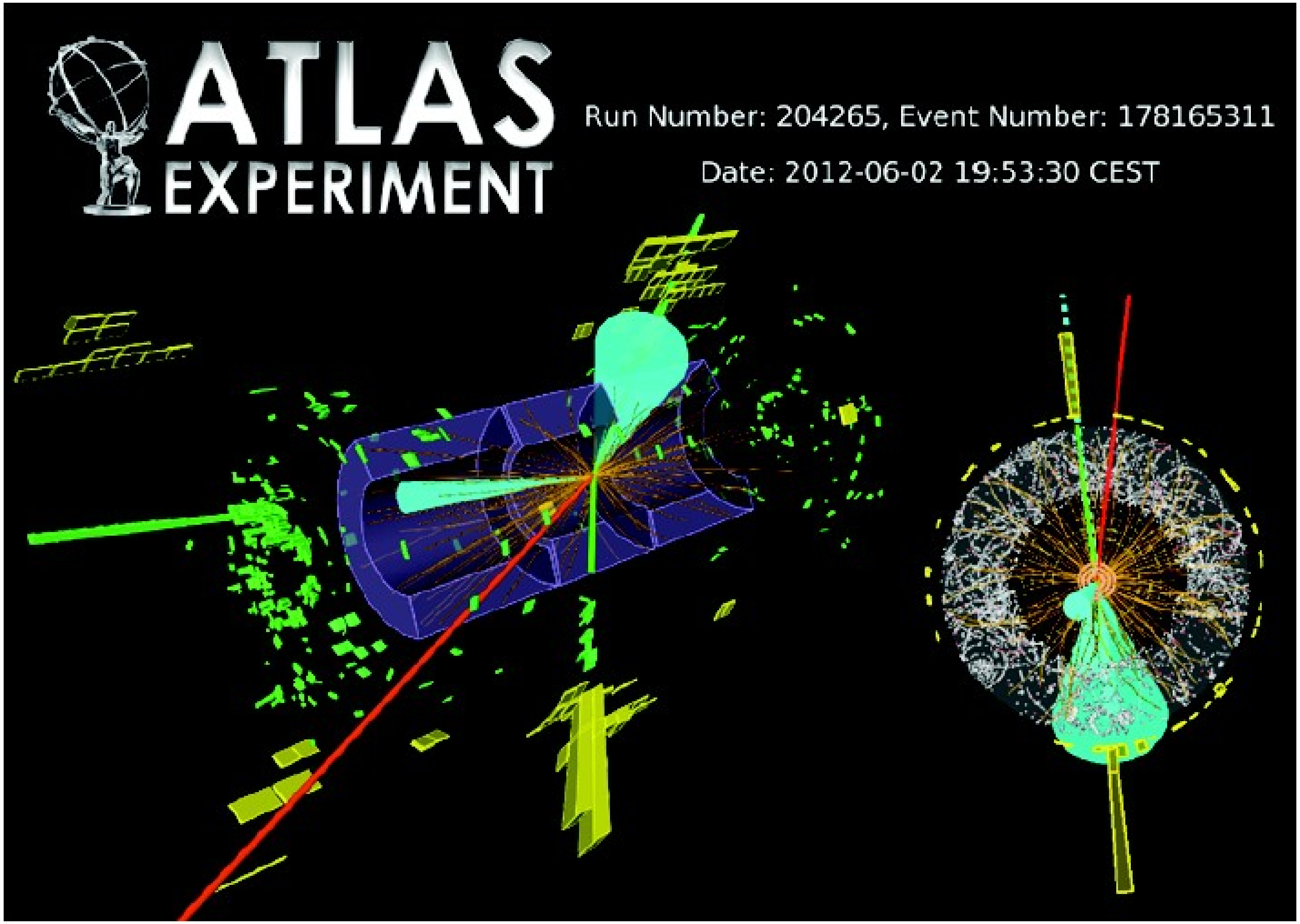
VBF $H \rightarrow \tau_e \tau_\mu$ candidate event

- $m_{MMC} = 126$ GeV
- $p_T(\mu) = 20$ GeV, $p_T(e) = 17$ GeV, $E_T^{miss} = 43$ GeV, $m_{jj} = 1610$ GeV



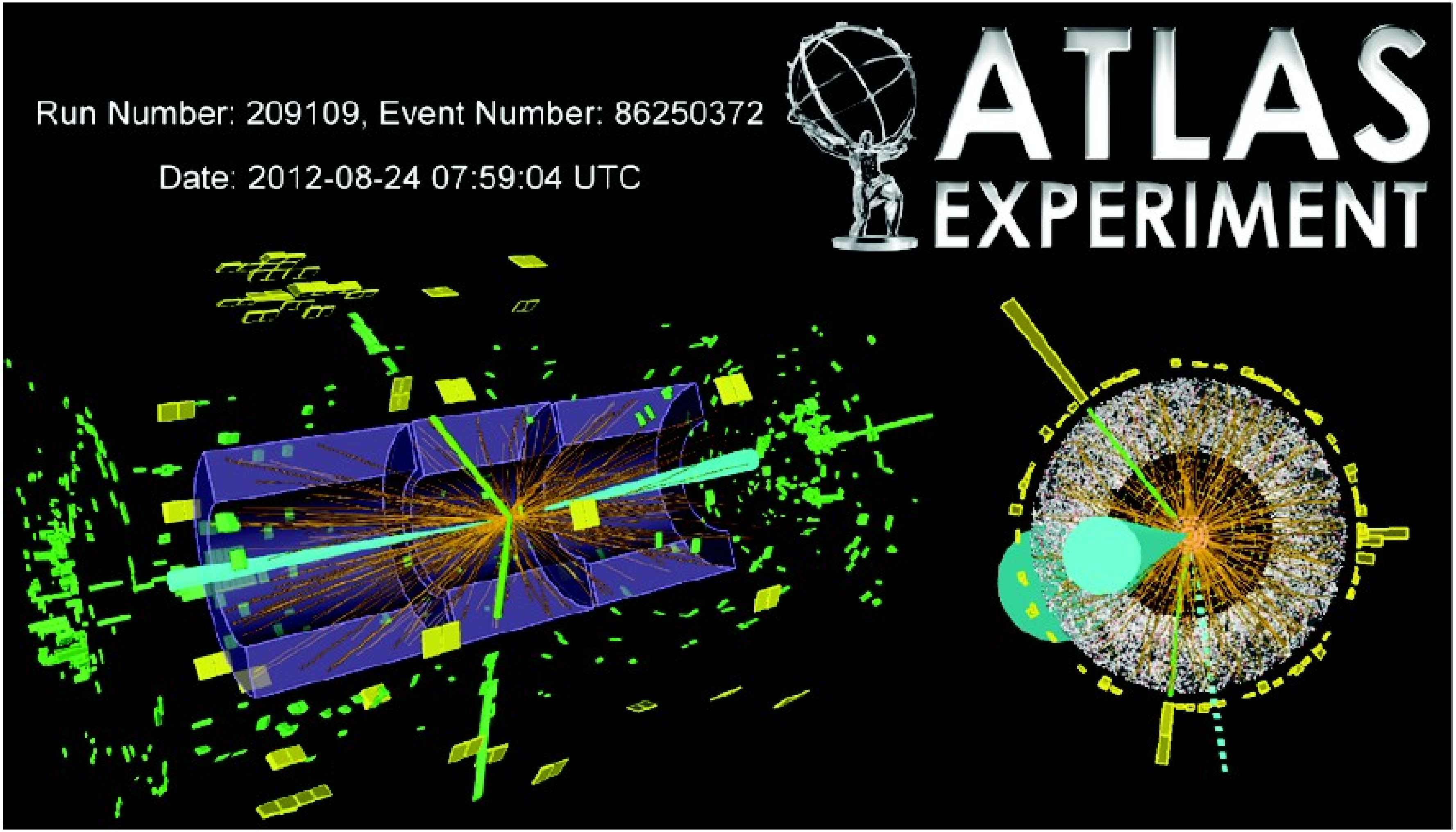
VBF $H \to \tau_{had}\, \tau_{\mu}$ candidate event

- m_{MMC}=129 GeV
- $p_T(\mu)$ = 63 GeV, $p_T(\tau_{had})$ = 96 GeV, E_T^{miss}=119 GeV, m_{jj}=625 GeV

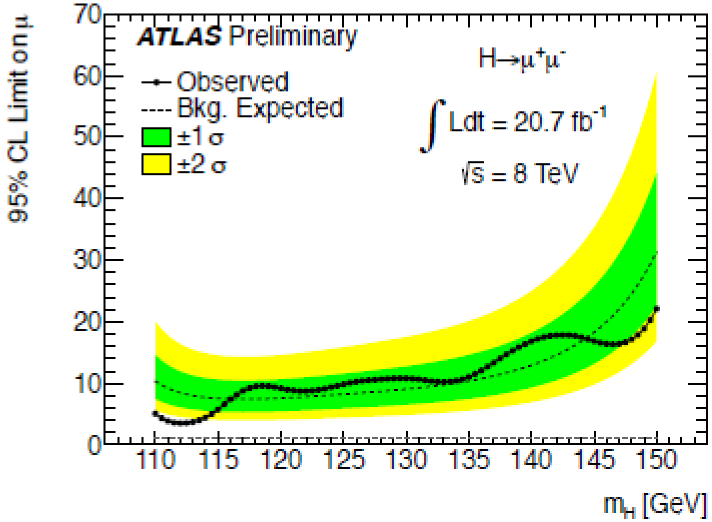


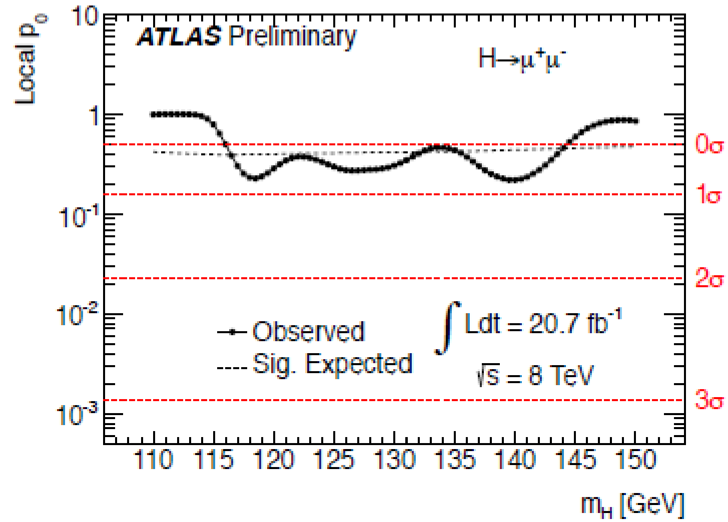
VBF $H \to \tau_{had} \tau_{had}$ candidate event

- $E_T^{miss} = 26$ GeV, $m_{jj} = 408$ GeV
- m_{MMC}=131 GeV



$H \to \mu^+\mu^-$ Results





m_H [GeV]	observed limits	exp. median	exp. $+2\sigma$	exp. $+1\sigma$	exp. -1σ	exp. -2σ
110	5.1	10.4	20.0	14.6	7.5	5.6
115	5.7	7.5	14.5	10.6	5.4	4.0
120	9.2	7.6	14.6	10.7	5.5	4.1
125	9.8	8.2	15.9	11.6	5.9	4.4
130	10.8	9.1	17.5	12.8	6.5	4.9
135	11.0	10.4	20.1	14.6	7.5	5.6
140	16.8	12.9	25.0	18.2	9.3	6.9
145	16.9	18.3	35.3	25.7	13.2	9.8
150	22.1	31.3	60.6	44.2	22.6	16.8