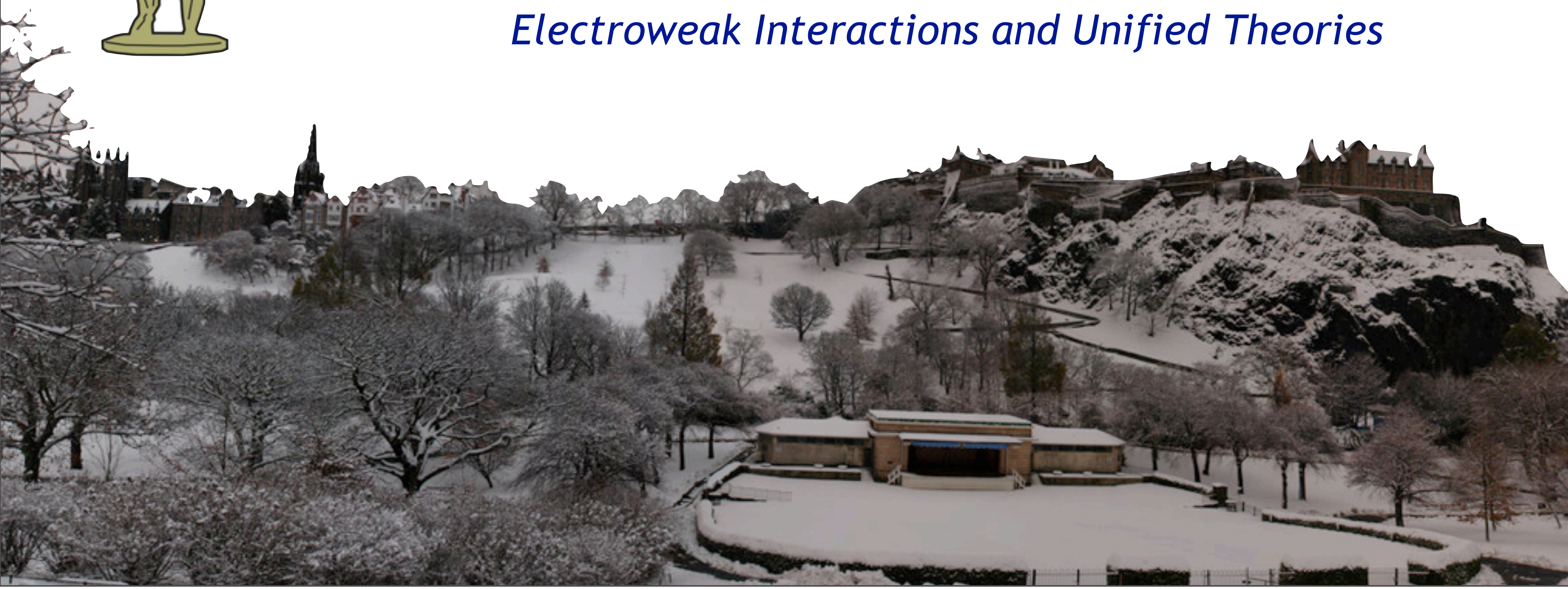
Searches for the BEH boson into fermions at ATLAS

Victoria Martin, University *of* Edinburgh
On behalf of the ATLAS collaboration

XXXXVIII Rencontres de Moriond:
Electroweak Interactions and Unified Theories

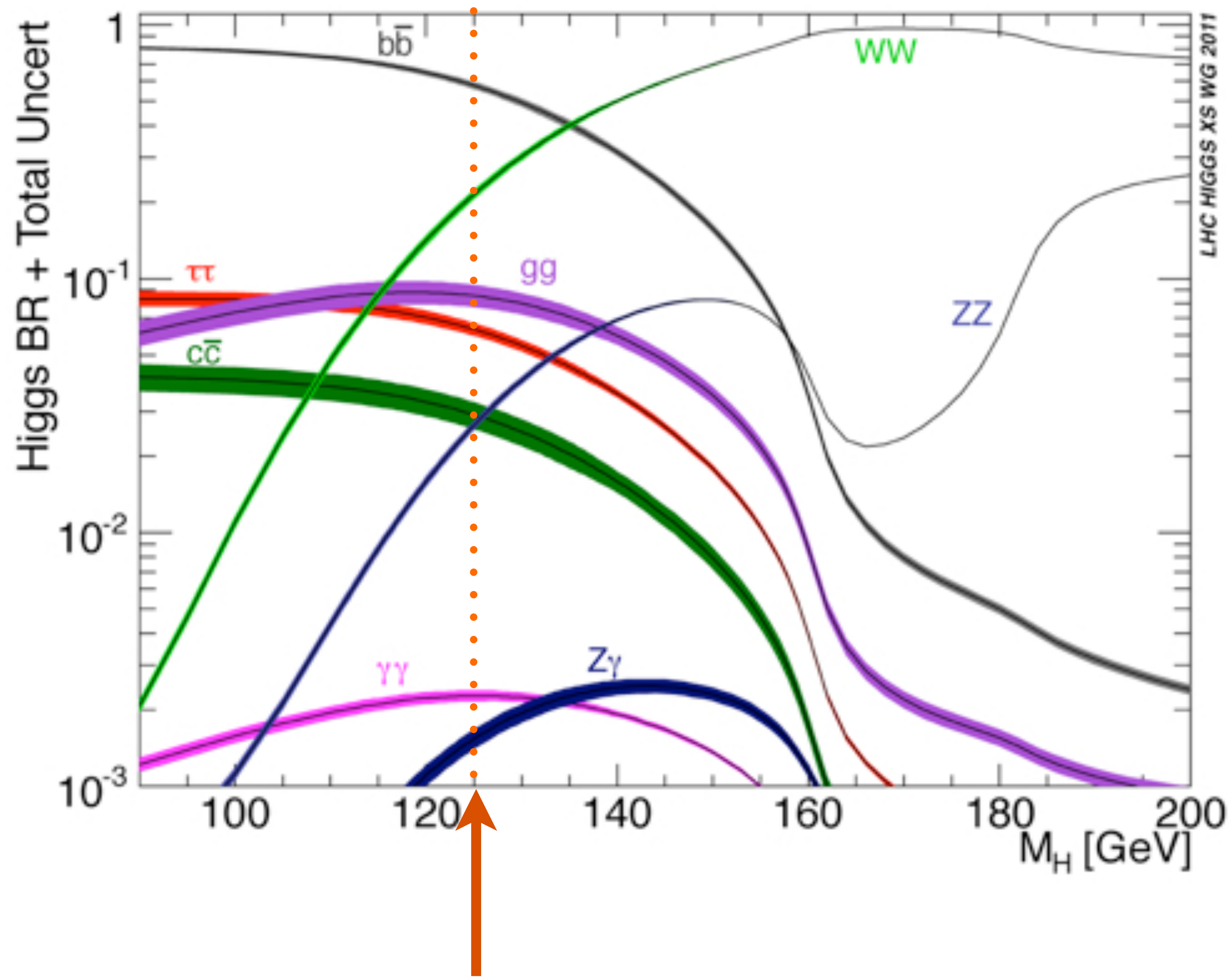


Why Higgs into fermions?

A Standard Model Higgs boson with $\mathbf{m}_H \sim \mathbf{125\ GeV}/c^2$ decays most frequently into fermions. *e.g.* for $m_H = \mathbf{125\ GeV}/c^2$

- ➡ 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)%

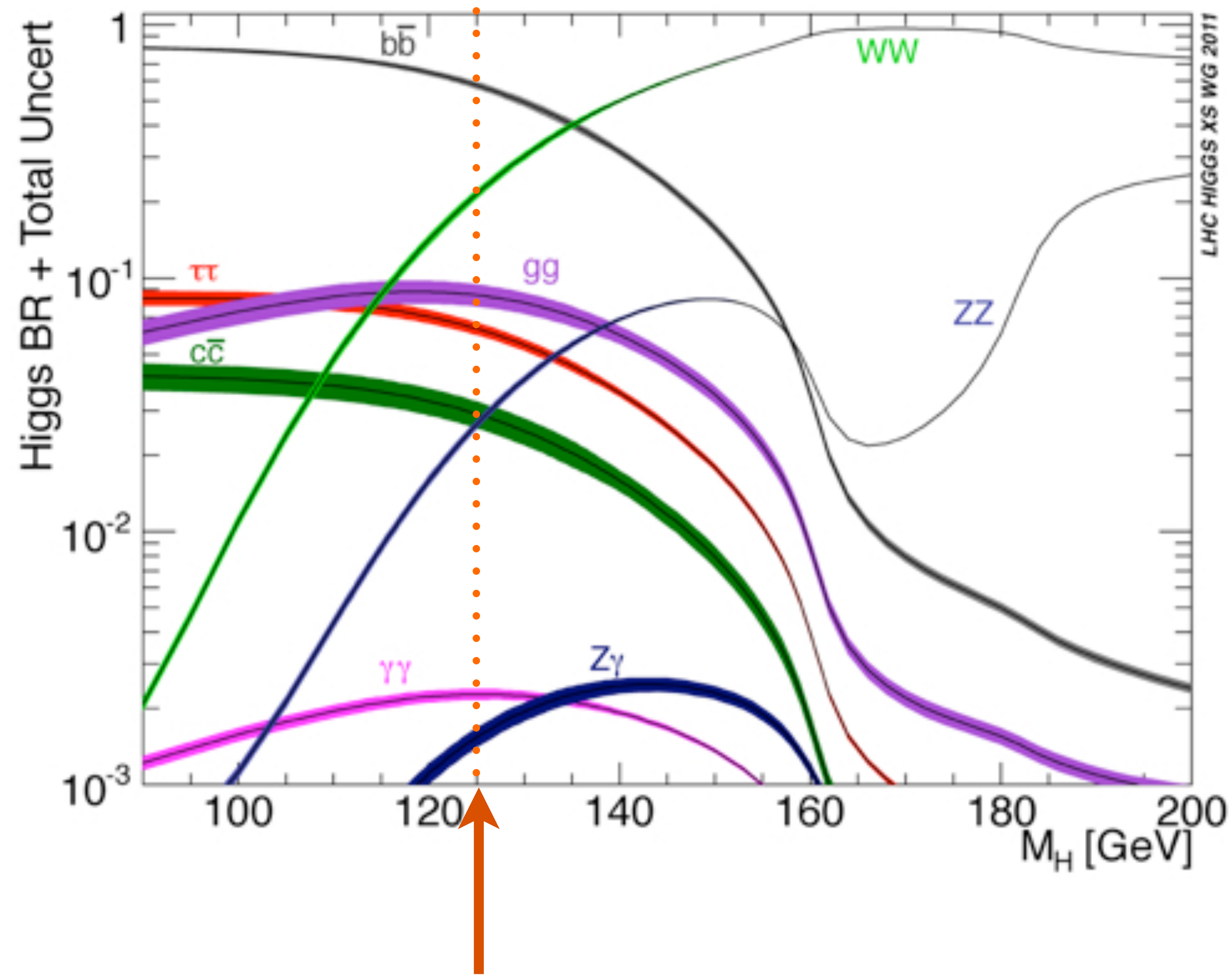
➡ Measurements of the Yukawa interactions between Higgs and fermions critical to determining the **true nature of the Higgs-like boson.**



Why Higgs into fermions?

A Standard Model Higgs boson with $\mathbf{m}_H \sim \mathbf{125\ GeV}/c^2$ decays most frequently into fermions. *e.g.* for $m_H = \mathbf{125\ GeV}/c^2$

- ➡ 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)%



➡ Measurements of the Yukawa interactions between Higgs and fermions critical to determining the **true nature of the Higgs-like boson.**

This talk: searches for SM Higgs boson production between $\mathbf{100 < m_H/GeV < 150}$ using up to $\mathbf{4.7\ fb^{-1}}$ of $\sqrt{s} = \mathbf{7\ TeV}$ data and up to $\mathbf{21\ fb^{-1}}$ of $\sqrt{s} = \mathbf{8\ TeV}$ data

$\boxed{VH, H \to b\bar{b} \quad \text{where} \quad V = W, Z}$

$\boxed{H \to \mu^+\mu^-}$ New!

$\boxed{ZH, H \to \text{invisible}}$ New!

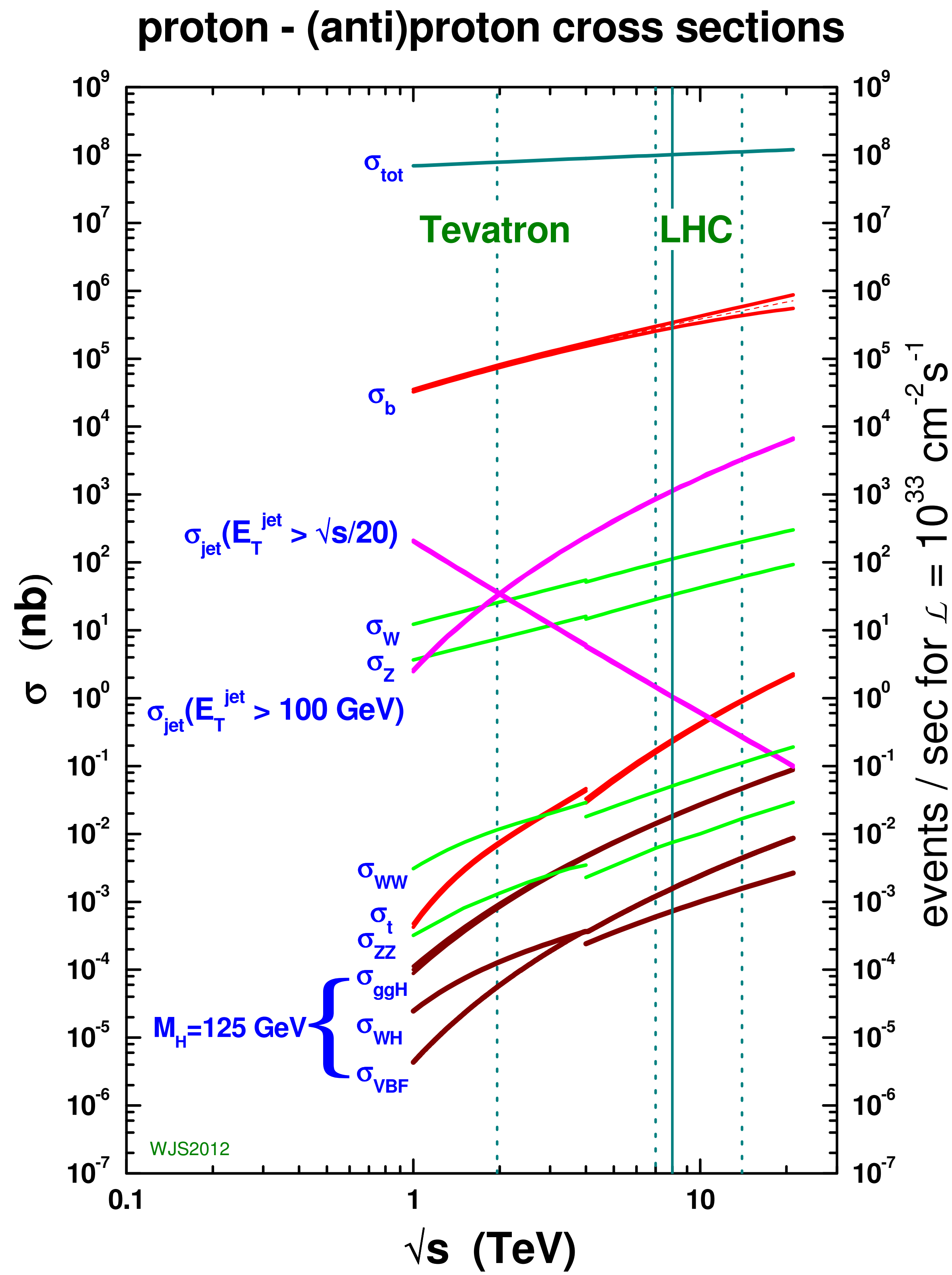
$\boxed{H \to \tau^+\tau^-}$

$\boxed{t\bar{t}H, H \to b\bar{b}}$

The Higgs needle in the LHC haystack

Huge backgrounds:

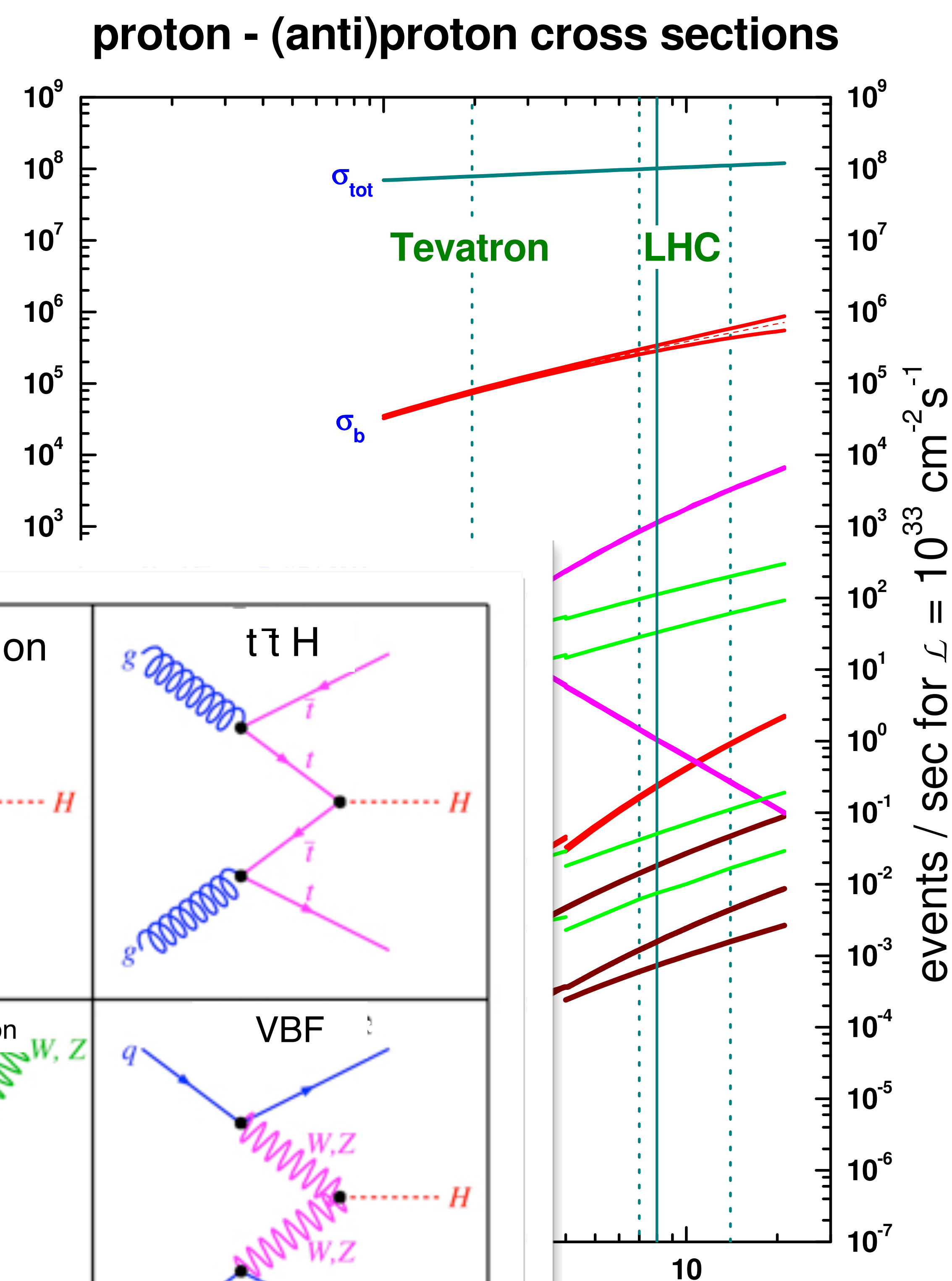
- high-p_T b-jet production:
  - ➡ ~10^6 larger than $H \to b\bar{b}$ production
- Drell-Yan/$Z \to \tau^+\tau^-$:
  - ➡ 10^5 larger than $H \to \tau^+\tau^-$ production



The Higgs needle in the LHC haystack

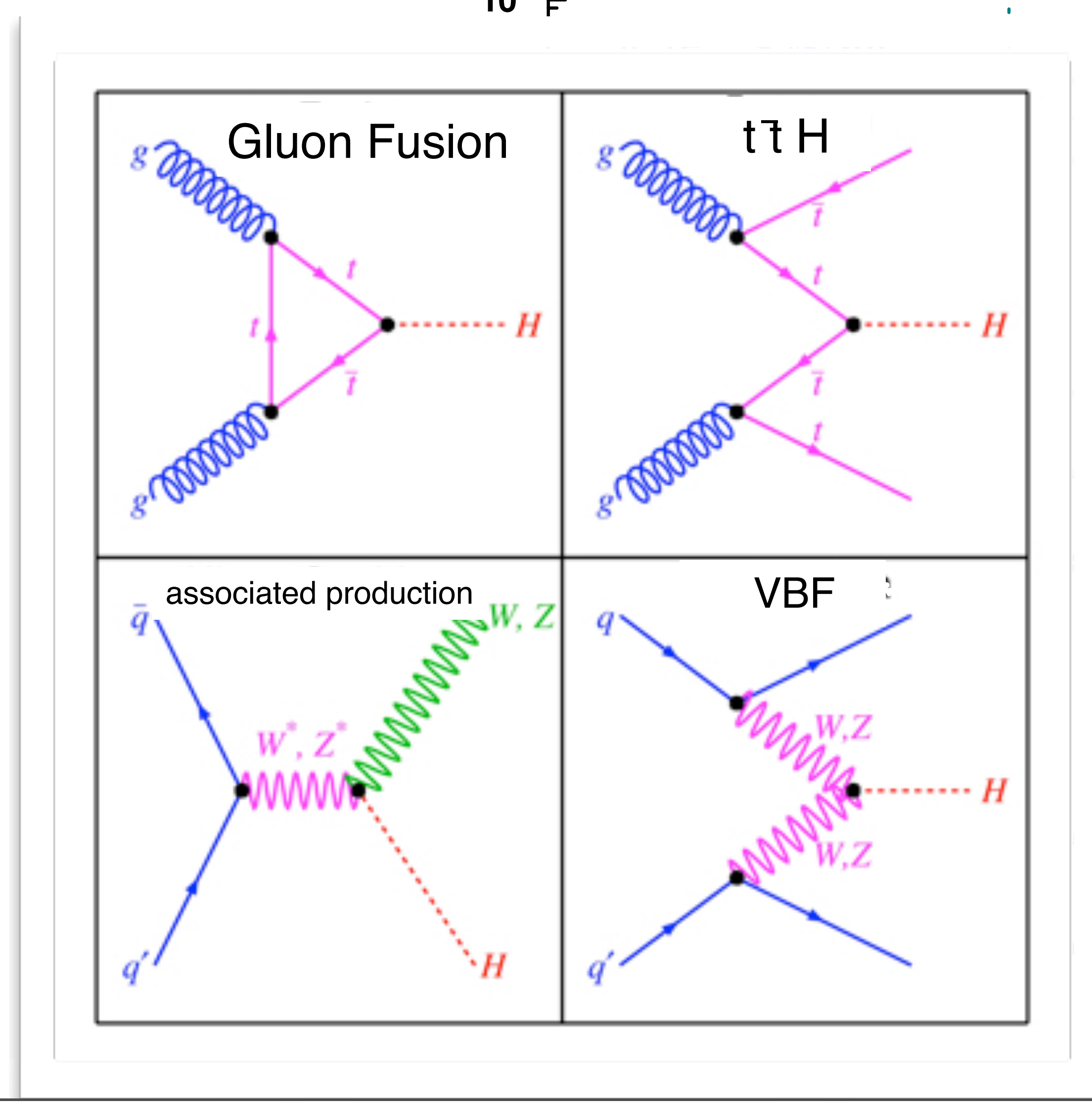
Huge backgrounds:

- high-p_T b-jet production:
  - ➡ $\sim 10^6$ larger than $H \rightarrow b\bar{b}$ production
- **Drell-Yan/$Z \rightarrow \tau^+\tau^-$:**
  - ➡ 10^5 larger than $H \rightarrow \tau^+\tau^-$ production



Exploit vector boson fusion and associated production:

- $pp \rightarrow jjVV \rightarrow jjH$
- $pp \rightarrow t\bar{t}H$
- $pp \rightarrow WH, pp \rightarrow ZH$



Identifying τ-leptons & Tagging b-jets

ATLAS-CONF-2012-142
ATLAS-CONF-2012-097
ATLAS-CONF-2012-043
ATLAS-CONF-2012-040
ATLAS-CONF-2011-102

- Exploit multivariant techniques to identify b-jets and hadronically decaying τ-leptons

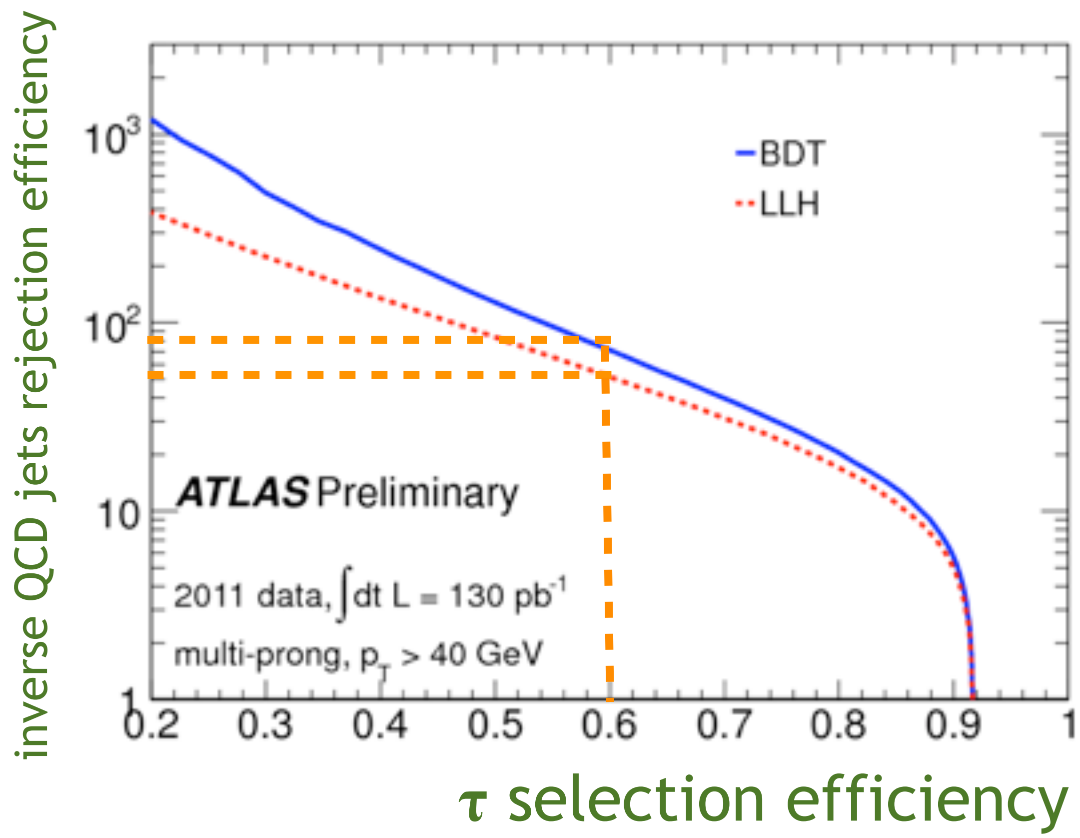
Identifying τ-leptons & Tagging b-jets

ATLAS-CONF-2012-142
ATLAS-CONF-2012-097
ATLAS-CONF-2012-043
ATLAS-CONF-2012-040
ATLAS-CONF-2011-102

- Exploit multivariant techniques to identify b-jets and hadronically decaying τ-leptons

$\tau \rightarrow \text{hadrons} + \nu_\tau$

- Jets + tracks used to form τ_{had} candidates
  - ➡ energy from MC
  - ➡ energy scale from isolated hadron data
- Analyses presented here use **60%** working point - selects **60%** of τ_{had}
- selects few% of QCD jets and <**1%** of electrons



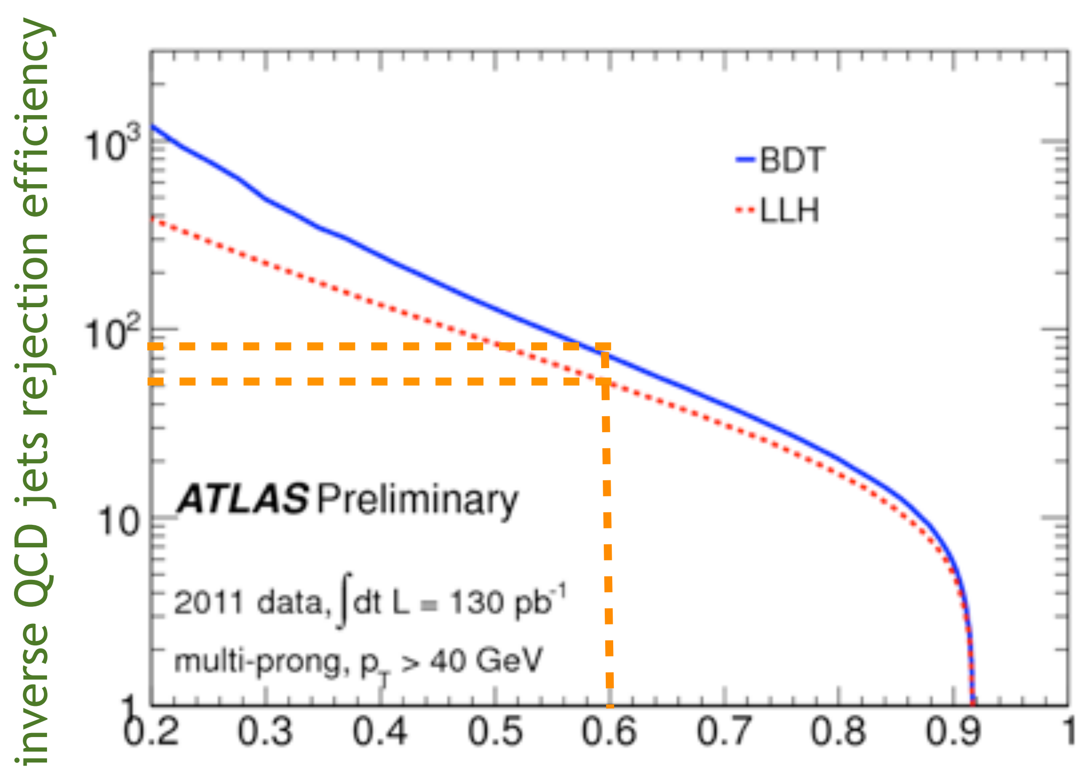
Identifying τ-leptons & Tagging b-jets

ATLAS-CONF-2012-142
ATLAS-CONF-2012-097
ATLAS-CONF-2012-043
ATLAS-CONF-2012-040
ATLAS-CONF-2011-102

- Exploit multivariant techniques to identify b-jets and hadronically decaying τ-leptons

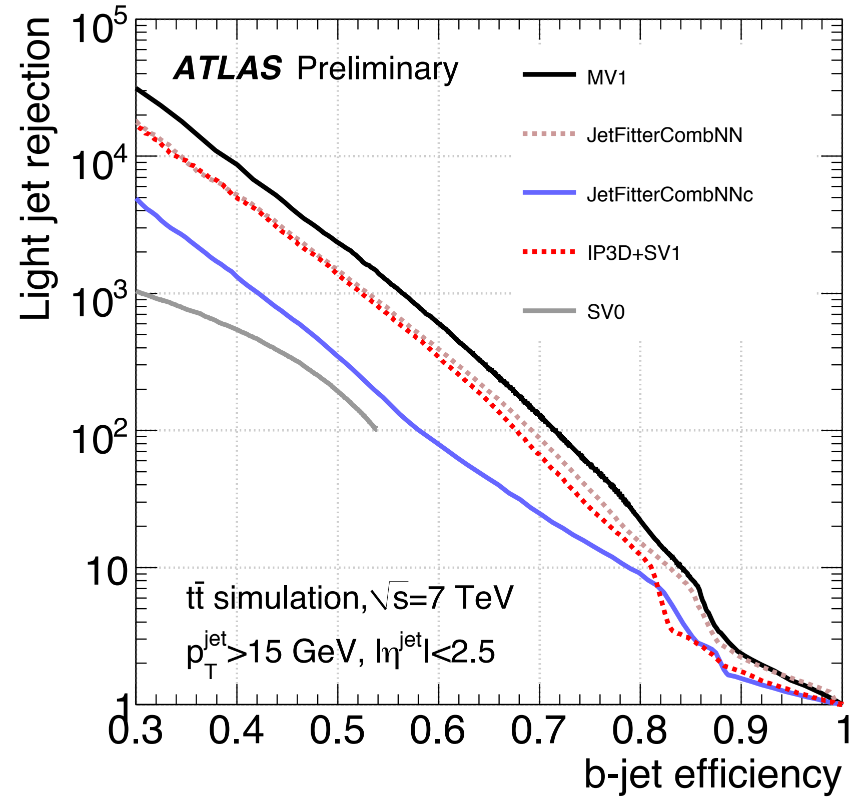
$\tau \rightarrow$ hadrons$+\nu_\tau$

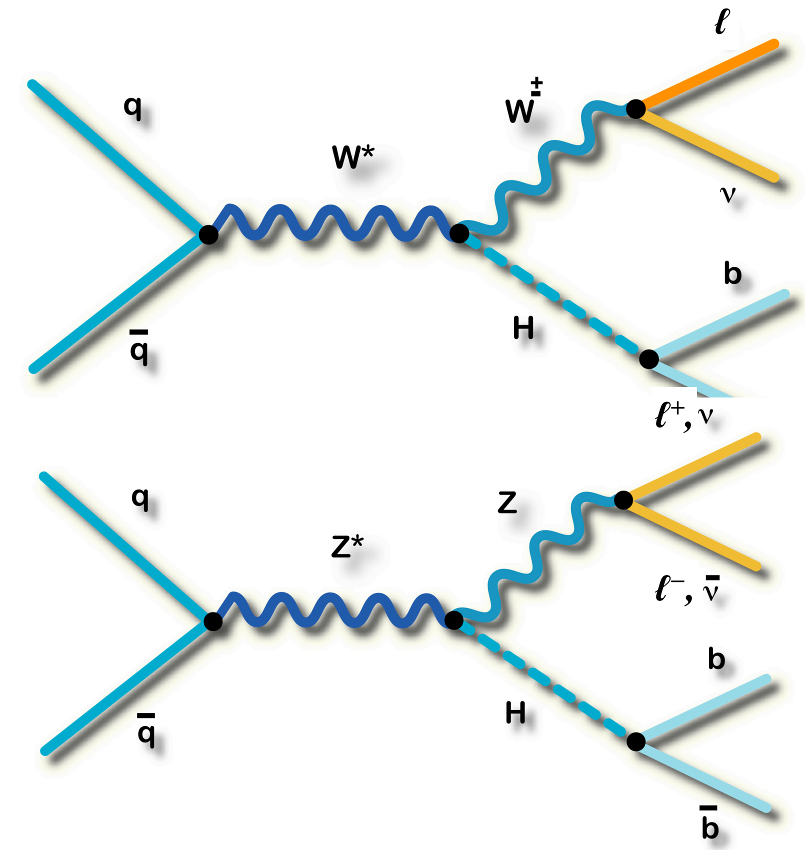
- Jets + tracks used to form τ_{had} candidates
  - ➡ energy from MC
  - ➡ energy scale from isolated hadron data
- Analyses presented here use **60%** working point - selects **60%** of τ_{had}
- selects few% of QCD jets and **<1%** of electrons



b-jet tagging

- Uses secondary & subsequent vertices along b-hadron line of flight
- Analyses presented here use **70%** working point
  - ➡ selects **70%** of b-jets
  - ➡ mistag rate for light jets ~**1%**



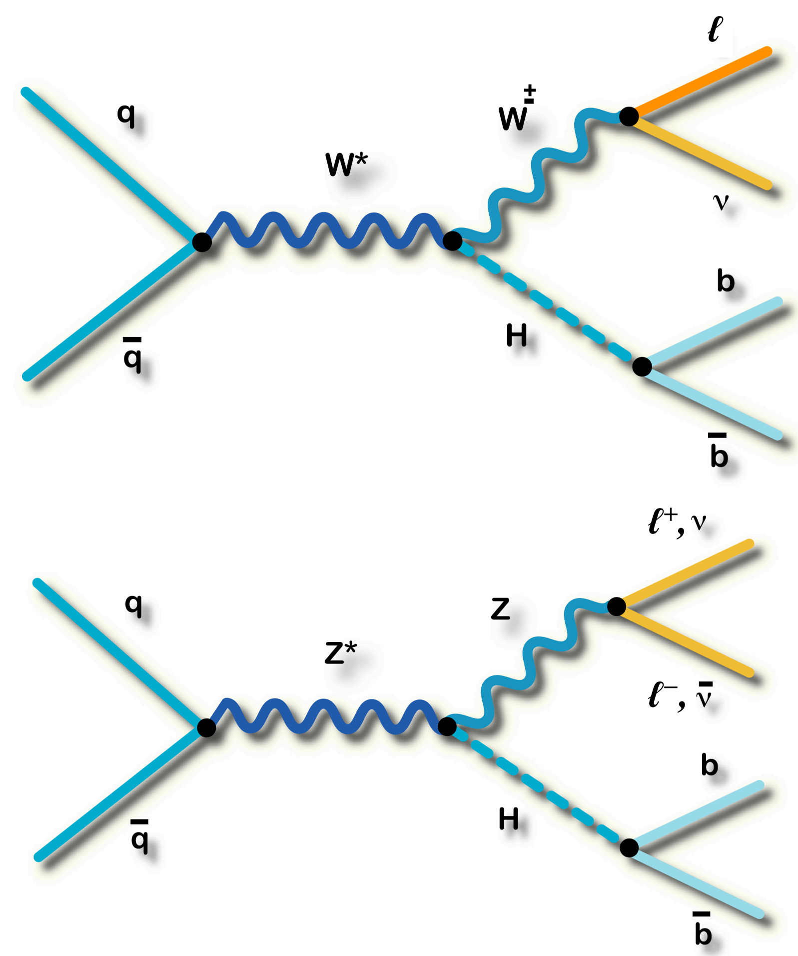


$H \rightarrow b\bar{b}$ searches using WH and ZH

ATLAS-CONF-2012-161

$VH \to Vb\bar{b}$ Analysis Strategy

$H \to b\bar{b}$ produced in association with leptonically decaying W or Z



Three channels: based on exactly 0, 1 or 2 charged leptons, $\ell=\{e, \mu\}$

➡ Two or three jets with two b-tags

➡ To improve sensitivity analysis performed in bins of vector boson p_T ($p_T^{\ell\ell/\ell\nu}$ or E_T^{miss}): **16 bins in total**

➡ $m_{b\bar{b}}$ used as discriminating variable

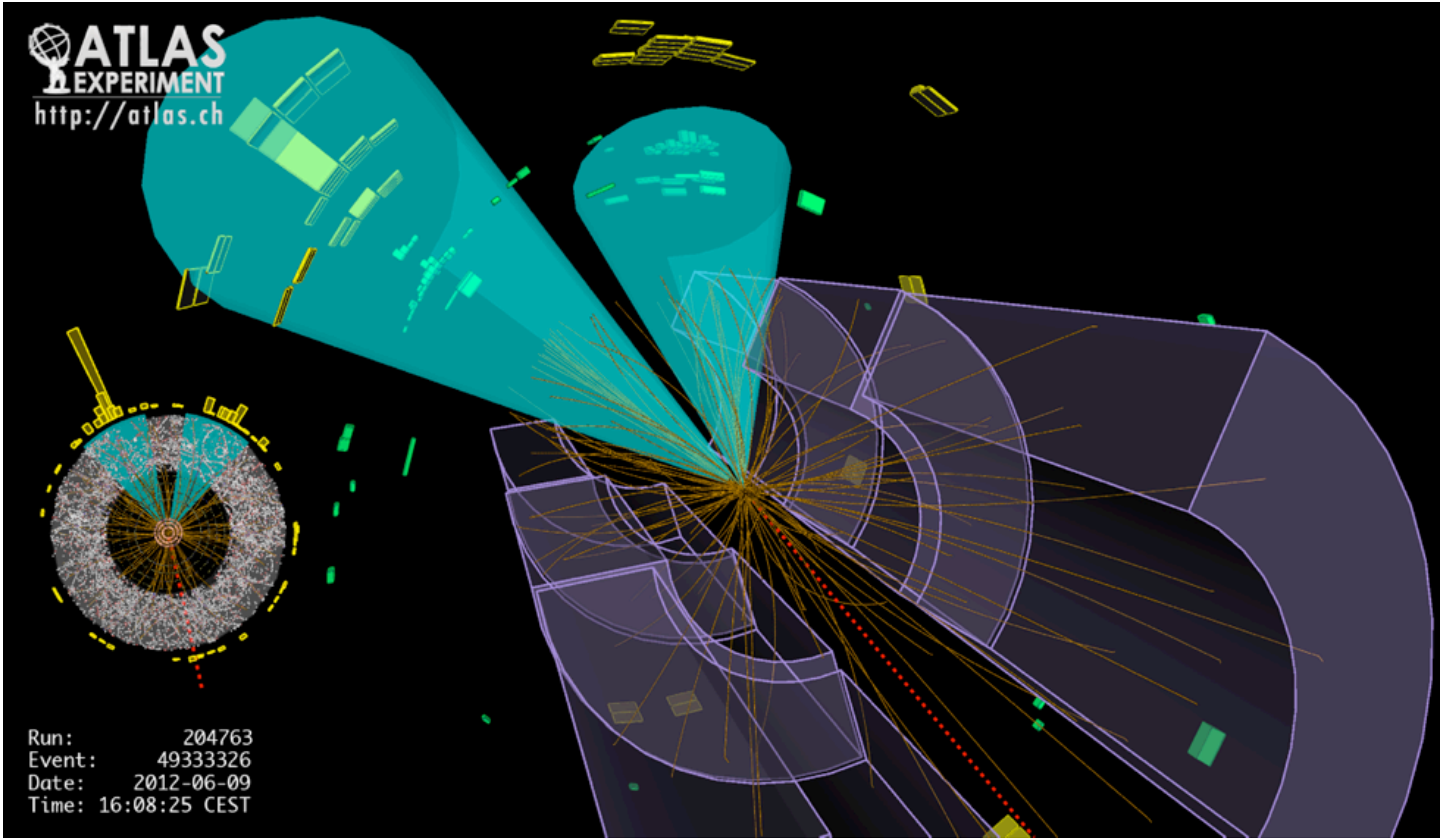
zero lepton ($ZH \to \bar{\nu}\nu b\bar{b}$)
- No electrons or muons
- $E_T^{miss} > 120$ GeV

one lepton ($WH \to \ell\nu b\bar{b}$)
- Exactly one high-p_T lepton
- $E_T^{miss} > 25$ GeV
- $40 < m_T^{\ell\nu}$ / GeV < 120

two leptons ($ZH \to \ell^+\ell^- b\bar{b}$)
- Exactly two high-p_T leptons
- opposite charge
- $E_T^{miss} < 60$ GeV
- $83 < m_{\ell\ell}$ / GeV < 99

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

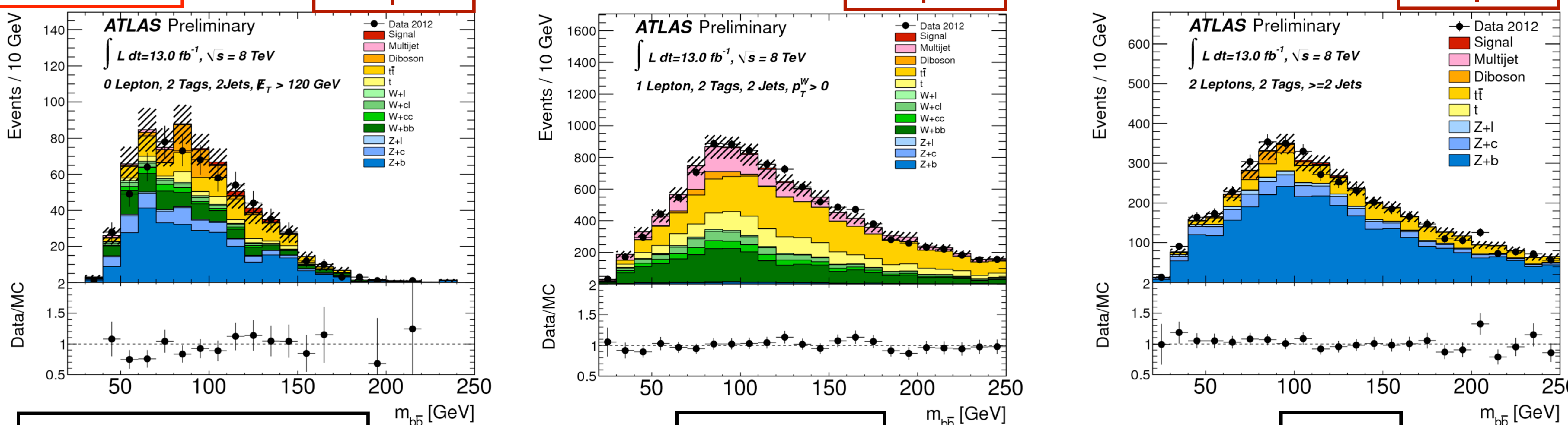
- $m_{b\bar{b}}$ = 123 GeV E_T^{miss} = 271 GeV



$VH \rightarrow Vb\bar{b}$ Backgrounds and Systematics

- Background shapes from simulation, normalised using data
- Multijet bkg determined by data-driven techniques
- $WZ(Z \rightarrow b\bar{b})$ & $ZZ(Z \rightarrow b\bar{b})$ background normalisation and shape from simulation

0-lepton 1-lepton 2-lepton



Z+jets *W*+jets top

W+jets top

Z+jets

Main uncertainties:

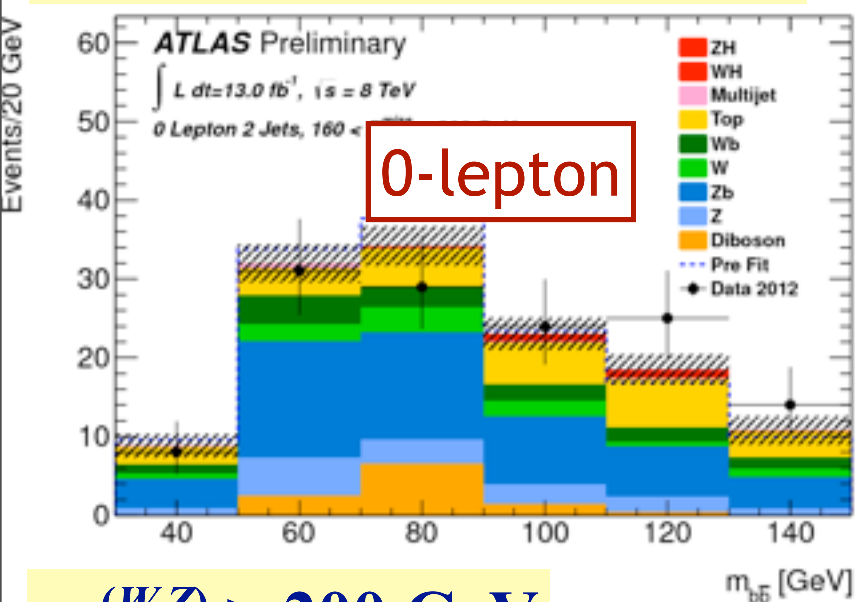
➡ *b*-/*c*-tagging ; jet energy scale & resolution ; MC statistics

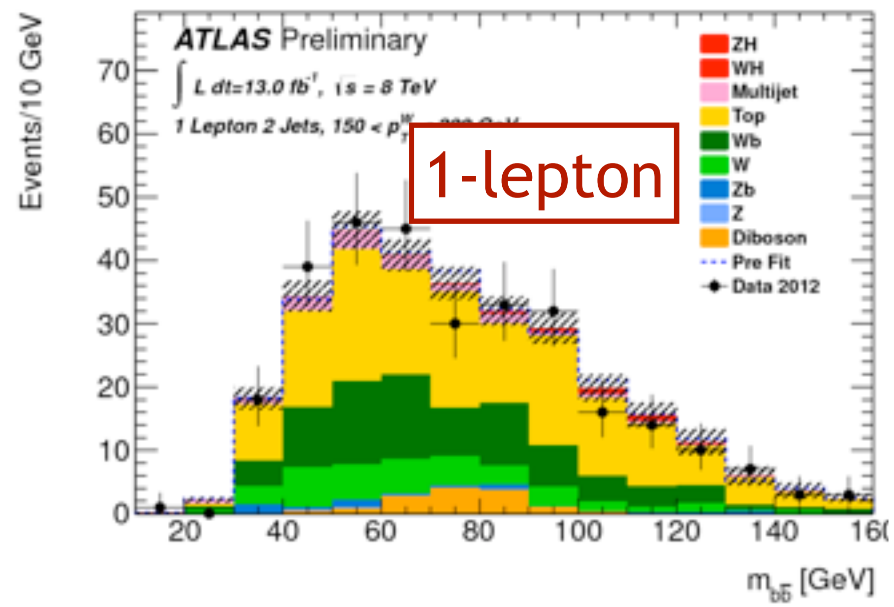
➡ Systematics are constrained by fitting m_{bb} distributions to the data

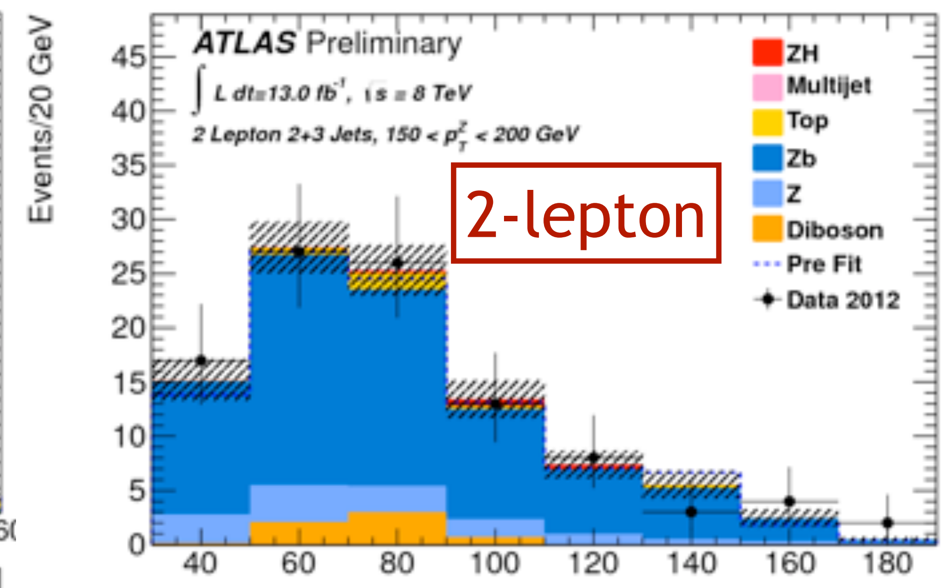
m_{bb} distributions at $\sqrt{s} = 8$ TeV

- Highest $p_T^{(W,Z)}$ bins are the most sensitive to Higgs signal

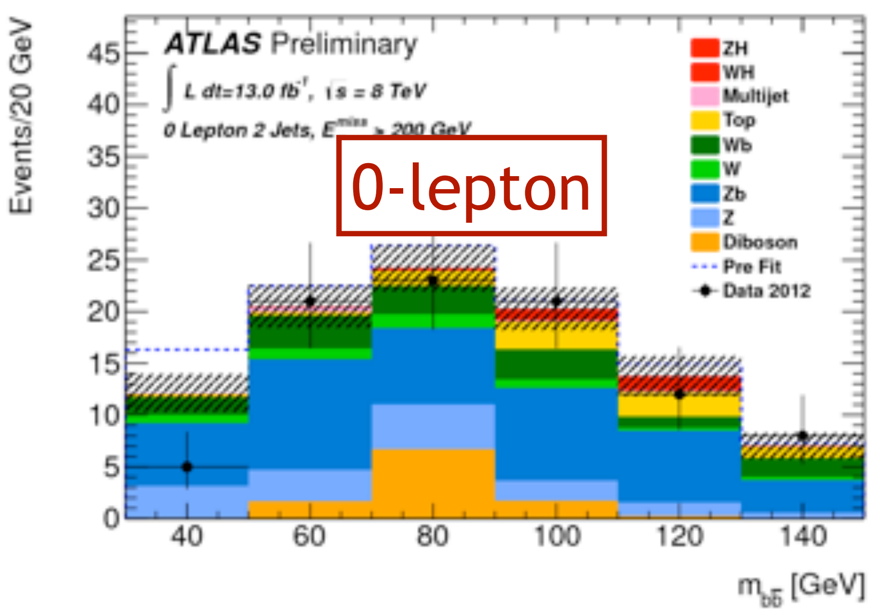
$150, 160 < p_T^{(W,Z)}/\mathrm{GeV} < 200$

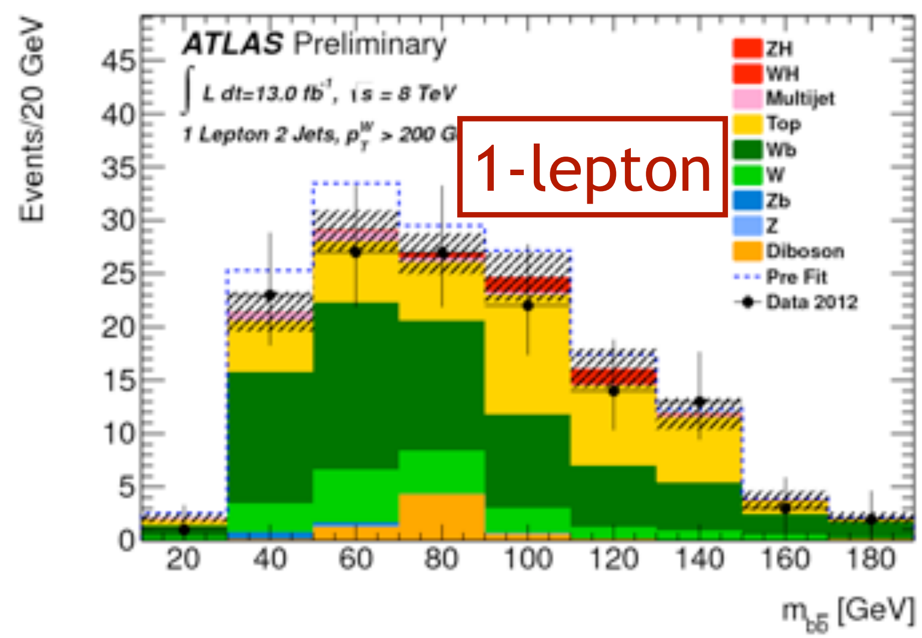


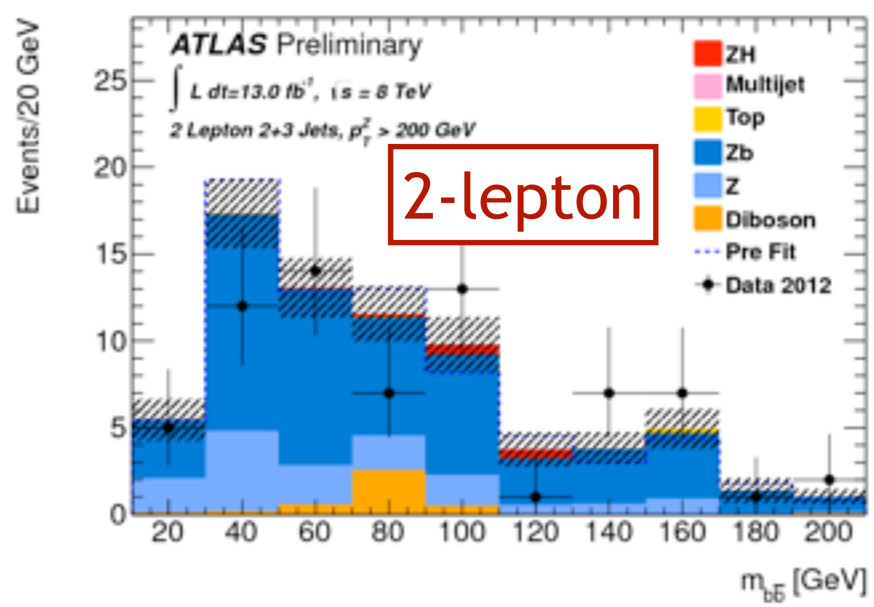




$p_T^{(W,Z)} > 200$ GeV







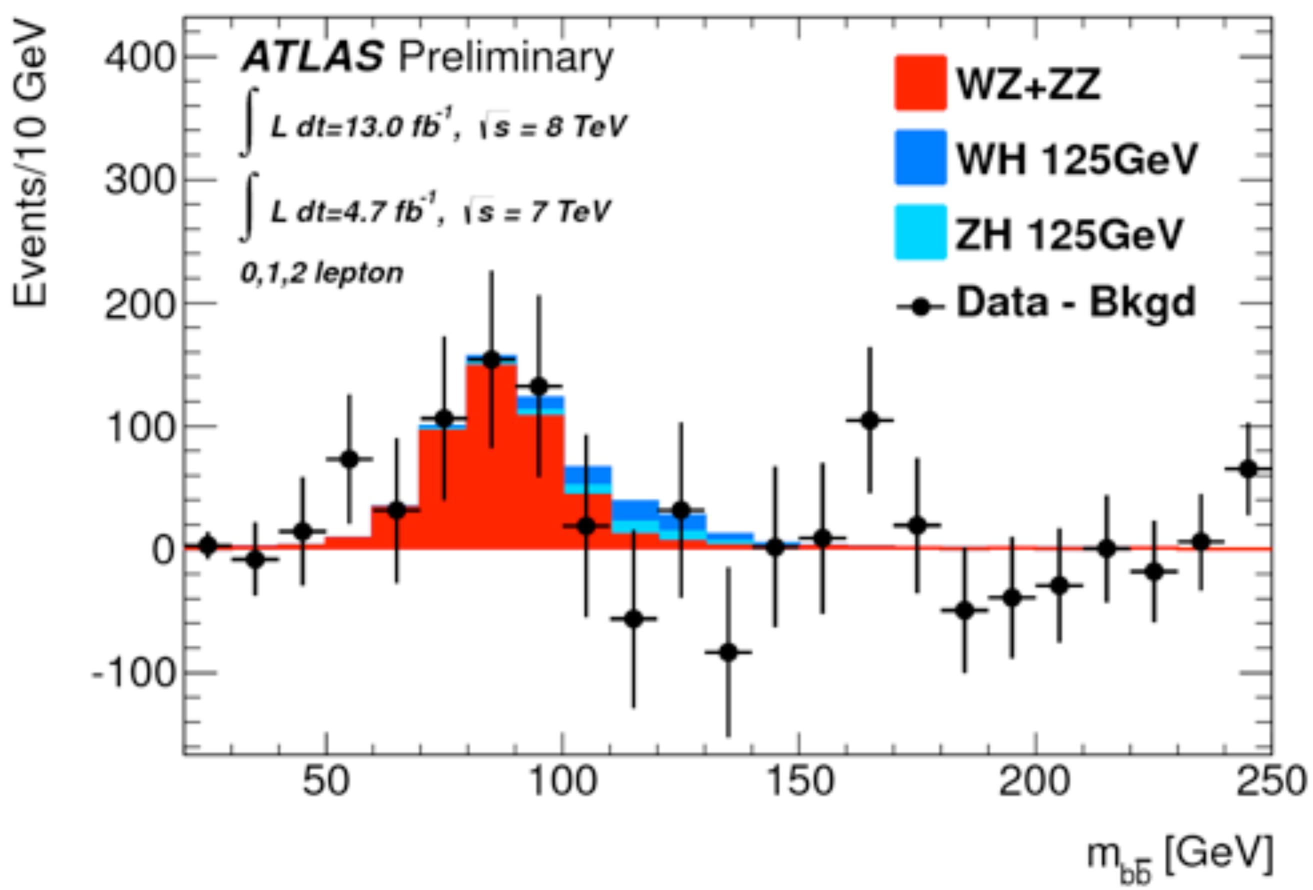
No observation of deviation from SM backgrounds

95% CL limit on σ/σ_{SM} for m_H=125 GeV:

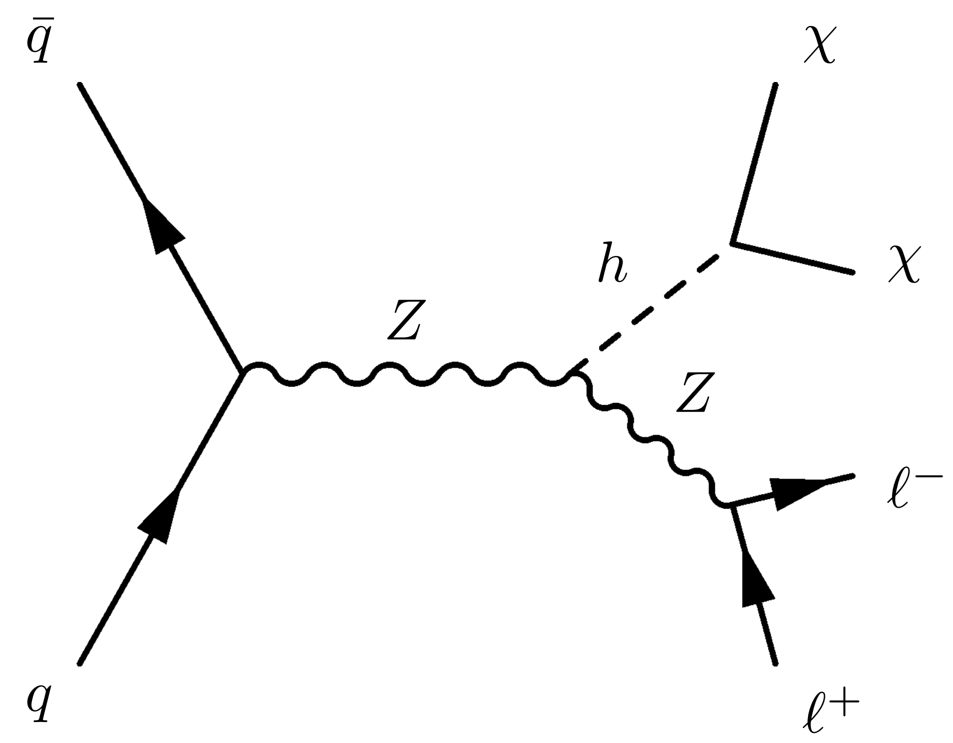
1.8 (measured); **1.9** (expected)

$VH \to Vb\bar{b}$ cross check: observation of $VZ \to Vb\bar{b}$

- WZ, ZZ production with $Z \to b\bar{b}$ similar signature, but $5 \times$ cross-section
- Perform a separate fit to find $Z \to b\bar{b}$ and validate the analysis
  - ➡ Backgrounds - except VZ & VH are subtracted
  - ➡ Uses full $p_T^{W,Z}$ range, performed individually for 0, 1, 2-lepton channels and for $\sqrt{s}$=7, 8 TeV



Result: $\sigma/\sigma_{SM} = \mu_D = 1.09 \pm 0.20$ (stat) ± 0.22 (syst). Significance of 4.0σ



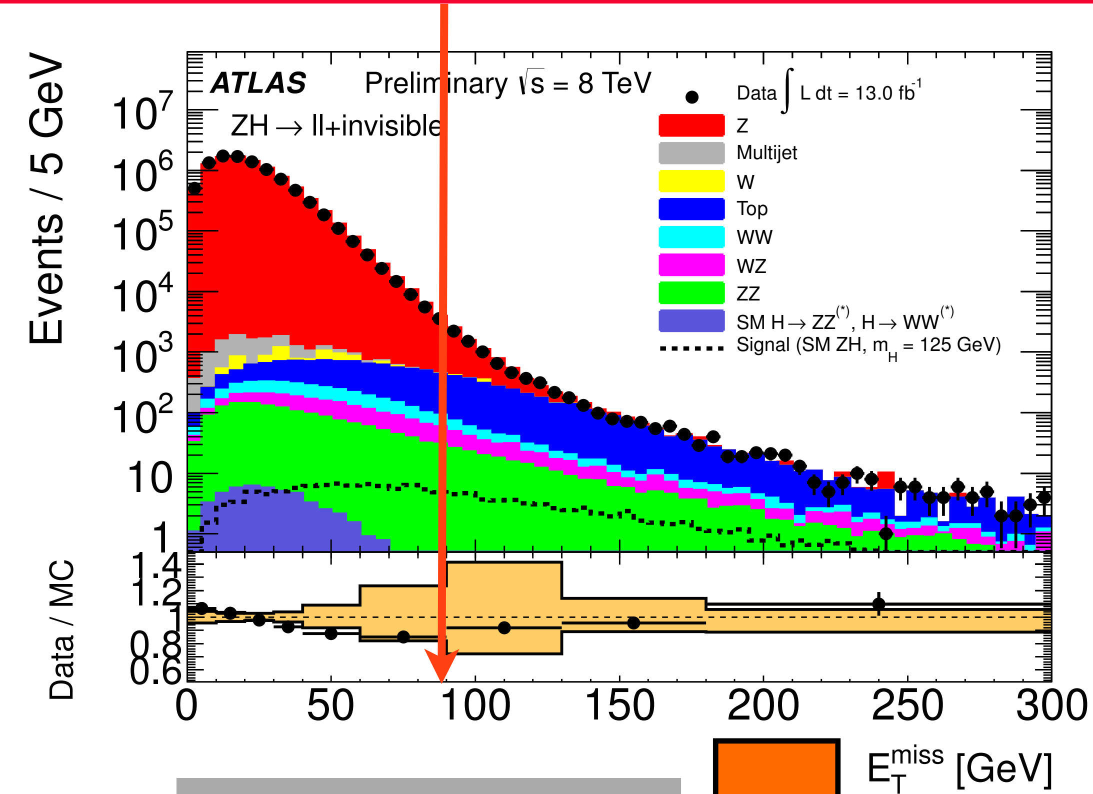
ZH, *H*→invisible searches

ATLAS-CONF-2013-011

New!

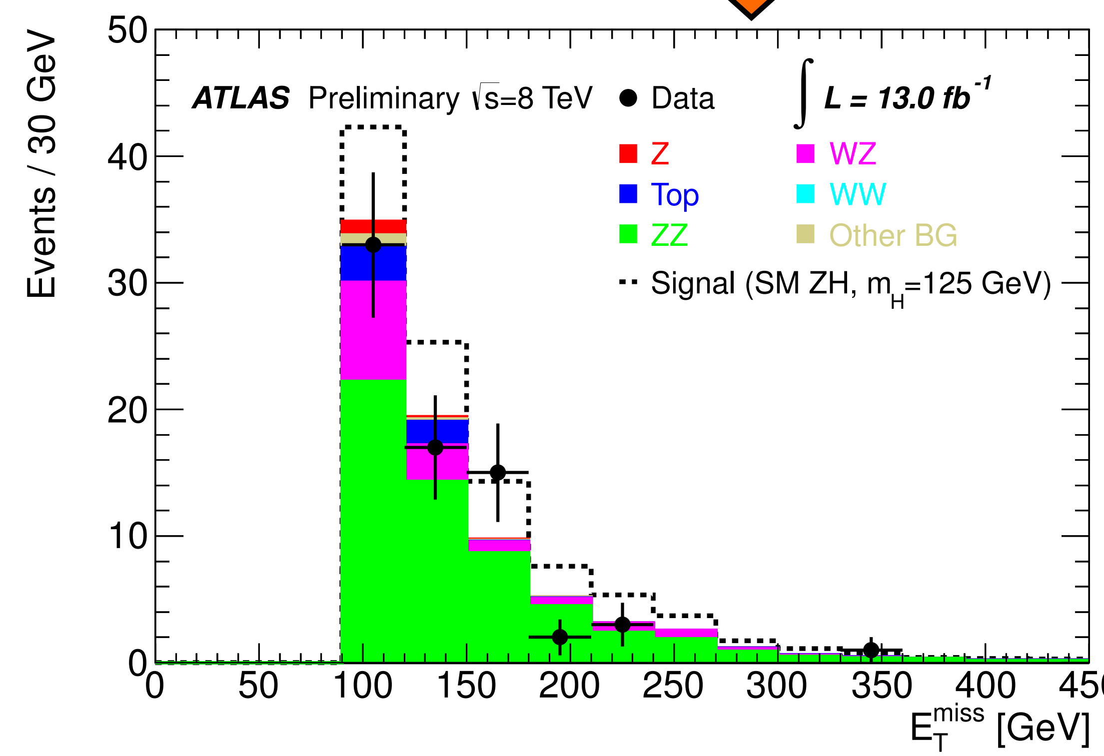
ZH, *H*→invisible search

- Signature: $Z \to e^+e^-$ or $Z \to \mu^+\mu^-$ with large E_T^{miss}
- Main backgrounds:
  - $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ (70%)
  - $WZ \to \ell\nu\ell^+\ell^-$, one ℓ escaping detection (20%)
  - $WW \to \ell^+\nu\ell^-\bar{\nu}$ (5%)
  - Require $E_T^{miss} > 90$ GeV and optimise selection cuts to select *ZH*-like events



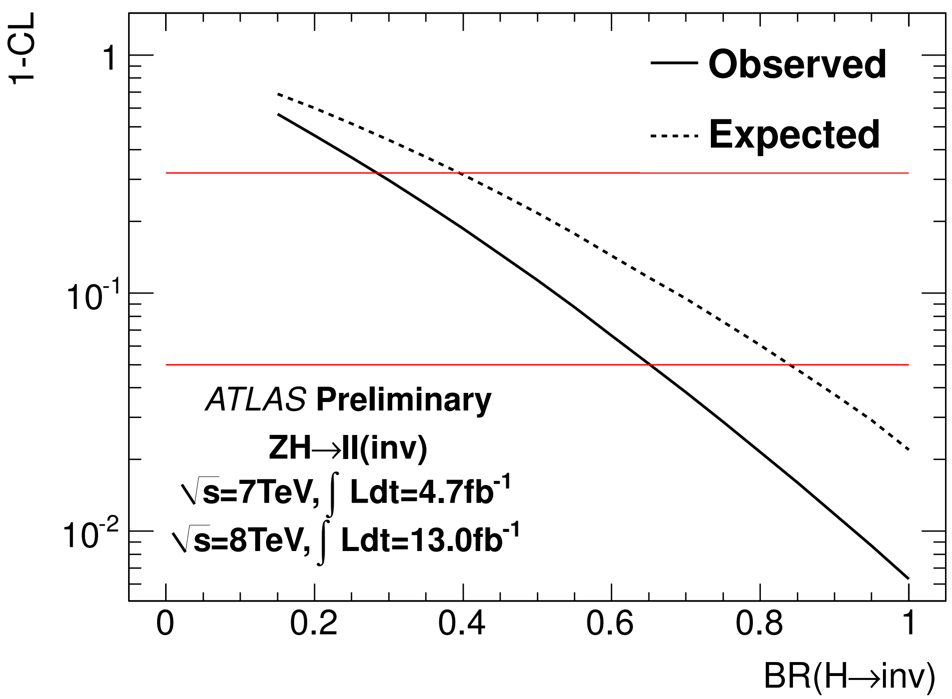
Optimised selection cuts

	expected SM backgrounds	observed events
√s = 7 TeV 4.7 fb^{-1}	32.7 ± 1.0 (stat) ± 2.6 (syst)	27
√s = 8 TeV 13.0 fb^{-1}	78.0 ± 2.0 (stat) ± 6.5 (syst)	71



ZH, *H*→invisible results

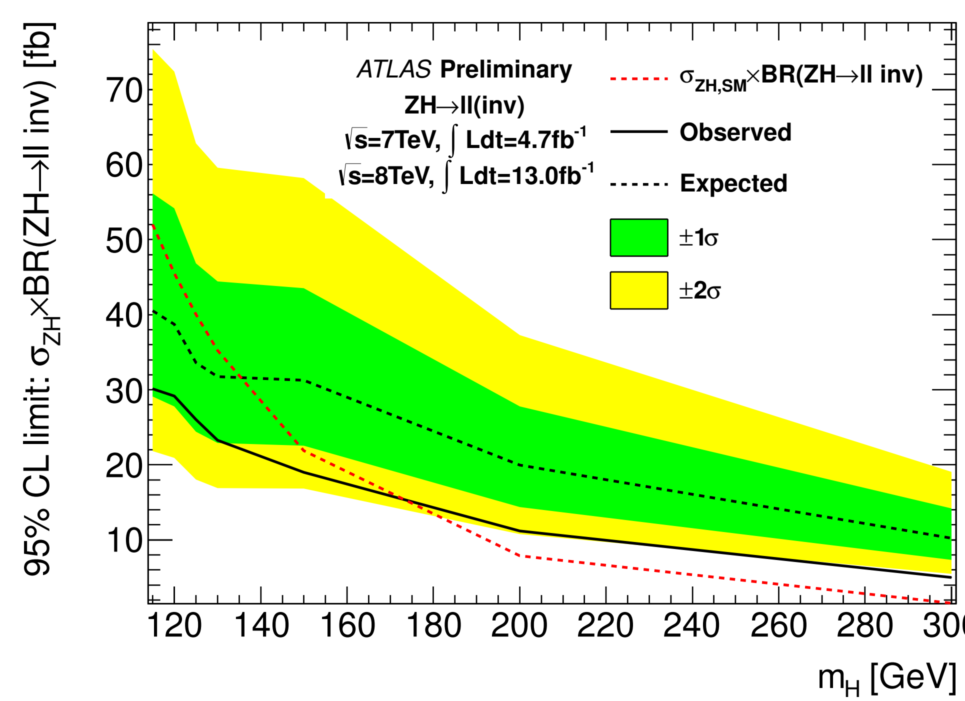
- Results are interpreted two ways:
  - ➡ Limit on **BR(*H*→invisible)** for SM **m_H=125 GeV** production

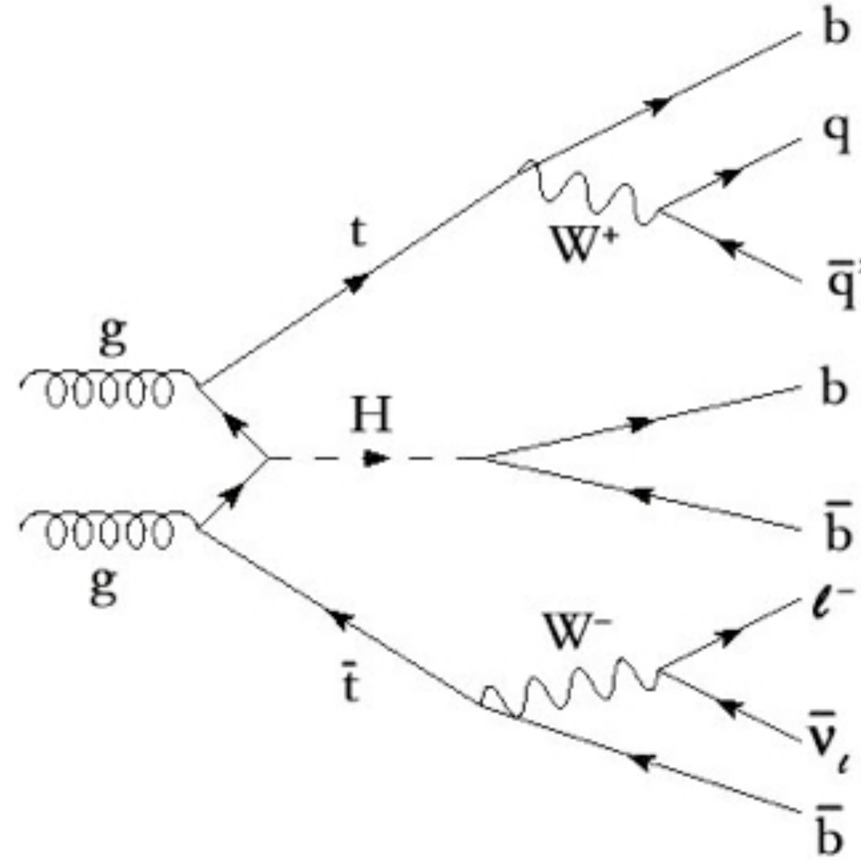


95% CL limit on **BR(*H*→invisible)** for **m_H=125 GeV**:

<65% (measured); **<84%** (expected)

➡ Limits on **σ(*ZH*) * BR(*ZH*→ℓℓ invisible)** for further Higgs-like states with **115 < m_H / GeV < 300**





$t\bar{t}H, H \rightarrow b\bar{b}$ searches

ATLAS-CONF-2012-135

$t\bar{t}H,\, H \rightarrow b\bar{b}$ Reconstruction

$$t\bar{t}H \rightarrow W^{+}b\; W^{-}\bar{b}\; b\bar{b} \rightarrow \ell^{+}\nu b\; j\bar{j}\bar{b}\; b\bar{b}$$

- Events with ≥ 3 ***b*-tags**, $\geq$ **6** jets use **kinematic likelihood fitter** to assign (within decay widths and detector resolutions):

➡ 1 $e^{\pm}$ or $\mu^{\pm}$
➡ E_{T}^{miss}
➡ 4 ***b***-jets
➡ 2 light jets

- **2 *W***-bosons
- **2** top-quarks
- **1** Higgs boson

$t\bar{t}H,\, H \to b\bar{b}$ Reconstruction

$$t\bar{t}H \to W^{+}b\ W^{-}\bar{b}\ b\bar{b} \to \underbrace{\ell^{+}\nu}_{m_W} b\ \underbrace{j\bar{j}}_{m_W}\bar{b}\ b\bar{b}$$

- Events with ≥ 3 b-tags, ≥ 6 jets use **kinematic likelihood fitter** to assign (within decay widths and detector resolutions):

➡ 1 $e^{\pm}$ or $\mu^{\pm}$
➡ E_{T}^{miss}
➡ 4 b-jets
➡ 2 light jets

- 2 W-bosons
- 2 top-quarks
- 1 Higgs boson

$t\bar{t}H,\, H \to b\bar{b}$ Reconstruction

$$t\bar{t}H \to W^+b\; W^-\bar{b}\; b\bar{b} \to \underbrace{\underbrace{\ell^+\nu}\,b}_{m_t}\; \underbrace{\underbrace{j\bar{j}}\,\bar{b}}_{m_t}\; b\bar{b}$$

- Events with ≥ 3 ***b*-tags**, ≥ 6 **jets** use **kinematic likelihood fitter** to assign (within decay widths and detector resolutions):

➡ 1 $e^{\pm}$ or $\mu^{\pm}$
➡ E_T^{miss}
➡ 4 b-jets
➡ 2 light jets

- **2** W-bosons
- **2** top-quarks
- **1** Higgs boson

$t\bar{t}H,\, H \to b\bar{b}$ Reconstruction

$$t\bar{t}H \to W^+b\; W^-\bar{b}\; b\bar{b} \to \underbrace{\underbrace{\ell^+\nu}\,b}_{m_t}\; \underbrace{\underbrace{j\bar{j}}\,\bar{b}}_{m_t}\; \underbrace{b\bar{b}}_{\text{no mass constraint}}$$

- Events with ≥ 3 ***b***-tags, ≥ 6 jets use **kinematic likelihood fitter** to assign (within decay widths and detector resolutions):

➡ 1 $e^{\pm}$ or $\mu^{\pm}$
➡ $E_{\mathrm{T}}^{\mathrm{miss}}$
➡ 4 ***b***-jets
➡ 2 light jets

- **2** ***W***-bosons
- **2** top-quarks
- **1** Higgs boson

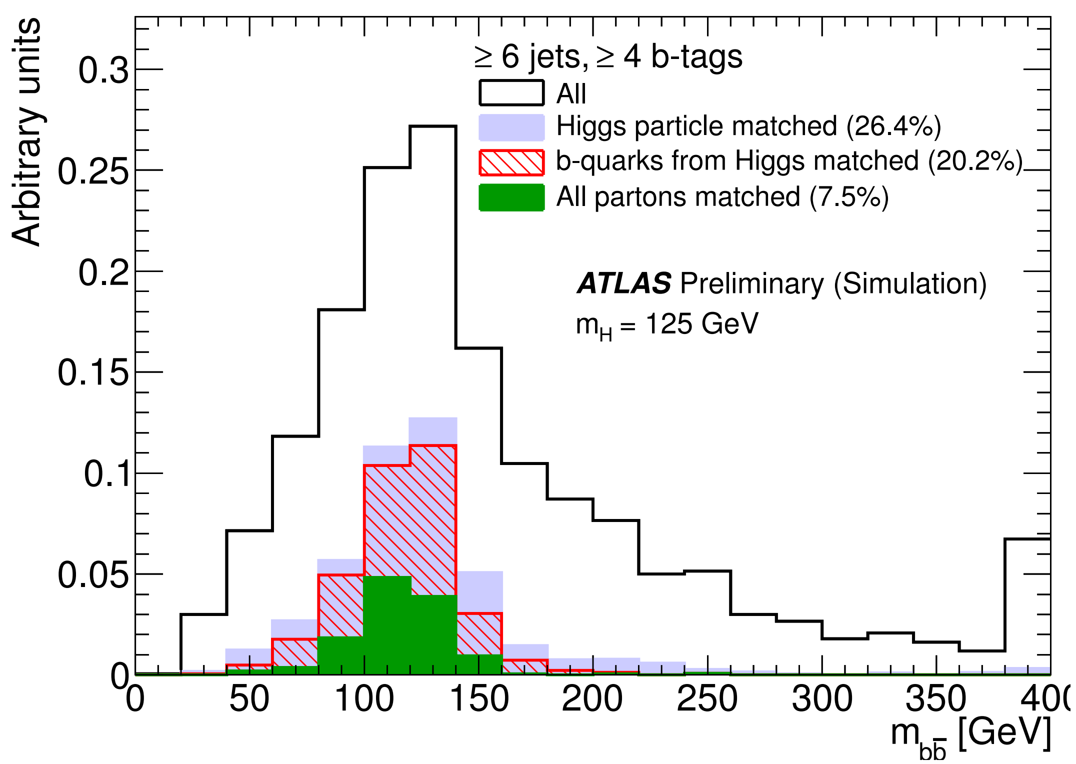
$t\bar{t}H,\ H \to b\bar{b}$ Reconstruction

$$t\bar{t}H \to W^+b\ W^-\bar{b}\ b\bar{b} \to \underbrace{\underbrace{\ell^+\nu}b}_{m_t}\ \underbrace{\underbrace{j\bar{j}}\bar{b}}_{m_t}\ \underbrace{b\bar{b}}_{\text{no mass constraint}}$$

- Events with ≥ 3 b-tags, ≥ 6 jets use **kinematic likelihood fitter** to assign (within decay widths and detector resolutions):

➡ 1 $e^\pm$ or $\mu^\pm$ ➡ E_T^{miss} ➡ 4 b-jets ➡ 2 light jets	• 2 W-bosons • 2 top-quarks • 1 Higgs boson

➡ No constraint on $m_{b\bar{b}}$ ⇒ used as discriminating variable



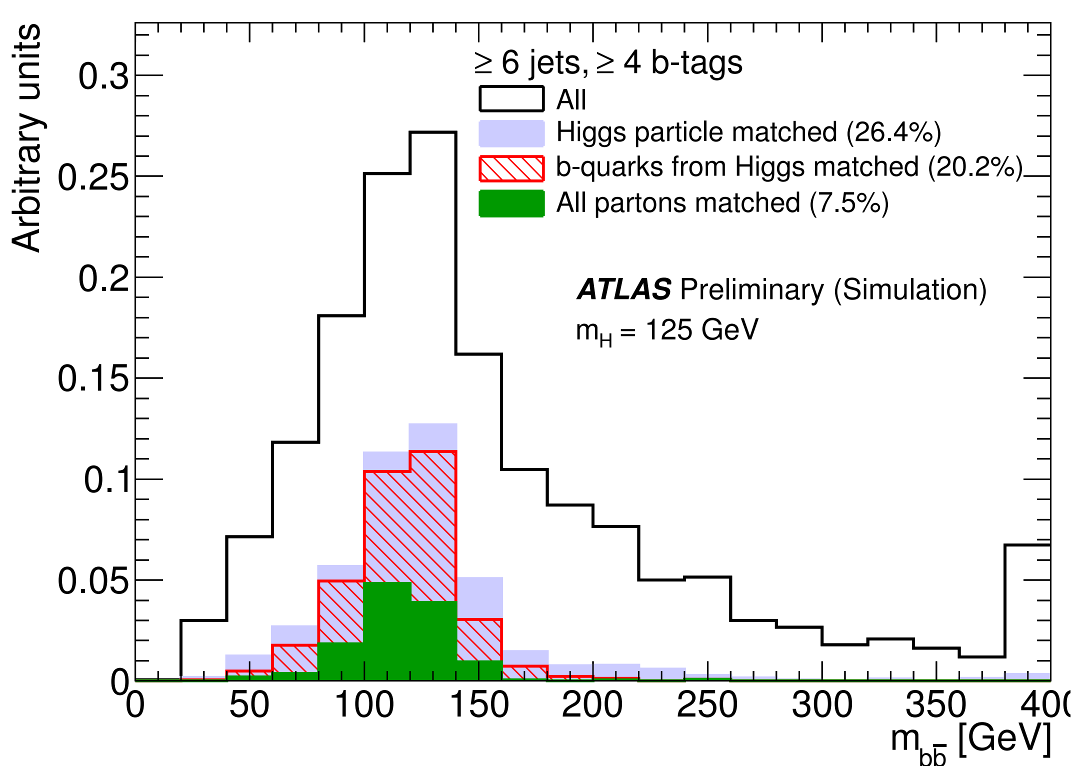
$t\bar{t}H, H \rightarrow b\bar{b}$ Reconstruction

$$t\bar{t}H \rightarrow W^+b\ W^-\bar{b}\ b\bar{b} \rightarrow \underbrace{\ell^+\nu b}_{m_t}\ \underbrace{j\bar{j}\bar{b}}_{m_t}\ \underbrace{b\bar{b}}_{\text{no mass constraint}}$$

- Events with ≥ 3 b-tags, ≥ 6 jets use **kinematic likelihood fitter** to assign (within decay widths and detector resolutions):

➡ 1 $e^{\pm}$ or $\mu^{\pm}$ ➡ E_T^{miss} ➡ 4 b-jets ➡ 2 light jets	• 2 W-bosons • 2 top-quarks • 1 Higgs boson

➡ No constraint on $m_{b\bar{b}}$ ⇒ used as discriminating variable



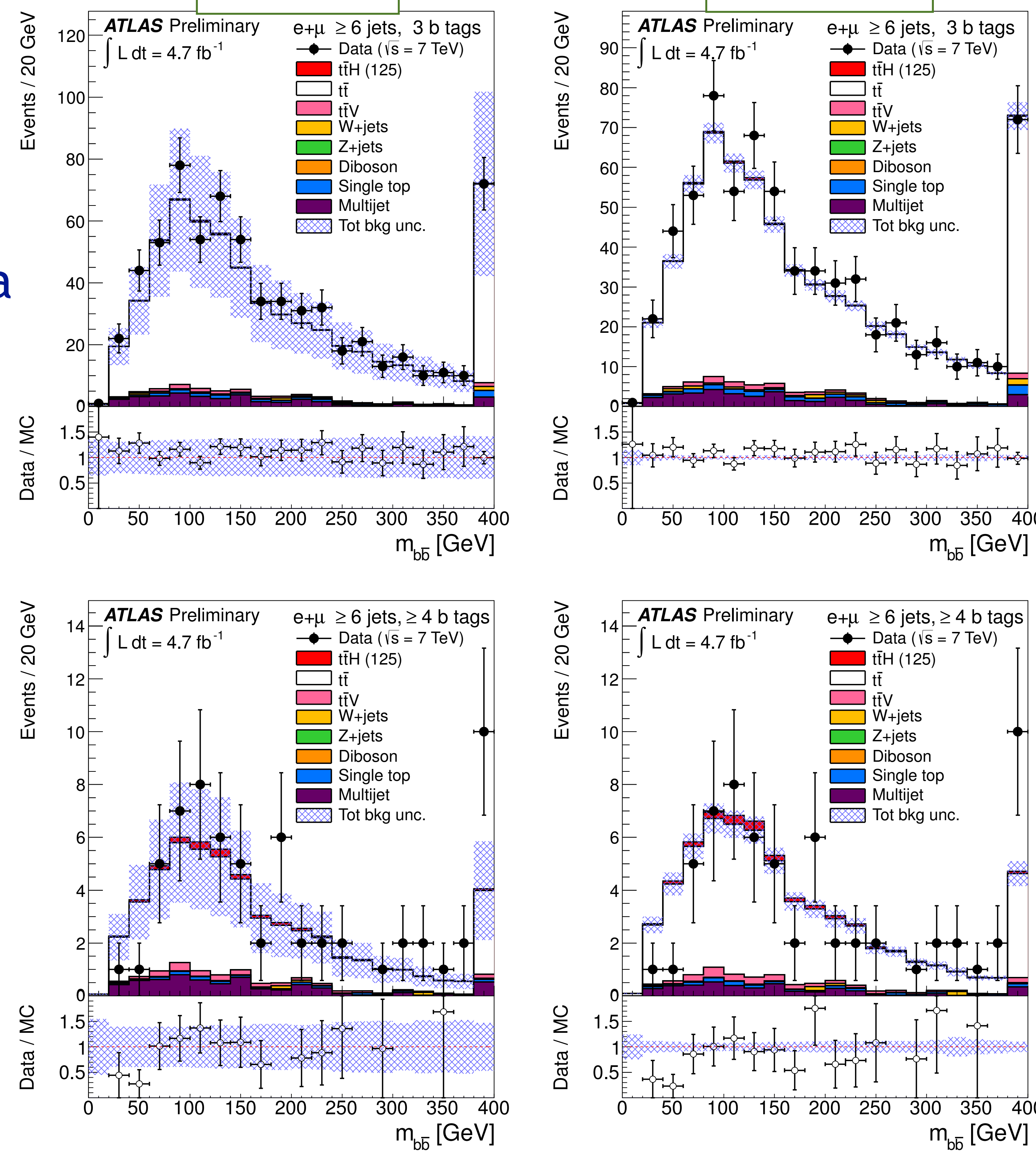
- Events with < 3 b-tags or < 6 jets included to improve sensitivity & constrain backgrounds
- examine H_T^{had}, scalar sum of jet p_T

$t\bar{t}H, H \rightarrow b\bar{b}$: $m_{b\bar{b}}$ and Fit

- Main background is $t\bar{t}$ production
- Main systematic due to ***b***- and ***c***-tagging uncertainties
  - Systematics are constrained by fitting the distributions to the data
  - Normalisations and shapes are allowed to vary in $m_{b\bar{b}}$ and H_T^{had}.

Pre-Fit

Post-Fit



No observation of deviation from SM backgrounds

95% CL limit on σ/σ_{SM} for m_H=125 GeV:

13.1 (measured); **10.5** (expected)

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

ATLAS-CONF-2012-160

$H \to \tau^+\tau^-$ searches

- Uses ~**10 exclusive** analysis categories dependent on τ final states, number of additional jets and kinematic features

- $m_{\tau\tau}$ is used as the discriminating variable.
  - $m_{\tau\tau}$ from Missing Mass Calculator (MMC) using measured momenta, E_T^{miss} and the simulated distribution of angle between visible and missing momenta

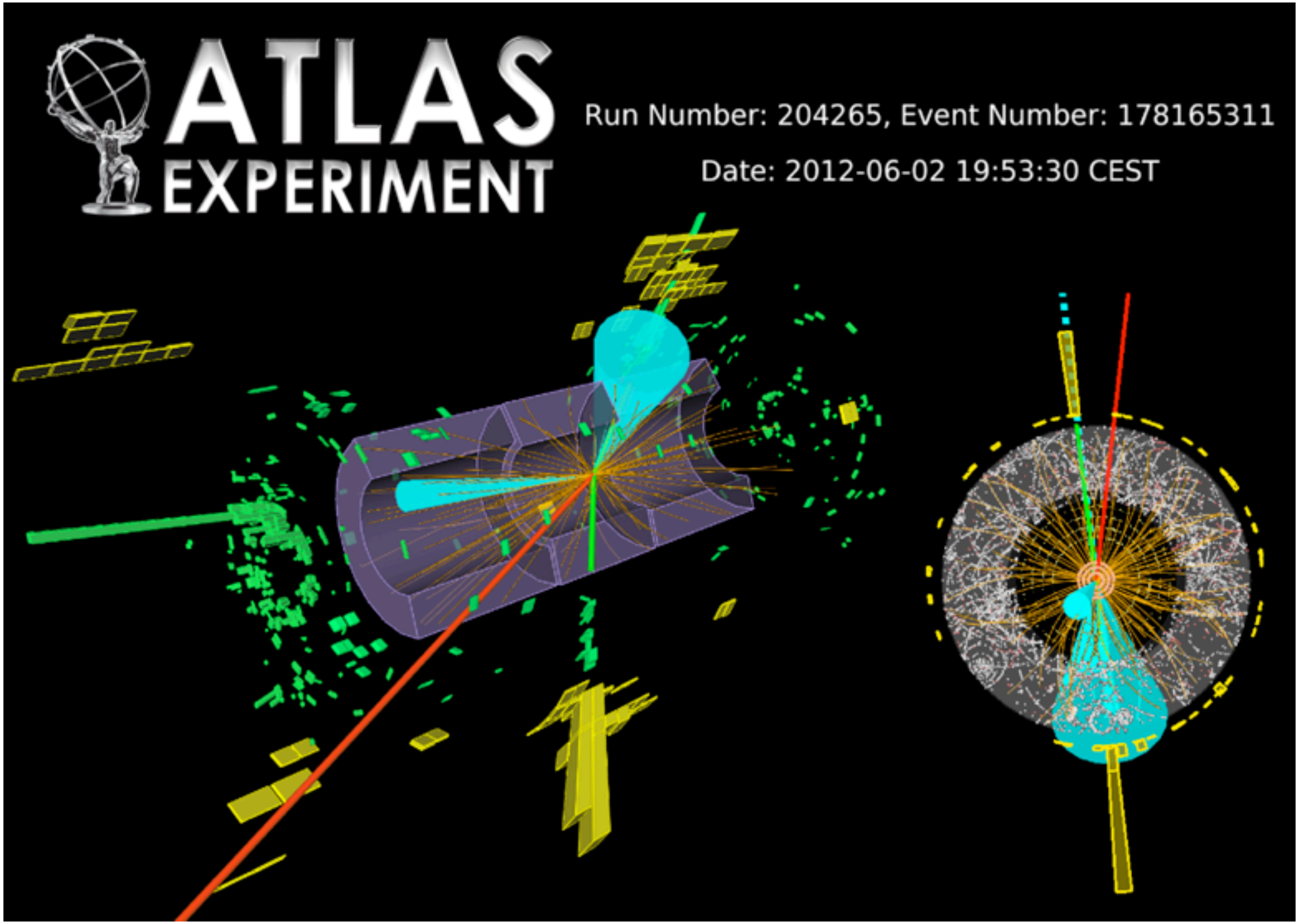
Categories for $\sqrt{s} = 8$ TeV data (similar for 7 TeV data)

	2-jet VBF 2 jets with $\Delta\eta > 3$ central jet veto	Boosted $p_T(\tau\tau) > 100$ GeV	2-jet VH $30 < m_{jj}/\mathrm{GeV} < 160$	1 QCD jet	0 QCD jets
$H \to \tau_{lep}\,\tau_{lep}$ (BR ~12.4%) acceptance ~1.6%				$m_{\tau\tau j} > 225$ GeV	
$H \to \tau_{had}\,\tau_{lep}$ (BR ~ 45.6%) acceptance ~2.4%					
$H \to \tau_{had}\,\tau_{had}$ (BR ~ 42%) acceptance ~0.3%					

Common selection: $E_T^{miss} > 20$ GeV, most jets have b-tag veto → Priority

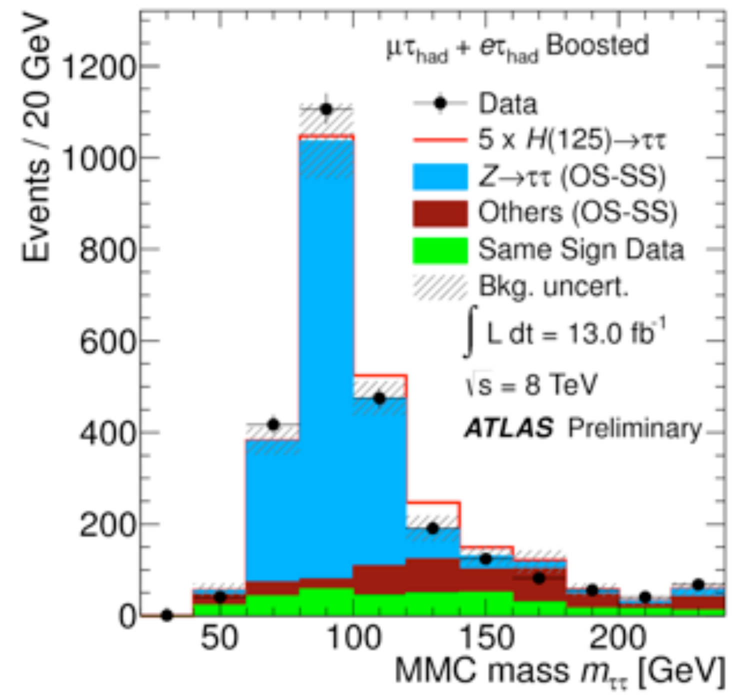
VBF $H \rightarrow \tau_{\mathrm{had}}\, \tau_{\mu}$ candidate event

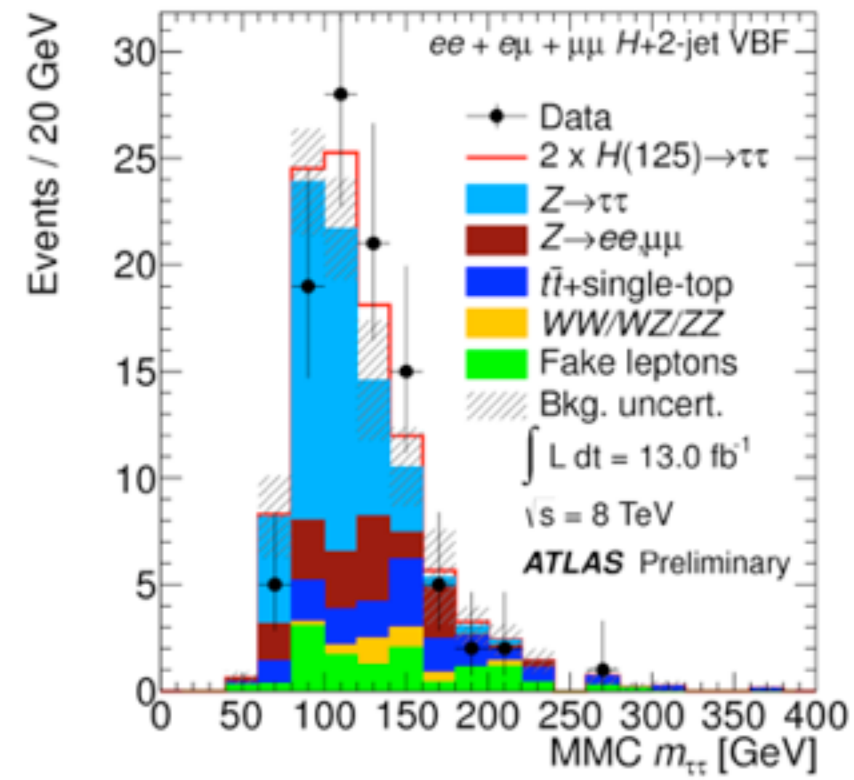
- m_{MMC}=129 GeV
- $p_{\mathrm{T}}(\mu)$ = 63 GeV, $p_{\mathrm{T}}(\tau_{\mathrm{had}})$ = 96 GeV, $E_{\mathrm{T}}^{\mathrm{miss}}$=119 GeV, m_{jj}=625 GeV



$m_{\tau\tau}$ distributions and backgrounds

- $Z \to \tau\tau$ from a data-driven technique
  - Use $Z \to \mu\mu$ data, replacing μ with τ signatures taken from MC simulation
- $Z\ (\to ee/\mu\mu)$ + **jets**, top, di-boson: estimated from MC with corrections from data
- QCD from data driven estimate





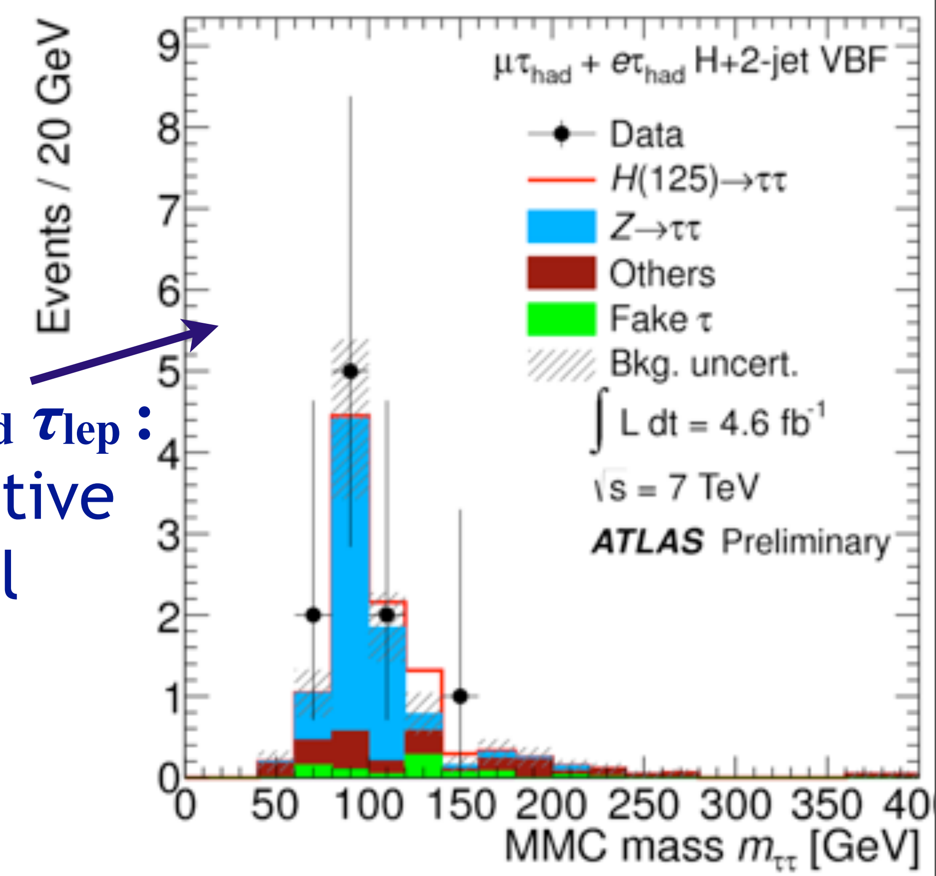
- Main systematics: τ energy scale and theoretical uncertainties

No significant excess above predicted backgrounds

95% CL limit on σ/σ_{SM} for m_H=125 GeV:

1.9 (measured); **1.2** (expected)

VBF $H\to\tau_{had}\ \tau_{lep}$: most sensitive channel



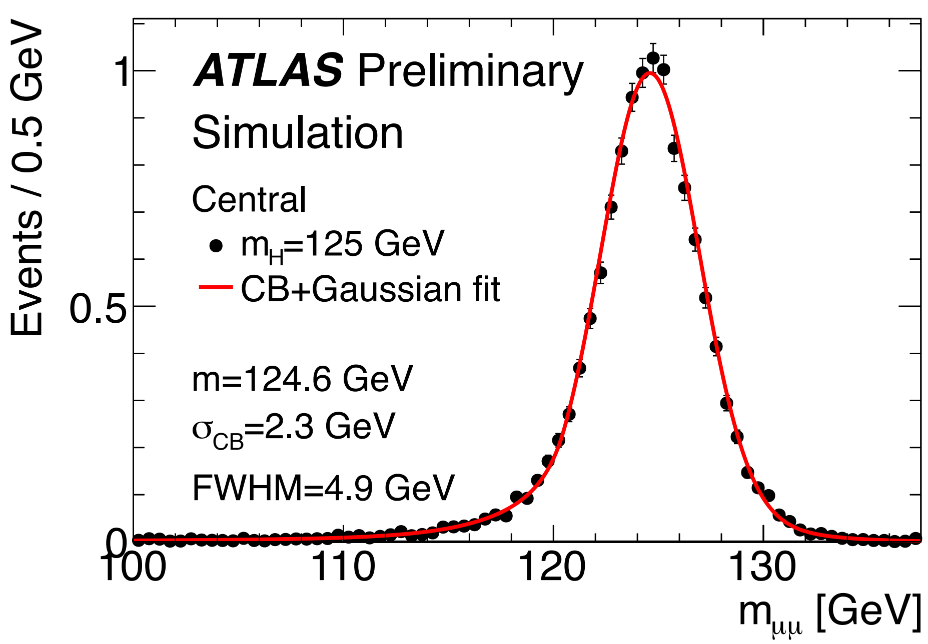
$H \rightarrow \mu^+\mu^-$ searches

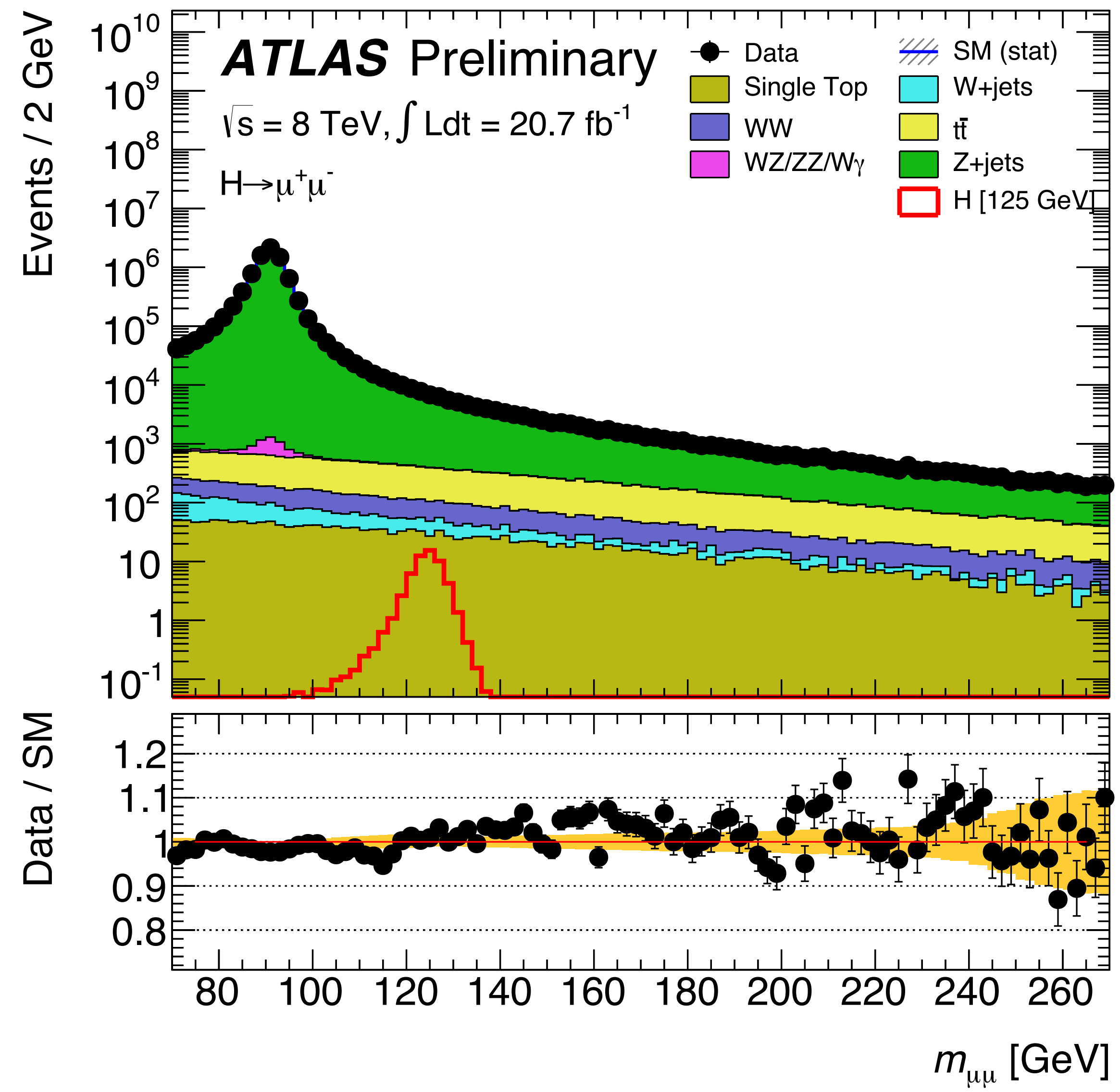
New!

ATLAS-CONF-2013-010

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

- Search for $H\to\mu^+\mu^-$ using full 2012 $\sqrt{s}$=8 TeV dataset.
- Huge background from $Z/\gamma^*\to\mu^+\mu^-$
- At 125 GeV, $m_{\mu\mu}$ resolution is ~ 2.3 GeV.





95% CL limit on σ/σ_{SM} for m_H=125 GeV:

9.8 (measured); **8.2** (expected)

Search Results

Results

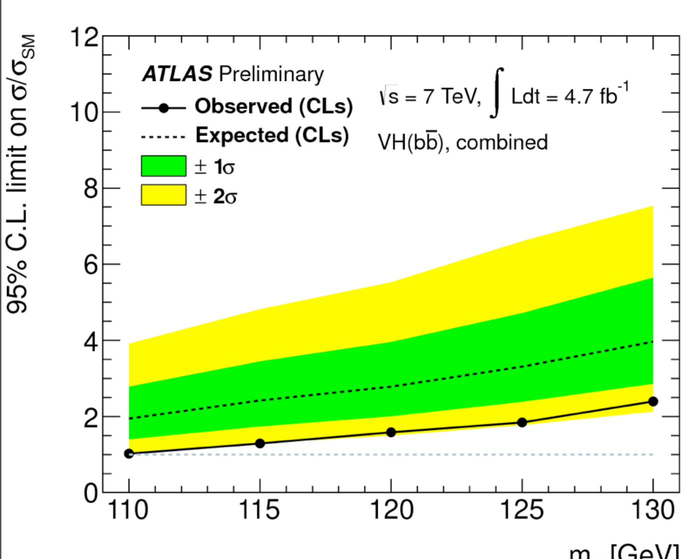
- **No observation** of SM Higgs boson production, decaying into fermions or invisibly, in the range **100 < m_H/GeV < 150**.

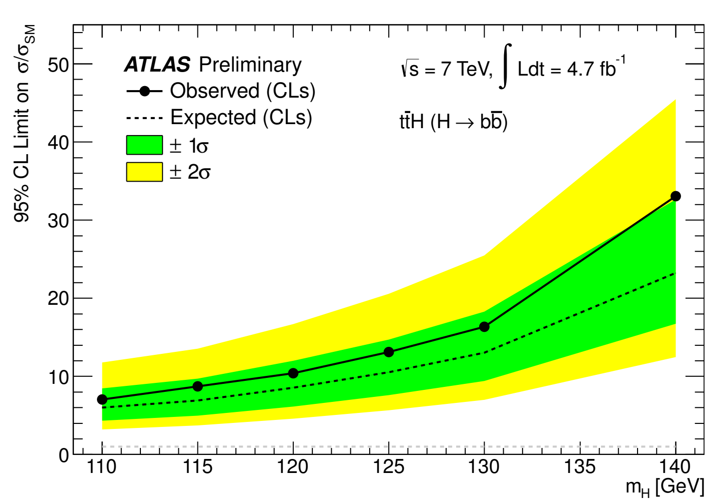
95% CL limits on SM Higgs production, for m_H=125 GeV

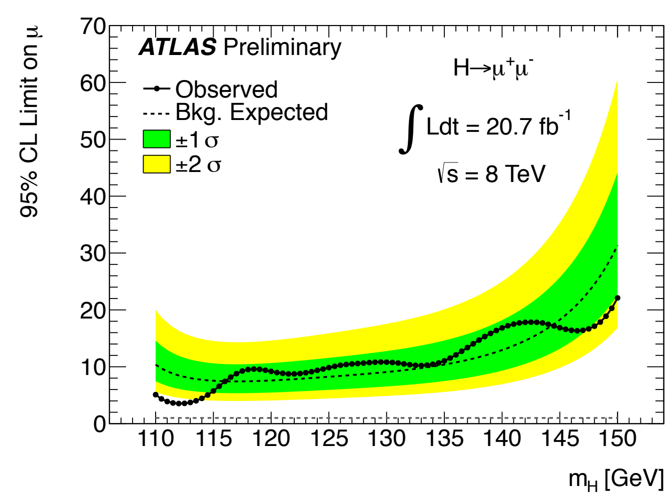
	observed	expected
$VH \to Vb\bar{b}$	1.8	1.9
$t\bar{t}H, H \to b\bar{b}$	13.1	10.5
$H \to \tau^+\tau^-$	1.9	1.2
$H \to \mu^+\mu^-$	9.8	8.2

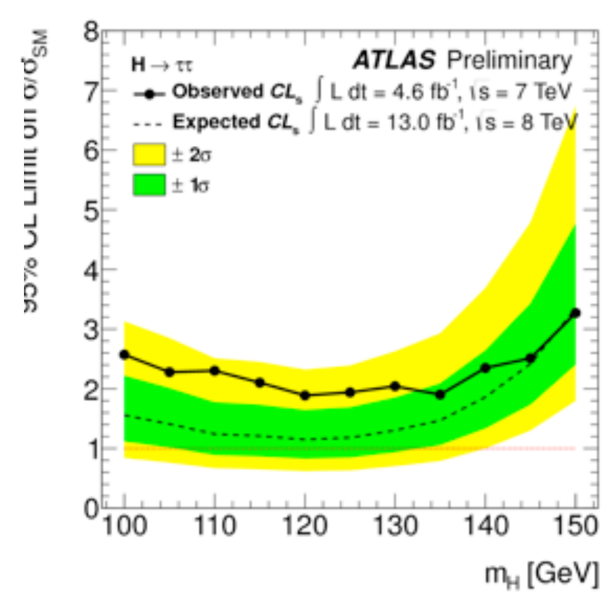
95% CL limits on SM Higgs, for m_H=125 GeV

	observed	expected
BR ($H \to$invisible)	< 65%	< 84%



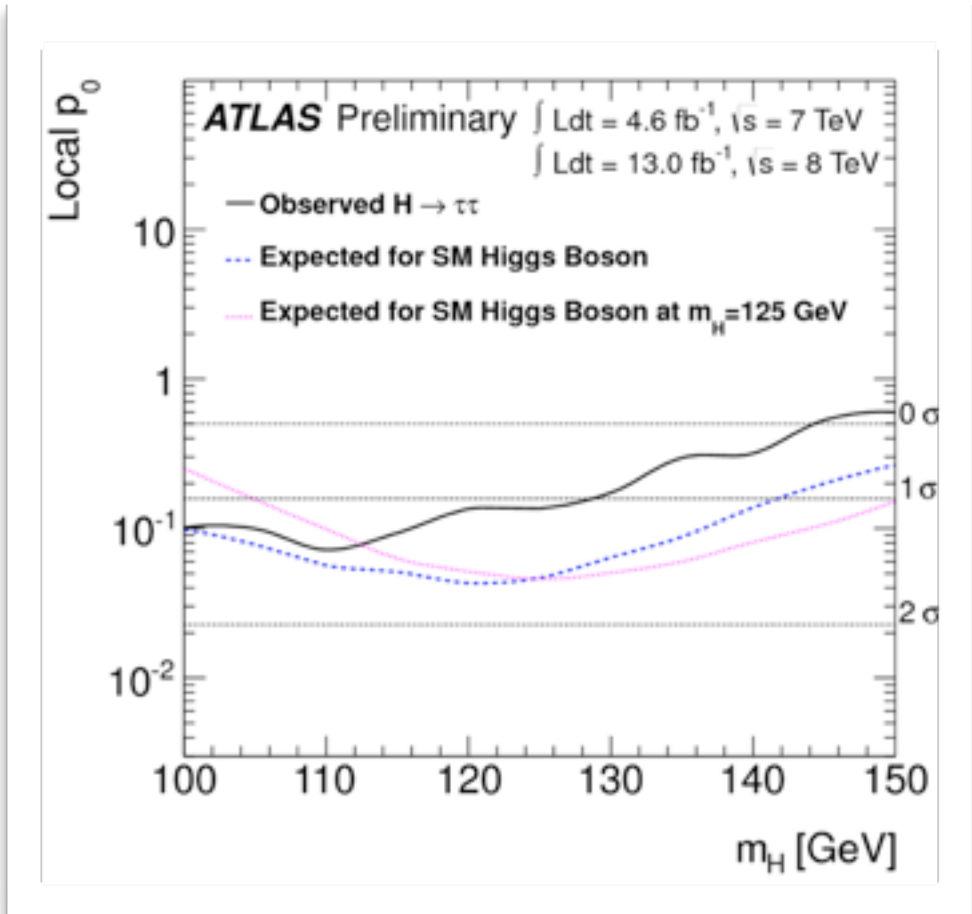


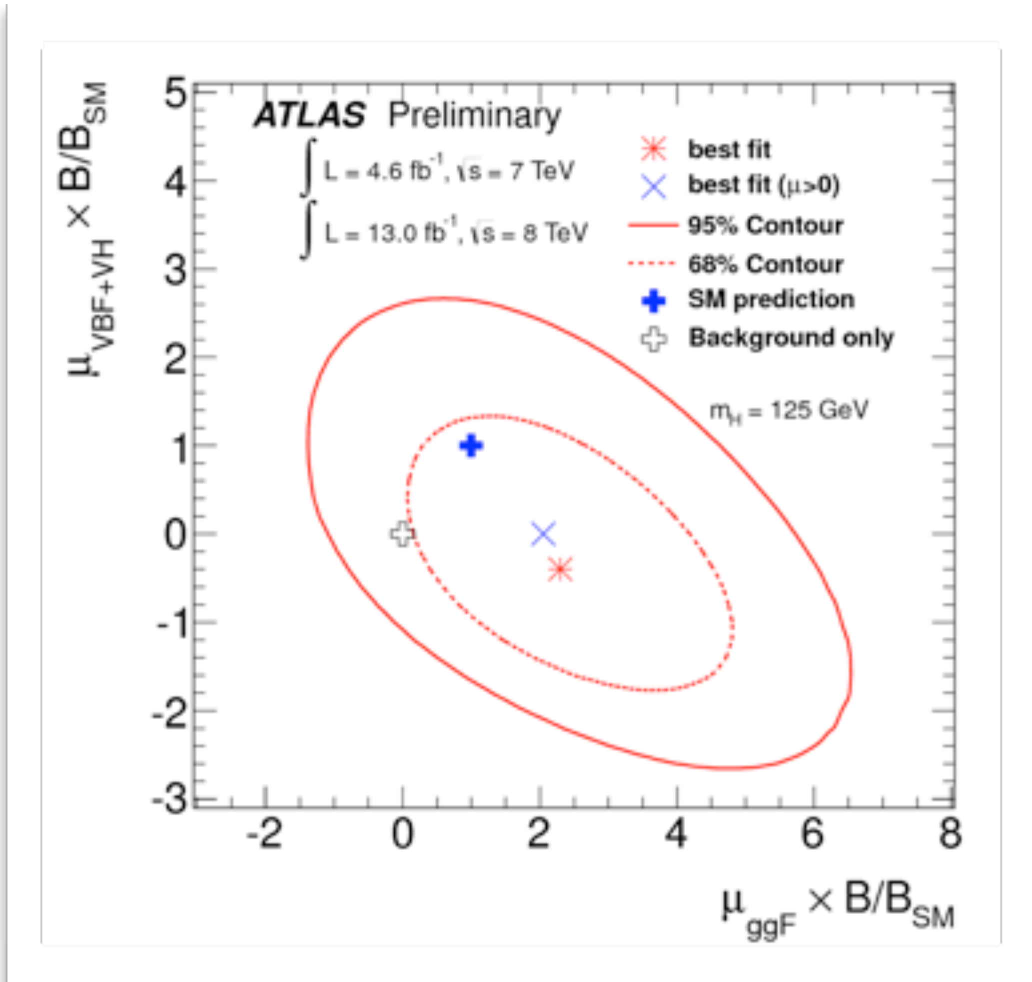




$H \rightarrow \tau^+\tau^-$ Production Properties

- Observed (expected) p_0 value: **1.1σ (1.7σ)** at m_H**=125 GeV**





Best fit signal strengths for:

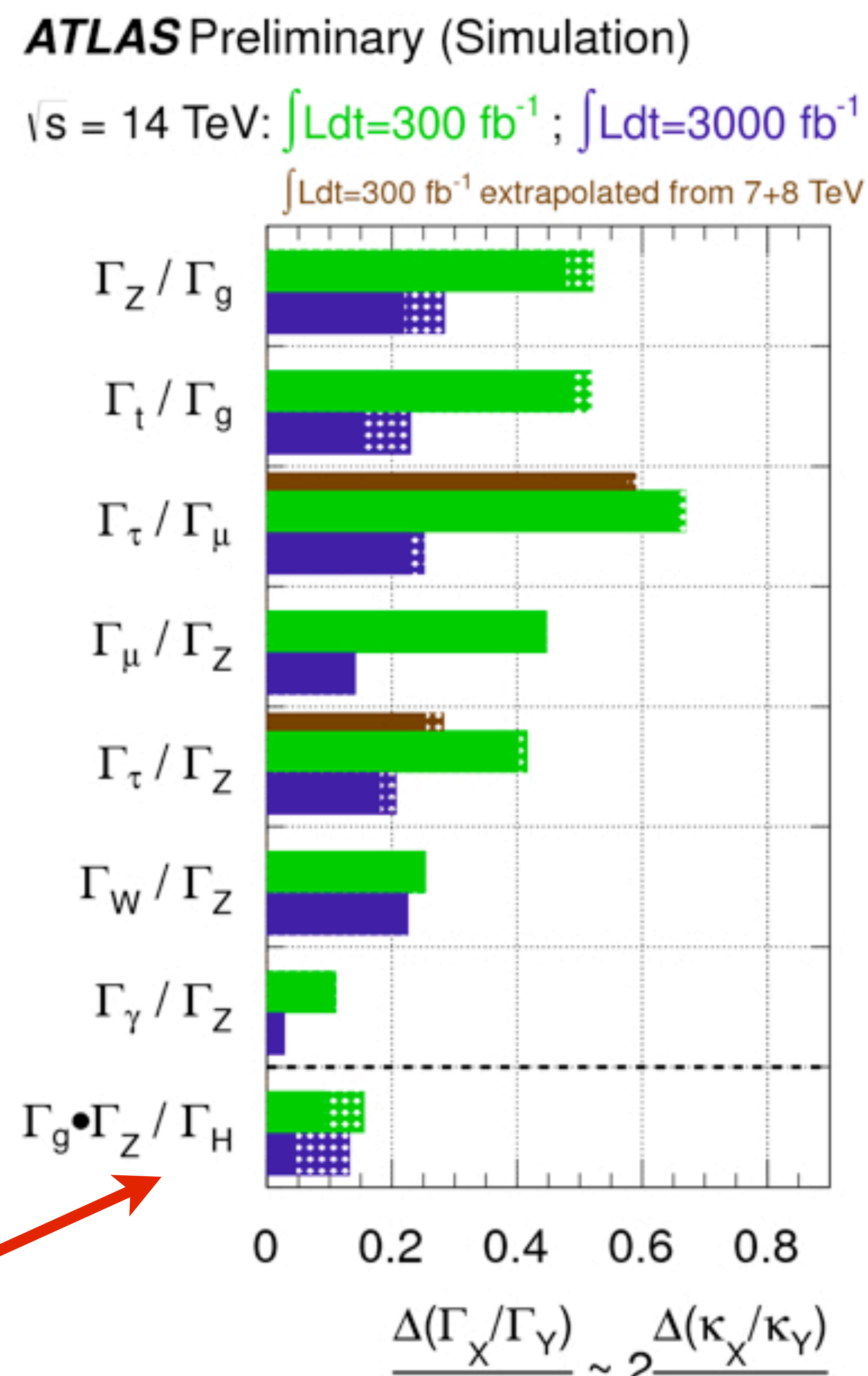
Higgs production from weak bosons vs Higgs production from gluons

Planned Improvements

- Study of $\mathbf{21\ fb^{-1}}$ of $\sqrt{s} = \mathbf{8\ TeV}$ data is underway for $VH \rightarrow Vb\bar{b}$, ttH and $H \rightarrow \tau^+\tau^-$ searches.

- Further sensitivity will be gained by:
  - ➡ **Adding more final states**, such as
$$t\bar{t}H \rightarrow \ell^+\nu b\ \ell^-\bar{\nu}\bar{b}\ b\bar{b}$$
  - ➡ **Using advanced data techniques** to understand systematics and gain better separation between signal and background, *e.g.*
    - multivariate event selection
    - exploiting *b*-tag weights
    - kinematic fits of the observed final states
  - ➡ **Better understanding of flavour tagging and tau reconstruction.**

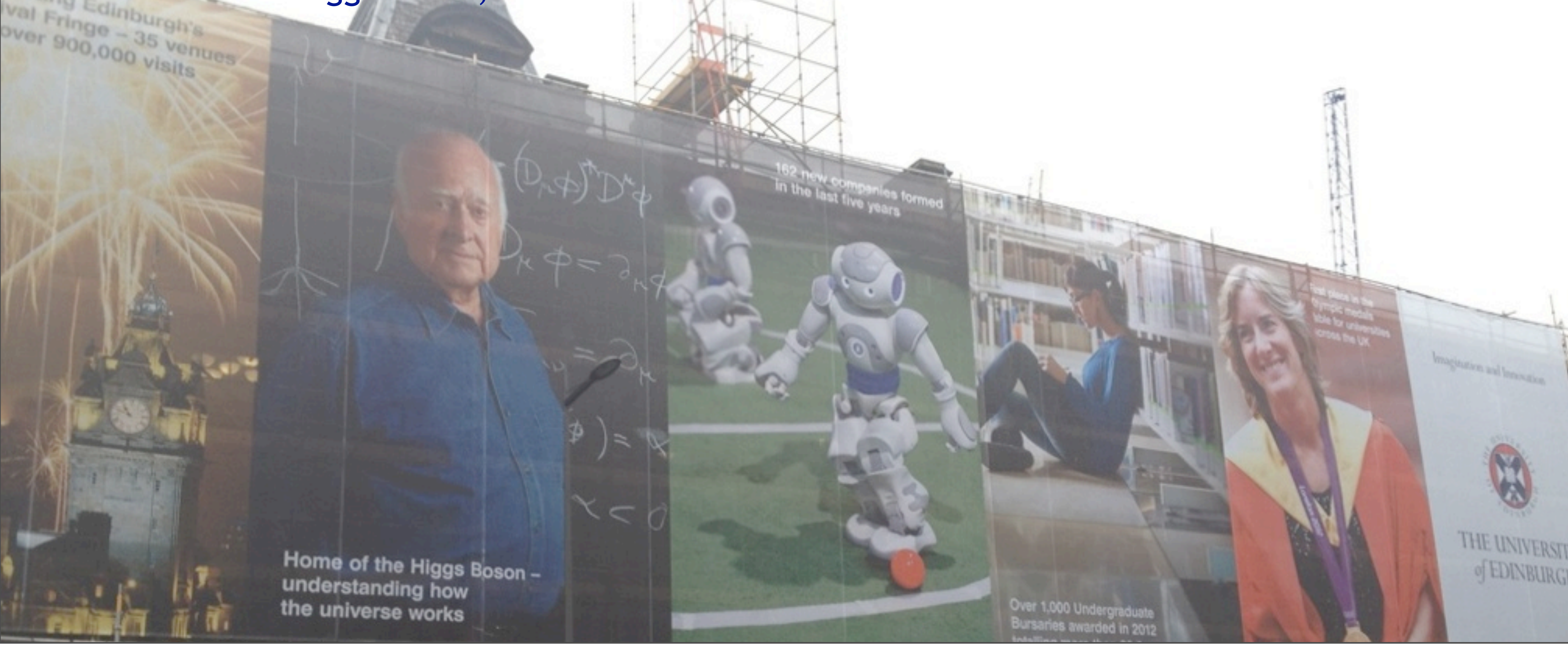
- If the **125 GeV** Higgs-like boson is the SM Higgs boson, need post shutdown data for reasonable values for the Higgs-Yukawa couplings.



ATL-PHYS-PUB-2012-004

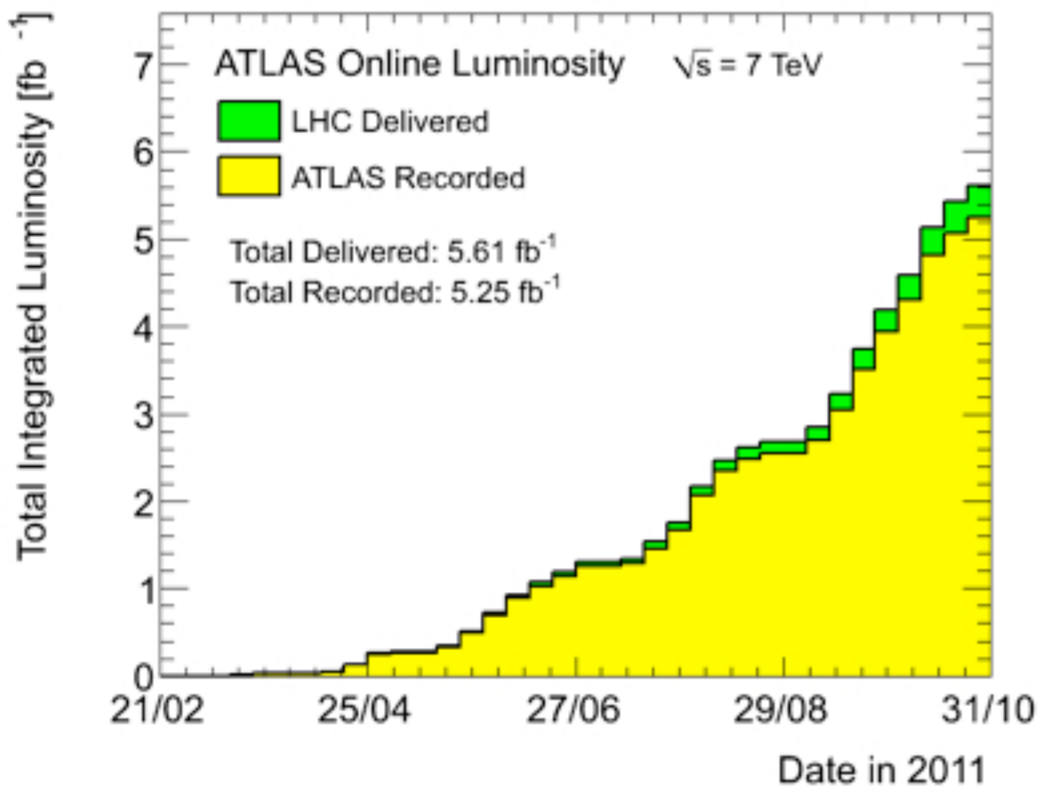
Conclusions

- The ATLAS experiment has searched for evidence of the SM Higgs boson decaying into fermions.
- Large backgrounds and complex final states make these analyses very challenging.
- No observation of fermion or invisible final states; but we didn't expect to see any with the data analysed so far.
- More data and more sophisticated techniques are under study.
- The observation of $VZ \rightarrow Vb\bar{b}$ gives us confidence we will be able to observe fermionic final states of the Higgs boson, if nature allows them.



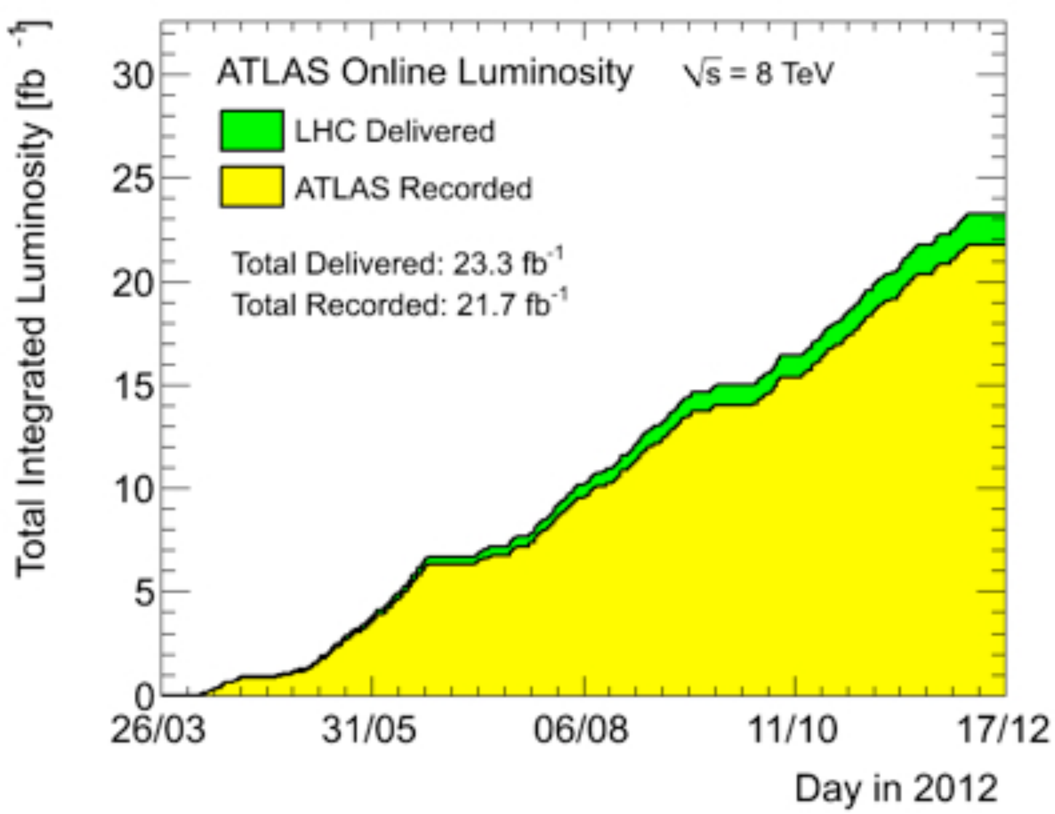
Backup Slides

Data Samples



Searches presented here use:

- ➡ **4.7 fb^{-1}** of $\sqrt{s} = 7$ TeV (except $H \to \mu^+\mu^-$)
- ➡ **13 fb^{-1}** of $\sqrt{s} = 8$ TeV ($VH \to Vb\bar{b}$, $H \to \tau^+\tau^-$, $H \to$ invisible)
- ➡ **21 fb^{-1}** of $\sqrt{s} = 8$ TeV ($H \to \mu^+\mu^-$)



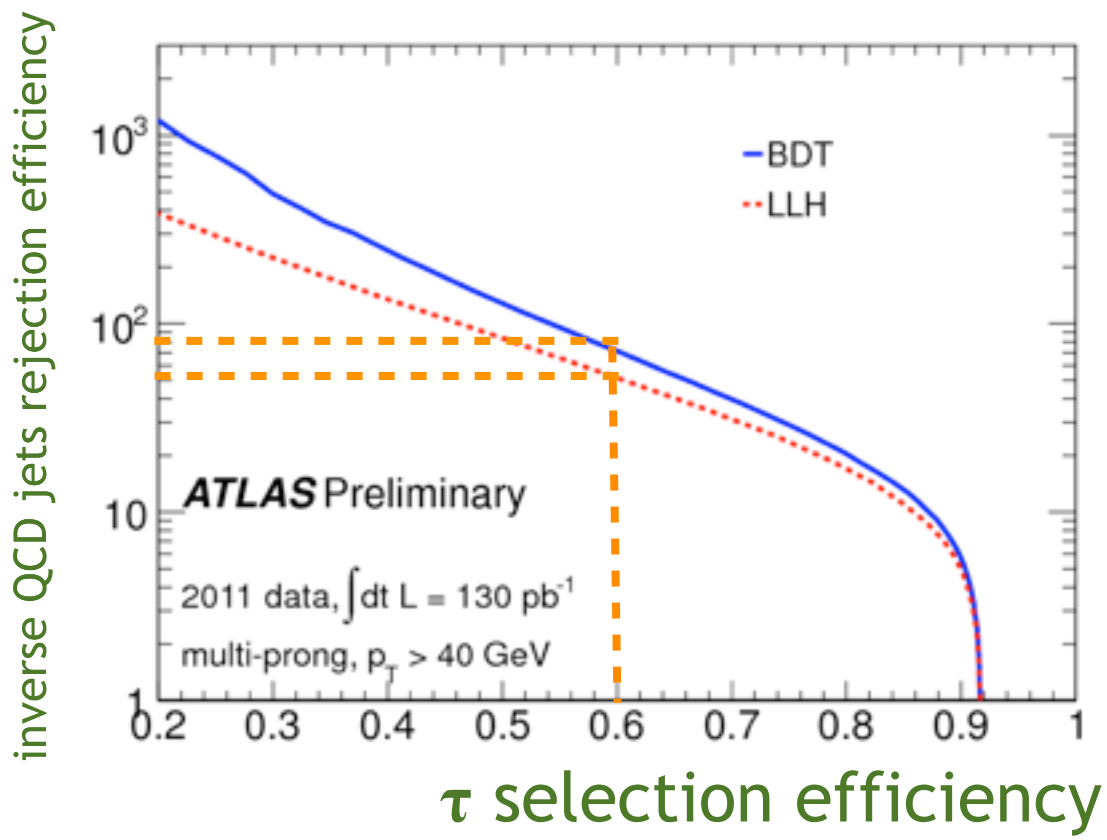
Identifying τ leptons

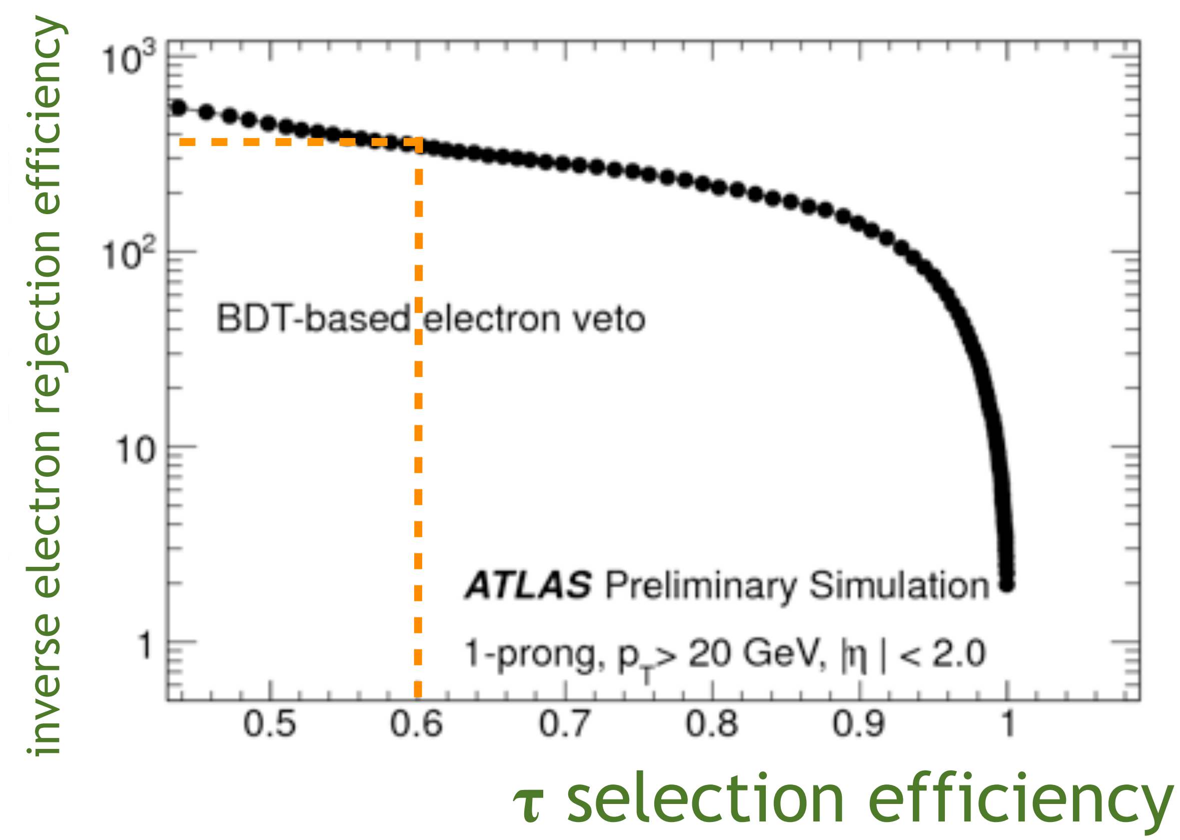
ATLAS-CONF-2012-142

- τ-leptons decay inside the LHC beam pipe
  - ➡ Leptonic decays: τ_{lep} $\tau \to e\bar{\nu}_e\nu_\tau$ (17.8%) $\tau \to \mu\bar{\nu}_\mu\nu_\tau$ (17.4%)
  - ➡ Hadronic decays: τ_{had} $\tau \to \mathbf{hadrons} + \nu_\tau$ (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





Tagging *b*-jets

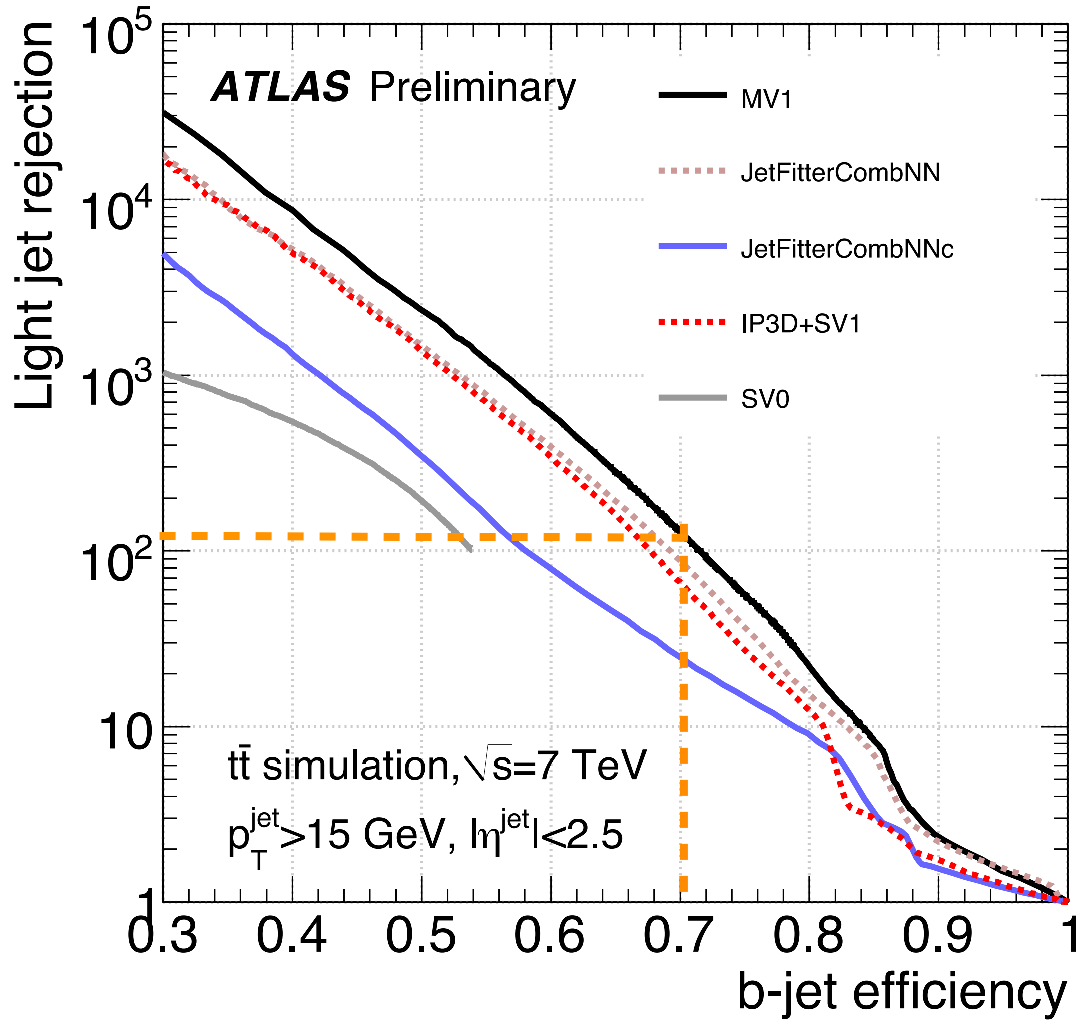
ATLAS-CONF-2012-097

ATLAS-CONF-2012-043

ATLAS-CONF-2012-040

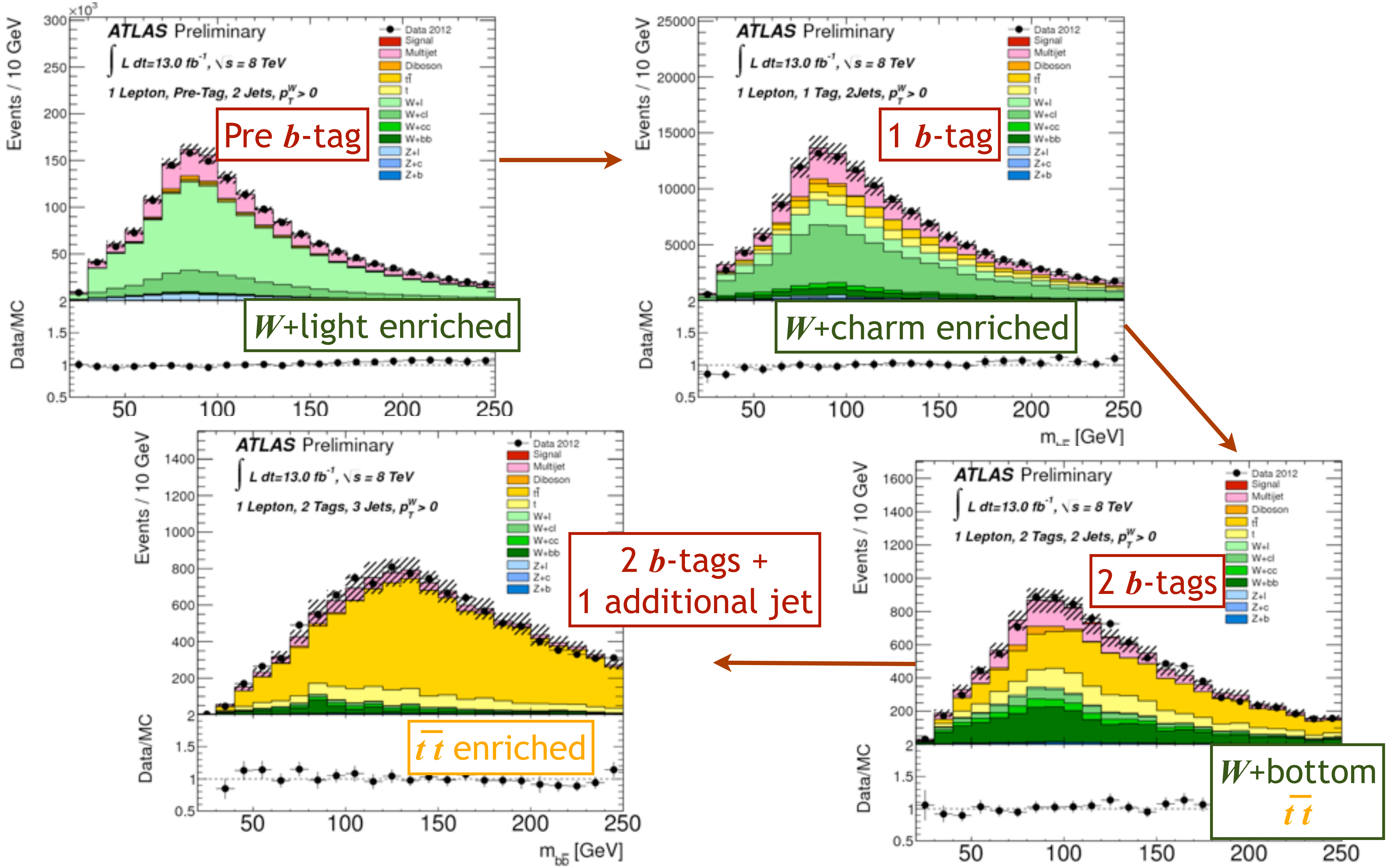
ATLAS-CONF-2011-102

- ***b*-tagging algorithm (“MV1”) uses a neural net**
  - based on secondary and subsequent vertices along the *b*-hadron line of flight
- Analyses presented here use **70%** working point
  - selects **70%** of *b*-jets
  - mistag rate for light jets **~1%**



$VH \to Vb\bar{b}$ 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

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

Main uncertainties:

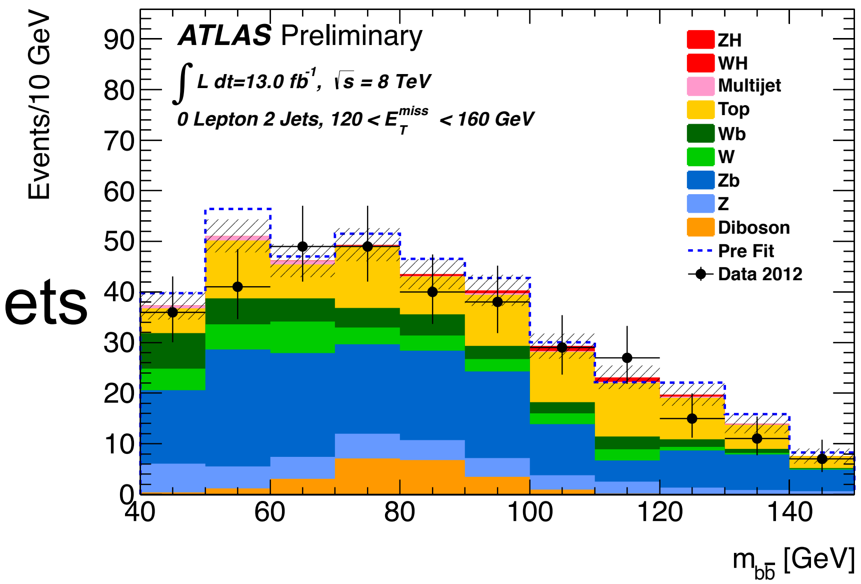
- ➡ b-/c-tagging
- ➡ jet energy scale & resolution
- ➡ MC statistics

	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 ± 29	127 ± 11	98 ± 12	164 ± 13	63 ± 8	42 ± 5	3810 ± 150	4310 ± 86	1730 ± 90	297 ± 27	138 ± 14	1500 ± 90	1770 ± 110	665 ± 47	97 ± 12	72 ± 12
Data	342	131	90	175	65	32	3821	4301	1697	297	132	1485	1773	657	100	69

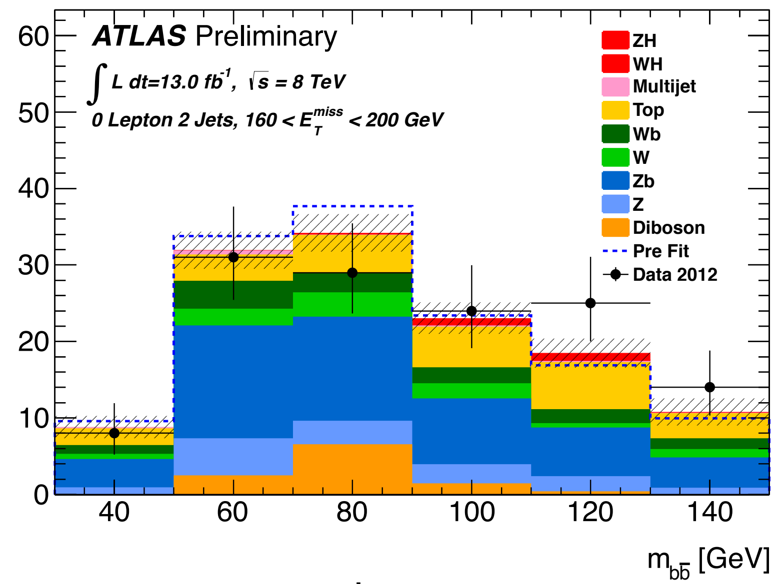
$VH \rightarrow Vb\bar{b}$, 0-lepton: m_{bb} distributions

$\sqrt{s} = 8$ TeV

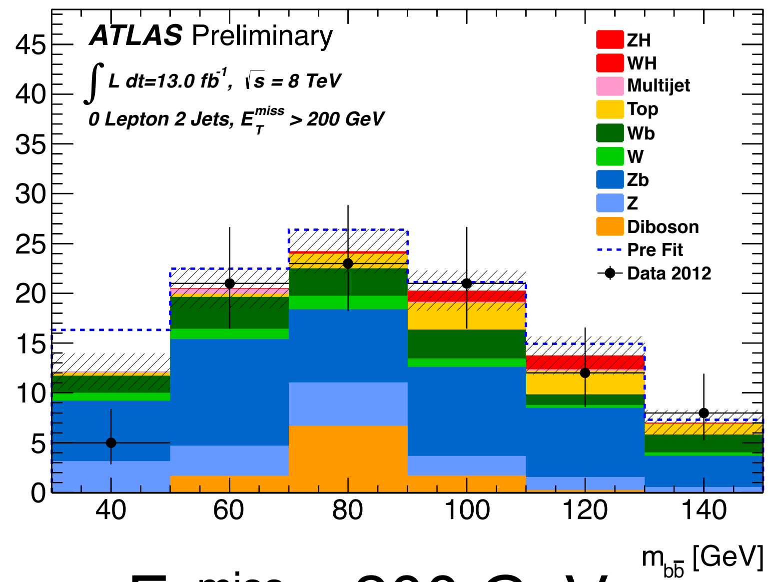
2 jets



$120 < E_T^{miss} < 160$ GeV

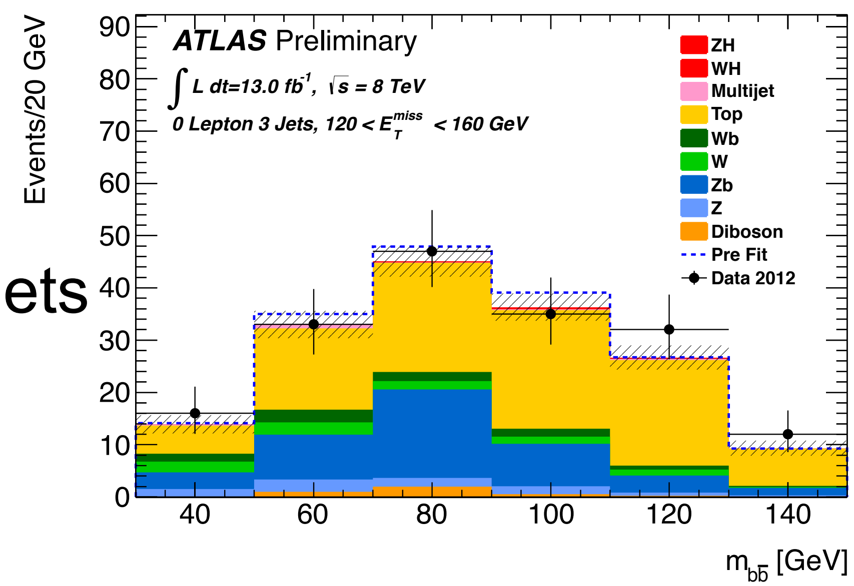


$160 < E_T^{miss} < 200$ GeV

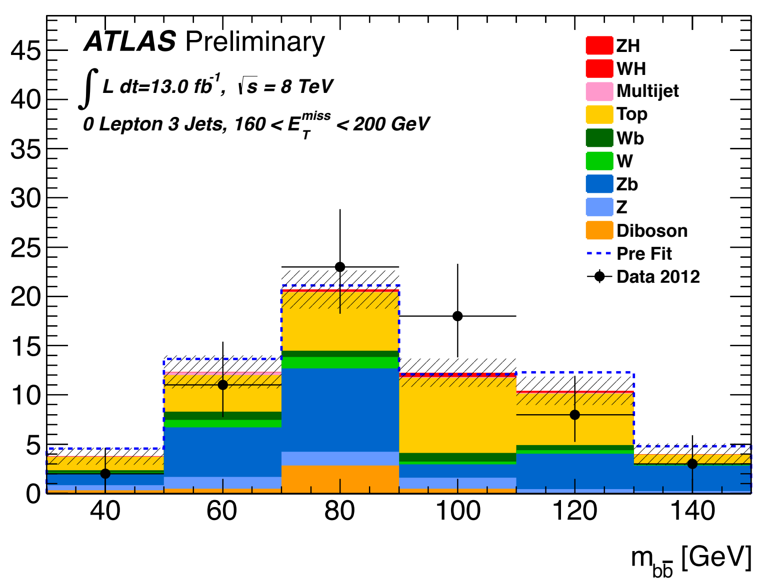


$E_T^{miss} > 200$ GeV

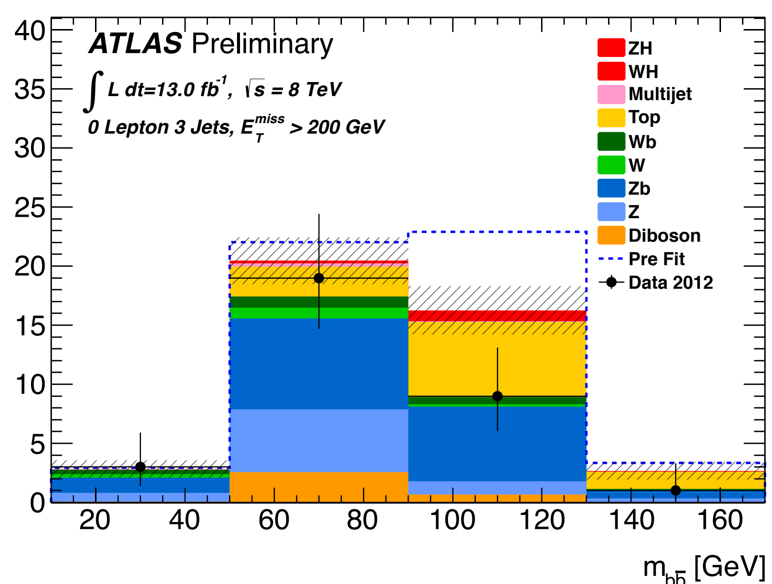
3 jets



$120 < E_T^{miss} < 160$ GeV



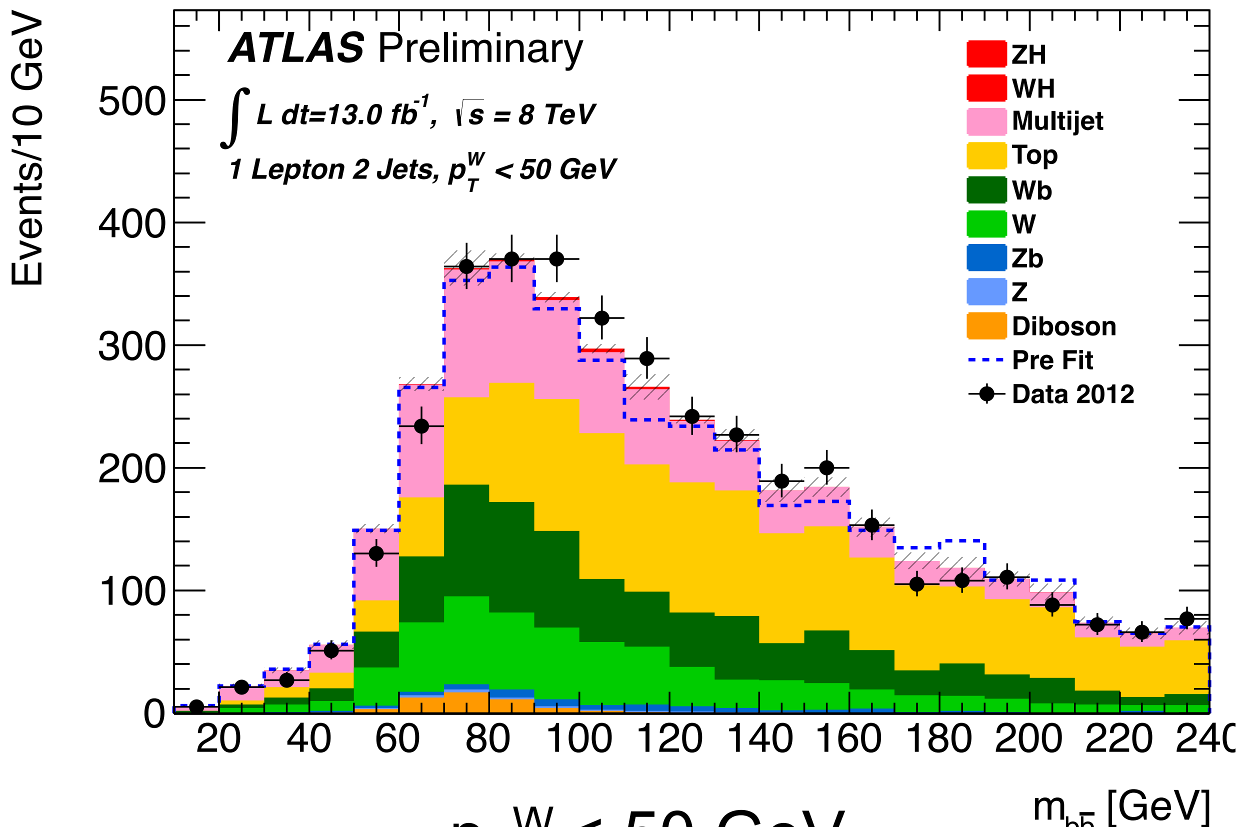
$160 < E_T^{miss} < 200$ GeV



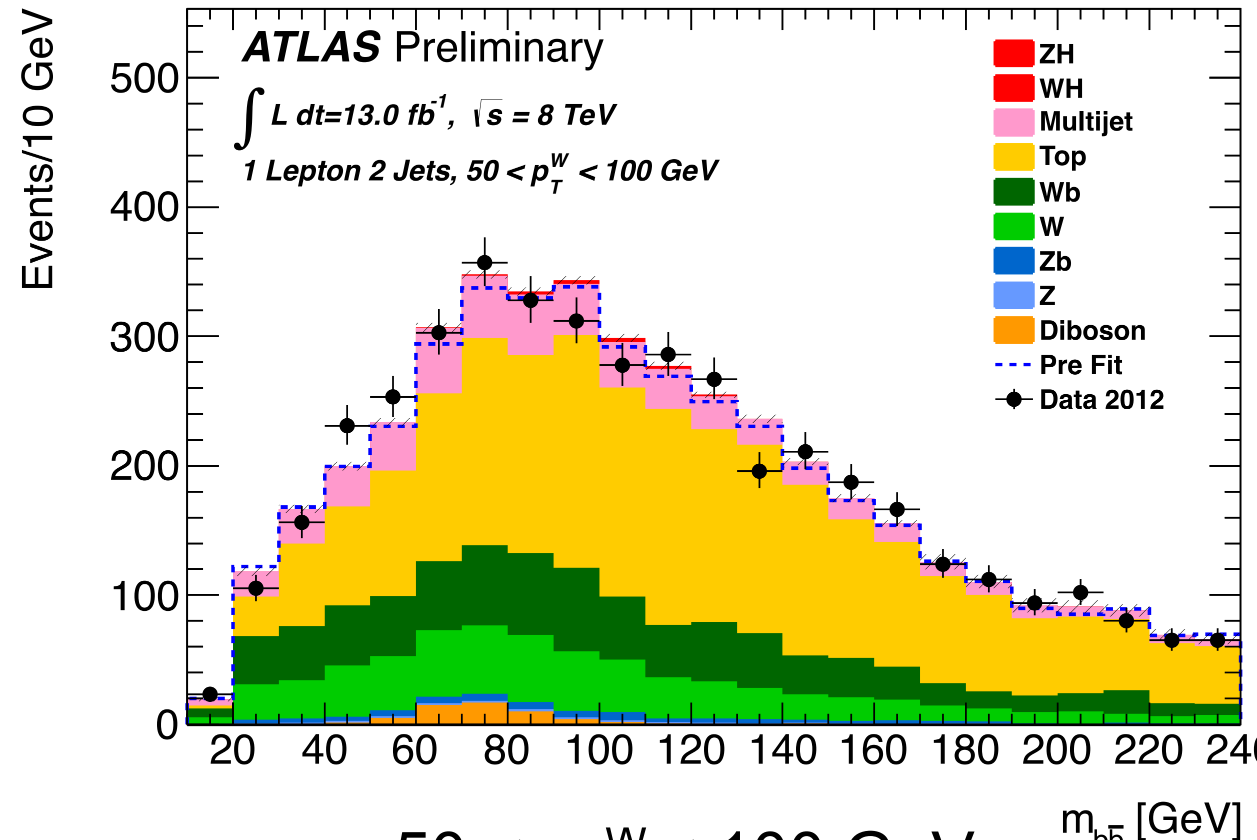
$E_T^{miss} > 200$ GeV

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

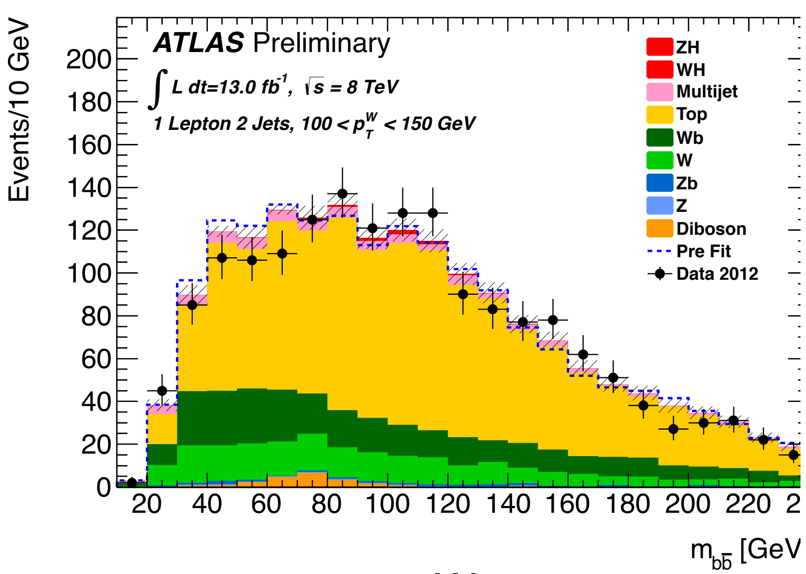
$\sqrt{s} = 8$ TeV



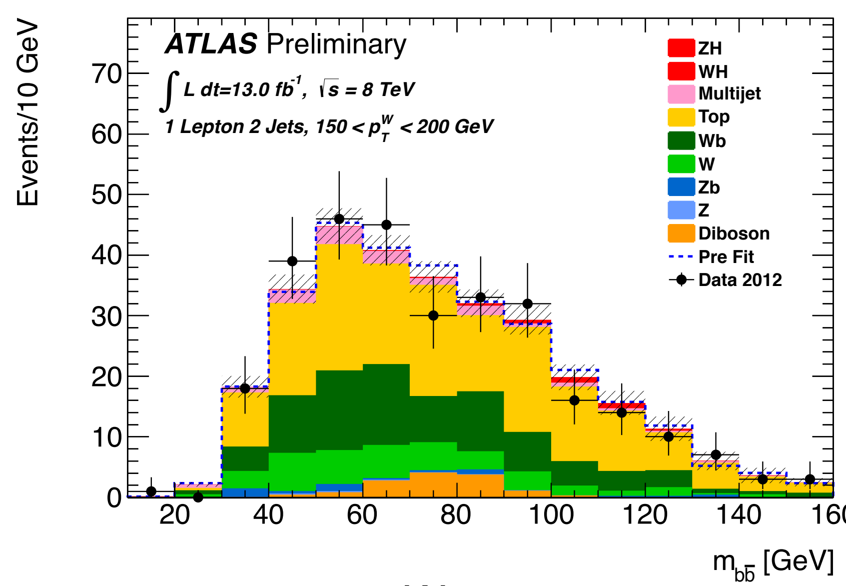
$p_T{}^W < 50$ GeV



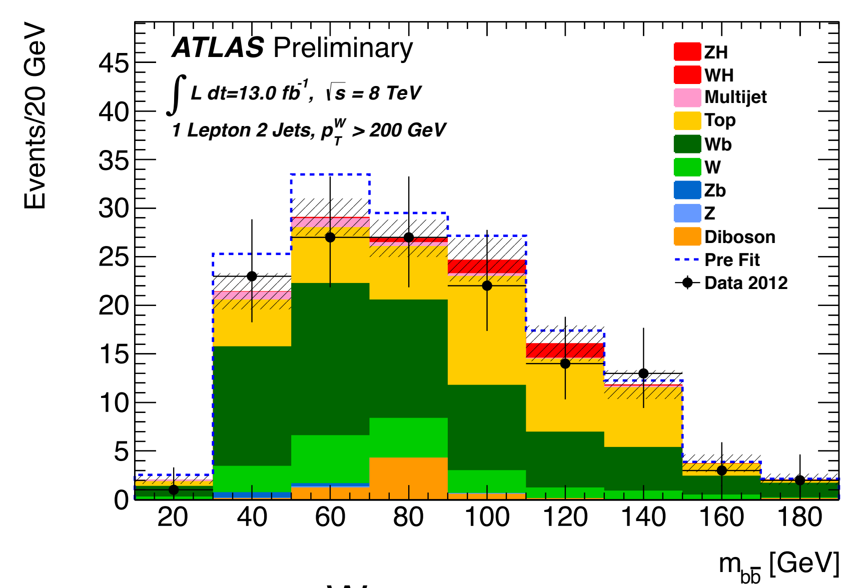
$50 < p_T{}^W < 100$ GeV



$100 < p_T{}^W < 100$ GeV



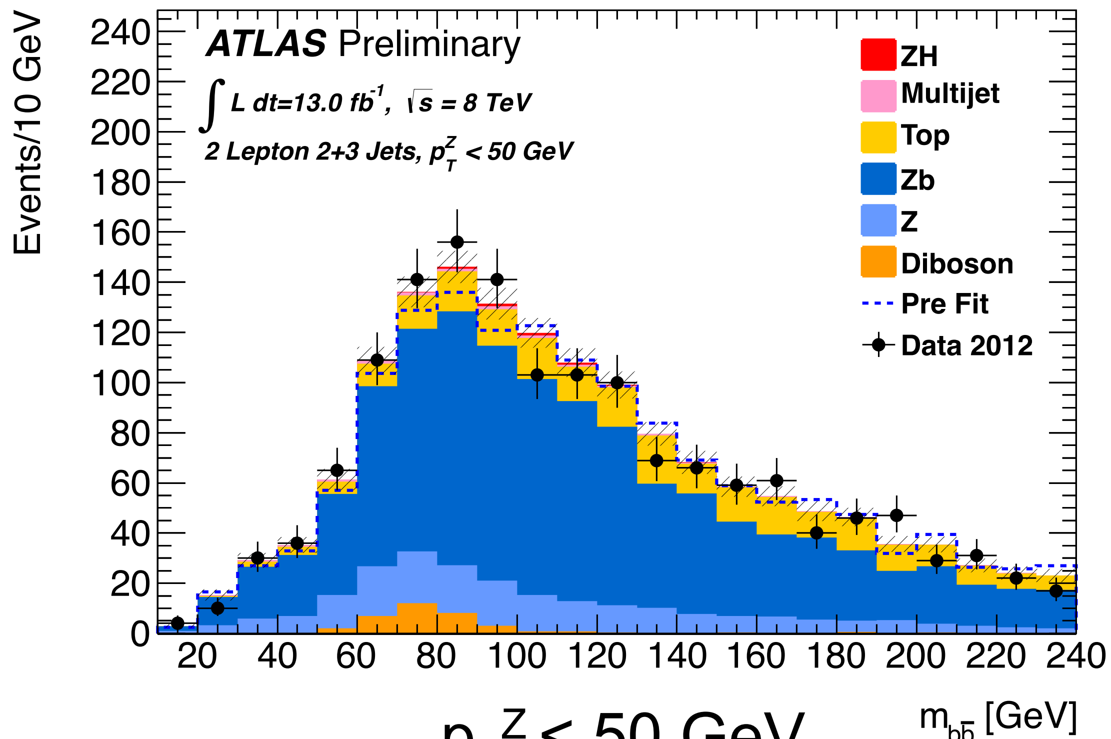
$150 < p_T{}^W < 200$ GeV



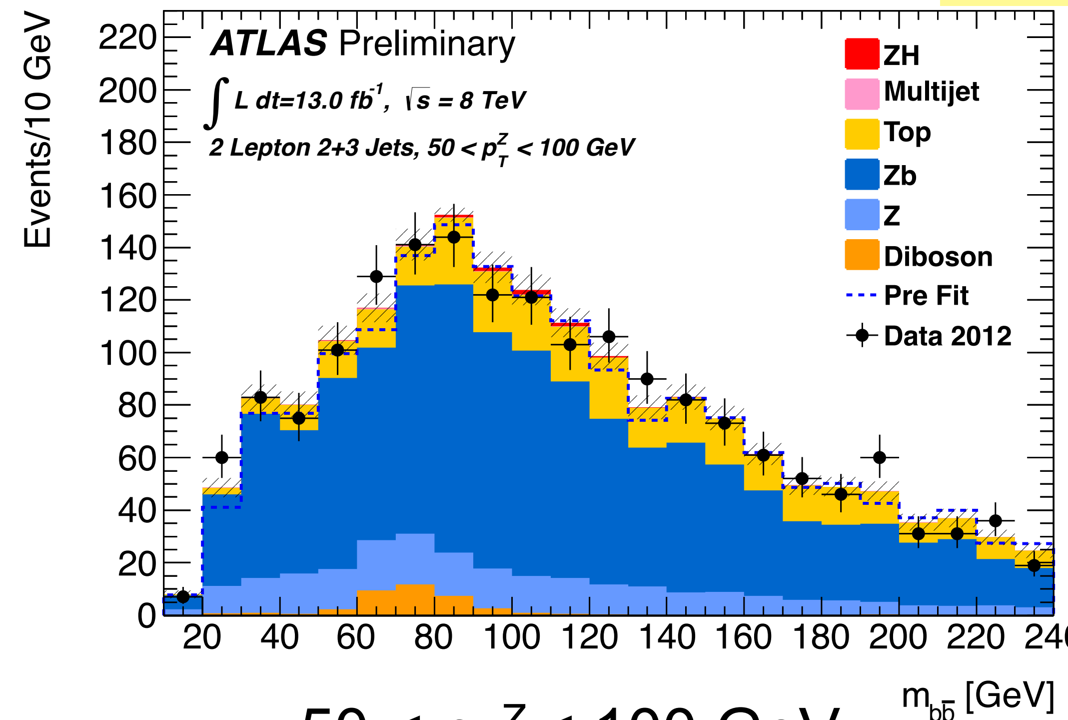
$p_T{}^W > 200$ GeV

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

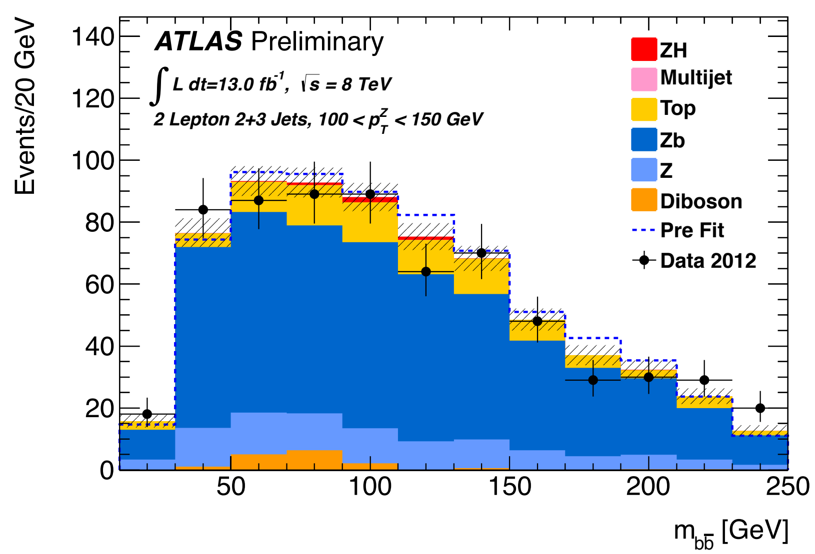
$\sqrt{s} = 8$ TeV



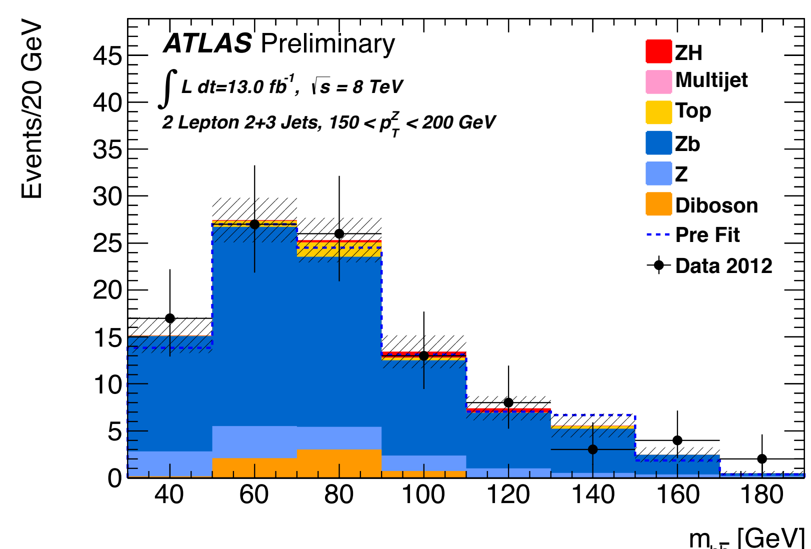
$p_T{}^Z < 50$ GeV



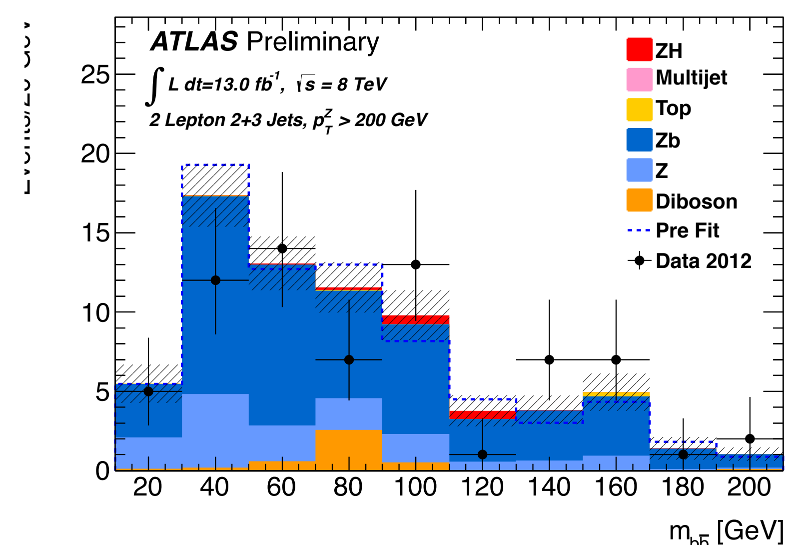
$50 < p_T{}^Z < 100$ GeV



$100 < p_T{}^Z < 150$ GeV



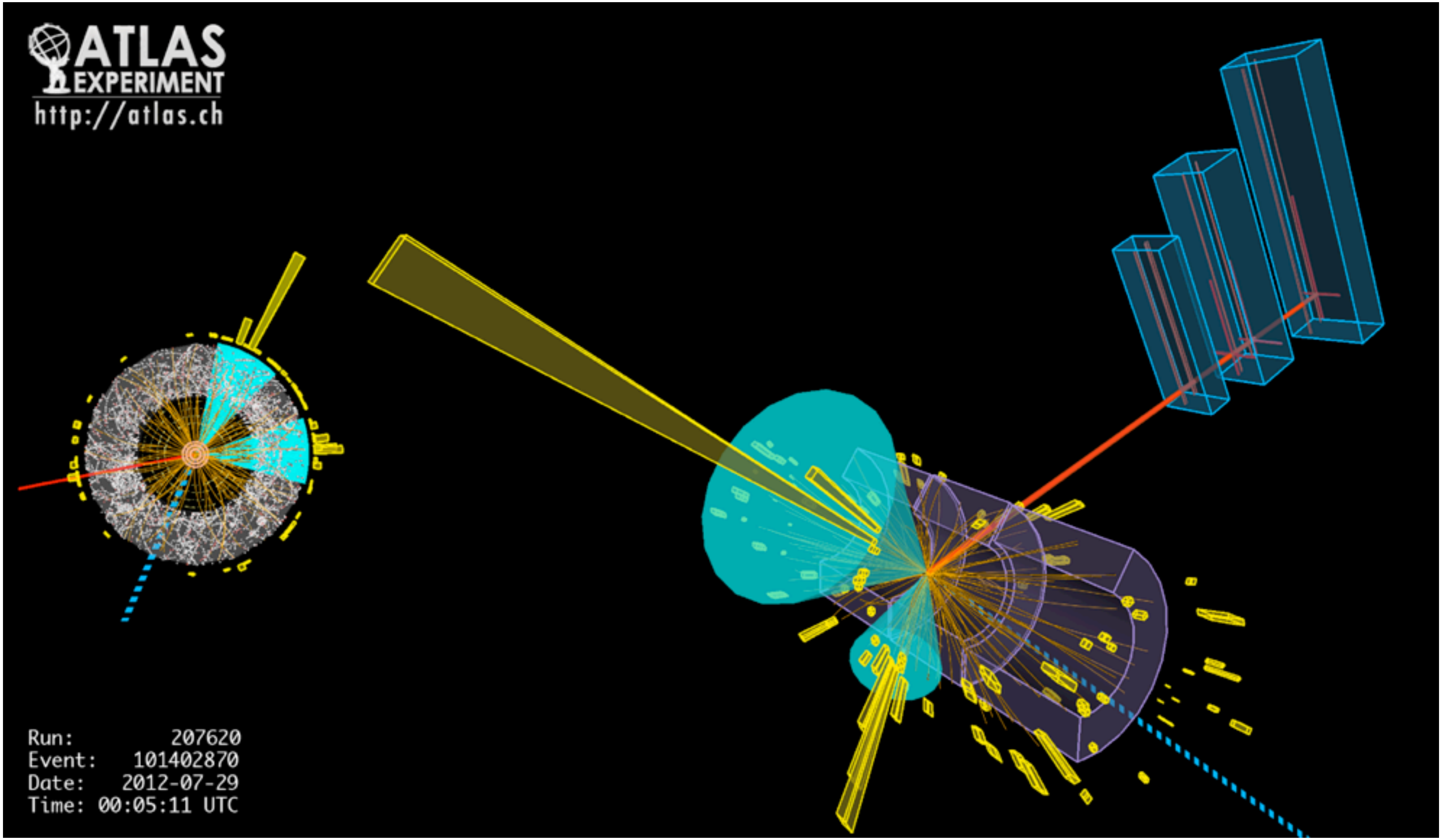
$150 < p_T{}^Z < 200$ GeV



$p_T{}^Z > 200$ GeV

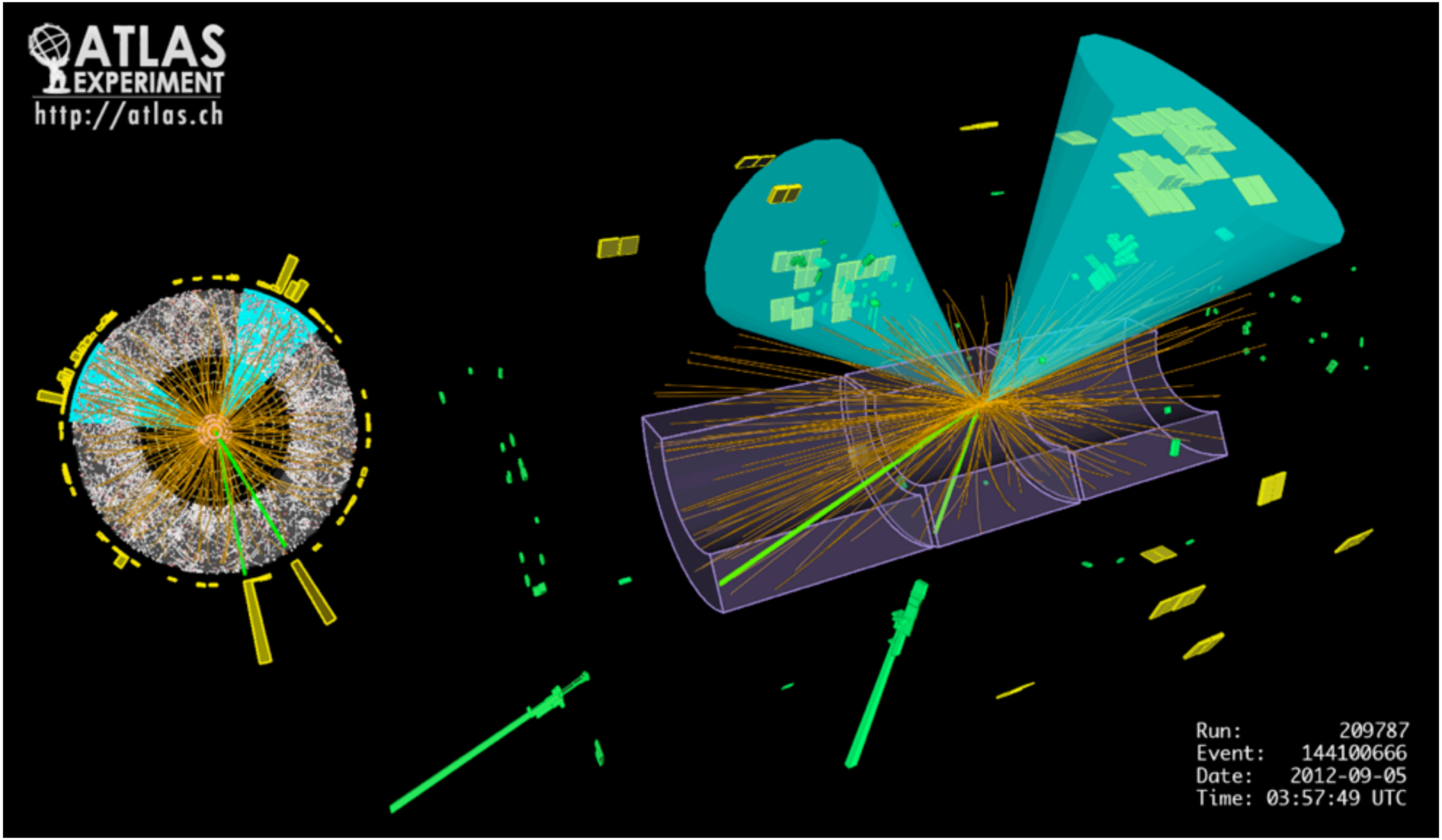
$WH \rightarrow \mu\nu\, b\bar{b}$ candidate event

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



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

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



ZH, $Z \rightarrow$invisible backgrounds

Process	Estimation method	Uncertainty (%) 2011	2012
ZH Signal	MC	7	6
ZZ	MC	11	10
WZ	MC	12	14
WW	MC	14	not used
Top quark	MC	90	not used
Top quark, WW and $Z \rightarrow \tau\tau$	$e\mu$ CR	not used	4
Z	ABCD method	56	51
W + jets, multijet	Matrix method	15	22

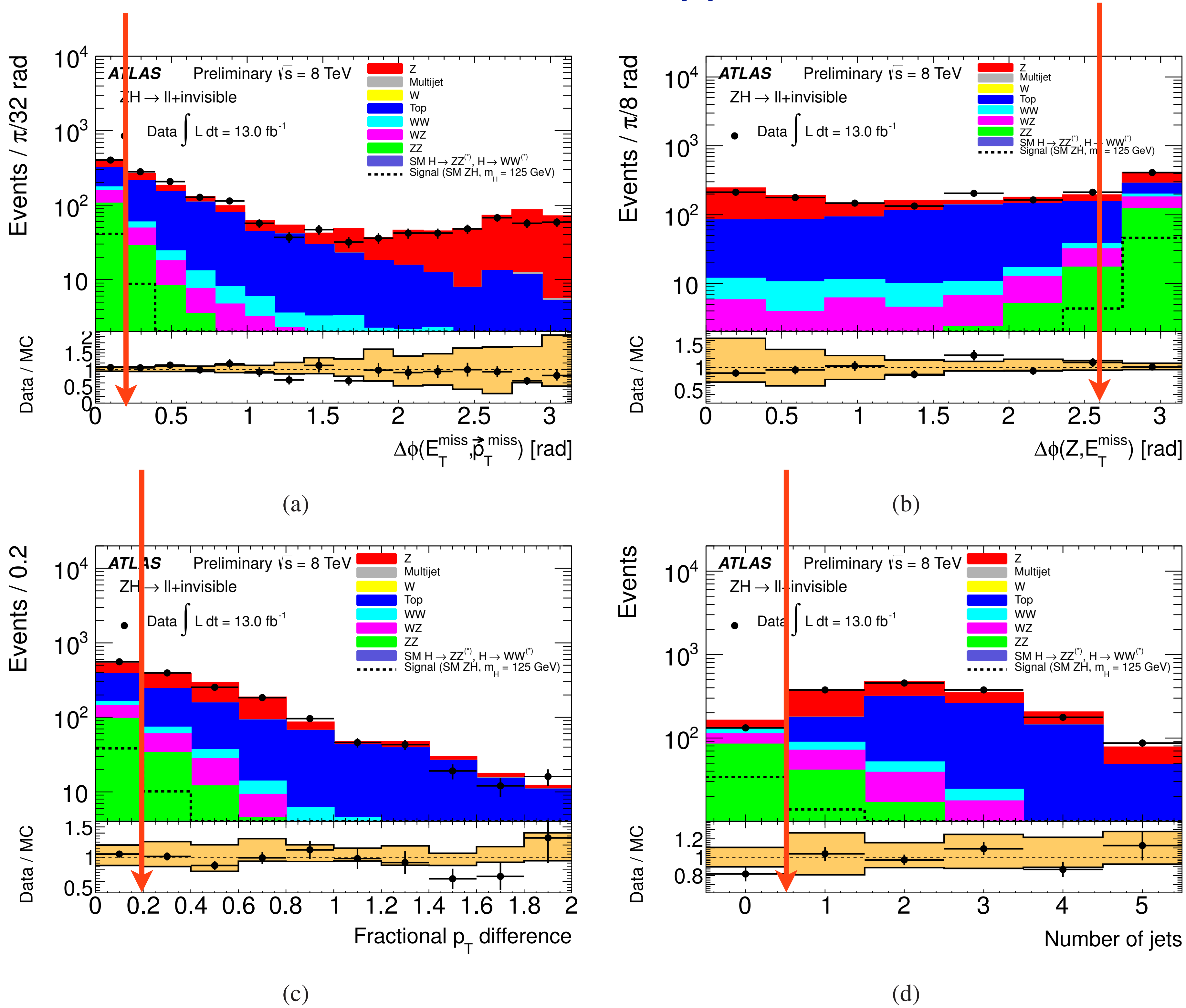
Table 2: Summary of the systematic uncertainties on each background and on the signal yield. The method used to estimate the backgrounds and the associated sources of systematic uncertainties are given. The total systematic uncertainties for each data taking period are given.

Data Period	2011 (7 TeV)	2012 (8 TeV)
ZZ	23.5 ± 0.8 ± 2.5	56.5 ± 1.2 ± 5.7
WZ	6.2 ± 0.4 ± 0.7	13.9 ± 1.2 ± 2.1
WW	1.1 ± 0.2 ± 0.2	used $e\mu$ data-driven
Top quark	0.4 ± 0.1 ± 0.4	used $e\mu$ data-driven
Top quark, WW and $Z \rightarrow \tau\tau$ ($e\mu$ data-driven)	used MC	4.9 ± 0.9 ± 0.2
Z	0.16 ± 0.13 ± 0.09	1.4 ± 0.4 ± 0.7
W + jets, multijet	1.3 ± 0.3 ± 0.2	1.4 ± 0.4 ± 0.3
Total BG	32.7 ± 1.0 ± 2.6	78.0 ± 2.0 ± 6.5
Observed	27	71

Table 3: Observed number of events and expected contributions from each background source separated into the 2011 and 2012 data taking periods. Uncertainties associated with the background predictions are presented with the statistical uncertainty first and the systematic uncertainty second.

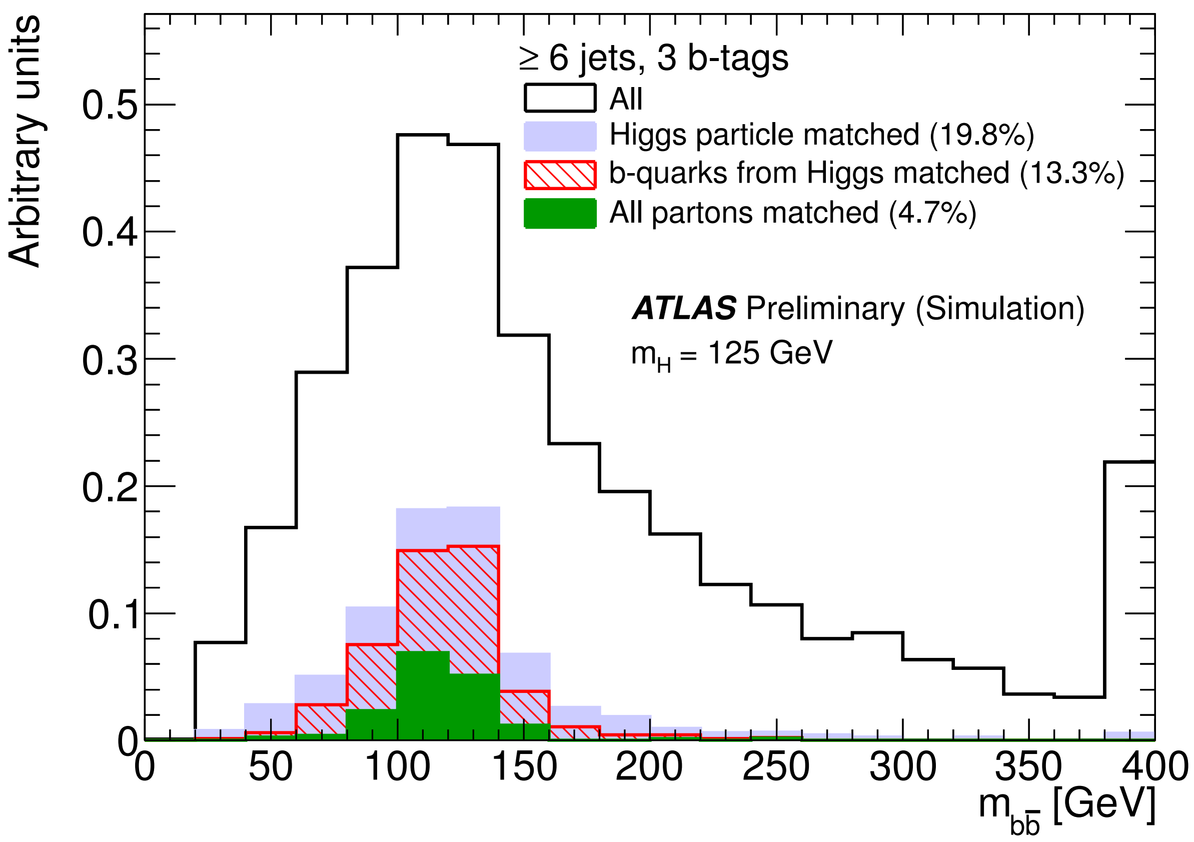
ZH, *Z*→invisible selection cuts

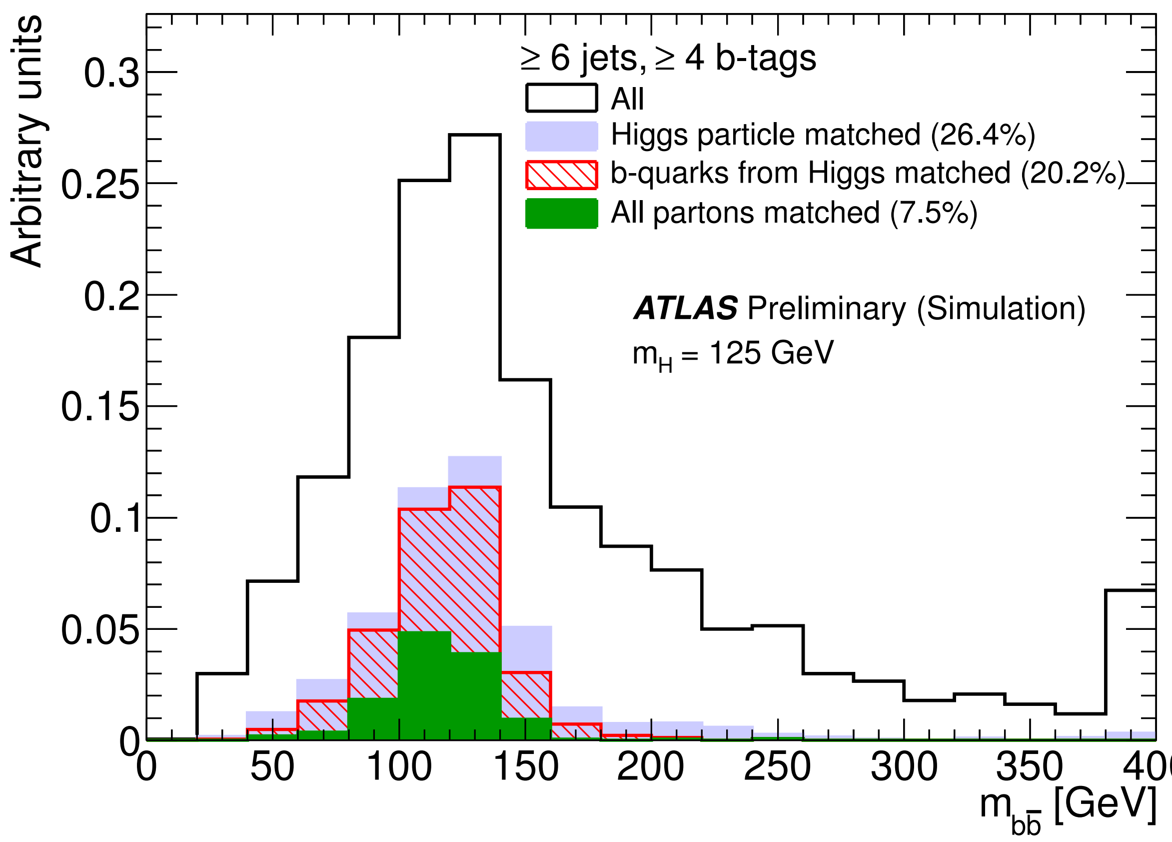
- Plots for $76 < m_{\ell\ell}/\mathrm{GeV} < 106$ and $E_T^{miss} > 90$ GeV
- The arrows indicate the selection cuts applied



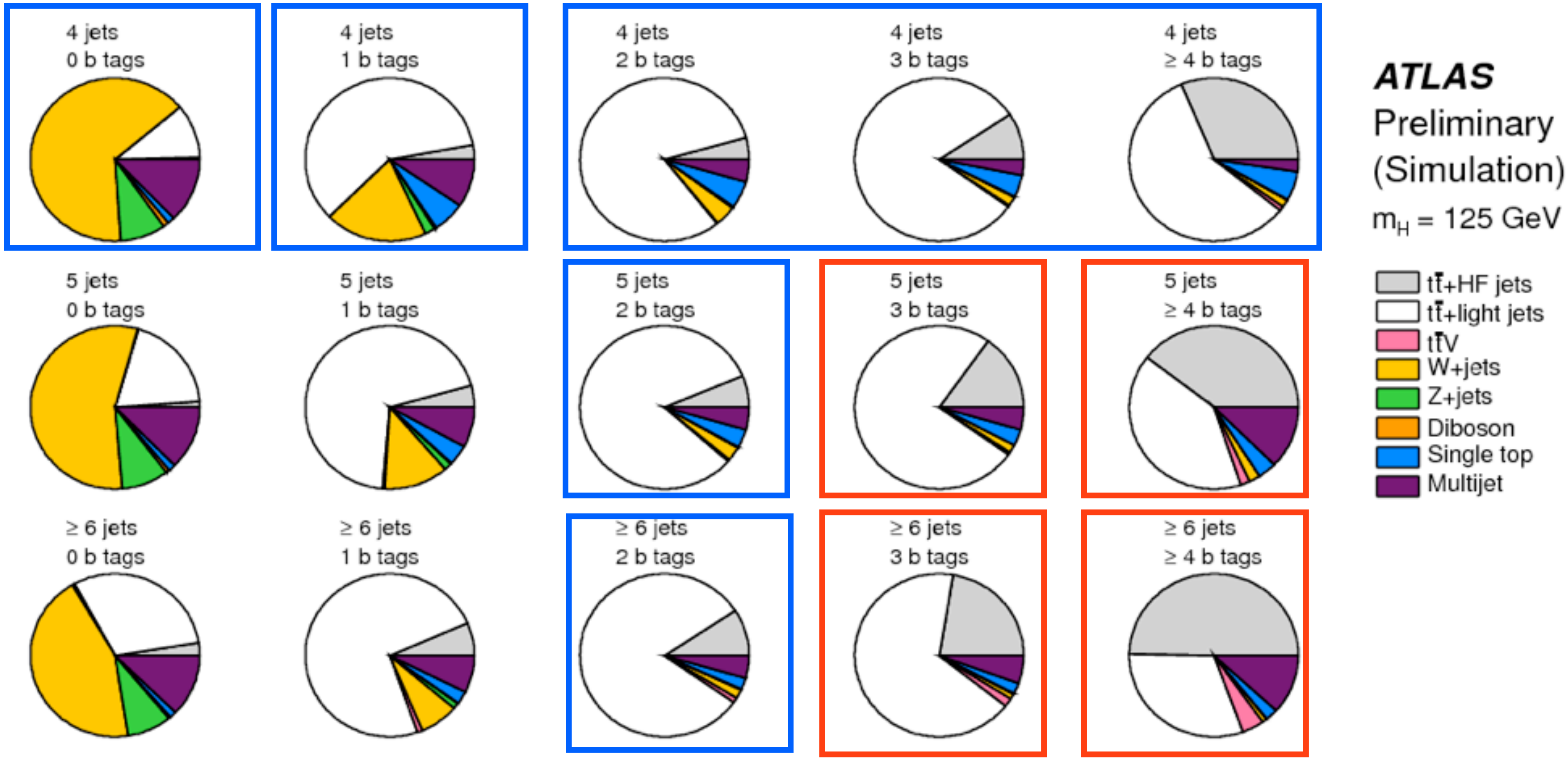
(a) (b) (c) (d)

$t\bar{t}H, H \to b\bar{b}$ $m_{b\bar{b}}$ Reconstruction





$t\bar{t}H$, $H \rightarrow b\bar{b}$ Backgrounds and Analysis Categories



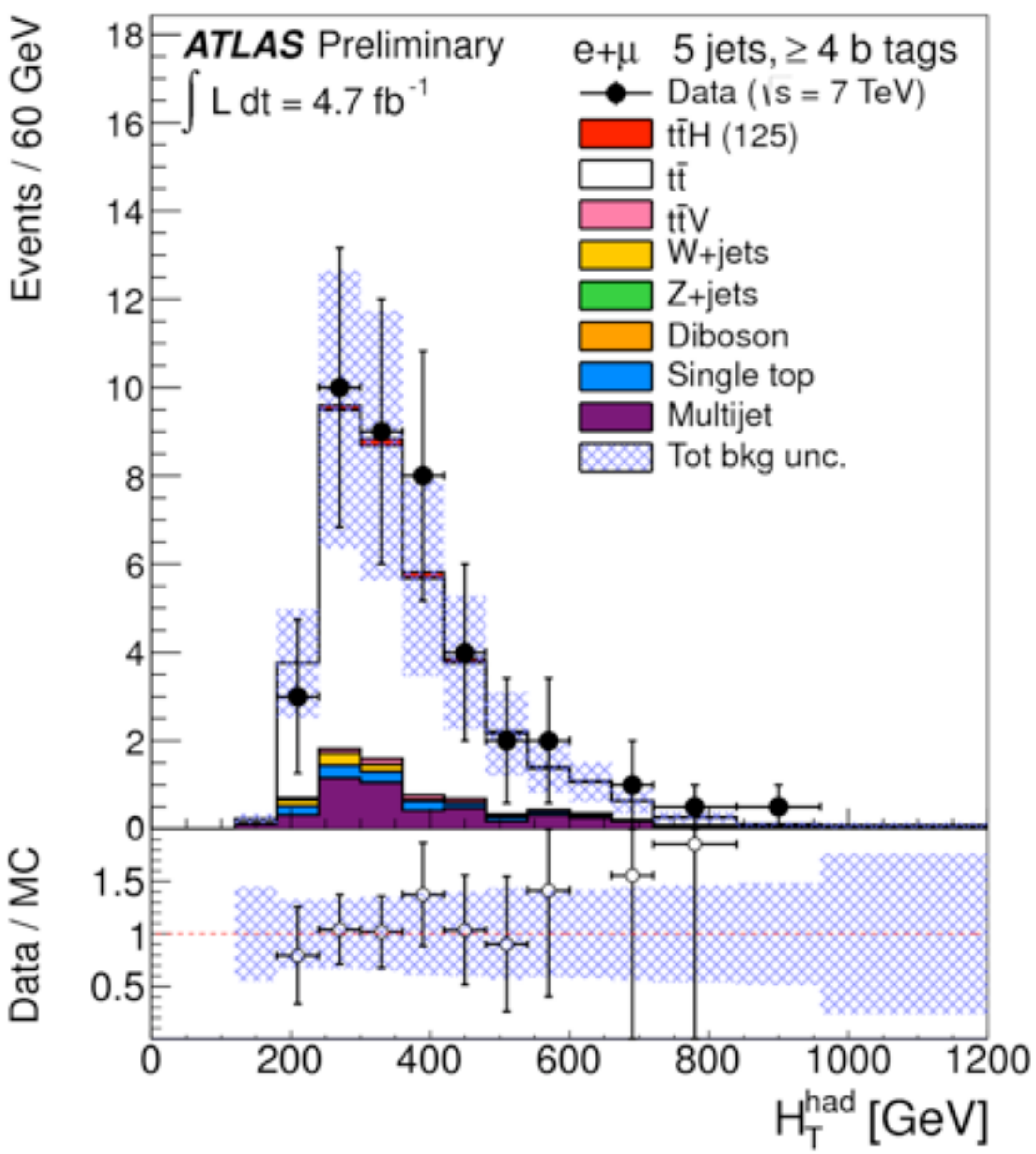
- **9 analysis categories:** based on number of reconstructed jets and number of b-tags
  - **blue** - background regions with $S/\sqrt{B} < 7\%$; included to constrain backgrounds
  - **red** - **signal regions** with $S/\sqrt{B} > 7\%$
- Two discriminating variables, based on the number of reconstructed jets and b-tags:

  ≥ 6 reconstructed jets, ≥ 3 b-tags : $m_{b\bar{b}}$

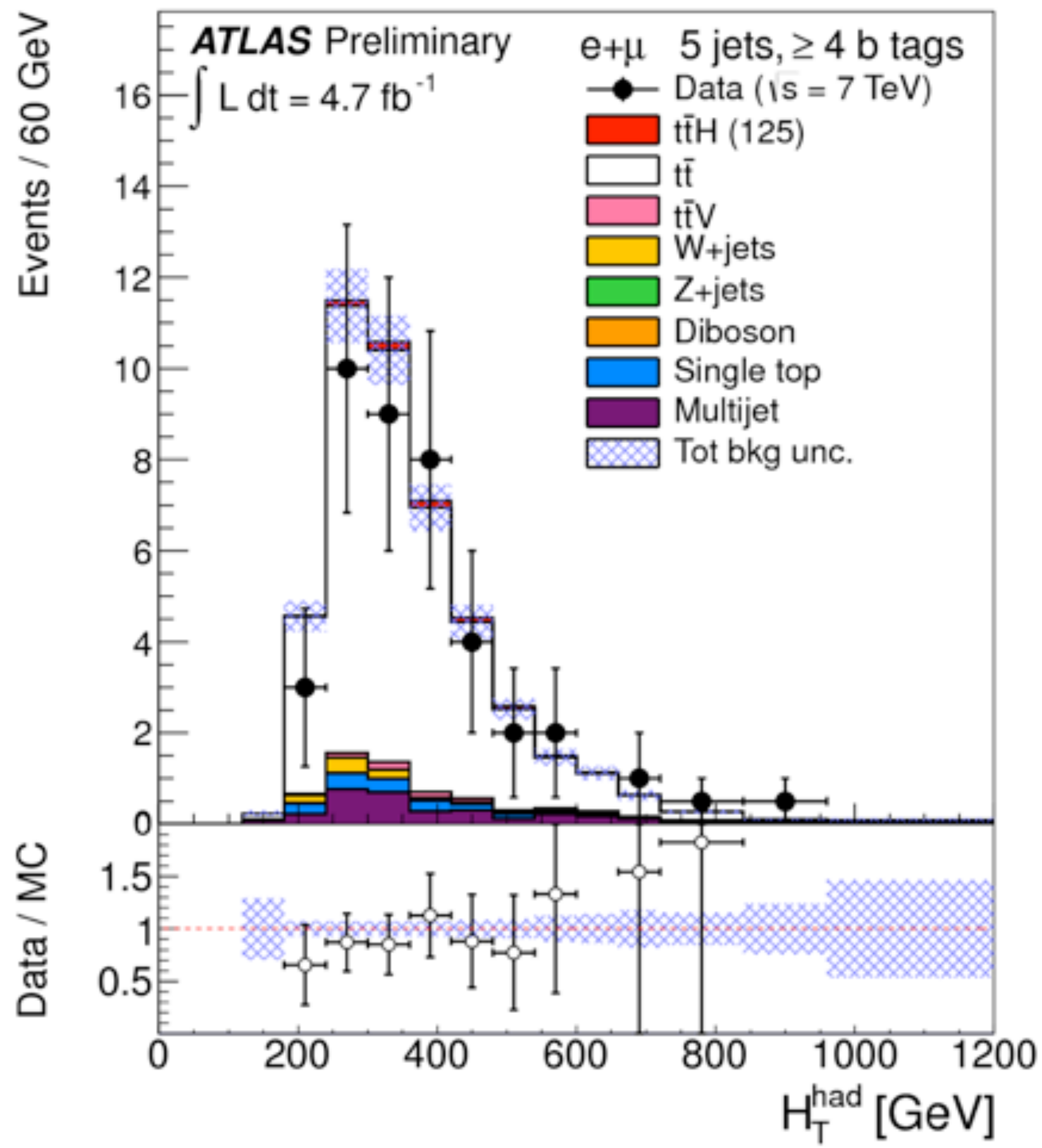
  <6 reconstructed jets or <3 b-tags: H_T^{had}, scalar sum of jet p_T

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

Pre-Fit



Post-Fit



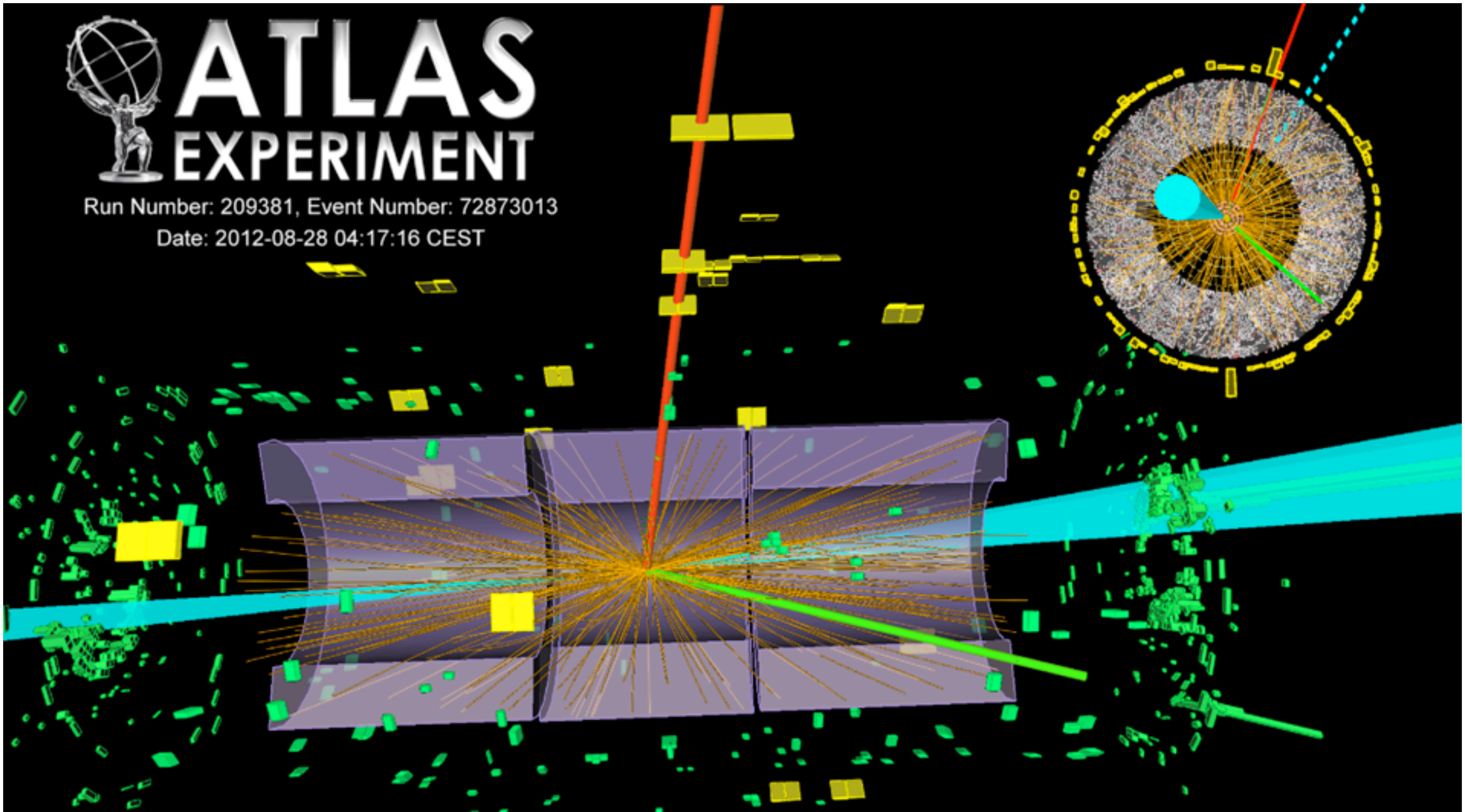
$H\rightarrow\tau^+\tau^-$ Systematics

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	$H \rightarrow \tau_{\text{lep}}\tau_{\text{lep}}$	$H \rightarrow \tau_{\text{lep}}\tau_{\text{had}}$	$H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$
		$Z \rightarrow \tau^+\tau^-$	
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%

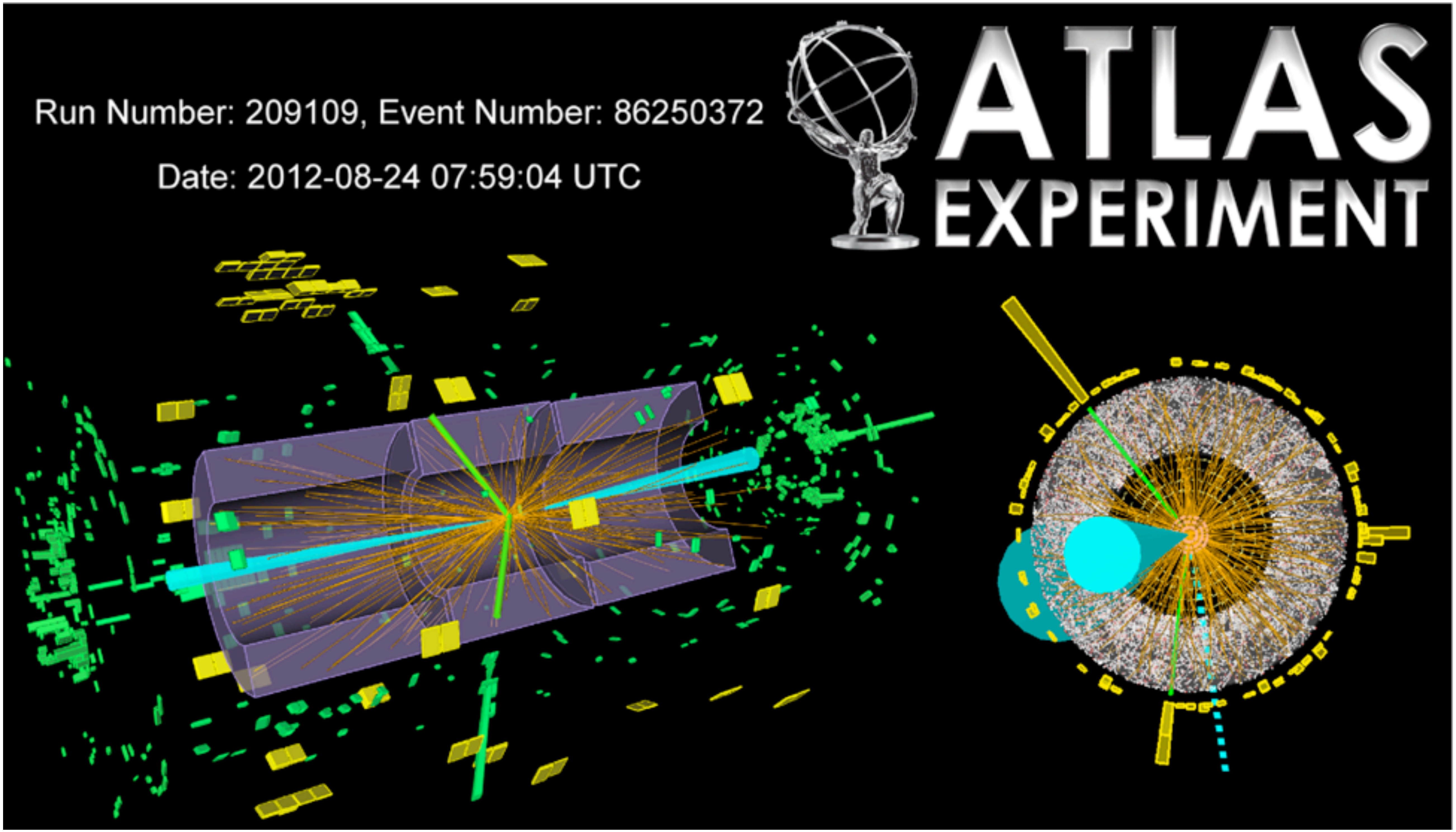
VBF $H\to\tau_e\,\tau_\mu$ candidate event

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

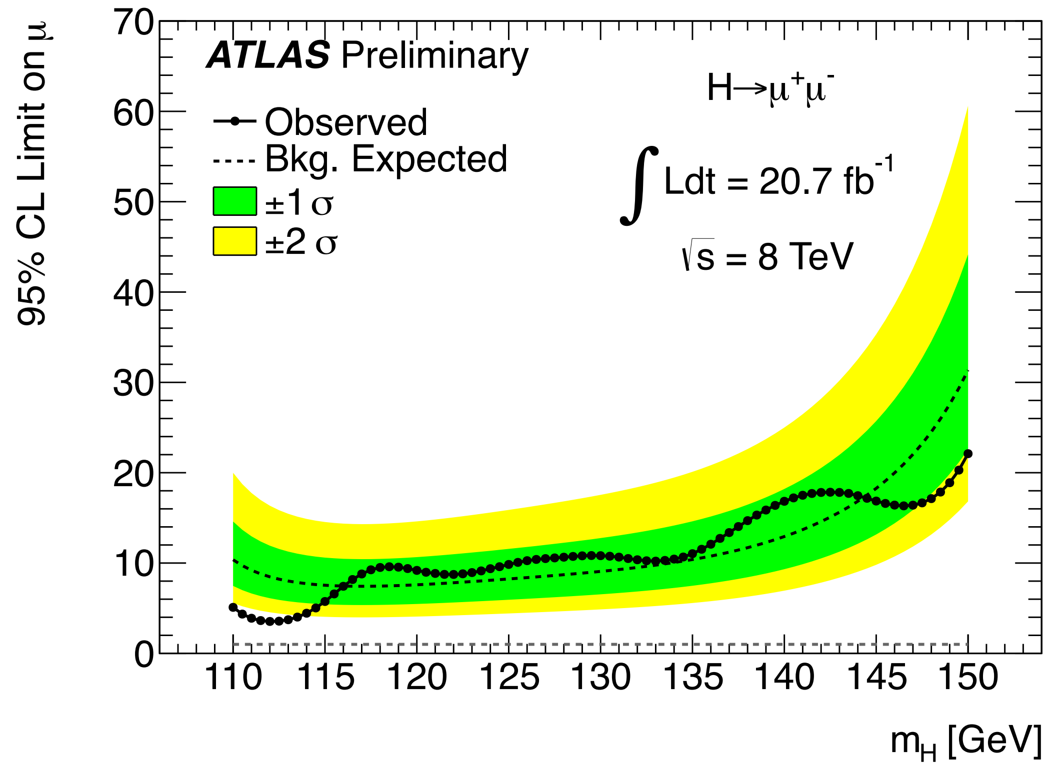


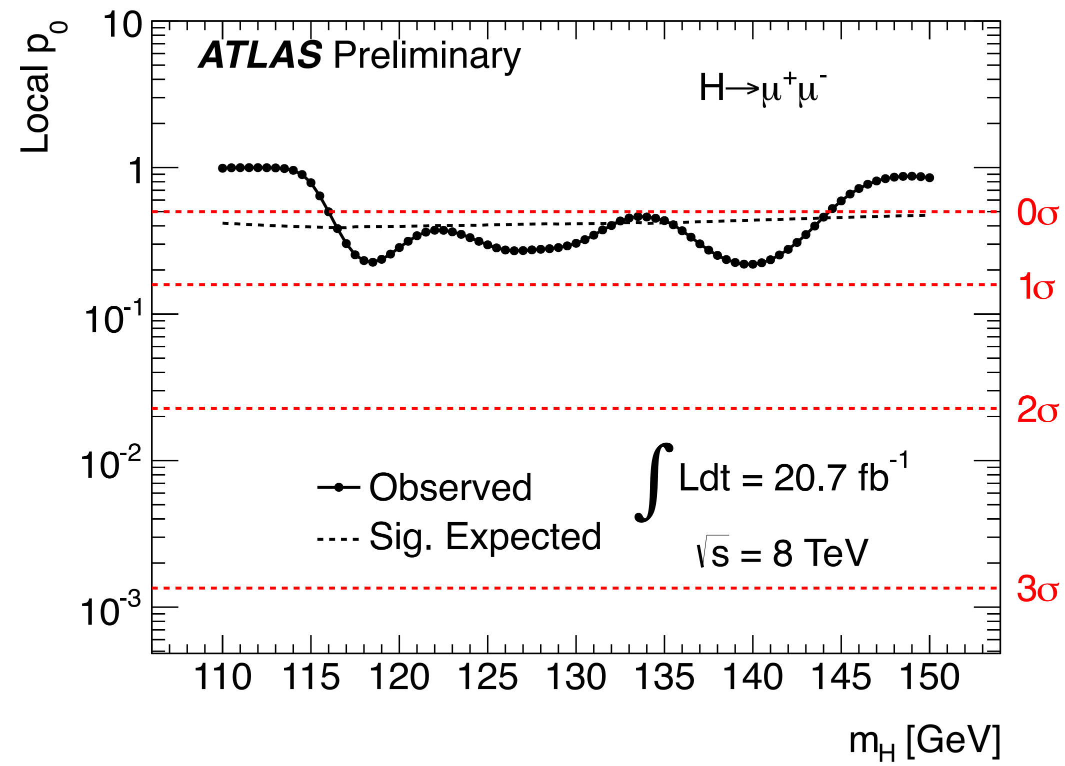
VBF $H \rightarrow \tau_{\mathrm{had}}\, \tau_{\mathrm{had}}$ candidate event

- $E_{\mathrm{T}}^{\mathrm{miss}} = 26$ 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