Measurement of properties of the Higgs boson in bosonic decay channels using the ATLAS detector

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on behalf of the ATLAS Collaboration

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Introduction

* Since the July 2012 Higgs discovery, the LHC dataset has more than doubled

* We are now in the precision measurement era!

  * More precise mass measurement, reduced experimental uncertainties

  * Event categorization: increase production mode sensitivity and test couplings

  * First differential cross-section measurement ($\gamma\gamma$ channel)

* Will look at latest measurements with 25 fb^{-1} of data at $\sqrt{s}$ = 7 & 8 TeV

  * H→$\gamma\gamma$, H→ZZ*→4l, and H→WW*→$\ell\nu\ell\nu$
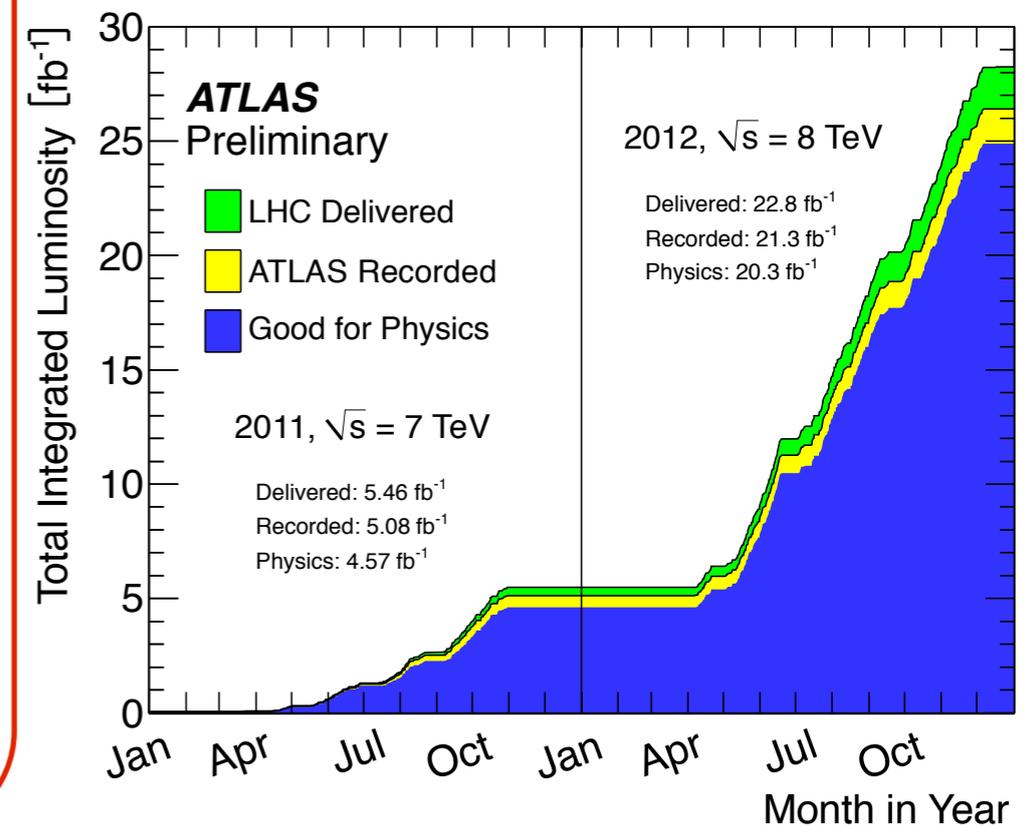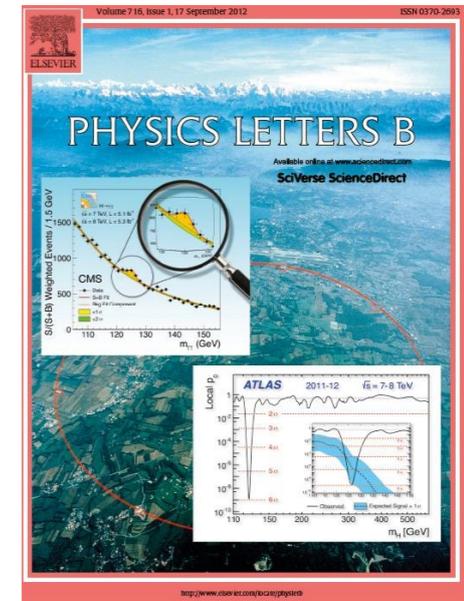
Higgs production and decay modes
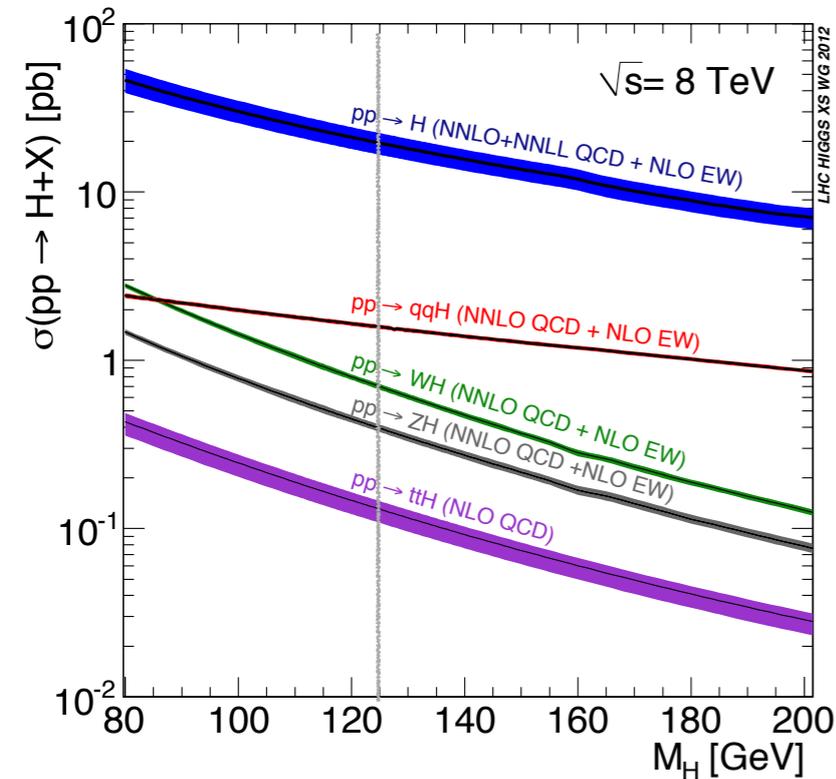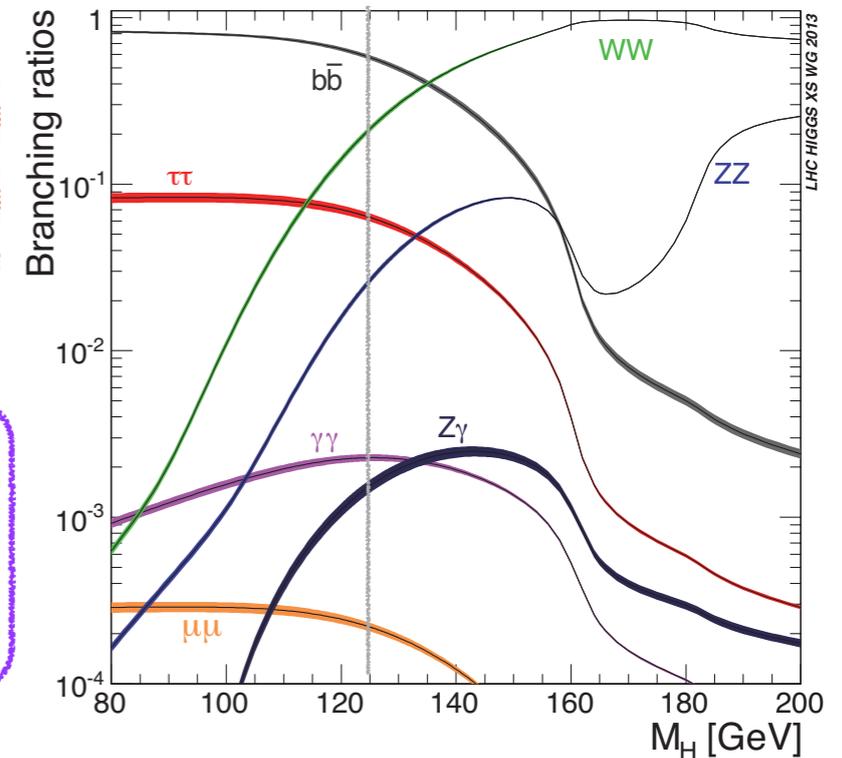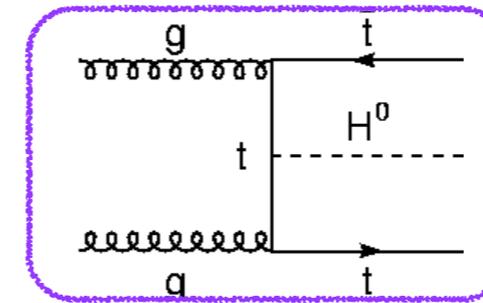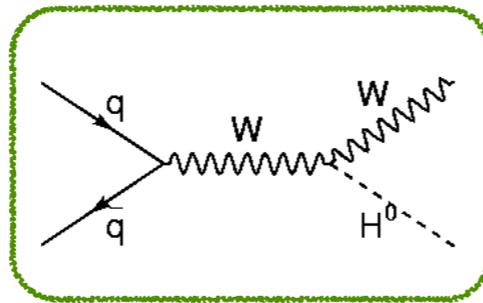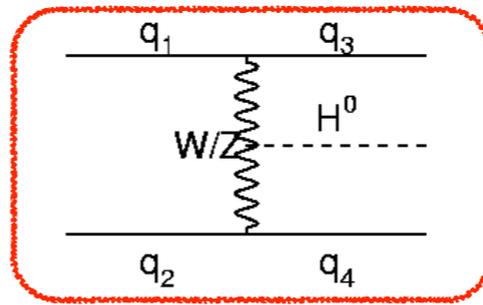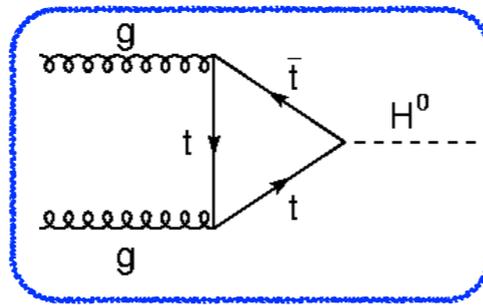
Production modes

* **ggF (87.2%)**: signature from Higgs decay only

* **VBF (7.1%)**: dijet signature

* **VH (5.1%)**: look for vector boson decay in final state

* **ttH (0.6%)**: very rare, but can test top coupling

Decay modes

* H→WW*→ℓνℓν: high statistics, poor mass resolution

* H→ZZ*→4ℓ: golden channel; good mass resolution, but low statistics

* H→γγ: distinct, clean signature, but low BR, high background

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H→γγ: event selection

* Clean, distinct signature:

  * Two high-p_T, isolated photons in range 100 GeV $< M_{\gamma\gamma} <$ 160 GeV

  * Photon identification based on EM calorimeter shower shapes: 85-95% efficiency

* Backgrounds modelled using fits to the data:

  * Diphoton continuum (~75%)

  * γ + jet, dijet, Drell-Yan (~25%)

VBF H → γγ candidate

Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC
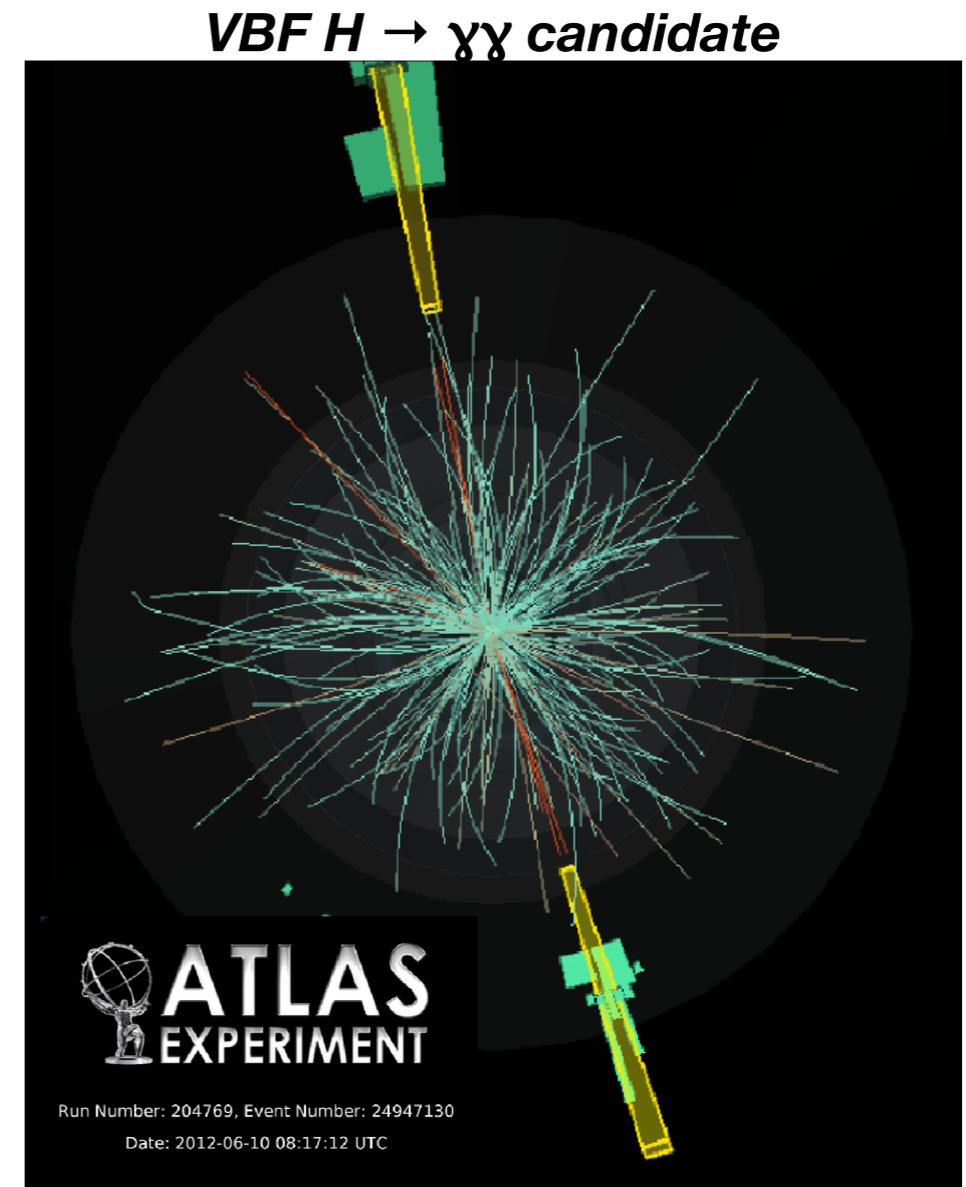
H→γγ: event categorization

* Events subdivided into 14 categories

  * Based on production mode, mass resolution, signal / background

  * Improved sensitivity to various production modes

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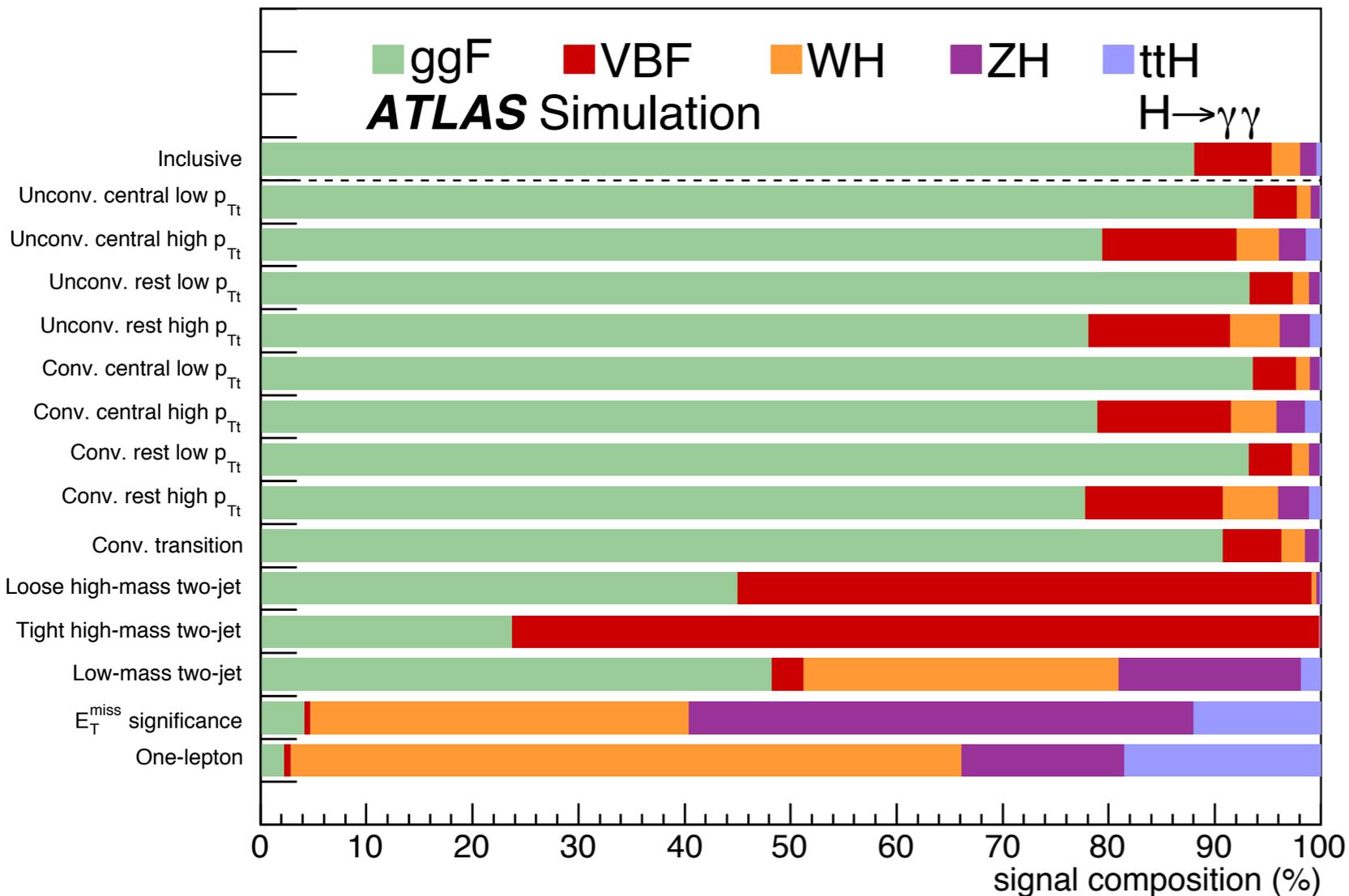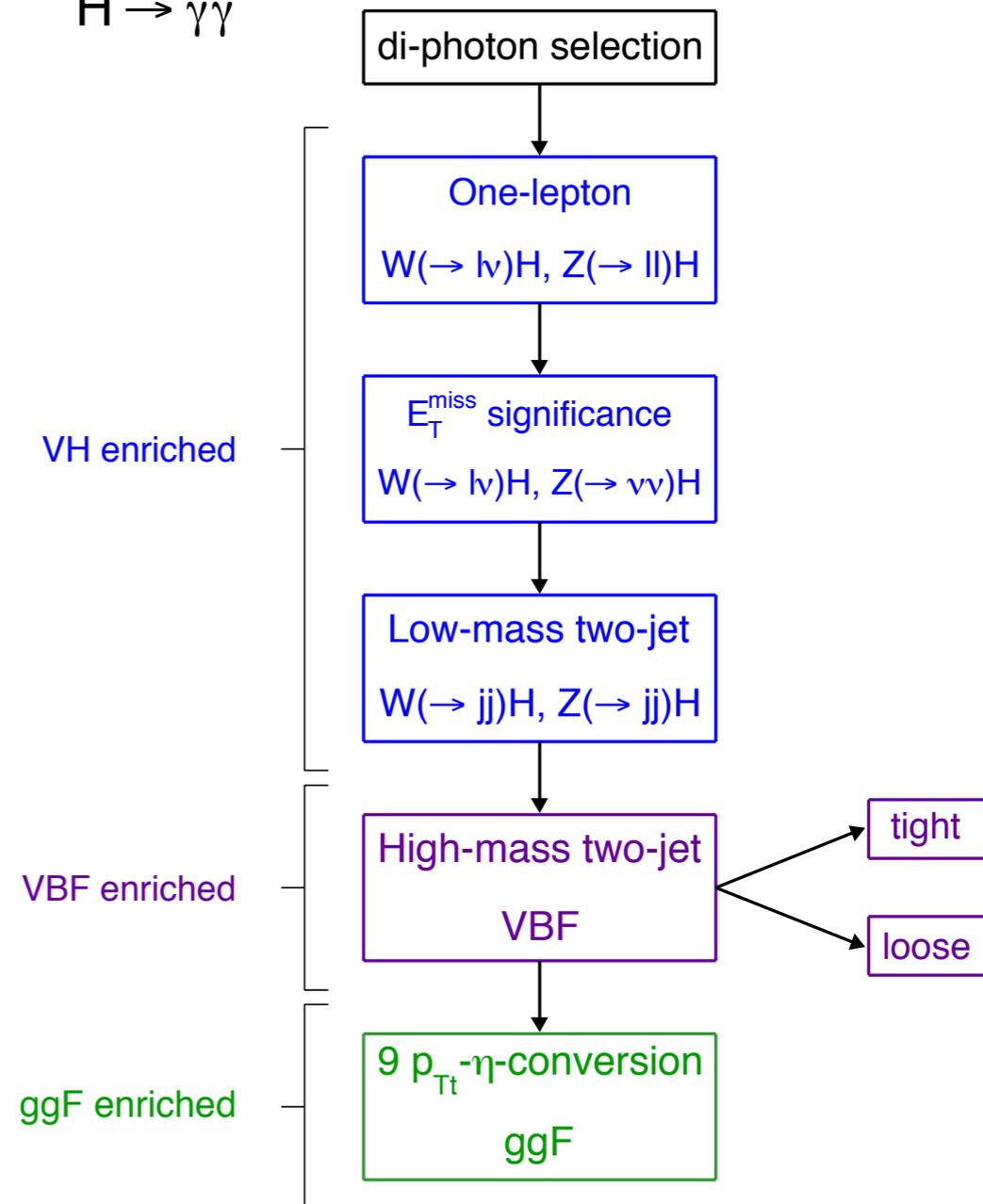
H→γγ: mass & signal strength

* Diphoton invariant mass:

$$m_{\gamma\gamma} = \sqrt{2E_1 E_2(1 - cos(\theta))}$$

* Signal modelled using a Crystal Ball function + Gaussian

* Observed excess with largest local significance: 7.4σ @ m_H = 126.5 GeV

* Best fit mass:
  m_H = 126.8 ± 0.2 (stat.) ± 0.7 (syst.) GeV

* Signal strength (at m_H = 125.5 GeV):

$$\mu = 1.57^{+0.33}_{-0.28}$$
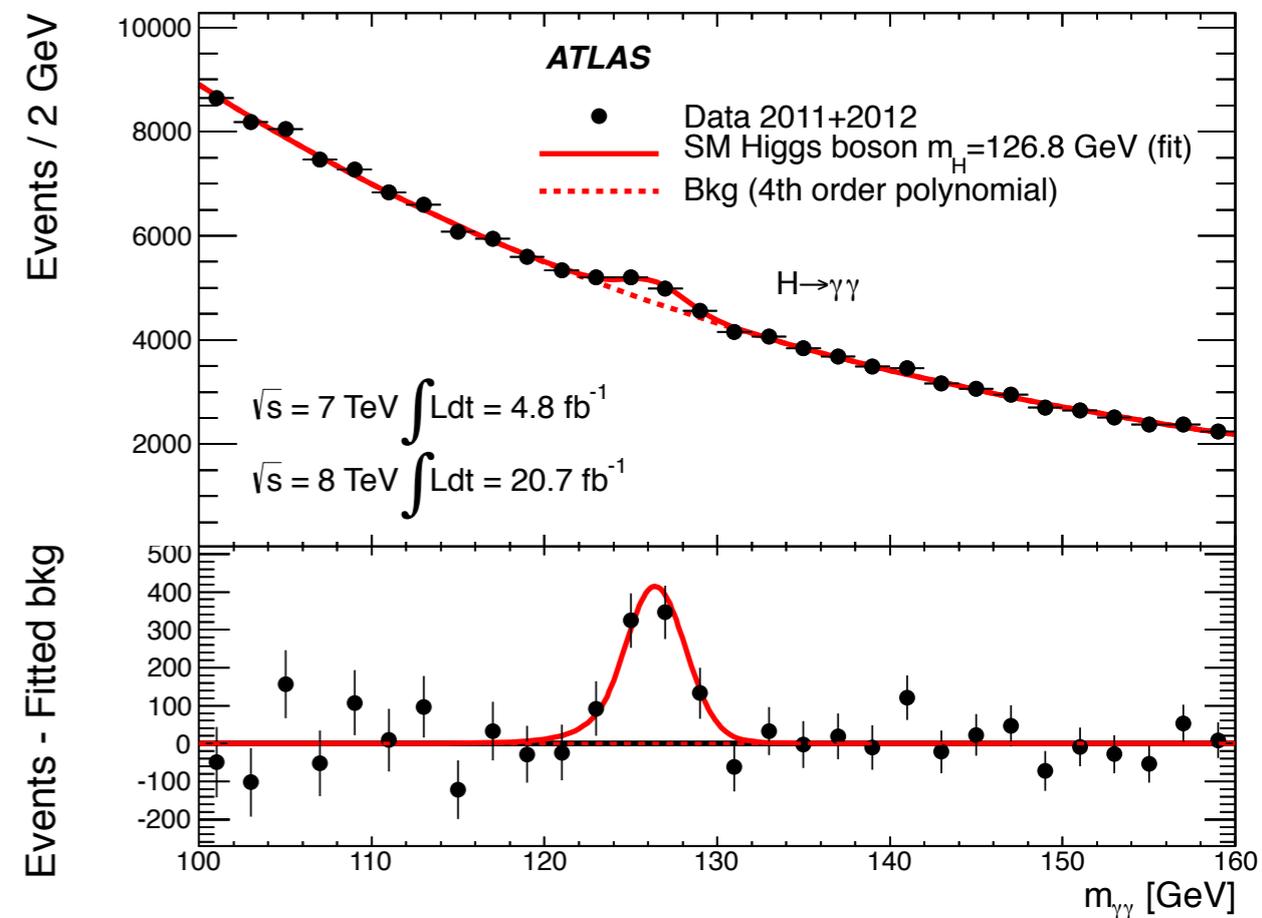
H→γγ: differential cross-section

* Measurements are binned in eight observables sensitive to Higgs kinematics, production modes, QCD corrections, etc.

* Signal yield extracted with unbinned likelihood fit to $M_{\gamma\gamma}$ distribution

* Unfold to particle level using correction factors: $c_i = n_{i,\,\text{particle level}} / n_{i,\,\text{reco}}$

* No significant deviation from SM expectation

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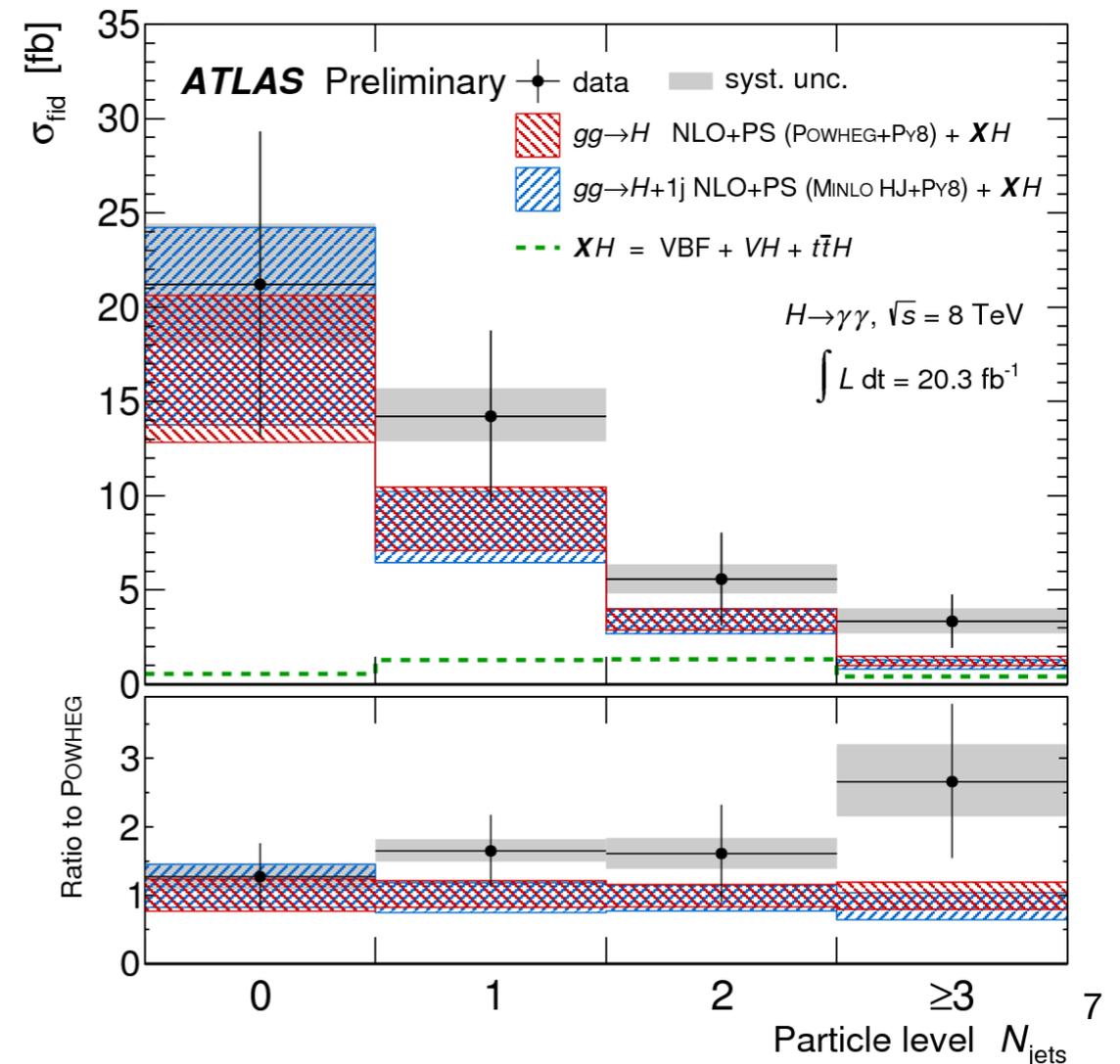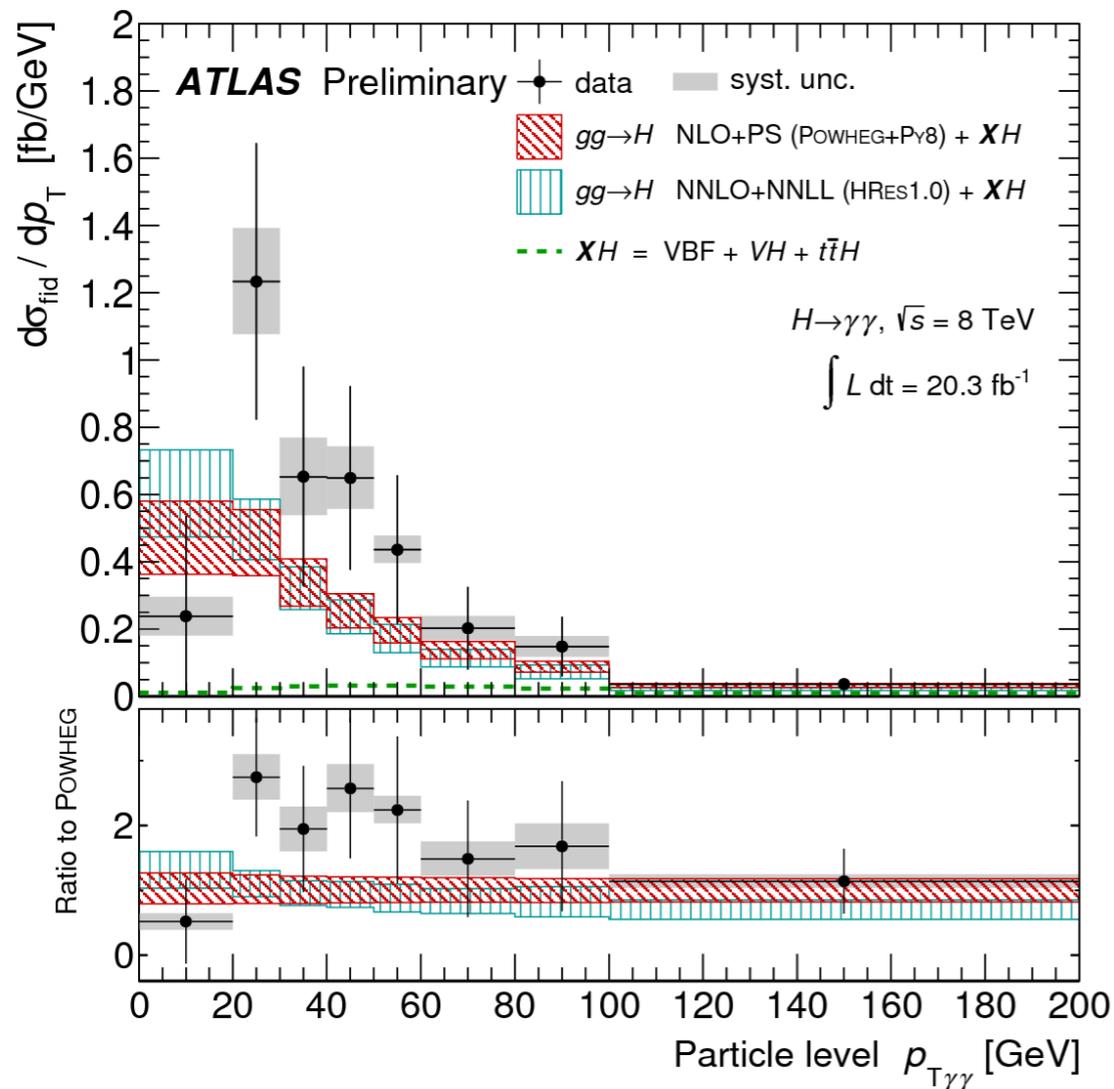
H→ZZ(*)→4ℓ: event selection

* Two same-flavour, opposite-sign pairs (4e, 4μ, 2e2μ, 2μ2e)

* Improvements in 2012 analysis:

  * Likelihood-based electron ID: 2x reduction in background

  * FSR photon recovery & Z mass constraint: improved mass resolution

* Data-driven reducible Z+jets background estimation (different methods for subleading ee, μμ channels)

* Event categorization:

  * VBF: two widely separated, high-p_T jets

  * VH: additional lepton with p_T > 8 GeV

  * ggF: everything else

H→ZZ(*)→4e candidate event

ATLAS EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
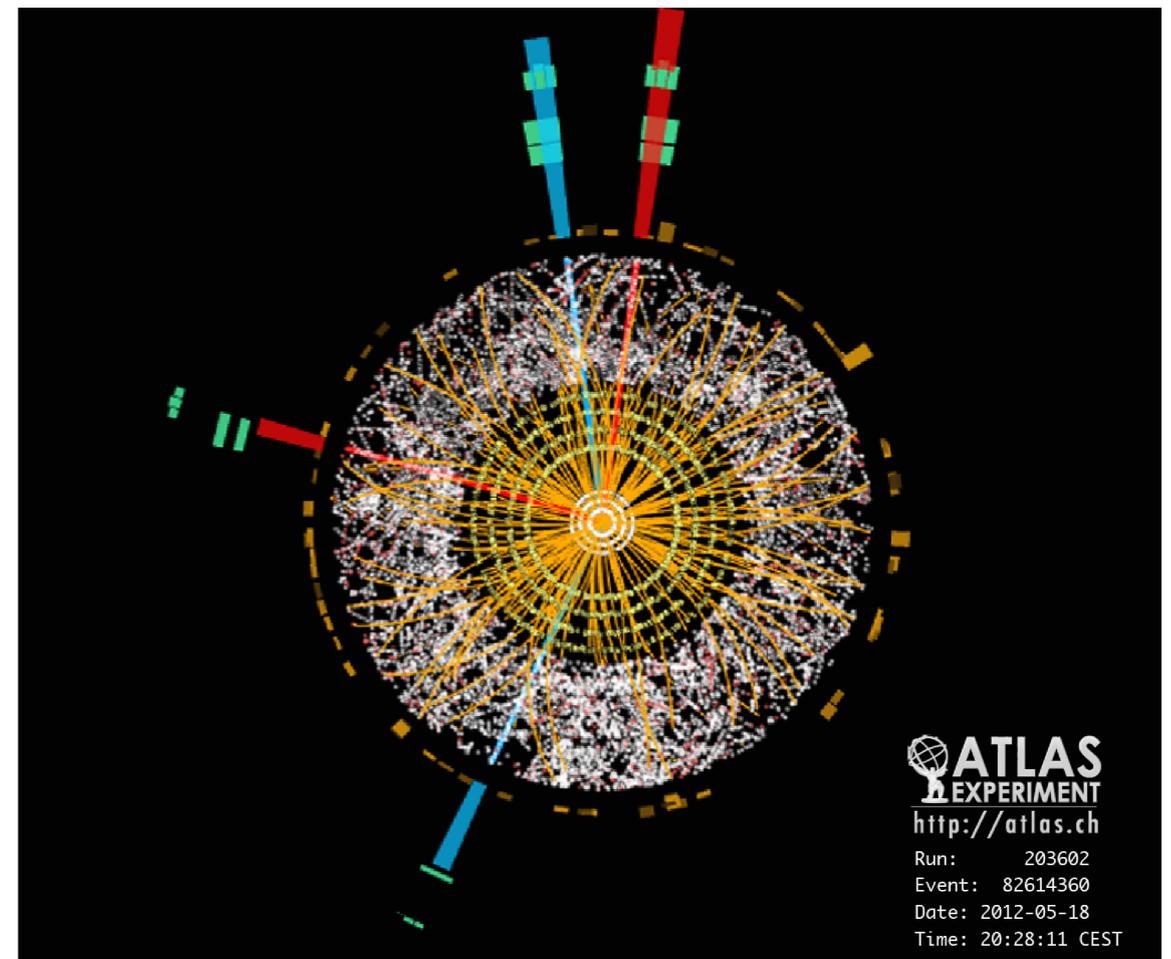
H→ZZ(*)→4ℓ: mass, μ, and categories

* Observed excess with local significance: 6.6σ at m_H = 124.3 GeV

* Best fit mass:

$$m_H = 124.3^{+0.6}_{-0.5}\,(\text{stat})^{+0.5}_{-0.3}\,(\text{syst})\ \text{GeV}$$

* Signal strength (at m_H = 125.5 GeV):

$$\mu = 1.44^{+0.40}_{-0.35}$$

* Categories:

  * 1 VBF-like candidate in mass window 125 ± 5 GeV (0.4 expected)

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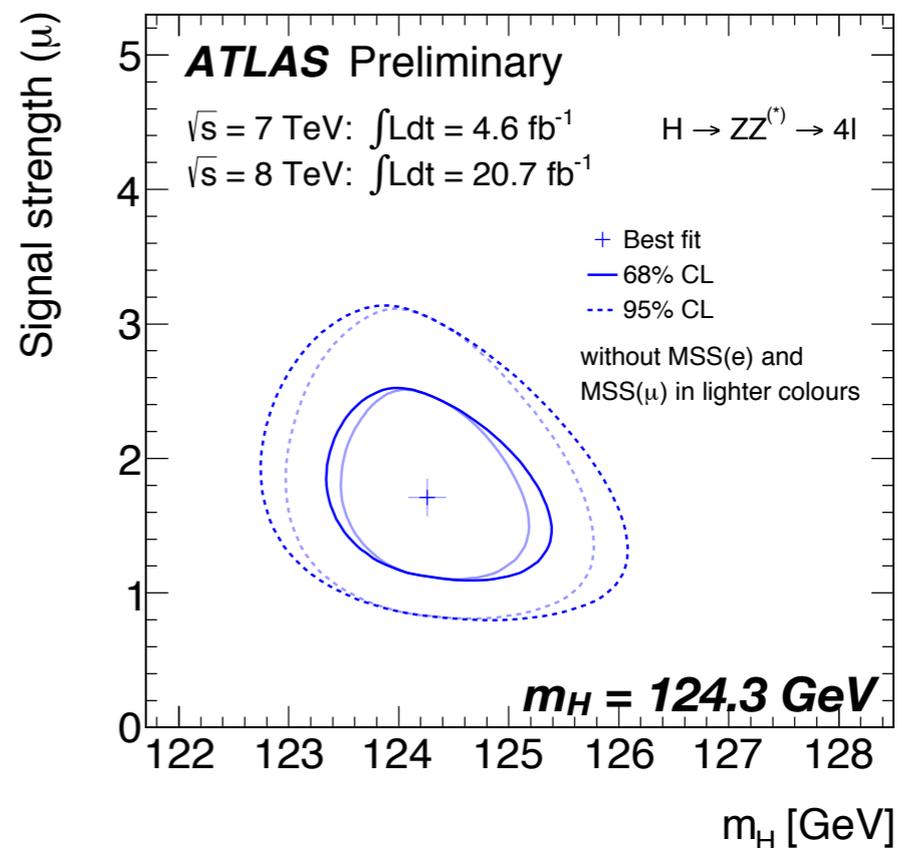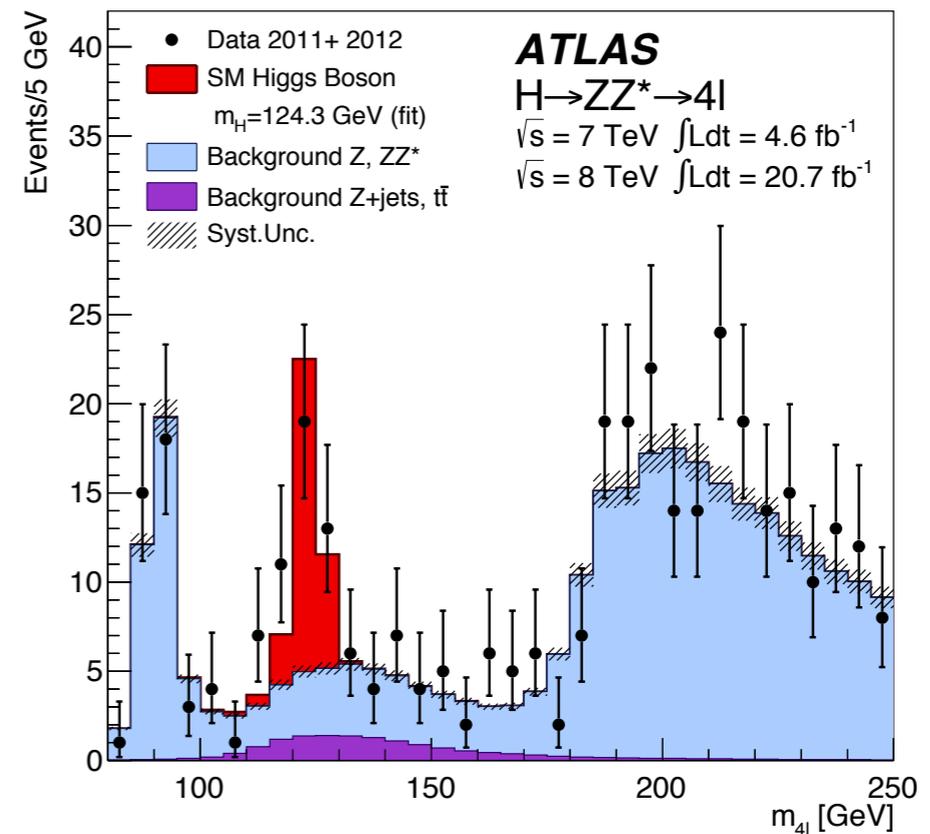
H→ZZ(*)→4ℓ: spin / parity

✱ Production / decay angles and Z_1, Z_2 masses sensitive to the spin / parity

✱ Test $J^P = 0^\pm$, $1^\pm$, $2^\pm$ hypotheses using BDT & MELA methods

✱ Results consistent with 0^+ hypothesis, in agreement with WW & ɣɣ

  ✱ 0^-, 1^+ excluded at 97.8% CL or higher

  ✱ 1^- excluded at 94% CL or higher

  ✱ 2^+: 81.8% CL
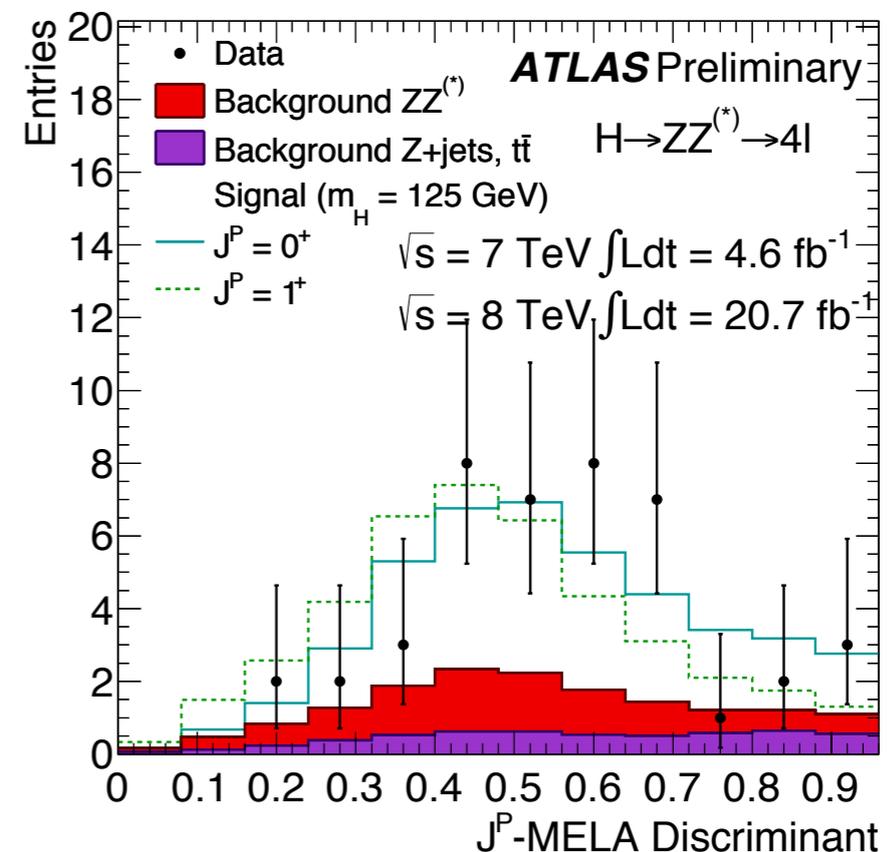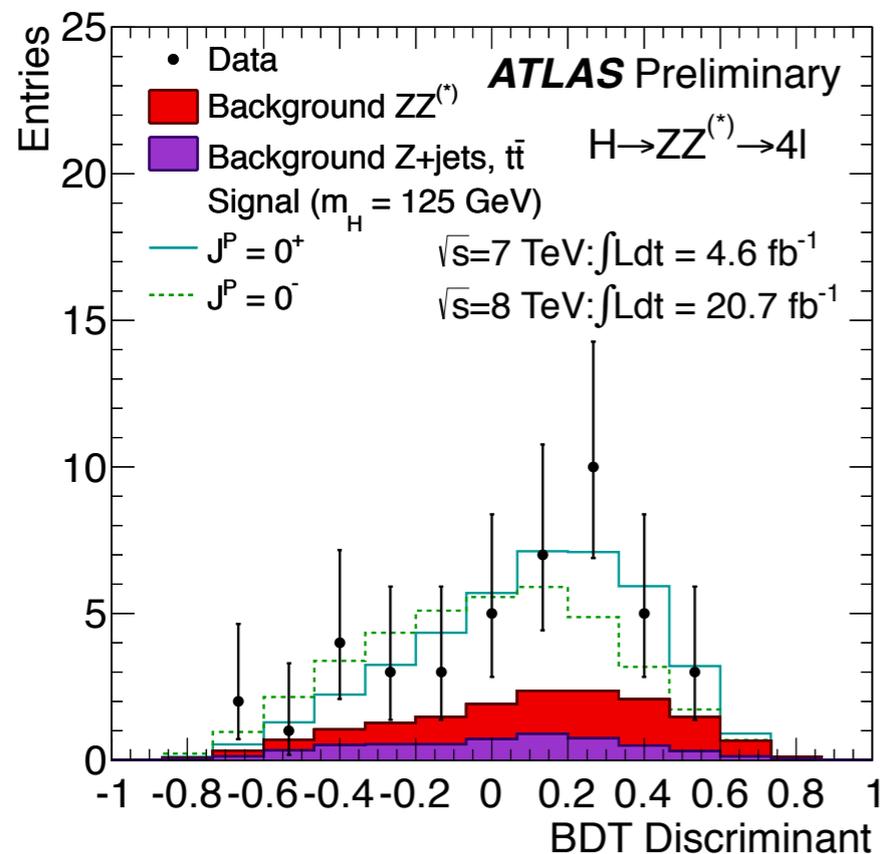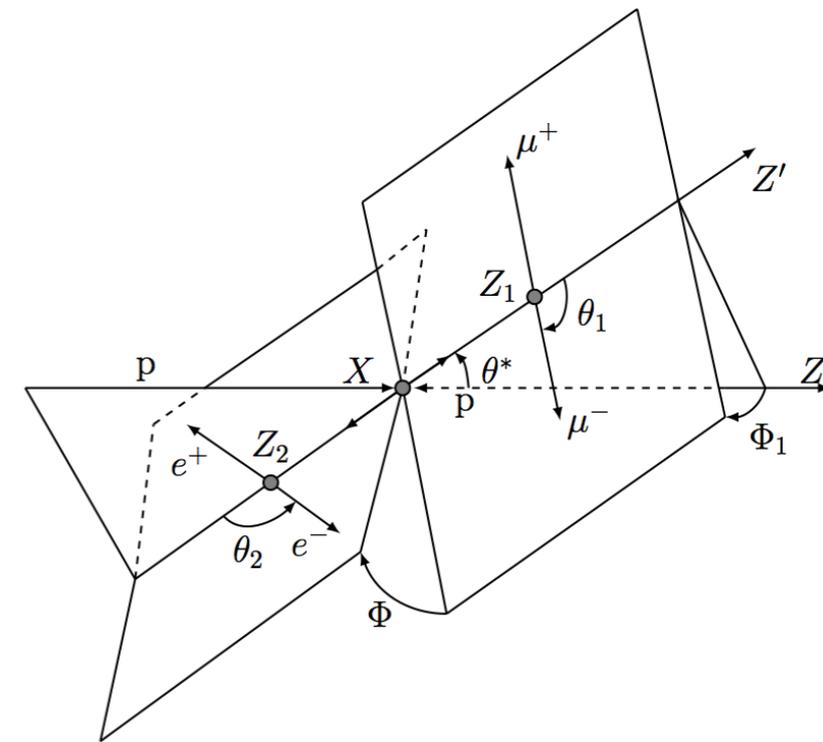
H→WW[*]→ℓνℓν: event selection

* Two isolated, high-p_T leptons with opposite charge

* Large missing E_T

* Events categorized in jet multiplicity & flavour (eνμν, eνeν/μνμν)

    * $N_{jets} \leq 1$: ggF-dominated production, WW-dominated background

    * $N_{jets} \geq 2$: VBF-dominated production, $t\bar{t}$-dominated background

* Poor mass resolution due to missing E_T

* Transverse mass:

$$m_T = ((E_T^{\ell\ell} + E_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}|^2)^{1/2}$$

$$E_T^{\ell\ell} = (|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2)^{1/2}$$

VBF H→WW*→eνμν candidate event

Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET
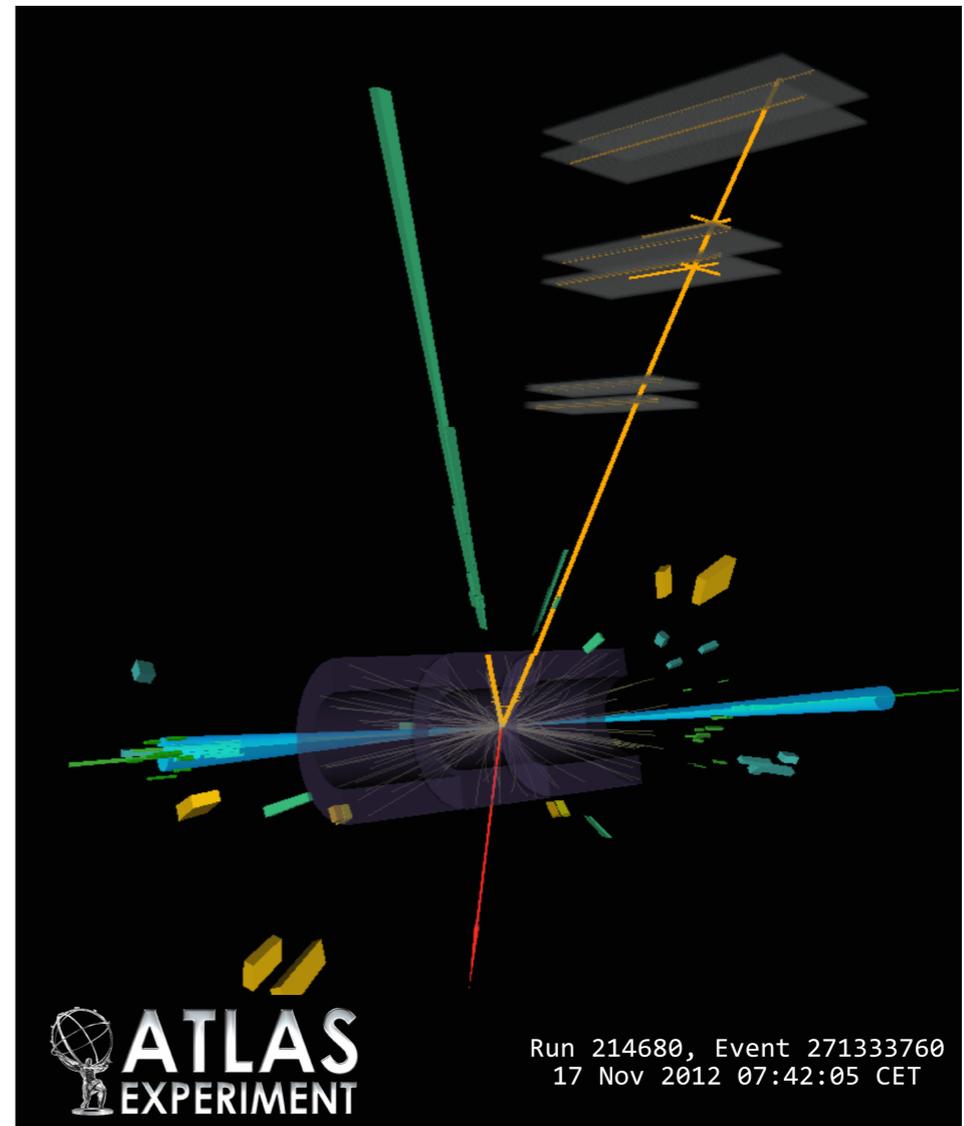
H→WW$^{(*)}$→ℓνℓν: transverse mass

* Excess of events observed in data

* Maximum local significance: 4.1σ at m_H = 140 GeV

* Signal strength at m_H = 125.5 GeV:

$$\mu = 1.00^{+0.32}_{-0.29}$$

0/1 jet category

2+ jets category

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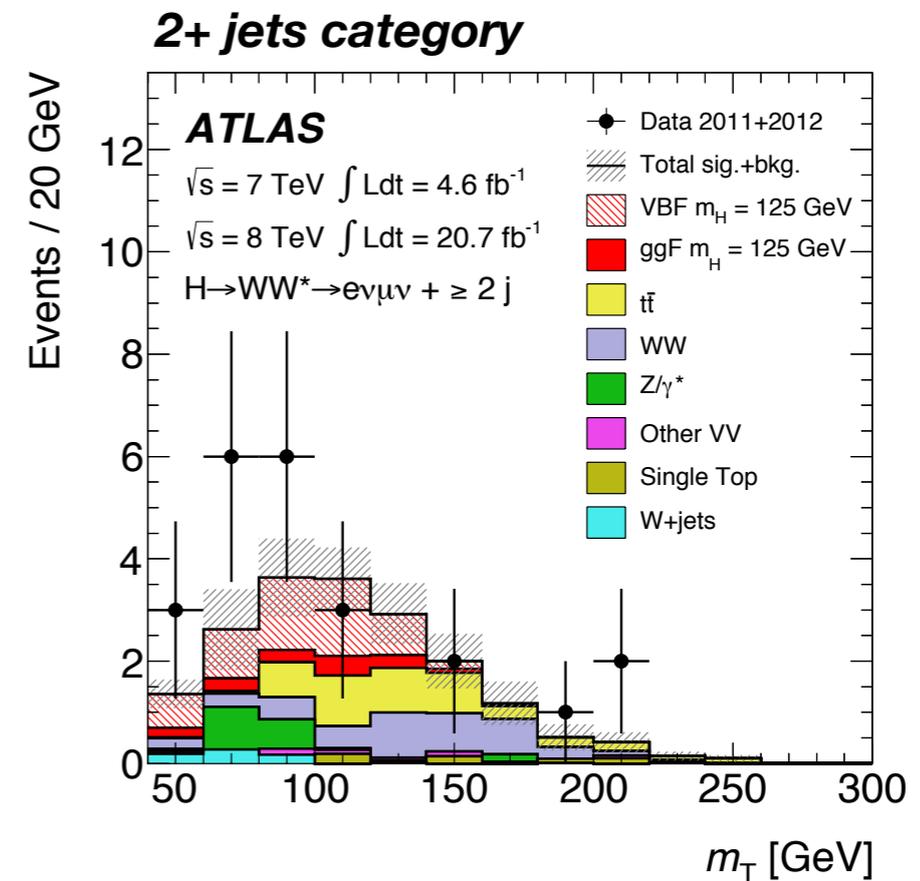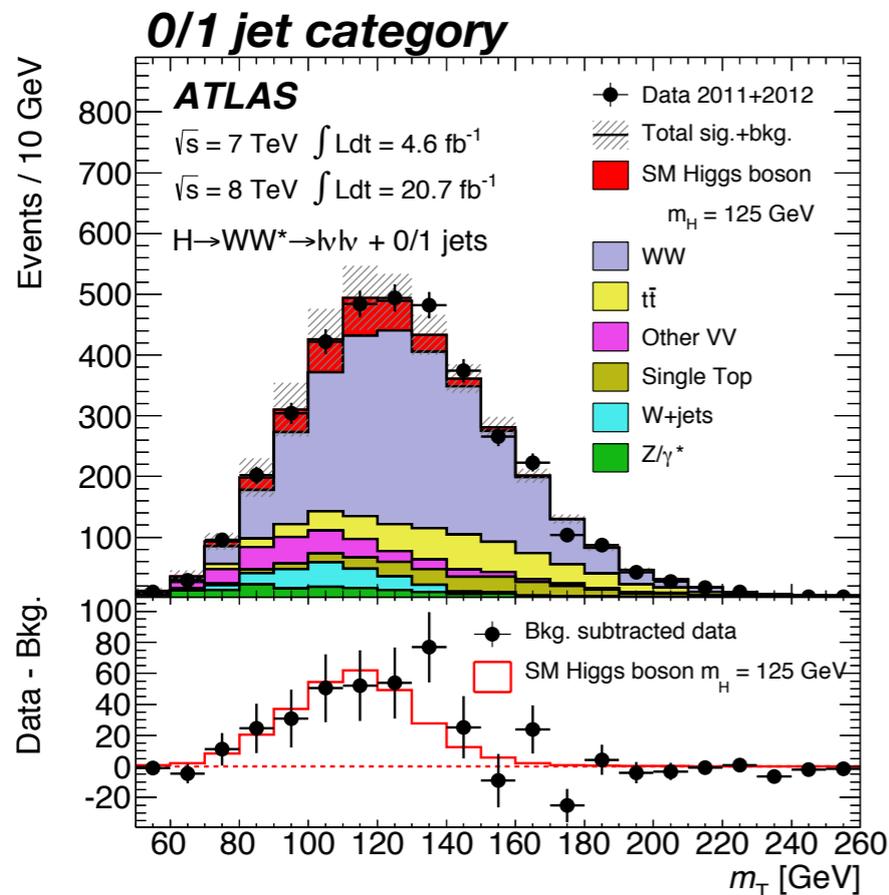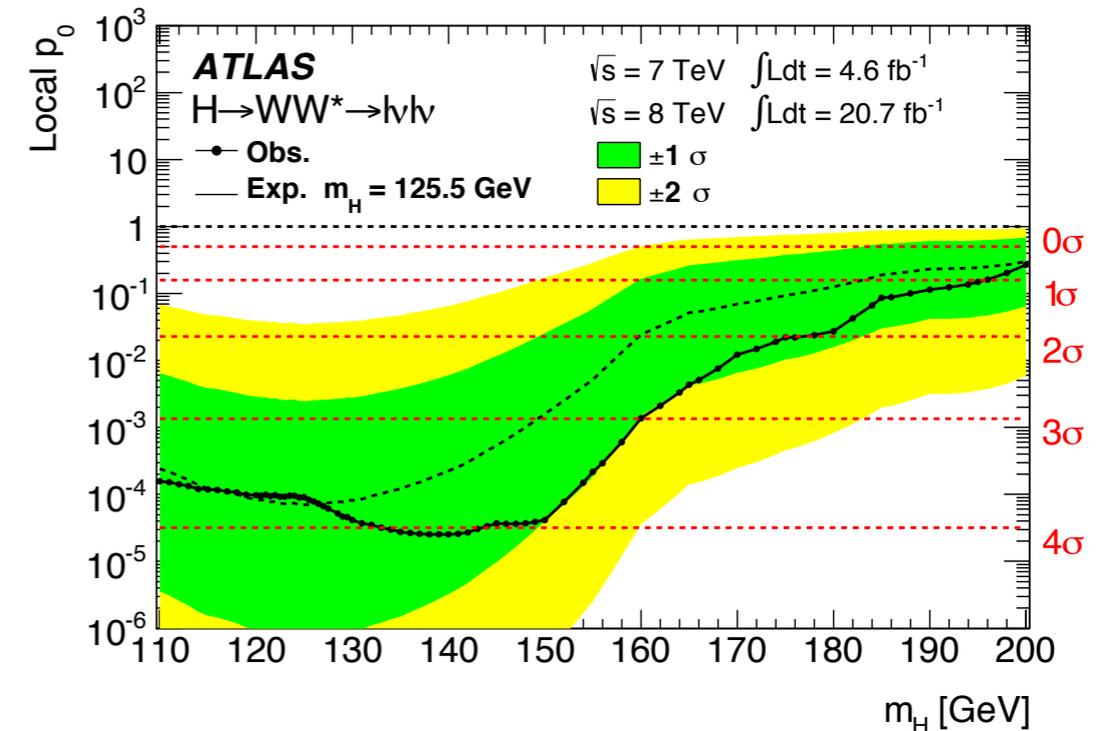
Combined results: mass & signal strength

* Combined mass using H→γγ and H→ZZ$^{(*)}$→4ℓ channels:

$$m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys}) \text{ GeV}$$

* See J. Saxon's talk for more combined measurements
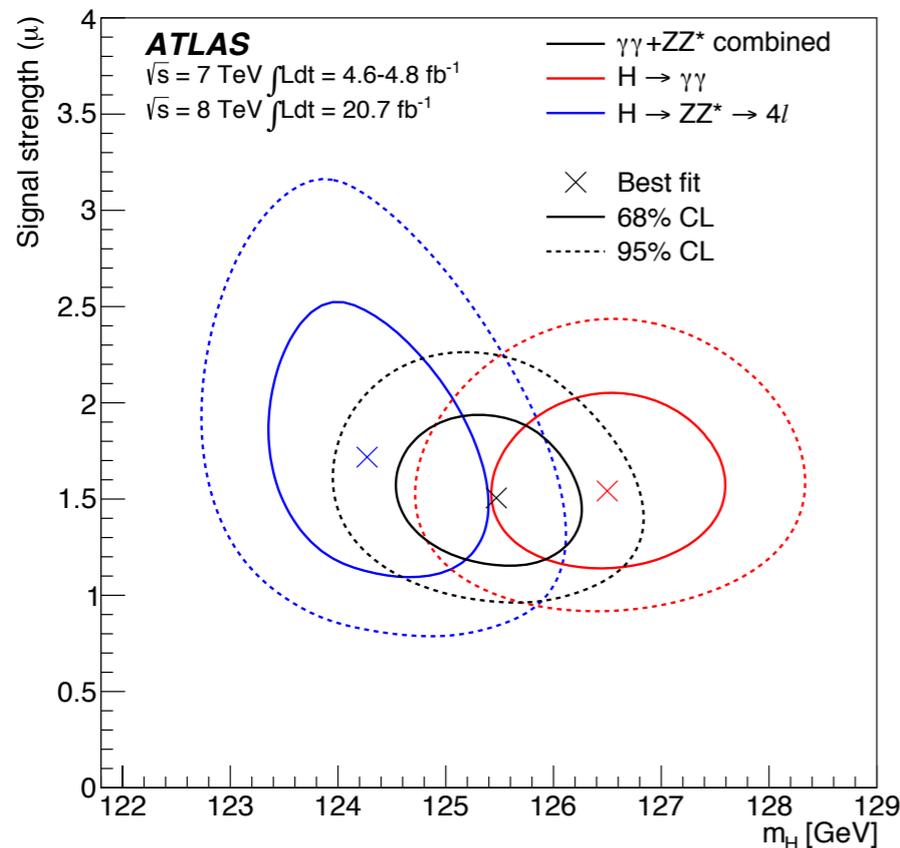
ATLAS Prelim.
$m_H = 125.5$ GeV

— σ(stat.)
— σ(sys inc. theory)
— σ(theory)

Total uncertainty
± 1σ on μ

Channel		stat	sys inc. theory	theory
H → γγ	$\mu = 1.57^{+0.33}_{-0.28}$	+0.23 / −0.22	+0.24 / −0.18	+0.17 / −0.12
H → ZZ* → 4l	$\mu = 1.44^{+0.40}_{-0.35}$	+0.35 / −0.32	+0.20 / −0.13	+0.17 / −0.10
H → WW* → lνlν	$\mu = 1.00^{+0.32}_{-0.29}$	+0.21 / −0.21	+0.24 / −0.19	+0.16 / −0.08
Combined H→γγ, ZZ*, WW*	$\mu = 1.35^{+0.21}_{-0.20}$	+0.14 / −0.14	+0.16 / −0.14	+0.13 / −0.11
W,Z H → b$\bar{\text{b}}$	$\mu = 0.2^{+0.7}_{-0.6}$	±0.5	±0.4	<0.1
H → ττ (8 TeV data only)	$\mu = 1.4^{+0.5}_{-0.4}$	+0.3 / −0.3	+0.4 / −0.3	+0.2 / −0.1
Combined H→b$\bar{\text{b}}$, ττ	$\mu = 1.09^{+0.36}_{-0.32}$	+0.24 / −0.24	+0.27 / −0.21	+0.08 / −0.04
Combined	$\mu = 1.30^{+0.18}_{-0.17}$	+0.12 / −0.12	+0.14 / −0.11	+0.10 / −0.08

$\sqrt{s} = 7$ TeV $\int$Ldt = 4.6-4.8 fb^{-1}
$\sqrt{s} = 8$ TeV $\int$Ldt = 20.3 fb^{-1}

-0.5 0 0.5 1 1.5 2

Signal strength (μ)

ATLAS
$\sqrt{s} = 7$ TeV $\int$Ldt = 4.6-4.8 fb^{-1}
$\sqrt{s} = 8$ TeV $\int$Ldt = 20.7 fb^{-1}

— γγ+ZZ* combined
— H → γγ
— H → ZZ* → 4l

× Best fit
— 68% CL
---- 95% CL

Signal strength (μ)
m_H [GeV]

Summary

* With 25 fb^{-1} of data collected in 2011-2012, ATLAS can claim discovery of the Higgs boson in two individual dibosonic decay channels

* A wide variety of property measurements have been performed in the H→ɣɣ, H→ZZ$^{(*)}$→4ℓ, and H→WW$^{(*)}$→ℓνℓν channels

    * Mass, signal strength, differential cross-sections, spin / parity

    * No significant deviation from Standard Model predictions

ATLAS results:

✱ Discovery paper:

     ✱ Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ([Phys. Lett. B 716 (2012), 1-29](#))

✱ Updated diboson decay channel results:

     ✱ Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC ([Phys. Lett. B 726 (2013), 88-119](#))

✱ Couplings:

     ✱ Updated coupling measurements of the Higgs boson with the ATLAS detector using up to 25 fb^{-1} of proton-proton collision data ([ATLAS-CONF-2014-009](#))

✱ H→γγ:

     ✱ Measurements of the properties of the Higgs-like boson in the two photon decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data ([ATLAS-CONF-2013-012](#))

     ✱ Differential cross sections of the Higgs boson measured in the diphoton decay channel using 8 TeV pp collisions ([ATLAS-CONF-2013-072](#))

✱ H→ZZ*→4ℓ:

     ✱ Measurements of the properties of the Higgs-like boson in the four lepton decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data ([ATLAS-CONF-2013-013](#))

✱ H→WW*→ℓνℓν:

     ✱ Measurements of the properties of the Higgs-like boson in the WW*→ℓνℓν decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data ([ATLAS-CONF-2013-030](#))

✱ All ATLAS public results:

     ✱ https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Backup slides

Systematic uncertainties: diboson channels

Source (experimental)	Uncertainty (%)
Luminosity	± 1.8 (2011), ± 3.6 (2012)
Electron efficiency	$\pm 2\text{--}5$
Jet energy scale	$\pm 1\text{--}5$
Jet energy resolution	$\pm 2\text{--}40$
Source (theory)	Uncertainty (%)
QCD scale	± 8 (ggF), ± 1 (VBF, VH), $^{+4}_{-9}$ (ttH)
PDFs $+ \alpha_s$	± 8 (ggF, ttH), ± 4 (VBF, VH)

H→γγ

Systematic uncertainties

Source	Uncertainty (%)
On signal yield	
Photon identification	± 2.4
Trigger	± 0.5
Isolation	± 1.0
Photon energy scale	± 0.25
ggF (theory), tight high-mass two-jet cat.	± 48
ggF (theory), loose high-mass two-jet cat.	± 28
ggF (theory), low-mass two-jet cat.	± 30
Impact of background modelling	$\pm(2\text{--}14)$, cat.-dependent
On category population (migration)	
Material modelling	-4 (unconv), $+3.5$ (conv)
p_T modelling	± 1 (low-p_{Tt}),
	$\mp(9\text{--}12)$ (high-p_{Tt}, jets),
	$\pm(2\text{--}4)$ (lepton, E_T^{miss})
$\Delta\phi_{\gamma\gamma,jj}$, η^* modelling in ggF	$\pm(9\text{--}12)$, $\pm(6\text{--}8)$
Jet energy scale and resolution	$\pm(7\text{--}12)$ (jets),
	$\mp(0\text{--}1)$ (others)
Underlying event two-jet cat.	± 4 (high-mass tight),
	± 8 (high-mass loose),
	± 12 (low-mass)
E_T^{miss}	± 4 (E_T^{miss} category)
On mass scale and resolution	
Mass measurement	± 0.6, cat.-dependent
Signal mass resolution	$\pm(14\text{--}23)$, cat.-dependent

$H \rightarrow \gamma\gamma$

For the $H \rightarrow \gamma\gamma$ analysis of the $\sqrt{s} = 8$ TeV data, the numbers of events observed in the data (N_D), the numbers of background events (N_B) estimated from fits to the data, and the expected SM Higgs boson signal (N_S) for $m_H = 126.8$ GeV, split by category. All numbers are given in a mass window centred at $m_H = 126.8$ GeV and containing 90% of the expected signal (the size of this window changes from category to category and for the inclusive sample). The predicted numbers of signal events in each of the ggF, VBF, WH, ZH and $t\bar{t}H$ processes are also given.

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_T^{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

	N_{jets}	$p_T^{\gamma\gamma}$	$|y^{\gamma\gamma}|$	$|\cos\theta^*|$	$p_T^{j_1}$	$\Delta\phi_{jj}$	$p_T^{\gamma\gamma jj}$
POWHEG	0.54	0.55	0.38	0.69	0.79	0.42	0.50
MINLO	0.44	–	–	0.67	0.73	0.45	0.49
HRES 1.0	–	0.39	0.44	–	–	–	–

Table 2: Displayed are the probabilities from χ^2 tests for the agreement between the unfolded observation and the theoretical predictions, calculated with the full covariance between bins of the observables.

For the $H \to ZZ^* \to 4\ell$ inclusive analysis, the number of expected signal ($m_H = 125$ GeV) and background events, together with the number of events observed in the data, in a window of size ± 5 GeV around $m_{4\ell} = 125$ GeV, for the combined $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data.

	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

Systematic uncertainties

Source	Uncertainty (%)			
	4μ	$2\mu2e$	$2e2\mu$	$4e$
Signal yield				
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.		$\pm 32/11/11$		
ZZ^* contribution to VBF-like cat.		± 36		
ggF/VBF/VH contributions to VH-like cat.		$\pm 15/5/6$		
ZZ^* contribution to VH-like cat.		± 30		
Mass measurement	4μ	$2\mu2e$	$2e2\mu$	$4e$
Lepton energy and momentum scale	± 0.2	± 0.2	± 0.3	± 0.4

H→ZZ(*)→4ℓ
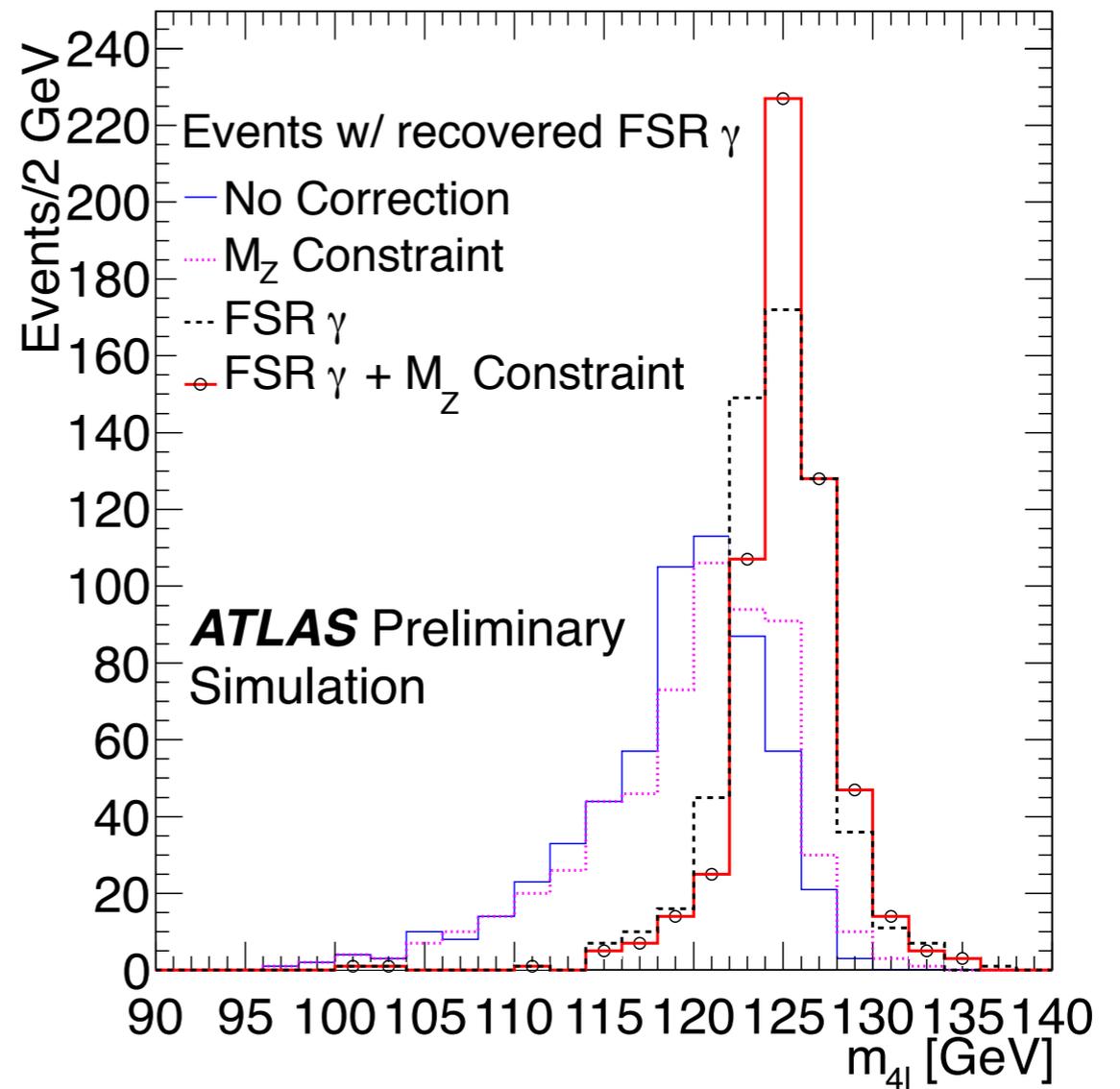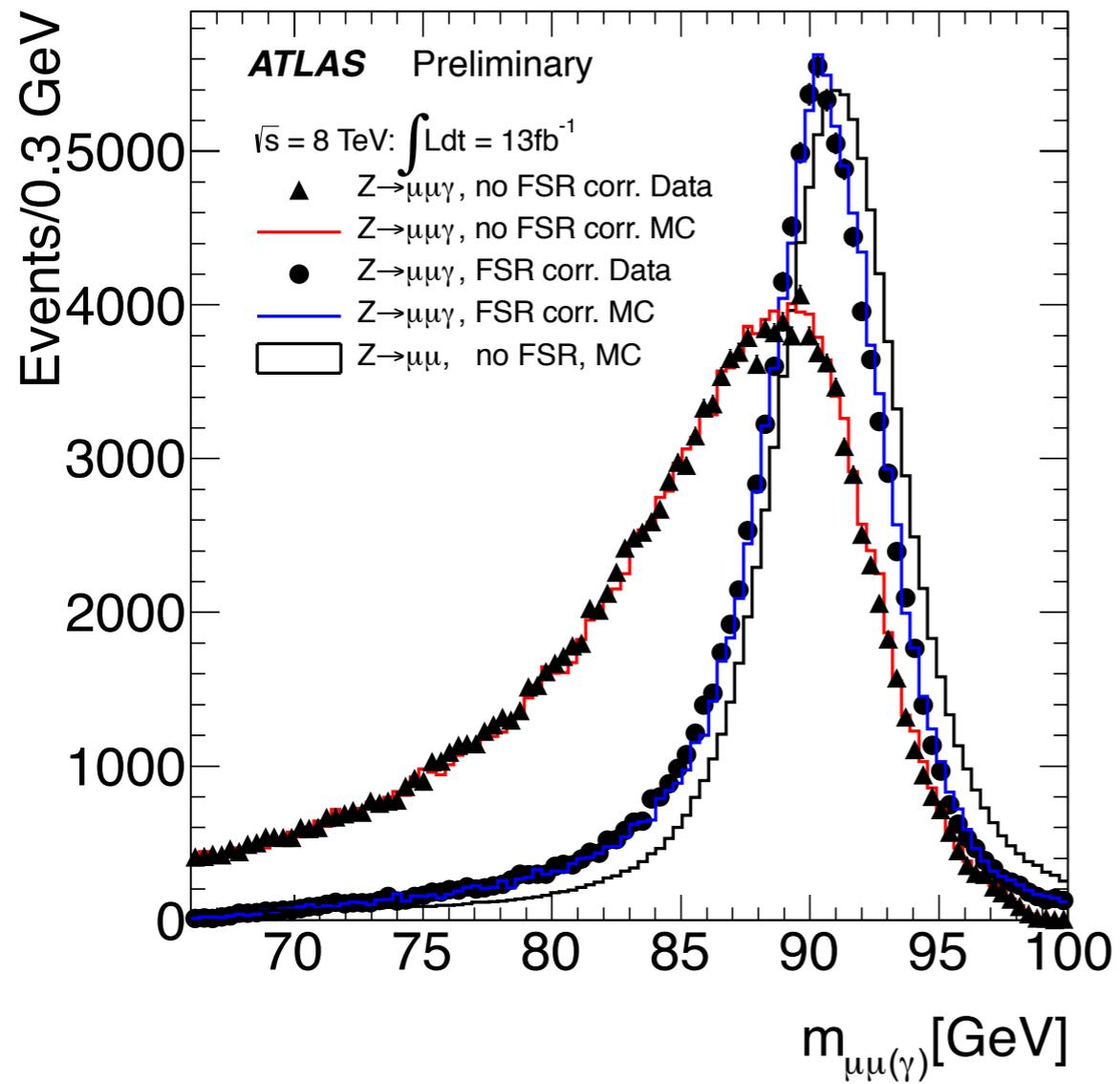
For the $H \to WW^* \to \ell\nu\ell\nu$ analysis of the 8 TeV data, the numbers of events observed in the data and expected from signal ($m_H = 125.5$ GeV) and backgrounds inside the transverse mass regions $0.75m_H < m_T < m_H$ for $N_{jet} \leqslant 1$ and $m_T < 1.2m_H$ for $N_{jet} \geqslant 2$. All lepton flavours are combined. The total background as well as its main components are shown. The quoted uncertainties include the statistical and systematic contributions, and account for anticorrelations between the background predictions.

	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geqslant 2$
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 W	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

Source	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geqslant 2$
Theoretical uncertainties on total signal yield (%)			
QCD scale for ggF, $N_{jet} \geqslant 0$	+13	–	–
QCD scale for ggF, $N_{jet} \geqslant 1$	+10	−27	–
QCD scale for ggF, $N_{jet} \geqslant 2$	–	−15	+4
QCD scale for ggF, $N_{jet} \geqslant 3$	–	–	+4
Parton shower and underlying event	+3	−10	±5
QCD scale (acceptance)	+4	+4	±3
Experimental uncertainties on total signal yield (%)			
Jet energy scale and resolution	5	2	6
Uncertainties on total background yield (%)			
Jet energy scale and resolution	2	3	7
WW transfer factors (theory)	±1	±2	±4
b-tagging efficiency	–	+7	+2
f_{recoil} efficiency	±4	±2	–