Search for the SM Higgs boson in the diboson decay modes with the ATLAS detector

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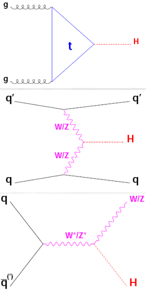
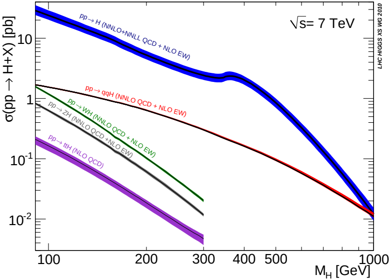
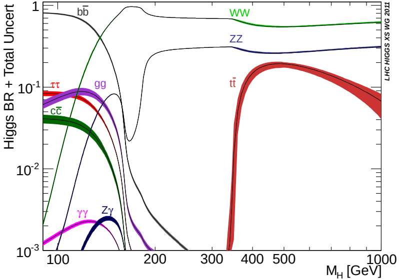
Workshop on discovery physics, Kruger - South Africa
December 4th - 2012

The SM Higgs boson

NNLO, NNLL, EW corrections, uncertainties inclusive & exclusive P_T^H, line-shape, interference, BR, etc... [link]







Trigger and s/b discrimination $\rightarrow$ not easy for **all** channels at hadron colliders.

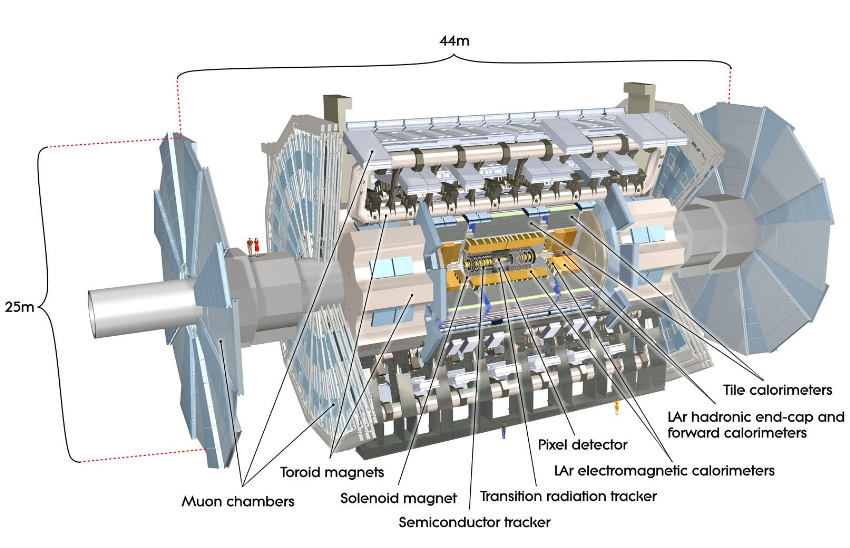
In the mass region below $\sim$150 GeV:

- $\gamma\gamma$ (great resolution but large backgrounds)
- ZZ (Small backgrounds, but statistically limited)
- WW (good s/b, but virtually no resolution)
- $b\bar{b}$, $\tau\tau$ (reviewed by A. Farilla)

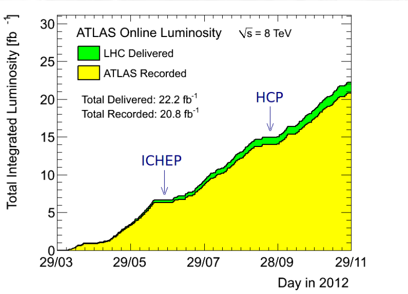
for a m_H of, let's say 125 GeV:

$\sqrt{s}$ [TeV]	7	8
$\sigma_{pp\rightarrow H}$ [pb]	17.5	22.3
σ_{ggF} [pb]	15.3	19.5
σ_{VBF} [pb]	1.2	1.6

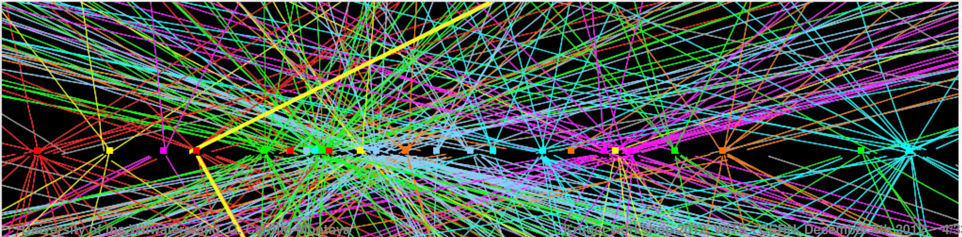
A Toroidal **L**HC **A**pparatu**S** - 4π solid angle



Luminosity → pileup interactions

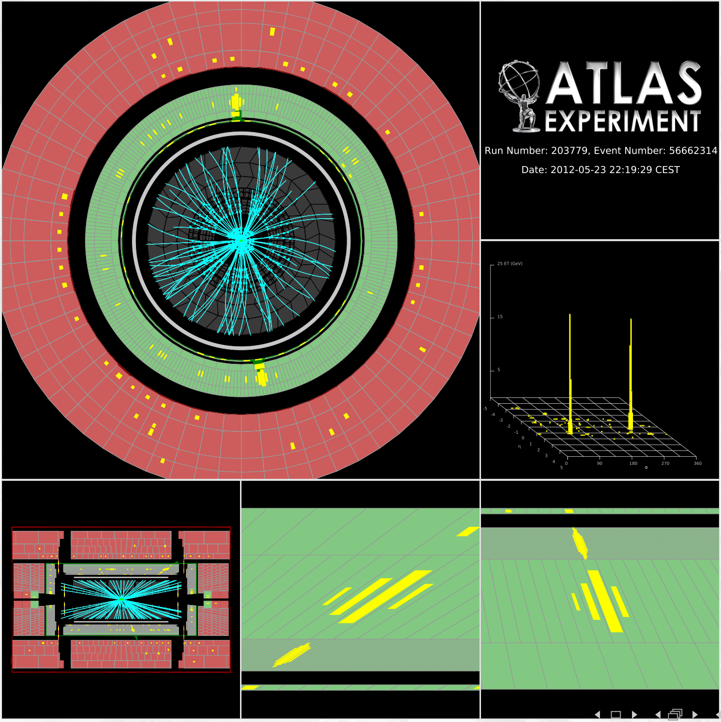


- During 2012, the LHC provided us larger integrated luminosities, still with 50 ns bunch separation:
  - More interactions per bunch crossing.
  - Reconstruction of objects need even robuster methods → performance of physics analysis:
    - Sustain high identification efficiencies and resolution
    - Missing transverse energy under control




HUGS BISON

Content



$\sqrt{s} = 8$ TeV.

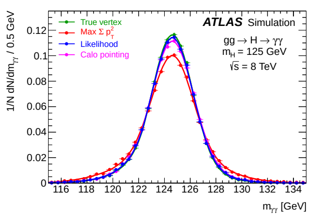
Leading γ:
$E_T = 62.2$ GeV,
$\eta = 0.39$

Subleading γ:
$E_T = 55.5$ GeV
$\eta = 1.18$

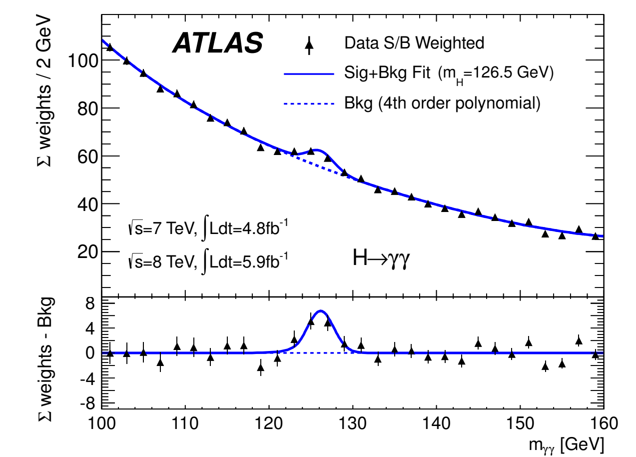
$m_{\gamma\gamma} = 126.9$ GeV.

Only reconstructed tracks with $P_T > 1$ GeV, hits in the pixel and SCT layers and TRT hits with a high threshold are shown.

Strategy



Two well isolated & "tight" identified photons with $E_T > 40(30)$ GeV Leading(Sub-leading)



- **10 categories,** as function of resolution, s/b, production mechanism:
  - Converted/unconverted, η of selected photons, high/low transverse component of the system's trust (P_{Tt}) and 2 jets

Strategy

Large, falling distribution of backgrounds: **$\gamma\gamma$:74%, γ-jet:22%, jet-jet:3% and Drell-Yan:1%**

$\sqrt{s}$	7 TeV		8 TeV		
$\sigma \times B(H \to \gamma\gamma)$ [fb]		39		50	FWHM
Category	N_D	N_S	N_D	N_S	[GeV]
Unconv. central, low p_{Tt}	2054	10.5	2945	14.2	3.4
Unconv. central, high p_{Tt}	97	1.5	173	2.5	3.2
Unconv. rest, low p_{Tt}	7129	21.6	12136	30.9	3.7
Unconv. rest, high p_{Tt}	444	2.8	785	5.2	3.6
Conv. central, low p_{Tt}	1493	6.7	2015	8.9	3.9
Conv. central, high p_{Tt}	77	1.0	113	1.6	3.5
Conv. rest, low p_{Tt}	8313	21.1	11099	26.9	4.5
Conv. rest, high p_{Tt}	501	2.7	706	4.5	3.9
Conv. transition	3591	9.5	5140	12.8	6.1
2-jet	89	2.2	139	3.0	3.7
All categories (inclusive)	23788	79.6	35251	110.5	3.9

Systematic uncertainties:

- Background modelling, object ID, pileup, energy scale, isolation, trigger, luminosity ...
- Theory uncertainties (at 125 GeV): Scale & PDF, underlying event simulation, P_T^H modelling

Documentation:

https://cdsweb.cern.ch/record/1460410/files/ATLAS-CONF-2012-091.pdf

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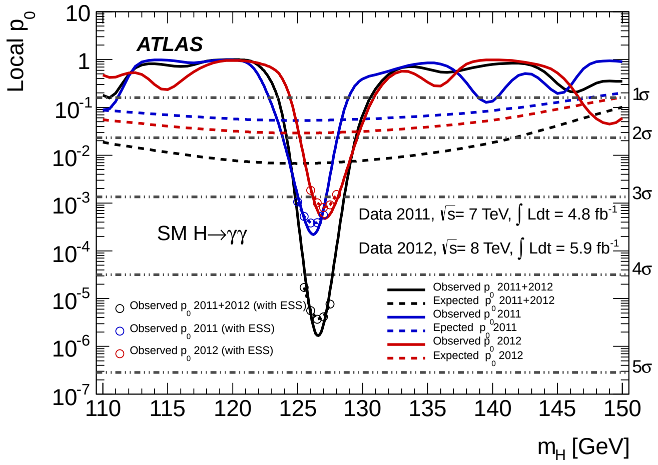
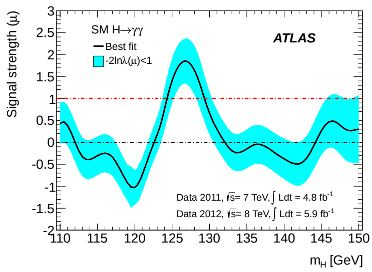
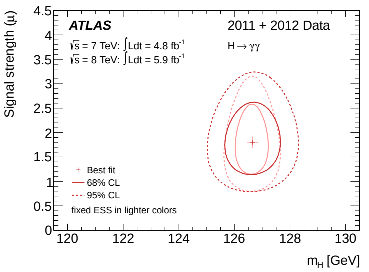
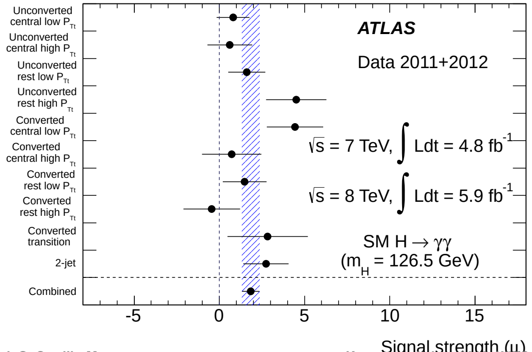
Quantifying the excess, p_0. (against background-only hypothesis)



- Excess (m_H): 126.5 GeV
- Expected (local-significance): 2.5σ
- Observed (local-significance): 4.5σ
- Fitted signal strength: $\hat{\mu}$ =1.8±0.5


SM H→γγ
Best fit
-2lnλ(μ)<1
ATLAS
Data 2011, √s= 7 TeV, ∫ Ldt = 4.8 fb-1
Data 2012, √s= 8 TeV, ∫ Ldt = 5.9 fb-1
Signal strength (μ)
mH [GeV]


ATLAS
2011 + 2012 Data
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.9 fb-1
H→γγ
Best fit
68% CL
95% CL
fixed ESS in lighter colors
Signal strength (μ)
mH [GeV]

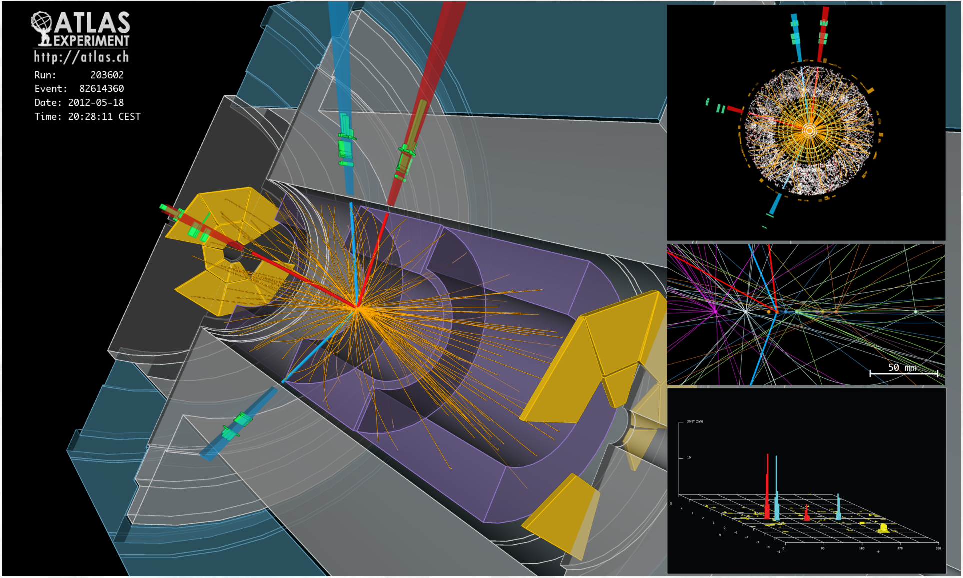

Unconverted central low PTt
Unconverted central high PTt
Unconverted rest low PTt
Unconverted rest high PTt
Converted central low PTt
Converted central high PTt
Converted rest low PTt
Converted rest high PTt
Converted transition
2-jet
Combined
ATLAS
Data 2011+2012
√s = 7 TeV, ∫ Ldt = 4.8 fb-1
√s = 8 TeV, ∫ Ldt = 5.9 fb-1
SM H → γγ
(mH = 126.5 GeV)
Signal strength (μ)

Content

4e candidate. $m_{4\ell} = 124.6$ GeV, $m_{12} = 70.6$ GeV, $m_{34} = 44.7$ GeV.

e_1: $P_T = 24.9$ GeV, $\eta = -0.33$, $\phi = 1.98$ e_2: $P_T = 53.9$ GeV, $\eta = -0.40$, $\phi = 1.69$

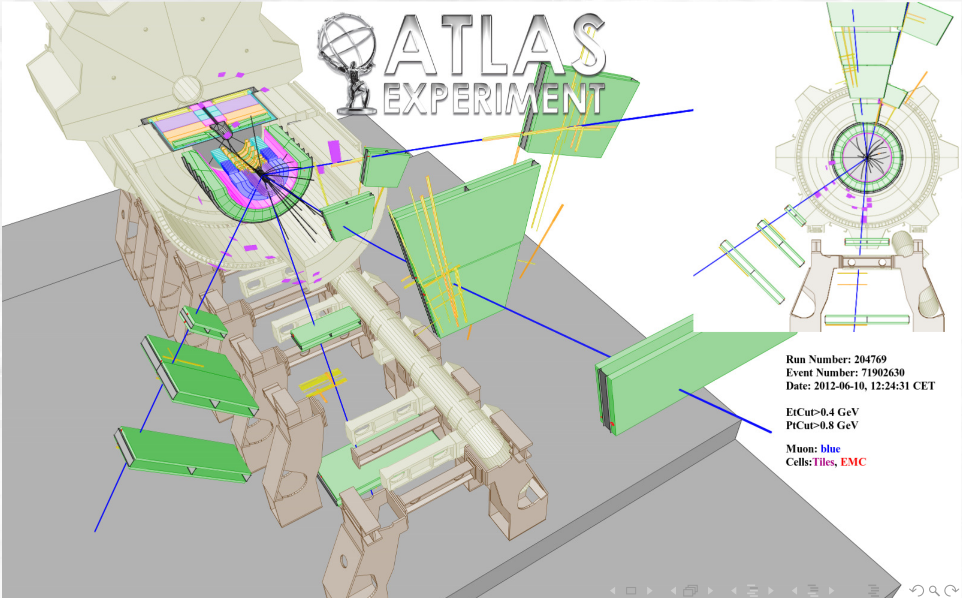
e_3: $P_T = 61.9$ GeV, $\eta = -0.12$, $\phi = 1.45$ e_4: $P_T = 17.8$ GeV, $\eta = -0.51$, $\phi = 2.84$



4μ candidate. $m_{4\ell} = 125.1$ GeV, $m_{12} = 86.3$ GeV, $m_{34} = 31.6$ GeV.

μ_1: $P_T = 36.1$ GeV, $\eta = 1.29$, $\phi = 1.33$ μ_2: $P_T = 47.5$ GeV, $\eta = 0.69$, $\phi = -1.65$

μ_3: $P_T = 26.4$ GeV, $\eta = 0.47$, $\phi = -2.51$ μ_4: $P_T = 71.7$ GeV, $\eta = 1.85$, $\phi = 1.65$

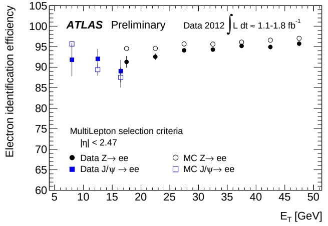


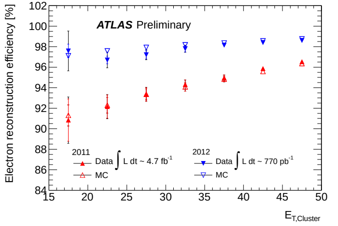
The golden channel - $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$

- 4-lepton (coming from Z decays: same-flavour, opposite charge) $\to$ very good resolution, high reconstruction and trigger efficiencies $\to$ mass peak can be reconstructed
- **Almost background free:** s/b between 0.9 ($4e$) and 1.6 4μ
- Very robust against systematic uncertainties
- Very small yield: signal cross section $\times$ branching ratio ($Z \to \ell\ell \sim 3\%$).
- Low P_T objects needed to maximise signal acceptance

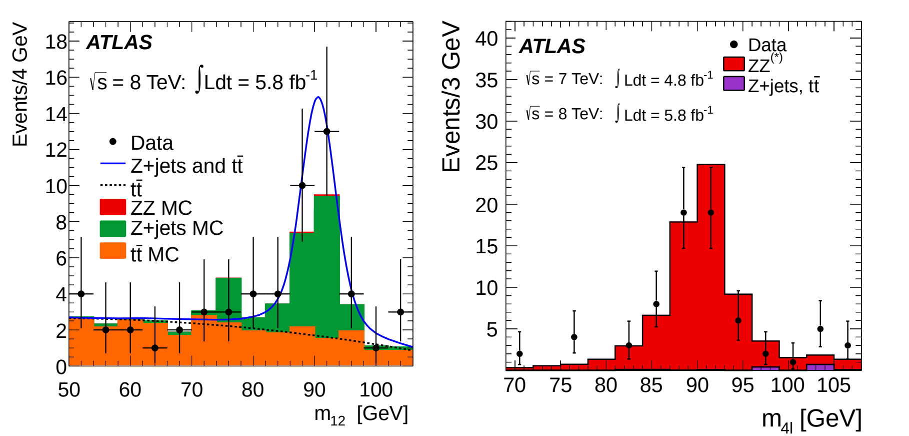
Kinematic requirements:

- Muons:
  $P_T > 6$ GeV,
  $|\eta| < 2.7$
- Electrons:
  $P_T > 7$ GeV,
  $|\eta| < 2.47$





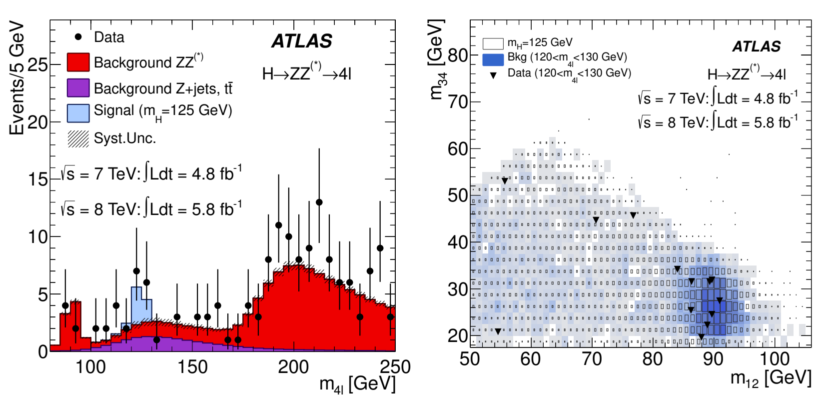
- Various control samples are used to measured contributions of reducible backgrounds (**Z+jets and $t\bar{t}$**), depending on the flavour of the sub-leading pair.
- Irreducible background (**ZZ**), constraint by fit on the full $m_{4\ell}$ range. Cross checked by the single-resonant production peak.



Inverted d_0 requirement for one of the two subleading leptons

Relaxed kinematic cuts

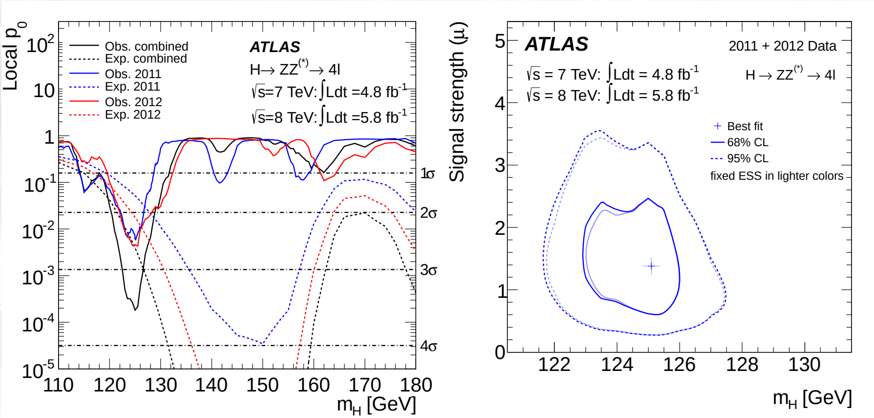
Final expected and observed yields



In a $m_{4\ell}$ window around 120-130 GeV:

	Signal	$ZZ^{(*)}$	$Z+$jets, $t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

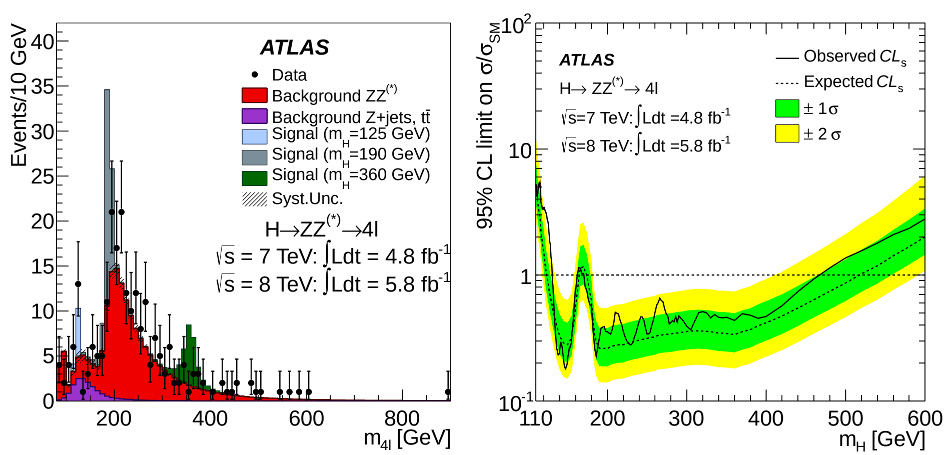
Quantifying the excess, p_0



- Excess (m_H): 125 GeV
- Expected (local-significance): 2.7σ
- Observed (local-significance): 3.6σ
- $\hat{\mu} = 1.2 \pm 0.6$

Exploring large Higgs mass hypotheses

The 4ℓ channel is also very sensitive at high m_H, no excess found:



Documentation:

https://cdsweb.cern.ch/record/1460411/files/ATLAS-CONF-2012-092.pdf

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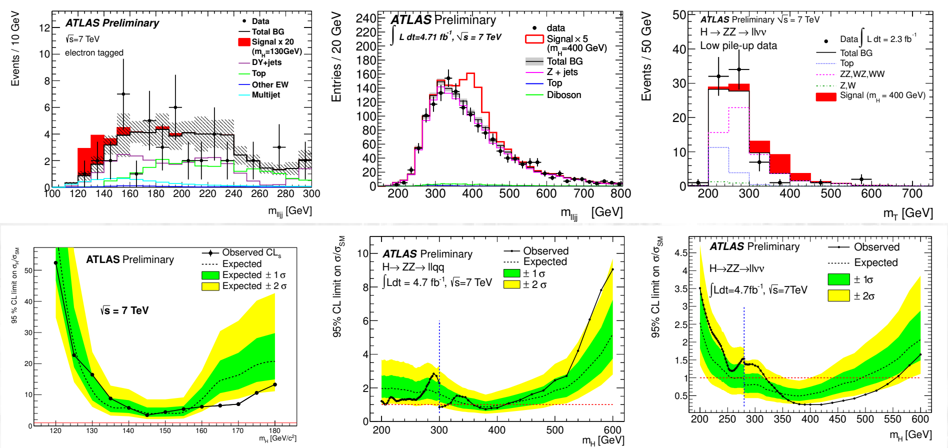
Other ZZ channels:

$H \to ZZ \to \ell^+\ell^- q\bar{q}$ and $H \to ZZ \to \ell^+\ell^- \nu\bar{\nu}$: 4.7 fb^{-1}



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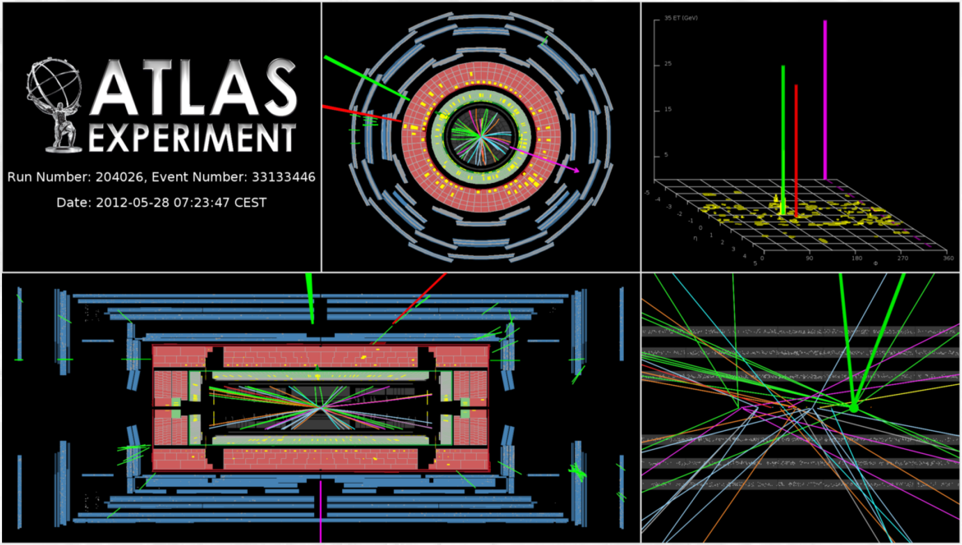
- The $H \to ZZ$ decay allows us to explore a very wide region using many different topologies

Content

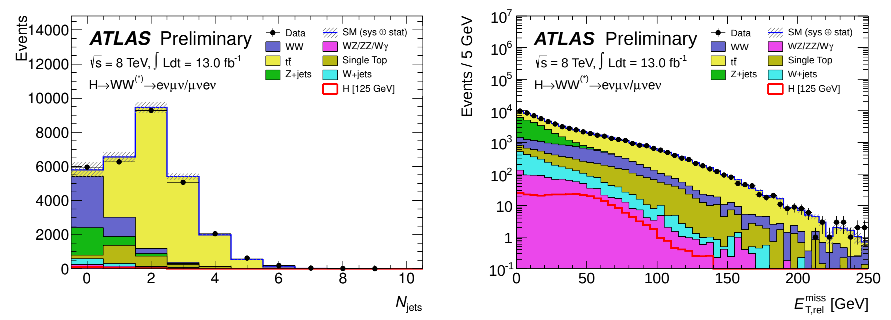
1. $H \rightarrow \gamma\gamma$
2. $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-\ell^+\ell^-$
3. $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$

$\sqrt{s} = 8$ TeV - $e\mu$ - Zero jet - P_T^e =33 GeV and $P_T^\mu = 29$ GeV, $E_T^{miss,rel} = 35$ GeV, $m_T = 94$ GeV.



$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ strategy

- Large backgrounds carrying large systematic uncertainties.
- m_H can't be reconstructed... Quite challenging
- Binned in jet multiplicity $\to$ enhanced sensitivity

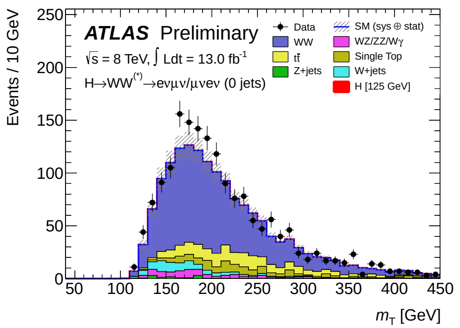


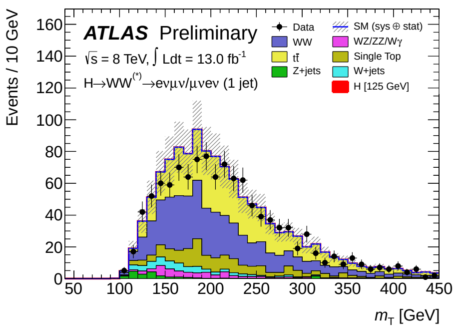
- A complete set of data-driven methods to estimate nearly **ALL** backgrounds from data.

Results presented here: update with **13 fb^{-1} of $\sqrt{s} = 8$ TeV data**, for the opposite flavour, zero and one jet channels

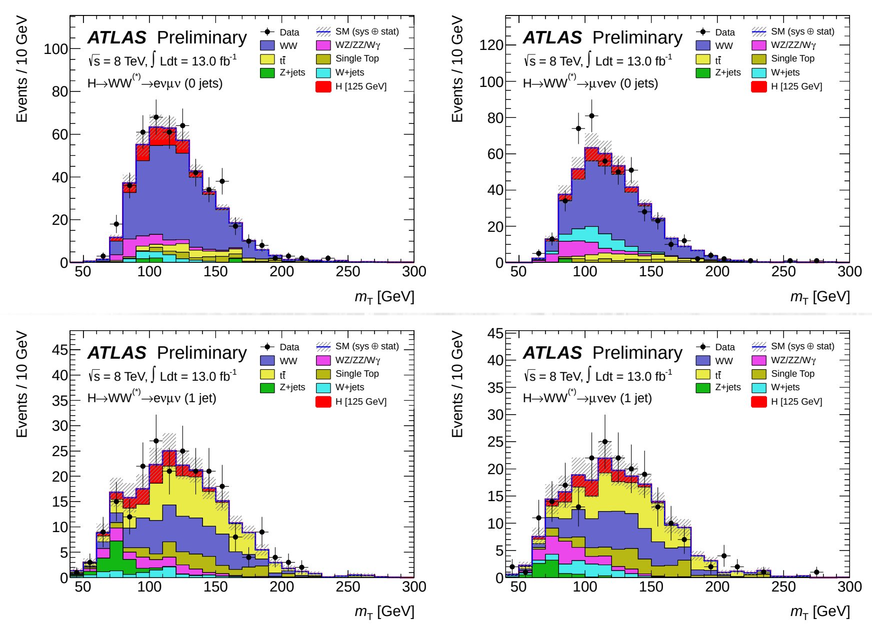
Control regions

- ***W*+jets:** “failed ID” requirement (important when subleading lepton is an electron).
- ***Z*+jets ($\tau\tau$):** large $\Delta\phi(\ell\ell)$ and $m_{\ell\ell} < 80$ GeV.
- **Top:** *b*-jet veto survival probability, or with the presence of a *b*-jet in the one jet bin.
- ***WW*:** no $\Delta\phi(\ell\ell)$ requirement, and large $m_{\ell\ell}$.
  Contributions from *W*+jets and Top are subtracted appropriately from the control regions.

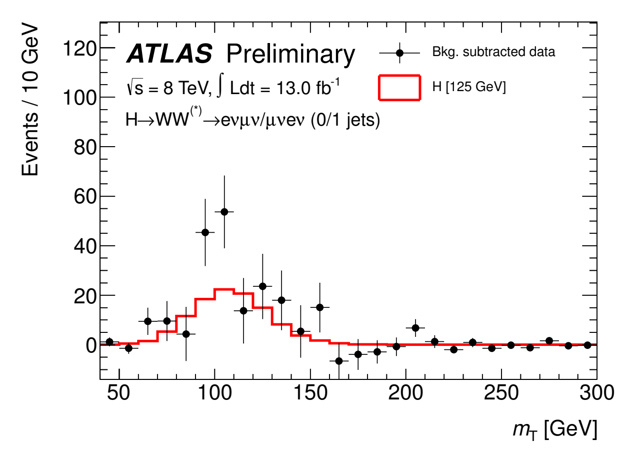




$$H \to \gamma\gamma$$
$$H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$$
$$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$$

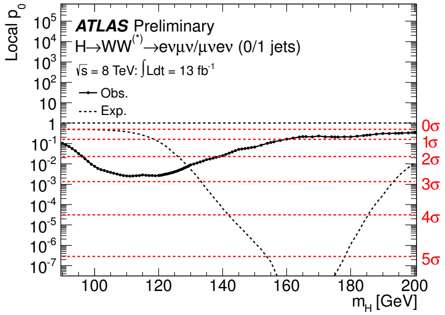


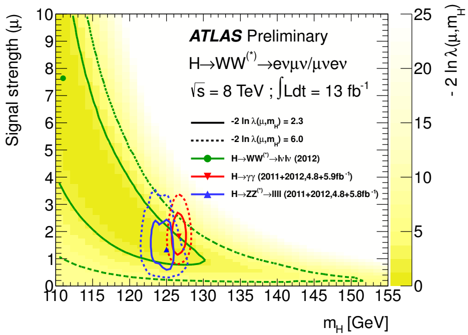
Final expected and observed yields



	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	Single top	Drell-Yan	W+jets	Tot 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

Events in window $0.75m_H < m_T < m_H$





At $m_H = 125$ GeV:

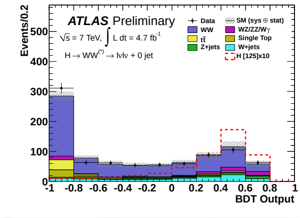
- Expected (local-significance): 1.9σ
- Observed (local-significance): 2.6σ
- $\hat{\mu} = 1.5 \pm 0.6$: ${}^{+0.35}_{-0.33}$(stat)${}^{+0.41}_{-0.27}$(syst theory)${}^{+0.28}_{-0.27}$(syst exp)± 0.05(lumi)

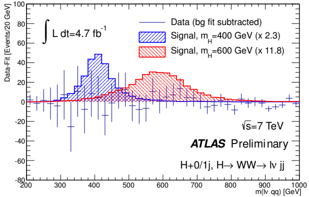
Documentation:

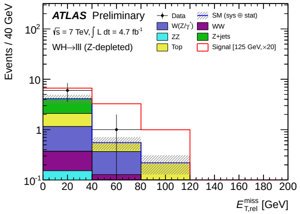
https://cdsweb.cern.ch/record/1493601/files/ATLAS-CONF-2012-158.pdf

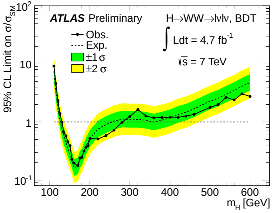
Other WW channels:

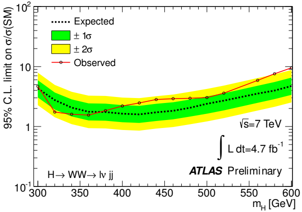
$H \to WW \to \ell\nu\ell\nu$ (BDT), $WH \to WWW$ and $H \to WW \to \ell\nu qq$ (4.7 fb^{-1})

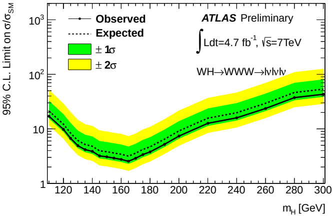












MVA:ATLAS-CONF-2012-060
CutBase:Phys. Lett. B 716 (2012) 62-81

Phys. Lett. B 718 (2012) 391-410

ATLAS-CONF-2012-078

- In ATLAS, also MVA (*WW* dilepton analysis); other production mechanism (*WH*) and *WW* decays $\ell\nu qq$ exploring the high mass region.

Outlook

The search of the SM Higgs boson in the diboson decay channels are presented, the observed excess is consistently present in all of them.

- The $H \to \gamma\gamma$ channel
  using 4.8 fb^{-1} of $\sqrt{s} = 7$ TeV + 5.9 fb^{-1} of $\sqrt{s} = 8$ TeV data: 4.5 σ at 126.5 GeV.
- The $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ channel
  using 4.8 fb^{-1} of $\sqrt{s} = 7$ TeV + 5.8 fb^{-1} of $\sqrt{s} = 8$ TeV data: 3.4 σ at 125 GeV.
- The $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ channel
  using 13.0 fb^{-1} of $\sqrt{s} = 8$ TeV data: 2.6 σ at 125 GeV.

The discovery phase of the LHC is just starting, it simply is the beginning:

- A **Higgs-like boson** was discovered, now we have to characterise it
  The diboson decays are powerful tools to discriminate Spin/CP states and to measure Higgs couplings.
- Higgs searches will continue. With the current dataset, ATLAS, with the *WW* and *ZZ* modes, can explore larger Higgs masses, up $\sim$1 TeV. This is as important as measuring the properties of the one found in the low mass.

THANK YOU ...

BACKUP SLIDES ...

Signal yields 4ℓ channel

	4μ		$2e2\mu/2\mu2e$		$4e$	
	Low mass	High mass	Low mass	High mass	Low mass	High mass
$\sqrt{s} = 8$ TeV						
Int. Luminosity	5.8 fb^{-1}		5.8 fb^{-1}		5.9 fb^{-1}	
$ZZ^{(*)}$	6.3±0.3	27.3±2.0	3.9±0.2	41.4±3.1	2.9±0.3	17.7±1.4
$Z+$jets, and $t\bar{t}$	0.4±0.2	0.15±0.07	3.9±0.9	1.4±0.3	2.9±0.8	1.0±0.3
Total Background	6.7±0.3	27.4±2.0	7.8 ±1.0	42.8±3.1	5.8±0.8	18.7±1.4
Data	4	34	11	61	7	25
$m_H = 125$ GeV	1.4±0.2		1.7±0.2		0.8±0.1	
$m_H = 150$ GeV	4.5±0.6		5.9±0.8		2.7±0.4	
$m_H = 190$ GeV	8.2±1.0		12.5±1.7		5.3±0.8	
$m_H = 400$ GeV	3.9±0.5		6.6±0.9		2.9±0.4	
$\sqrt{s} = 7$ TeV						
Int. Luminosity	4.8 fb^{-1}		4.8 fb^{-1}		4.9 fb^{-1}	
$ZZ^{(*)}$	4.6±0.2	18.6±1.3	2.4±0.2	28.0±2.1	1.4±0.1	10.5±0.8
$Z+$jets, and $t\bar{t}$	0.2±0.1	0.07±0.03	2.1±0.5	0.7±0.2	2.3±0.6	0.8±0.2
Total Background	4.8±0.2	18.6±1.3	4.5±0.5	28.7±2.0	3.6±0.6	11.3±0.9
Data	8	25	5	28	4	18
$m_H = 125$ GeV	1.0±0.1		1.0±0.2		0.4±0.1	
$m_H = 150$ GeV	3.0±0.4		3.4±0.5		1.4±0.2	
$m_H = 190$ GeV	5.1±0.7		7.4±1.1		2.8±0.4	
$m_H = 400$ GeV	2.3±0.3		3.8±0.6		1.6±0.3	

Low/High mass threshold at 160 GeV

Signal injection $p0$ plot, $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$