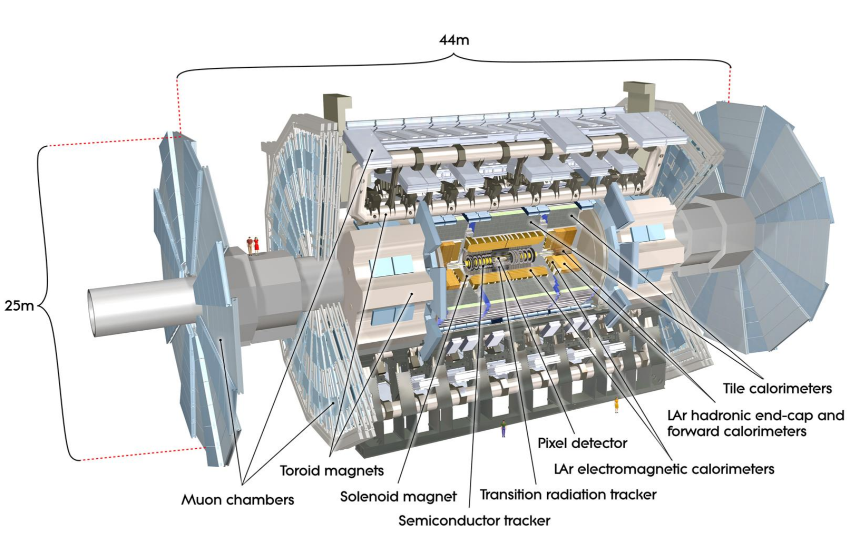
Constraining Beyond the Standard Model physics using the newly discovered Higgs boson with the ATLAS detector.

G. Carrillo-Montoya

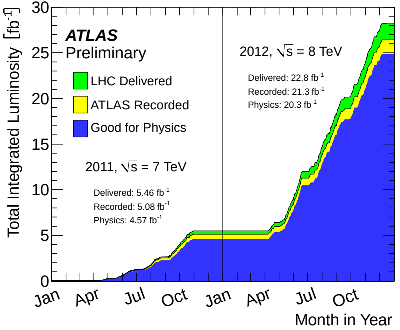
SAIP2014 - Johannesburg South Africa
July 8th - 2014

A Toroidal LHC ApparatuS - 4π solid angle

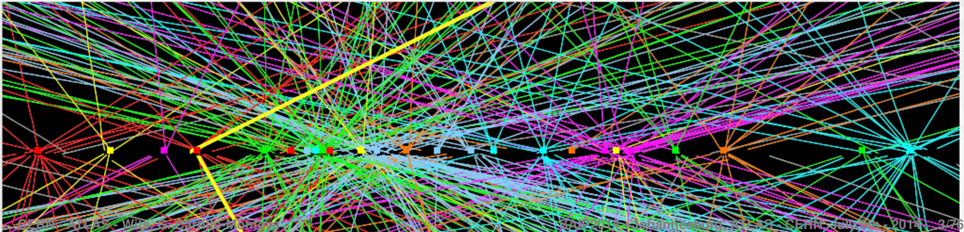


...

Luminosity $\rightarrow$ pileup interactions

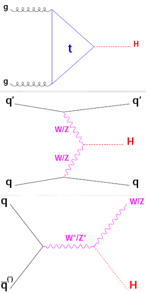


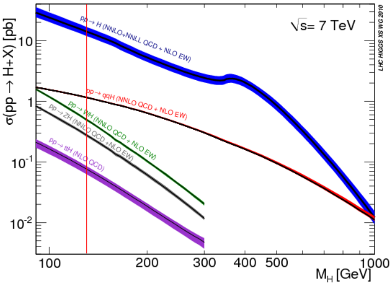
- During 2012, the LHC provided us larger integrated luminosities, still with 50 ns bunch separation:
- More interactions per bunch crossing.
- Reconstruction of objects need even robuster methods $\rightarrow$ performance of physics analysis:
  - Sustain high identification efficiencies and resolution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

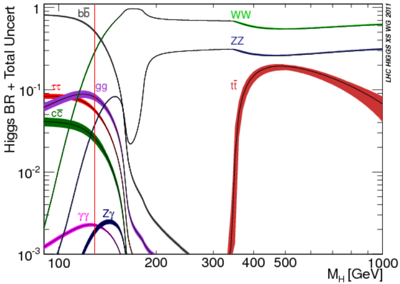


The SM Higgs boson

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







Nature is very kind: around $m_H = 125$ GeV $\rightarrow$ many modes... not easy for **all** channels in a hadron collider.

- $\gamma\gamma$ (great resolution but large backgrounds)
- ZZ (Small backgrounds, but statistically limited)
- WW (good s/b, but virtually no resolution)
- $b\bar{b}$, $\tau\tau$, $Z\gamma$ ... / ttH, VH, VBF ...

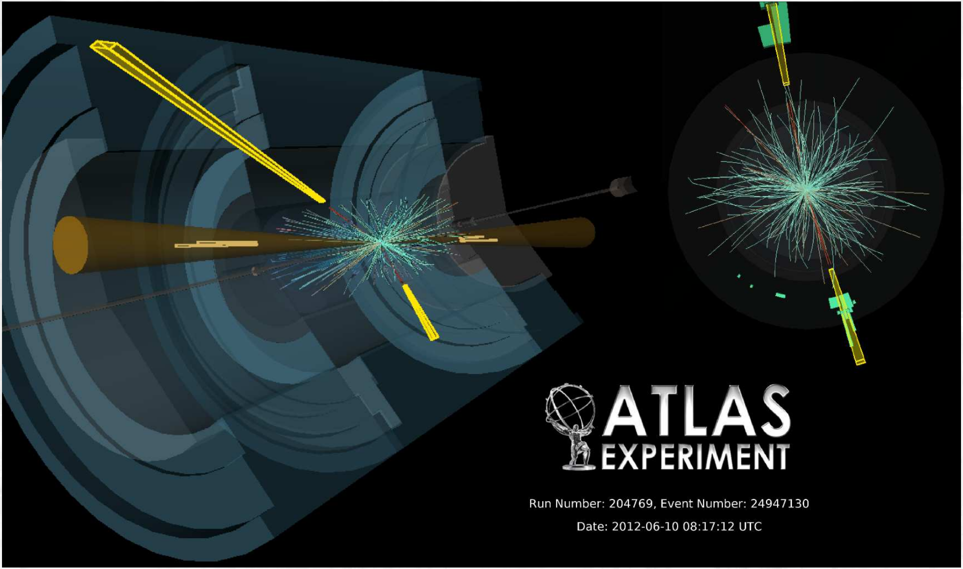
for a m_H of 125 GeV:

$\sqrt{s}$ [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

Content

1. Discovery Channels
   - $H \to \gamma\gamma$
   - $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$
   - $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$
2. Is it the SM Higgs?
   - Properties:Signal strength, production rates, couplings
   - Light Higgs coupling measurements constraining BSM physics
   - Invisible Higgs?: $ZH \to (\ell\ell)$INV
3. Multiple Higgs bosons and other searches
   - 2HDM
   - Additional Higgs bosons
   - Search of FCNC with the 125 GeV Higgs

Content

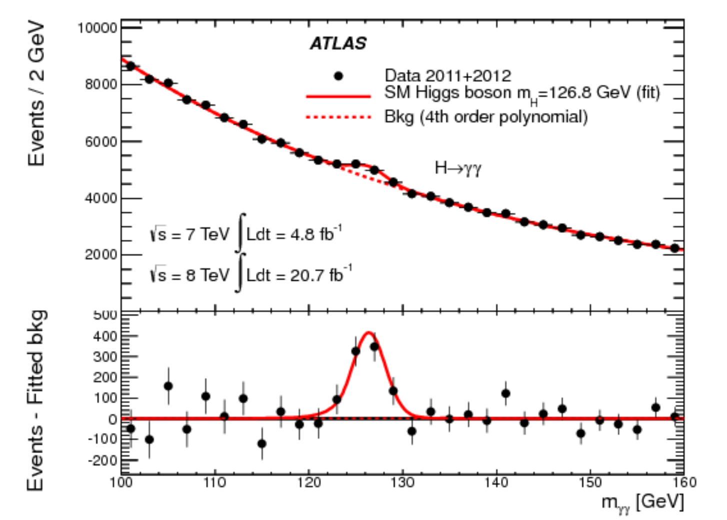


$\sqrt{s} = 8$ TeV

Leading-γ: $E_T = 80.1$ GeV, $\eta = 1.01$ Subleading-γ: $E_T = 36.2$ GeV $\eta = 0.17$

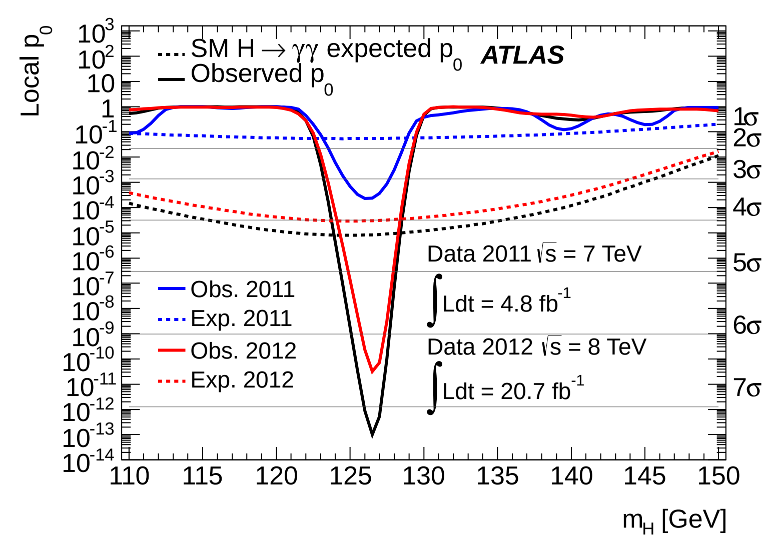
$m_{\gamma\gamma} = 126.9$ GeV. VBF-like two high p_T jets at 121.6 and 82.8 GeV.

$H \to \gamma\gamma$ - Phys. Lett. B716 (2012) 1-29



- **Categories** as function of resolution, s/b, production mechanism:
  - Converted/unconverted, η of selected photons, high/low transverse component of

local p_0-values



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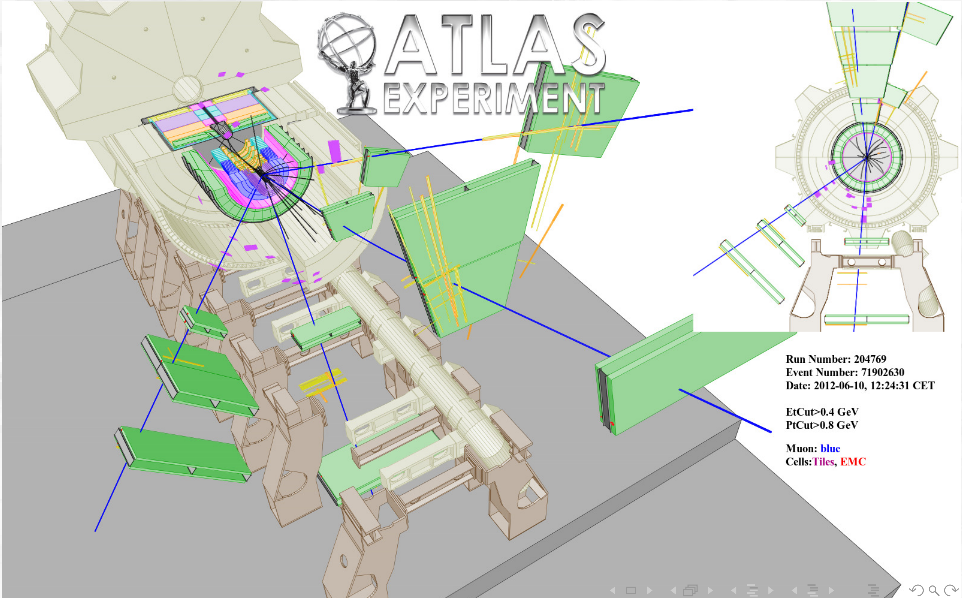
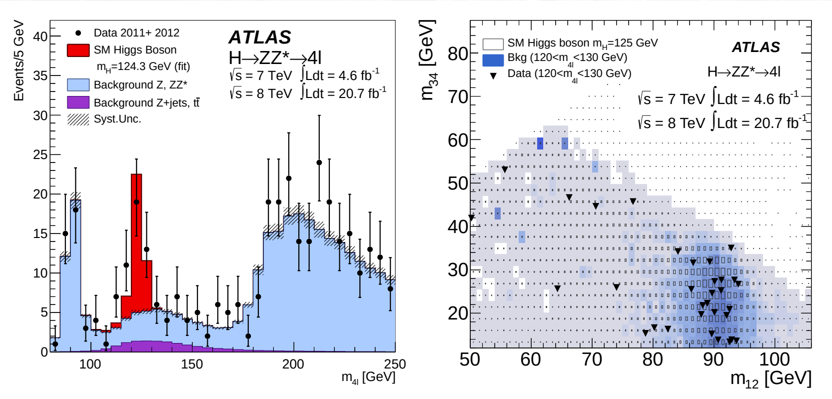
4μ candidate. $m_{4\ell} = 125.1$ GeV, $m_{12} = 86.3$ GeV, $m_{34} = 31.6$ GeV.

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, $\eta = 1.85$, $\phi = 1.65$



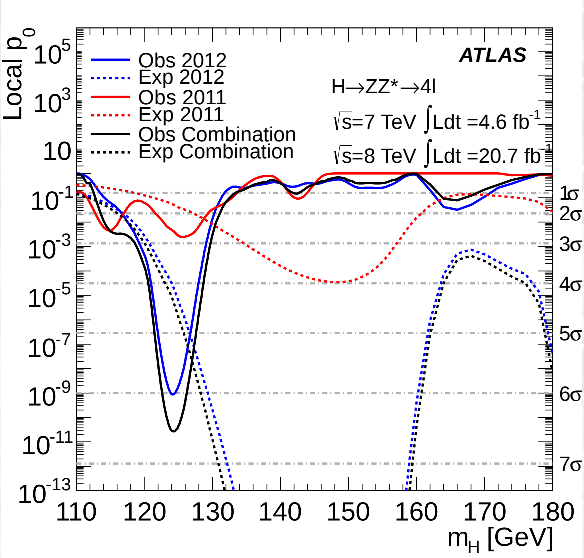
$H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$ - Phys. Lett. B716 (2012) 1-29



Also categorised by prod. mechanism
In a $m_{4\ell}$ window around 120-130 GeV:

	Signal	ZZ^*	$Z+\text{jets}, t\bar{t}$	Observed
4μ	6.3±0.8	2.8±0.1	0.55±0.15	13
$2e2\mu/2\mu2e$	7.0±0.6	3.5±0.1	2.11±0.37	13
$4e$	2.6±0.4	1.2±0.1	1.11±0.28	6

p-values


Local p0
Obs 2012
Exp 2012
Obs 2011
Exp 2011
Obs Combination
Exp Combination
ATLAS
H→ZZ*→4l
√s=7 TeV ∫Ldt =4.6 fb-1
√s=8 TeV ∫Ldt =20.7 fb-1
10^5
10^3
10
10^-1
10^-3
10^-5
10^-7
10^-9
10^-11
10^-13
1σ
2σ
3σ
4σ
5σ
6σ
7σ
110
120
130
140
150
160
170
180
mH [GeV]

Content

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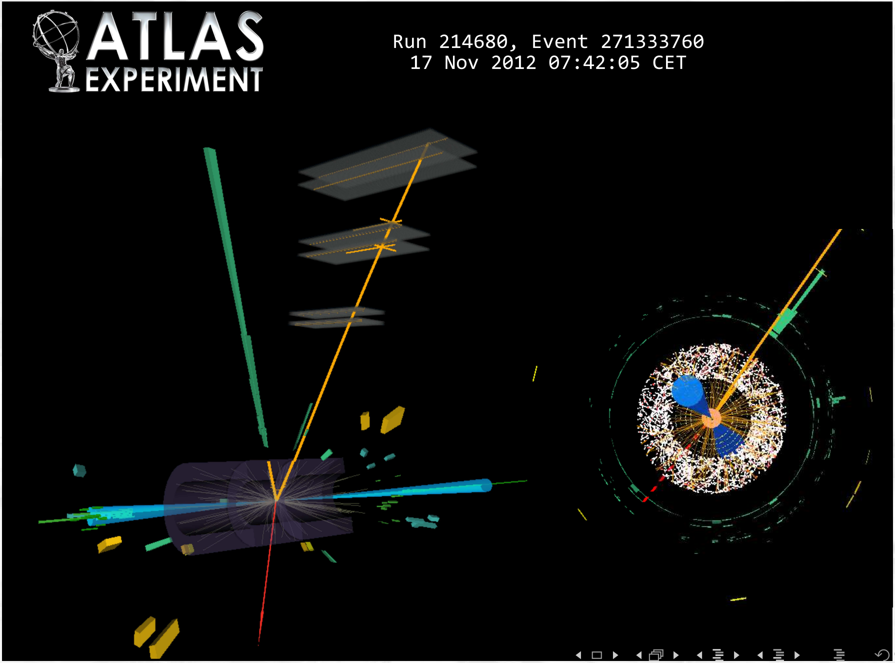
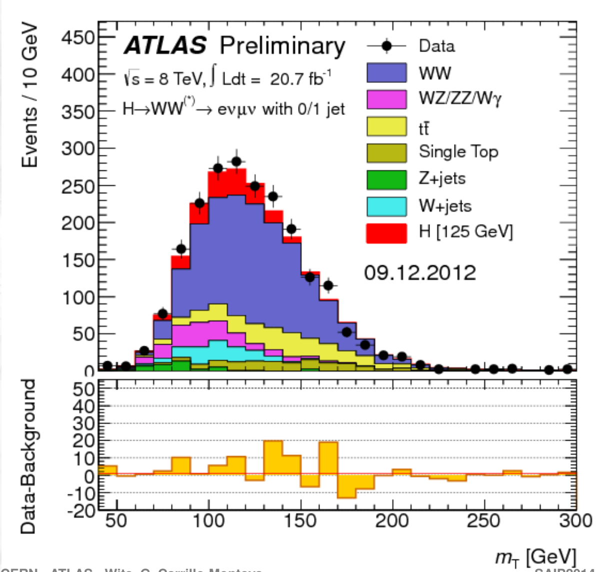
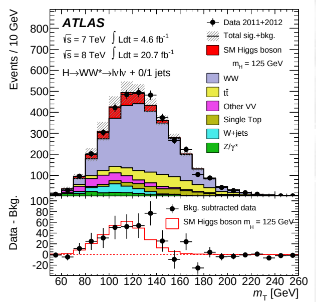
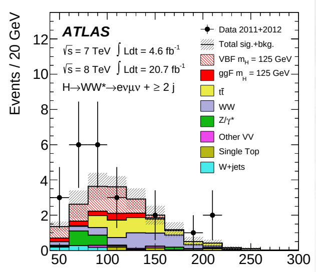
$\sqrt{s} = 8$ TeV - $e\mu$ - 2-jet - P_T^e =51 GeV and $P_T^\mu = 15$ GeV, $E_T^{miss,rel} = 33$ GeV, $m_T = 95$ GeV.



$H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ - Phys. Lett. B716 (2012) 1-29







Content

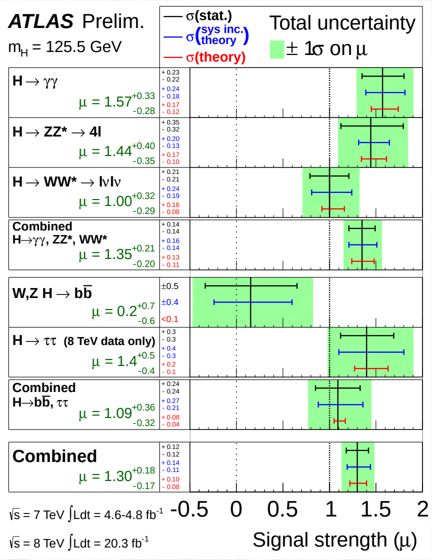
The new 125 GeV boson as a portal to new physics?

- Clear signature in all di-boson channels $\to$ are compatible?
- fermionic modes ($b\bar{b}$, $\tau\tau$) are less powerful but equally important. recent preliminary combination results
- Everything indicates it definitely is **a Higgs boson**, but, is it "the" SM Higgs boson?
  - Are the production rates compatible with the ones the SM predicts?
  - Does it couple to the massive particles as predicted by the SM?
  - Does it look like an impostor or a composite boson?
  - Are there more Higgs bosons: and additional real electroweak singlet? is it part of a 2HDM?
  - Does it decay to other particles, invisible (dark-matter)?
  - With it, can we observed non-SM phenomena (Flavour Changing Neutral Currents / Custodial Asymmetries)?
  - Is the width the 4 MeV the SM predicts?

Content

- Best fitted mass:
  $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV
- Combined signal strength
  $\sigma/\sigma_{SM} = \mu = 1.30 \pm 0.12(\text{stat})^{+0.14}_{-0.11}(\text{sys})$
- Spin Hypothesis:
  $JP = 0^+$
  others ($JP = 0^-; 1^+; 1^-; 2^+$) excluded at 97.8% CL

  Phys. Lett. B726 (2013) 120-144



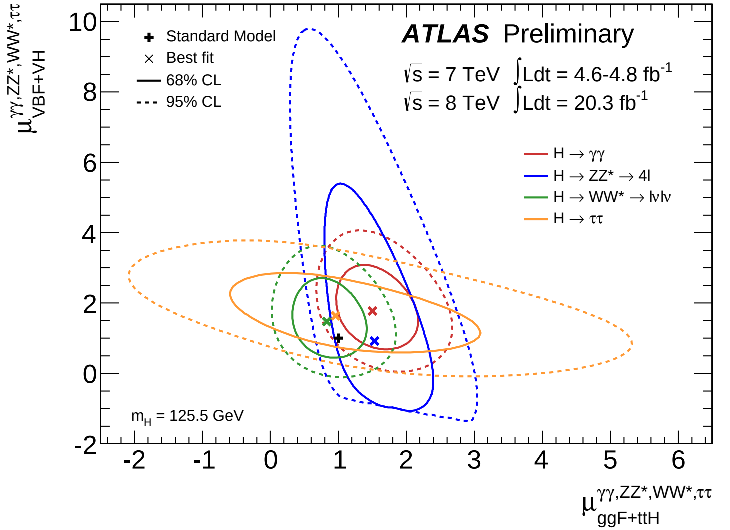
3.7σ evidence of Higgs into fermions

Documentation:

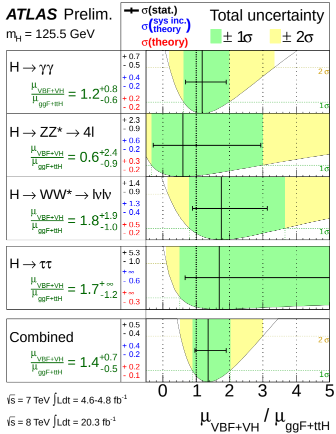
ATLAS-CONF-2014-009

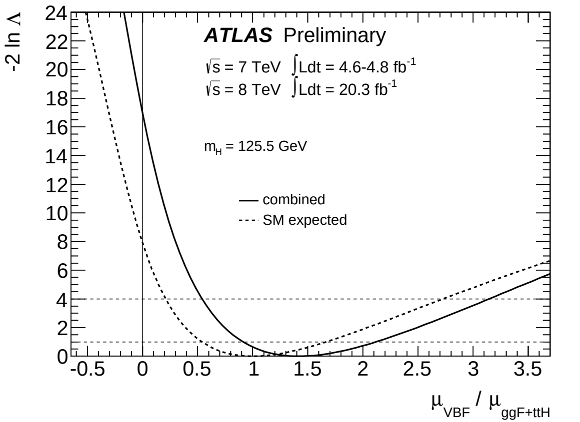
Phys.Lett. B726 (2013) 88-119

Higgs boson production mechanisms



Higgs boson production mechanisms II





Use the categorisation by production mechanisms
→ ratio: **NO** assumptions on the branching ratios

4.1σ evidence of *VBF* production

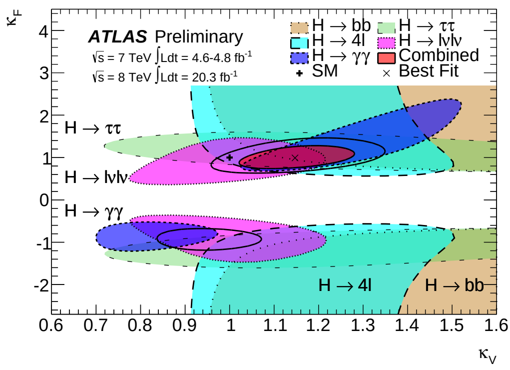
$$\frac{\mu_{\rm VBF}}{\mu_{{\rm ggF}+ttH}} = 1.4^{+0.5}_{-0.4}\,(\text{stat})\,^{+0.4}_{-0.3}\,(\text{sys})$$

Higgs boson couplings

One needs to:

- Disentangle individual couplings from production and decays ($\gamma\gamma$)
- Assumptions (LO benchmark arxiv:1307.1427):
  - Higgs $\to$ single resonance
  - Narrow width approximation $\sigma \times BR(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$
  - No modification on the Tensor structure of the couplings (only absolute values are modified)
- Factors κ_i such as

$$\frac{\sigma \times BR(gg \to H \to \gamma\gamma)}{(\sigma_{gg} \times BR(H \to \gamma\gamma))_{SM}} = \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

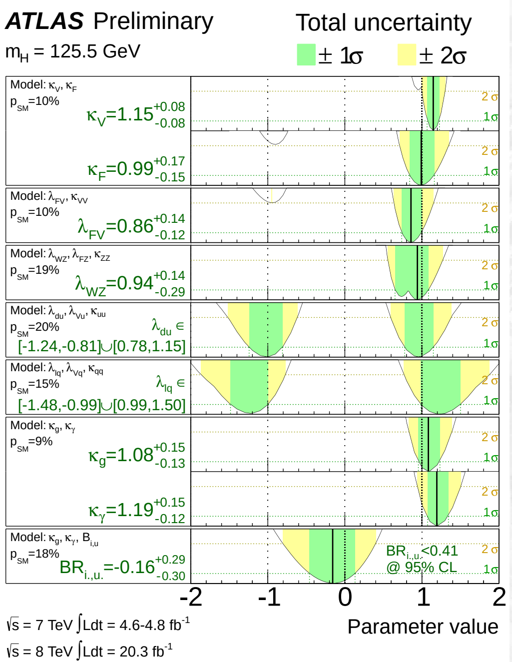


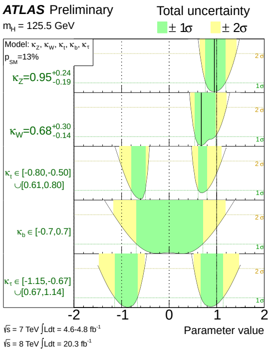
Note that κ_g^2 and κ_γ^2 are loop-induced depending on (κ_t, κ_b and κ_W).

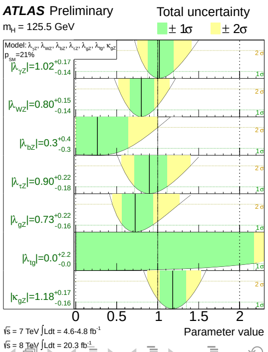
Higgs boson couplings benchmarks

Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $gg \to H \to \gamma\gamma$
Couplings to fermions and bosons	κ_V, κ_F	✓	✓	✓	✓	✓	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)/\kappa_H^2(\kappa_F, \kappa_V)$
	$\lambda_{FV}, \kappa_{VV}$	✓	✓	✓	✓	-	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, \lambda_{FV}, \lambda_{FV}, 1)$
Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	✓	✓	✓	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$
Up-/down-type fermions	$\lambda_{du}, \lambda_{Vu}, \kappa_{uu}$	✓	κ_u, κ_d	✓	✓	-	$\kappa_{uu}^2 \cdot \kappa_g^2(\lambda_{du}, 1) \cdot \kappa_\gamma^2(\lambda_{du}, 1, \lambda_{du}, \lambda_{Vu})$
Leptons/Quarks	$\lambda_{lq}, \lambda_{Vq}, \kappa_{qq}$	✓	κ_l, κ_q	✓	✓	-	$\kappa_{qq}^2 \cdot \kappa_\gamma^2(1, 1, \lambda_{lq}, \lambda_{Vq})$
Vertex loops	κ_g, κ_γ	=1	=1	-	-	✓	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma)$
$+H \to$inv/und decays	κ_g, κ_γ, BR$_{i,u}$	=1	=1	-	-	✓	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma) \cdot (1 - \mathrm{BR}_{i,u})$
Generic models with and w/o assumptions on vertex loops and Γ_H	$\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau$	-	-	✓	✓	✓	$\frac{\kappa_g^2(\kappa_b,\kappa_t)\cdot\kappa_\gamma^2(\kappa_b,\kappa_t,\kappa_\tau,\kappa_W)}{\kappa_H^2(\kappa_b,\kappa_t,\kappa_\tau,\kappa_W,\kappa_Z)}$
	$\lambda_{WZ}, \lambda_{tg}, \lambda_{bZ}, \lambda_{\tau Z}, \lambda_{gZ}, \lambda_{\gamma Z}, \kappa_{gZ}$	-	-	-	-	-	$\kappa_{gZ}^2 \cdot \lambda_{\gamma Z}^2$

Summary of the coupling benchmark models.
$\lambda_{ij} = \kappa_i/\kappa_j$, $\kappa_{ii} = \kappa_i\kappa_i/\kappa_H$, and the functional dependence assumptions are:
$\kappa_V = \kappa_W = \kappa_Z$, $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$ (and similarly for the other fermions)
$\kappa_g = \kappa_g(\kappa_b, \kappa_t)$, $\kappa_\gamma = \kappa_\gamma(\kappa_b, \kappa_t, \kappa_\tau\kappa_W)$, and $\kappa_H = \kappa_H(\kappa_i)$.
The tick marks indicate which assumptions are made in each case.

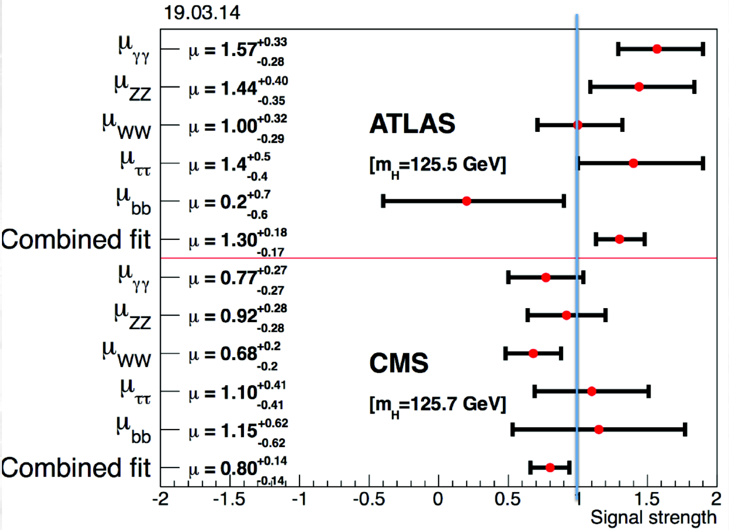






Compatibility with SM, ranging *p*-value: 7 to 21%

ATLAS and CMS - $\hat{\mu} \sim 1.0 \pm 0.12$ - non official



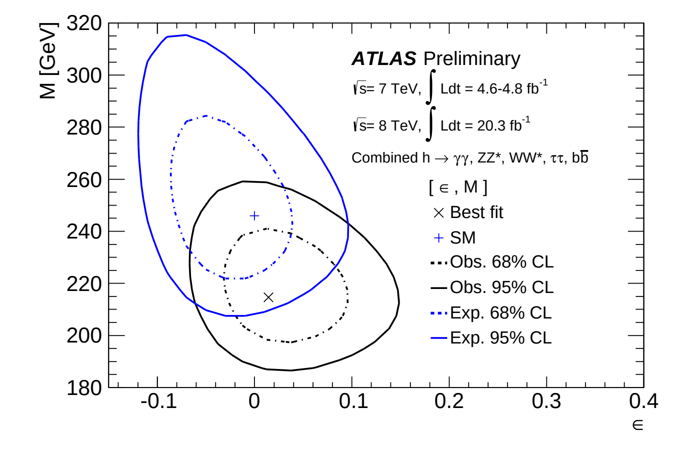
Higgs Couplings, Moriond 2014, Eilam Gross

Content

"Mass-scaling" dependence of couplings

- Each coupling in terms of vev ($v \approx 246$ GeV) and parameter ϵ.($\epsilon = 0 \to$ SM)

$$\kappa_{f,i} = v\frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}} \qquad \kappa_{V,j} = v\frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$

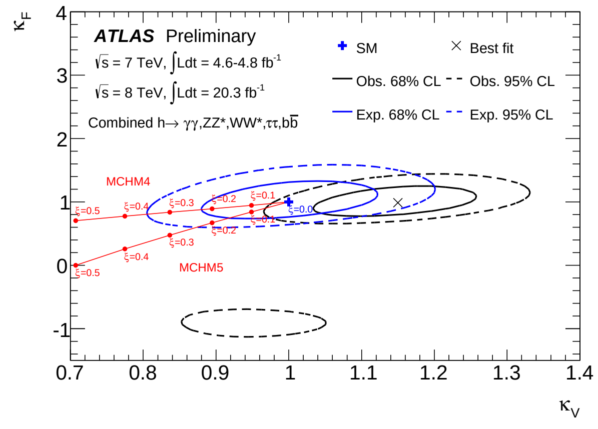


Ellis and You arXiv:1303.3879

Minimal Composite Higgs Model

- Higgs is composite pseudo Nambu-Goldstone boson
- Higgs couplings modified as function of compositeness scale f
  $\xi = v^2/f^2$

- MCHM4:
  $\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$
- MCHM5:
  $\kappa_V = \sqrt{1-\xi}$
  $\kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$



- SM recovered in the limit $\xi \to 0$, namely $f \to \infty$.

95% CL obs (exp) boundaries on ξ: MCHM4:$\xi < 0.12(0.29)$; MCHM5:$\xi < 0.15(0.20)$

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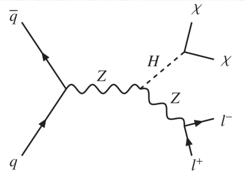
Is the Higgs decaying into an invisible state?

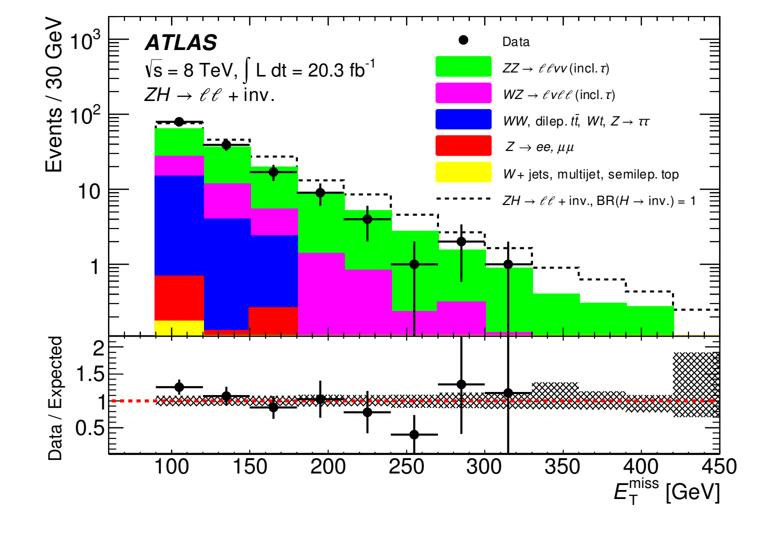
- In order to Trigger and tag events with large missing energy one needs to use the particles produced together with the Higgs boson, in this case the production of the Higgs in association with a Z boson (or Higgs-strahlung):



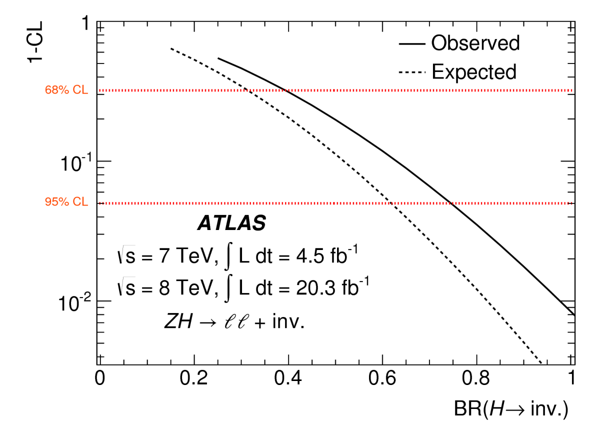
- Using the same analysis one can look for **additional** Higgs bosons in the rest of the mass range.

- Documentation (very recent):
  Phys. Rev. Lett. 112, 201802 (2014)

Final yields

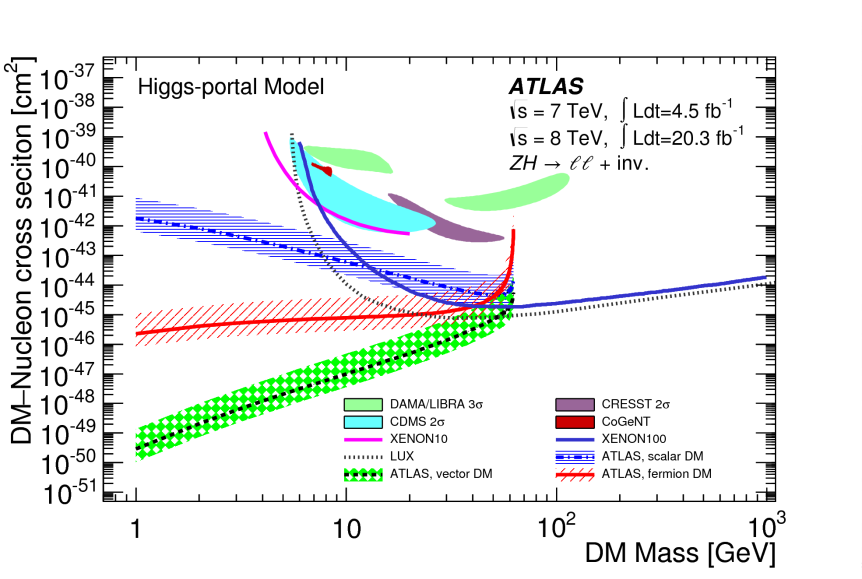


Statistical interpretation



- Higgs BR to invisible exclusion at 95% CL:
  Expected:84%, Observed:65%
- Higgs BR to invisible exclusion at 68% CL:
  Expected:39%, Observed:28%

Dark-Matter interpretation **(Higgs Portal)**



Content

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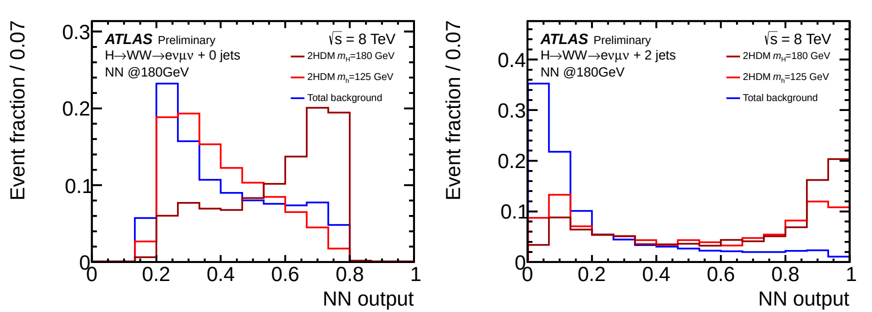
Two Higgs Doublet Model potential

- Natural path to explore $\rightarrow$ two identical complex scalar fields($SU(2)$)
- The 2HDM scalar potential is a Z_2 broken symmetric 2HDM
- In the CP-conserving case, parameters can be reduced to:
  3 masses $m_h, m_H, m_{H^\pm}, m_A$,, 2 angles α, β and 1 potential parameter m_{12}^2
- $\tan\beta = v_1/v_2$: ratio of vevs (satisfying $v_1^2 + v_2^2 = v^2 \approx (264\ \mathrm{GeV})^2$
  α: mixing angle between h and H
- For the VV final states $\rightarrow$ type I and II are relevant (no FCNC)

Coupling scale factor	Type I (fermiophobic)	Type II (MSSM-like)	Type III (lep. specific)	Type IV (flipped)
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

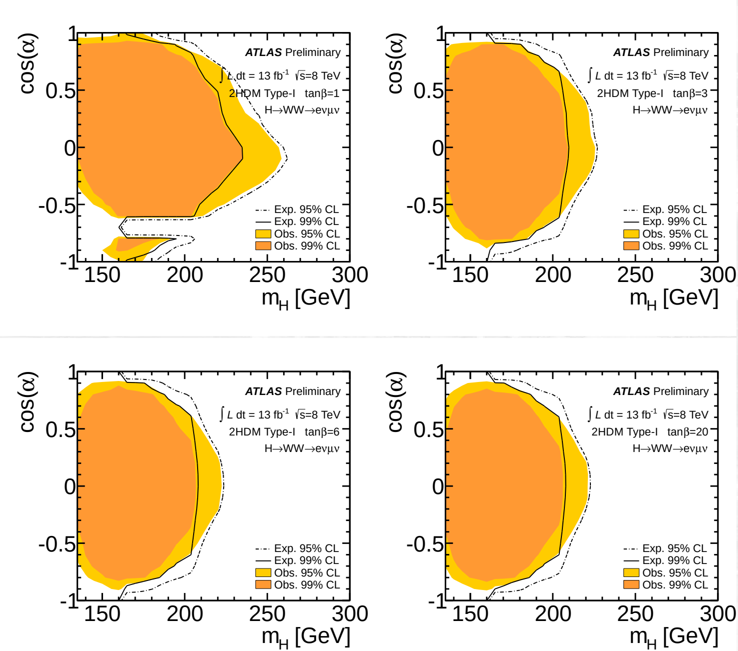
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ 2HDM

- It is one of the most sensitive channels in the intermediate mass range
- Recast the analysis used for the discovery ($e\mu\otimes$ 0 and 2jet final state), but profit the separation given by a Neural-Network
- A number of modifications were included to reduce possible signal "cross-feed"
- Light and Heavy Higgs bosons are fitted simultaneously

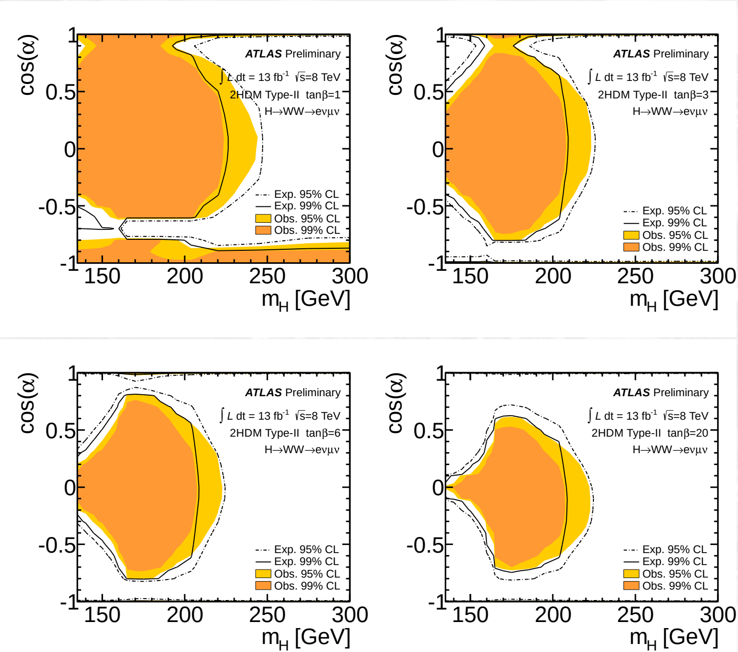


Documentation: ATLAS-CONF-2013-027

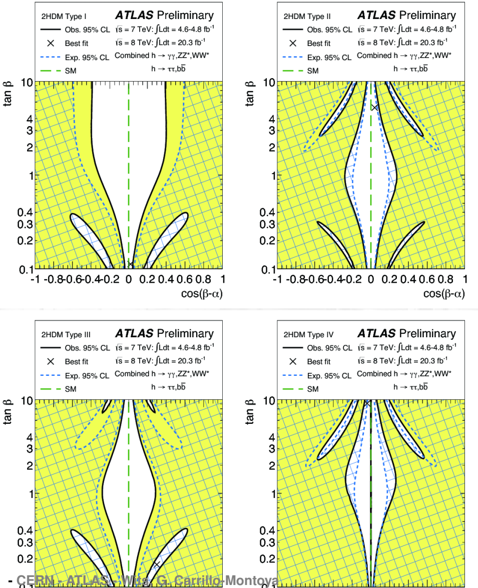
$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ 2HDM results Type I

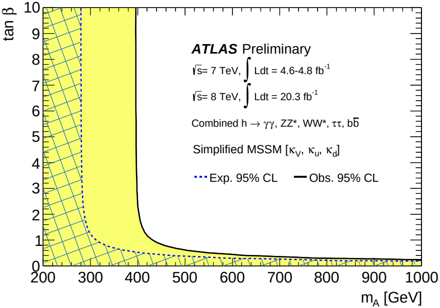


$H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ 2HDM results Type II



Using couplings constraints (light Higgs channels)



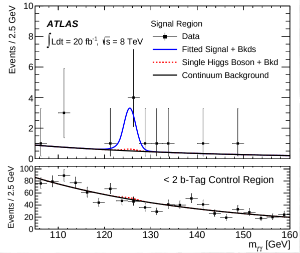


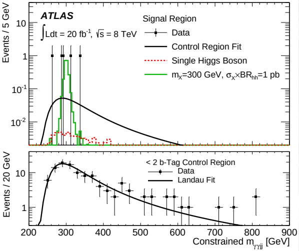
VERY Simplified MSSM, couplings constraints

ATLAS-CONF-2014-009

Content

$hh \to b\bar{b}\gamma\gamma$

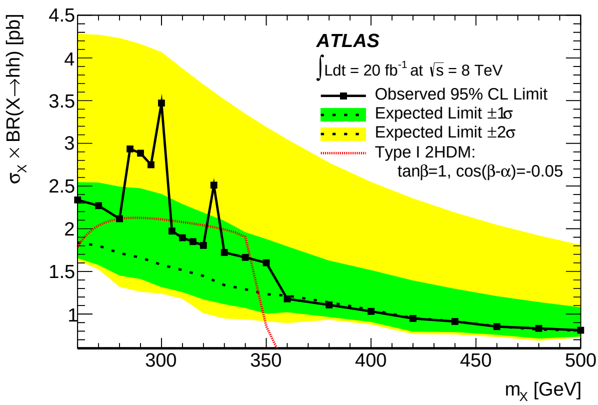




Search of resonant and non resonant *hh* production

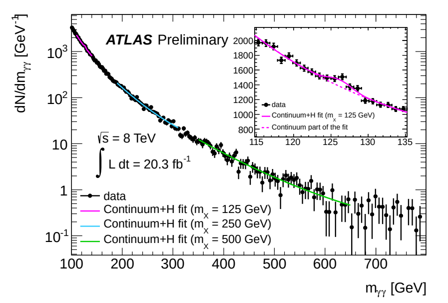
Non resonant 95% CL limit: 2.2 (1.0) pb obs (exp)

Narrow Resonant 95% CL limit range: 0.8–3.5 pb



Documentation: Submitted to PRL - arxiv link

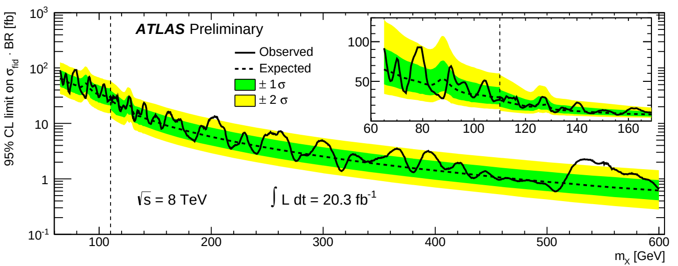
$X/H \to \gamma\gamma$ extended mass range



Search of additional $\gamma\gamma$ narrow resonaces (fiducial cross section limit)

$h(125) \to \gamma\gamma$ production consireded as a background (assuming SM prod. rates)

Documentation: ATLAS-CONF-2014-031

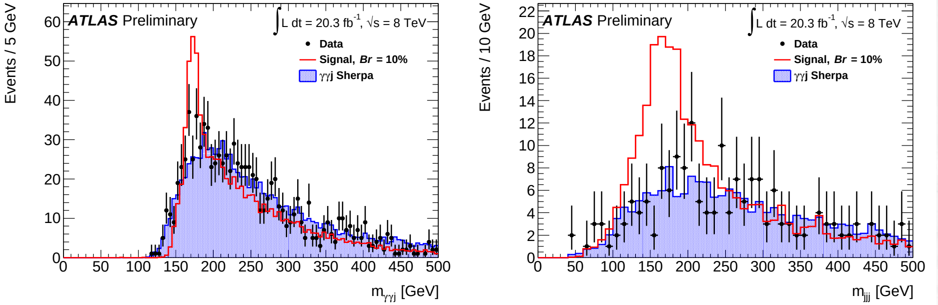


Content

1. Discovery Channels
   - $H \to \gamma\gamma$
   - $H \to ZZ^{(*)} \to \ell^+\ell^-\ell^+\ell^-$
   - $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$
2. Is it the SM Higgs?
   - Properties:Signal strength, production rates, couplings
   - Light Higgs coupling measurements constraining BSM physics
   - Invisible Higgs?: $ZH \to (\ell\ell)$INV
3. Multiple Higgs bosons and other searches
   - 2HDM
   - Additional Higgs bosons
   - Search of FCNC with the 125 GeV Higgs

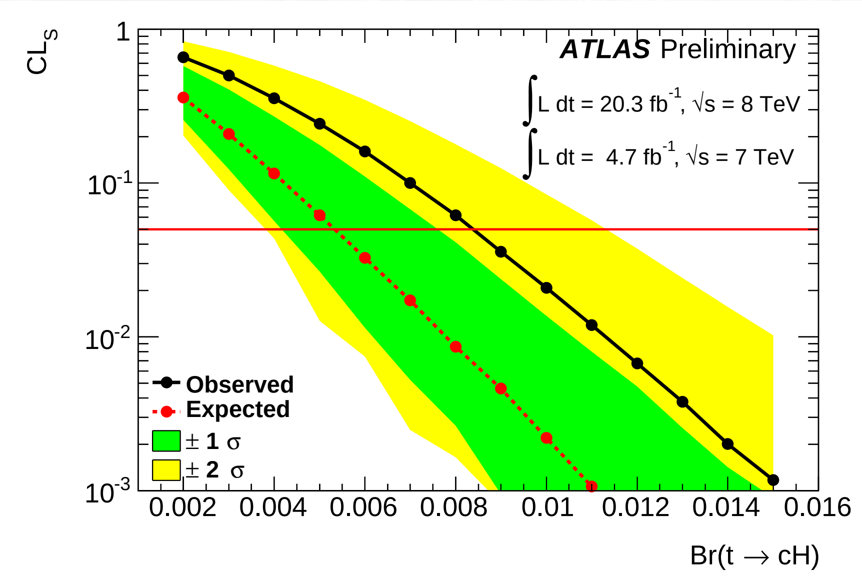
BSM Flavour Changing Neutral Currents

- In top pair events, look for possible $t \to cH$ decays with the $H \to \gamma\gamma$ (m_H =126 GeV)
- The second top quark decay into a Wb pair, both hadronic and leptonic modes of the W are explored



Documentation: ATLAS-CONF-2013-081

$t \rightarrow cH$ Branching ration limit



Outlook

- Higgs discovery, great achievement of the LHC program... it is just the beginning
  - **Higgs boson** was discovered, now we are in the process of characterising it The diboson decays are powerful tools to discriminate Spin/CP states. The addition of the Fermionic channels allows further constrains on the Higgs boson couplings to the SM particles.
  - Higgs searches will continue. With the current dataset, can explore a large Higgs masses ranges up $\sim$1 TeV. This is as important as measuring the properties of the one found in the low mass.
- Understanding of the real nature of the Electroweak Symmetry Breaking $\rightarrow$ tool to explore new physics!

- Right now, experiments and accelerator are under a scheduled shutdown, it will allow to increase the $\sqrt{s}$ closer to the design energy ($\sim$ 13 TeV).
- Restarting in 2015, thousands of fb^{-1} of integrated luminosity will be collected. It will allow us to probe and push the limits of our current knowledge.

THANK YOU ...

BACKUP SLIDES ...

ATLAS Data-taking efficiency

ATLAS 2011 p–p run													
Inner Tracking			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	97.5	99.2	99.5	99.2	99.4	98.8	99.4	99.1	99.8	99.3

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and October 30th (in %), after the summer 2011 reprocessing campaign

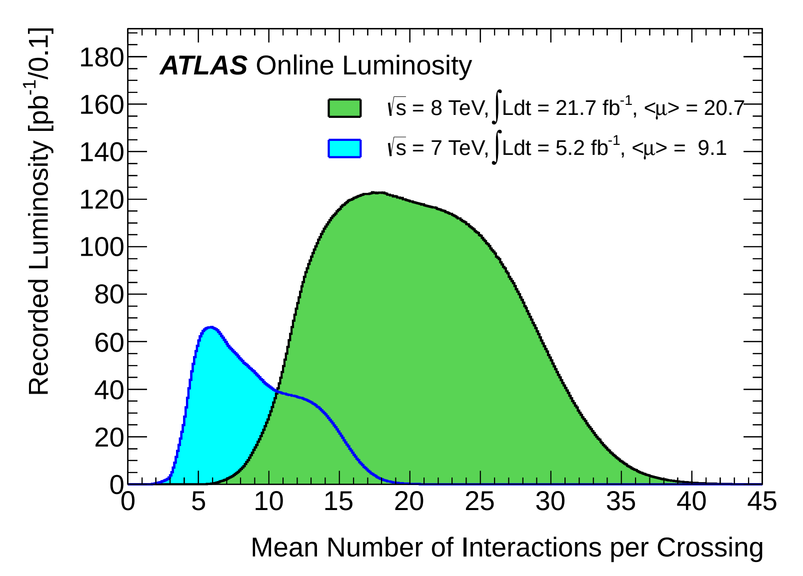
ATLAS p-p run: April-December 2012										
Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.1	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5
All good for physics: 95.5%										

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.3 fb^{-1} of recorded data.

ATLAS Detector DQ Status

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.0%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.9%
Tile calorimeter	9800	98.3%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	100%
LVL1 Muon RPC trigger	370 k	100%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	96.0%
RPC Barrel Muon Chambers	370 k	97.1%
TGC Endcap Muon Chambers	320 k	98.2%

Luminosity → pileup interactions



Standard Model Parameters

m_e	Electron mass	511 keV
m_μ	Muon mass	105.7 MeV
m_τ	Tau mass	1.78 GeV
m_u	Up quark mass	1.9 MeV
m_d	Down quark mass	4.4 MeV
m_s	Strange quark mass	87 MeV
m_c	Charm quark mass	1.32 GeV
m_b	Bottom quark mass	4.24 GeV
m_t	Top quark mass	172.7 GeV
θ_{12}	CKM 12-mixing angle	13.1°
θ_{23}	CKM 23-mixing angle	2.4°
θ_{13}	CKM 13-mixing angle	0.2°
δ	CKM CP-violating Phase	0.995
g_1 or g'	$U(1)$ gauge coupling	0.357
g_2 or g	$SU(2)$ gauge coupling	0.652
g_3 or g_s	$SU(3)$ gauge coupling	1.221
θ_{QCD}	QCD vacuum angle	$\sim$0
ν	Higgs vacuum expectation value	246 GeV
m_H	Higgs mass	$\sim$125 GeV

Two Higgs Doublet Model potential

- Natural path to explore $\rightarrow$ two identical complex scalar fields($SU(2)$)
- The 2HDM scalar potential is a Z_2 broken symmetric 2HDM

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = {} & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 + (m_{12}^2\Phi_1^\dagger\Phi_2 + \mathrm{h.c}) \\
& + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 \\
& + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c}]
\end{aligned}
$$

- In the CP-conserving case, parameters can be reduced to:
  3 masses $m_h, m_H, m_{H\pm}, m_A$,, 2 angles α, β and 1 potential parameter m_{12}^2

- For the VV final states $\rightarrow$ type I and II where there are not FCNC

Mass mixing matrix for the neutral, CP-even Higgs bosons:

$$\mathcal{M}_S^2 = (m_Z^2+\delta_1)\begin{bmatrix}\cos^2(\beta) & -\cos(\beta)\sin(\beta)\\ -\cos(\beta)\sin(\beta) & \sin^2(\beta)\end{bmatrix} + m_A^2\begin{bmatrix}\sin^2(\beta) & -\cos(\beta)\sin(\beta)\\ -\cos(\beta)\sin(\beta) & \cos^2(\beta)\end{bmatrix} + \begin{bmatrix}0 & 0\\ 0 & \frac{\delta}{\sin^2(\beta)}\end{bmatrix}$$

δ_1 and δ are radiative corrections involving top quarks and stops.
The couplings in a simplified MSSM model can be obtained from this mass mixing matrix as follows: The trace of the mass mixing matrix is taken and evaluated at the light Higgs boson mass of $m_h = 125.5$ GeV, allowing the δ_1 and δ corrections to be determined as a function of m_A and $\tan\beta$. Neglecting the sub-leading correction δ_1, then by substituting for δ the mass mixing matrix is fully determined by m_A and $\tan\beta$. This matrix is diagonalised to find the eigenvectors, and in particular those components of the eigenvector corresponding to the light Higgs boson, s_u and s_d. This allows the Higgs boson couplings to be determined as functions of m_A and $\tan\beta$ only:

$$\kappa_V = \frac{s_d(m_A,\tan\beta)+\tan\beta\ s_u(m_A,\tan\beta)}{\sqrt{1+\tan^2\beta}}$$

$$\kappa_u = s_u(m_A,\tan\beta)\,\frac{\sqrt{1+\tan^2\beta}}{\tan\beta}$$

$$\kappa_d = s_d(m_A,\tan\beta)\sqrt{1+\tan^2\beta},$$

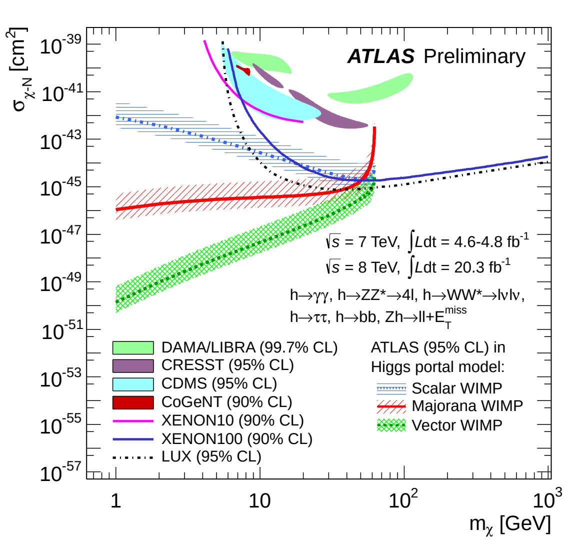
where the functions s_u and s_d are given by:

$$s_u = \frac{1}{\sqrt{1+\frac{\left(m_A^2+m_Z^2\right)^2\ \tan^2\beta}{\left(m_Z^2+m_A^2\ \tan^2\beta - m_h^2\left(1+\tan^2\beta\right)\right)^2}}}$$

$$s_d = \frac{\left(m_A^2+m_Z^2\right)\ \tan\beta}{m_Z^2+m_A^2\ \tan^2\beta - m_h^2\left(1+\tan^2\beta\right)}\, s_u.$$

Adding coupling constraints from SM Higgs channels

Observed (Expected) 95%CL on BR_{inv} Limit from 0.65 (0.84)%CL $\rightarrow$ 0.41 (0.55)



Higgs Portal Dark-Matter interpretation - $ZH \to$INV

$$\Gamma^{\text{Majorana}}(h \to \chi\chi) = \frac{\lambda_{h\chi\chi}^{2\ \text{Majorana}} v^2 m_h}{32\pi\Lambda^2}\left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{3/2}$$

$$\Gamma^{\text{Scalar}}(h \to \chi\chi) = \frac{\lambda_{h\chi\chi}^{2\ \text{Scalar}} v^2}{64\pi m_h}\left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2}$$

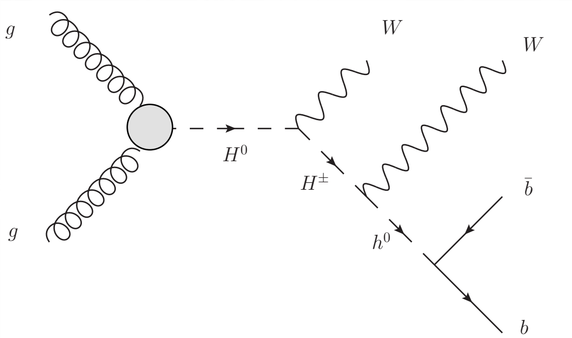
$$\Gamma^{\text{Vector}}(h \to \chi\chi) = \frac{\lambda_{h\chi\chi}^{2\ \text{Vector}} v^2}{256\pi m_\chi^4 m_h}\left[m_h^4 - 4m_\chi^2 m_h^2 + 12 m_\chi^4\right]\left[1 - \left(\frac{2m_\chi}{m_h}\right)^2\right]^{1/2}$$

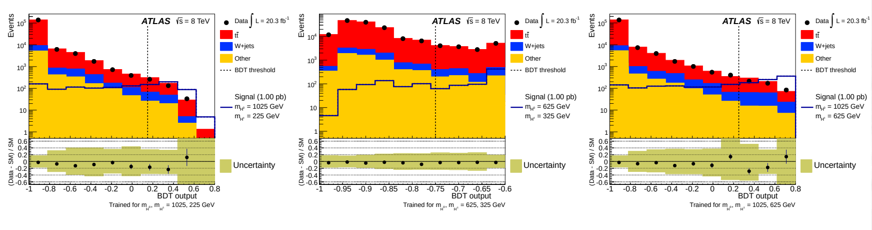
$$\sigma_{\chi N}^{\text{Majorana}} = \frac{\lambda_{h\chi\chi}^{2\ \text{Majorana}}}{4\pi\Lambda^2 m_h^4}\frac{m_\chi^2 m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

$$\sigma_{\chi N}^{\text{Scalar}} = \frac{\lambda_{h\chi\chi}^{2\ \text{Scalar}}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

$$\sigma_{\chi N}^{\text{Vector}} = \frac{\lambda_{h\chi\chi}^{2\ \text{Vector}}}{16\pi m_h^4}\frac{m_N^4 f_N^2}{(m_\chi + m_N)^2}$$

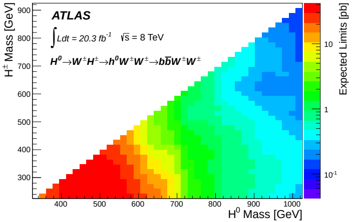
Multi-Higgs-boson cascade in *WWbb* events

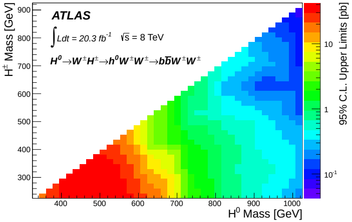


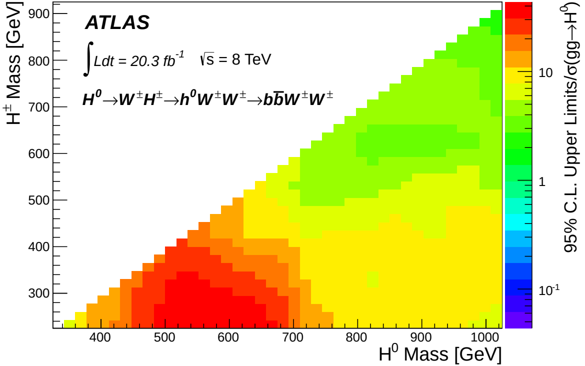


Documentation (very recent): Submitted to PRD - arxiv link

Multi-Higgs-boson cascade 95%CL limits

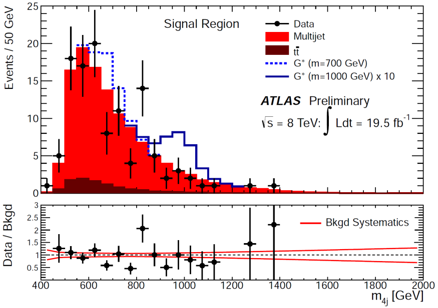


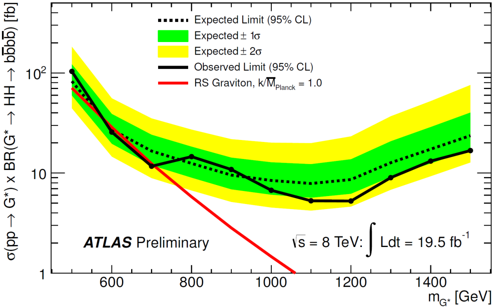




Documentation: Submitted to PRD - arxiv link

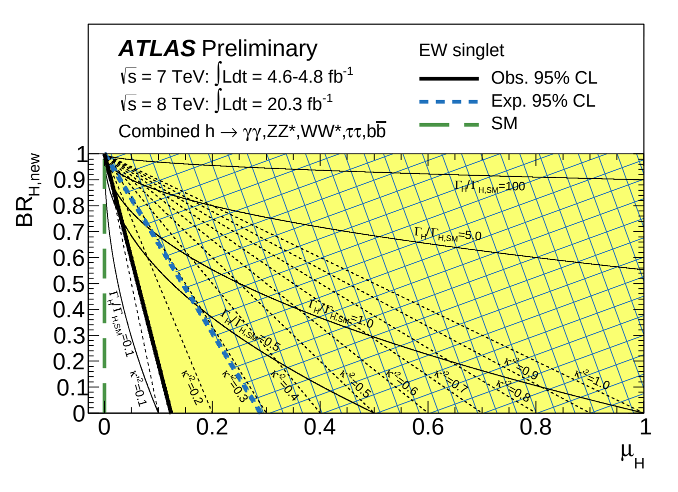
$hh \to b\bar{b}b\bar{b}$





Additional Real Electroweak Singlet (couplings constraints from SM Higgs channels)

- Simple extension of additional singlet that completes unitarity $\kappa^2 + \kappa'^2 = 1$



$95\%\text{CL } \kappa'^2 < 0.12(0.29)$

$H \to \gamma\gamma$
Categories $\to$ production mechanism

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

Category	N_D	N_B	N_S	ggF	VBF	WH	ZH	$t\bar{t}H$
Untagged	14248	13582	350	320	19	7.0	4.2	1.0
Loose high-mass two-jet	41	28	5.0	2.3	2.7	< 0.1	< 0.1	< 0.1
Tight high-mass two-jet	23	13	7.7	1.8	5.9	< 0.1	< 0.1	< 0.1
Low-mass two-jet	19	21	3.1	1.5	< 0.1	0.92	0.54	< 0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	8	4	1.2	< 0.1	< 0.1	0.43	0.57	0.14
Lepton	20	12	2.7	< 0.1	< 0.1	1.7	0.41	0.50
All categories (inclusive)	13931	13205	370	330	27	10	5.8	1.7

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:

Phys.Lett. B726 (2013) 88-119

Phys.Lett. B716 (2012) 1-29

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

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

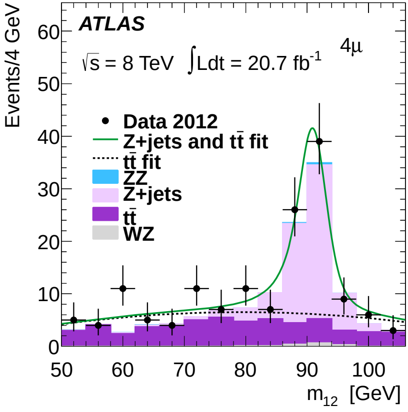
Documentation:

Phys.Lett. B726 (2013) 88-119

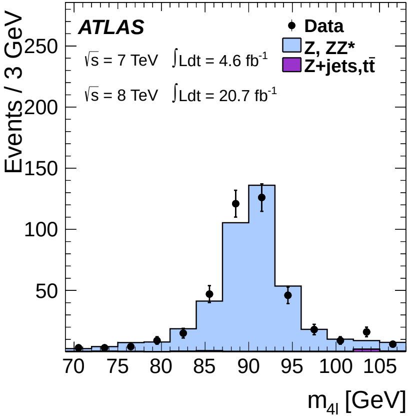
https://cdsweb.cern.ch/record/1460411/files/ATLAS-CONF-2012-092.pdf

Phys.Lett. B716 (2012) 1-29

- 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.



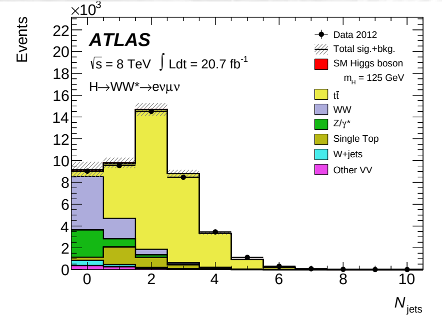
Inverted d_0 requirement for one of the two subleading leptons

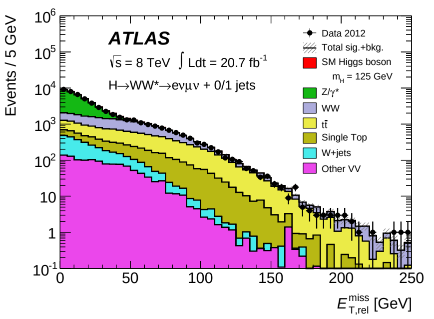


Relaxed kinematic requirements

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

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

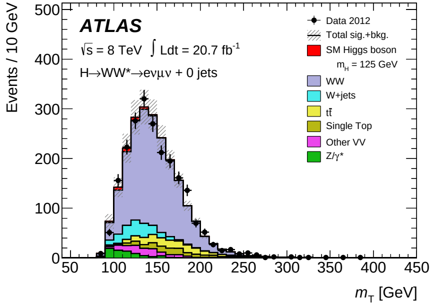




- A complete set of data-driven methods to estimate nearly **ALL** backgrounds from data.

Signal and Background yields

- ***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.



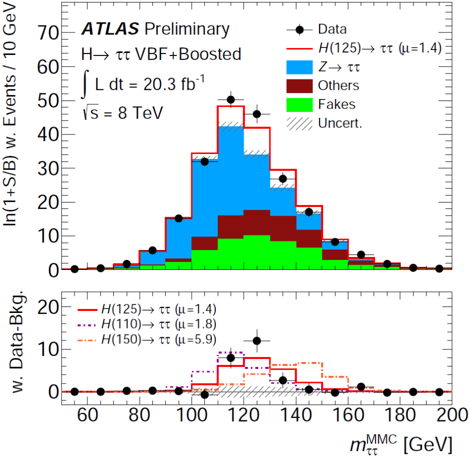
	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 2$	$N_{\text{jet}} \leq 2$
Observed	831	309	55
Signal	100 ± 21	41 ± 14	10.9 ± 1.4
Total background	739 ± 39	261 ± 28	36 ± 4
WW	551 ± 41	108 ± 40	4.1 ± 1.5
Other *VV*	58 ± 8	27 ± 6	1.9 ± 0.4
Top-quark	39 ± 5	95 ± 28	5.4 ± 2.1
Z+jets	30 ± 10	12 ± 6	22 ± 3
W+jets	61 ± 21	20 ± 5	0.7 ± 0.2

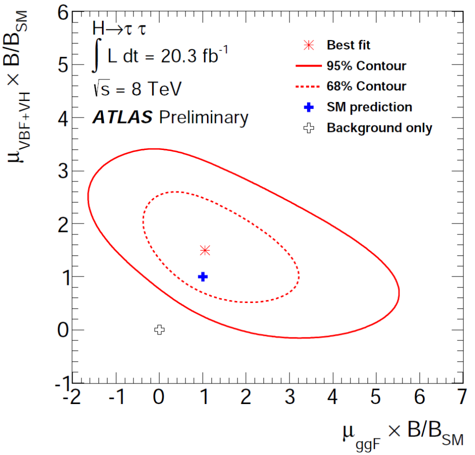
Systematic uncertainties 4ℓ channel

Source	Uncertainty (%)			
Signal yield	4μ	$2\mu 2e$	$2e2\mu$	$4e$
Muon reconstruction and identification	±0.8	±0.4	±0.4	-
Electron reconstruction and identification	-	±8.7	±2.4	±9.4
Reducible background (inclusive analysis)	±24	±10	±23	±13
Migration between categories				
ggF/VBF/VH contributions to VBF–like cat.	$\pm32/11/11$			
ZZ^* contribution to VBF–like cat.	±36			
ggF/VBF/VH contributions to VH–like cat.	$\pm15/5/6$			
ZZ^* contribution to VH–like cat.	±30			
Mass measurement	4μ	$2\mu 2e$	$2e2\mu$	$4e$
Lepton energy and momentum scale	±0.2	±0.2	±0.3	±0.4

Fermionic channels

Direct evidence of Higgs-fermion coupling → 3.7σ





Event Selection - $ZH \rightarrow$INV

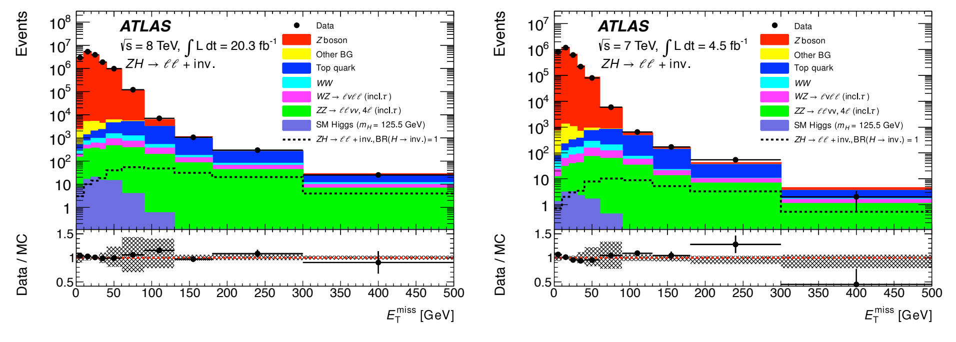
- Object selection:
  Well identified leptons:
  μ (Inner-Detector+Muon-Spectrometer),
  e (Tight Electromagnetic Shower-Shape requirements)
  Track & Caloremeter isolations, impact parameter requirements.

- 2 opposite sign same flavour leptons compatible with a *Z* decay
- Missing Transverse Energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) $E_{\mathrm{T}}^{\mathrm{miss}} >$90 GeV
- Third lepton veto (To reduced *WZ* background)
- **Full jet veto:** (To reduce Top background)
- Series of requirements to ensure that the $E_{\mathrm{T}}^{\mathrm{miss}}$ is genuine. i.e. it isn't produced by leptons or jets that are miss-measured. (To reduce $Z + jets$ background)

Backgrounds - $ZH \rightarrow$INV

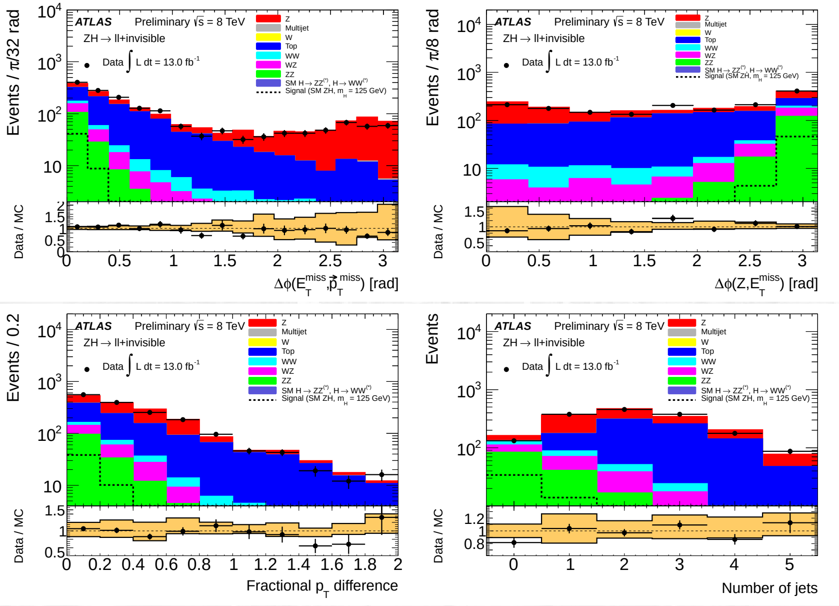
- ZZ:
  Main, irreducible background **MC estimated.**
  Corroborated by high end 4ℓ and ZZ measurements
- WZ:
  Sub-leading background, **MC estimated.**
  Checked using a control sample with a third lepton
- Top, WW, $Z \rightarrow \tau\tau$: non resonant backgrounds
  Taken form a $e\mu$ **Control Region.**
  Additional CR: $m_{\ell\ell}$ side bands, with and without b-jet tagging/veto
- Z+jets:
  Taken from a **2D sideband CR** using $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ and frac. p_T difference
  Additional control region: γ+jets $E_{\mathrm{T}}^{\mathrm{miss}}$ template, $\gamma - Z$ kinematic match
- QCD and W+jets:
  Taken from **Control Regions using a fake-lepton template**
  Additionally: Loose no Medium templates, and like-sign control samples
- SM Higgs:
  Mainly $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ and $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$). Suppressed by large $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement and $m_{\ell\ell}$ window. **MC estimated** $\rightarrow$ negligible.

E_T^{miss} - $ZH \to$INV (preselection cuts)



This analysis is about understanding $E_{\mathrm{T}}^{\mathrm{miss}}$ tails in a very precise corner of our phase space

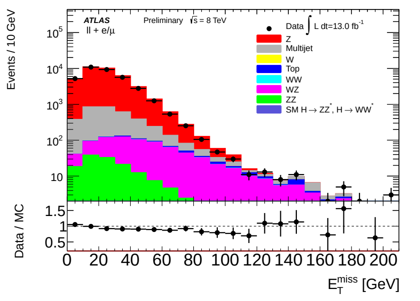
Discriminating variables (after $m_{\ell\ell}$ and E_T^{miss} requirements)

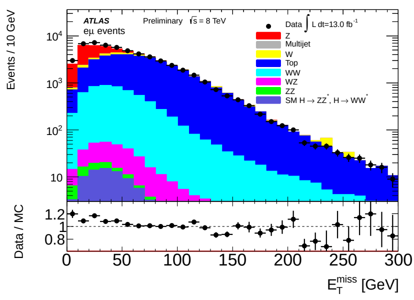


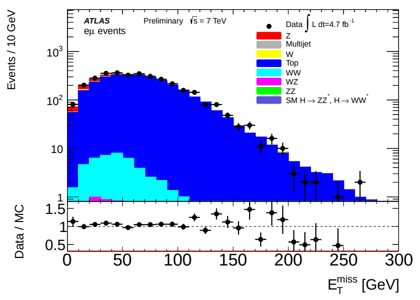
Systematic Uncertainties - $ZH \rightarrow$INV

- Signal and Diboson ZZ/WZ:
  - Theory
    - Signal:
      PDF($q\bar{q}$)=4.2%, QCD Scale=$^{2.1\%}_{-2.7\%}$, Higgs P_T.
    - ZZ and WZ:
      PDF($q\bar{q}$)=4%, QCD Scale=5%, MC model=9.1%
  - Experimental:
    - Energy Scale and Energy Resolution Uncertainties:
      For Electrons, Muons and Jets.
    - Pile-up Uncertainty
  - Luminosity: 1.8% (3.6)% for 2011 (2012)
  - They affect both, shapes and normalisations):
- Backgrounds measured from data using Control Regions:
  - WW/Top/$Z\tau\tau$: $\rightarrow$ ($e\mu$)
  - Z+jets: $\rightarrow$ (2-Dimensional side-band)
  - W+jets/QCD: $\rightarrow$ (Fake-lepton template)

Control Regions examples (3ℓ for WZ, and $e\mu$ for non-resonant backg)

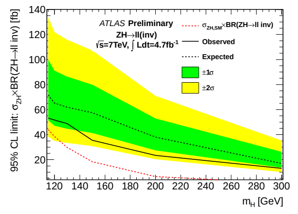




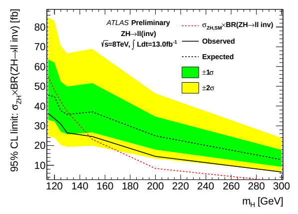


Looking for additional resonances (Invisible) - $ZH \rightarrow$INV

2011



2012



Combined