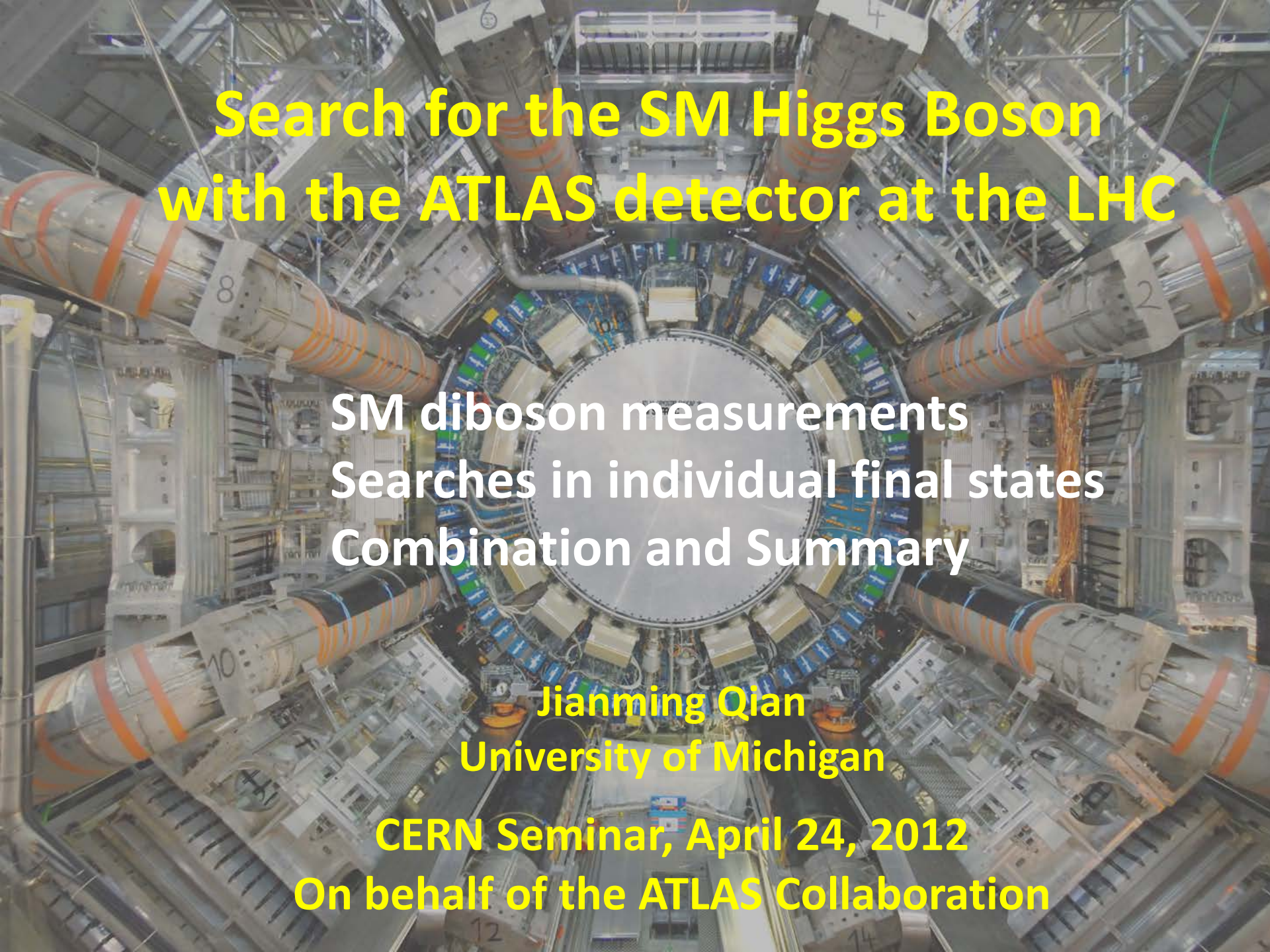


Search for the SM Higgs Boson with the ATLAS detector at the LHC

SM diboson measurements
Searches in individual final states
Combination and Summary

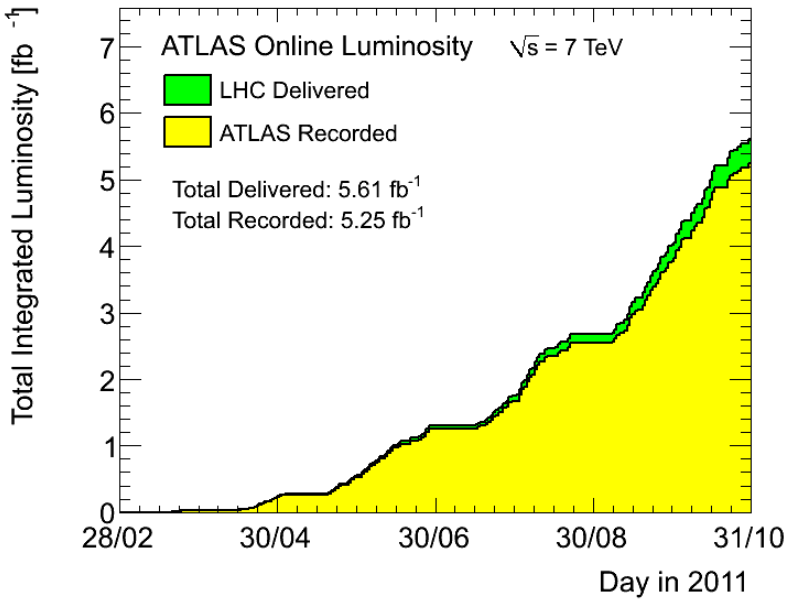
Jianming Qian
University of Michigan

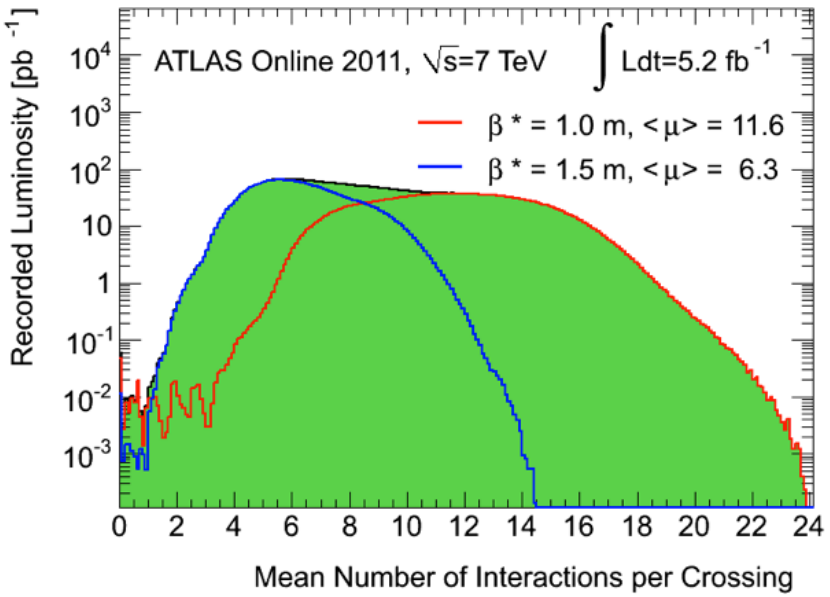
CERN Seminar, April 24, 2012
On behalf of the ATLAS Collaboration

Data Samples

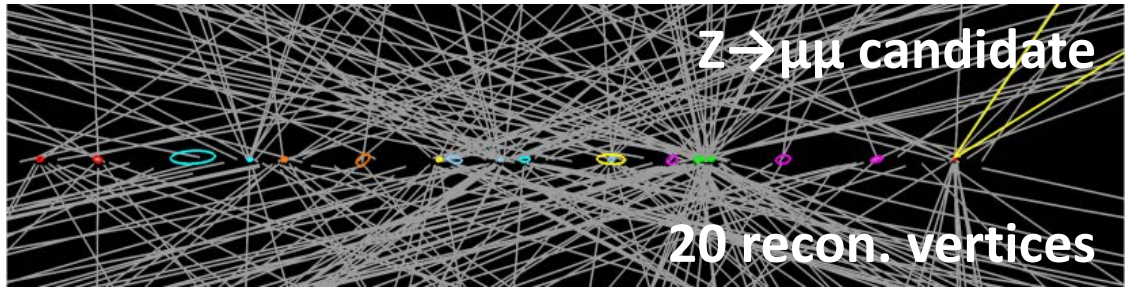
Full 2011 data set:

5.6 fb^{-1} delivered, 5.3 fb^{-1} recorded, ~4.7 fb^{-1} after DQ requirements

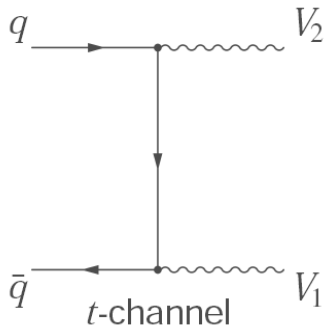


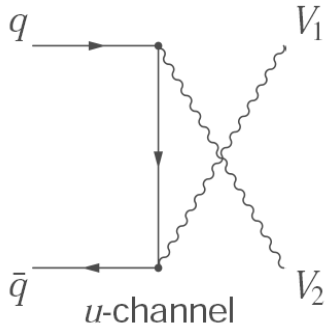


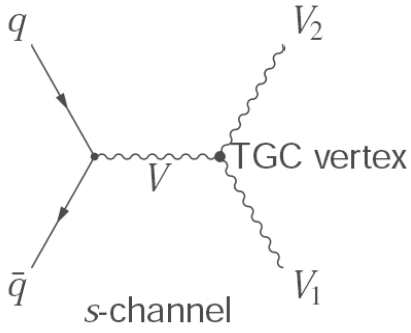
High pileup ⇒ challenging analyses, particularly for final states with jets and ETmiss !



SM Diboson Production







Diboson processes are often irreducible backgrounds to some Higgs searches

ZZ to H→ZZ, WW to H→WW, …

⇒ important to experimentally verify their production cross sections.

Dibosons are mainly produced through t-channel diagrams, their cross sections have been calculated up to NLO with uncertainties around 5%.

Diboson cross section measurements are interesting in their own right:

Test electroweak and QCD calculations;

Explore triple-gauge boson couplings;

Search for new physics beyond SM, …

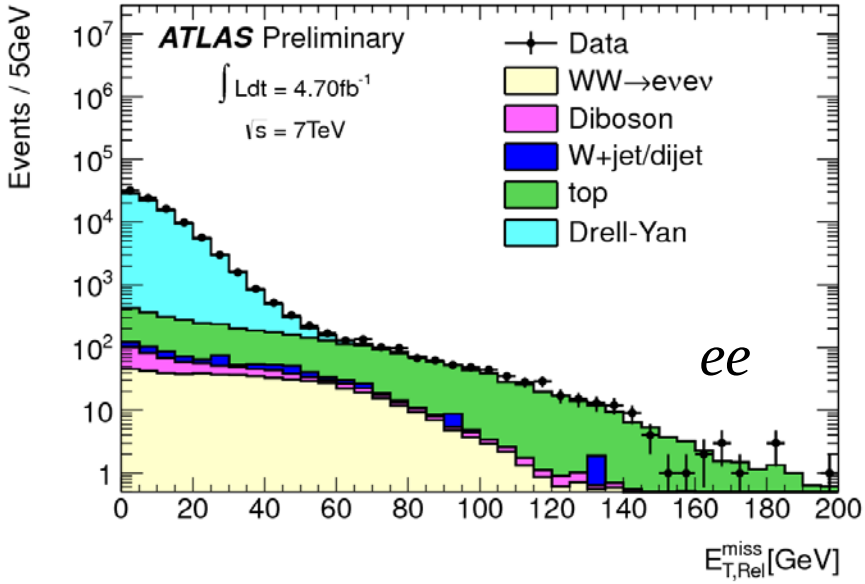
SM WW→lvlv

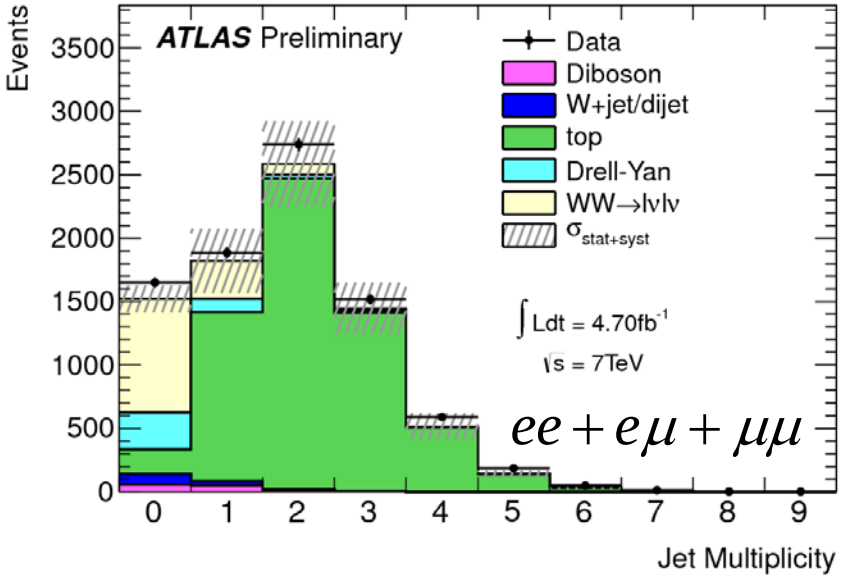
Measured in leptonic decays: $e\nu e\nu,\ \mu\nu\mu\nu,\ e\nu\mu\nu$

- $p_T^{\ell} > 25\,/\,20$ GeV $(ee, e\mu, \mu\mu)$, $20\,/\,20$ (μe);
- $m_{\ell\ell} > 15\,/\,15\,/\,10$ GeV $(ee, \mu\mu, e\mu)$, Z veto for $ee\,/\,\mu\mu$;
- $E_{T,\mathrm{Rel}}^{\mathrm{miss}} > 50\,/\,55\,/\,25$ GeV $(ee, \mu\mu, e\mu)$;
- No jets with $p_T > 25$ GeV and $|\eta| < 4.5$; no b-jet with $p_T > 20$ GeV

$$E_{T,\mathrm{Rel}}^{\mathrm{miss}} = \begin{cases} E_T^{\mathrm{miss}} & \Delta\phi \geq \pi/2 \\ E_T^{\mathrm{miss}} \sin\Delta\phi & \Delta\phi < \pi/2 \end{cases}$$
$$\Delta\phi = \min\left\{\Delta\phi\left(\vec{E}_T^{\mathrm{miss}}, \ell/\mathrm{jets}\right)\right\}$$

Main backgrounds: Z/γ^{*} + jets, top, W+jets, $W\gamma^{(*)}$ / WZ / ZZ,...





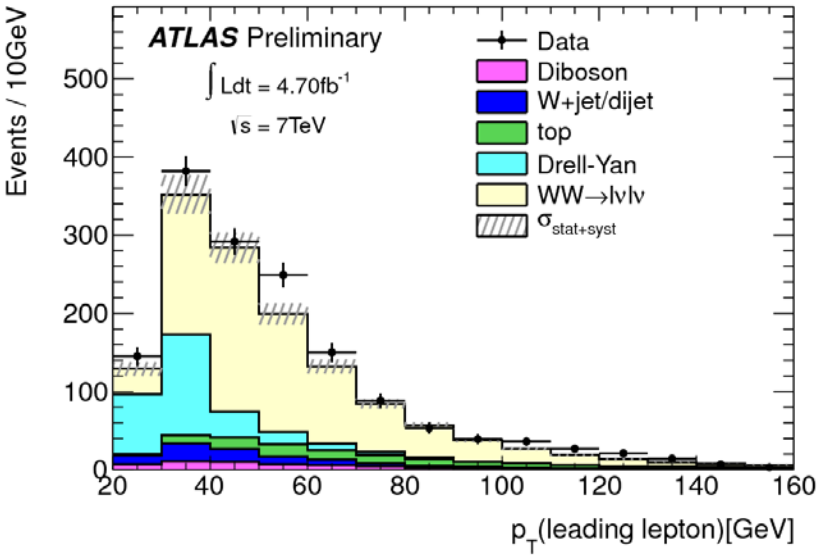
SM WW→lvlv

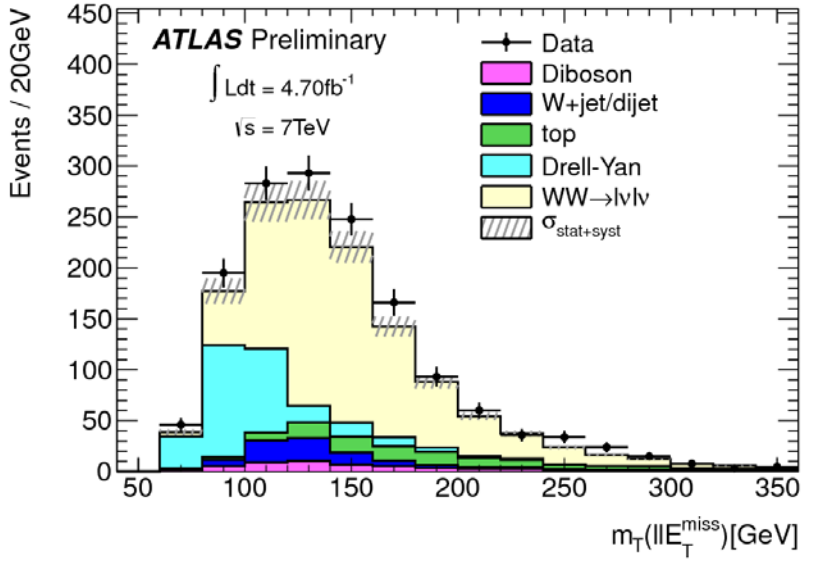
Event Yields:

Final State	Combined
Observed Events	1524
Total expected events (S+B)	1370.1±14.3±96.5
MC WW Signal	839.0±4.2±83.3
Background estimations	
Top(data-driven)	110.0±6.2±22.4
W+jets (data-driven)	79.0±1.4±39.0
Drell-Yan (MC/data-driven)	284.2±11.7±17.2
Other dibosons (MC)	57.6±3.2±7.4
Total background	531.1±13.7±48.7

$$\sigma_{WW} = 53.4 \pm 2.1(\text{stat}) \pm 4.5(\text{syst}) \pm 2.1(\text{lumi}) \text{ pb}$$

Theory: $\sigma_{NLO} = 45.1 \pm 2.8$ pb





ATLAS-CONF-2012-025

SM ZZ→4l

– Four leptons with $p_T > 7$ GeV, at least one $p_T^e > 25$ GeV or one $p_T^\mu > 20$ GeV;
– two same-flavor and opposite charge pairs: $66 < m_{\ell\ell} < 116$ GeV

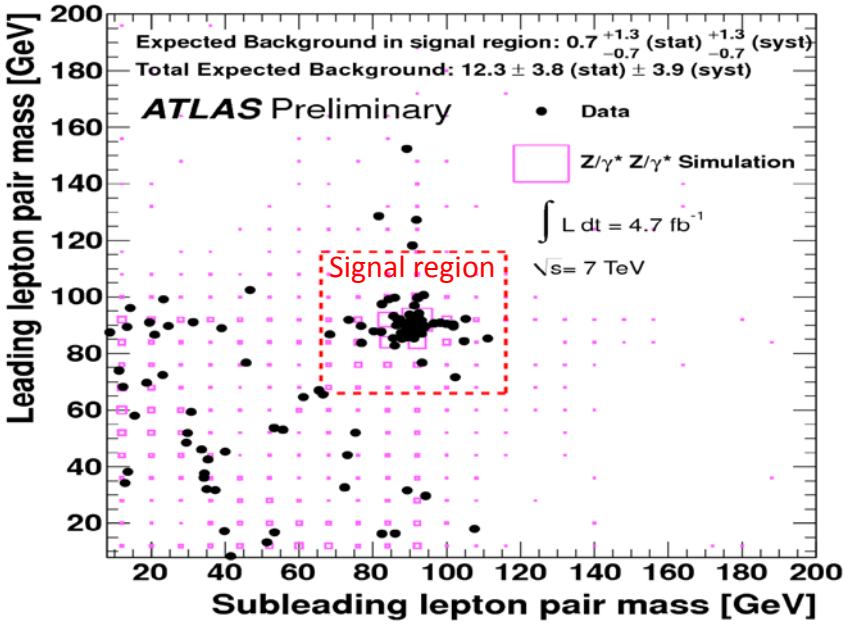
$Z \equiv "Z/\gamma^*"$

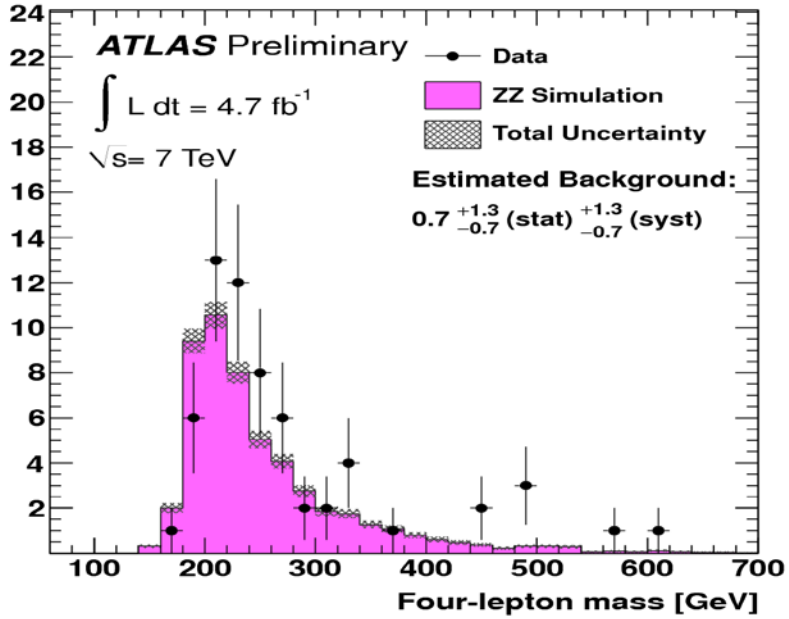
$$\sigma_{ZZ} = 7.2^{+1.1}_{-0.9}\,(\text{stat})^{+0.4}_{-0.3}\,(\text{syst}) \pm 0.3\,(\text{lumi})\ \text{pb}$$

Theory: $\sigma_{NLO} = 6.5^{+0.3}_{-0.2}$ pb

$(66 < m_{\ell\ell} < 116\ \text{GeV})$

Final state	combined ($\ell\ell\ell\ell$)
Observed	62
Signal(MC)	$53.2 \pm 1.1 \pm 1.9$
Bkg(d.d.)	$0.7^{+1.3+1.3}_{-0.7-0.7}$
Bkg(MC)	1.0 ± 0.6





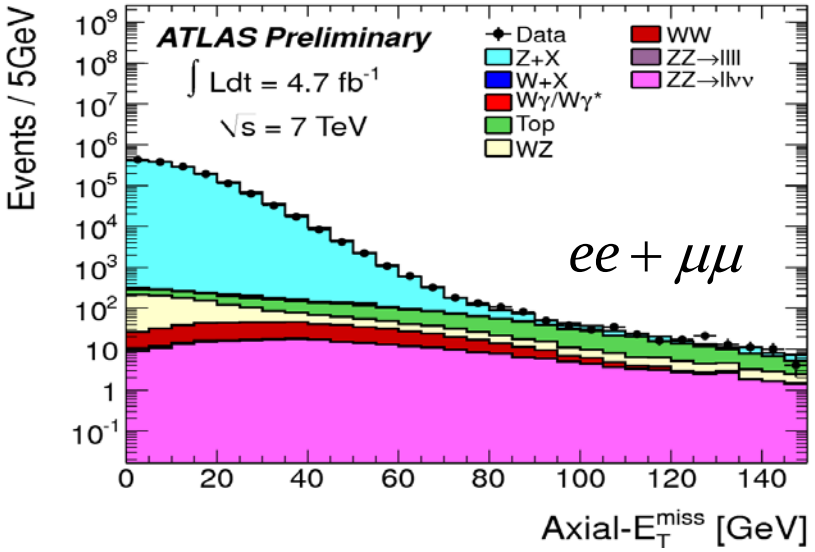
ATLAS-CONF-2012-026

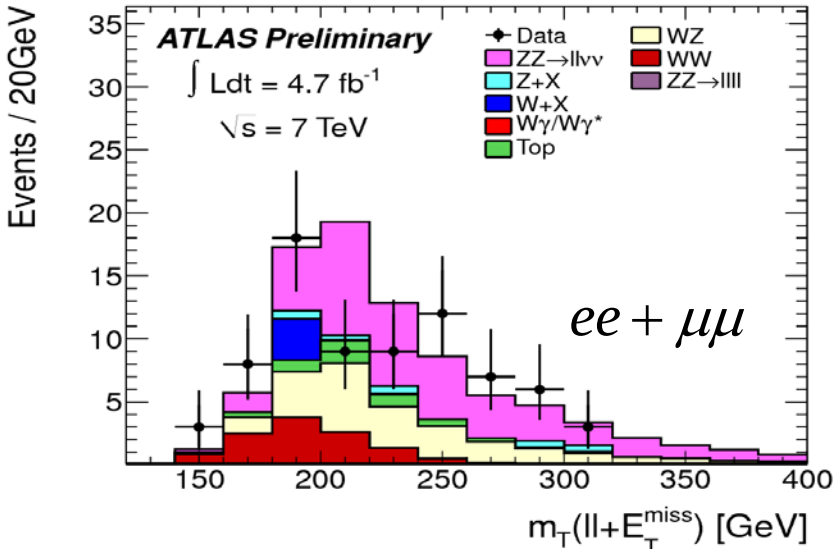
SM ZZ→llvv

- 2 same-flavor leptons with $p_T > 20$ GeV;
- $\left|m_{\ell\ell} - M_Z\right| < 15$ GeV;
- Axial-$E_T^{\text{miss}} > 80$ GeV $\left(\text{projection along } \vec{p}_T^{\,Z}\right)$;
- No jet with $p_T > 25$ GeV and $\left|\eta\right| < 4.5$;
- $\left|E_T^{\text{miss}} - p_T^Z\right| < 0.6\, p_T^Z$

$$\sigma_{ZZ} = 5.4^{+1.3}_{-1.2}\left(\text{stat}\right)^{+1.4}_{-1.0}\left(\text{syst}\right) \pm 0.2\left(\text{lumi}\right)\ \text{pb}$$

Final State	$\ell^+\ell^-\nu\bar{\nu}$
Observed	78
Expected ZZ	$42.3 \pm 0.8 \pm 1.8$
Background estimations:	
$W^{\pm}Z$ (MC)	$22.7 \pm 0.8 \pm 3.5$
$W^{\pm}+\gamma$ (MC)	$0.29 \pm 0.12 \pm 0.01$
$t\bar{t}$, $W^{\pm}t$, W^+W^- and $Z \to \tau\tau$	$14.7 \pm 4.1 \pm 0.6$
Z+jets (data-driven)	$1.7 \pm 0.5 \pm 0.8$
$W^{\pm}$+jets (data-driven)	$1.3 \pm 0.4 \pm 0.3$
Total Background	$40.7 \pm 4.3 \pm 3.7$

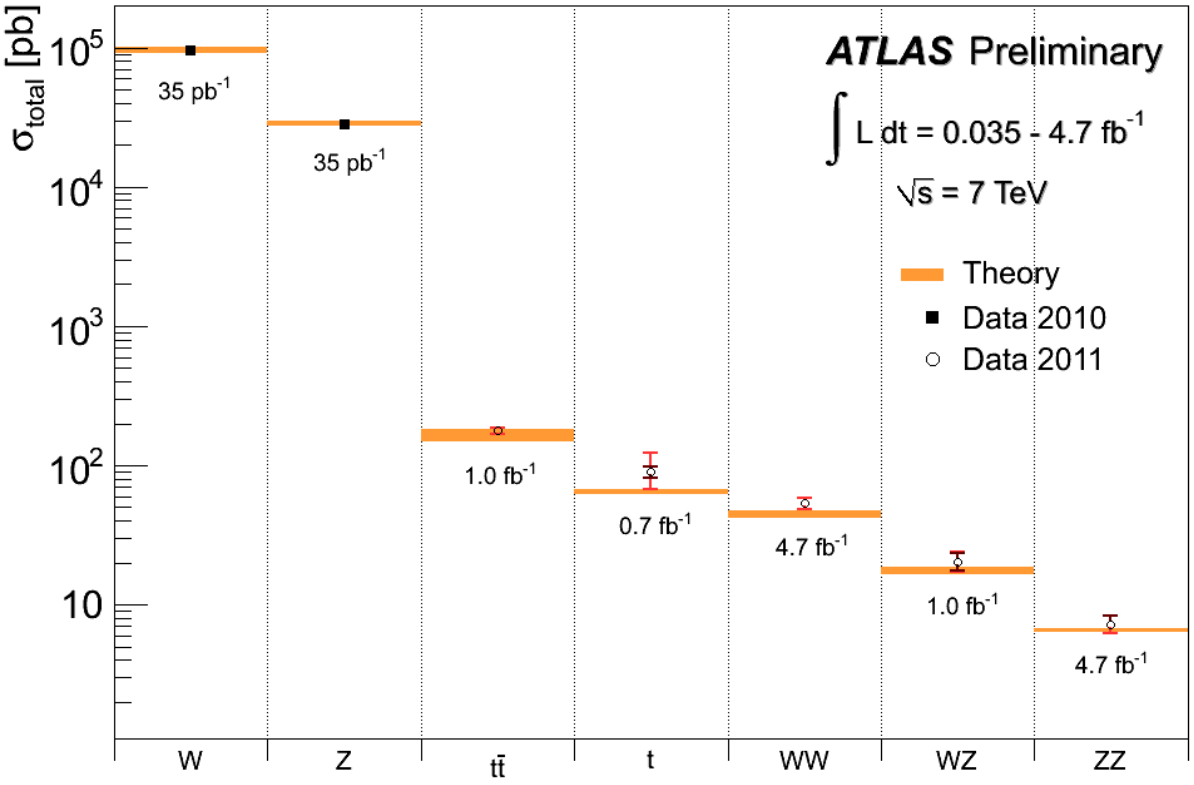




ATLAS-CONF-2012-027

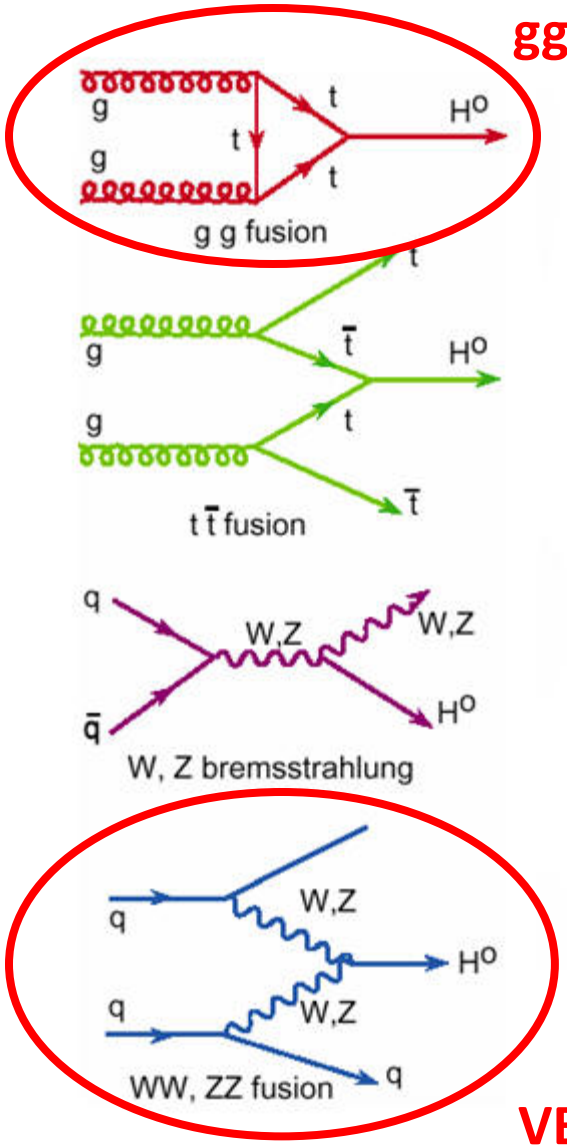
Cross Section Measurements

Higgs searches are built upon the successes of numerous studies/measurements of Standard Model physics

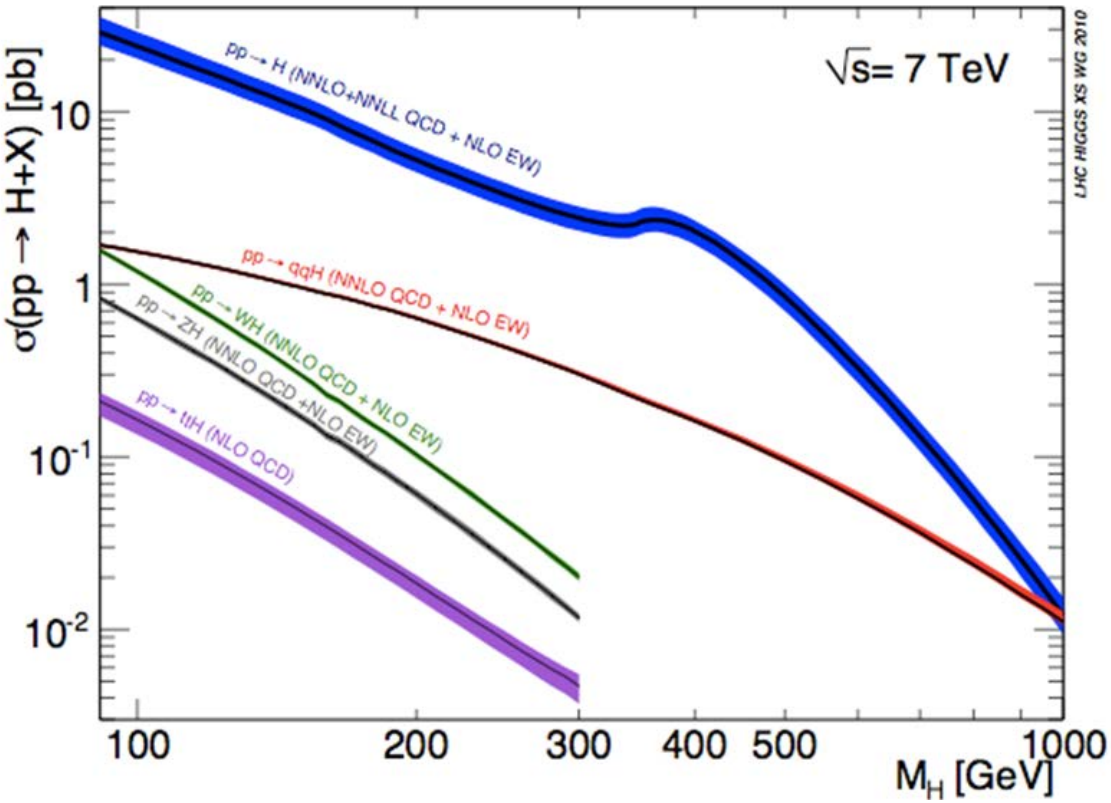


These measurements validate detector/physics simulation, object reconstructions, event selections and in general analysis techniques

Higgs Boson Production



gluon-gluon fusion gg→H and vector-boson fusion qq→qqH diagrams dominate



$\sigma_H \approx 15$ pb @ 125 GeV, 10 pb @ 150 GeV

Typical uncertainty: <10%

Higgs Boson Decay

Many decay modes, but two dominate:

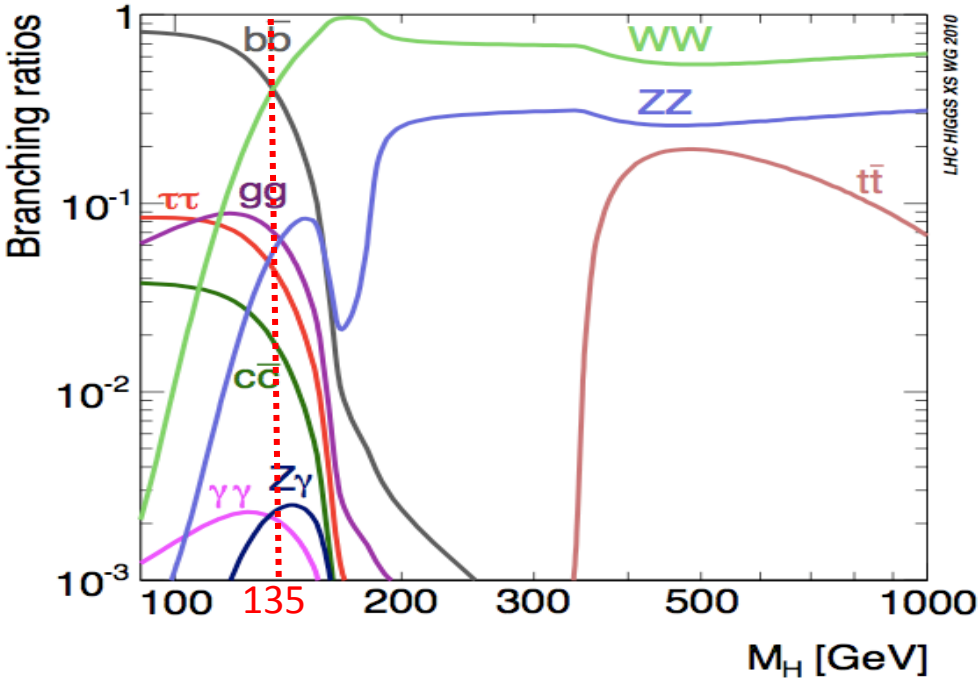
- $H \to b\bar{b}$ for $m_H < 135$ GeV;
- $H \to WW$ for $m_H > 135$ GeV

neither is ideal for the search and the study of properties

- $b\bar{b}$: suffers from huge QCD background, poor mass resolution;
- WW : easy identification in $\ell\nu\ell\nu$, but no full reconstruction

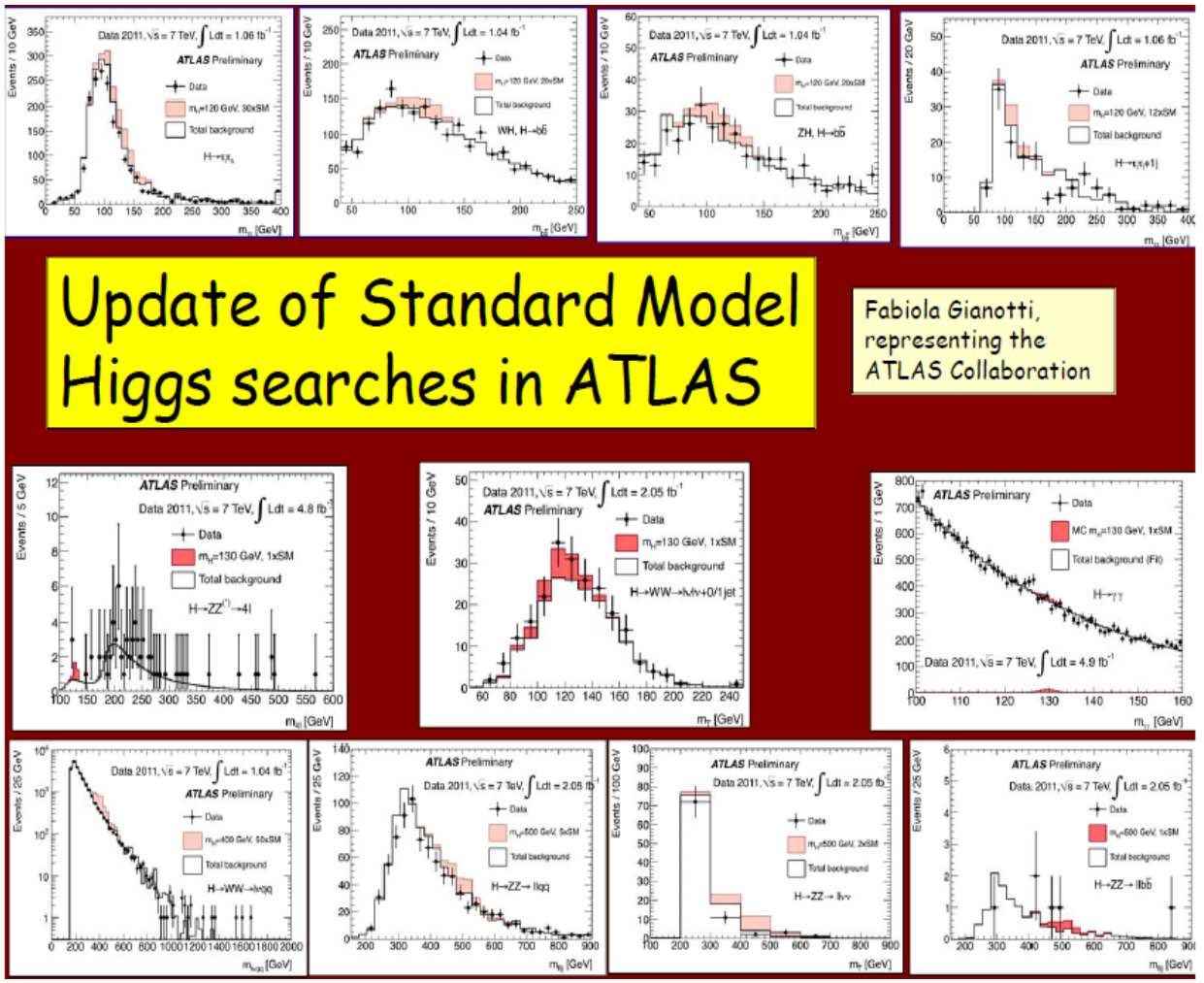
Difficult low mass region:

- **many decay modes, but most of them suffer from large backgrounds;**
- **promising high mass-resolution channels:**
  - $H \to \gamma\gamma$;
  - $H \to ZZ^{(*)} \to 4\ell$



CERN December Seminar

CERN Seminar, December 13, 2011



Fabiola presented the H→γγ and H→ZZ→4l analyses in details last December, I will therefore focus on other channels

Search Overview

High resolution channels: full reconstruction, good mass resolution

Channel	Mass Range (GeV)	Int. Lumi (fb^{-1})	Signal Events Before Selection	Main Backgrounds
$H\to\gamma\gamma$	110-150	4.9	~200 (125 GeV)	$\gamma\gamma$, γj, jj
$H\to ZZ\to 4l$	110-600	4.8	~10 (125 GeV)	ZZ, Z+jets, top
$H\to bb$ (WH/ZH)	110-130	4.6-4.7	~2400 (125 GeV)	W/Z+jets, top
$H\to\tau\tau$ (ll, lτ_h, $\tau_h\tau_h$)	100-150	4.7	~5200 (125 GeV)	Z+jets, jets
$H\to WW\to l\nu l\nu$	110-600	4.7	~820 (125 GeV)	WW, W/Z+jets, top, Wγ
$H\to WW\to l\nu qq$	300-600	4.7	~1800 (400 GeV)	W+jets, jets
$H\to ZZ\to ll\nu\nu$	200-600	4.7	~75 (400 GeV)	Z+jets, ZZ, top
$H\to ZZ\to llqq$	200-600	4.7	~260 (400 GeV)	Z+jets, ZZ, top

Published!

Preliminary Results
Publication in Preparation

Low resolution channels: no full reconstruction or poor mass resolution

Analysis Strategies

Maximum utilization of leptonic (e, μ) and photonic signatures:

simple to trigger and identify, lower rates, good energy and position resolutions, …

Take advantage of varying signal-background ratios of detector regions and event topologies through categorization:

central vs forward, high and low Higgs pT, jet multiplicity bins, …

Use data-driven methods to estimate backgrounds whenever possible to minimize systematics:

control regions , sidebands, fake leptons, mismeasured ETmiss,…

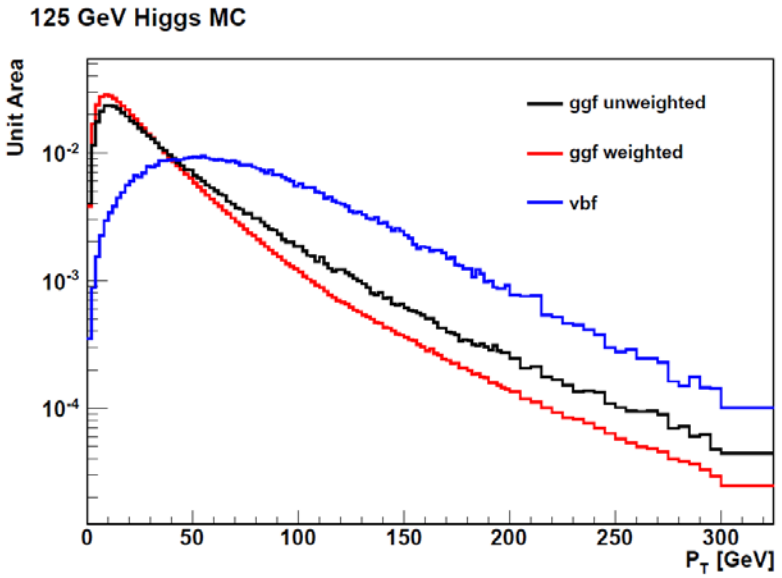
Fit the distributions of the reconstructed Higgs boson (transverse) mass or equivalent to improve sensitivities:

$$m(\gamma\gamma),\ m(4\ell),\ m(b\bar{b}),\ m(\tau\tau),\ m_T(\ell\nu\ell\nu),\ m(\ell\nu qq),\ m_T(\ell\ell\nu\nu),\ m(\ell\ell qq)$$

Theory and MC

Signal MC:

ggF and VBF: POWHEG+PYTHIA;
WH and ZH: PYTHIA
For gg→H, the Higgs pT is reweighted to the HqT (NNLO+NNLL) calculation.



Background MC:

W/Z+jets: ALPGEN;
Top: MC@NLO (tt), AcerMC (t);
Dibosons: MC@NLO (WW, WZ), SHERPA (ZZ), ALPGEN (Wγ), MadGraph (Wγ*)

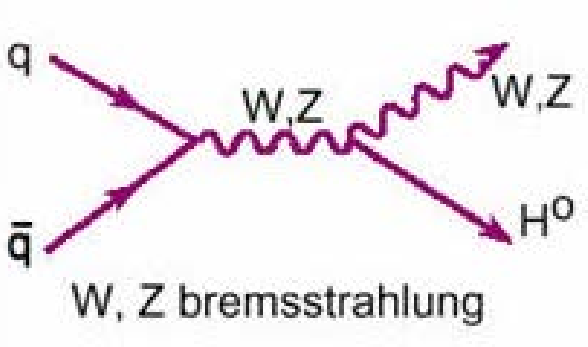
Many other generators are used as cross checks. Normalize to data control regions or the latest N^nLO calculations.

$WH / ZH \rightarrow \left(\ell\nu b\bar{b},\ \ell\ell b\bar{b},\ \nu\nu b\bar{b}\right)$

H→bb has the largest branching ratio at low mass, but suffers from overwhelming backgrounds in the dominant ggF and VBF production.

Explore the associated production, analyzing three different final states

$$WH \rightarrow \ell\nu b\bar{b},\ ZH \rightarrow \ell\ell b\bar{b},\ ZH \rightarrow \nu\nu b\bar{b}$$



Main backgrounds:

- **W/Z+jets: shape from simulation, normalization from data;**
- **Top: shape from simulation, normalization from data;**
- **Diboson: both shape and normalization from simulation**

Categorization to take advantage of different S/B ratios:

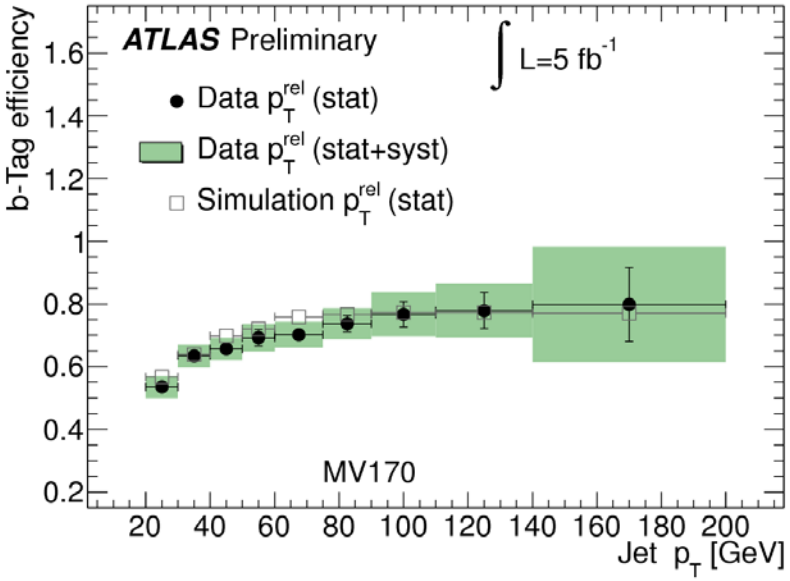
- 4 p_T^W categories for WH $\rightarrow \ell\nu b\bar{b}$: 0 – 50, 50 – 100, 100 – 200, >200 GeV;
- 4 p_T^Z categories for ZH $\rightarrow \ell\ell b\bar{b}$: 0 – 50, 50 – 100, 100 – 200, >200 GeV;
- 3 E_T^{miss} categories for ZH $\rightarrow \nu\nu b\bar{b}$: 120 – 160, 160 – 200, >200 GeV

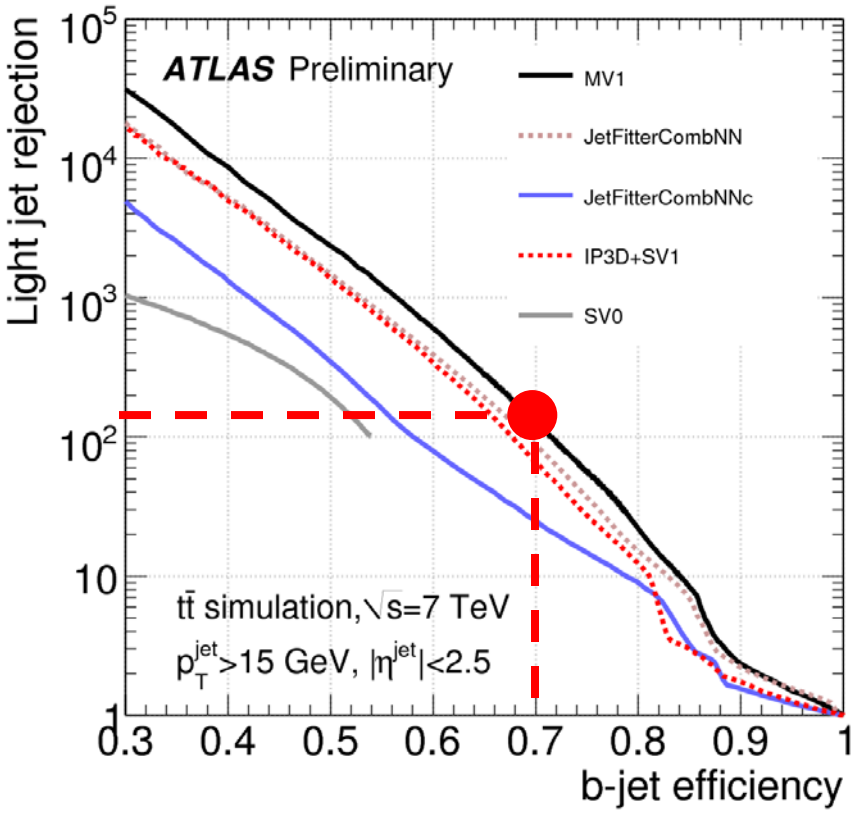
b-jet Tagging

b-quark jets tagging is the key for the analysis…

- **Tagging b-quark jets based on relatively long lifetime (cτ~450 μm) of B hadrons; construct a single discriminant from track impact parameters and secondary vertices**

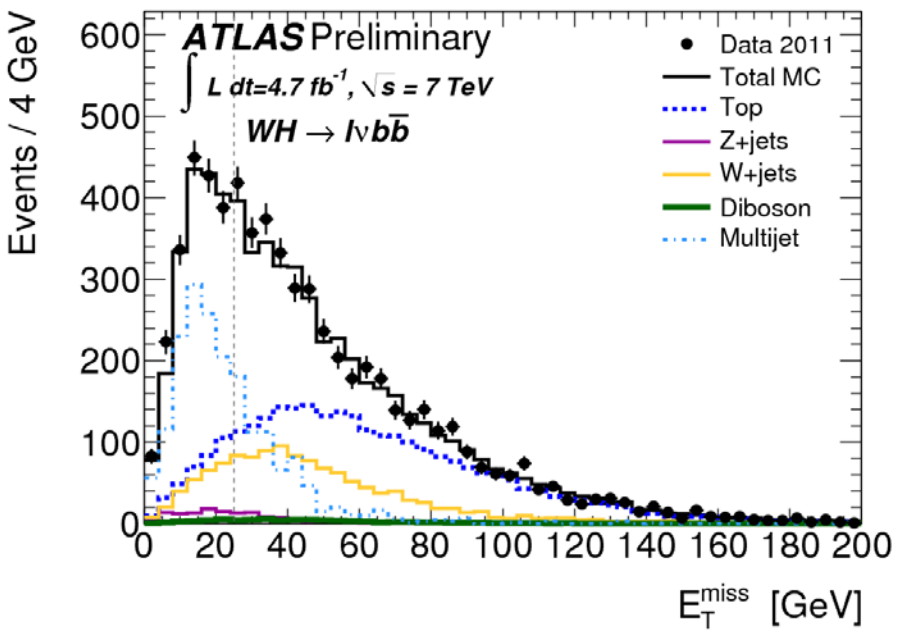
- **Operating point:**
  b-jet efficiency: ~70%
  light-jet rejection: ~130

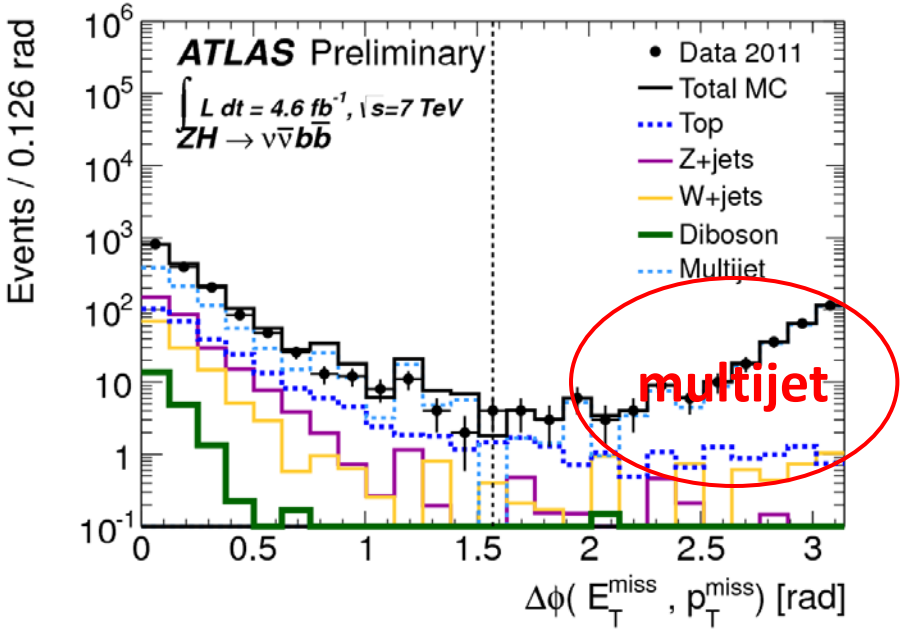




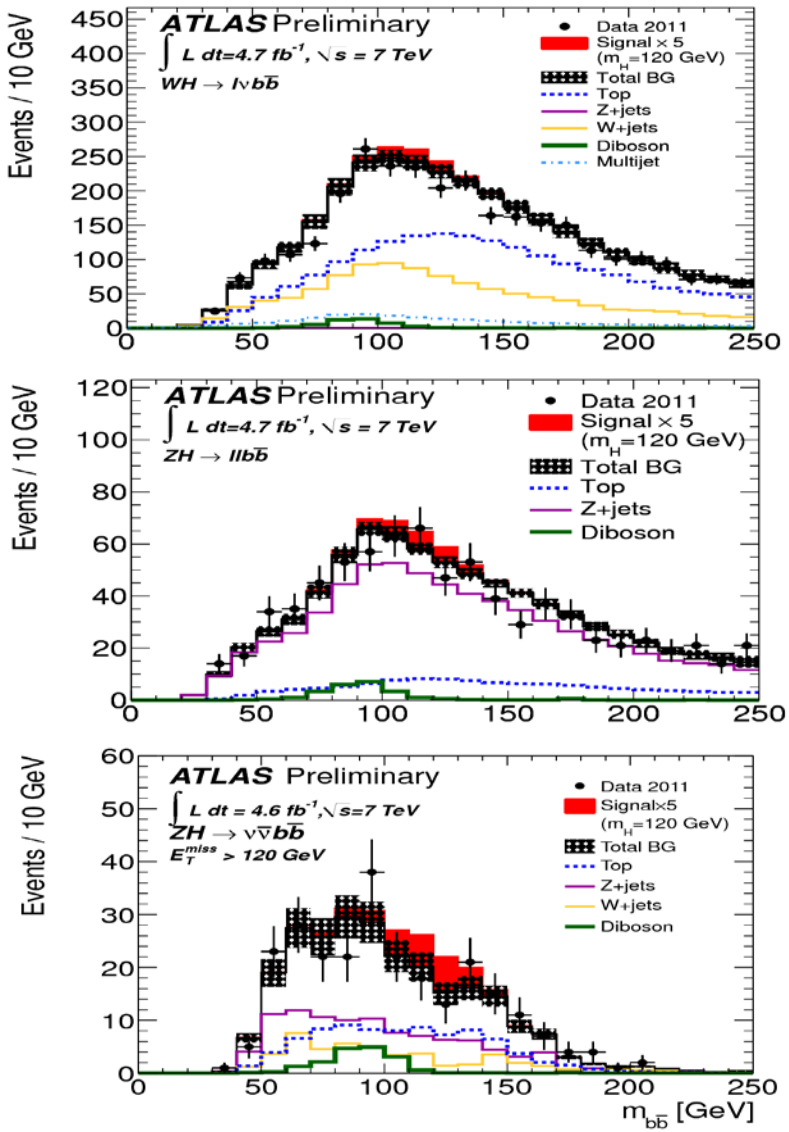
$WH\,/\,ZH \rightarrow \left(\ell\nu b\bar{b},\ \ell\ell b\bar{b},\ \nu\nu b\bar{b}\right)$

- $p_T^{\ell} > 20\,/\,25$ GeV $\left(\ell\ell b\bar{b},\ \ell\nu b\bar{b}\right)$; $p_T^{j} > 25$ GeV;
- mass: $m_T > 40$ GeV $\left(\ell\nu b\bar{b}\right)$, $83 < m_{\ell\ell} < 99$ GeV $\left(\ell\ell b\bar{b}\right)$;
- $E_T^{\text{miss}} > 25$ GeV $\left(\ell\nu b\bar{b}\right)$, < 50 GeV $\left(\ell\ell b\bar{b}\right)$, > 120 GeV $\left(\nu\nu b\bar{b}\right)$;
- Exactly two b-tagged jets with $p_T^{b} > 45, 25$ GeV;
- For $\nu\nu b\bar{b}$, $\Delta\phi\left(\vec{E}_T^{\text{miss}}, \vec{p}_T^{\text{miss}}\right)$ for additional multijet rejection



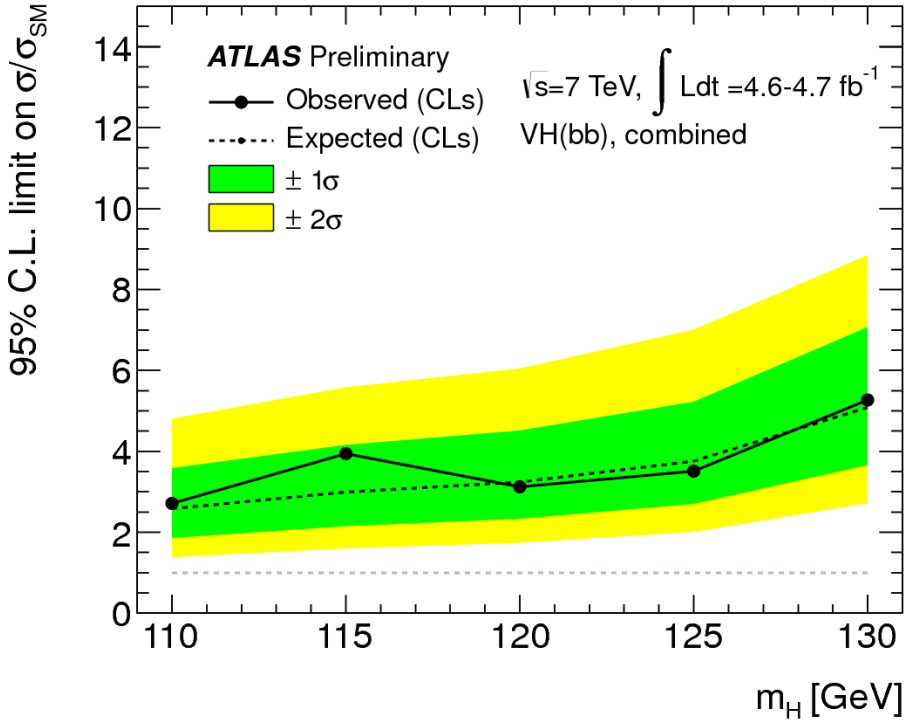


$WH / ZH \rightarrow \left(\ell\nu b\bar{b},\ \ell\ell b\bar{b},\ \nu\nu b\bar{b}\right)$



Binned likelihood fit to the observed m_{bb} distribution between 80-150 GeV to extract the cross section limits.

The observed upper cross section limit is 2.7-5.3 times the SM prediction.



ATLAS-CONF-2012-015

H→ττ

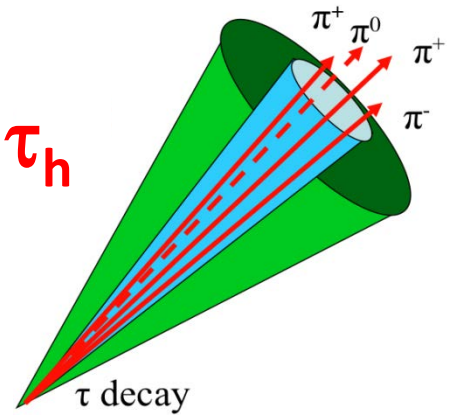
An important search channel at low mass, likely the only final state for Higgs-lepton coupling measurements upon discovery.

Three search final states depending on tau decays:

$$H \to \tau\tau \to \ell\ell + 4\nu \ (12\%)$$
$$H \to \tau\tau \to \ell\,\tau_h + 3\nu \ (46\%)$$
$$H \to \tau\tau \to \tau_h\tau_h + 2\nu \ (42\%)$$

Hadronic tau identification:

- One or three charged tracks;
- Collimated calorimeter energy deposits;
- Large leading track momentum



Major backgrounds:

- Z(→ττ)+jets, estimated using embedding method
- Multijets, estimated using same-sign events.

H→ττ

Separate exclusive analysis categories

jet bin $\otimes$ lepton flavor $\otimes$ $\not{E}_T$: 4 for $\ell\ell$, 7 for $\ell\tau_h$ and 1 for $\tau_h\tau_h$

Main selections:

ll: 0j, 1j, 2j VBF and 2j VH

$p_T > 15(e),\ 10(\mu)$ GeV;

$\not{E}_T > 40(20)$ for SF(OF)

$30 < m_{\ell\ell} < 70(100)$ GeV for SF(OF)

lτ$_h$: 0j, 1j, 2j VBF, ETmiss

$p_T^\tau > 25(e\tau_h),\ 20(\mu\tau_h)$ GeV;

$m_T(\ell, \not{E}_T) < 30$ GeV;

$\not{E}_T > 20$ GeV for 1j/2j

τ$_h$τ$_h$: 1j only

$p_T^\tau > 25,35$ GeV;

$\not{E}_T > 20$ GeV;

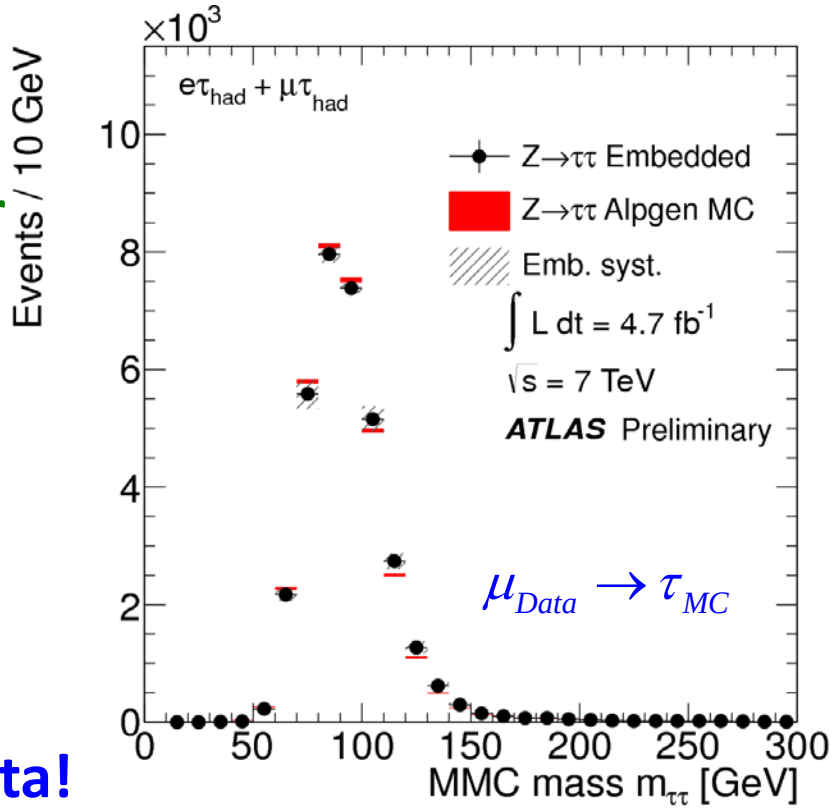
1j with $E_T^j > 40$ GeV

…plus category-dependent selections

H→ττ

Z→ττ is the most dominant background for all H→ττ searches, its contribution is estimated from the Z→μμ data through τ embedding

- select Z→μμ candidates in data;
- remove muon tracks and their expected calorimeter energy deposits from the events;
- replace them by simulated tau decay products;
- re-run the full event reconstruction

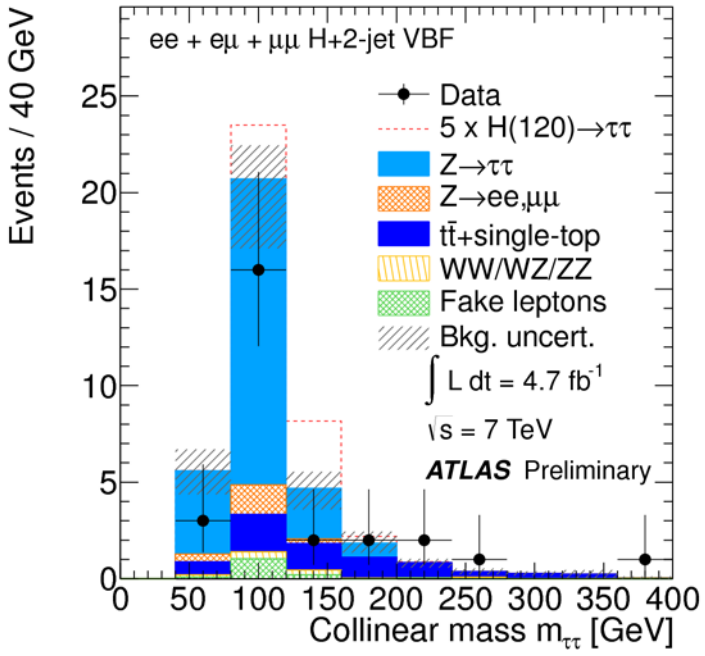


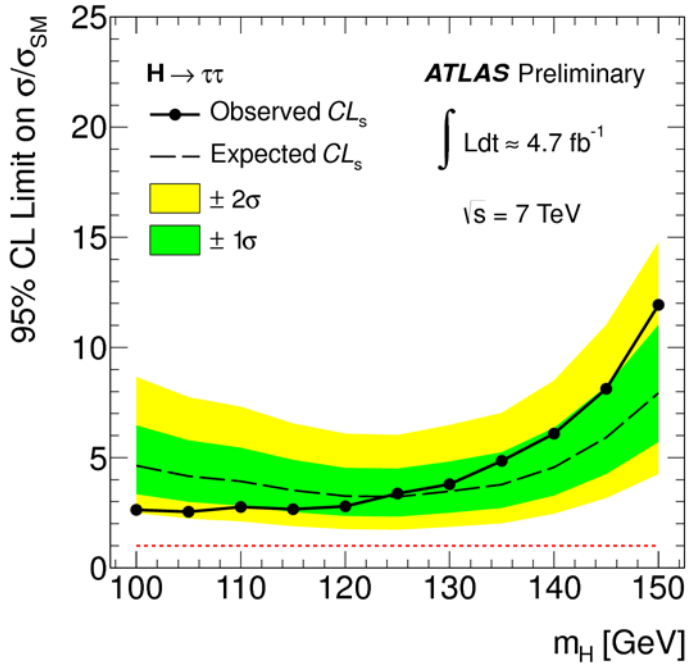
⇒ All except τ decays are from data!

H→ττ

- No significant excess in the mass range of 100-150 GeV is observed in any of the 12 categories studied;
- Upper limits on the Higgs production rates are extracted from fits to the observed mass distributions.

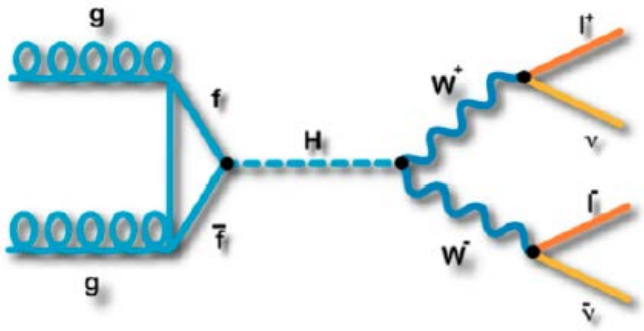
The observed upper limit on the H→ττ rate is between 2.5-11.9 of that of the Standard Model predictions.





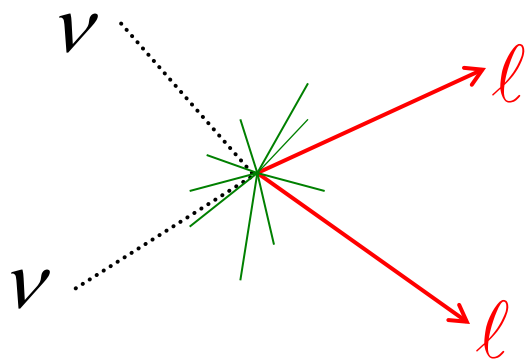
ATLAS-CONF-2012-014

H→WW→lνlν



$$\sigma\left(H \to WW^* \to \ell\nu\ell\nu\right) \approx 0.18 \text{ pb}$$

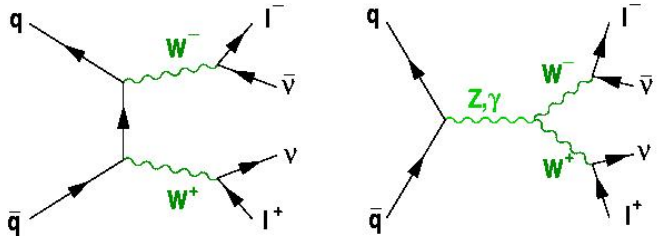
(m_H=125 GeV)



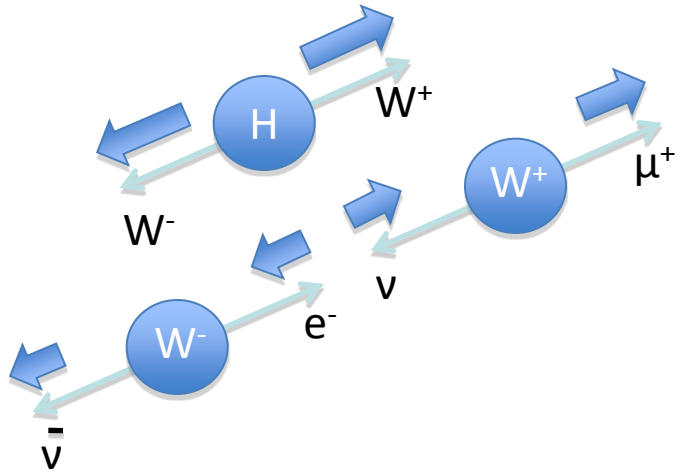
Main background:

WW, W/Z+jets, $t\bar{t}$, ,...

The SM WW is said to be "irreducible"



However, WW from the scalar Higgs is expected to have different kinematics



The spin correlation leads to a smaller average opening angle between the two leptons

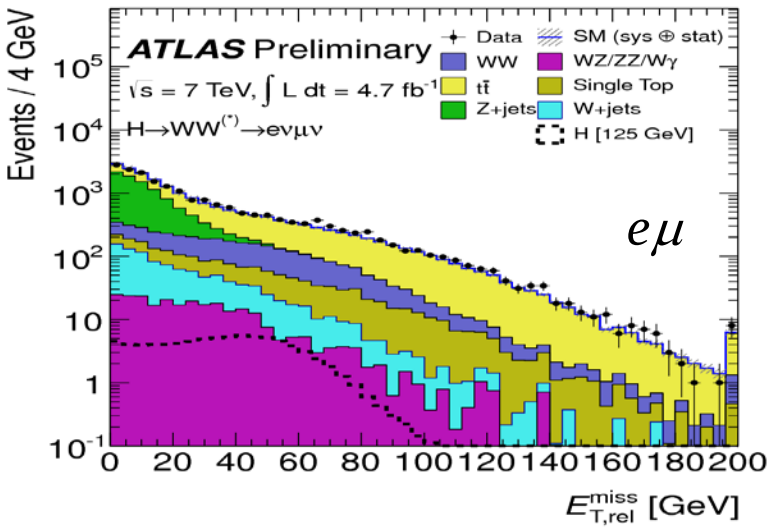
H→WW→lνlν

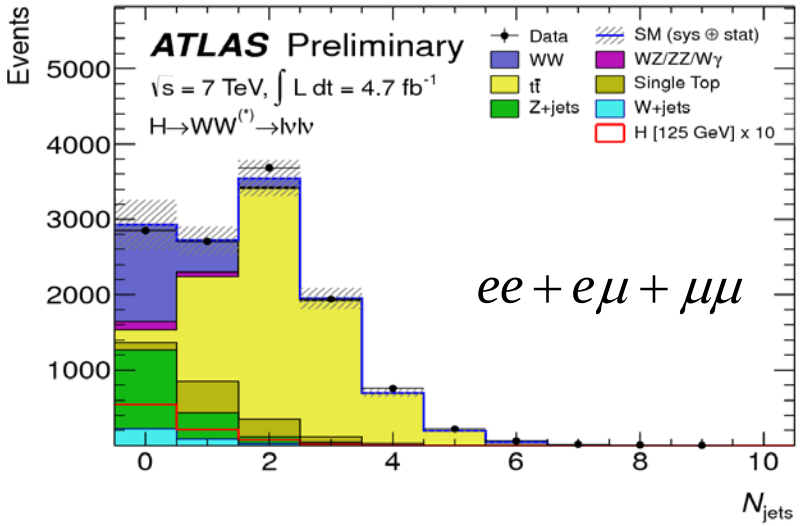
Wide variation of backgrounds in lepton flavors and different jet multiplicity ⇒ Separate analysis in lepton flavor and jet bin:

9 categories: $(ee, e\mu, \mu\mu) \otimes (\text{0-jet, 1-jet, 2-jet})$

Preselection:

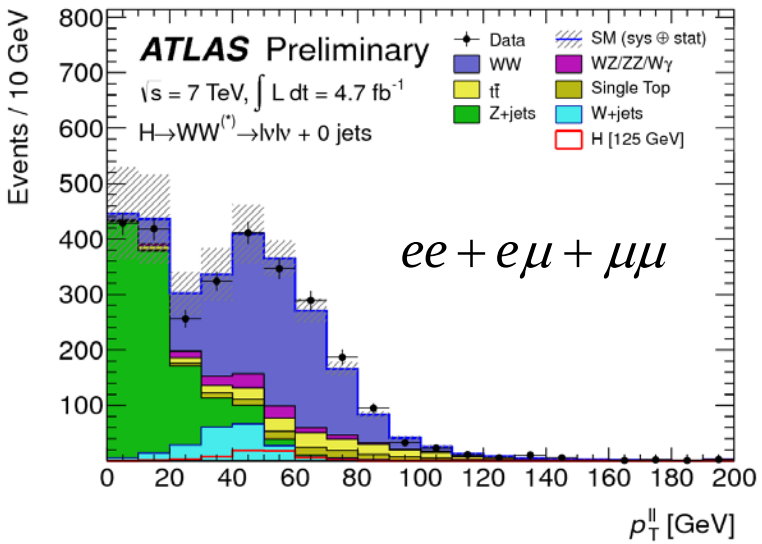
- $p_T^{\ell_1,\ell_2} > 25{,}15$ GeV with $|\eta| < 2.5$;
- Same flavor: $|m_{\ell\ell} - M_Z| > 15$ GeV;
- $E_{T,\text{Rel}}^{\text{miss}} > 45 / 45 / 25$ GeV $(ee, \mu\mu, e\mu)$;
- Jets: $p_T > 25$ GeV and $|\eta| < 4.5$.

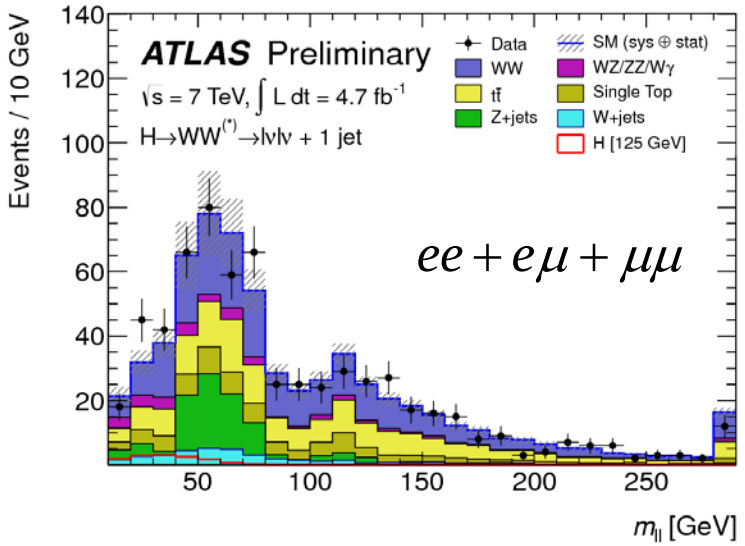




H→WW→lνlν

Significant background remains after pre-selection, apply topological selections for further background reduction:





Higgs decay topology depends strongly on its mass, dividing into 3 search regions: 110-200, 200-300, 300-600 GeV (low, medium, high)

H+0-jet selections

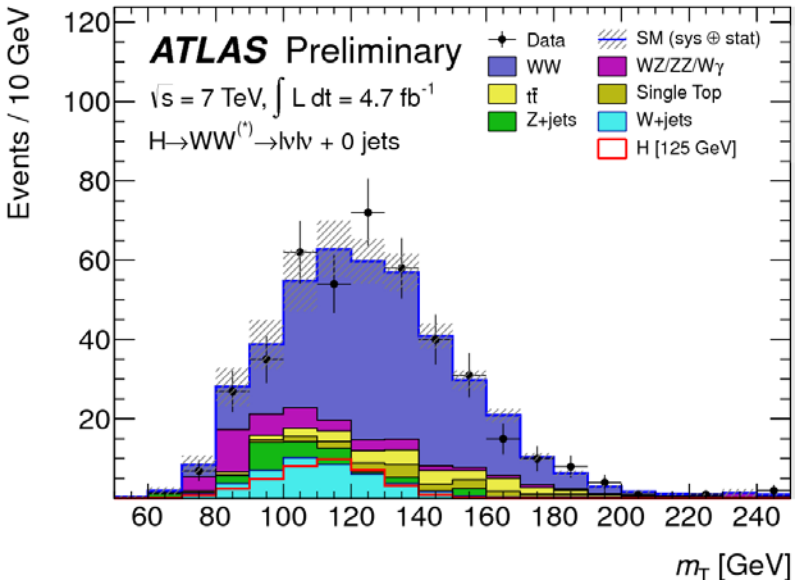
- $p_T^{\ell\ell} > 45$ GeV $(ee, \mu\mu)$, 30 GeV $(e\mu)$;
- $m_{\ell\ell} < 50 / 150 / \infty$ GeV (low, medium, high mass)
- $\Delta\phi_{\ell\ell}$ <1.8 (low mass)

H→WW→lνlν

Remaining backgrounds:

- WW and top:
  real leptons and genuine E_T^{miss};
- W+jets and Z/γ^*+jets:
  fake lepton or E_T^{miss};
- Diboson: WZ/ZZ/W$\gamma^{(*)}$

$$m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left(\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}\right)^2}$$



125 GeV: $0.75m_H < m_T < 1.0m_H$; 240 GeV: $0.6m_H < m_T < 1.0m_H$

(m_T cut for illustration)

		Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	Z/γ^* + jets	W + jets	Total Bkg.	Obs.
0-jet	m_H = 125 GeV	25 ± 7	110 ± 12	12 ± 3	7 ± 2	5 ± 2	13 ± 8	27 ± 16	173 ± 22	174
	m_H = 240 GeV	60 ± 17	432 ± 49	24 ± 3	68 ± 15	39 ± 9	8 ± 2	36 ± 24	607 ± 63	629
1-jet	m_H = 125 GeV	6 ± 2	18 ± 3	6 ± 3	7 ± 2	4 ± 2	6 ± 1	5 ± 3	45 ± 7	56
	m_H = 240 GeV	23 ± 9	99 ± 22	8 ± 1	73 ± 27	35 ± 19	6 ± 2	7 ± 7	229 ± 55	232
2-jet	m_H = 125 GeV	0.4 ± 0.2	0.3 ± 0.2	negl.	0.2 ± 0.1	negl.	0.0 ± 0.1	negl.	0.5 ± 0.2	0
	m_H = 240 GeV	2.5 ± 0.6	1.1 ± 0.7	0.1 ± 0.1	2.6 ± 1.3	0.3 ± 0.3	negl.	0.1 ± 0.1	4.2 ± 1.7	2

S/B~0.15

H→WW→lvlv

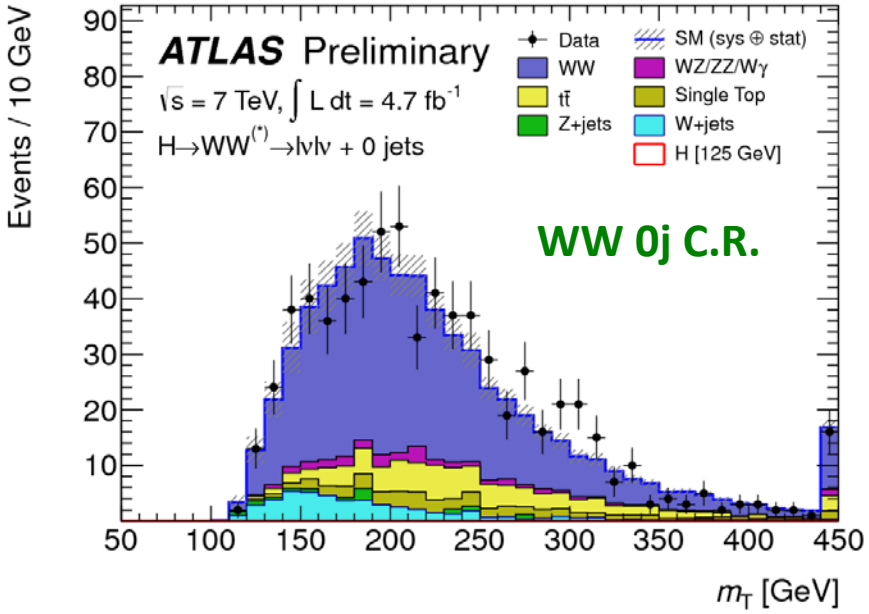
Estimating WW and top background from data:

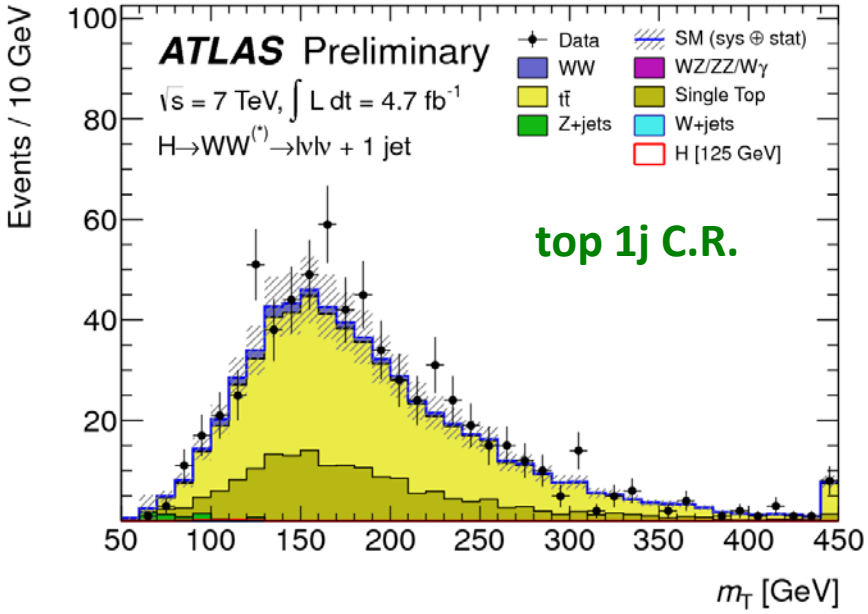
$$N_{S.R.}^{est.} = \left(\frac{N_{S.R.}}{N_{C.R.}} \right)_{MC} \times N_{C.R.}^{Data} = \alpha_{MC} \times N_{C.R.}^{Data}$$

scaling using data control regions (C.R.):

WW : $m_{\ell\ell} > 80$ GeV and no topo selection for low mass, MC otherwise;
Top : reverse b-jet veto (1j, 2j)

most experimental systematics cancel out.





H→WW→lνlν

W+jets and multijets: from data using bad/nonisolated leptons:

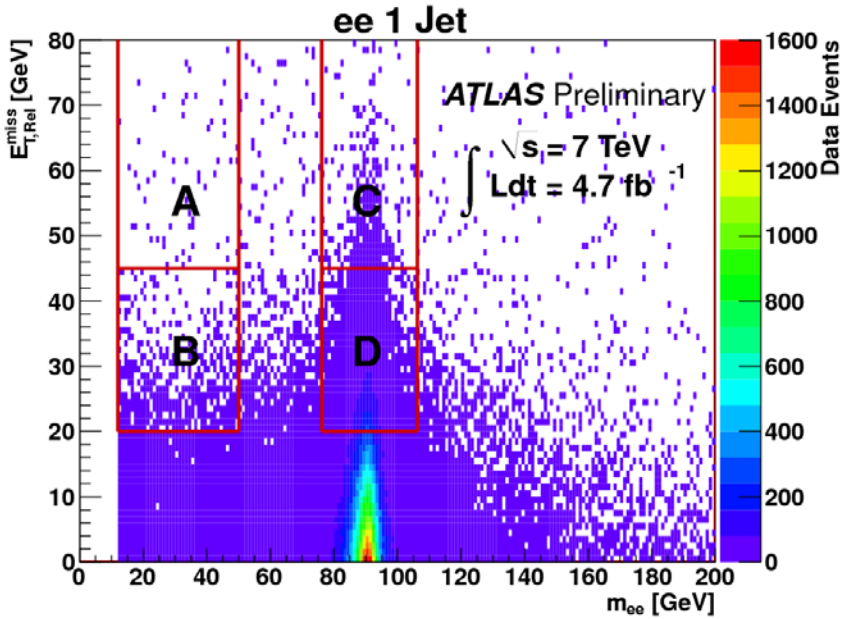
Select events with one good lepton and one bad/nonisolated lepton and then apply the scale factor determined from control samples

Z/γ*+jets: from both data and Monte Carlo

$$\left(\frac{A/B}{C/D}\right)_{Data} \approx \left(\frac{A/B}{C/D}\right)_{MC}$$

$$A^{est} \approx B^{Data} \times \left(\frac{C}{D}\right)_{Data} \times \left(\frac{A/B}{C/D}\right)_{MC}$$

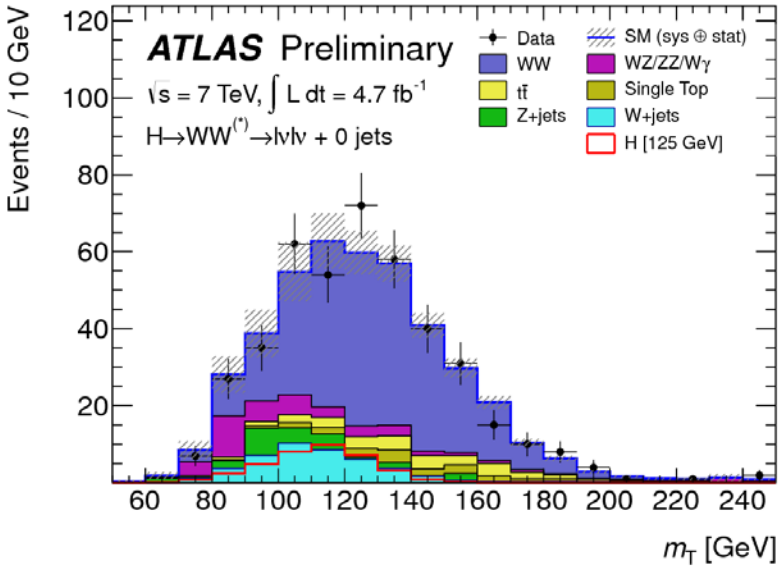
(agree with MC estimate within 30%)

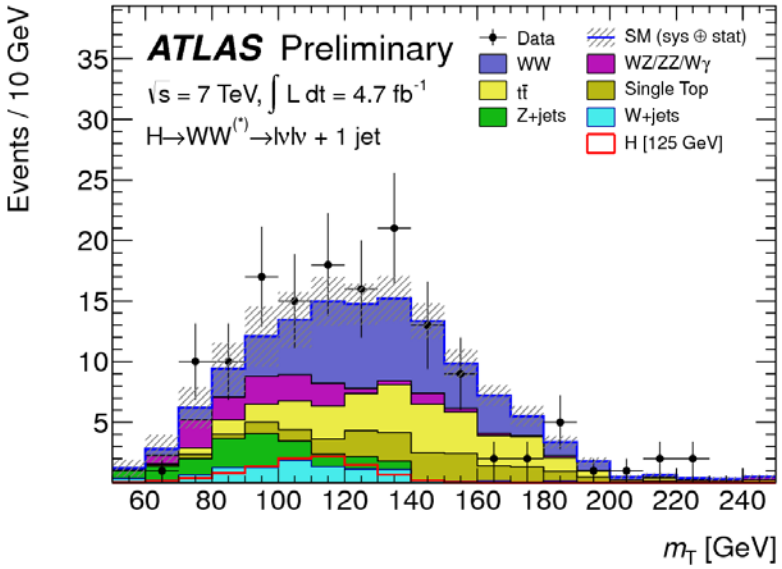


WZ, ZZ, Wγ(*): from Monte Carlo

Generally small backgrounds with well predicted cross sections, but Wγ(*) are important backgrounds for low mass searches!

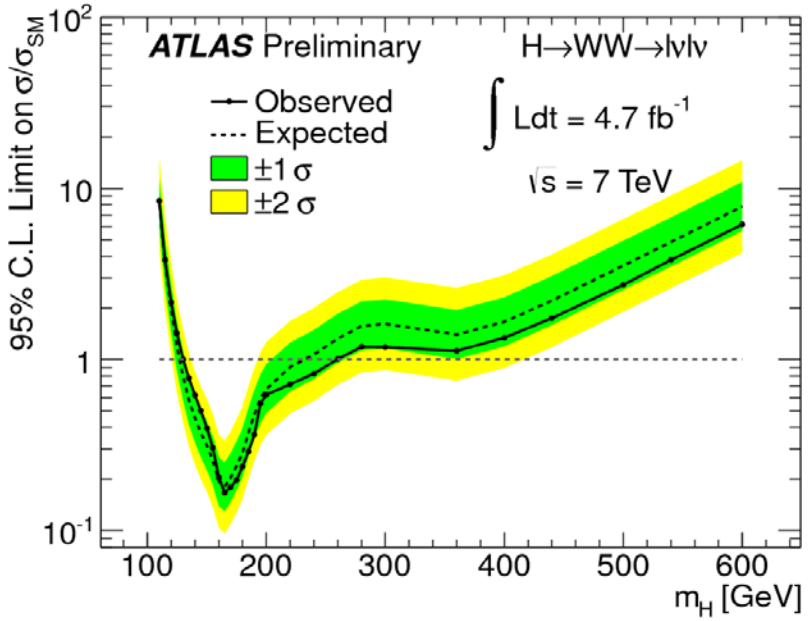
H→WW→lνlν





Fit the transverse mass distribution to improve the sensitivity:

- **set the cross section limit;**
- **determine signal strength**



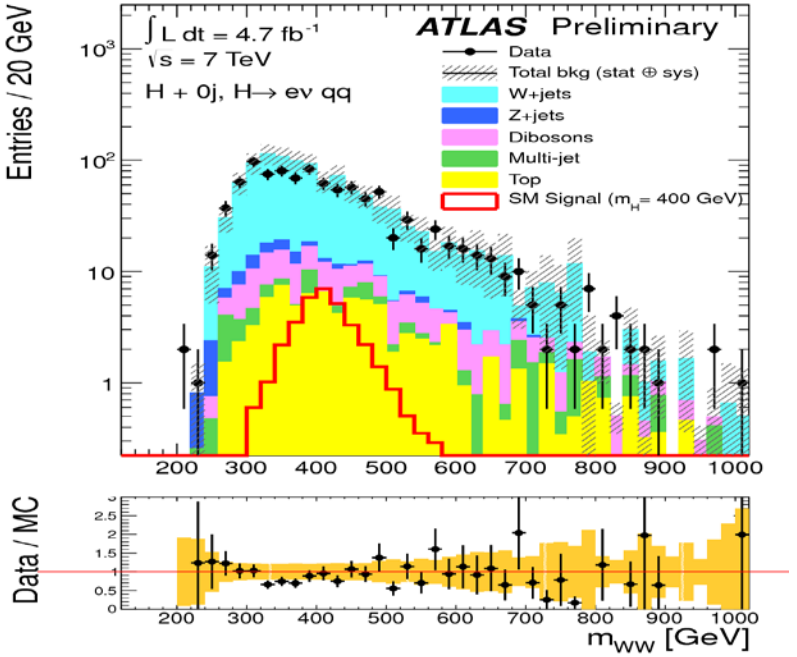
ATLAS-CONF-2012-012

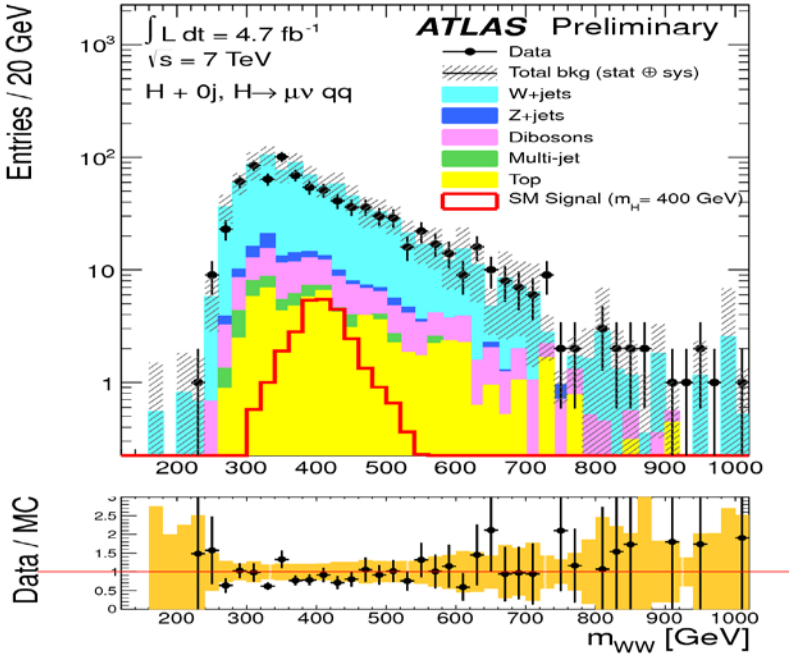
Observed Exclusion: 130-260 GeV (expected: 127-234 GeV)

H→WW→lνqq

Good sensitivities when both W's are on-shell ⇒ 300-600 GeV search range

- 6 categories: lepton flavor ⊗ jet bin; ggF ∈ (0-jet, 1-jet), 2-jet ∈ VBF;
- 0-jet, 1-jet: $\left(p_T^{\ell}, E_T^{\text{miss}}, p_T^{j}\right) > 40$ GeV; 2-jet: $\left(p_T^{\ell}, E_T^{\text{miss}}\right) > 30$ GeV, $p_T^{j} > 25$ GeV;
- W mass constraints: $71 < m_{jj} < 91$ GeV and $m_{\ell\nu} = M_W$;
- additional tagging-jet cuts for 2-jet: $\eta_1 \times \eta_2 < 0$, $\Delta\eta_{jj} > 3$, $m_{jj} > 600$ GeV;
- no b-tagged jets (top rejection);



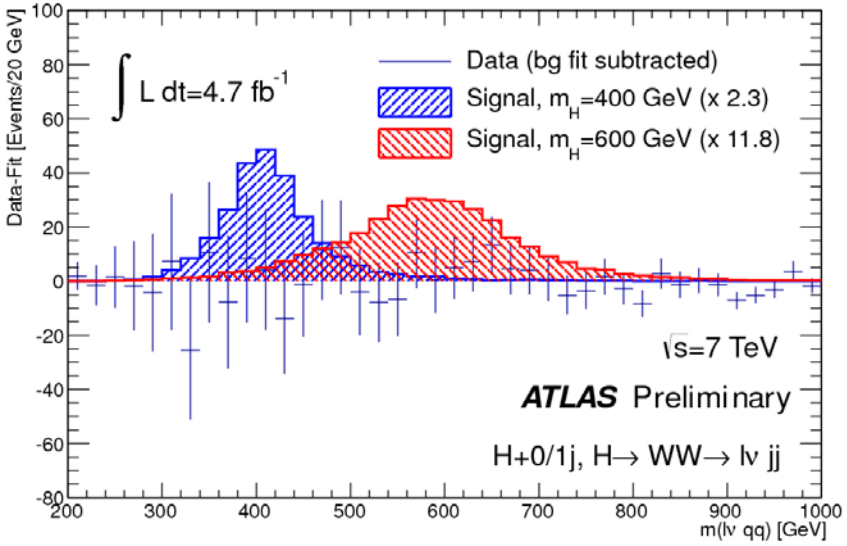


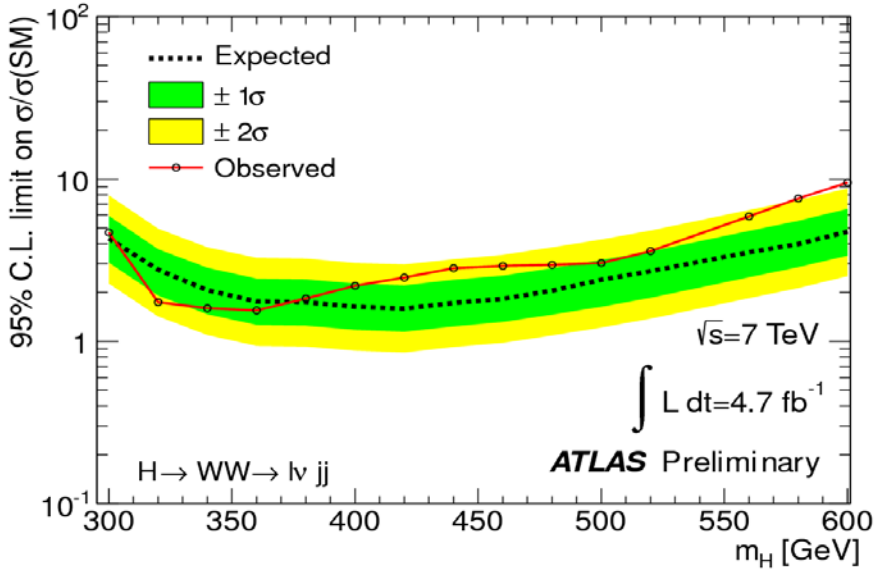
H→WW→lνqq

Search for a bump over the "smooth" background dominated by W+jets.

Model background and signal contributions using parameterized functions, chosen based on MC and data side-band studies. The signal mass resolution is about 9% at 400 GeV.

Limits are extracted from the binned likelihood fit to the observed mass distribution. Not yet sensitive to a SM Higgs boson.





ATLAS-CONF-2012-018

H→ZZ→llνν

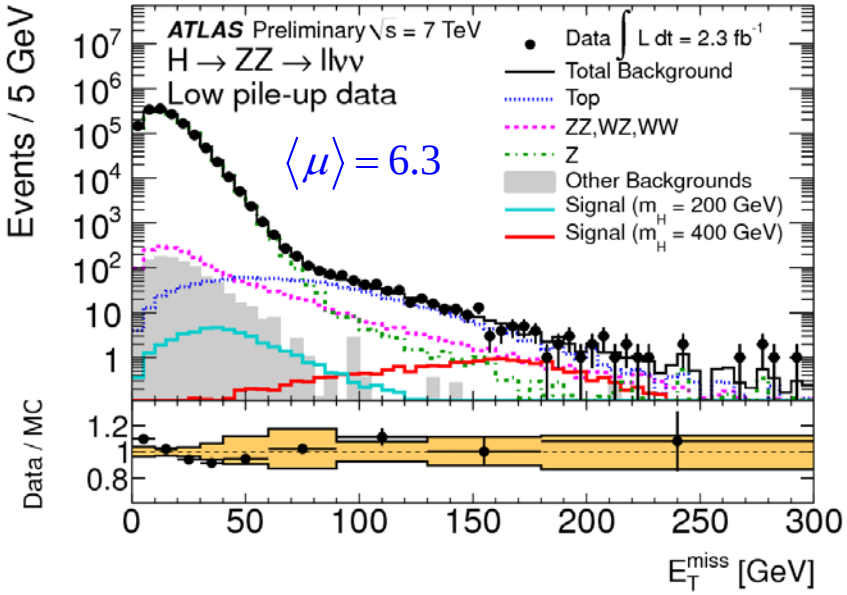
Good S/B ratio when Z's are on-shell ⇒ high mass 200-600 GeV.

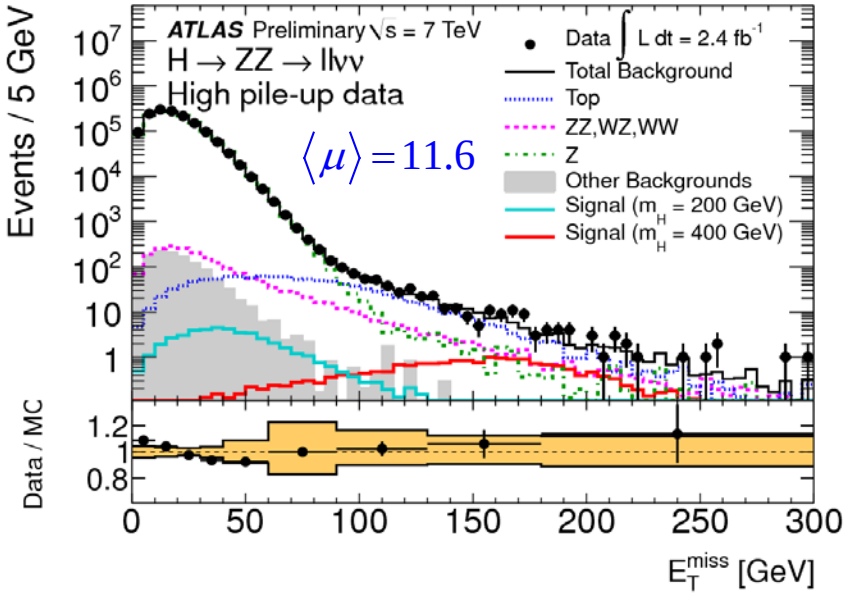
The most sensitive search channel for a heavy Higgs boson.

- two same-flavor leptons with $|m_{\ell\ell} - M_Z| < 15$ GeV;
- two mass search bins: 200 - 280 GeV and 280 - 600 GeV;
- E_T^{miss} and $\Delta\phi_{\ell\ell}$ cuts, and b-jet veto to reject background;
- analyze low and high pileup datasets separately

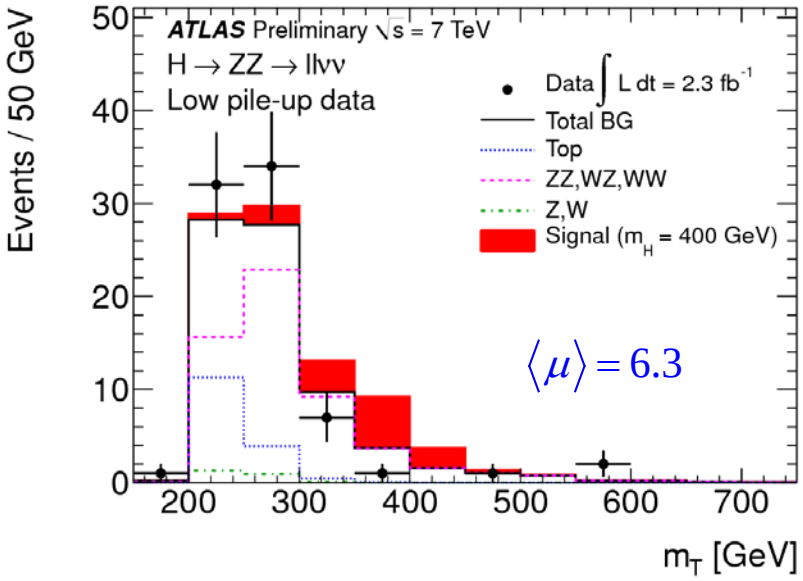
Main backgrounds:

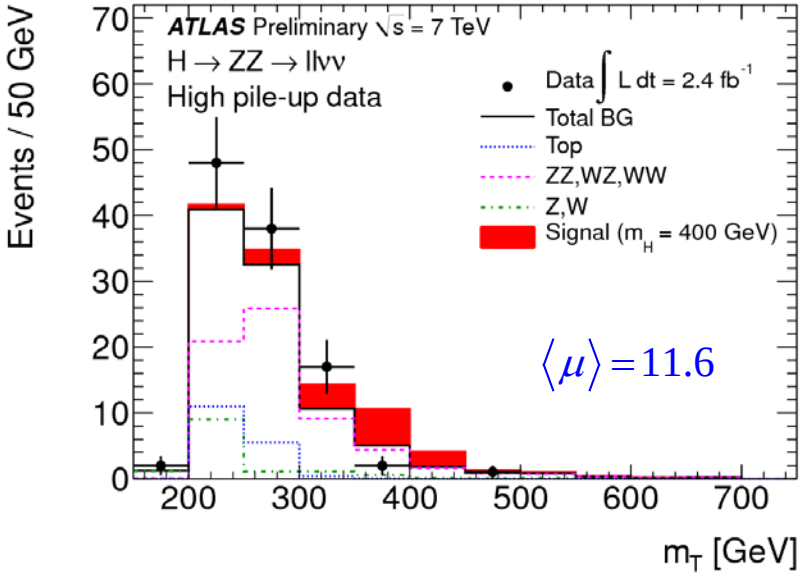
- ZZ/WZ/ZZ;
- top;
- W+jets





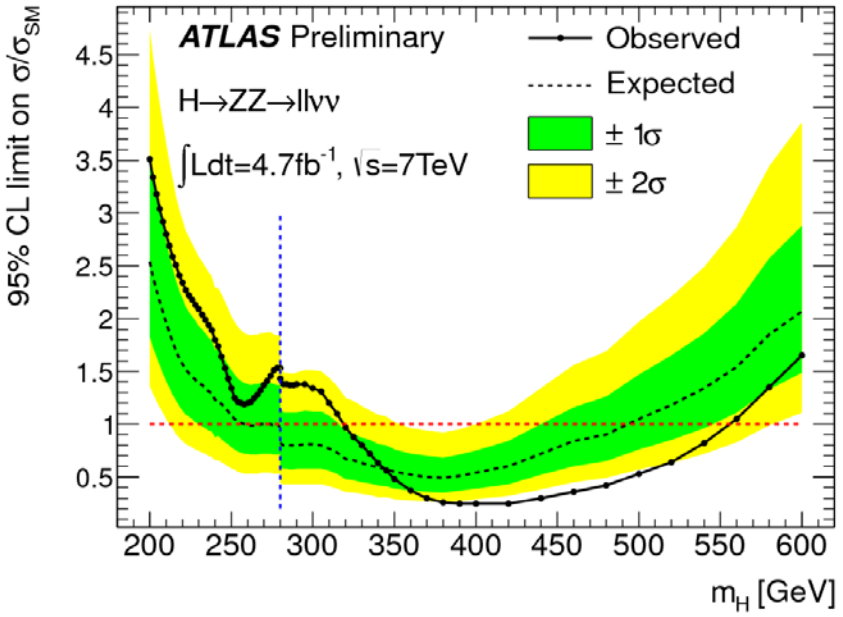
H→ZZ→llνν





No significant excess is observed.
Fit the mT distribution to extract the upper limit on Higgs cross section.

Exclusion:
320 – 560 GeV (observed)
260 – 490 GeV (expected)



ATLAS-CONF-2012-016

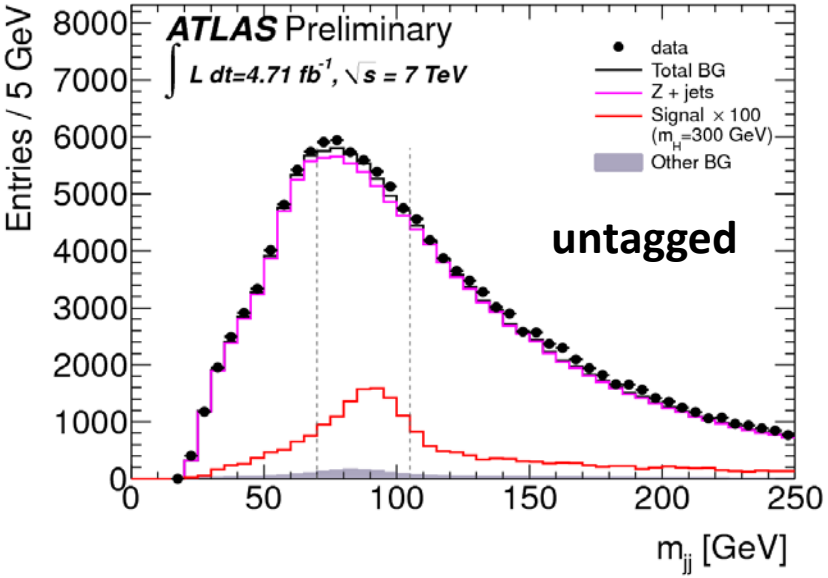
H→ZZ→llqq

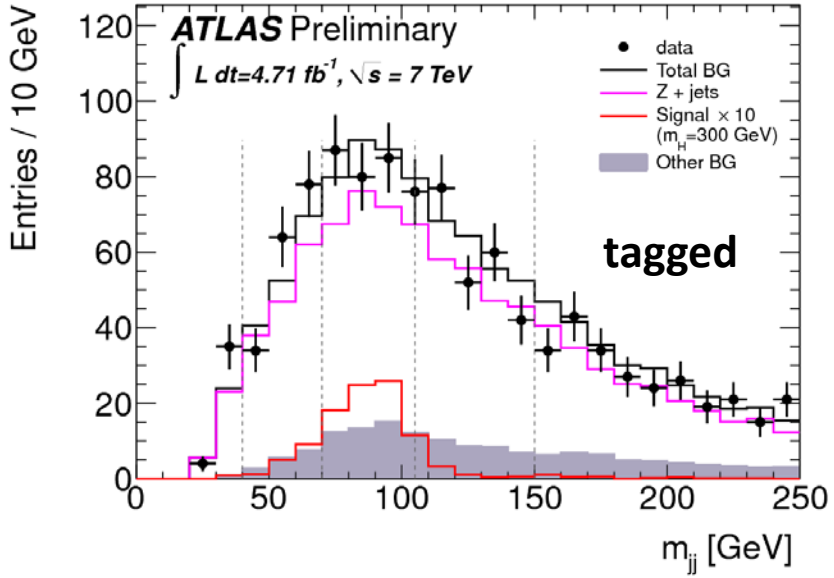
Highest rate among all ZZ channels with leptons (10x 4l rate), full reconstruction of Higgs decays. But large Z+jets background …
So far focused on two on-shell Zs ⇒ 200-600 GeV

- two leptons with $83 < m_{\ell\ell} < 99$ GeV;
- two jets with $70 < m_{jj} < 105$ GeV;
- $E_T^{\text{miss}} < 50$ GeV;
- separate analysis w/o two b-tagged jets;
- additional selections for $m_H > 300$ GeV

Main backgrounds:

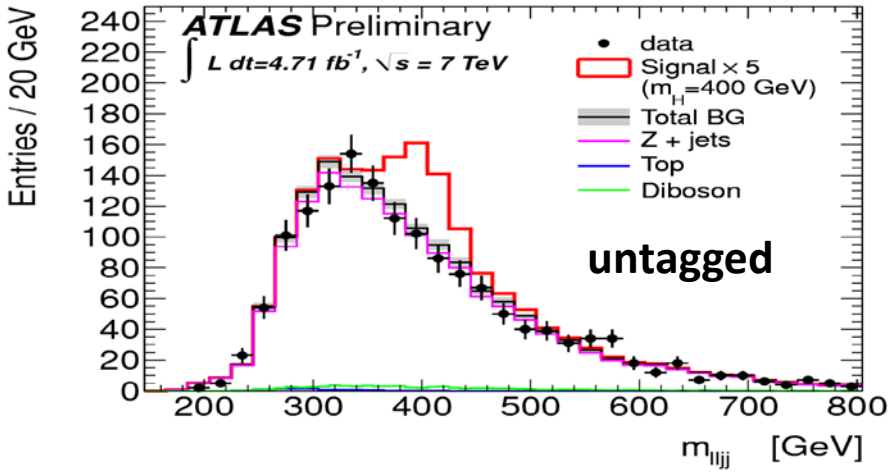
- Z+jets (m_{jj} side band);
- ZZ, WZ (simulation);
- top (m_{jj} sideband)

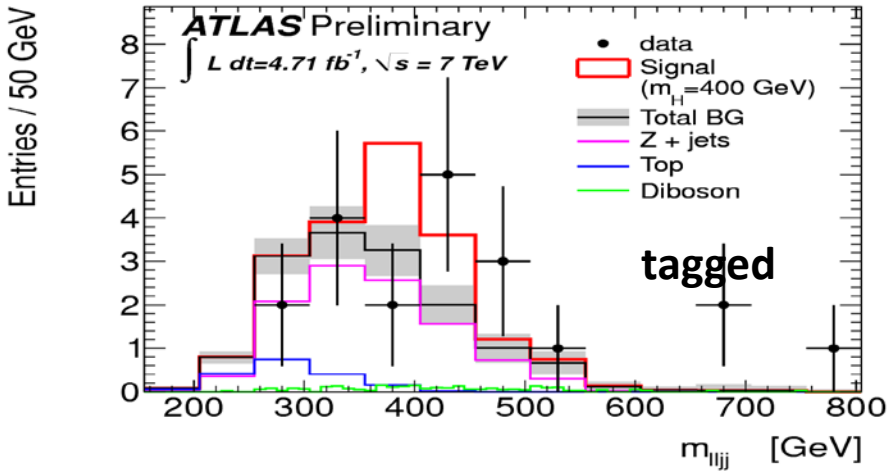




H→ZZ→llqq

Search for peak in m_{lljj} over "continuum" background. Typical signal resolution ~5% at high mass. No significant excess above the expected backgrounds.



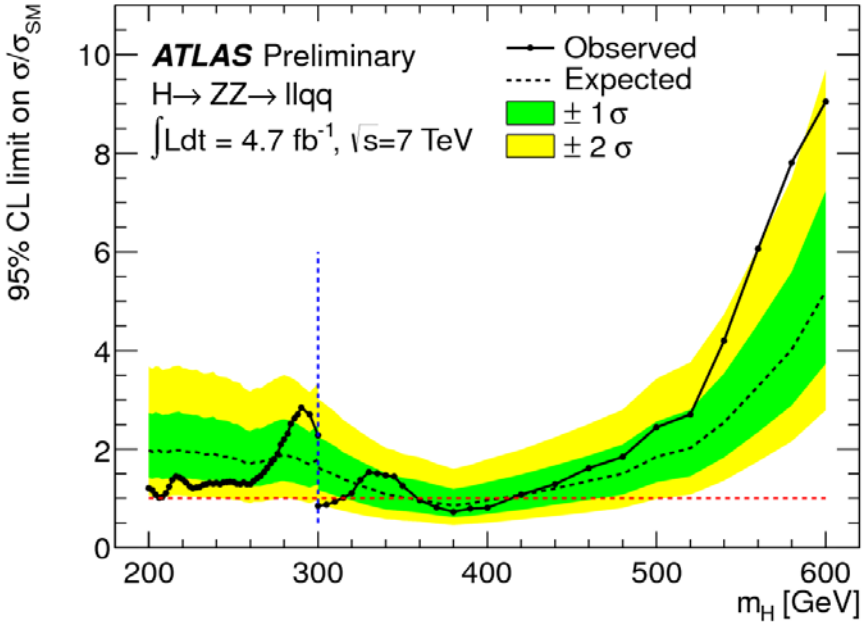


Observed exclusions:

300-310, 360-400 GeV

Expected exclusion:

360-400 GeV



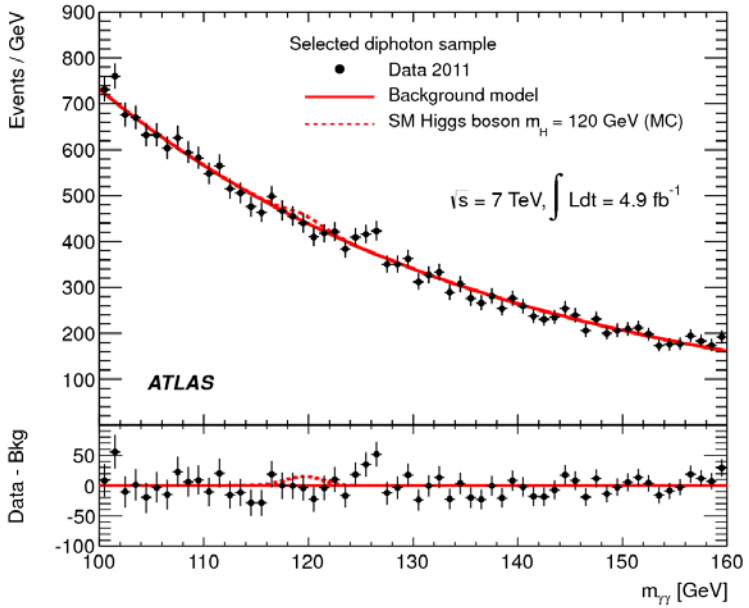
ATLAS-CONF-2012-017

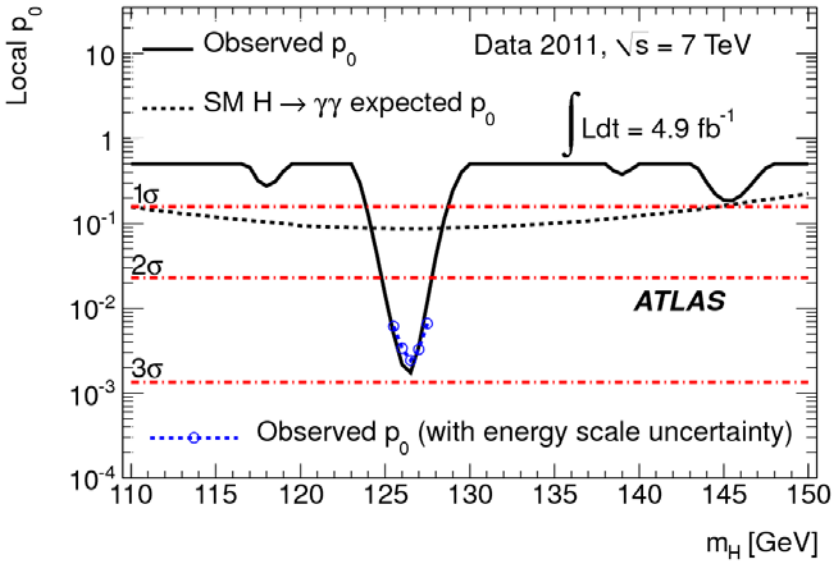
H→γγ

No significant changes since December seminar…

Fit observed γγ mass distribution with signal + background model:

- **Exponential spectrum for background;**
- **Crystal-ball function to describe the signal**





Observed exclusion:

113-115 GeV

134.5-136 GeV

Phys. Rev. Lett. 108, 111803 (2012)

Excess at 126.5 GeV with a significance of

2.8σ – local

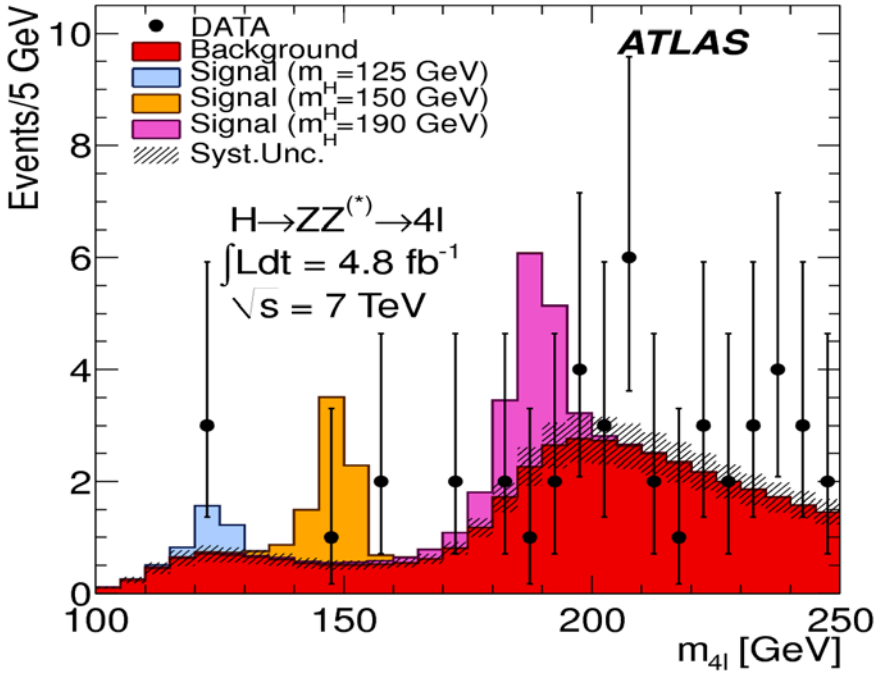
1.5σ – global (110-150 GeV)

H→ZZ→4l

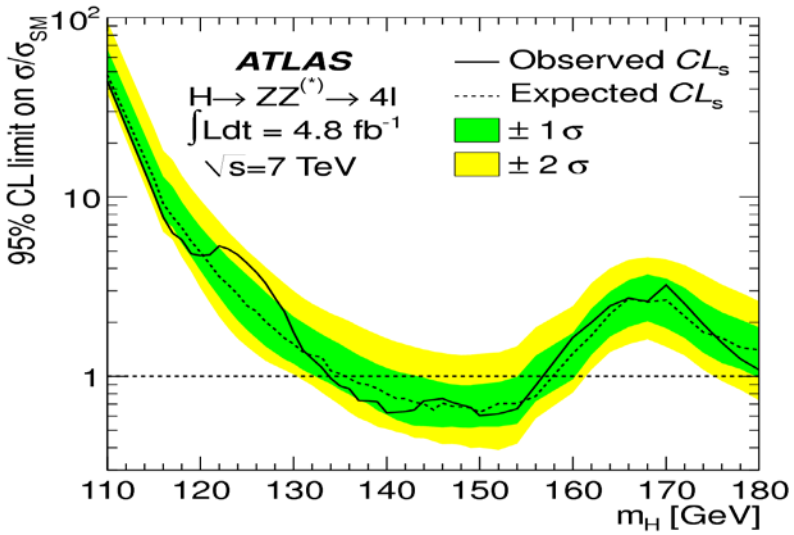
No substantial change either…

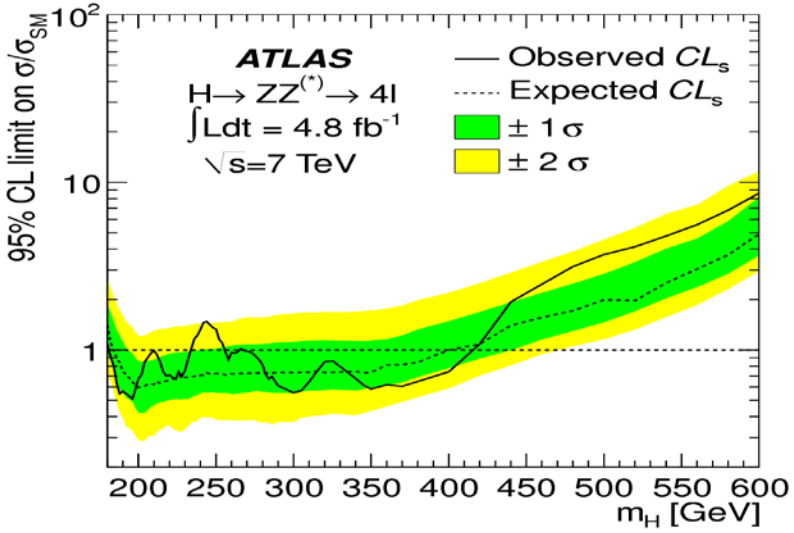
Event yield (full search range)

	4e	2e2μ	4μ
Background	13.4±2.0	29.7±4.5	18.6±2.8
Signal (130 GeV)	0.43±0.08	1.22±0.21	1.00±0.17
Data	17	30	24



Phys. Lett. B710 (2012) 383





Combination: Channels

Higgs Decay	Subsequent Decay	Additional Sub-Channels	m_H Range	L [fb^{-1}]
$H \to \gamma\gamma$	–	9 sub-channels ($p_{T_t} \otimes \eta_\gamma \otimes$ conversion)	110-150	4.9
$H \to ZZ$	$\ell\ell\ell'\ell'$	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	110-600	4.8
	$\ell\ell\nu\bar{\nu}$	$\{ee, \mu\mu\} \otimes$ {low pile-up, high pile-up}	200-280-600	4.7
	$\ell\ell q\bar{q}$	{b-tagged, untagged}	200-300-600	4.7
$H \to WW$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu\mu\} \otimes$ {0-jet, 1-jet, VBF}	110-300-600	4.7
	$\ell\nu q\bar{q}'$	$\{e, \mu\} \otimes$ {0-jet, 1-jet}	300-600	4.7
$H \to \tau^+\tau^-$	$\ell\ell 4\nu$	$\{e\mu\} \otimes$ {0-jet} $\oplus$ {1-jet, VBF, VH}	110-150	4.7
	$\ell\tau_{\text{had}}3\nu$	$\{e, \mu\} \otimes$ {0-jet} $\otimes \{E_T^{\text{miss}} \gtrless 20$ GeV$\}$ $\oplus \{e, \mu\} \otimes$ {1-jet, VBF}	110-150	4.7
	$\tau_{\text{had}}\tau_{\text{had}}2\nu$	{1-jet}	110-150	4.7
$VH \to b\bar{b}$	$Z \to \nu\bar{\nu}$	$E_T^{\text{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\}$	110-130	4.6
	$W \to \ell\nu$	$p_T^W \in \{<50, 50-100, 100-200, \geq 200$ GeV$\}$	110-130	4.7
	$Z \to \ell\ell$	$p_T^Z \in \{<50, 50-100, 100-200, \geq 200$ GeV$\}$	110-130	4.7

12 different final states and 59 different categories are combined at likelihood level taking into account correlations of both experimental and theoretical uncertainties.

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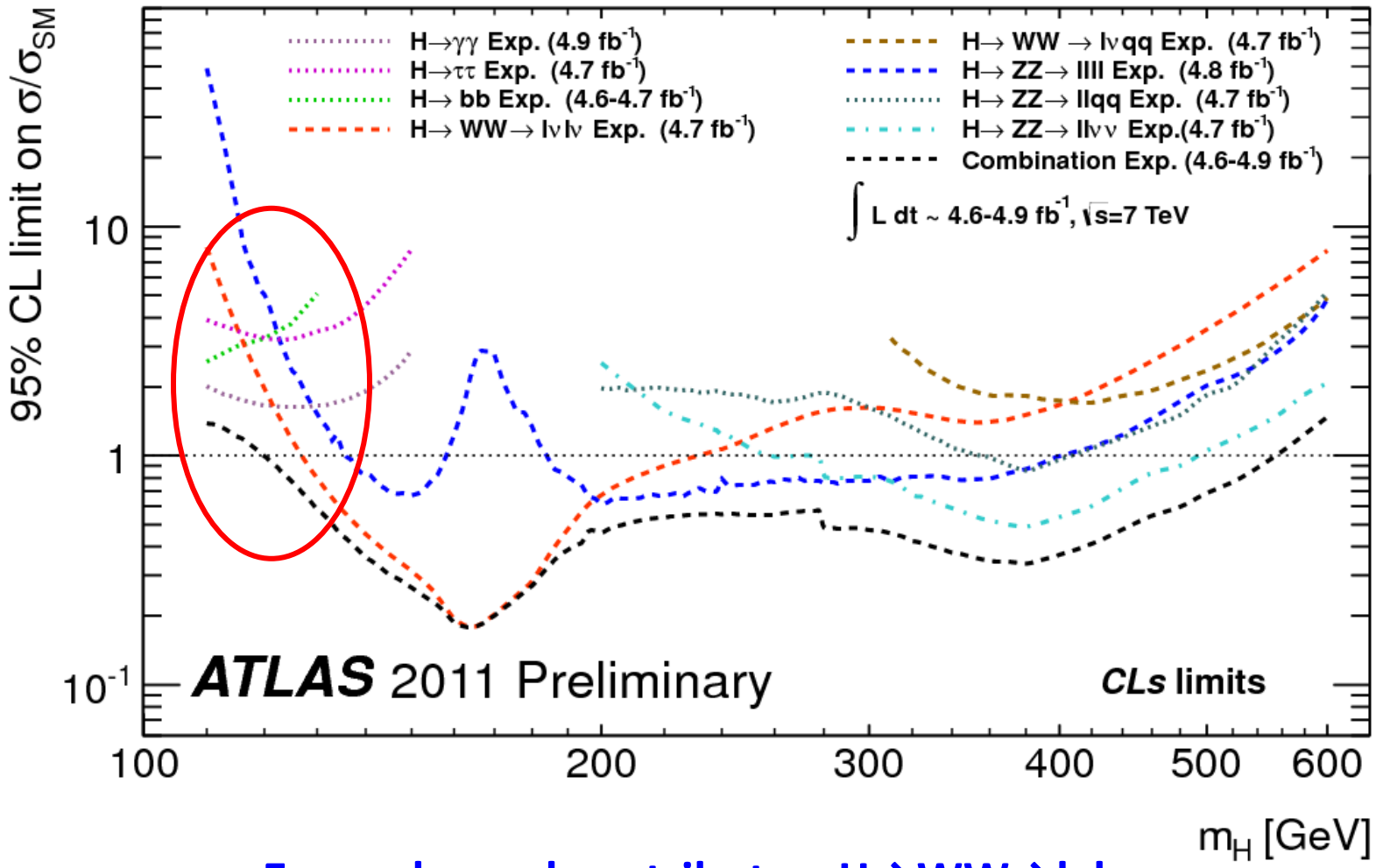
Combination: Sensitivities



Every channel contributes, H→WW→lνlν
has the best sensitivity between 125 GeV and ~200 GeV

Combination: Exclusion

The combination excludes a wide range of SM Higgs boson mass

Observed exclusions:

95% CL: 110-117.5, 118.5-122.5, 129-539 GeV

(99% CL: 130-486 GeV)

Expected exclusion:

95% CL: 120-555 GeV

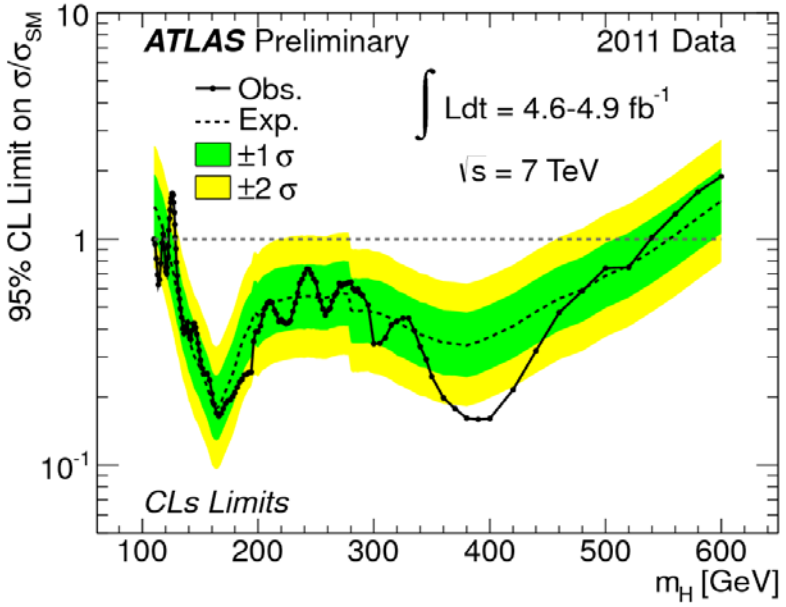
Unexcluded ranges:

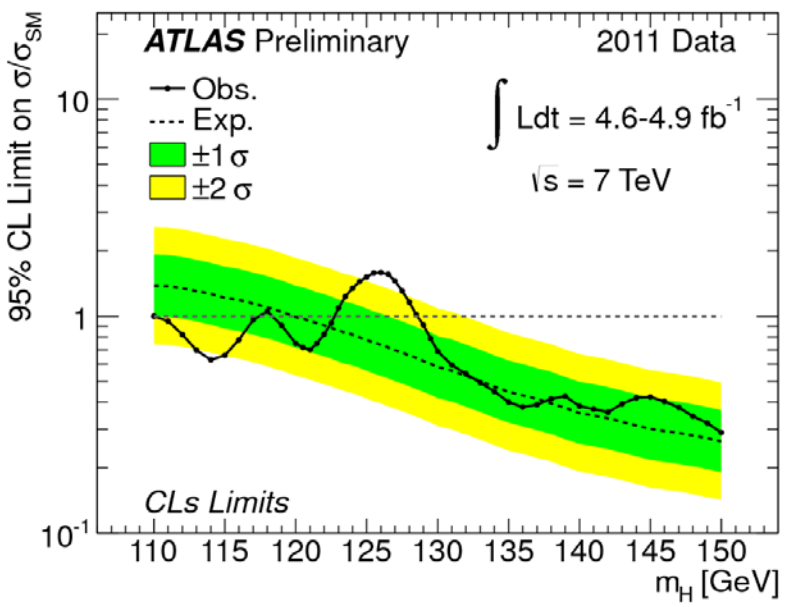
117.5-118.5 GeV

122.5-129 GeV

>539 GeV

at 95% CL





Combination: Excesses

The most significant excess is at 126 GeV with a local significance:

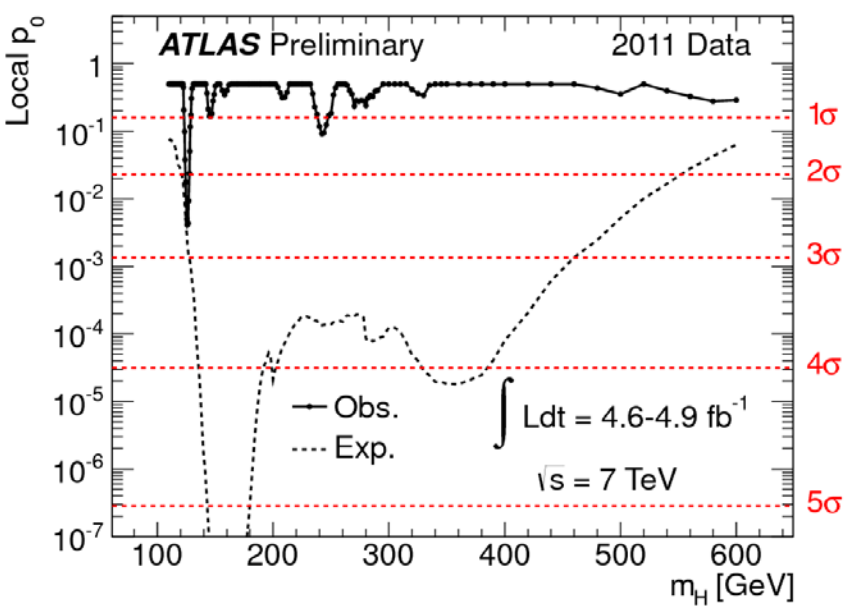
2.5σ (observed) and 2.9σ (expected from a 126 GeV SM Higgs boson)

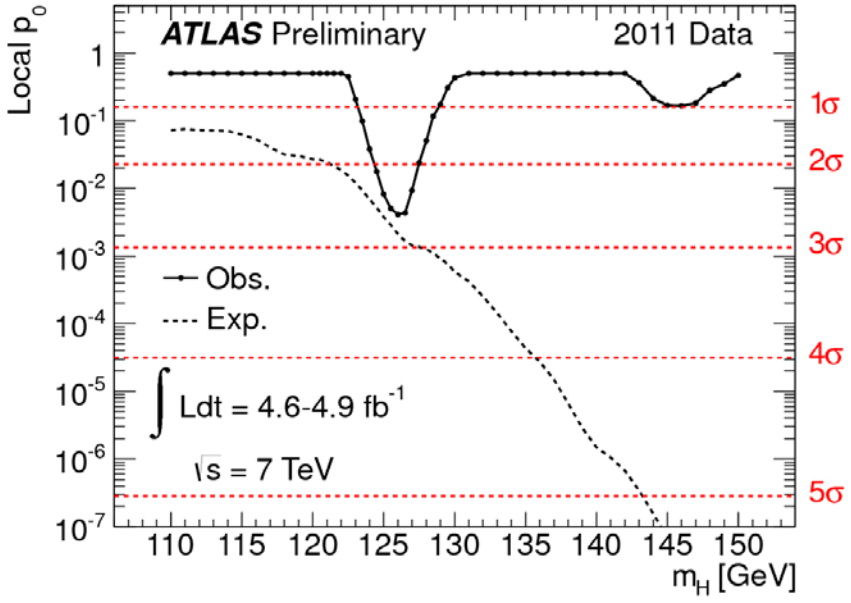
The probability for such an excess to occur anywhere in the absence of a signal

in the full search mass range (110-600 GeV): 30%

in the previously unexcluded (99% CL) range (110-146 GeV): 10%

Local probability from background fluctuation:





Combination: Breakdowns

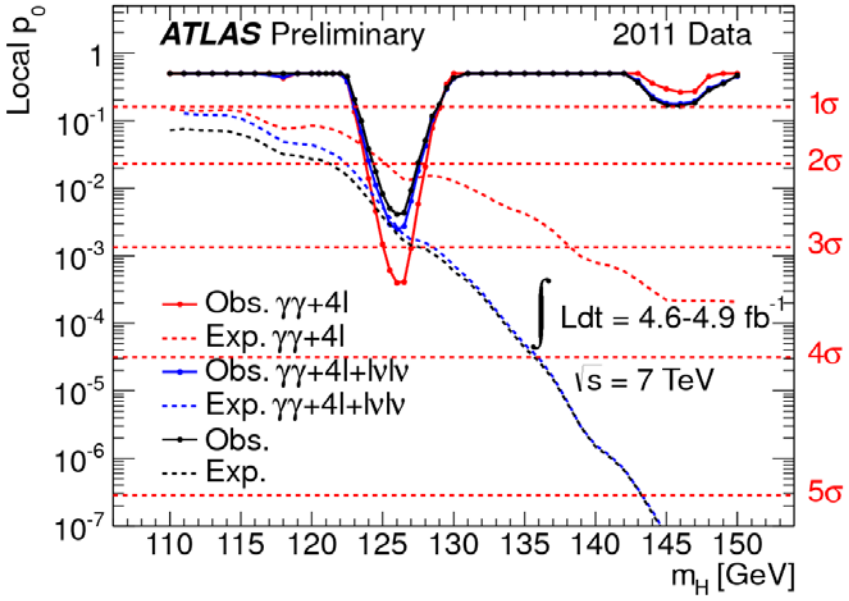
The excess is dominated by the high mass-resolution channels:

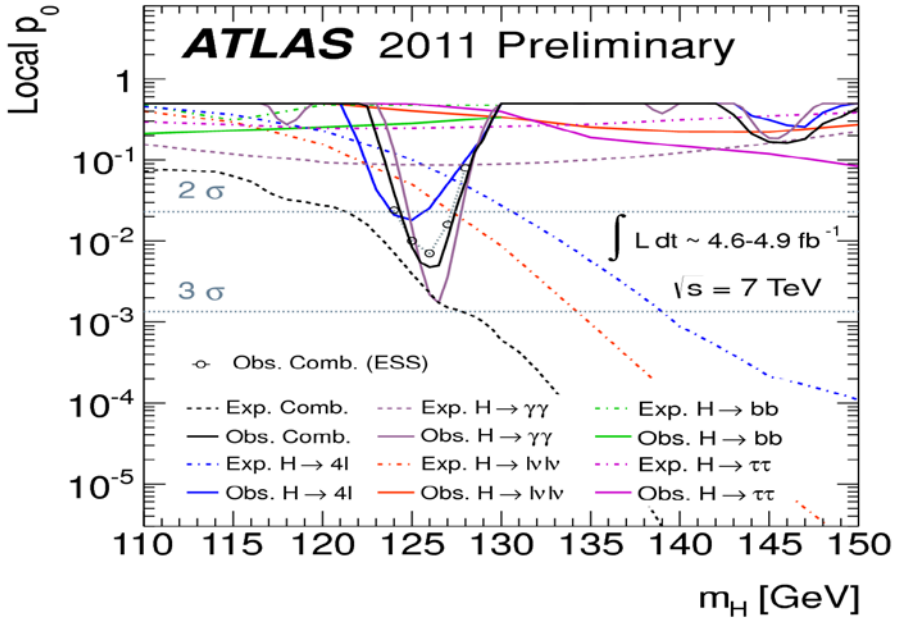
$H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4\ell$ combined to a 3.4σ local significance

No significant excess in low mass-resolution channels:

$H \to WW^{(*)} \to \ell\nu\ell\nu$, $H \to b\bar{b}$, $H \to \tau\tau$

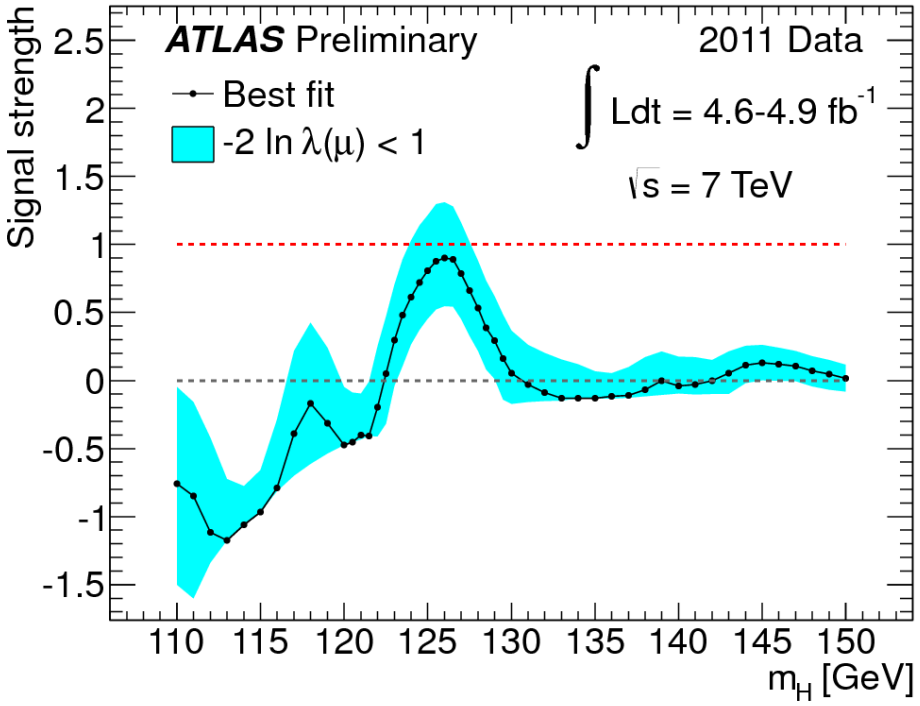
However, these low mass-resolution channels do not exclude a 126 GeV Standard Model Higgs boson.

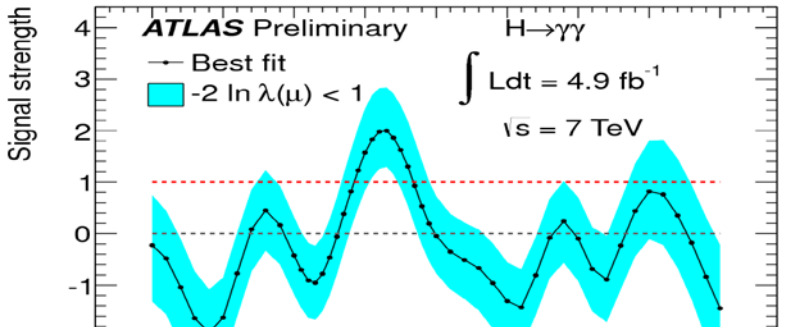


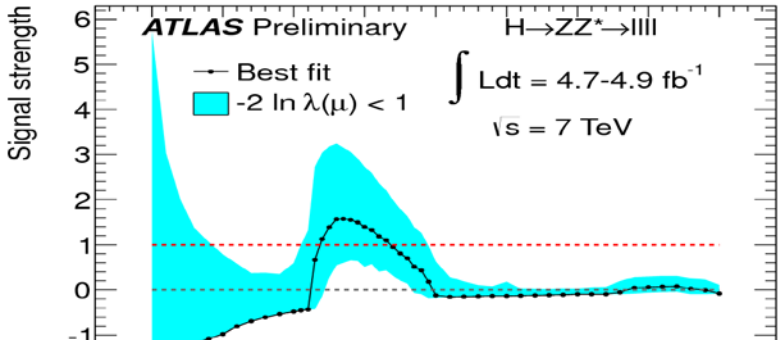


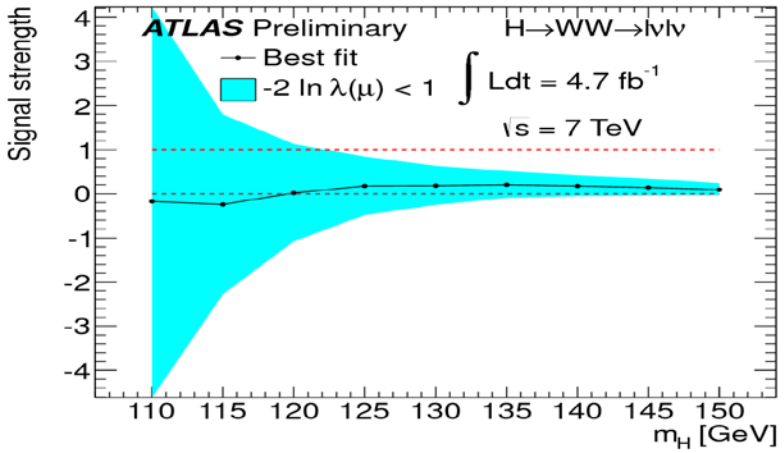
Combination: Signal Strength

The combined signal rate is consistent with the Standard Model expectation of a 126 GeV Higgs boson.









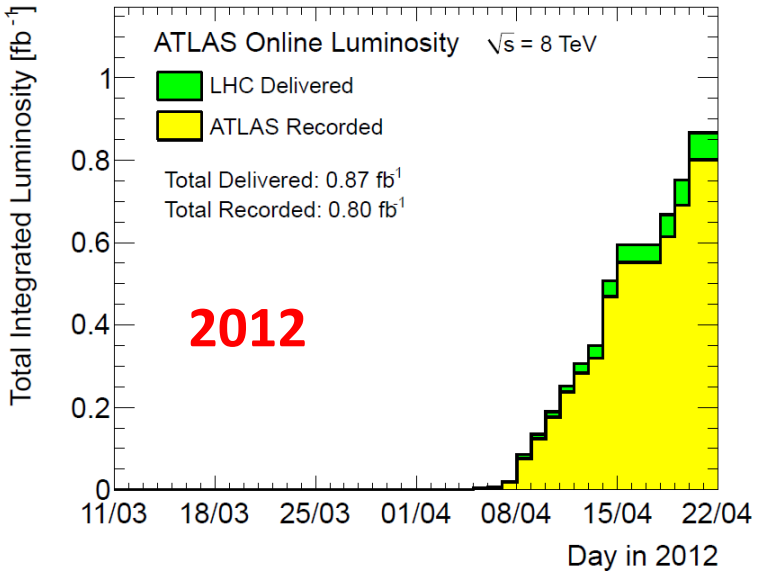
Summary

ATLAS has a strong program in Standard Model Higgs boson searches. All analyses have updated to the full 2011 dataset. The combination of these searches has cornered the allowed mass ranges at 95% CL to:

117.5-118.5 GeV, 122.5-129 GeV and above 539 GeV

An excess with a local significance of 2.5σ is observed. It is compatible with a Standard Model Higgs boson at 126 GeV, but it is too early to draw definite conclusions.

More studies and more data are needed… Excited to analyze 2012 data!



Statistical Method

Construct likelihood from Poisson probabilities :

$$L\left(\text{data}\,|\,\mu,\theta\right)=\text{Poisson}\left(\text{data}\,|\,\mu\cdot s\left(\theta\right)+b\left(\theta\right)\right)\times p\left(\tilde{\theta}\,|\,\theta\right)$$

μ : signal strength; θ: 'nuisance' parameters (efficiencies...)

Compare data with background-only and signal+background models using test statistics

$$q_\mu=-2\ln\frac{L\left(\text{data}\,|\,\mu,\hat{\theta}_\mu\right)}{L\left(\text{data}\,|\,\hat{\mu},\hat{\theta}\right)}\quad\text{with}\quad 0\le\hat{\mu}\le\mu$$

Calculate the ratio of these two p-values

$$CL_s\left(\mu\right)=\frac{CL_{s+b}}{CL_b}=\frac{P\left(q_\mu>q_\mu^{obs}\,|\,s+b\right)}{P\left(q_\mu>q_\mu^{obs}\,|\,b\right)}$$

The signal model is excluded at 95% CL if

$$CL_s\left(\mu=1\right)<5\%$$

Higgs Boson Width

Strong mass dependence

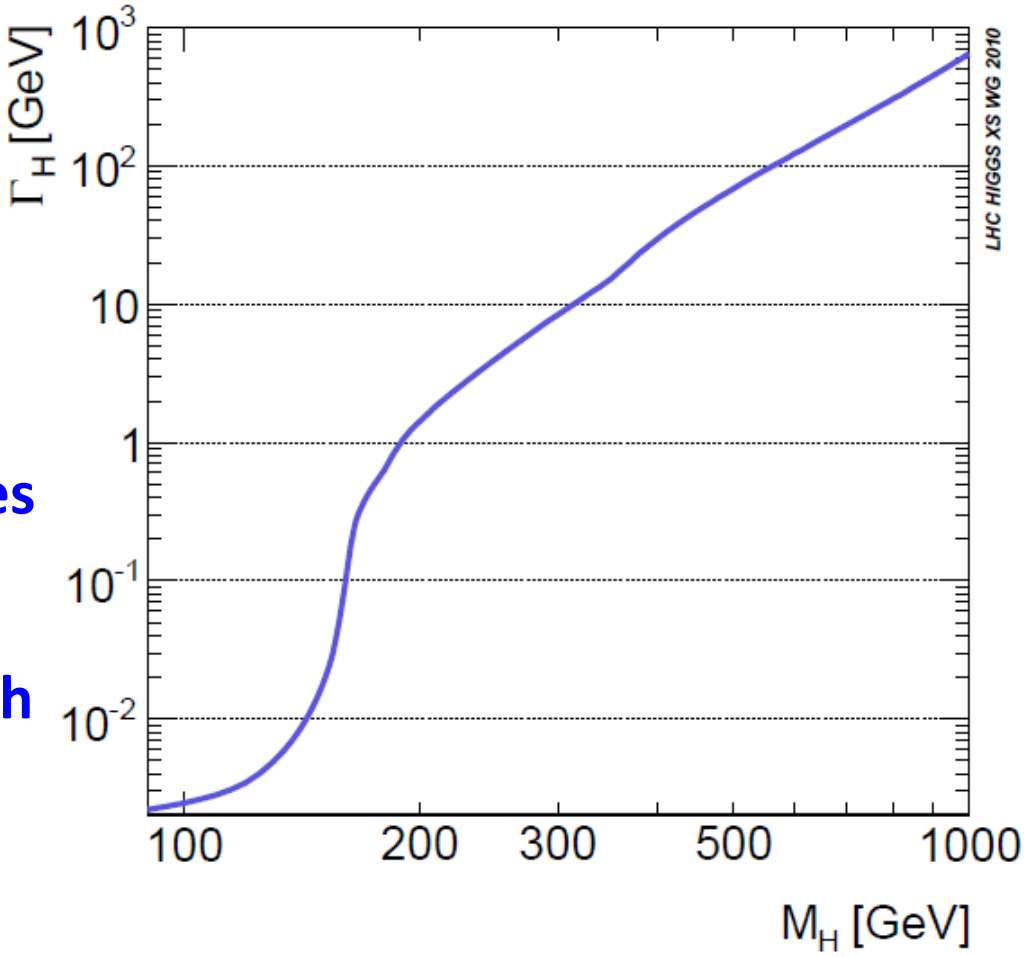
$$\Gamma_H = 3.5 \text{ MeV @ } 120 \text{ GeV},$$
$$1.43 \text{ GeV @ } 200 \text{ GeV},$$
$$8.43 \text{ GeV @ } 300 \text{ GeV},$$
$$68.0 \text{ GeV @ } 500 \text{ GeV}$$

At low mass (<300 GeV), detector resolution dominates mass resolution.

At higher mass, intrinsic width becomes dominant.

$$\Gamma_H \approx \frac{3 G_F M_H^3}{16\pi\sqrt{2}}$$

$$\approx 500 \text{ GeV} \cdot \left(\frac{M_H}{1 \text{ TeV}}\right)^3$$



Systematic Uncertainties

Signal theoretical uncertainties

	ggF	VBF	WH/ZH	ttH
QCD scale	+12%, -8%	±1%	±1%	+3%, -9%
PDF + as	±8%	±4%	±4%	±8%
Higgs mass line shape		$150\% \times (m_H/1\ \text{TeV})^3$		

Detector related uncertainties

Luminosity		3.90%
Photon	efficiency	~5%
Electron	efficiency	2-5%
	energy scale	< 1%
	energy resolution	< 0.5%
Muon	efficiency	< 1%
	momentum scale	< 0.1%
	momentum resolution	< 5%
Jet	energy scale	2-14%
	energy resolution	2-5%
ETmiss	energy scale	10-16%
b-tagging	efficiency	5-14%
τ_h-jet	efficiency	5-8%
	energy scale	2-5%

H→ττ

H→ττ mass estimate is a key variable for signal extraction. Depending on the categories, three different estimates are utilized:

Effective mass (lep-lep 0jet category):

Mass of the visible τ decay products and ETmiss.

Easiest to calculate, but has poorest resolution.

Collinear mass (lep-lep, 1jet, 2jet and had-had):

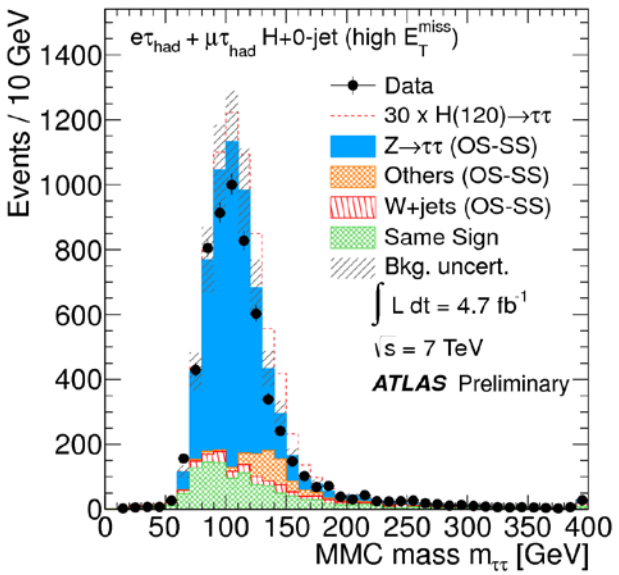
Assuming (1) neutrinos are collinear with visible τ decay products and (2) ETmiss is due only to neutrinos from τ decays.

only applicable to non back-to-back events

Missing Mass Calculator MMC (lep-had):

The mutual orientations of neutrinos and visible energies are consistent with the mass and decay kinematics of τ leptons.

an improved version of collinear mass



H→ZZ→4l: Event Selection

Two same-flavor and opposite-sign isolated lepton pairs:

Each with $p_T > 7$ GeV and $|\eta| < 2.5$, at least two with $p_T > 20$ GeV;

Mass combinations: $|m_{12} - M_Z| < 15$ GeV, $m_{threshold} < m_{34} < 115$ GeV

$m_{threshold}$ depends on reconstructed $m_{4\ell}$

A total of 71 events are selected: 17ee, 30eμ, 24μμ compared with 62±9 expected

	$\mu^+\mu^-\mu^+\mu^-$		$e^+e^-\mu^+\mu^-$		$e^+e^-e^+e^-$	
	Low-$m_{4\ell}$	High-$m_{4\ell}$	Low-$m_{4\ell}$	High-$m_{4\ell}$	Low-$m_{4\ell}$	High-$m_{4\ell}$
Int. Luminosity	4.8 fb^{-1}		4.8 fb^{-1}		4.9 fb^{-1}	
$ZZ^{(*)}$	2.1 ± 0.3	16.3 ± 2.4	2.8 ± 0.6	25.2 ± 3.8	1.2 ± 0.3	10.4 ± 1.5
$Z+$ jets and $t\bar{t}$	0.16 ± 0.06	0.02 ± 0.01	1.4 ± 0.5	0.17 ± 0.08	1.6 ± 0.7	0.18 ± 0.08
Total Background	2.2 ± 0.3	16.3 ± 2.4	4.3 ± 0.8	25.4 ± 3.8	2.8 ± 0.8	10.6 ± 1.5
Data	3	21	3	27	2	15
$m_H = 130$ GeV	1.00 ± 0.17		1.22 ± 0.21		0.43 ± 0.08	
$m_H = 150$ GeV	2.1 ± 0.4		2.9 ± 0.4		1.12 ± 0.18	
$m_H = 200$ GeV	4.9 ± 0.7		7.7 ± 1.0		3.1 ± 0.4	
$m_H = 400$ GeV	2.0 ± 0.3		3.3 ± 0.5		1.49 ± 0.21	
$m_H = 600$ GeV	0.34 ± 0.04		0.62 ± 0.10		0.30 ± 0.06	