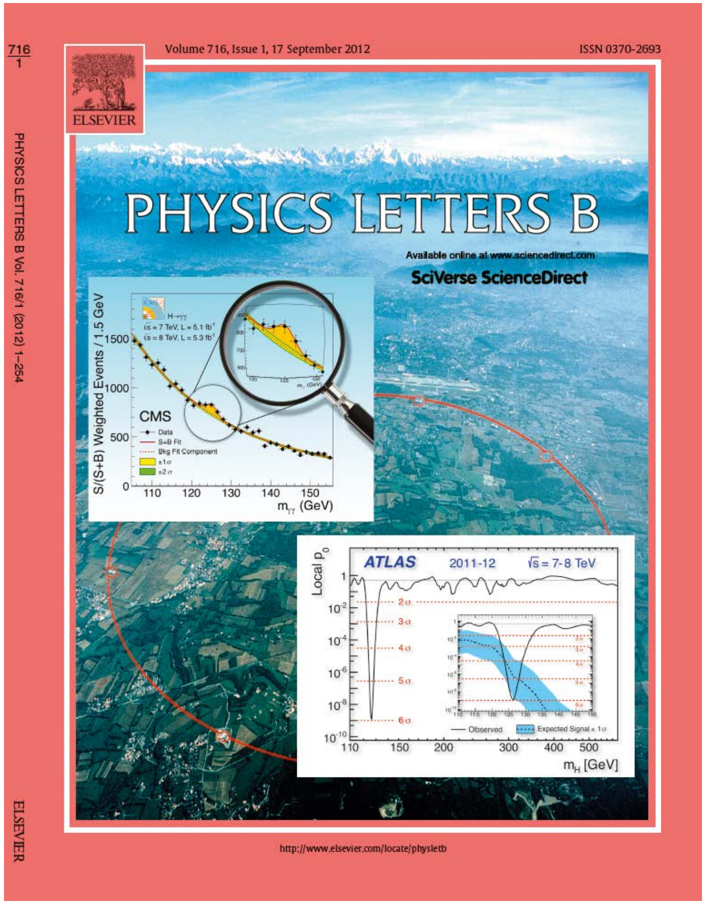
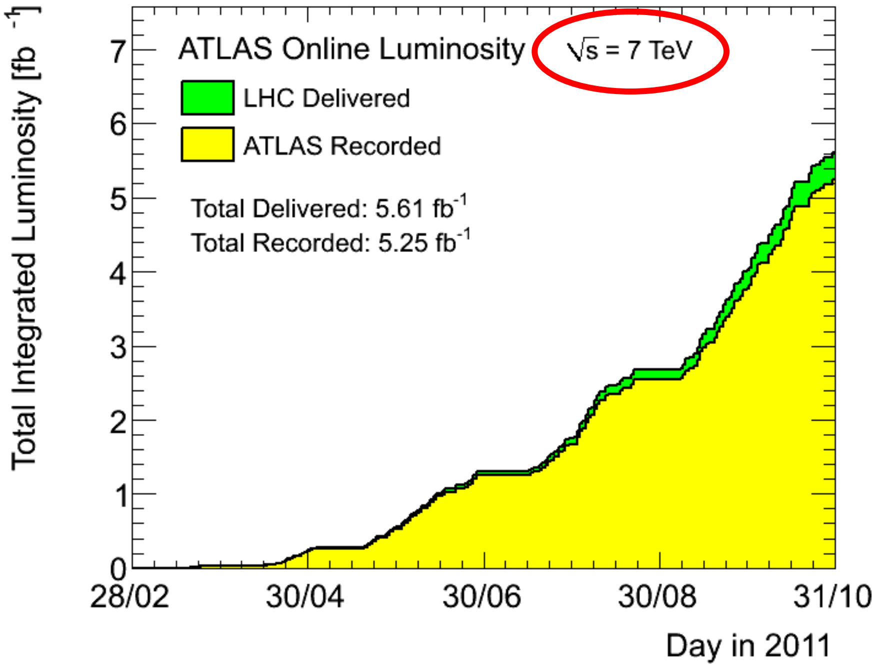
ATLAS Higgs Results at HCP



Jianming Qian
University of Michigan

Higgs Identification Workshop, Santa Barbara, December, 2012

Data Samples



2011 data taking at 7 TeV

5.3 fb^{-1} recorded

~4.8 fb^{-1} for analysis

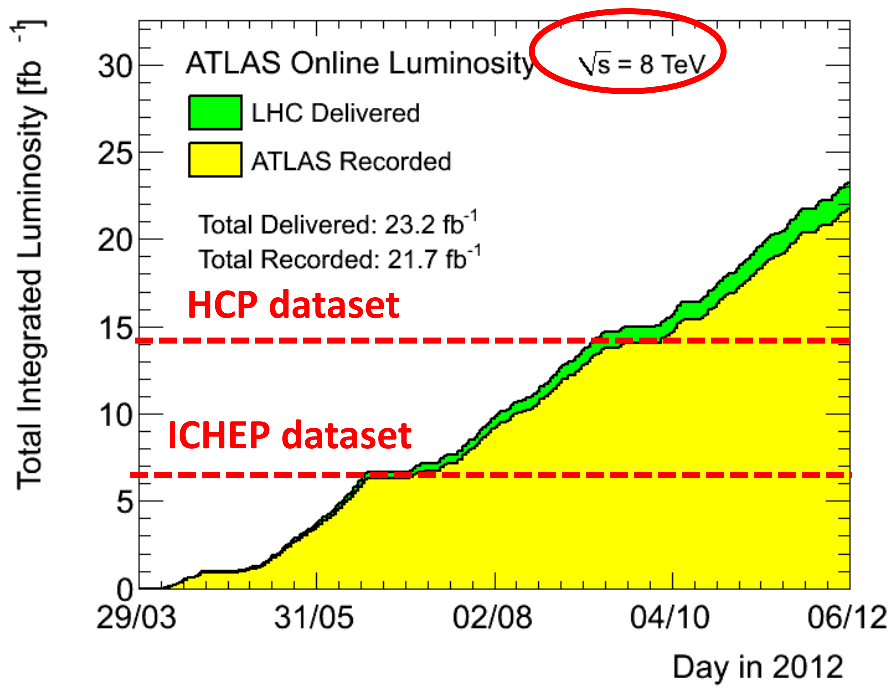
2012 data taking at 8 TeV

Recorded: 21.7 fb^{-1}

Analyzed:

5.8 fb^{-1} for ICHEP

and 13 fb^{-1} for HCP



Search Overview

High resolution channels: clean signature, full reconstruction, good mass resolution. ***5.8 fb^{-1} 2012 data today, 13 fb^{-1} Thursday?***

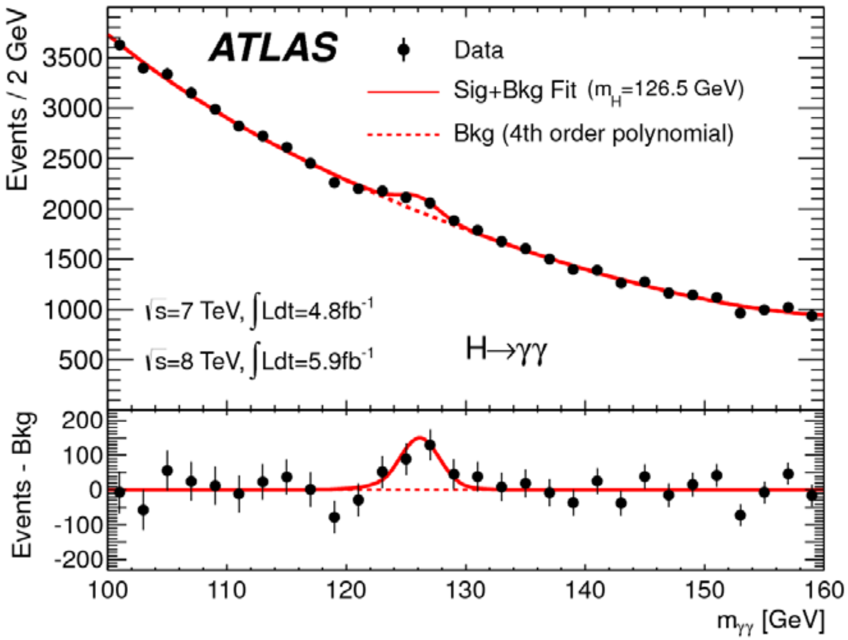
Channel	Mass range (GeV)	Key detector requirements	Main backgrounds
$H \to \gamma\gamma$	110-150	photon	$\gamma\gamma$, γj, jj
$H \to ZZ \to 4l$	110-600	lepton	ZZ, Z+jets, top
$H \to bb$ (WH/ZH)	110-130	jets, b-tagging	W/Z+jets, top
$H \to \tau\tau$ (ll, $l\tau_h$, $\tau_h\tau_h$)	100-150	lepton, jets, ETmiss	Z+jets, jets
$H \to WW \to l\nu l\nu$	110-600	lepton, jets, ETmiss, b-veto	WW, W/Z+jets, top, Wγ
$H \to WW \to l\nu qq$	300-600	lepton, jets, ETmiss, b-veto	W+jets, jets
$H \to ZZ \to ll\nu\nu$	200-600	lepton, ETmiss	Z+jets, ZZ, top
$H \to ZZ \to llqq$	200-600	lepton, jets, ETmiss, b-veto	Z+jets, ZZ, top

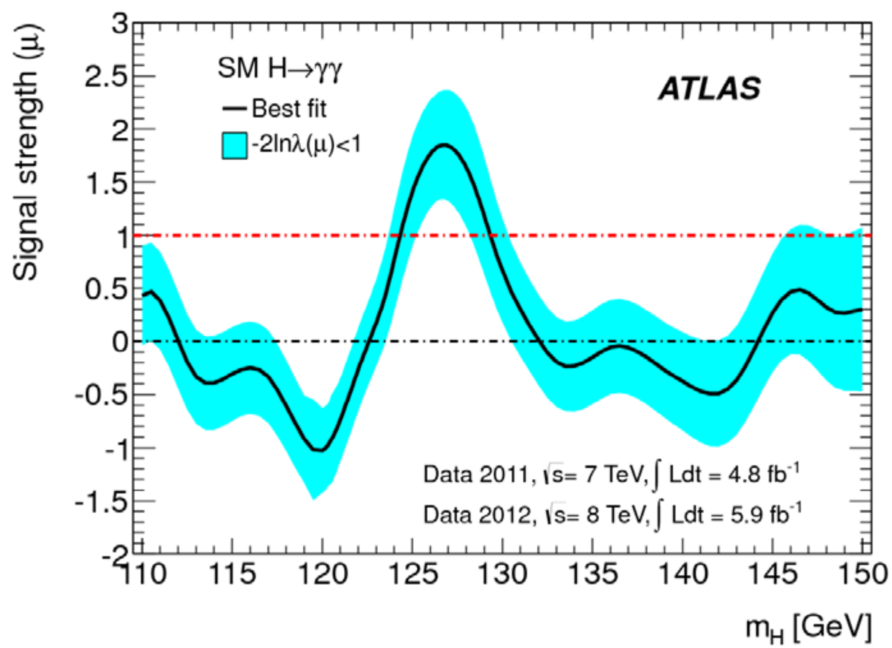
low mass

Low resolution channels: poor mass resolution, strong dependence on jet and ETmiss performance, ***updated with 13 fb^{-1} 2012 data.***

H → γγ: Discovery Results

A minimum p_0 at 126.5 GeV: $p_0 = 2\times10^{-6} \Rightarrow 4.5\sigma$

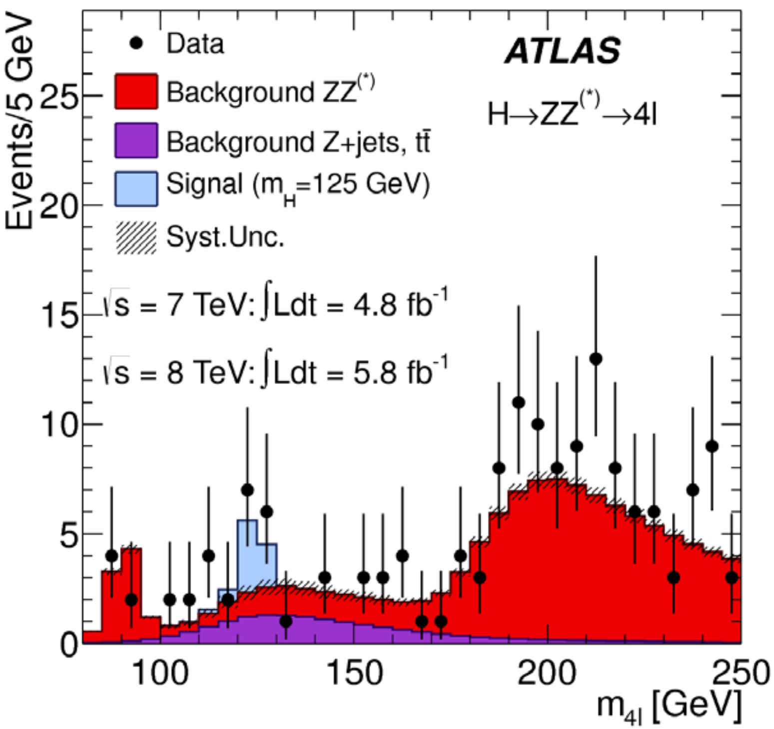


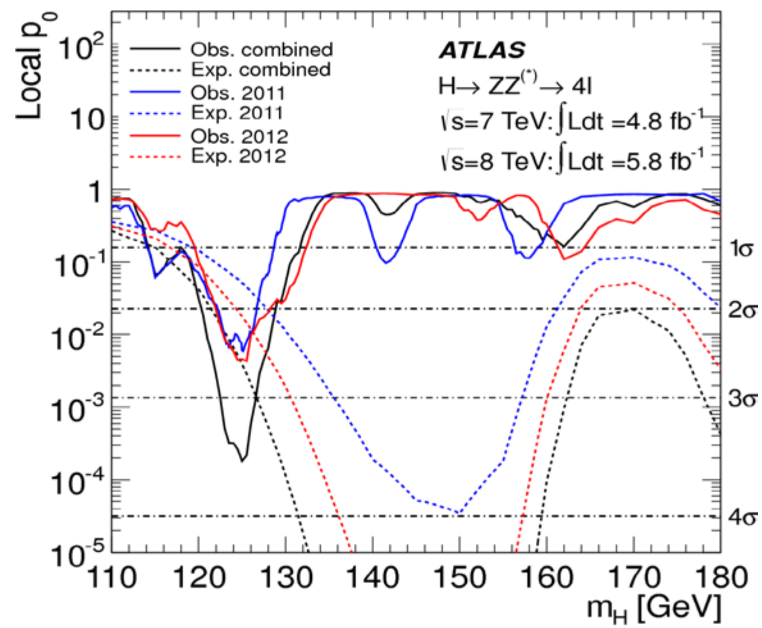


The best fit signal strength: $\mu = \dfrac{\sigma\times Br}{(\sigma\times Br)_{SM}} = 1.8\pm0.5$

H→ZZ*→4l: Discovery Results

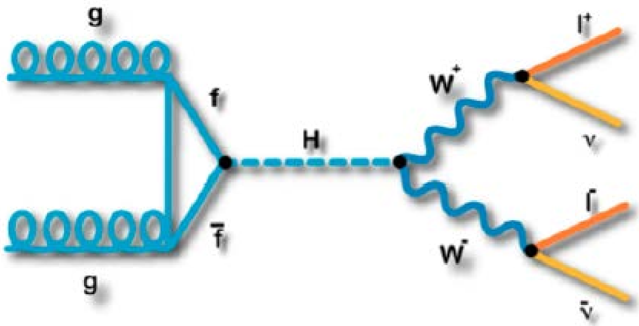
A minimum p_0 at 125 GeV: $p_0 = 2\times10^{-4} \Rightarrow 3.6\sigma$

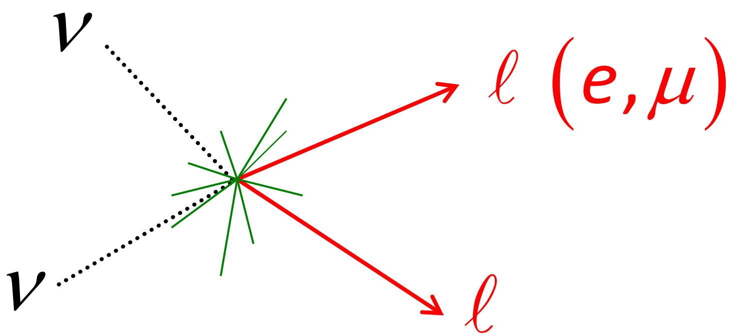




The best fit signal strength: $\mu = \frac{\sigma\times Br}{(\sigma\times Br)_{SM}} = 1.4\pm0.6$

H→WW*→lνlν





HCP analysis:

- 13 fb^{-1} of 2012 data;
- 0- and 1-jet

$$\sigma(H \to WW^* \to \ell\nu\ell\nu) \approx 220 \text{ fb}$$

(8 TeV, m_H=125 GeV)

⇒ ~2900 events in the sample

Main background:

SM WW (irreducible)

MC shape, data normalization
(Powheg, MCNLO, MCFM, …)

Top (pair or single):

MC shape, data normalization
(MCatNLO, Powheg, AcerMC,…)

WZ, Wγ, Wγ*, ZZ:

MC, validated with same-sign
(Powheg, Sherpa, MadGraph…)

W+jets:

Data shape and normalization

Z+jets:

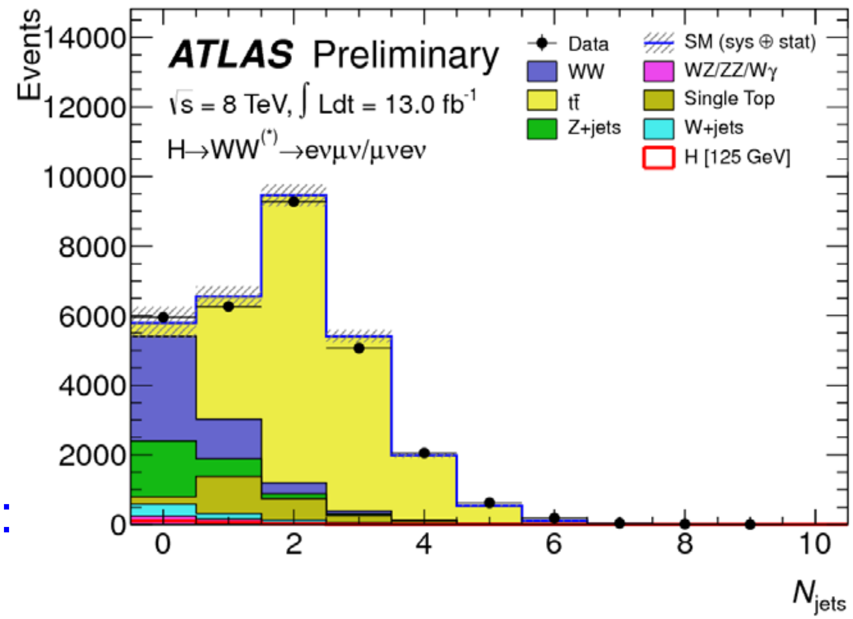
MC shape, data normalization
(ALPGEN, Powheg, Sherpa)

Jet Binning

Background composition varies strongly with jet multiplicity;

Signal-background ratio degrades as jet multiplicity increases.

$\Rightarrow$ Separate analysis for 0-, 1- and 2-jets.



gg→H signal cross section in jet bin n:

$$\text{Jet bin n: } \sigma_n = \sigma_{tot} \times f_n(\text{MC})$$

σ_n: NNLO+NLL calculation, f_n from MC simulation. Their uncertainties are calculated separately as (Stewart-Tackman):

$$\sigma_n = \sigma_{\geq n} - \sigma_{\geq n-1} \quad \Rightarrow \quad (\Delta\sigma_n)^2 = (\Delta\sigma_{\geq n})^2 + (\Delta\sigma_{\geq n-1})^2$$

$$\Delta\sigma_{\geq 0}/\sigma_{\geq 0} \sim 8\%, \quad \Delta\sigma_{\geq 1}/\sigma_{\geq 1} \sim 20\%, \quad \Delta\sigma_{\geq 2}/\sigma_{\geq 2} \sim 70\%,$$

$\Delta\sigma_{\geq 1}/\sigma_{\geq 1}$ and $\Delta\sigma_{\geq 2}/\sigma_{\geq 2}$ are currently calculated using fixed order program.

H→WW*→eμνν

Due to large pileups in 2012, *only eμ final state has been analyzed*

$$6 \text{ categories: } (e\mu, \mu e) \otimes (\text{0-jet, 1-jet, 2-jet})$$

- Separate final states depending on leading leptons;
- 2-jet analysis is ongoing

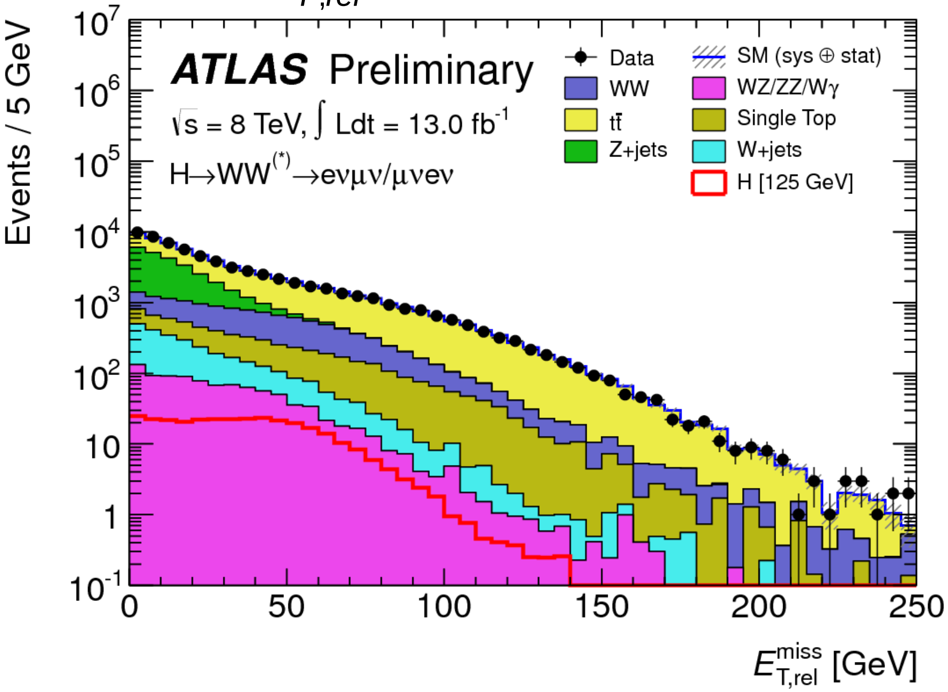
Preselection:

- $p_T^{\ell_1,\ell_2} > 25{,}15$ GeV with $|\eta| < 2.5$;
- $E_{T,\text{Rel}}^{\text{miss}} > 25$ GeV;
- Jets: $p_T > 25$ GeV and $|\eta| < 2.5$ otherwise $p_T > 30$ GeV

$$E_{T,\text{Rel}}^{\text{miss}} = \begin{cases} E_T^{\text{miss}} & \Delta\phi \ge \pi/2 \\ E_T^{\text{miss}} \sin\Delta\phi & \Delta\phi < \pi/2 \end{cases}$$

$$\Delta\phi = \min\left\{\Delta\phi\left(\vec{E}_T^{\text{miss}}, \ell/\text{jets}\right)\right\}$$

$E_{T,rel}^{miss}$ before the cut



H→WW*→eμνν

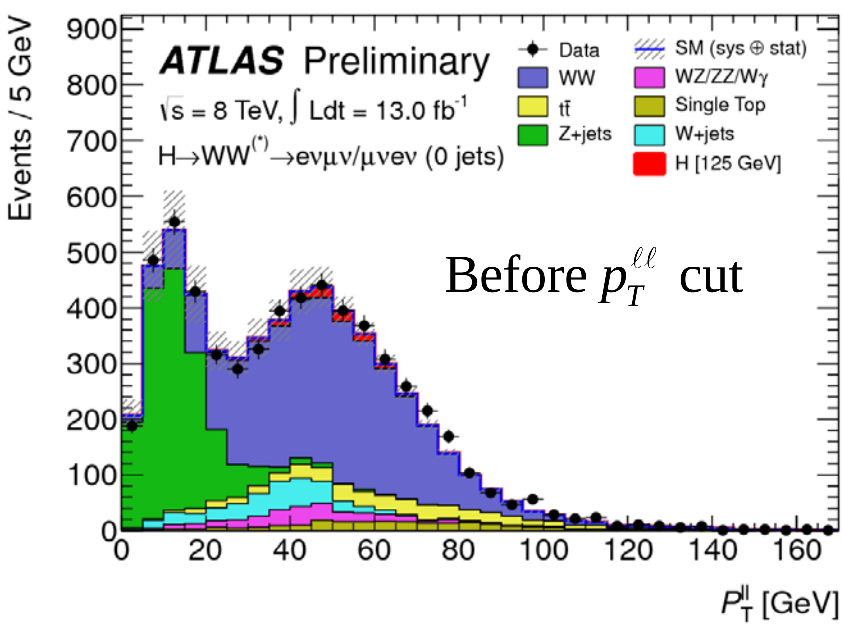
Significant background remains after pre-selection, apply topological selections for further background reduction:

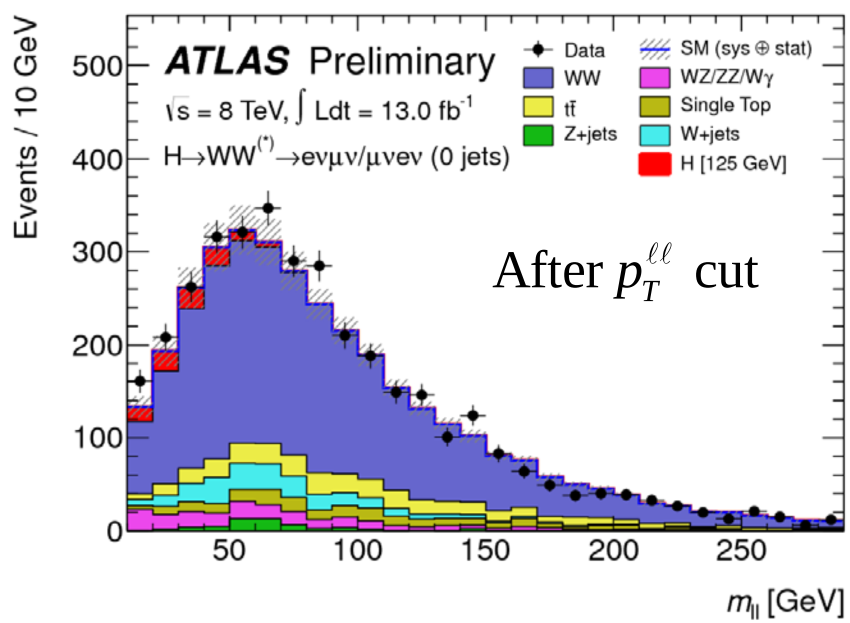
0-jet selections

$$- p_T^{\ell\ell} > 30 \text{ GeV};$$
$$- m_{\ell\ell} < 50 \text{ GeV};$$
$$- \Delta\phi_{\ell\ell} < 1.8$$

$\Rightarrow$ Focus on low mass region.

Similar for 1-jet analysis, with additional b-jet veto





H→WW*→eμνν

Non-WW dibosons (WZ/ZZ/Wγ) and Z/DY:

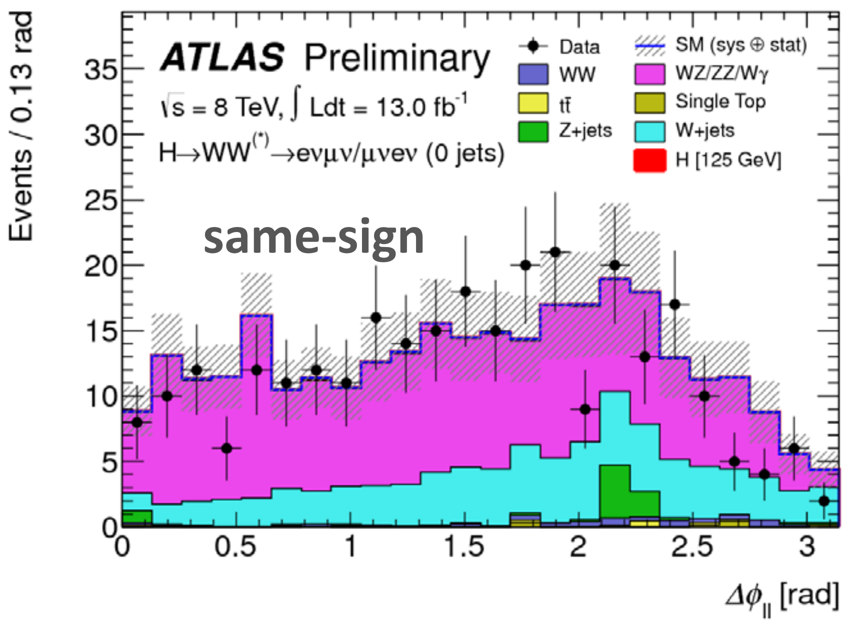
Diboson: real leptons, real ETmiss; Z/DY: real lepton, fake or real ETmiss

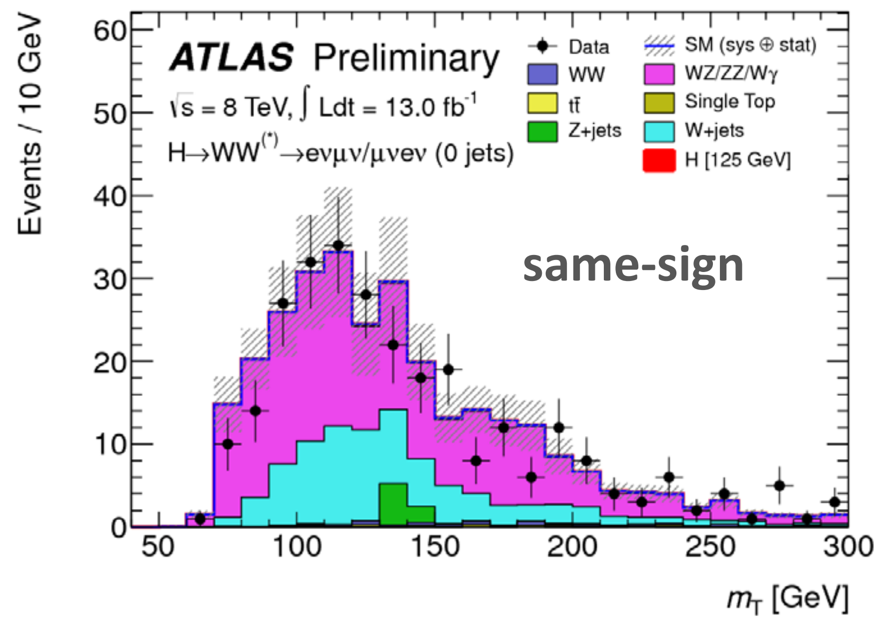
Both normalization and m_T shape from MC

W+jets:

Fake leptons, real ETmiss: both normalization and m_T shape from data

Non-WW dibosons and W+jets processes contribute to both same- and opposite-sign dilepton events ⇒ validation with same-sign events





H→WW*→eμνν

WW and backgrounds: real leptons and real ETmiss

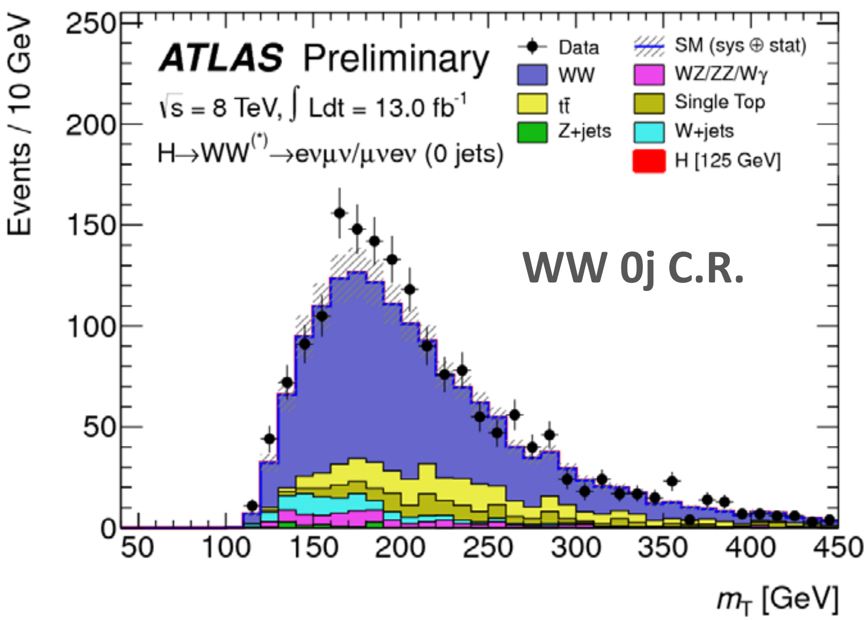
Normalization from data and m_T shape from MC

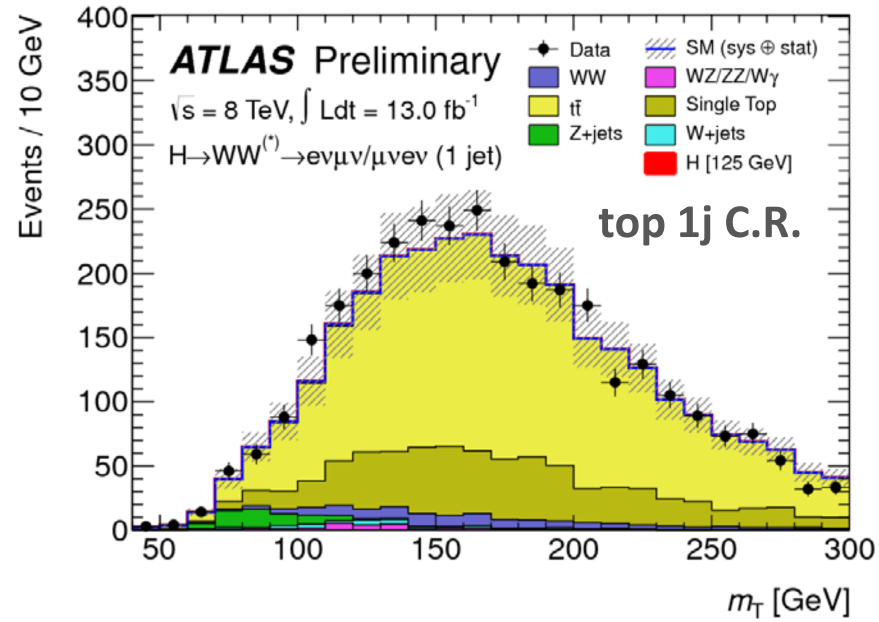
Estimating WW and top background from data:

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

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

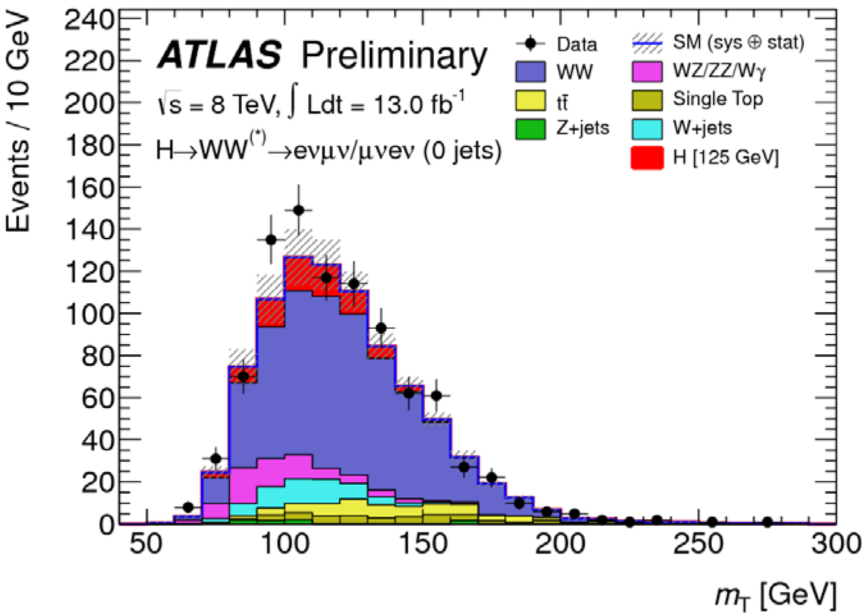
$$WW: \; m_{\ell\ell} > 80 \text{ GeV};$$
$$Top: \; \text{reverse b-jet veto}$$

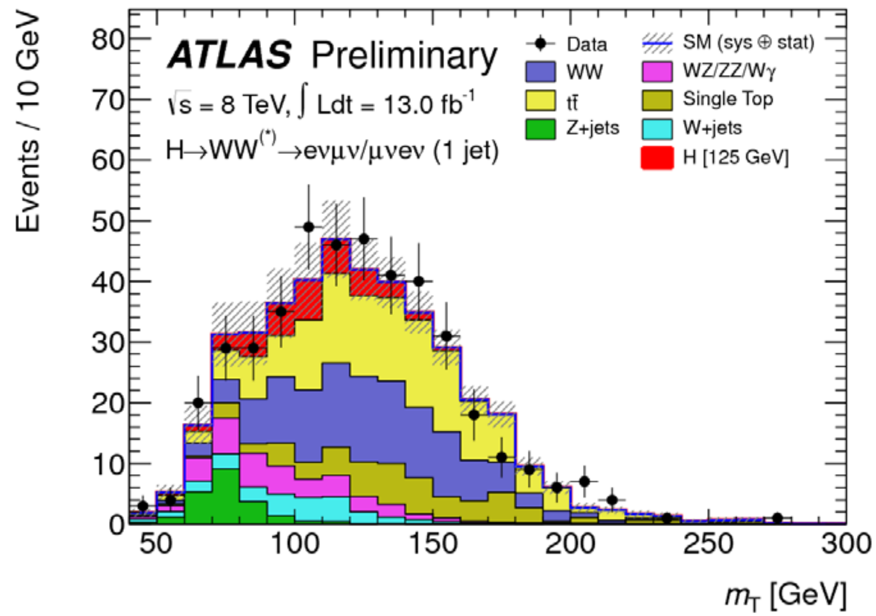




H→WW*→eμνν

The transverse mass as the final discriminant





125 GeV: $0.75 m_H < m_T < m_H$ (illustration only)

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
$H+$ 0-jet	45 ± 9	242 ± 32	26 ± 4	16 ± 2	11 ± 2	4 ± 3	34 ± 17	334 ± 28	423
$H+$ 1-jet	18 ± 6	40 ± 22	10 ± 2	37 ± 13	13 ± 7	2 ± 1	11 ± 6	114 ± 18	141

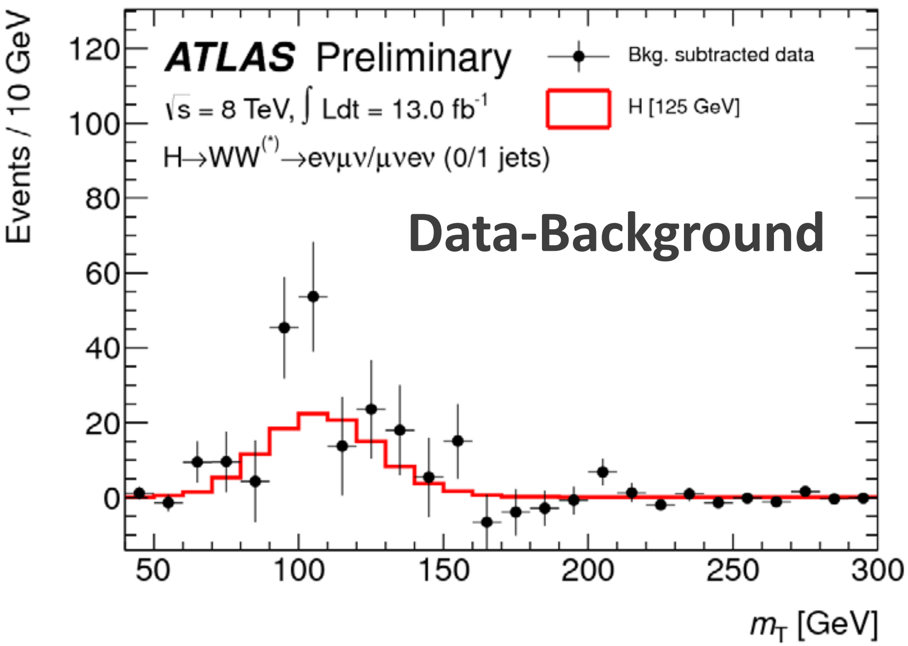
⇒ Significant excess over estimated background!

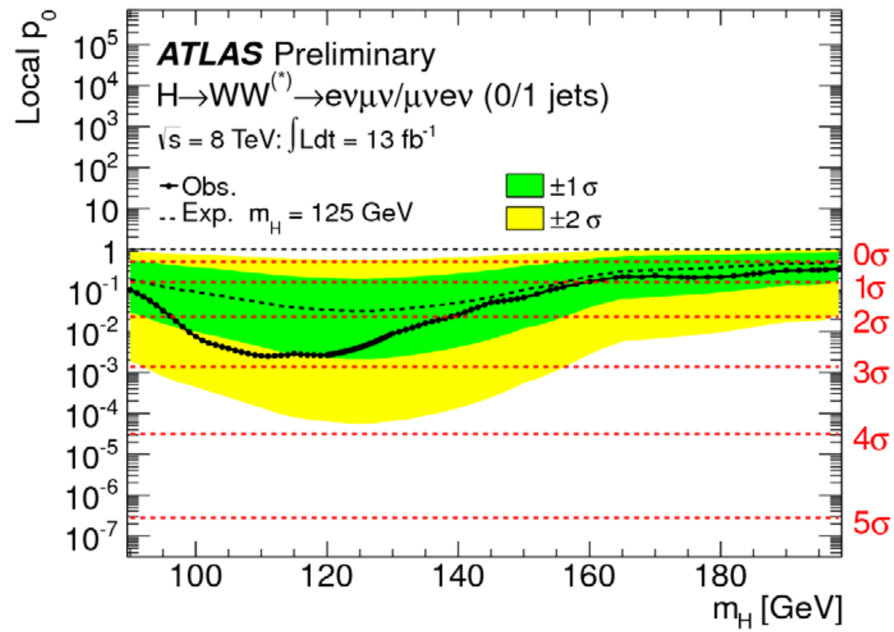
Systematic Uncertainties

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
PDF model (signal only)	8	-
QCD scale (acceptance)	4	-
Jet energy scale and resolution	4	2
W+jets fake factor	-	5
WW theoretical model	-	5
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	26	-
2-jet incl. ggF signal ren./fact. scale	15	-
Parton shower/ U.E. model (signal only)	10	-
b-tagging efficiency	-	11
PDF model (signal only)	7	-
QCD scale (acceptance)	4	2
Jet energy scale and resolution	1	3
W+jets fake factor	-	5
WW theoretical model	-	3

"Theoretical" uncertainties on the signal already dominate in this channel. Need your help to bring them down!

H→WW*→eμνν





p-value of background only hypothesis:

$$\text{Observed: } p_0 = 4\times10^{-3}\ \left(2.6\sigma\right);\ \ \text{Expected: } p_0 = 0.03\ \left(1.9\sigma\right)$$

Fitted signal strength at 125 GeV:

$$\mu = \frac{\sigma\times Br}{\left(\sigma\times Br\right)_{SM}} = 1.48^{+0.35}_{-0.33}\left(\text{stat}\right)^{+0.41}_{-0.36}\left(\text{syst theory}\right)^{+0.28}_{-0.27}\left(\text{syst expt}\right)\pm0.05\left(\text{lumi}\right)$$

$\mathbf{H \to b\bar{b}}$

H→bb has the largest branching ratio at low mass,

$$Br\left(H \to b\bar{b}\right) = 57.7\% \ @ \ m_H = 125 \text{ GeV}$$

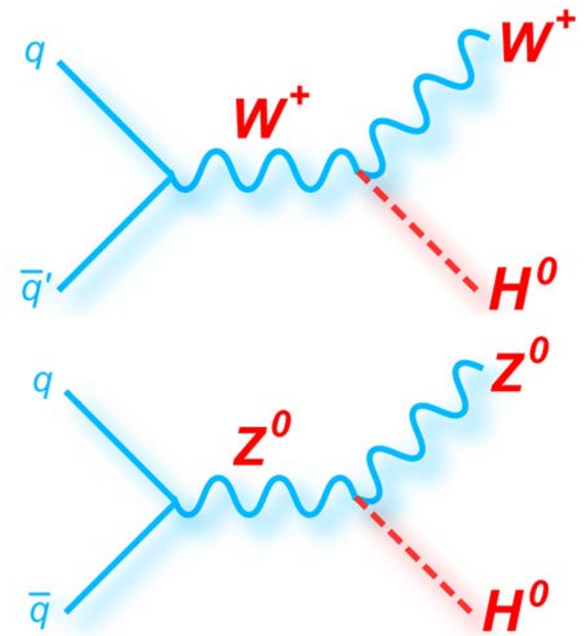
but suffers from overwhelming backgrounds in the dominant ggF and VBF productions without a leptonic signature

Exploring the leptonic decays of W/Z bosons of the associated production, analyzing three different final states

$$\begin{aligned} &\text{0 lepton:} && ZH \to \nu\nu b\bar{b} \\ &\text{1 lepton:} && WH \to \ell\nu b\bar{b} \\ &\text{2 leptons:} && ZH \to \ell\ell b\bar{b} \end{aligned}$$

Events in 13 fb^{-1} at 8 TeV

$$\begin{aligned} &ZH \to \nu\nu b\bar{b}: && \text{590 events} \\ &WH \to \ell\nu b\bar{b}: && \text{1130 events} \\ &ZH \to \ell\ell b\bar{b}: && \text{200 events} \end{aligned}$$



$H \to b\bar{b}$ Backgrounds

W/Z+jets:

shape from simulation, normalization from data (Powheg, ALPGEN, Sherpa, …)

Top pair and single top:

shape from simulation, normalization from data (MC@NLO, AcerMC, …)

Diboson (WW/WZ/ZZ):

both shape and normalization from simulation (Herwig, Powheg, …)

Multijets:

Data-driven methods

Categorization to take advantage of different S/B ratios:

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

$H \rightarrow b\bar{b}$: Selections

Pre-selection:

two b-tagged jets in all three final states

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV + ≤ 1 extra jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV + 0 extra jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV -
Missing E_T	$E_T^{miss} > 120$ GeV $p_T^{miss} > 30$ GeV $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$ $\mathrm{Min}[\Delta\phi(E_T^{miss}, \mathrm{jet})] > 1.5$ $\Delta\phi(E_T^{miss}, b\bar{b}) > 2.8$	-	$E_T^{miss} < 60$ GeV
Vector Boson	-	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

Category-dependent selections

0-lepton channel			
E_T^{miss} (GeV)	120-160	160-200	>200
$\Delta R(b, \bar{b})$	0.7-1.9	0.7-1.7	<1.5

1-lepton channel					
p_T^W (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b, \bar{b})$	>0.7			0.7-1.6	<1.4
E_T^{miss} (GeV)	> 25				> 50
m_T^W (GeV)	> 40			-	

2-lepton channel					
p_T^Z (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b, \bar{b})$	>0.7			0.7-1.8	<1.6

$H \to b\bar{b}$: W/Z+jets

W/Z+(light, b, c)-jets normalizations determined from data control regions (pre-tagged, 1-tagged, ...) through template fitting;

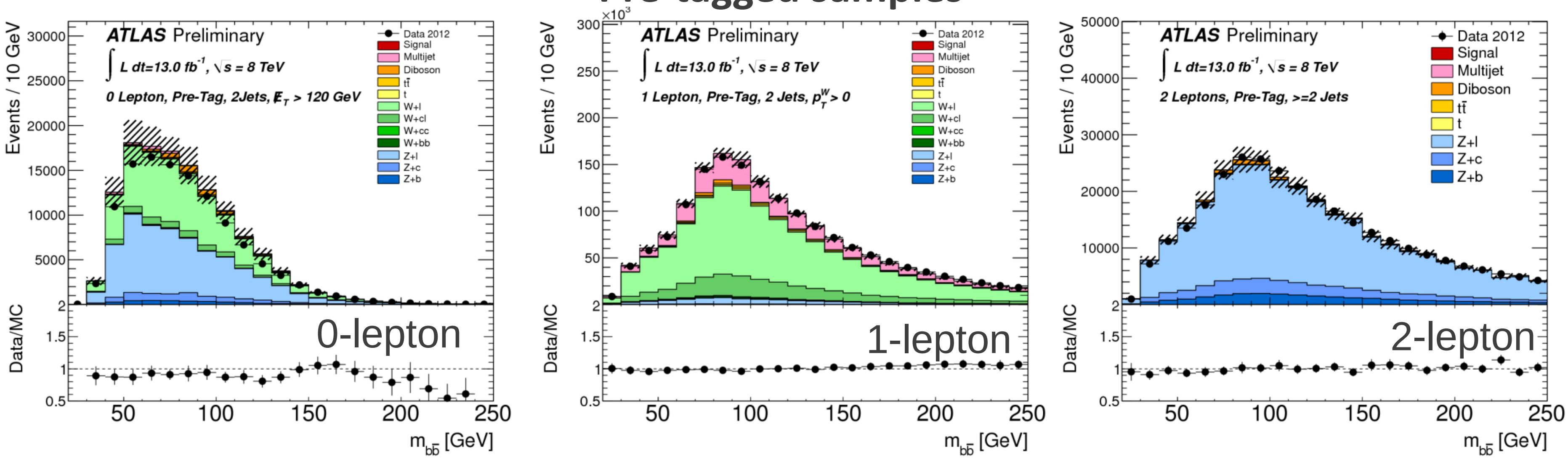
Shapes of individual components from MC simulations;

Correct MC predictions using rescaling factors.

	$\sqrt{s} = 8$ TeV
$Z + c$	0.71 ± 0.23
$Z+$ light	0.98 ± 0.11
$W + c$	1.04 ± 0.24
$W+$ light	1.01 ± 0.14

	$\sqrt{s} = 8$ TeV
Top	1.29 ± 0.16
$Z + b$	1.11 ± 0.15
$W + b$	0.79 ± 0.20

Pre-tagged samples



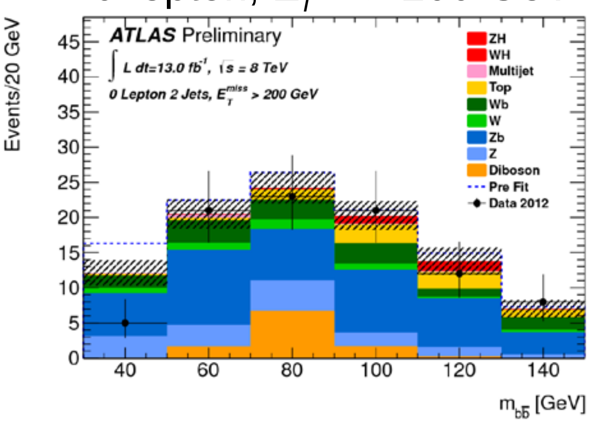
$H \rightarrow b\bar{b}$: Yields

Signal-background ratio ~ 1-3%

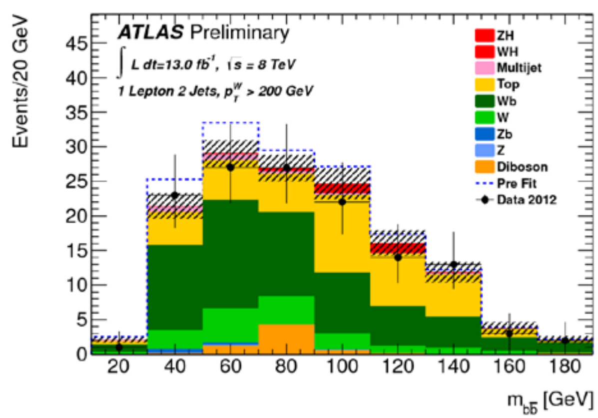
	0-lepton, 2 jet			0-lepton, 3 jet			1-lepton					2-lepton				
Bin	E_T^{miss} [GeV]						p_T^W [GeV]					p_T^Z [GeV]				
	120-160	160-200	>200	120-160	160-200	>200	0-50	50-100	100-150	150-200	> 200	0-50	50-100	100-150	150-200	>200
ZH	2.9	2.1	2.6	0.8	0.8	1.1	0.3	0.4	0.1	0.0	0.0	4.7	6.8	4.0	1.5	1.4
WH	0.8	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

m_{bb} as the final discriminant, typical mass resolution ~20%

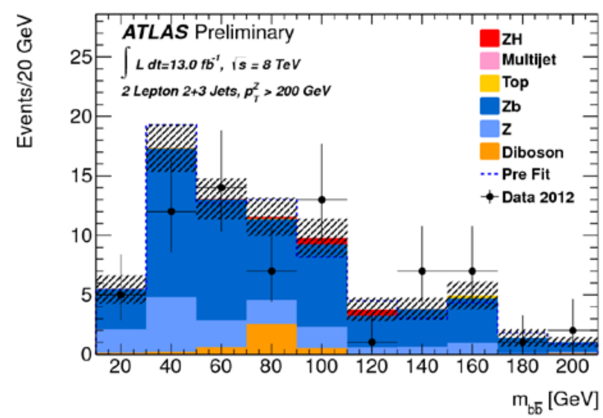
0-lepton, $E_T^{miss} > 200$ GeV



1-lepton, $p_T^W > 200$ GeV



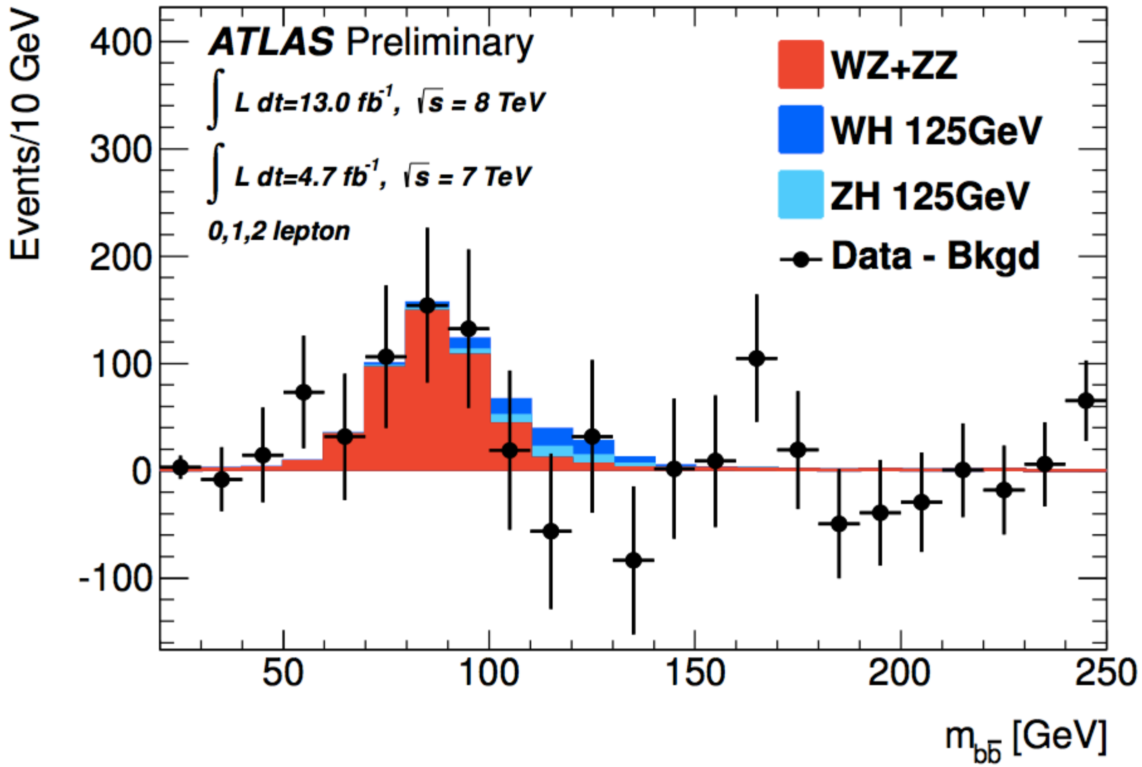
2-lepton, $p_T^Z > 200$ GeV



Diboson Production

WZ/ZZ production with Z→bb have the similar signature as the signal, but with 5x the rate;

Perform the similar analysis to validate the search, observe clear excess with a significance of 4.0σ and a signal strength 1.05±0.32.



$H \rightarrow b\bar{b}$: Systematics

Dominated by experimental systematics:

b- and c-jet tagging, pileup, jets and Etmiss, …

Major theoretical uncertainties are

Higgs pT spectrum, MC modeling, …

Background uncertainties

Systematic [%]	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_{T}^{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

Signal uncertainties

Systematic [%]	0 lepton		1 lepton	2 leptons
	ZH	*WH*	*WH*	*ZH*
b-tagging	8.9	9.0	8.8	8.6
c-tagging	0.1	0.1	0.0	0.1
light tagging	0.0	0.0	0.1	0.3
Jet/Pile-up/E_{T}^{miss}	19	25	6.7	4.2
Lepton	0.0	0.0	2.1	1.8
$H \rightarrow bb$ BR	3.3	3.3	3.3	3.3
VH p_T-dependence	5.3	8.1	7.6	5.0
VH theory PDF	3.5	3.5	3.5	3.5
VH theory scale	1.6	0.4	0.4	1.6
Luminosity	3.6	3.6	3.6	3.6

$H \rightarrow b\bar{b}$: Results

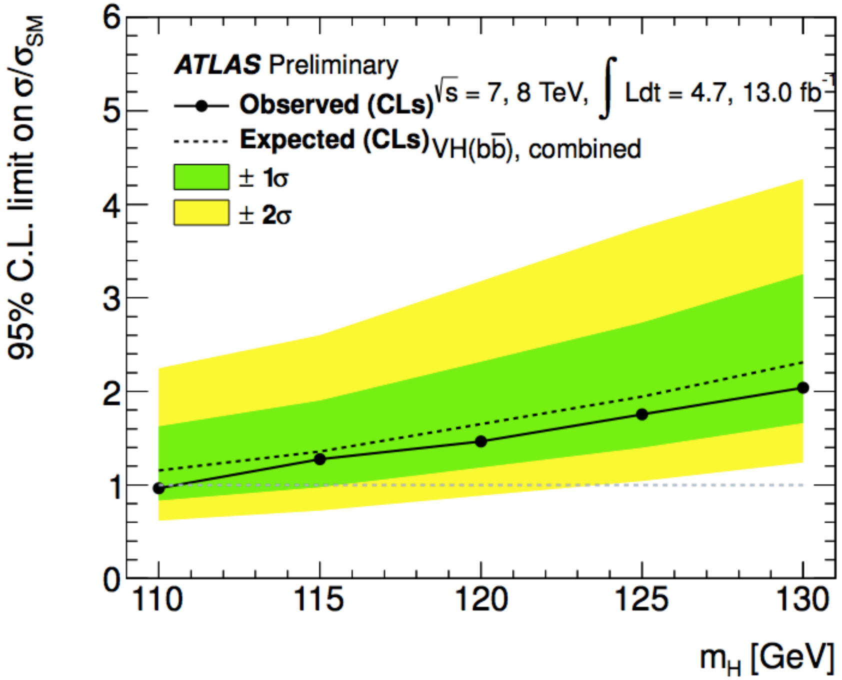
No significant excesses are observed:

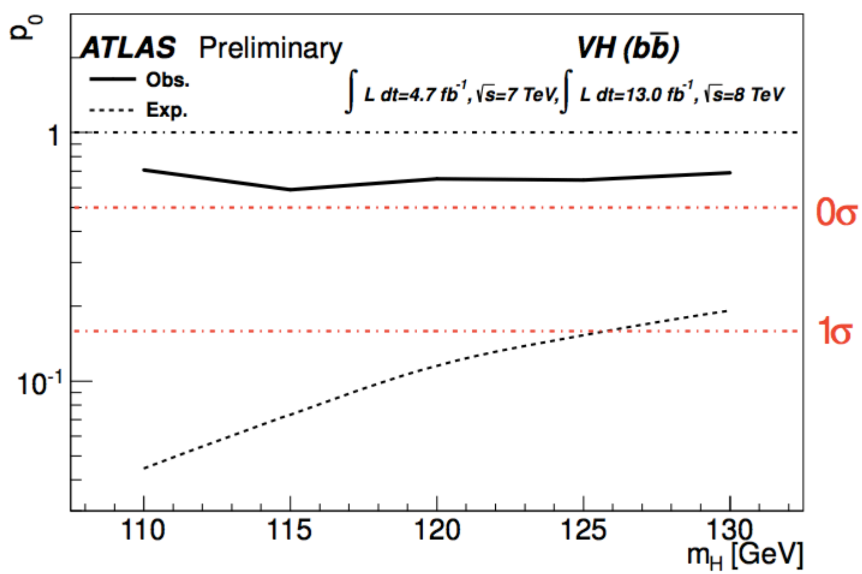
95% CL limit at 125 GeV 1.8 (1.9) x SM observed (expected);

p-value of background only hypothesis: 0.64 (0.15)

Signal strength:

$$\mu = \frac{\sigma \times Br}{(\sigma \times Br)_{SM}} = -0.4 \pm 0.7(\text{stat}) \pm 0.8(\text{syst})$$





H→ττ

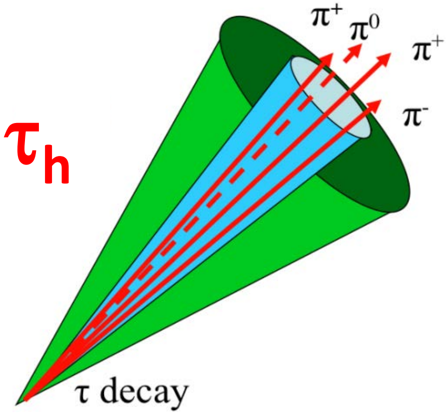
An important search channel at low mass, likely the only final state for Higgs-lepton coupling measurements for a while.

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;
- BDT with calorimeter and tracking variables



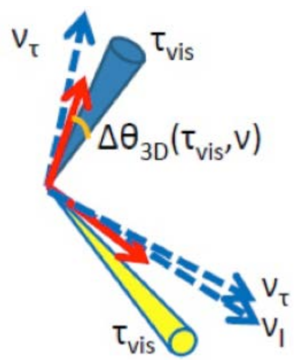
Major backgrounds:

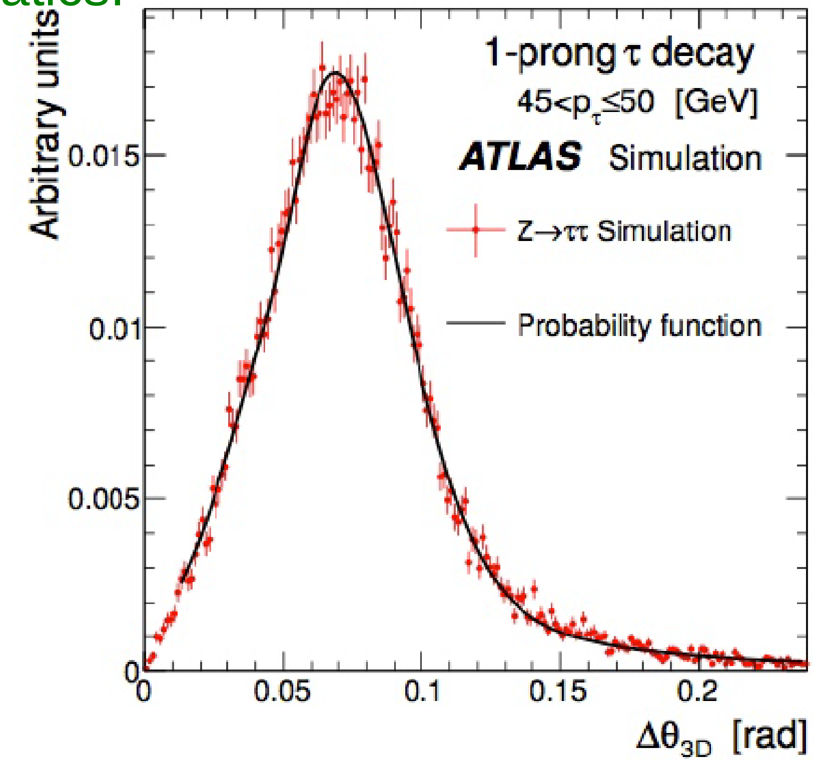
- Z(→ττ)+jets, estimated using embedding method
- Multijets, estimated using same-sign events.

H→ττ: MMC

Tau pair mass ($m_{\tau\tau}$) as the final signal-background discriminant, reconstructed through the Missing Mass Calculator (MMC)

- Advanced version of collinear approximation method;
- Take into account tau decay kinematics:





Neutrinos and visible tau decay have non-zero angle

- Under-constrained system
  ⇒ choose the solution with the maximum likelihood

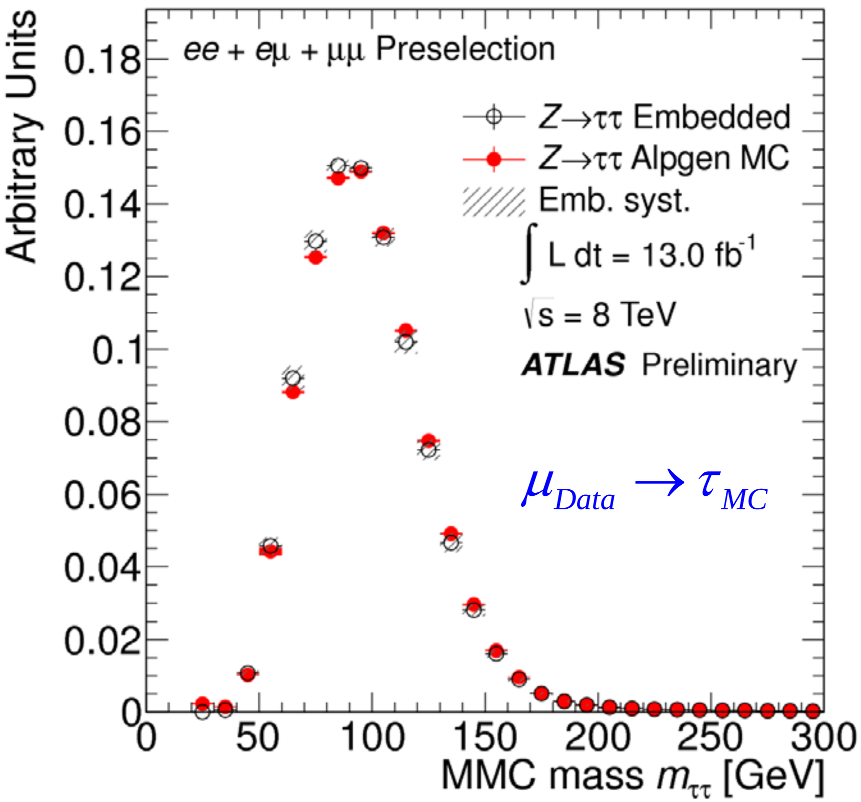
Resolution 13-20%, depending on decay mode.

H→ττ: Embedding

$Z\rightarrow\tau\tau$ is the most dominant background for all $H\rightarrow\tau\tau$ searches, its contribution is estimated from the $Z\rightarrow\mu\mu$ data through embedding

- select $Z\rightarrow\mu\mu$ 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

$\Rightarrow$ All except τ decays are from data!



MC does a decent job…

$H \rightarrow \tau\tau$: Categorization

Dividing analysis into different categories to improve sensitivity

Lepton-lepton final state:

- VBF topology: 2 jets, $\Delta\eta$(jj)>3, m(jj)>400 GeV;
- WH/ZH topology: 2 jets, $\Delta\eta$(jj)<2, 30<m(jj)<160 GeV
- Boosted topology: pT($\tau\tau$)>100 GeV
- 1-jet analysis: m($\tau\tau$j)>225 GeV

Lepton-hadron final state:

- VBF topology: $\Delta\eta$(jj)>3, m(jj)>500 GeV;
- Boosted topology: pT($\tau\tau$)>100 GeV;
- 1-jet analysis: exact one jet with pT>30 GeV
- 0-jet analysis: no jet with pT>30 GeV;

Hadron-hadron state:

- VBF topology: $\Delta\eta$(jj)>2.6, m(jj)>350 GeV
- Boosted: pT(τ)>70 GeV, ΔR(τ1,τ2)<1.9

H→ττ: Selections

These are very complicated analyses….

Lepton-lepton

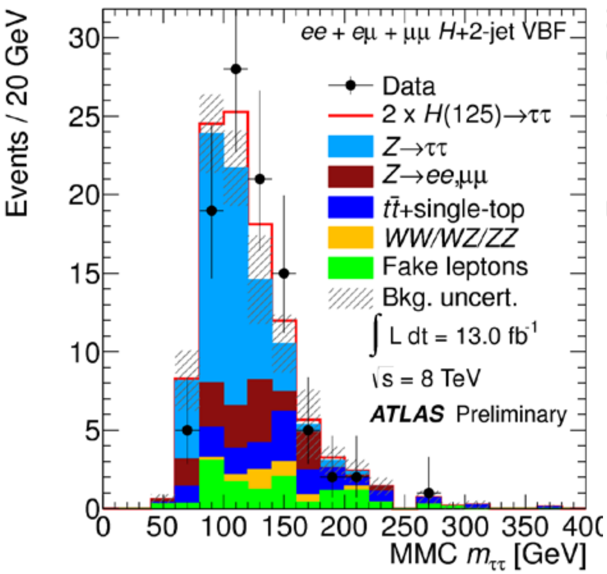
S/B ratio:

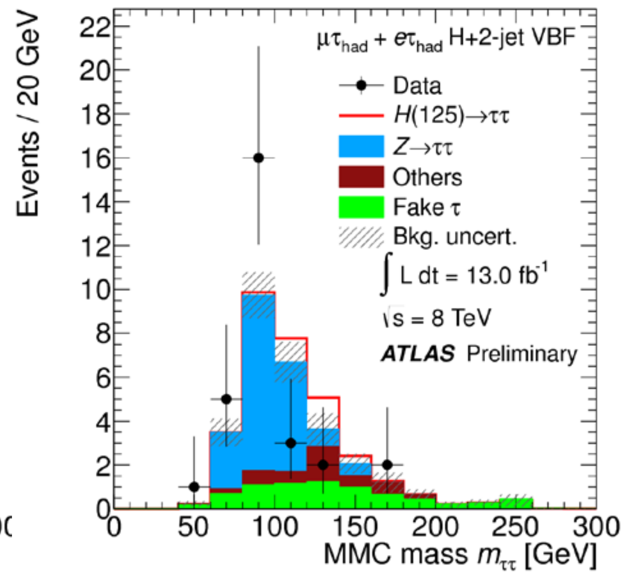
- 5-10% for VBF
- <~1% for the rest
- (integrated over whole mass range)

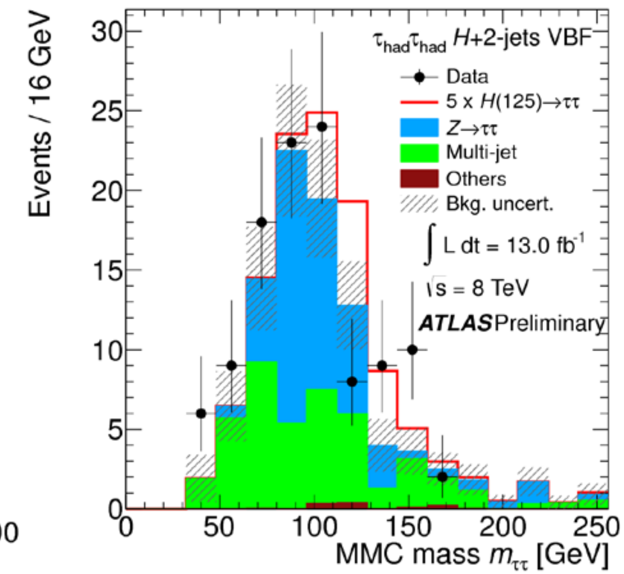
2-jet VBF	Boosted	2-jet VH	1-jet
Pre-selection: exactly two leptons with opposite charges			
30 GeV $< m_{\ell\ell} <$ 75 GeV (30 GeV $< m_{\ell\ell} <$ 100 GeV) for same-flavor (different-flavor) leptons, and $p_{T,\ell 1} + p_{T,\ell 2} >$ 35 GeV			
At least one jet with $p_T >$ 40 GeV ($\lvert JVF_{\rm jet}\rvert > 0.5$ if $\lvert\eta_{\rm jet}\rvert < 2.4$)			
$E_{\rm T}^{\rm miss} >$ 40 GeV ($E_{\rm T}^{\rm miss} >$ 20 GeV) for same-flavor (different-flavor) leptons			
$H_{\rm T}^{\rm miss} >$ 40 GeV for same-flavor leptons			
$0.1 < x_{1,2} < 1$			
$0.5 < \Delta\phi_{\ell\ell} < 2.5$			
$p_{T,j2} >$ 25 GeV (JVF)	excluding 2-jet VBF	$p_{T,j2} >$ 25 GeV (JVF)	excluding 2-jet VBF, Boosted and 2-jet VH
$\Delta\eta_{jj} > 3.0$	$p_{T,\tau\tau} >$ 100 GeV	excluding Boosted	$m_{\tau\tau j} >$ 225 GeV
$m_{jj} >$ 400 GeV	b-tagged jet veto	$\Delta\eta_{jj} < 2.0$	b-tagged jet veto
b-tagged jet veto	–	30 GeV $< m_{jj} <$ 160 GeV	–
Lepton centrality and CJV		b-tagged jet veto	

	$ee + \mu\mu + e\mu$ VBF category	Boosted category	VH category	1-jet category
$gg \to H$ (125 GeV)	1.3 ± 0.2 ± 0.4	12.4 ± 0.6 ± 2.9	2.5 ± 0.3 ± 0.6	7.0 ± 0.5 ± 1.6
VBF H (125 GeV)	3.63 ± 0.10 ± 0.02	3.36 ± 0.09 ± 0.30	0.21 ± 0.03 ± 0.02	1.82 ± 0.07 ± 0.18
VH (125 GeV)	0.01 ± 0.01 ± 0.01	2.20 ± 0.05 ± 0.22	0.64 ± 0.03 ± 0.09	0.44 ± 0.02 ± 0.05
$Z/\gamma^* \to \tau\tau$ embedded	47 ± 2 ± 1	$(1.24 \pm 0.01 \pm 0.08)\times 10^3$	393 ± 7 ± 26	$(0.86 \pm 0.01 \pm 0.06)\times 10^3$
$Z/\gamma^* \to \ell\ell$	14 ± 3 ± 2	$(0.21 \pm 0.02 \pm 0.04)\times 10^3$	$(0.08 \pm 0.01 \pm 0.02)\times 10^3$	$(0.16 \pm 0.01 \pm 0.03)\times 10^3$
Top	15 ± 2 ± 3	$(0.39 \pm 0.01 \pm 0.07)\times 10^3$	87 ± 4 ± 23	117 ± 5 ± 18
Diboson	3.6 ± 0.8 ± 0.6	55 ± 3 ± 10	15 ± 1 ± 4	40 ± 3 ± 7
Backgrounds with fake leptons	12 ± 2 ± 3	102 ± 7 ± 23	86 ± 4 ± 16	230 ± 8 ± 52
Total background	91 ± 5 ± 5	$(2.01 \pm 0.03 \pm 0.12)\times 10^3$	$(0.66 \pm 0.02 \pm 0.05)\times 10^3$	$(1.40 \pm 0.02 \pm 0.08)\times 10^3$
Observed data	98	2014	636	1405

$H \rightarrow \tau\tau$: $m_{\tau\tau}$





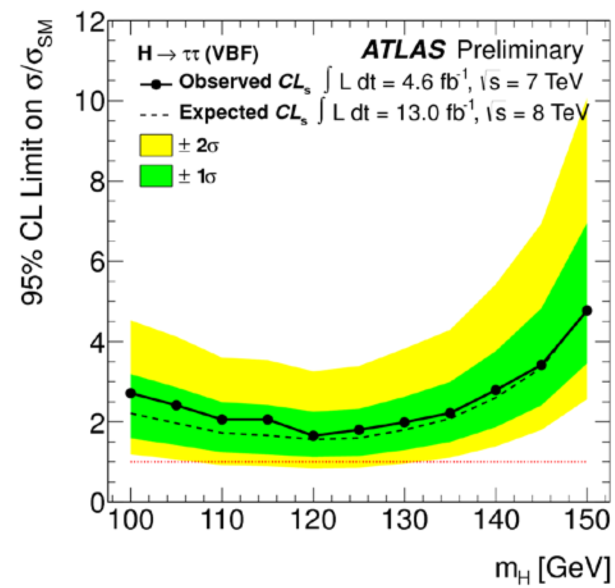


Likelihood fit to $m_{\tau\tau}$ distributions to extract upper limits and calculate significance.

VBF analysis as an example:

- excess in 2-lepton;
- deficits in 1-lepton and 0-lepton

$\Rightarrow$ Neither excess nor deficit combined

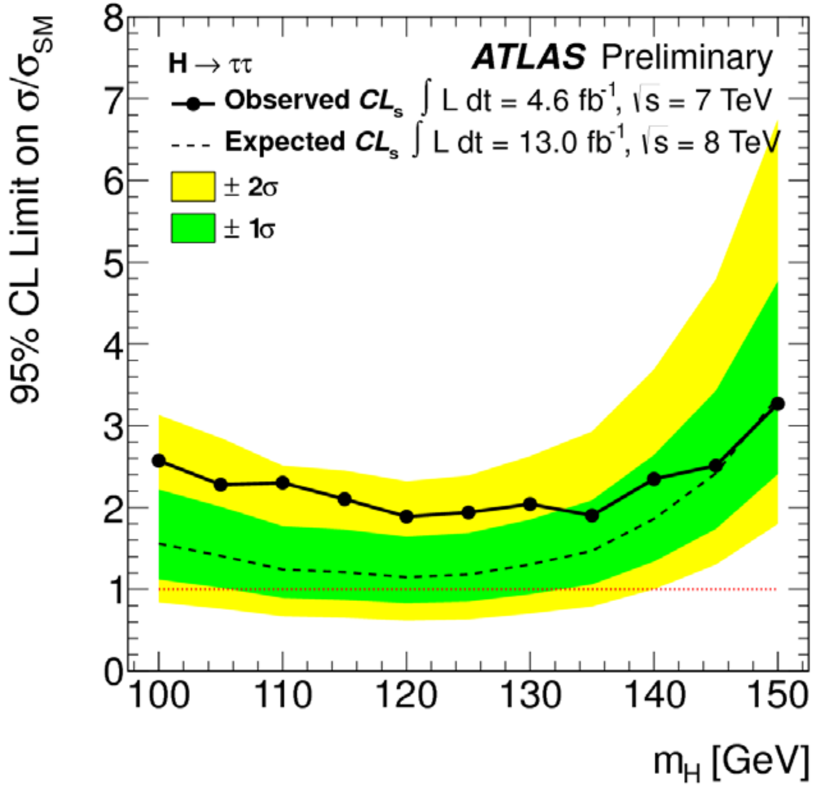


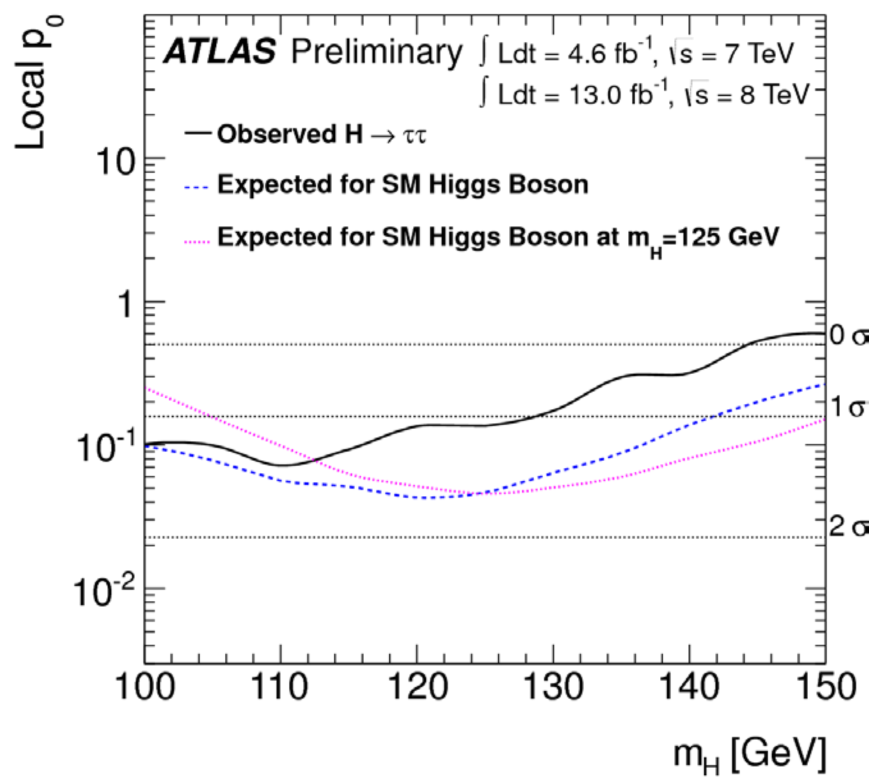
H→ττ: Results

Combined results from all searches at m_H=125 GeV:

95% CL limits: 1.9 x SM observed and 1.2 x SM expected

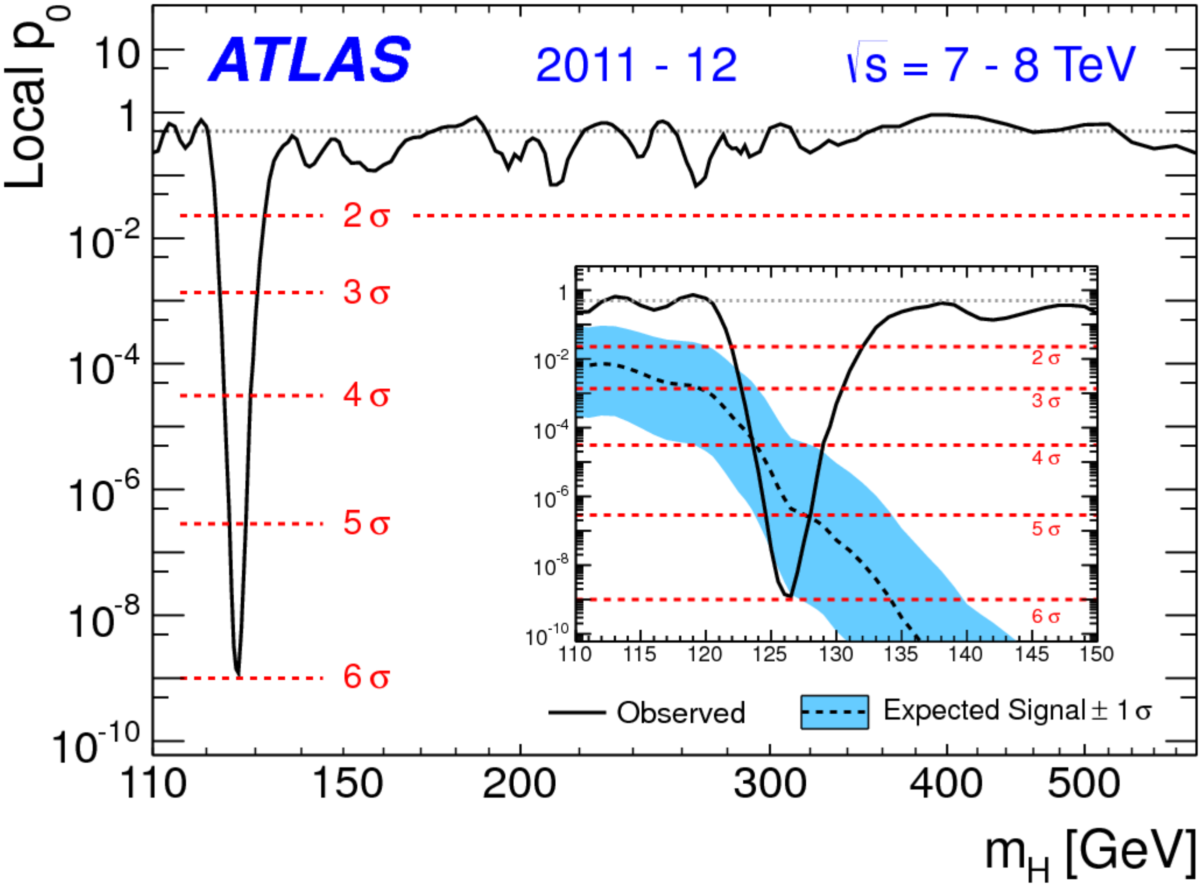
Significances: 1.1σ observed and 1.7σ expected





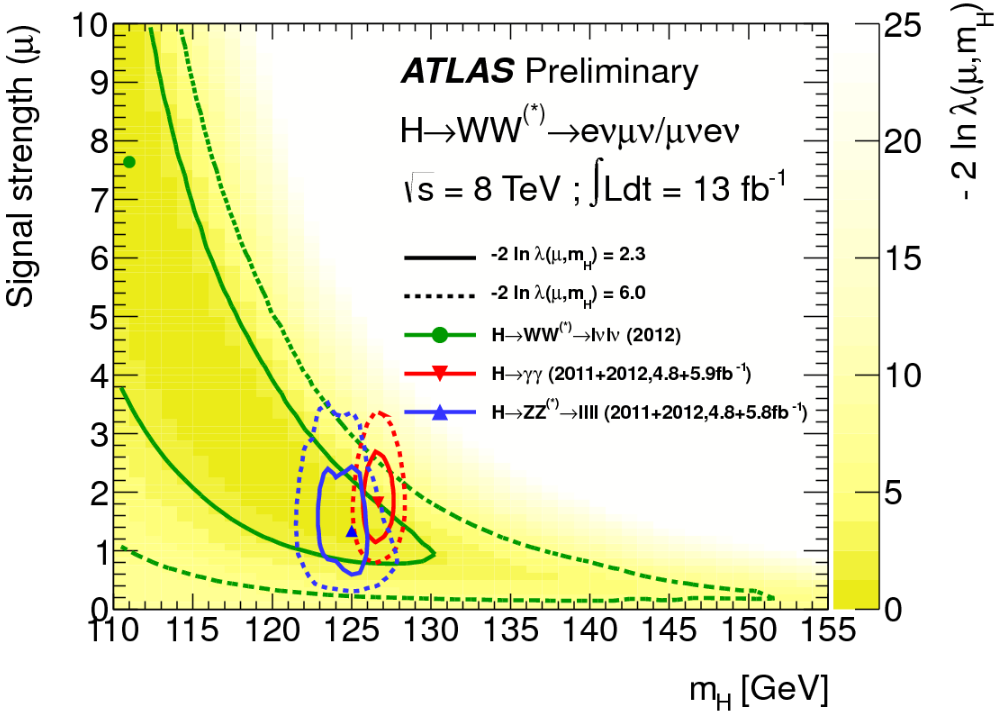
A small overall excess with a best fit signal strength μ=0.7±0.7

Combination



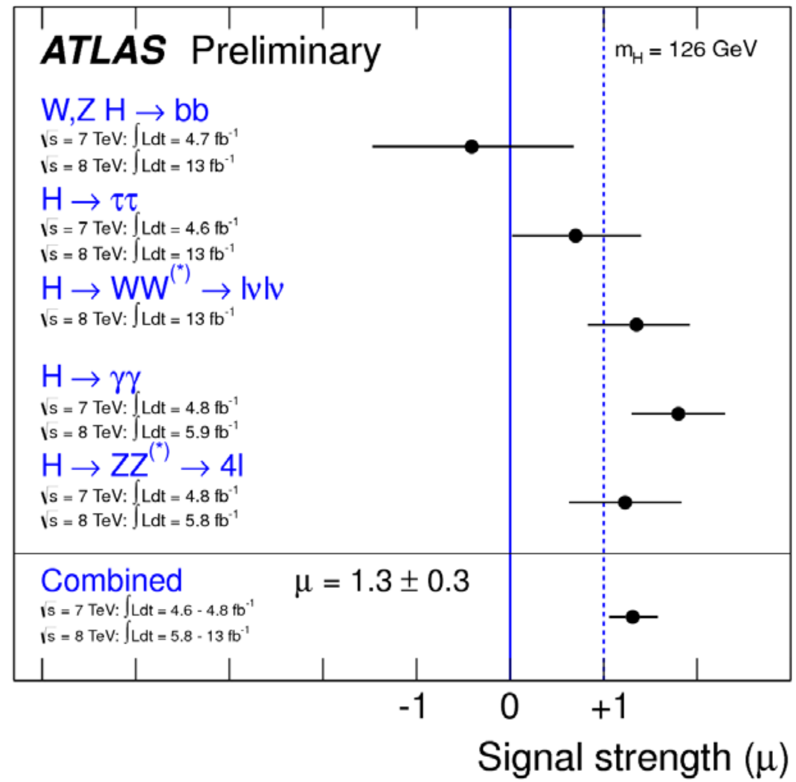
Moving beyond p-value and significances…

Mass and Signal Strength



The overall signal strength

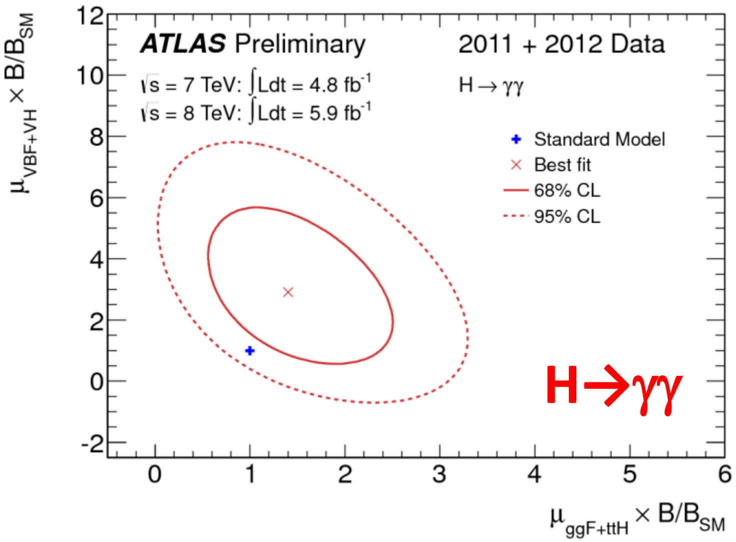
$$\mu = \frac{\sigma \times Br}{\left(\sigma \times Br\right)_{SM}} = 1.3 \pm 0.3$$



$\gamma\gamma$ and 4l dominate the mass measurement

The current best estimate
m = 126.0 ± 0.4(stat) ± 0.4(sys) GeV

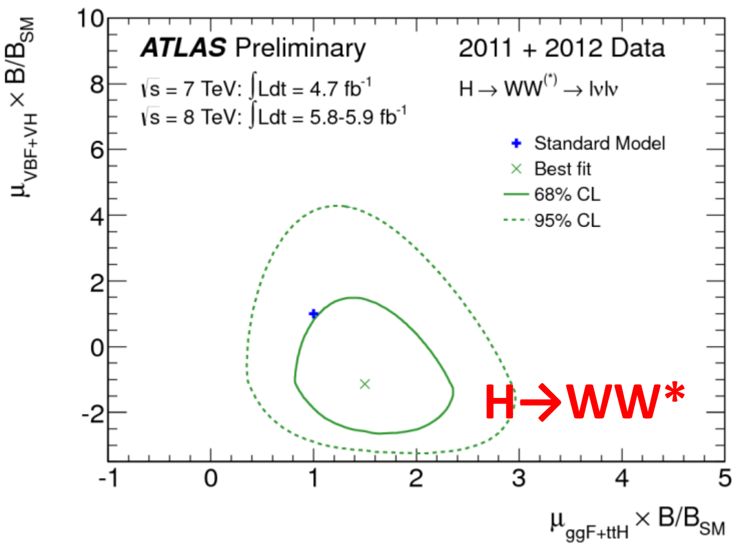
Production Processes

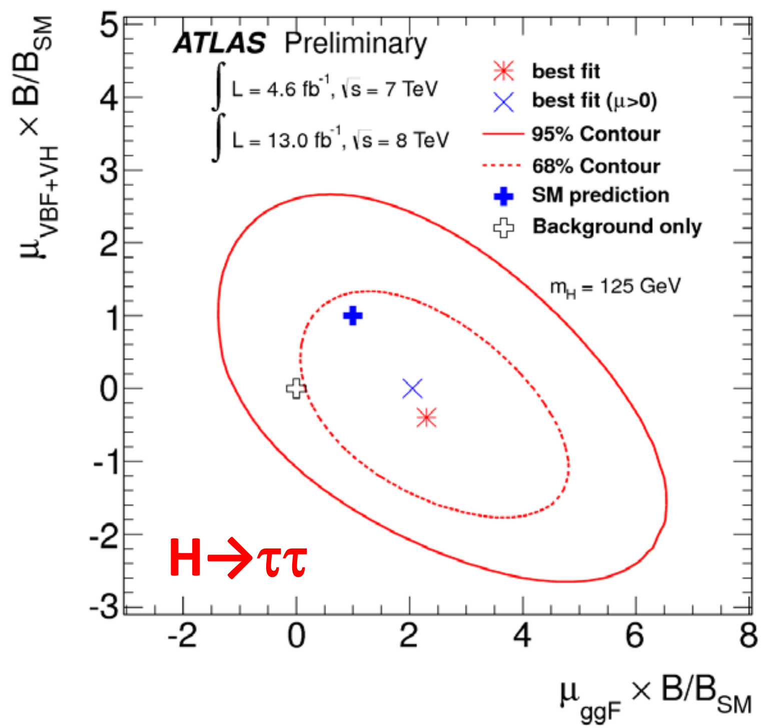


Separate the production processes

- fermion coupling: ggF and ttH;
- vector boson couplings: VBF & VH

consistent with SM within 1-2 sigma, but precision is poor…





Coupling Fits

Decompose production and decay as

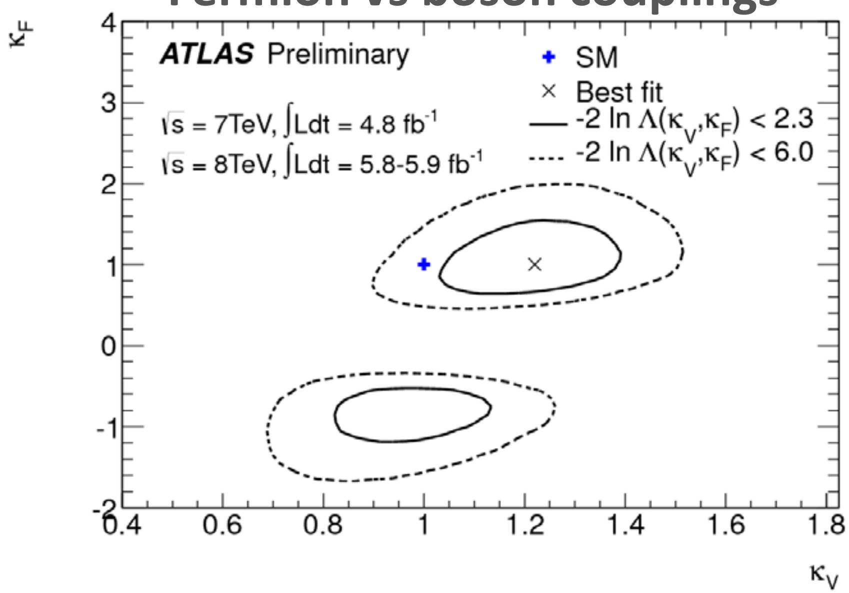
$$\sigma \times BR(ii \rightarrow \mathrm{H} \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

and parametrize couplings with rescale factors, for example

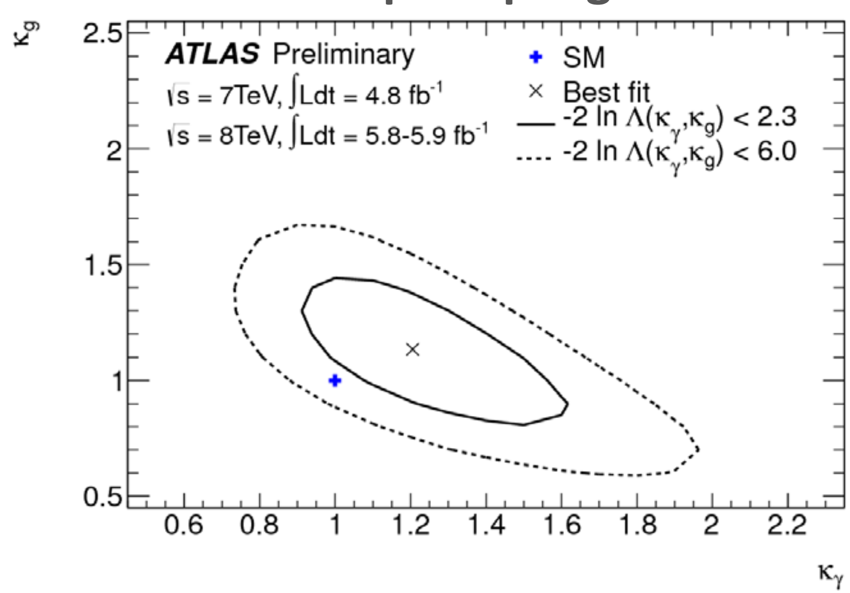
$$(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \rightarrow \mathrm{H} \rightarrow \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(\mathrm{gg} \rightarrow \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

Various assumptions to reduce number of rescale factors

Fermion vs boson couplings



Loop couplings



Summary

Nothing has really changed since summer

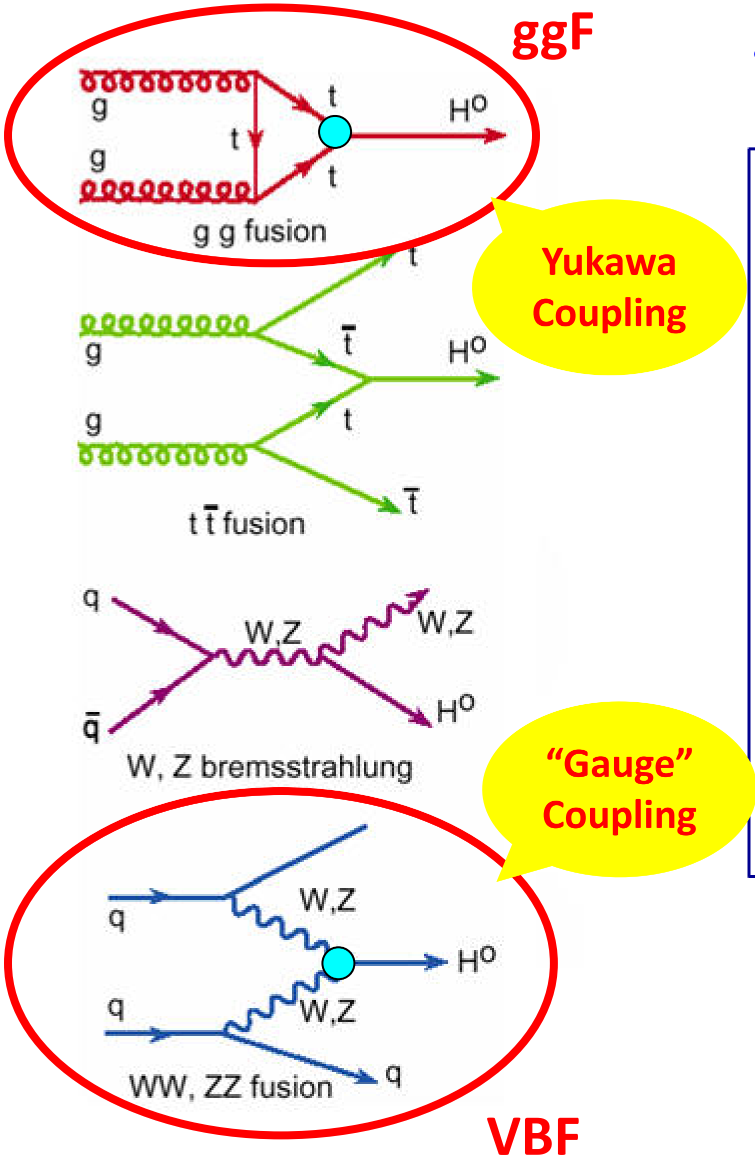
- the discovery is still there;
- still no conclusive results from fermion final states;

Transition from discovery to measurements:

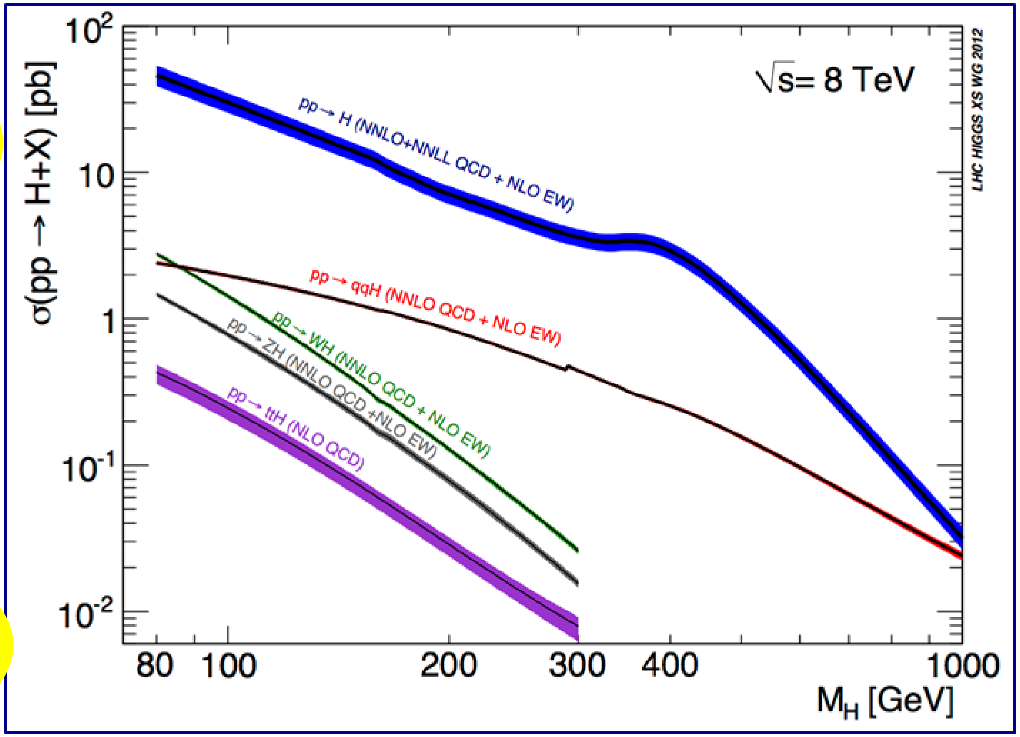
- precision measurements of the mass;
- production cross sections;
- separate production mechanisms;
- spin and CP measurements;
- coupling measurements

A few 2-3 sigma effects here and there, more headache than excitement so far, stay tuned…

Higgs Boson Production



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



$$@125\text{ GeV}: \ \sigma_{ggH} = 19.5 \text{ pb}, \ \sigma_{VBF} = 1.6 \text{ pb},$$

$$\sigma_{WH} = 0.70 \text{ pb}, \ \sigma_{ZH} = 0.39 \text{ pb}, \ \sigma_{ttH} = 0.13 \text{ pb}$$

⇒ ~290k events in 13 fb^{-1} at 8 TeV !

Higgs Boson Decay

To all particles kinematically allowed, but two dominant modes:

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

Neither is ideal for the search and the study of properties

- $b\bar{b}$ by itself suffers from huge QCD backgrounds
- WW: easy identification in dilepton mode, complex backgrounds and no full reconstruction

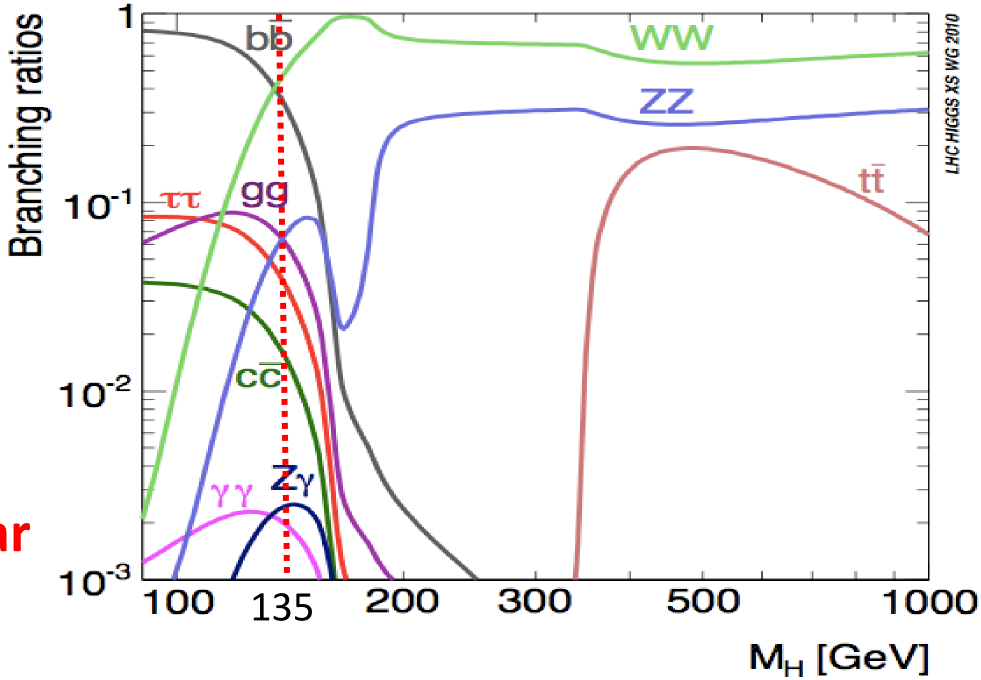
Branching ratios at 125 GeV

$b\bar{b}$:	57.7%
WW:	21.5%
ττ:	6.3%
ZZ:	2.6%
γγ:	0.23%

Difficulty level (least to most):

γγ, ZZ*→4l, WW*→lνlν ⇒ **This seminar**

bb and ττ



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:

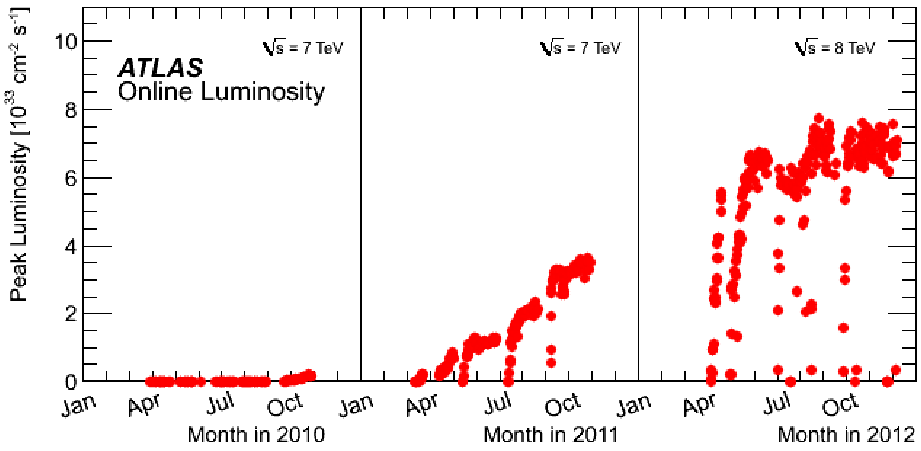
control regions , sidebands, fake leptons, mismeasured ETmiss,…

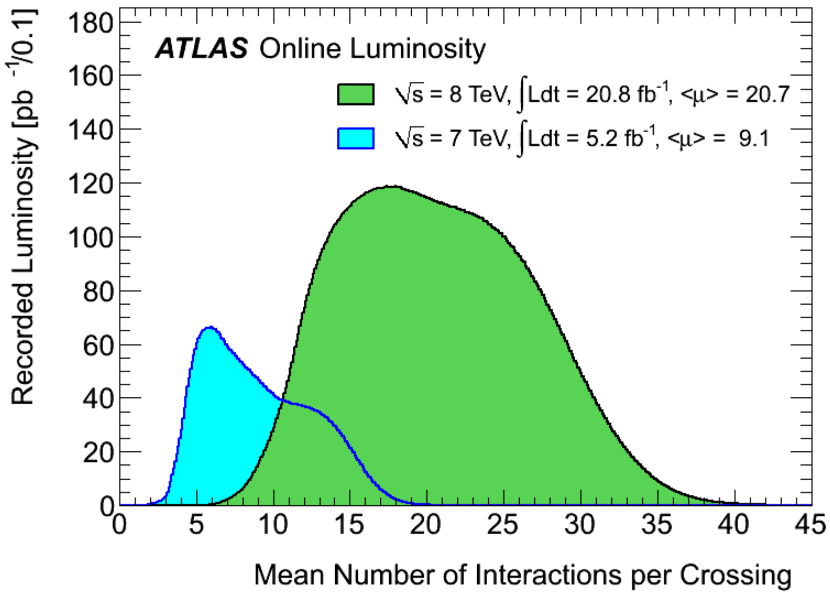
Fit the distributions of the reconstructed Higgs boson (transverse) mass or equivalent to improve sensitivities:

$$m(\gamma\gamma),\ m(4\ell),\ m(b\overline{b}),\ m(\tau\tau),\ m_T(\ell v\ell v),\ m(\ell vqq),\ m_T(\ell\ell vv),\ m(\ell\ell qq)$$

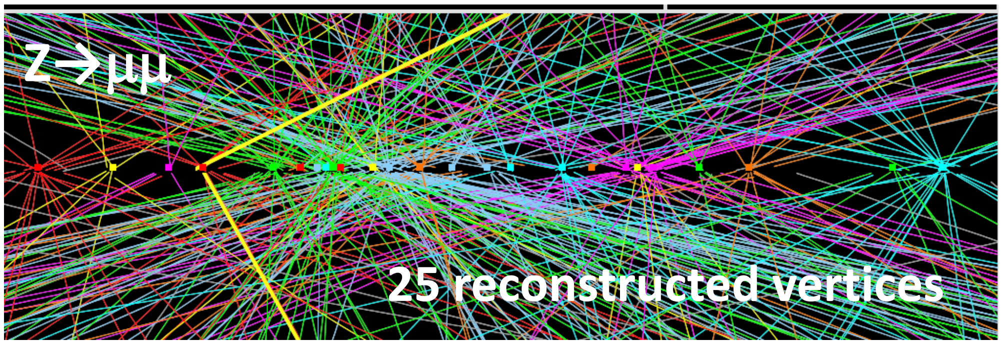
Challenge of High Luminosity

Peak luminosity





Multiple interactions !



Challenging pileup issues:

- Lepton reconstruction and isolation
- Primary vertex identification
- Jet energy and multiplicity
- ETmiss resolution

In particular, understanding ETmiss takes time…

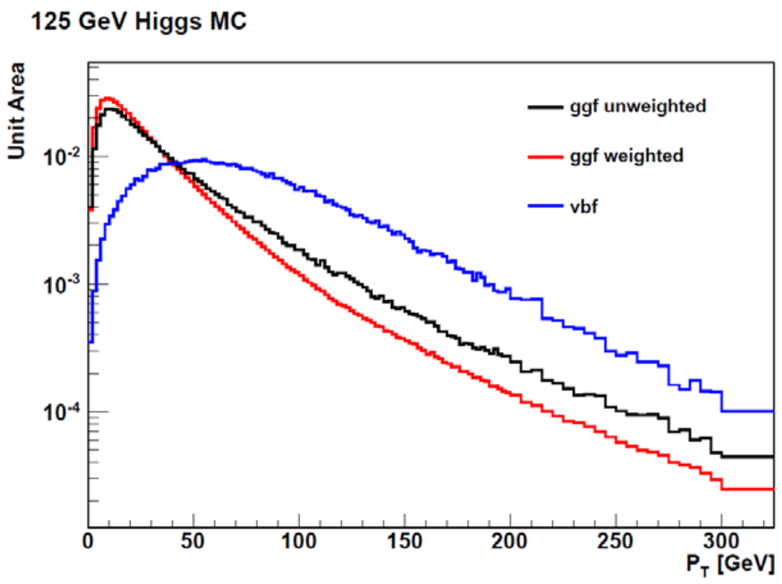
Theory and MC

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.

$H \rightarrow \gamma\gamma$

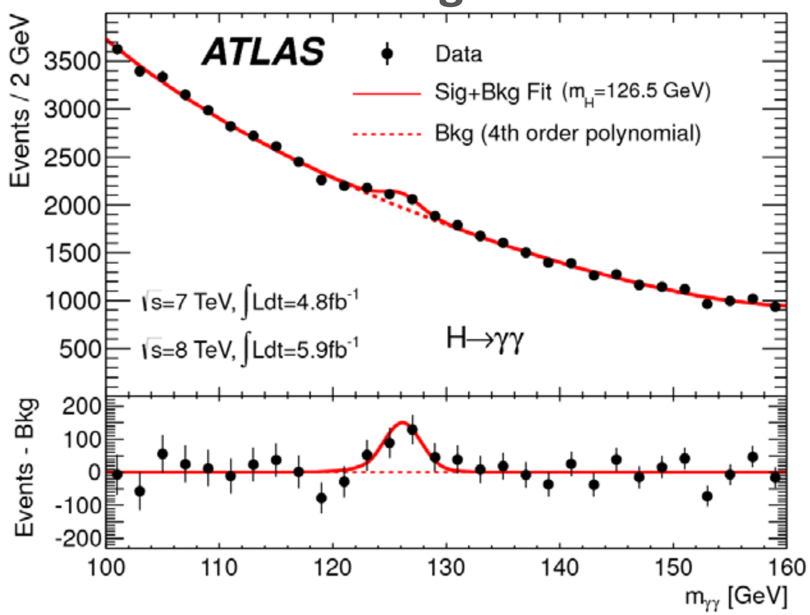
Diphoton mass $m_{\gamma\gamma}$ as the final discriminant variable

$$m^2 = 2E_{\gamma_1}E_{\gamma_2}\left(1 - \cos\Delta\phi_{\gamma\gamma}\right)$$

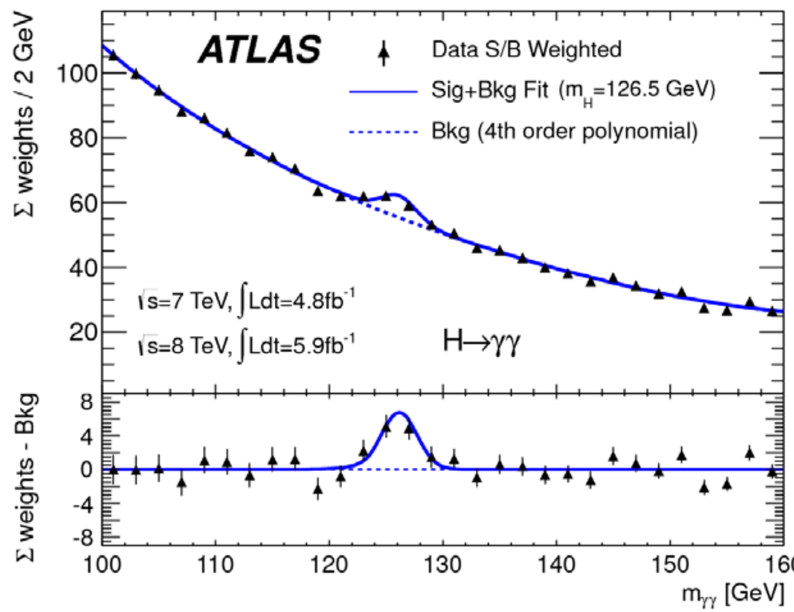
Model signal and background using analytical functions:

- **Signal: Crystal-Ball function (core) + Gaussian (outlier)**
- **Backgrounds: exponentials, polynomials, ...**

Unweighted



Weighted



A total 59059 events selected, expect ~170 signal events at 126 GeV

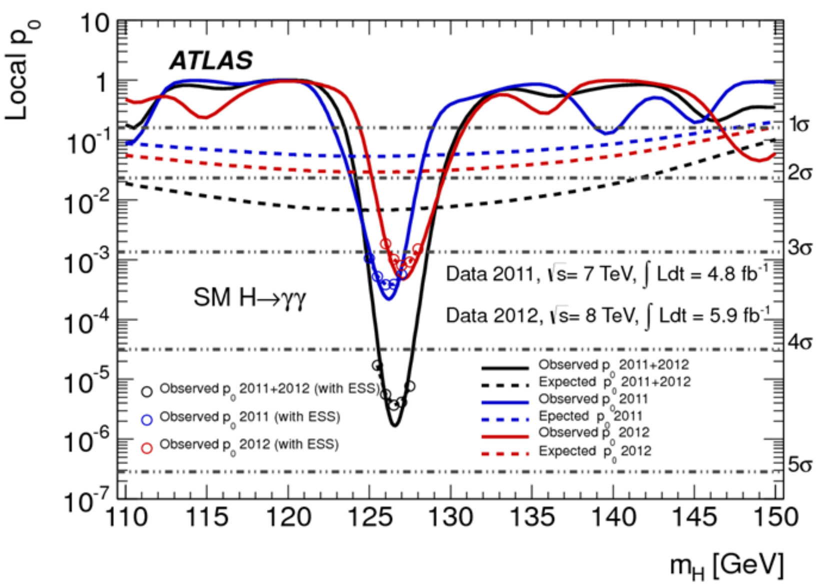
$H \rightarrow \gamma\gamma$

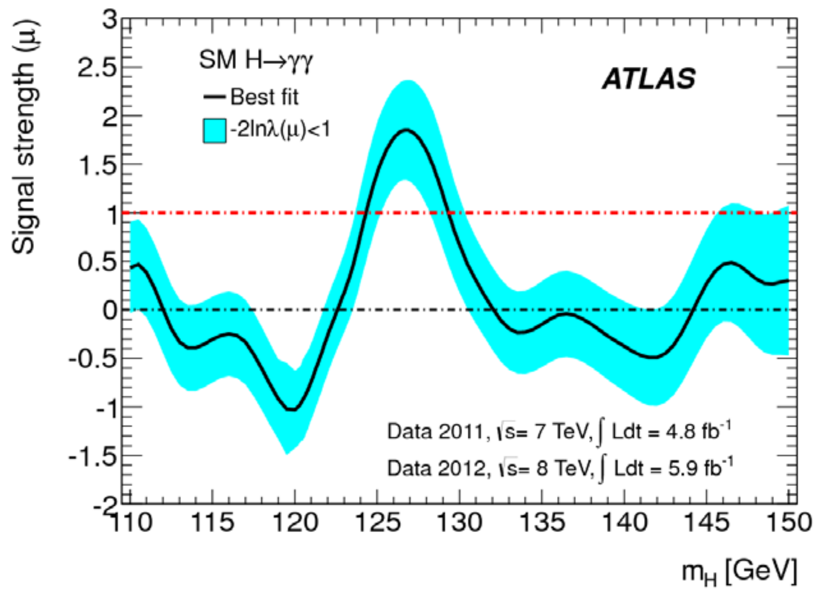
Consistent excesses in both 2011 and 2012 data

Samples	Mass (GeV)	p-value	Obs. Sig.	Exp. Sig.
2011	126	3×10^{-4}	3.4σ	1.6σ
2012	127	5×10^{-4}	3.2σ	1.9σ
Combined	126.5	2×10^{-6}	4.5σ	2.5σ

A minimum p_0 at 126.5 GeV

$$p_0 = 2\times10^{-6} \quad \Rightarrow \quad 4.5\sigma$$

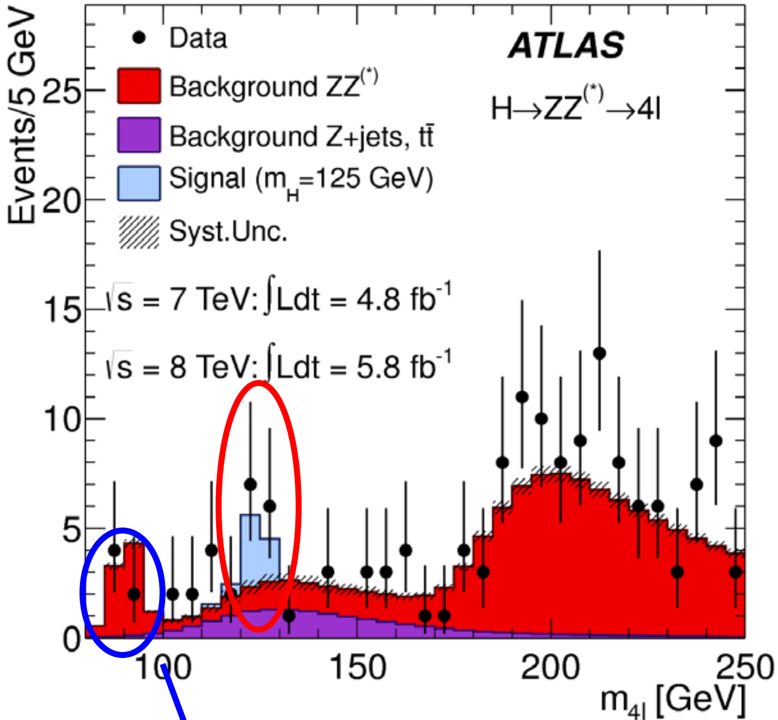


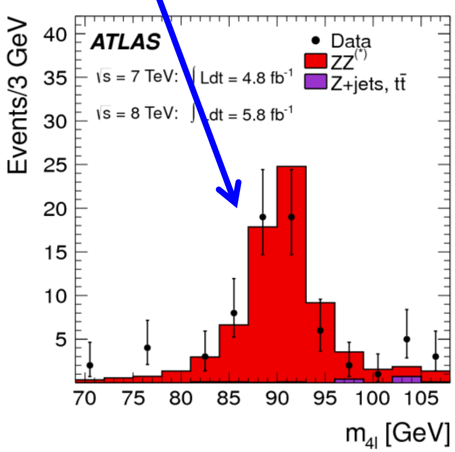


The measured signal strength, the excess relative to the SM expectation, at 126 GeV:

$$\mu = \frac{\sigma \cdot Br}{(\sigma \cdot Br)_{SM}} = 1.8 \pm 0.5$$

H→ZZ*→4l





A small cluster of events populates around 125 GeV

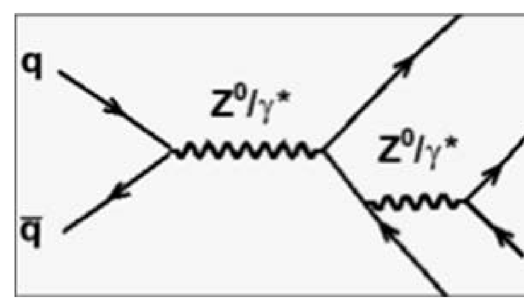
In the region 125 ± 5 GeV

Dataset	2011	2012	2011+2012
Expected B only	2±0.3	3±0.4	5.1±0.8
Expected S m_H=125 GeV	2±0.3	3±0.5	5.3±0.8
Observed in the data	4	9	13

2011+ 2012	4μ	2e2μ	4e
Data	6	5	2
Expected S/B	1.6	1	0.5
Reducible/total background	5%	45%	55%

Single resonant contributions

Enhanced by relaxing mass and pT requirements



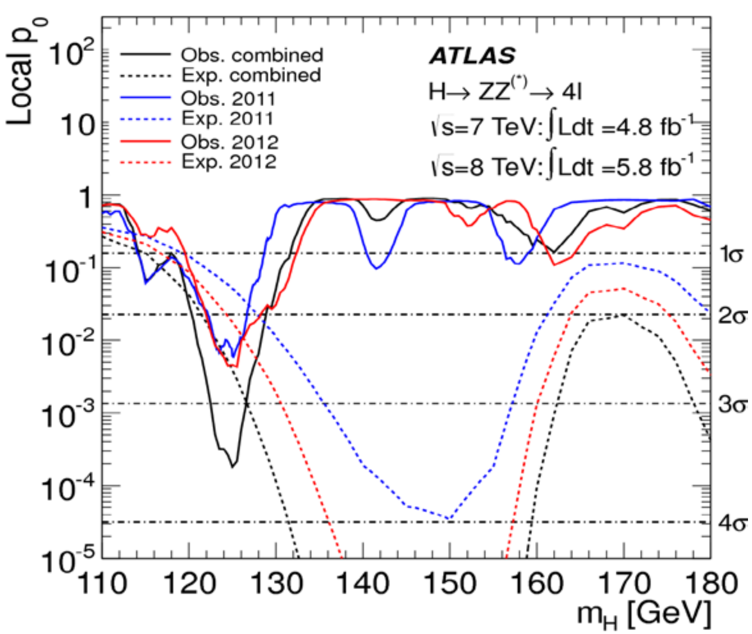
H→ZZ*→4l

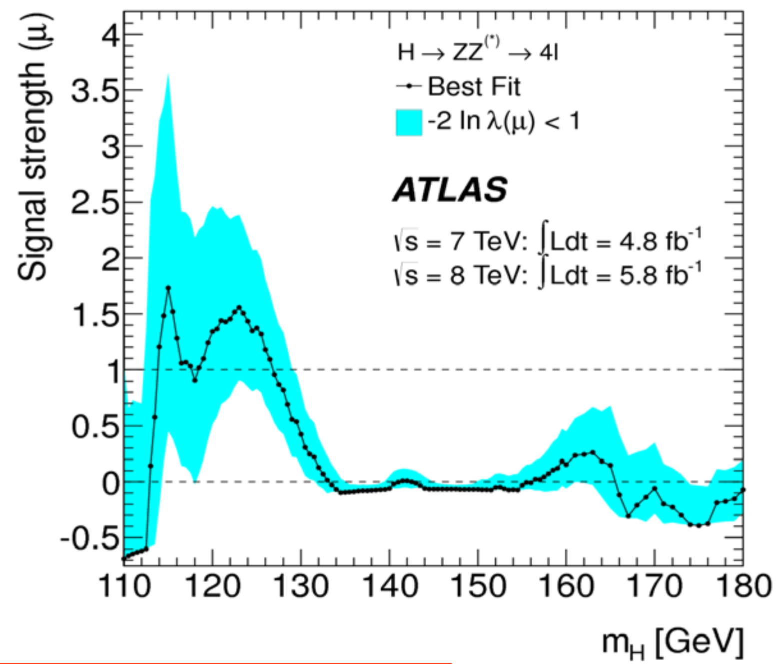
Consistent excesses in both 2011 and 2012 data

Samples	Mass (GeV)	p-value	Obs. Sig.	Exp. Sig.
2011	125	0.6%	2.5σ	1.6σ
2012	125.5	0.5%	2.6σ	2.1σ
Combined	125	0.02%	3.6σ	2.7σ

A minimum p_0 at 125 GeV

$$p_0 = 2\times10^{-4} \Rightarrow 3.6\sigma$$





Signal strength at 126 GeV: μ=1.4 ± 0.6

b-jet Tagging

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

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

- Operating point:
  b-jet efficiency: ~70%
  C-jet rejection: ~5
  light-jet rejection: ~130