Overview of Higgs Results from ATLAS

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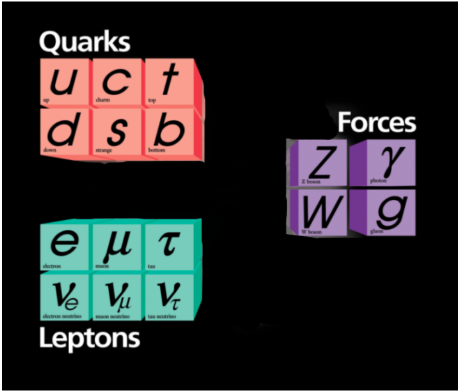
17th December 2012

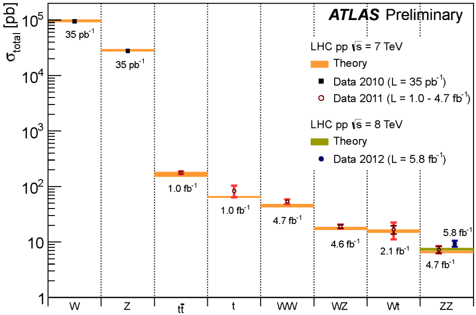
Outline

1. Motivation
   - Standard Model
2. ATLAS
   - Detector
   - Search Channels
3. Analyses and Latest Results
   - $H \to b\bar{b}$
   - $H \to \tau\tau$
   - $H \to WW$
   - $H \to \gamma\gamma$
   - $H \to ZZ^* \to 4l$
4. Combination

Outline



- Highly predictive theory.
- Survived experimental tests to exceptional precision.



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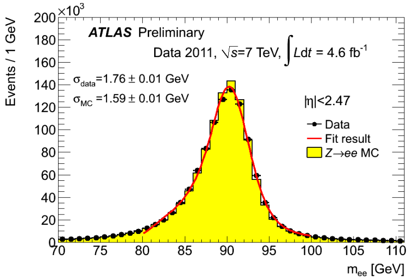
- Massive W/Z vector bosons.
- So electroweak symmetry is broken while satisfying relativity and gauge-invariance.
- Mechanism from Brout & Englert, Higgs, Guralnik, Hagen & Kibble.



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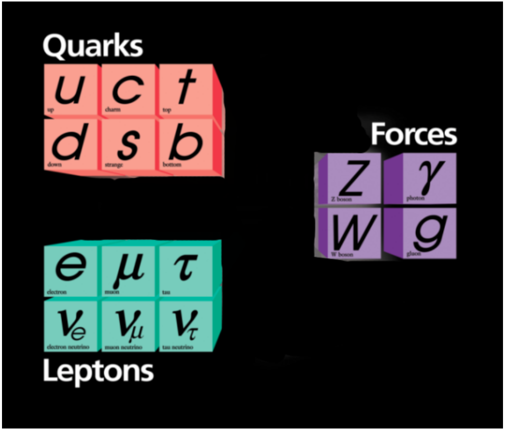

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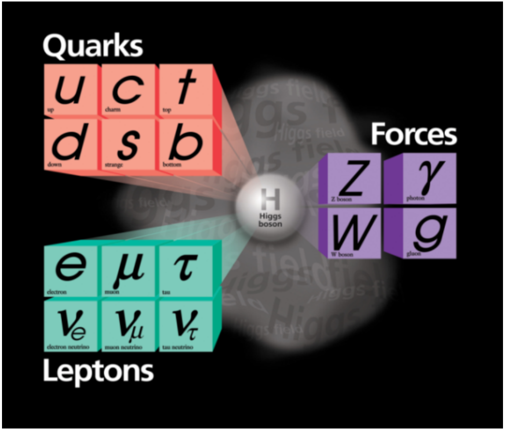
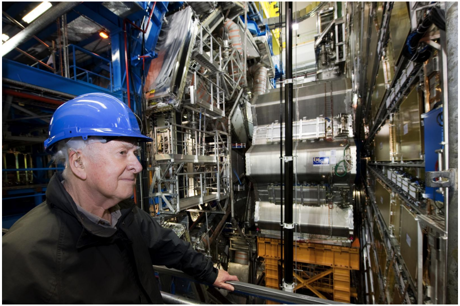
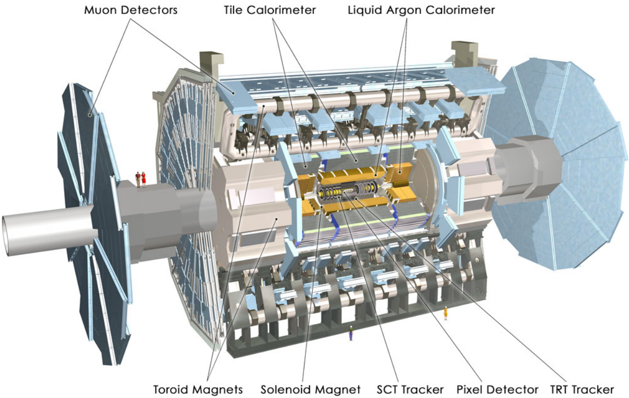


Mass not predicted.
For nearly 40 years it proved elusive.

Outline



ATLAS Detector



Inner tacking detector:

- Silicon pixels and strips (SCT)
- Straw-tube transistion radiation tracker (TRT)
- 2T superconducting solenoid

Calorimeter:

- EM: Liquid Argon (LAr) in barrel and endcap
- Hadronic: iron scintillator / tile calorimeter for central, LAr for end cap
- Forward LAr calorimeter for both EM and hadronic.

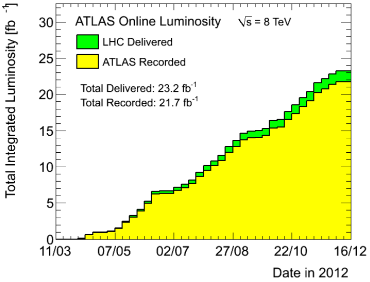
Muon spectrometer

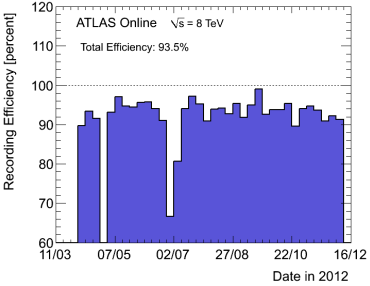
- 3 superconducting magnets for toriodal field with tracking chambers

Precise lepton, photon measurements. Jets, E_T^{miss} over full $|\eta| < 4.9$

Data

- Proton-Proton run ends today!
- Heavy-Ion run then long shutdown (LS1)
- So this is all we get for a while:
  - 23.2 fb^{-1} delivered in 2012
  - $>$ 90% recording efficiency
- Most of these analyses with "HCP" dataset:
  4.7-4.9 fb^{-1} $\sqrt{s} = 7$ TeV, 2011
  + 13.0 fb^{-1} $\sqrt{s} = 8$ TeV, 2012





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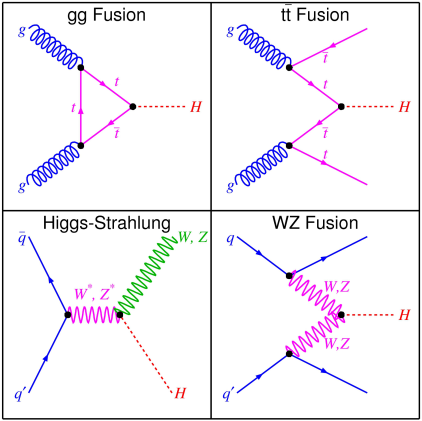
4. Combination

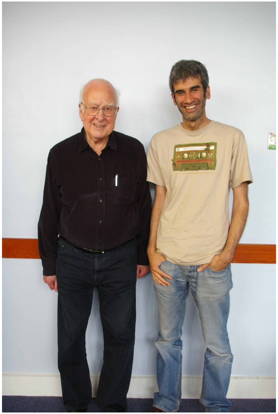
Higgs Production

- Gluon fusion
- Vector Boson Fusion
- Associated production with W or Z : Higgs-strahlung
- Associated production with tt - used for gamma gamma and bb



Higgs Production

- Gluon fusion
- Vector Boson Fusion
- Associated production with W or Z : Higgs-strahlung
- Associated production with tt - used for gamma gamma and bb
- Associated Higgs-Bhimji production (small x-sec)



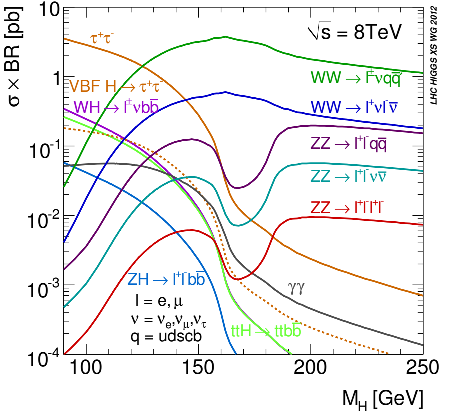
Higgs Decay Channels Explored

High-sensitivity channels, first observations:

- $\gamma\gamma$: Excellent mass resolution
- $ZZ^{(*)}(\rightarrow llll)$: Cleanest background seperation
- $WW^{(*)}(\rightarrow l\nu l\nu)$: Sensitive but poorer mass resolution

Lower-sensitivity channels, important for fermion couplings:

- $b\bar{b}$: Only associated production
- $\tau\tau$: Leptonic and Hadronic decay



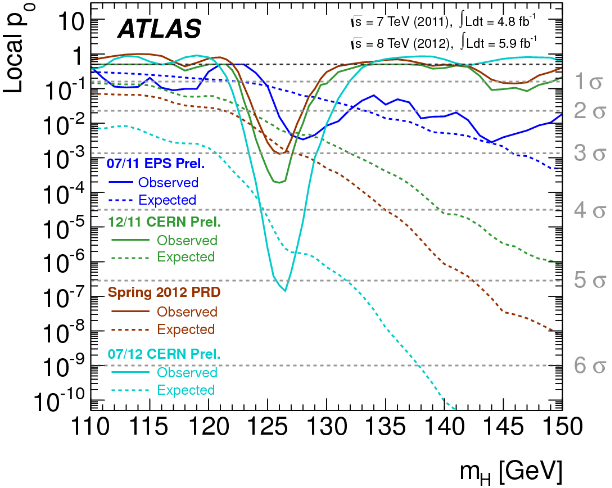
Summary of Analyses Presented Here

Higgs Decay	Channels	$\mathcal{L}$ (fb^{-1}) (2011 + 2012)	Conference Note
$H \to b\bar{b}$	$ZH \to \nu\bar{\nu}H$ $WH \to l\nu H$ + $ZH \to llH$	4.7 + 13.0	ATLAS-CONF-2012-161
	ttH	4.7	ATLAS-CONF-2012-135
$H \to \tau^+\tau^-$	$\tau_{lep}\tau_{lep}$ $\tau_{lep}\tau_{had}$ $\tau_{had}\tau_{had}$	4.7 + 13.0	ATLAS-CONF-2012-160
$H \to WW^{(*)}$	$l\nu l\nu$	13.0	ATLAS-CONF-2012-158
$H \to \gamma\gamma$	-	4.8 + 5.9	ATLAS-CONF-2012-091
NEW	-	4.8 + 13.0	ATLAS-CONF-2012-168
$H \to ZZ^{(*)}$	$llll$	4.8 + 5.8	ATLAS-CONF-2012-092
NEW	$llll$	4.6 + 13.0	ATLAS-CONF-2012-169

- July Combination Paper: Phys. Lett. B 716 (2012) 1-29
- Updated Combination for HCP: ATLAS-CONF-2012-162
- NEW Combination: ATLAS-CONF-2012-170

Higgsists! Combined ATLAS Higgs results Jul '12

- July 4 2012



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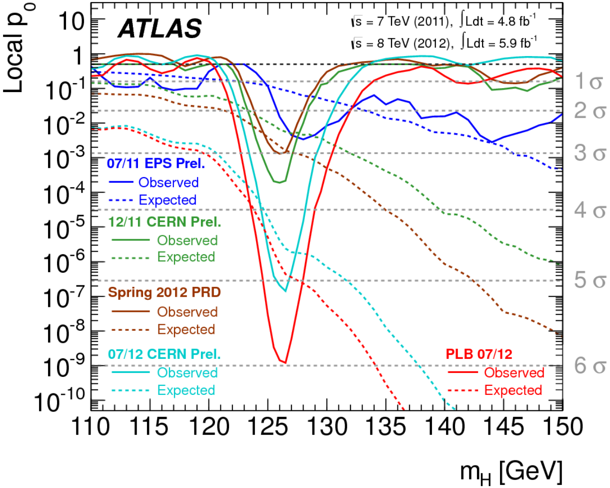
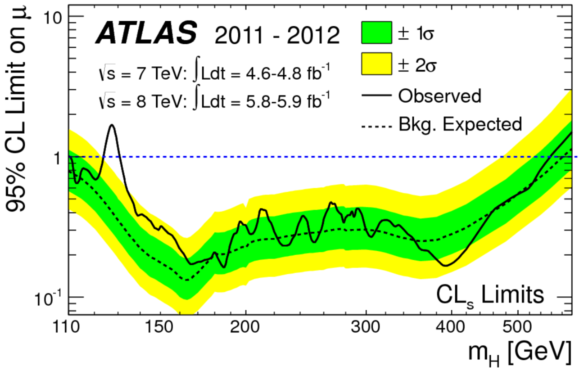


Higgsists! Combined ATLAS Higgs results Jul ’12

μ= Signal Strength = Ratio of measured yield to SM expectation

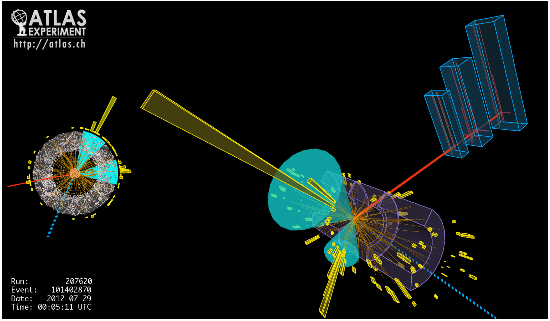
Today’s focus:

- Low mass
- Results since July $\tau\tau$, *bb* channels
- Updates measuring properties: mass, spin.



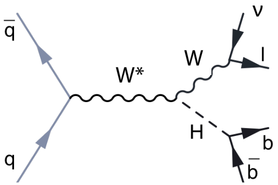
Statistical procedures link

Outline


ATLAS EXPERIMENT
http://atlas.ch
Run: 207620
Event: 101402870
Date: 2012-07-29
Time: 00:05:11 UTC

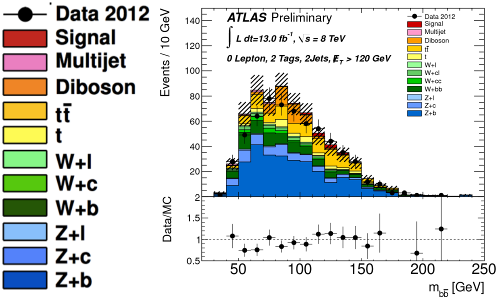
$H \to b\bar{b}$

- Associated production with W or Z to reduce backgrounds.
- Catagorised by number of (charged) leptons ($N_l, l = e, \mu$):
  - Two (llbb), one (lνbb) or zero ($\nu\nu$bb)
  - Common lepton selection

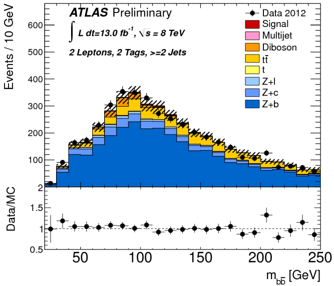


- Further categorised by regions in $p_{T_{W/Z}}$ or E_T^{miss}:
  - 0-lepton: E_T^{miss} [120-160] [160-200] [>200] GeV x (2 or 3 jets)
  - 1, 2-lepton: $p_{T_{W/Z}}$ [0-50][50-100][100-150][150-200] [>200] GeV
- Require 2 jets to be b-tagged (70% efficiency).
- Mass resolution improved by adding the energy from muons within the jet to the total jet energy.
- Experimental systematic uncertainties mainly b-tagging and jet energy (see backup slides for full table).

$H \to b\bar{b}$ backgrounds: Inclusive mass distributions

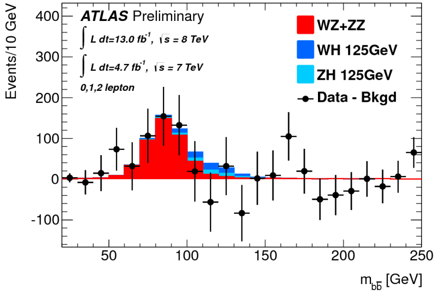


- Dominant: Z+jets W +jets, Top.
- Background shapes from MC, normalisation from data control regions: Relax b-tagging (W/Z + jets) or *nJet* or m_{ll} and E_T^{miss} (top).
- Diboson from MC,Multijet from data
- Signal $m_H = 125$ GeV



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

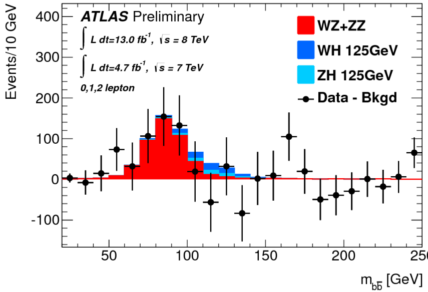
Background subtracted distribution

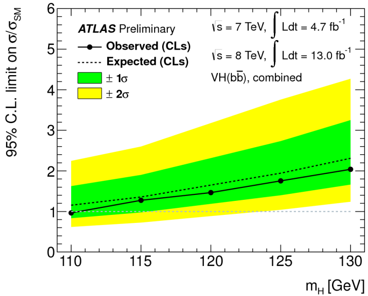


- Clear (4.0σ) di-boson signal extracted as a cross-check:
- $\mu_{(W/Z)Z} = 1.09 \pm 0.20 \pm 0.22$

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

Background subtracted distribution





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For m_H =125 GeV:

- Observed limit 1.8 x SM
- μ (Combined) $= -0.4 \pm 0.7 \pm 0.8$

μ ($\sqrt{s}$=7 TeV) $= -2.7 \pm 1.1 \pm 1.1$

μ ($\sqrt{s}$=8 TeV) $= 1.0 \pm 0.9 \pm 1.1$

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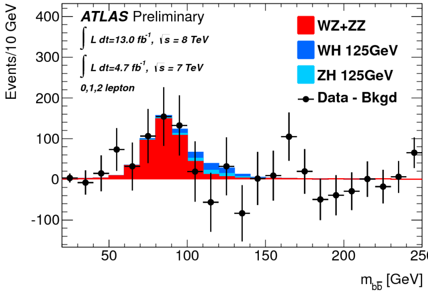

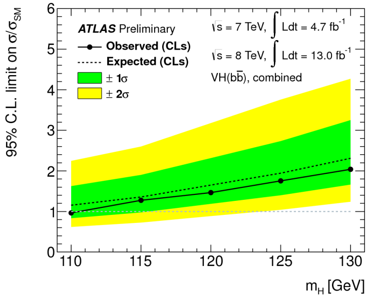

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- $ttH \to bb$ limit at m_H =125 GeV of 13.1 (10.5 expected) with 2011 data

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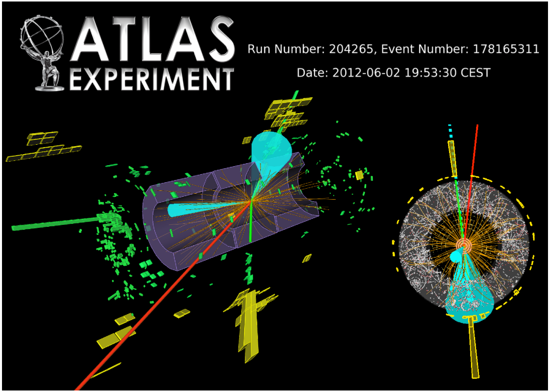


$H \to \tau\tau$

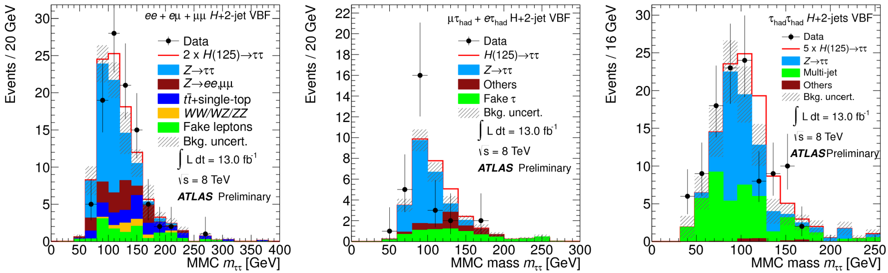
Separate analyses for three different decay modes:

- lep-lep ; lep-had ; had-had: 2, 1 or 0 charged leptons (e, μ)

Further split into categories, applied in sequence:

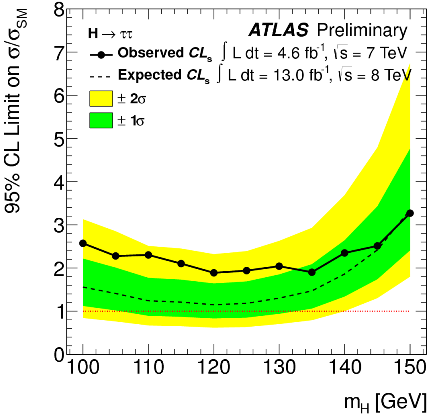
- 2-Jet VBF (lep-lep only); "Boosted" ($p_{T_{jet}} > 30$ GeV, $p_{T_H} > 100$ GeV)
- 2-Jet VH (lep-lep only); 1-jet; 0-jet

Main background: $Z \to \tau\tau$ "Embed" TAUOLA MC τs for μs in data $Z \to \mu\mu$.
Main systematics: Embedding, Tau and Jet Energy Scales.



Missing Mass Calculator (MMC): Fit decay orientations to τ kinematics: 13-20% $m_{\tau\tau}$ resolution

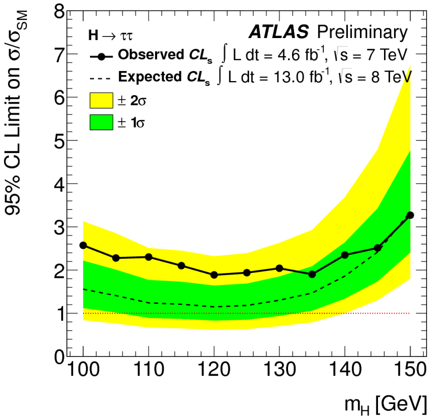
$H \to \tau\tau$: Results

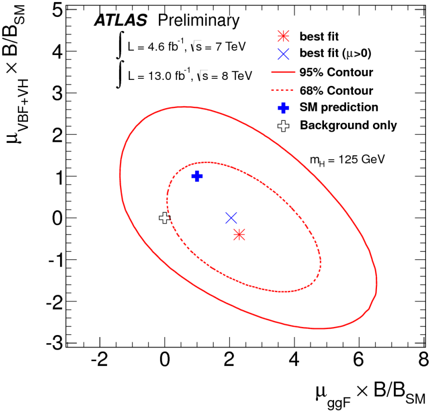


$m_H = 125$ GeV (all chan combined):

- Limit = 1.9 x SM (obs) (1.2 (exp))
- $\mu = 0.7 \pm 0.7$

$H \to \tau\tau$: Results





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(VBF + VH) vs (ggF) production signal-strength best-fit:

- $\mu_{VBF+VH} = -0.4$, $\mu_{ggF} = 2.4$

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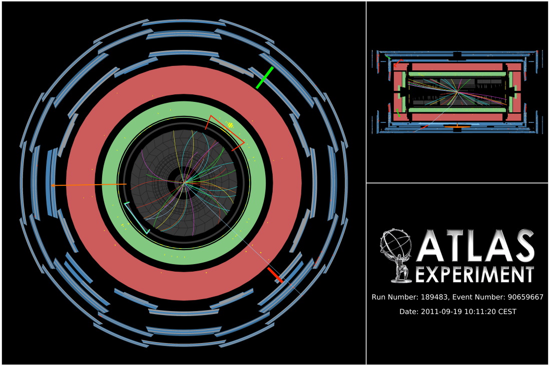
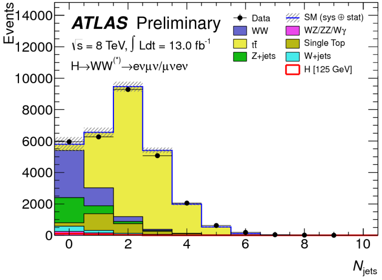


ATLAS EXPERIMENT
Run Number: 189483, Event Number: 90659667
Date: 2011-09-19 10:11:20 CEST

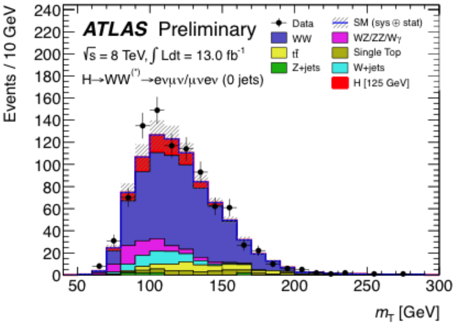
$H \rightarrow WW^*$

- July Results: 2.8σ signal (2.3σ exp.)
- Updated (13 fb^{-1}) 2012 result: focus on $e\nu\mu\nu$ channel only:
  - Provides 85% of sensitivity
  - E_T^{miss} resolution degraded with 2012 pileup.
  - Same-flavour channels suffer from Drell-Yan bgs $Z\gamma^* \rightarrow ee, \mu\mu$
- Analysis predominantly sensitive to gluon-gluon fusion production
- $H+$ 0-jet and H+1-jet channels
  - $<$ 2 jets reduces top background



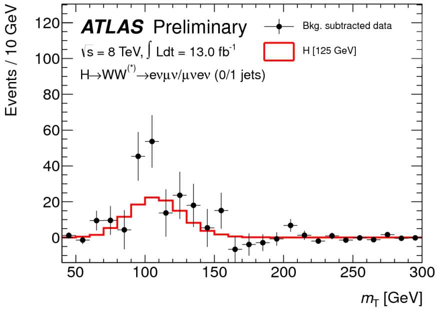
$H \to WW^*$ Backgrounds and Results

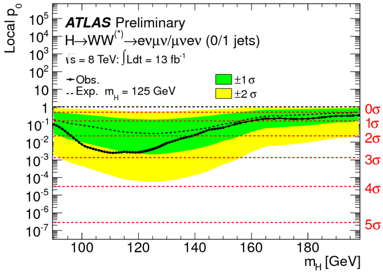
- W+jets fully estimated from data.
- WZ and ZZ from simulation.
- Cross checked together in same-charge data "validation region"
- Dominant WW and Top backgrounds normalised in control regions.
- WW modelling improved by change from MC@NLO to Powheg+Pythia8.

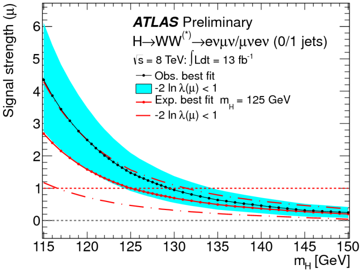


$$m_T^2 = (E_T^{ll} + E_T^{miss})^2 - |\vec{p}_T^{\,ll} + \vec{p}_T^{\,miss}|^2$$

$H \to WW^*$ Results

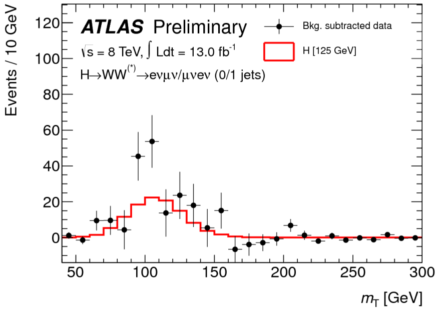


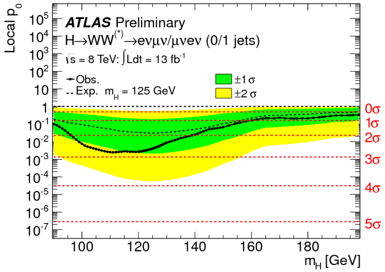




For $m_H = 125$ GeV:

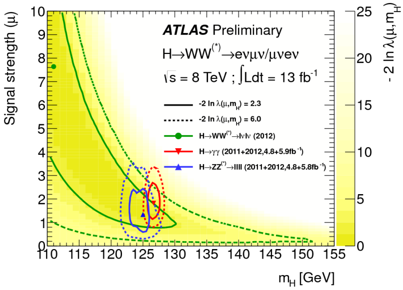
- Signal significance of 2.6σ (expected 1.9)
- $\mu = 1.5 \pm 0.6$





For $m_H = 125$ GeV:

- Signal significance of 2.6σ (expected 1.9)
- $\mu = 1.5 \pm 0.6$
- Poor-resolution in mass but result consistent with July results from high-res $\gamma\gamma$ and $ZZ^* \to 4l$.



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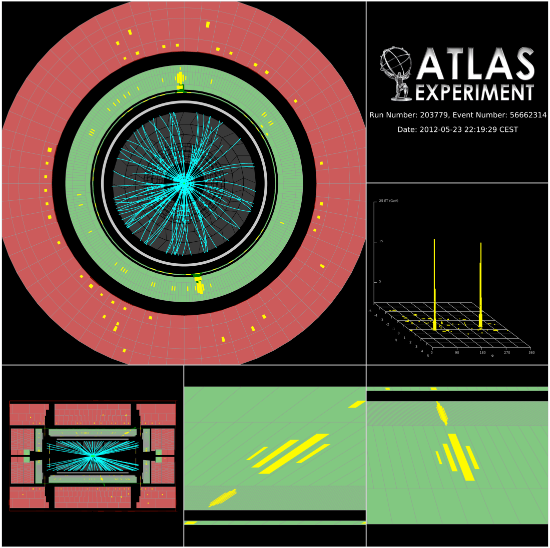


ATLAS EXPERIMENT
Run Number: 203779, Event Number: 56662314
Date: 2012-05-23 22:19:29 CEST

$H \rightarrow \gamma\gamma$

July Paper analysis:

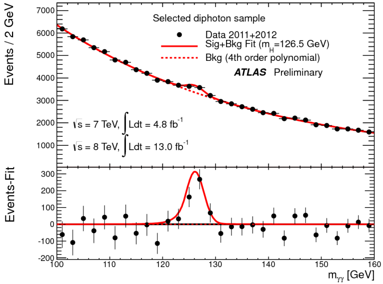
- Ten exclusive categories according to resolution, selected in:
  - (2-Jet) VBF
  - Converted / unconverted photons
  - η_γ
  - p_{T_t} (Component of diphoton pT orthogonal to the thrust axis)

New 13 fb^{-1} 2012 analysis (added to unchanged 2011 analysis):

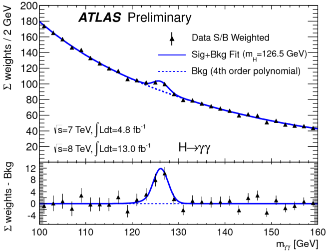
- Apply two additional categories for coupling measurement:
- Enriched in W/Z associated production:
  - "One-lepton": Leptonic W/Z decay, at least one *e*, *mu* in event
  - "Low-mass 2-jet": Consistent with hadronic W/Z decay
- Improved photon isolation and multi-variate primary-vertex finding.
- Performed mass measurement and spin analysis

$H \to \gamma\gamma$ Background Fit

- Backgrounds Include:
    - SM diphoton ($\approx$74%);
    - γ + jet (22%);
    - jet + jet (3%);
    - Drell Yan (1%)
- $m_{\gamma\gamma}$ fit to data.
- Signal: Crystal Ball + Gauss.
- Background model per category chosen using MC from:
    - Fourth-order Bernstein poly
    - Exponential of 2nd-order poly
    - Exponential function.
- Only functions with low signal yield in a bkg-only MC fit are used.
- Bkg parameters from data fit.

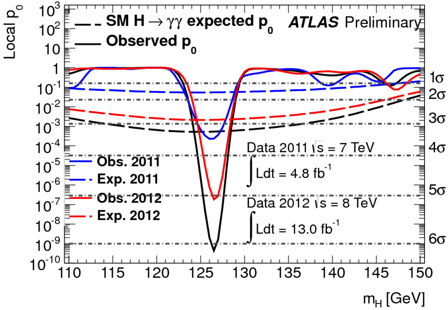


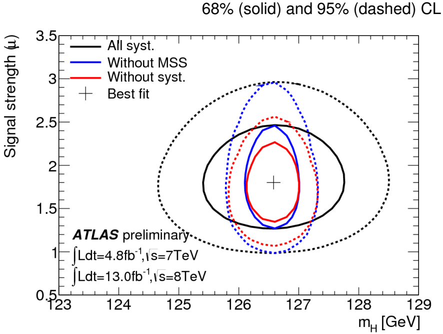
Events weighted by S/B per category:



At $m_H = 126.5$ GeV: $N_{sig} = 249$ $\sigma_{CB} = 1.64$ GeV

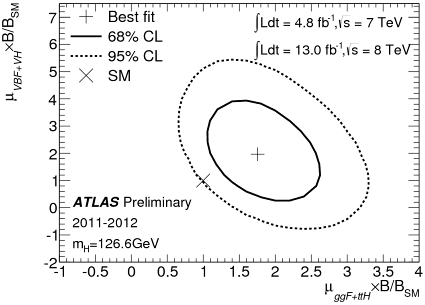
$H \to \gamma\gamma$ New Results: Mass and Signal Strength

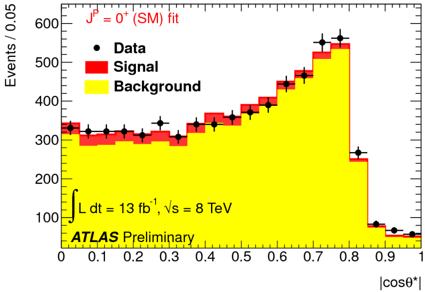




- Local Significance: 6.1σ = Single Channel Discovery
- Mass Measurement: $126.6 \pm 0.3(\mathit{stat.}) \pm 0.7(\mathit{sys.})$ GeV
- $\mu = 1.8 \pm 0.3(\mathit{stat.})^{+0.21}_{-0.15}(\mathit{sys.})^{+0.20}_{-0.14}(\mathit{theory})$
    - Theory uncertainty is that on Higgs production cross-section: such as QCD scale and Higgs decay BR

$H \to \gamma\gamma$ New Results: Couplings and Spin

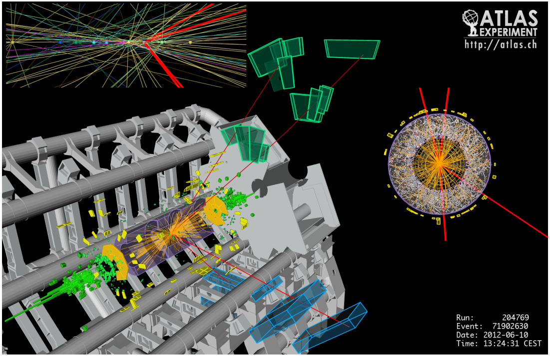




- Best-fit values of signal strength for ggF+ttH, VBF and VH processes
  - $\mu_{ggF+ttH} xB/B_{SM} = 1.8 \pm 0.4 \pm 0.2 \pm 0.2$
  - $\mu_{VBF} xB/B_{SM} = 2.0 \pm 1.2 \pm 0.6 \pm 0.3$
  - $\mu_{VH} xB/B_{SM} = 1.9 \pm 2.5 \pm 0.6 \pm 0.4$
- Angular analysis without categorisation, signal region [123.8,128.6] GeV
  - 0^+ SM Higgs favoured over JHU gluon-fusion produced, spin-2.

Outline

1. Motivation
   - Standard Model
2. ATLAS
   - Detector
   - Search Channels
3. Analyses and Latest Results
   - $H \to b\bar{b}$
   - $H \to \tau\tau$
   - $H \to WW$
   - $H \to \gamma\gamma$
   - $H \to ZZ^* \to 4l$
4. Combination



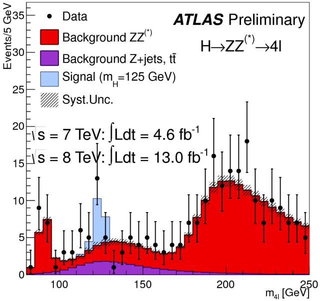
$H \to ZZ^* \to 4l$

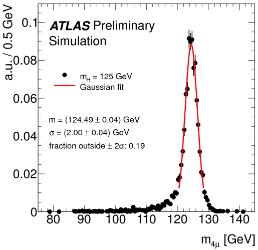
Four sub-channels

- 4e, 2e2μ, 2μ2e and 4μ

Backgrounds:

- ZZ^*: determined from simulation
- Z + jets and $t\bar{t}$ normalised from control regions





Four sub-channels

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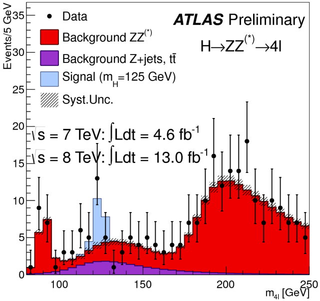
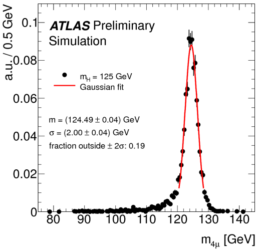
New 4.6 fb^{-1} + 13 fb^{-1} analysis

- Mass measurement





Four sub-channels

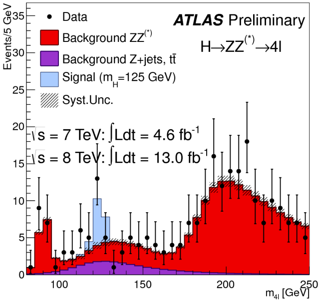
- 4e, 2e2μ, 2μ2e and 4μ

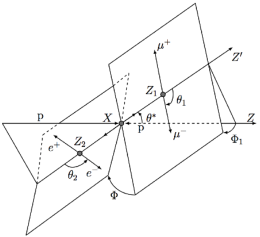
Backgrounds:

- ZZ^*: determined from simulation
- Z + jets and $t\bar{t}$ normalised from control regions

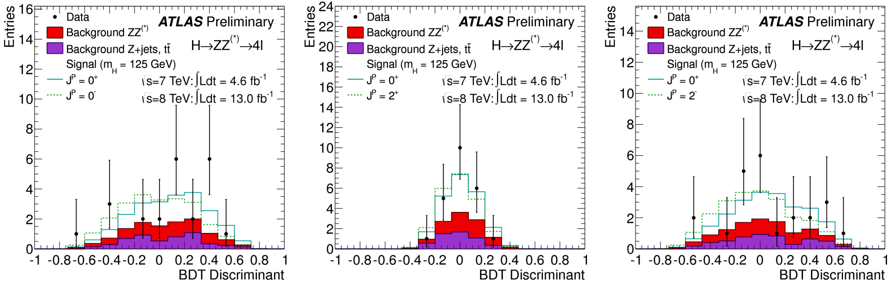
New 4.6 fb^{-1} + 13 fb^{-1} analysis

- Mass measurement
- Spin / Parity: 2 approaches:
  - Boosted Decision Tree
  - Matrix Element Approach ("J^P-MELA")
- $J^P = 0^+, 0^-, 2^+, 2^-$ compared pairwise in 2 m_{4l} regions.

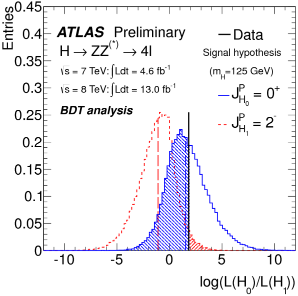




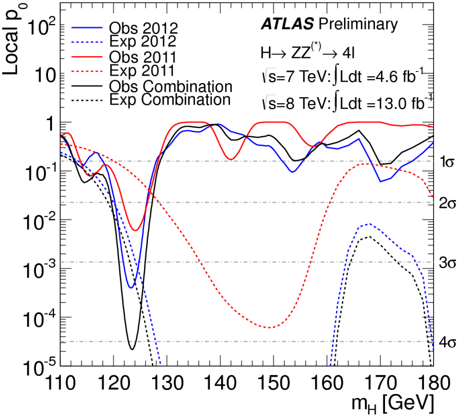
$H \to ZZ^* \to 4l$ New Results: Spin Analysis

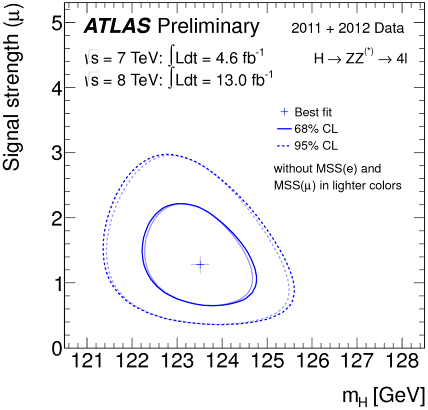


- BDT example distributions above
- BDT Variables: $\Phi, \theta_1, \theta_2, m_{12}, m_{34}$ (with θ^*, Φ_1 for $2^+, 2^-$).
- SM 0^+ favoured over 0^-, 2^+_m, 2^-
- Alternatives excluded by BDT (J^P-MELA) at
  98.9% (99.7%) for 0^-
  84% (83%) for 2^+_m
  97.1% (97.5%) for 2^-



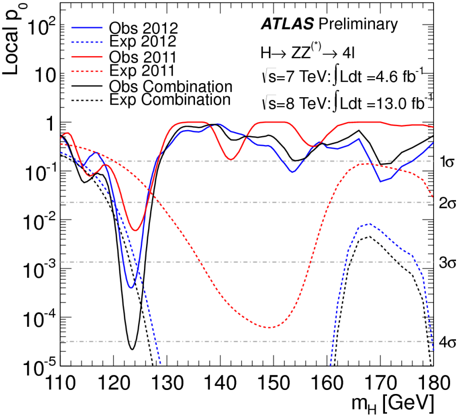
$H \to ZZ^* \to 4l$ New Results: Signal and Mass

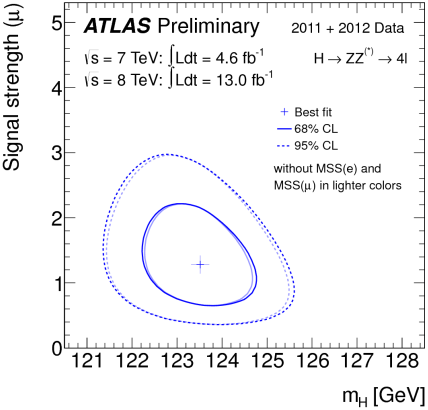




- Local Significance: 4.1 σ,
- $\mu = 1.3^{+0.5}_{-0.4}$ for best mass fit

$H \to ZZ^* \to 4l$ New Results: Signal and Mass

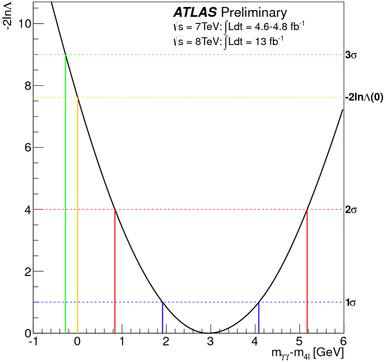




- Local Significance: $4.1\ \sigma$,
- $\mu = 1.3^{+0.5}_{-0.4}$ for best mass fit
- Mass Measurement: $M_{4l} = 123.5 \pm 0.9(stat) \pm 0.3(syst)$ GeV

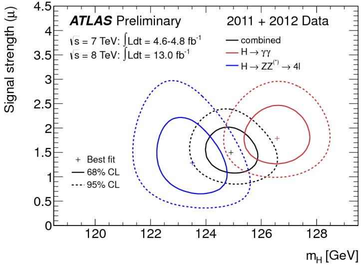
Outline

$H \to \gamma\gamma$, ZZ^* mass measurement consistency



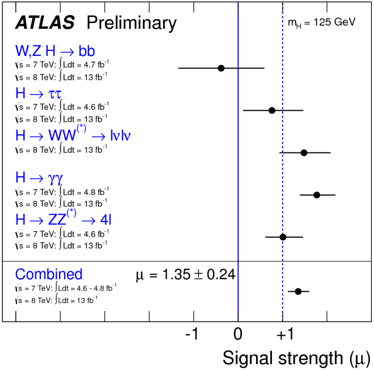
- Mass difference: $3.0^{+1.1}_{-1.0}$ GeV
- Corresponds to $2.3 - 2.7\sigma$

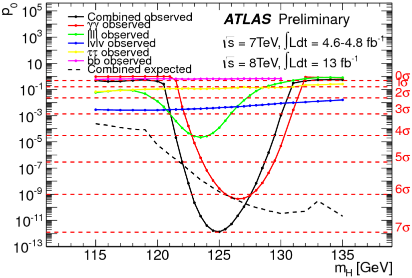
- Mass systematics thoroughly investigated (see backup)
- $\gamma\gamma$ mainly from γ energy scale: Total: $\pm$0.7 GeV (stat. = $\pm$0.3 GeV)
- $ZZ^* \to 4l$ dominated by 4 μ chan: Total: $\pm$0.3 GeV (stat. = $\pm$0.9 GeV)



$m_H = 125.2 \pm 0.3(stat) \pm 0.6(sys)$ GeV

Latest Combination: Signal Strength





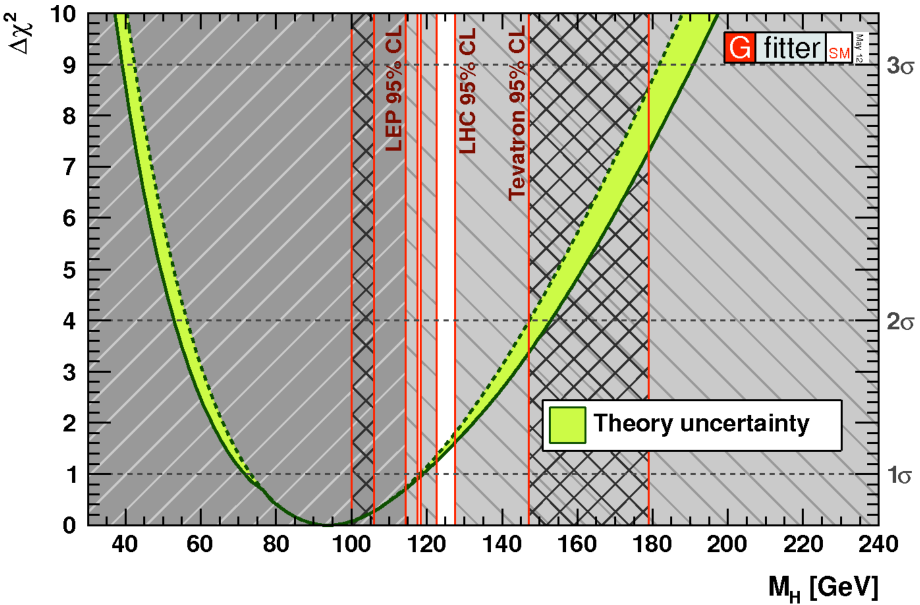
- $\mu =$ 1.35 $\pm$ 0.24 at 125 GeV
- Compatibility test to SM expectations: probability around 13%

Conclusions

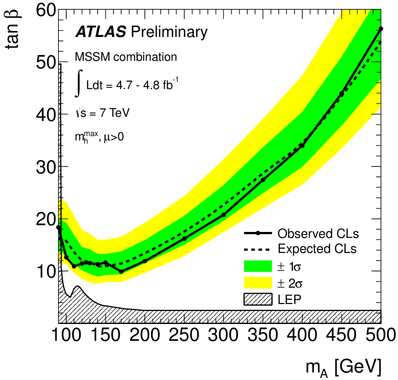
- Last July ATLAS discovered a new particle - that's now old news.
- In November, $\tau\tau$, $b\bar{b}$ and WW^* channels updated.
- Last week new $\gamma\gamma$ and $ZZ^* \rightarrow 4l$ results.
- Consistent with a SM Higgs but some things are "muddying the water".
- LHC (proton-proton) run ended today with almost 10 fb^{-1} more data
- Will it be enough to make things clear?

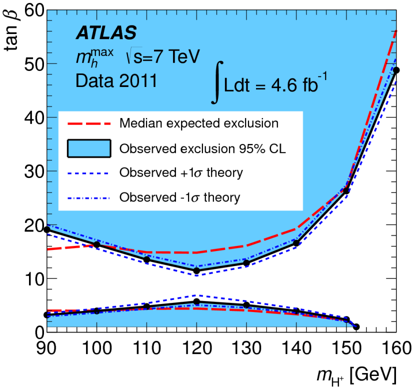
Backup Slides

Proved elusive... May 2012 Precision EW fit

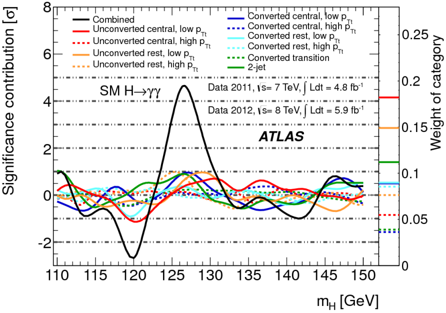


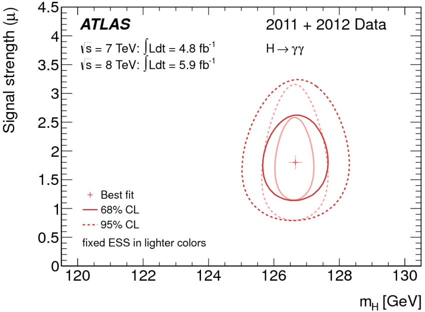
- Two-doublet Higgs sector:
  Neutrals: 2 CP-even: h, H, 1 CP-odd: A , 2 Charged H+, H-
- Couplings defined by m_A or m_{H^+} and tan $\beta = v_u/v_d$ (ratio of VEV).
- ATLAS searches: Neutral $\rightarrow \tau\tau, \mu\mu$ Charged $\rightarrow \tau\nu, cs$.
- No evidence found for MSSM Higgs.





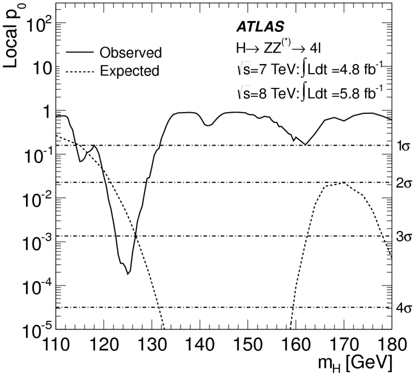
$H \to \gamma\gamma$ July Results

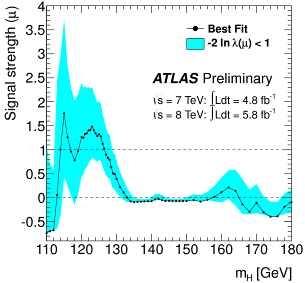


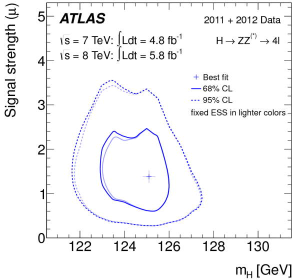


- Observed exclusion: 112-123 GeV and 132-143 GeV
- Maximum deviation at 126.5 GeV with a local significance of 4.5 σ
- For $m_H = 126$ GeV: $\mu = 1.8 \pm 0.5$

$H \to ZZ^* \to 4l$ July Results







- Exclusion: 131-162 and 170-460 GeV
- Excess 3.6σ at 125 GeV
- At $m_H = 125$: $\mu = 1.6 \pm 0.6$

$H \to \gamma\gamma$, ZZ^* mass details

$ZZ^{(*)} \to 4l$ result dominated by 4μ:

- High-stats $J/\Psi, \Upsilon$ and Z decays (> 20 M J/Ψs)
- Inner and Muon detector independent measurements.
- Overall muon momentum scale uncertainty $\pm$0.2%
- Each $H \to \mu\mu$ candidate examined: impact < 0.1 GeV

For electrons:

- E-scale from $Z \to ee$: 0.4%
- $E_{T_e} < 15$ GeV from $J/\Psi \to ee$
- QED radiation modelling; Background contamination.

$\gamma\gamma$ conservative systematics include:

- Energy scale: Extracted from high-stats $Z \to ee$ sample.
- Lateral leakage
- Different layer/ gain-range calibration biases.
- Material upstream of calorimeter.
- Non-linearities in electronics
- Pile-up
- Vertex angle measurement
- Conversion fraction in categories;
- Signal resolution uncertainty;
- Background modelling.

Couplings (based on July Results)

- Assume single, narrow resonance and zero-width approximation: $\sigma.BR(ii \rightarrow H \rightarrow ff) = \sigma_{ii}\Gamma_{ff}/\Gamma_{H}$
- Allow only modifications to absolute values of couplings: Tensor / CP-even scalar Higgs
- Scale-factors κ_i modify SM σ_{ii}, Γ_{ii}
- Constrain κ_i to probe couplings

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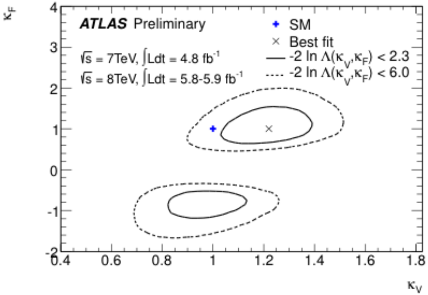
E.g. 1: Fermion and Vector Coupling:

- Assume only SM particles in loops and H decay.
- Fermion $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$ and Vector $\kappa_V = \kappa_W = \kappa_Z$



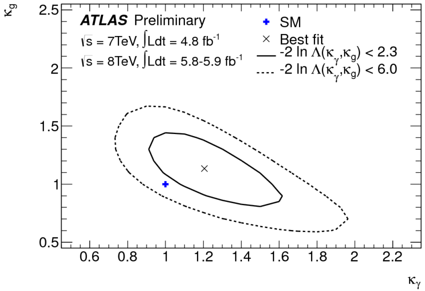
- Compatible with SM.
- Also true without assumptions on total width.

Couplings (based on July Results)

- Assume single, narrow resonance and zero-width approximation: $\sigma.BR(ii \to H \to ff) = \sigma_{ii}\Gamma_{ff}/\Gamma_H$
- Allow only modifications to absolute values of couplings: Tensor / CP-even scalar Higgs
- Scale-factors κ_i modify SM σ_{ii}, Γ_{ii}
- Constrain κ_i to probe couplings

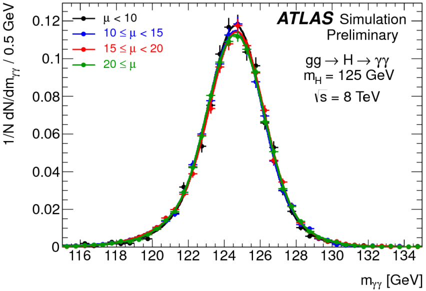
E.g 2: Non-SM particles in loops:

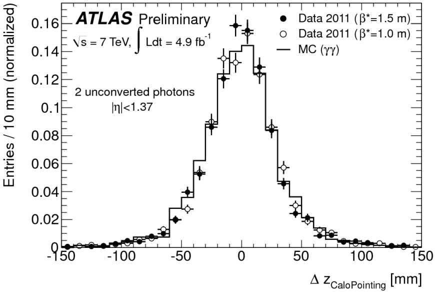
- κ_g and κ_γ for new contributions to $gg \to H$ and $H \to \gamma\gamma$ loops;



- $\kappa_g = 1.1^{+0.2}_{-0.3}$ $\kappa_\gamma = 1.2^{+0.3}_{-0.2}$
- No sizeable new contributions.

$\gamma\gamma$ pile-up dependence





- Dependence of the mass-resolution on the number of interactions per bunch-crossing.
- Primary vertex determined by calorimeter pointing in periods with different pile-up conditions.

$H \to b\bar{b}$ Systematic Uncertainties

Uncertainty [%]	0 lepton	1 lepton	2 leptons
b-tagging	6.5	6.0	6.9
c-tagging	7.3	6.4	3.6
light tagging	2.1	2.2	2.8
Jet/Pile-up/E_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
Total	25	15	14

Uncertainty [%]	0 lepton		1 lepton	2 leptons
	ZH	WH	WH	ZH
b-tagging	8.9	9.0	8.8	8.6
Jet/Pile-up/E_T^{miss}	19	25	6.7	4.2
Lepton	0.0	0.0	2.1	1.8
$H \to bb$ 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
Statistical	4.9	18	4.1	2.6
Luminosity	3.6	3.6	3.6	3.6
Total	24	34	16	13

- Background Systematics
- Signal Systematics