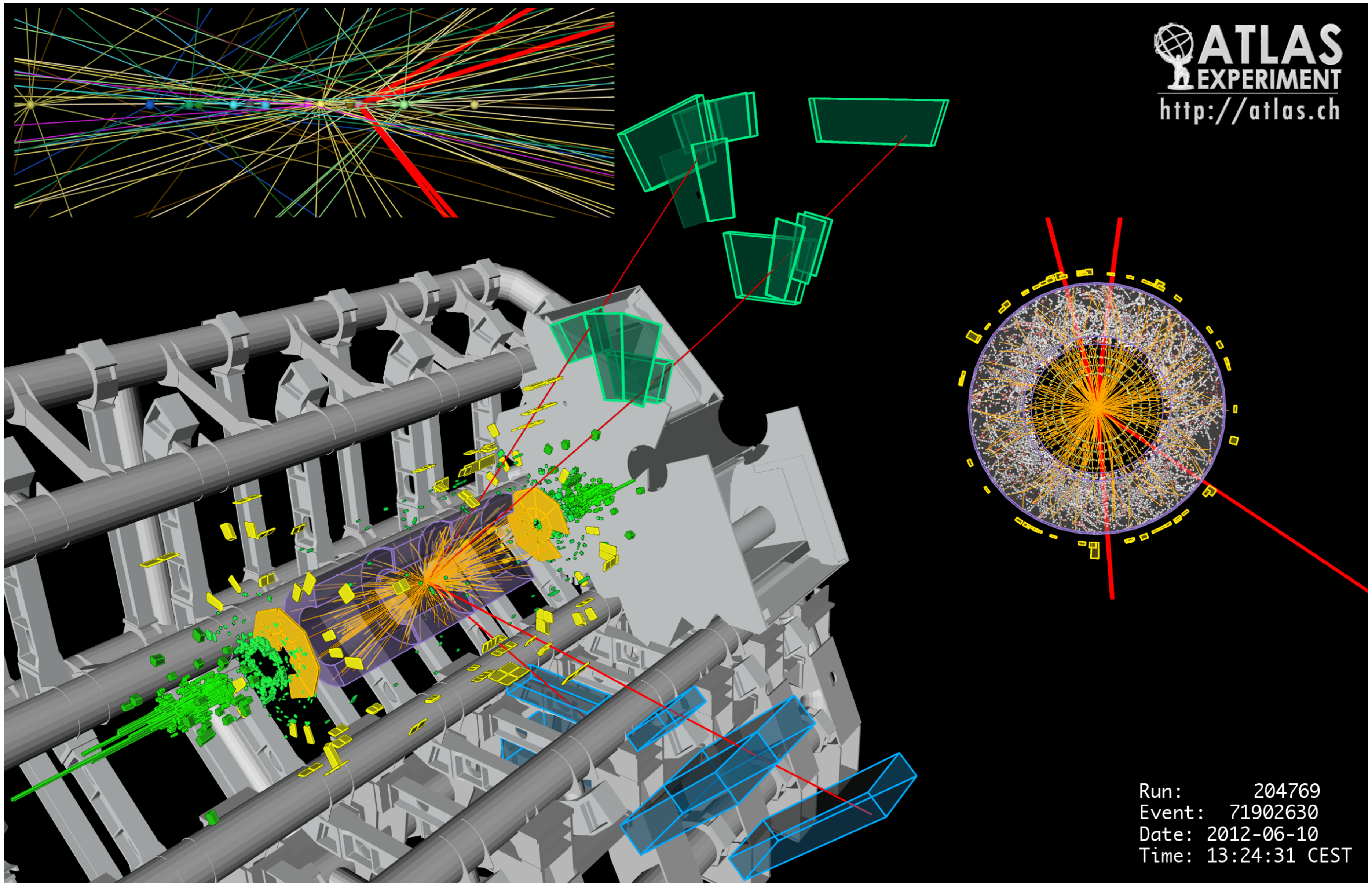

Observation and measurements of the Higgs boson in the 4-lepton decay mode in ATLAS

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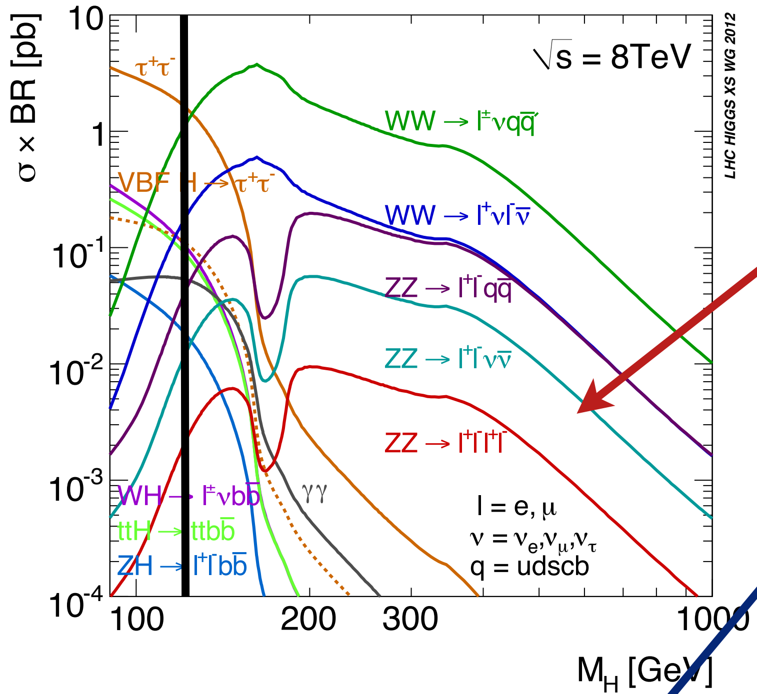
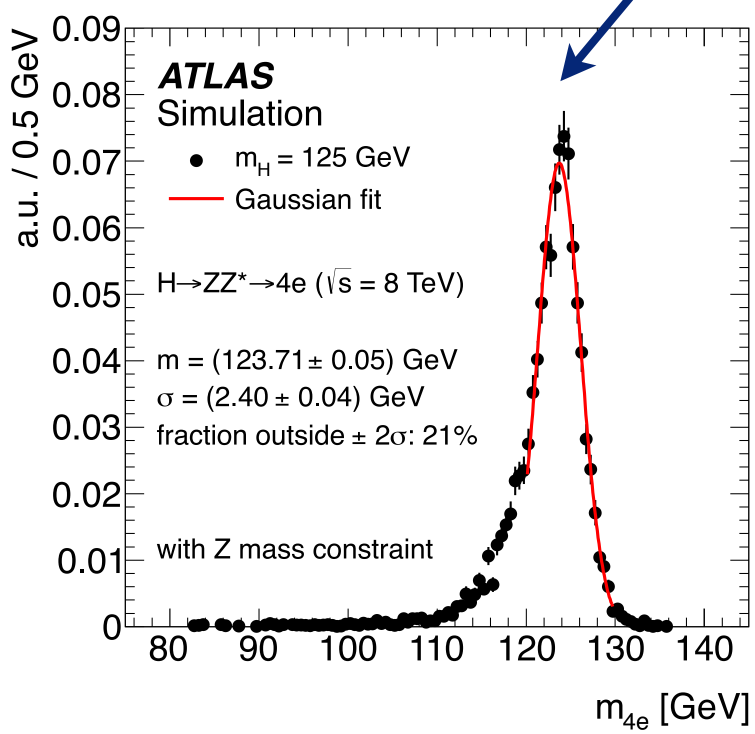
Outline

- Introduction
- Event selection
- Background estimation
- Systematic uncertainties
- Results
- Interpretation of the results
  - Limits and p-value
  - Mass and signal strength measurement
  - Coupling measurement
  - Spin/CP measurement

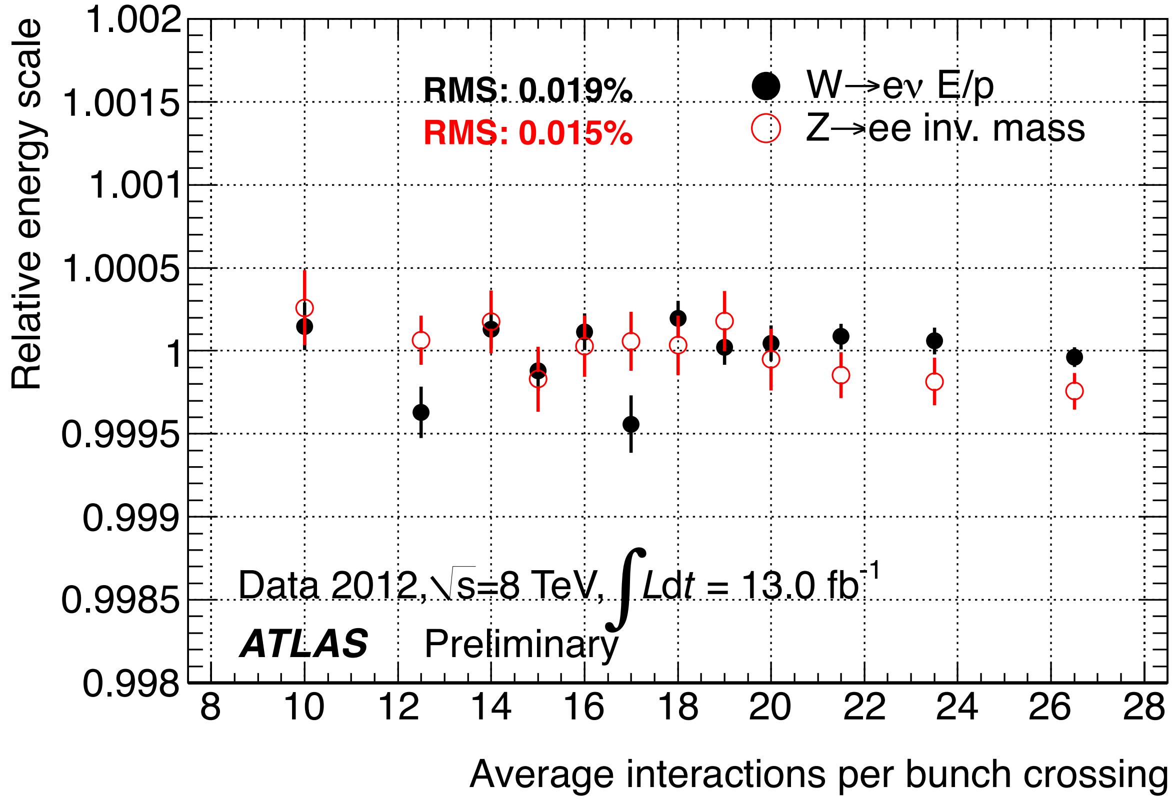
Golden channel

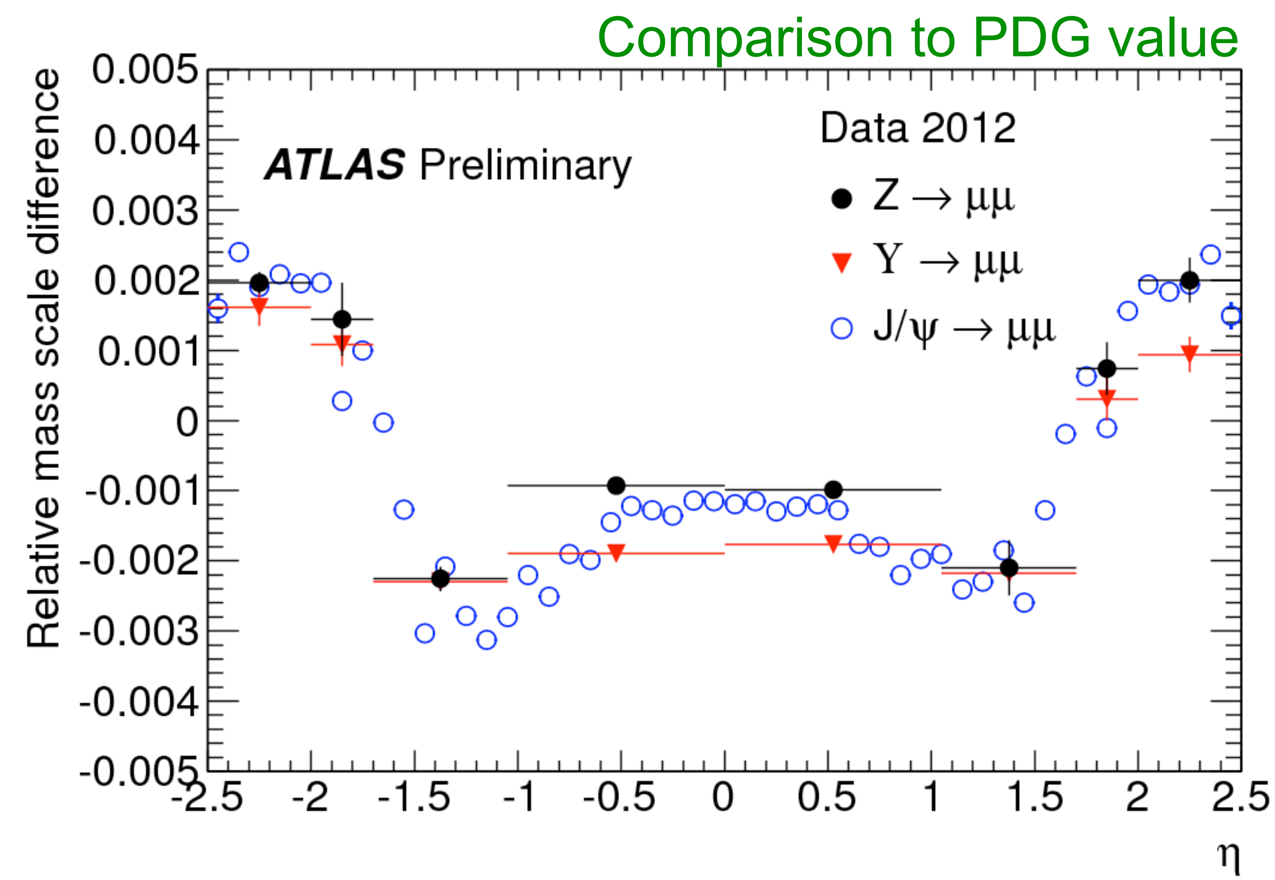




1. Low branching ratio, but high S/B ratio ~1
2. Clear mass peak with good resolution, ~2%
3. Four fully reconstructed leptons provide all the angular information needed for the spin studies
4. The challenge is to maximize the acceptance while keeping backgrounds under control
5. Update the analysis with full 7 TeV and 8TeV data (~25/fb) in ATLAS

Lepton energy calibration

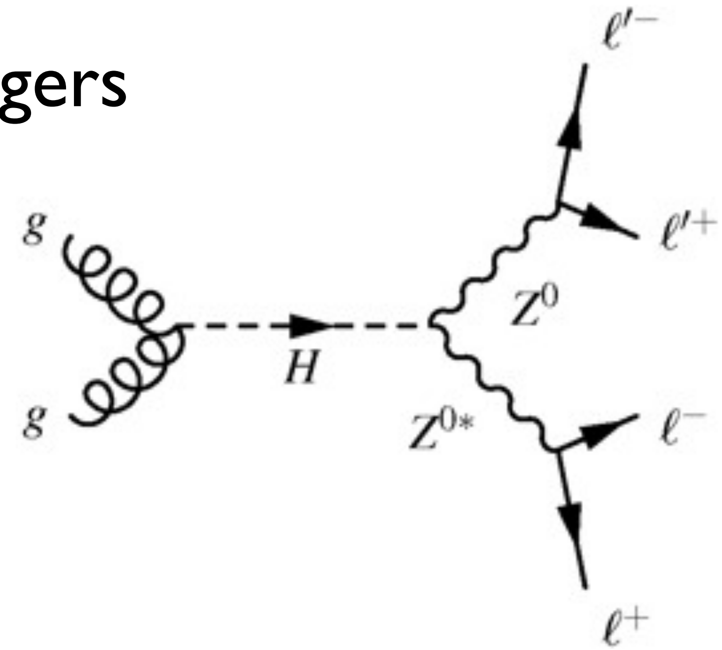




The uncertainties of lepton energy calibration is ~0.1%

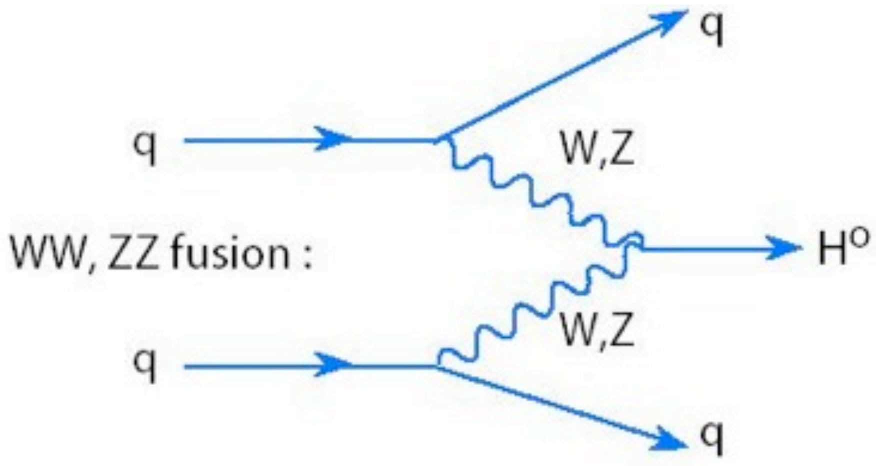
Event Selection

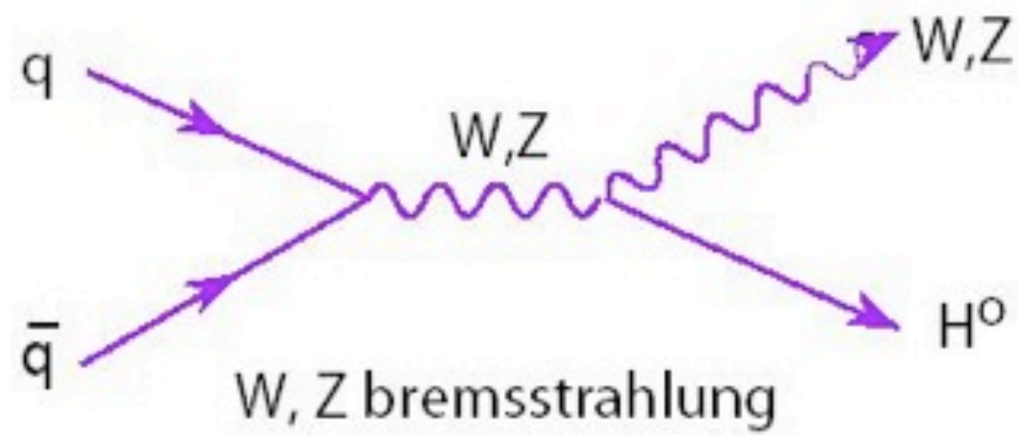
- Using both single-lepton and di-lepton triggers
- Electron selections
  - p_t > 7 GeV and $|\eta|$ < 2.47
  - optimized cut-based identification
- Muon selections
  - p_t > 6 GeV and $|\eta|$ < 2.7
  - Inner Detector requirements



- The mass of the leading same-flavor-opposite-charge lepton pair, m_{12}, in [50,106]GeV
- The other lepton pair mass, m_{34}, [12 - 115]GeV.
- four channels: 4e, 4μ, 2e2μ, 2μ2e
- Apply isolation and impact parameter cuts on all four leptons
- Add FSR photons to muon final states and apply Z-mass constraint to further improve the resolution of the four-lepton mass

Categorization





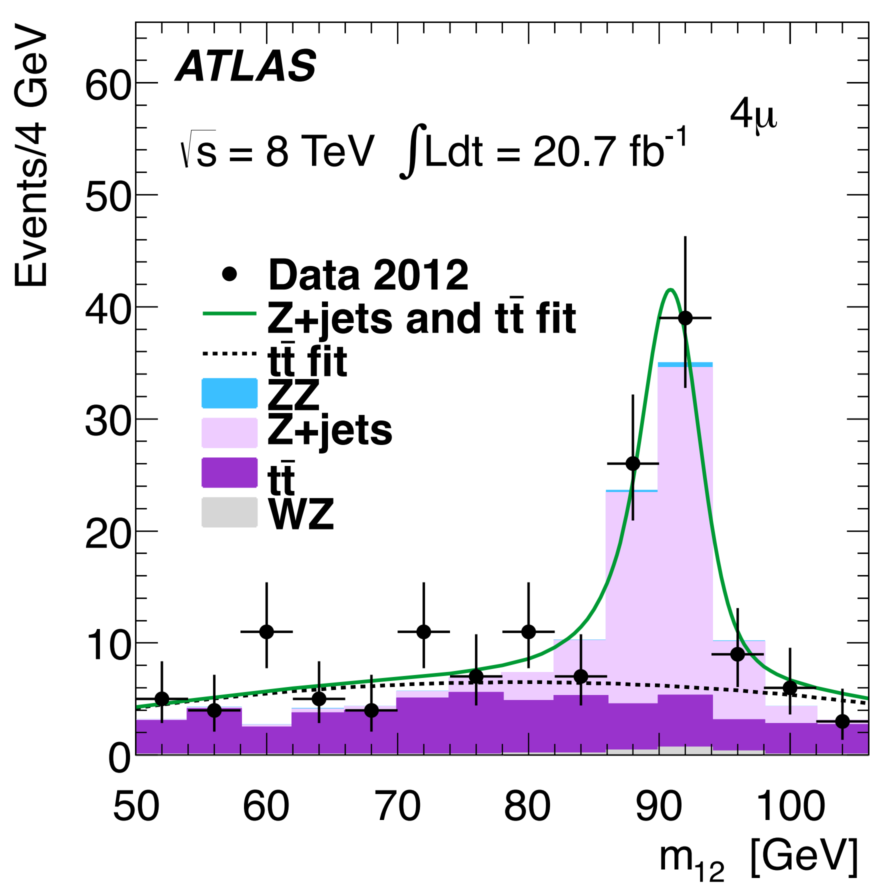
- to enhance the sensitivity to the individual production modes, for the first time, add VBF-like and VH-like categories
- Jet Selections:
  - p_t > 25 GeV ($|\eta|<2.4$); p_t > 30 GeV ($2.4<|\eta|<2.5$)
  - loose jet quality requirements
- VBF-like: $N_{jets} \geq 2$, the two highest p_t jets should satisfy

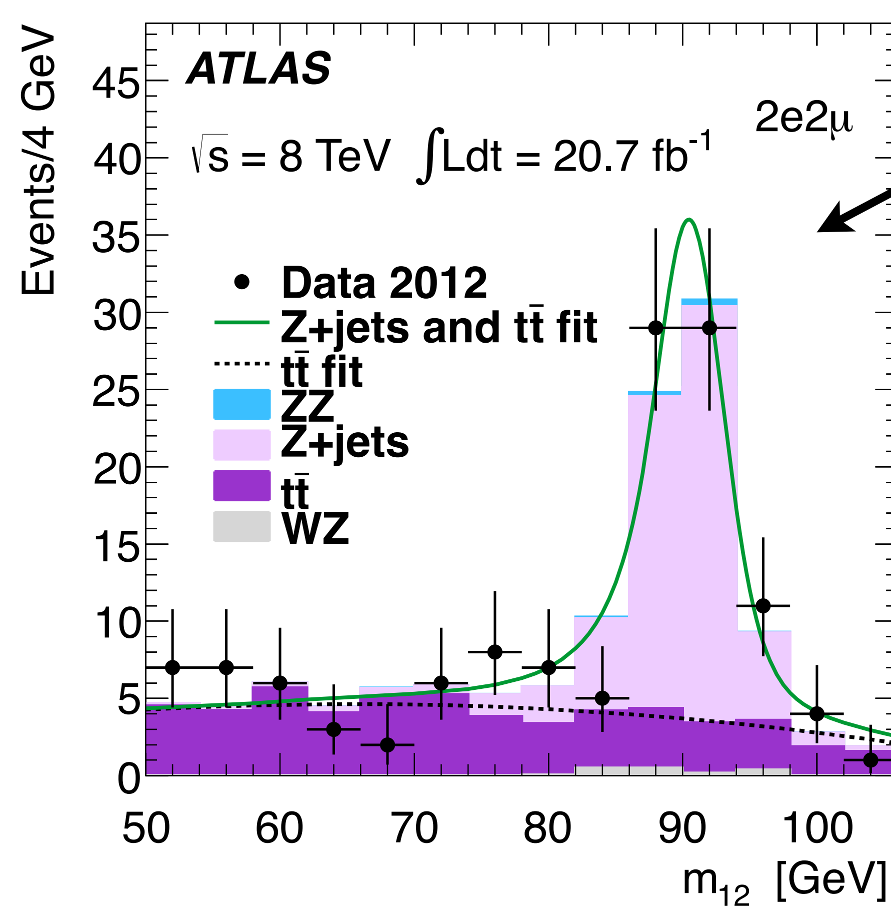
$|\eta_1-\eta_2|$ >3 and m_{jj} > 350 GeV; (60% Higgs production from VBF)

- VH-like: not VBF-like, if addtional lepton with p_T>8 GeV, pass isolation and impact parameter cuts (70% Higgs production from VH)
- ggF-like: the rest

Background Estimation(I)

- Irreducible ZZ background, estimated from MC (PowHeg, gg2ZZ)
- The Z+jets and tt estimate from control regions (CR) in data
  - The transfer factor (from control region to signal region) obtained in a background-enriched region in MC, cross checked with data, is a function of p_t and η .
  - The shapes obtained from CR





- CR for ll + μ μ , by reversing one of the isolation and impact parameter cuts
- A fit is used to obtain the yields of Z +jet and tt

Background Estimation(II)

The same procedure for backgrounds in VBF-like, VH-like categories

- In ll+ee, three different CRs are built to cross check the results
- CR is classified into different reconstruction categories and for each category the relative truth compositions are estimated from MC
- The transfer factor is obtained from a background-enriched control region in MC, cross checked with data.
- It's a function of pt, eta and the source of the leptons

Systematics

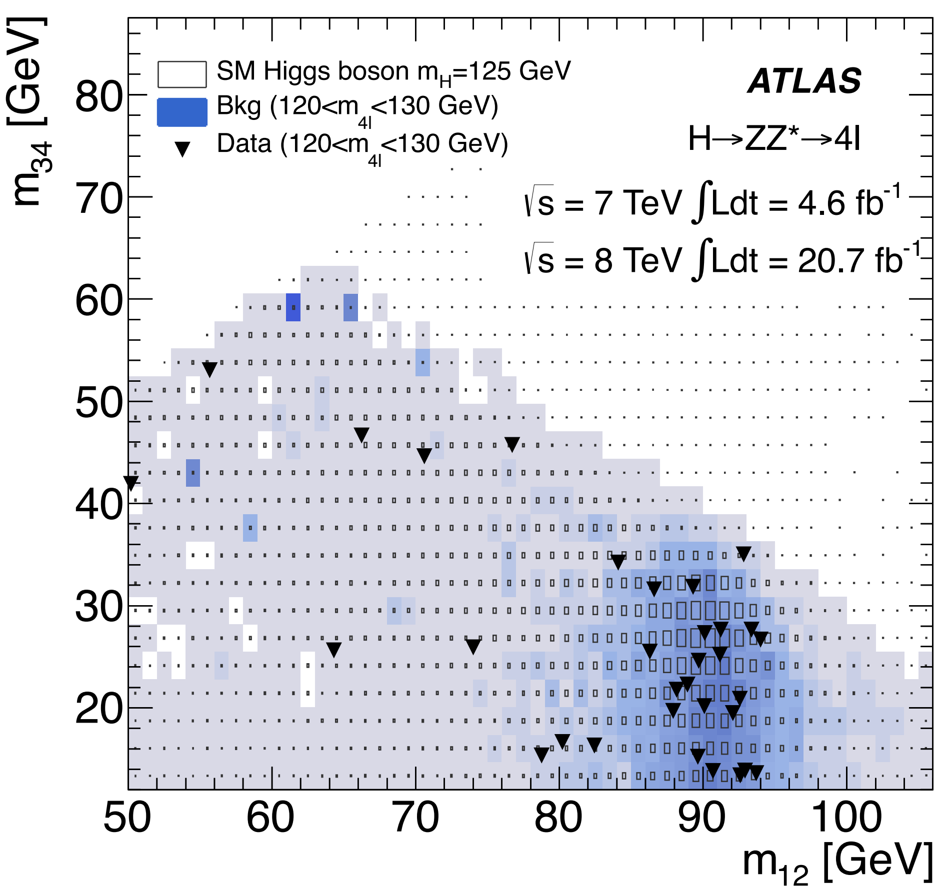
Main source of experimental and theoretical uncertainties on the signal expectation common to the four channels considered in this study

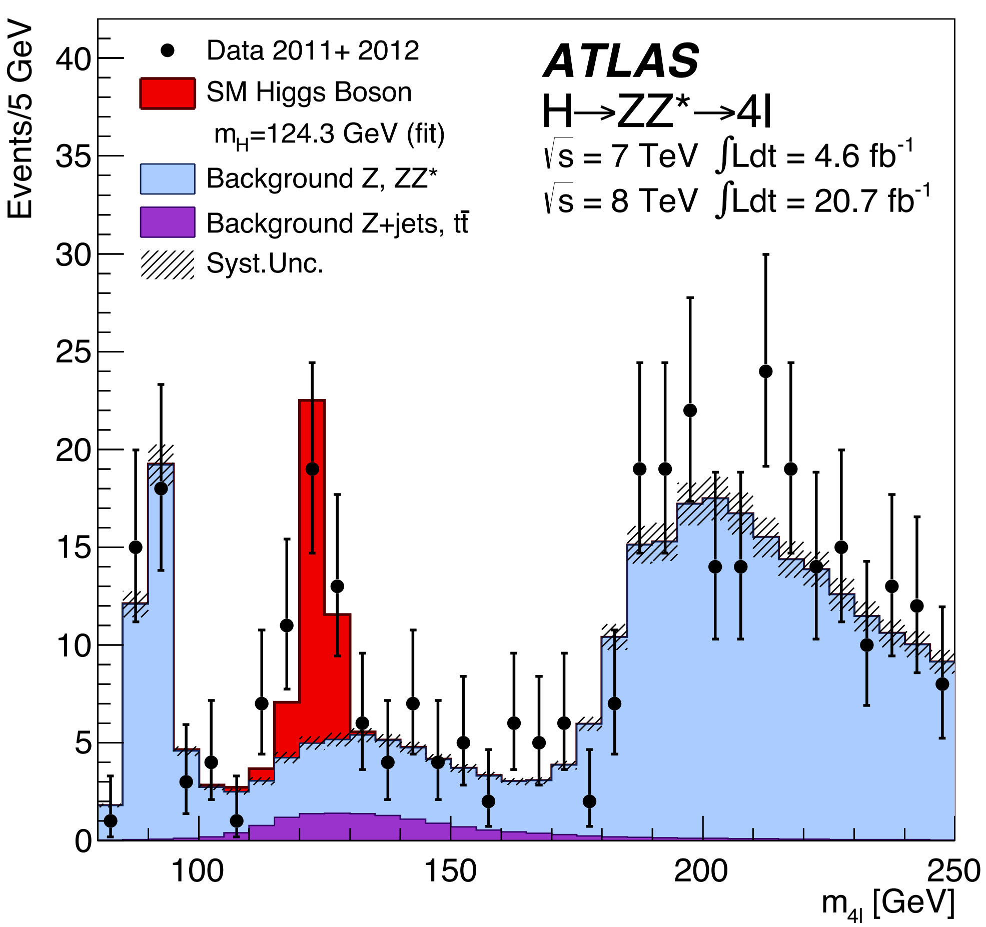
Source	Uncertainty (%)			
Signal yield	4μ	$2\mu 2e$	$2e2\mu$	$4e$
Muon reconstruction and identification	±0.8	±0.4	±0.4	-
Electron reconstruction and identification	-	±8.7	±2.4	±9.4
Reducible background (inclusive analysis)	±24	±10	±23	±13
Migration between categories				
ggF/VBF/VH contributions to VBF-like category	±32/11/11			
ZZ^* contribution to VBF-like category	±36			
ggF/VBF/VH contributions to VH-like category	±15/5/6			
ZZ^* contribution to VH-like category	±30			
Mass measurement	4μ	$2\mu 2e$	$2e2\mu$	$4e$
Lepton energy and momentum scale	±0.2	±0.2	±0.3	±0.4

Results with 2011+2012 data

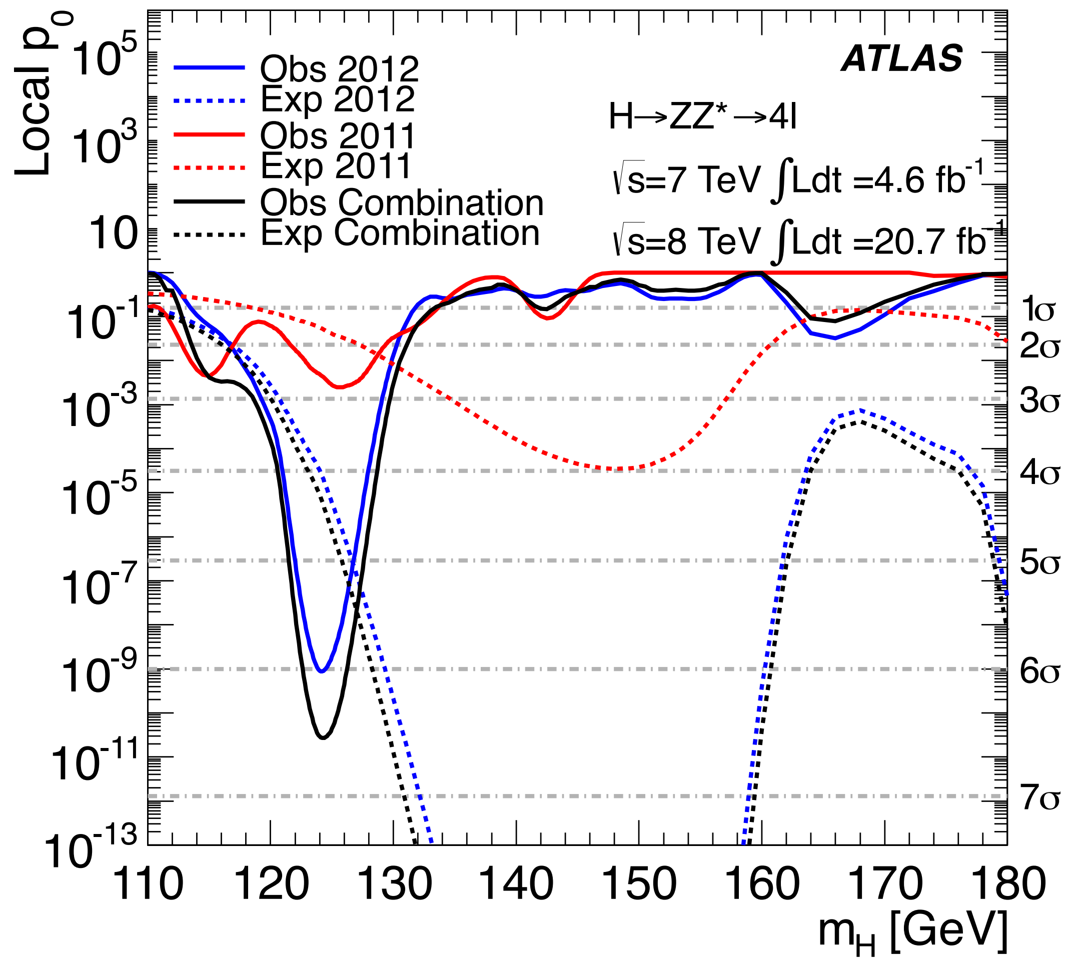
number of expected signal and background, together with data in a window of ±5GeV around 125GeV

	Signal	ZZ^*	$Z+\text{jets}, t\bar{t}$	Observed	S/B
4μ	6.3±0.8	2.8±0.1	0.55±0.15	13	1.9
$2e2\mu/2\mu2e$	7.0±0.6	3.5±0.1	2.11±0.37	13	1.2
$4e$	2.6±0.4	1.2±0.1	1.11±0.28	6	1.1



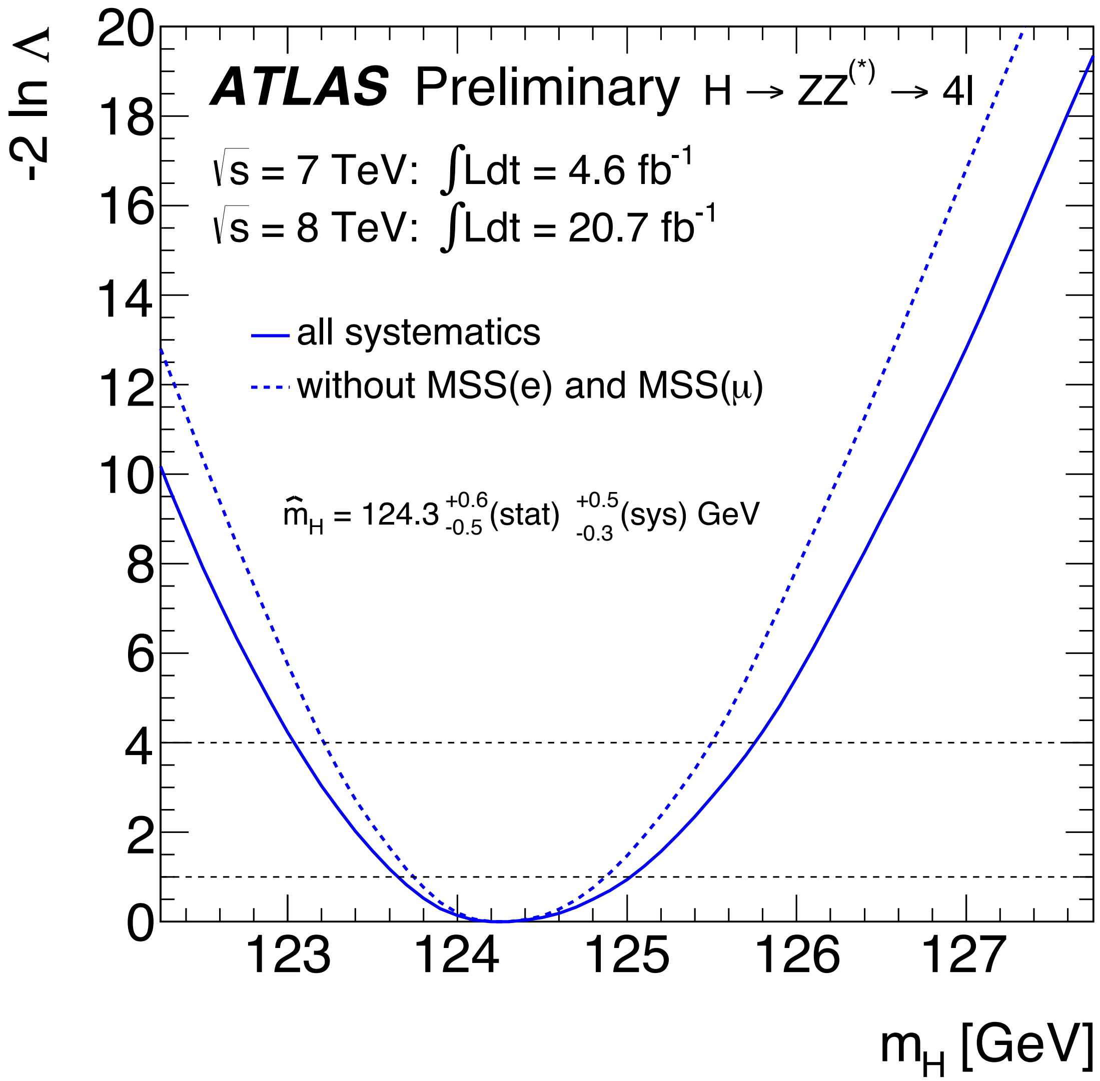


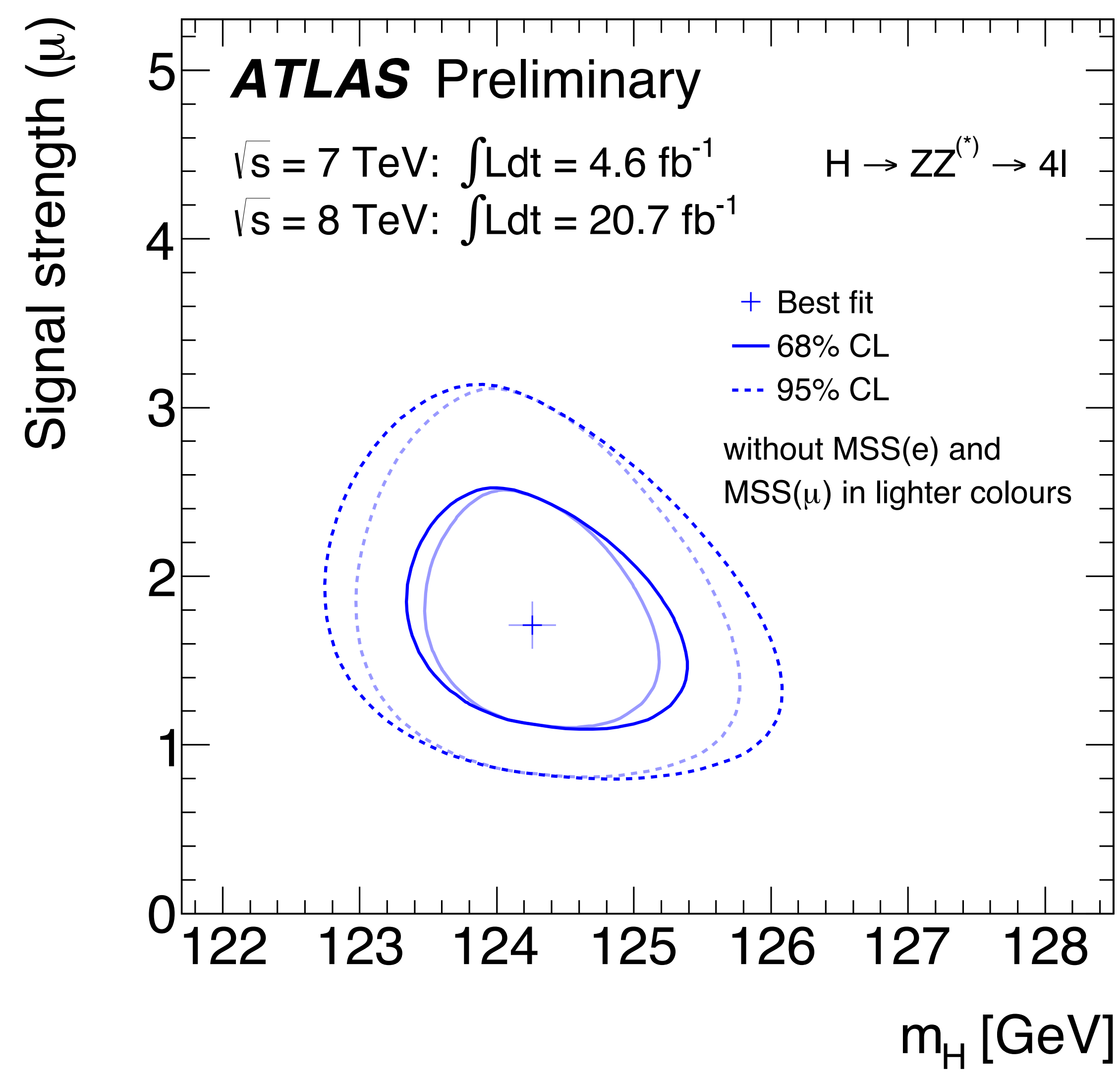
Limits and P-value



	observed			expected	
data set	min p_0	significance [σ]	$m_H(p_0)$	min $p_0(m_H)$	significance [σ]
$\sqrt{s}$ = 7 TeV	2.5×10^{-3}	2.8	125.6 GeV	3.5×10^{-2}	1.8
$\sqrt{s}$ = 8 TeV	8.8×10^{-10}	6.0	124.1 GeV	2.8×10^{-5}	4.0
combined	2.7×10^{-11}	6.6	124.3 GeV	5.7×10^{-6}	4.4

Mass and signal strength

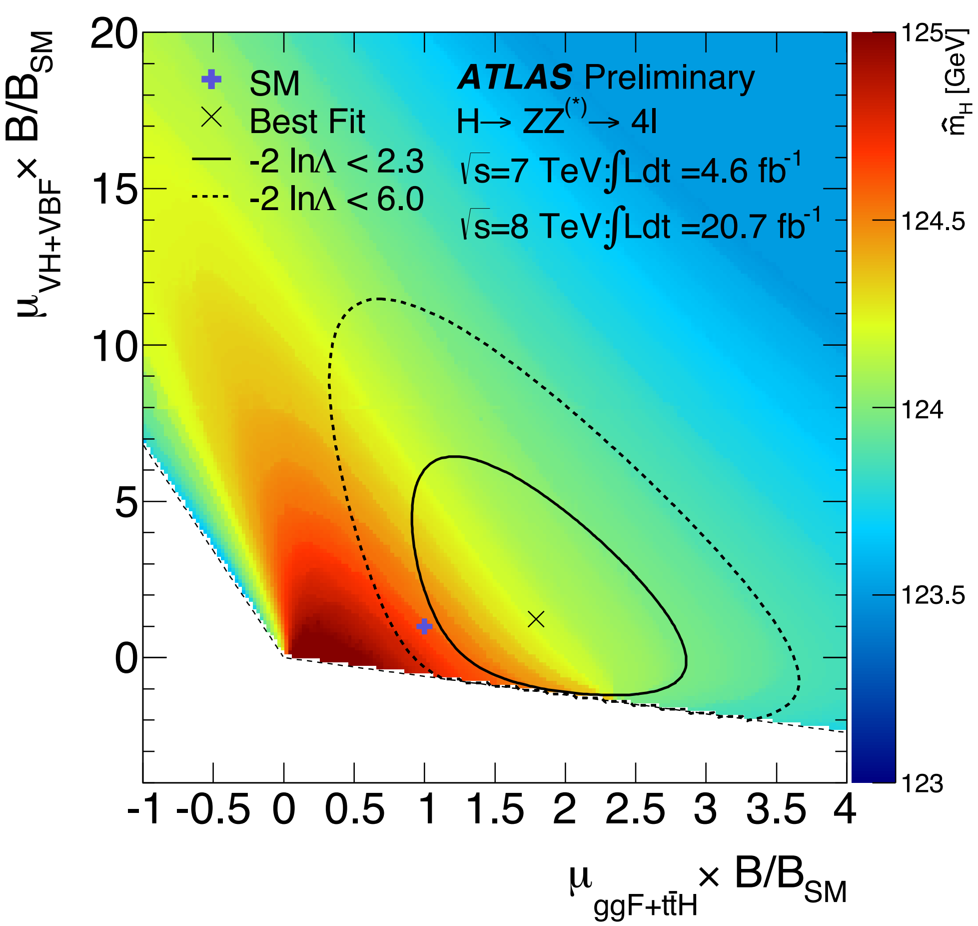


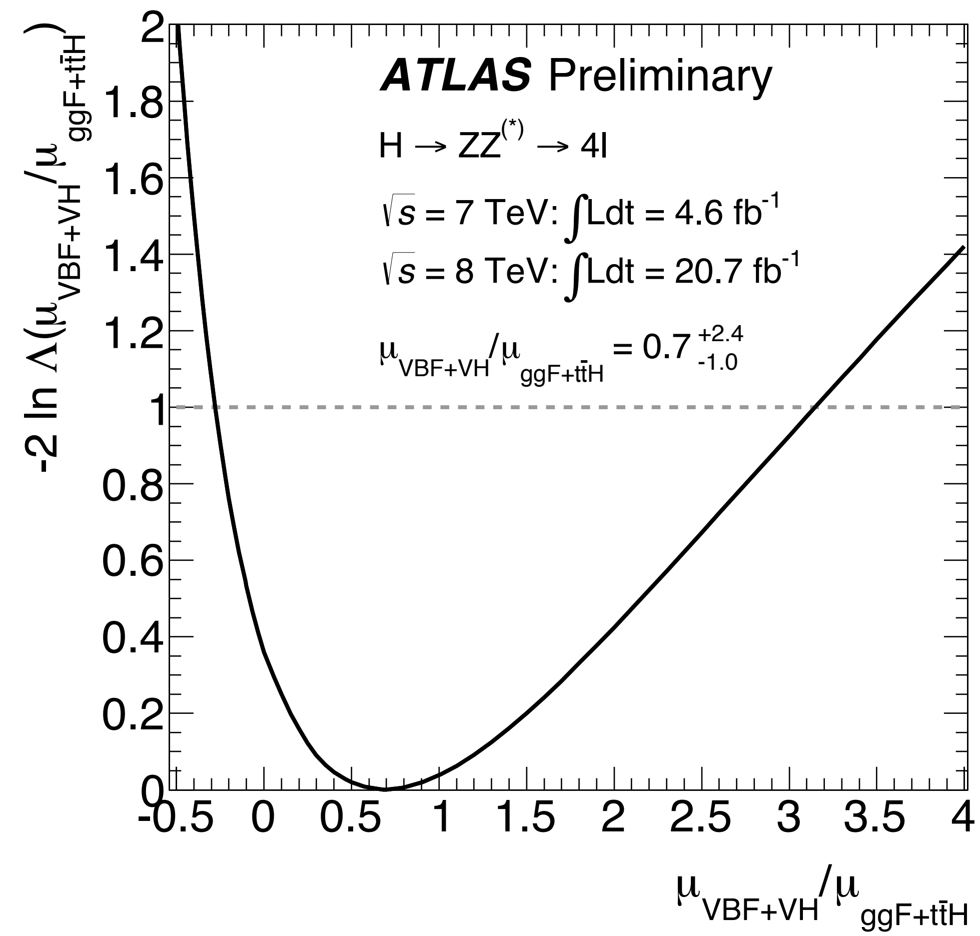


- Higgs mass: $\hat{m}_H = 124.3^{+0.6}_{-0.5}(\text{stat})\ ^{+0.5}_{-0.3}(\text{sys})$ GeV
- Signal strength μ : (normalize production rate to the SM)
- μ = 1.7 +0.5 -0.4 at 124.3 GeV (best-fit mass from 4l)

production strengths

- Sepearate signal strength into vector-boson-mediated process, VBF and VH from gluon-mediated process, ggF and ttH, involving fermion loops or legs

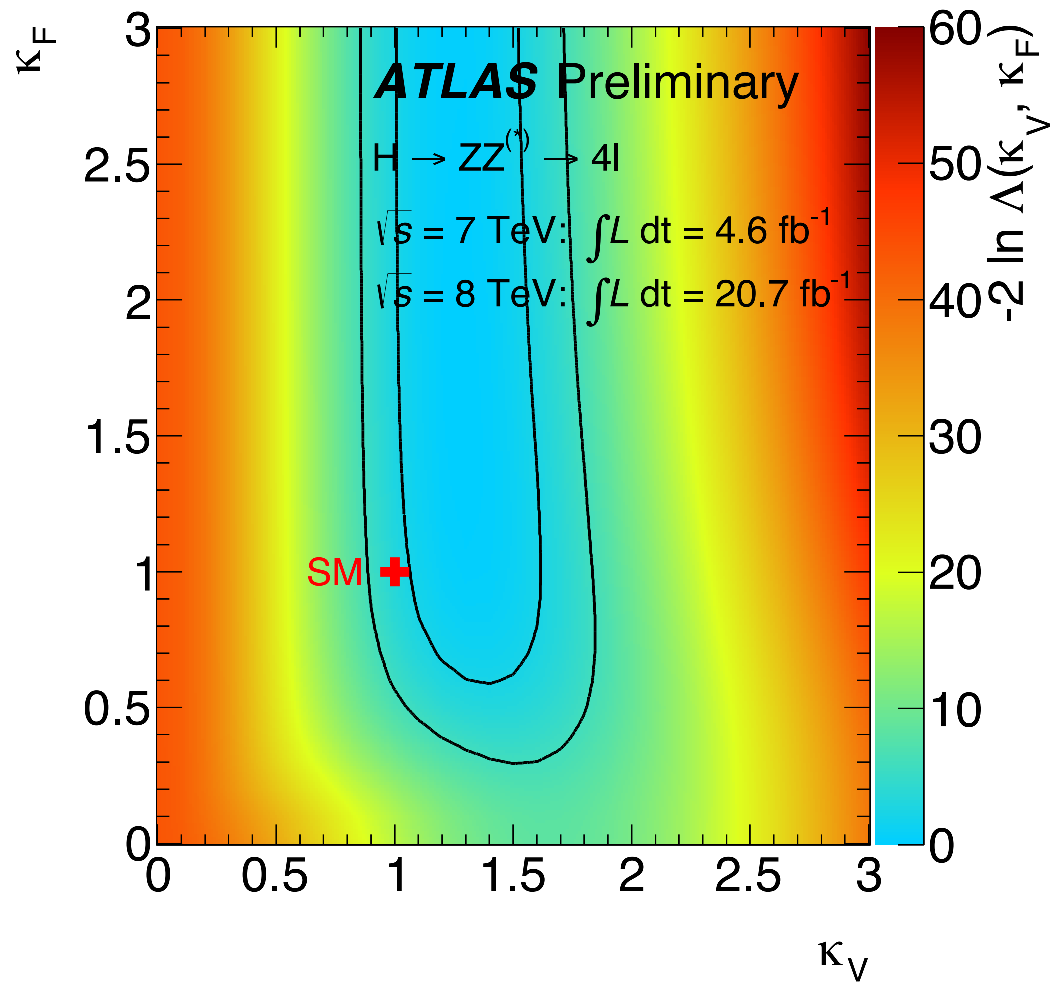


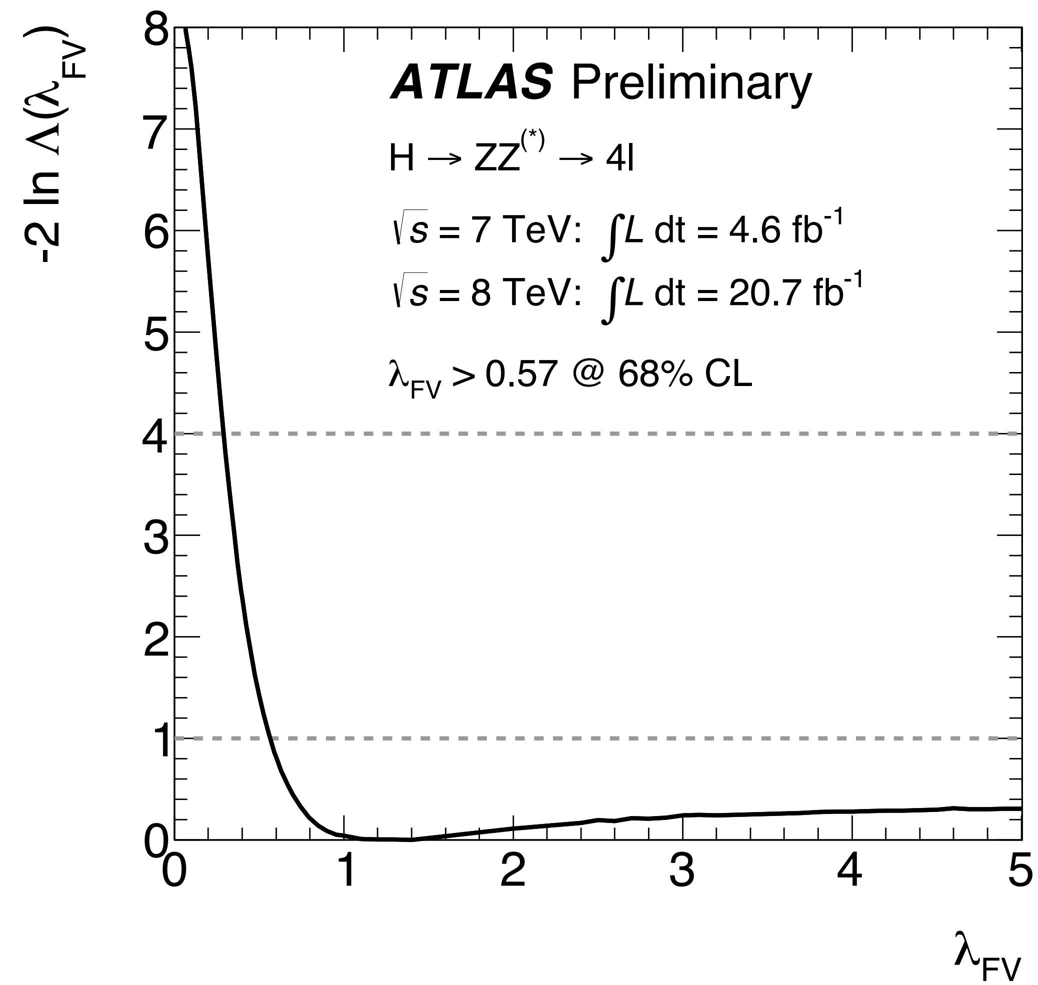


- Left: likelihood contour as a function of the μ_{VH+VBF} and $\mu_{ggF+ttH}$
- Right: likelihood distribution as a function of the ratio of μ_{VH+VBF} and $\mu_{ggF+ttH}$
- The Higgs mass is profiled

$$\mu_{ggf+t\bar{t}H} = 1.8^{+0.8}_{-0.5}\,\sigma/\sigma_{SM} \qquad \mu_{VBF+VH} = 1.2^{+3.8}_{-1.4}\,\sigma/\sigma_{SM}$$

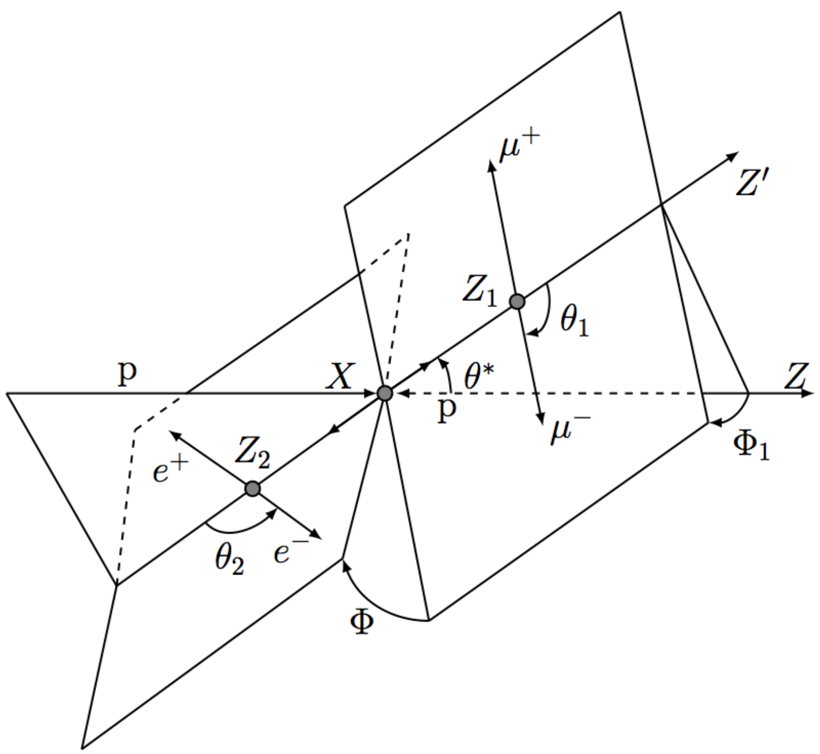
Couplings to Fermions and Bosons

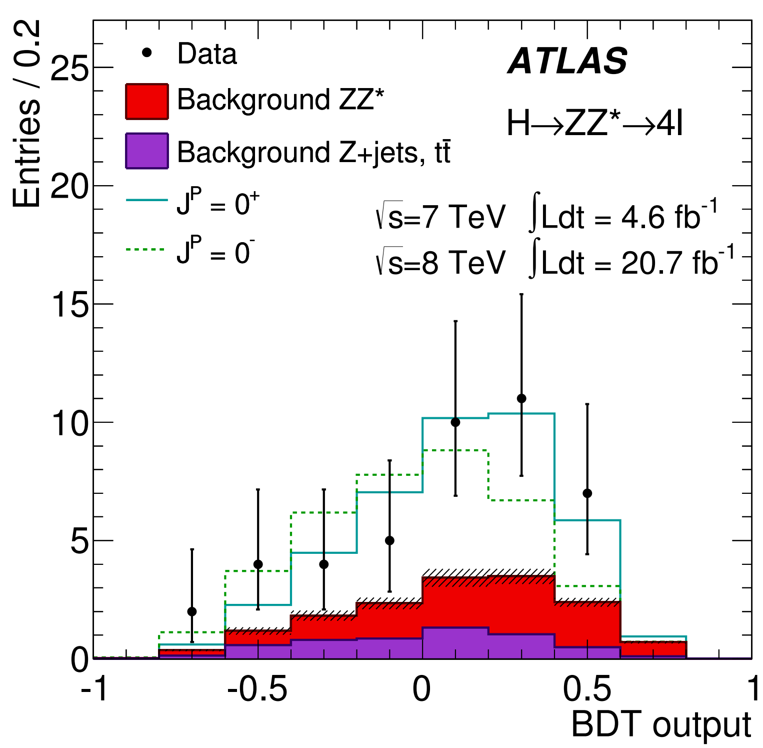




- Left: likelihood ratio contour as a function of the coupling strength k_v and k_f, assuming no non-SM contributions to the total width
- Right: likelihood ratio as a function of the ratio of fermion and weak vector boson couplings, no assumption on the total decay width
- The Higgs mass is a free parameter

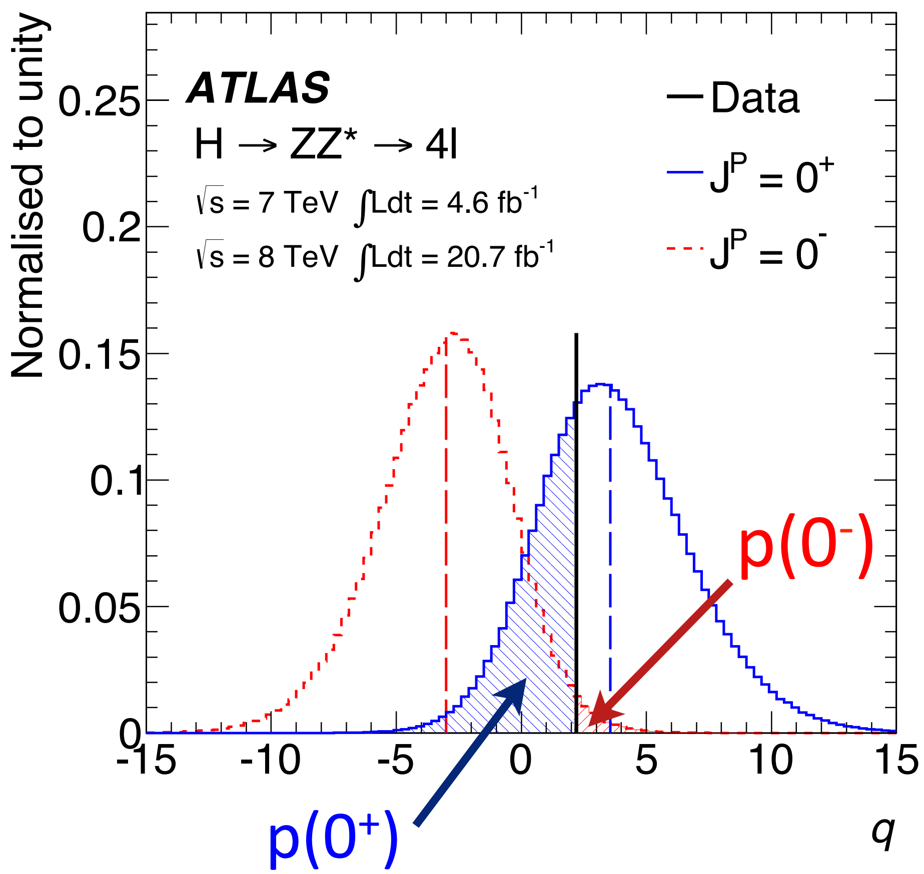
Spin/CP measurement





- Spin hypotheses of the SM Higgs: 0^+, Alternative hypothesises: 0^-, 1^+,1^-,2^+
- 4l is the only channel in ATLAS which is able to reject the 0^-
- Gluon-fusion process simulated using JHU generator, interfaced to PYTHIA for parton showering and hadronisation
- P_t spectrum is reweighted to reproduce the POWHEG+PYTHIA spectrum
- VBF and associated production is not considered
- BDT used to discriminate spin hypothesis, combining the angular variables and m_{12} and m_{34}
- Use [115-130]GeV, further separated into two regions high/low S/B

Hypothesis rejection

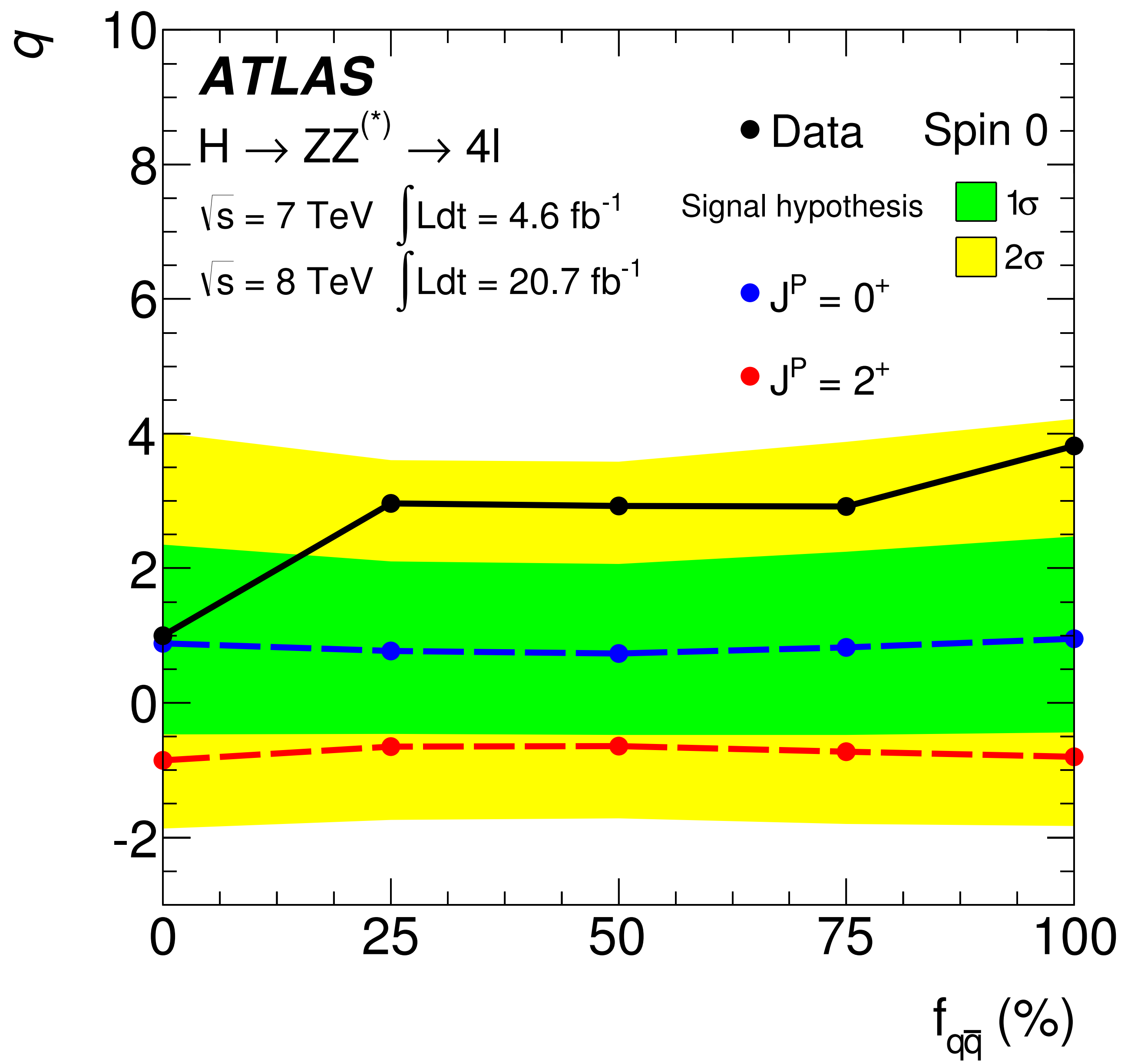


- The likelihood function: $L(J^P,\mu,\theta) = \Pi P(\mu^* S(\theta)+B(\theta)) \times A(\theta)$
- The test statistic q:

$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\rm alt}, \hat{\hat{\mu}}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})} \qquad \mathrm{CL_s}(J^P_{\rm alt}) = \frac{p_0(J^P_{\rm alt})}{1 - p_0(0^+)} .$$

		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	$\mathrm{CL_S}$
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168

More for spin-2 model



- 2^+ with a graviton-inspired tensor with minimal couplings to SM particles
- For 2^+, both gluon-fusion process and quark-antiquark process are considered
- Mix the two different production processes so that f_{qq} ranging from 0 to 100% in steps of 25%
- There is little variation in the expected discrimination as a function of f_{qq}

Summary

✶ 6.6σ observation of the Higgs boson in the 4-lepton channel using 25fb^{-1} in ATLAS.

✶ Higgs boson mass from 4l: $\hat{m}_H = 124.3\,^{+0.6}_{-0.5}\,(\text{stat})\,^{+0.5}_{-0.3}\,(\text{sys})$ GeV

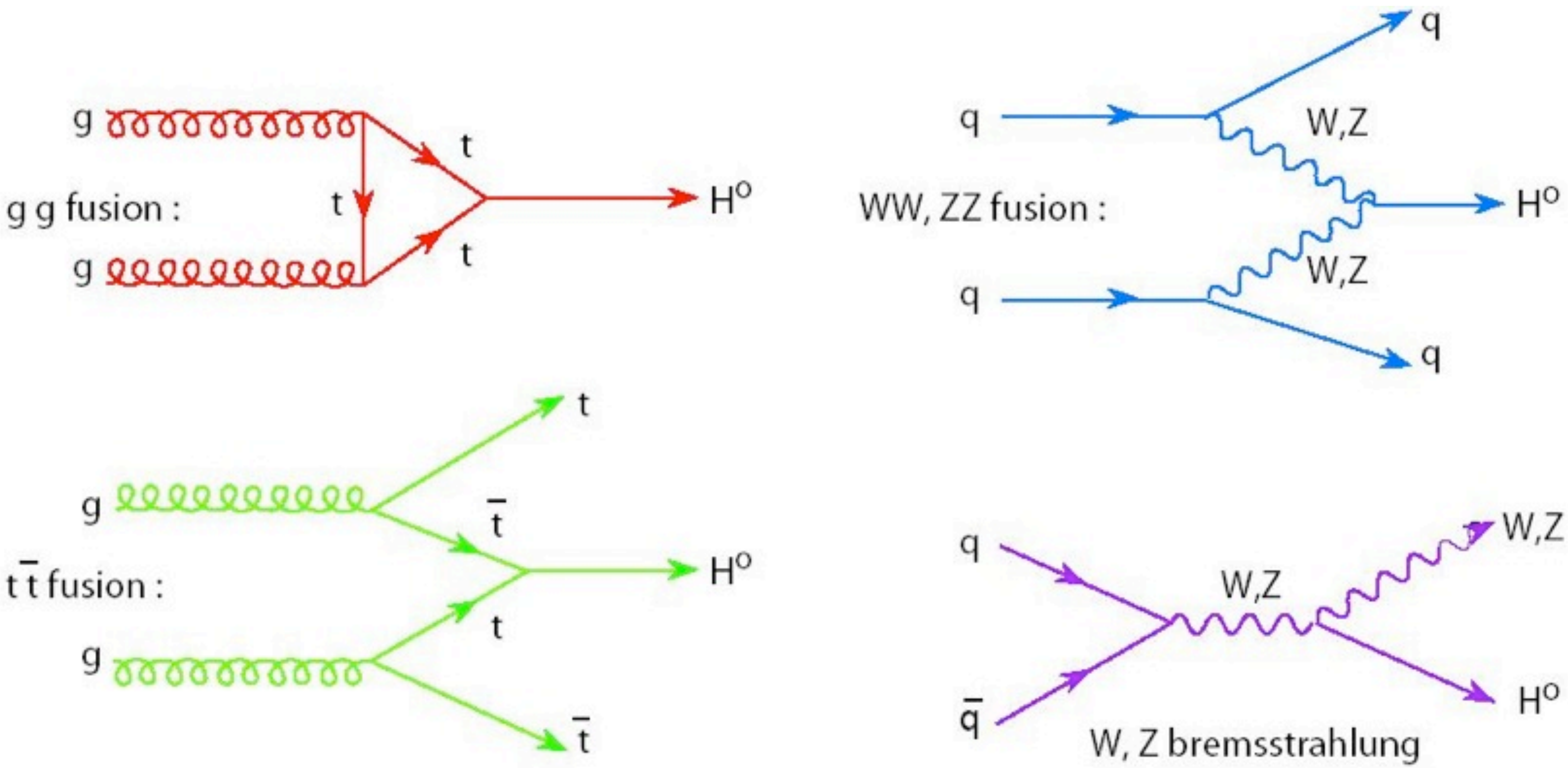
✶ The signal strength of individual production modes is compatible with SM, so is the coupling to fermions and bosons

✶ The data favors SM expectation of 0^+ over the alternatives. The 0^- is excluded at 97.8% confidence level.

✳ Back Up

References

- ✳ 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
- ✳ Measurements of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC


g
g g fusion :
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WW, ZZ fusion :
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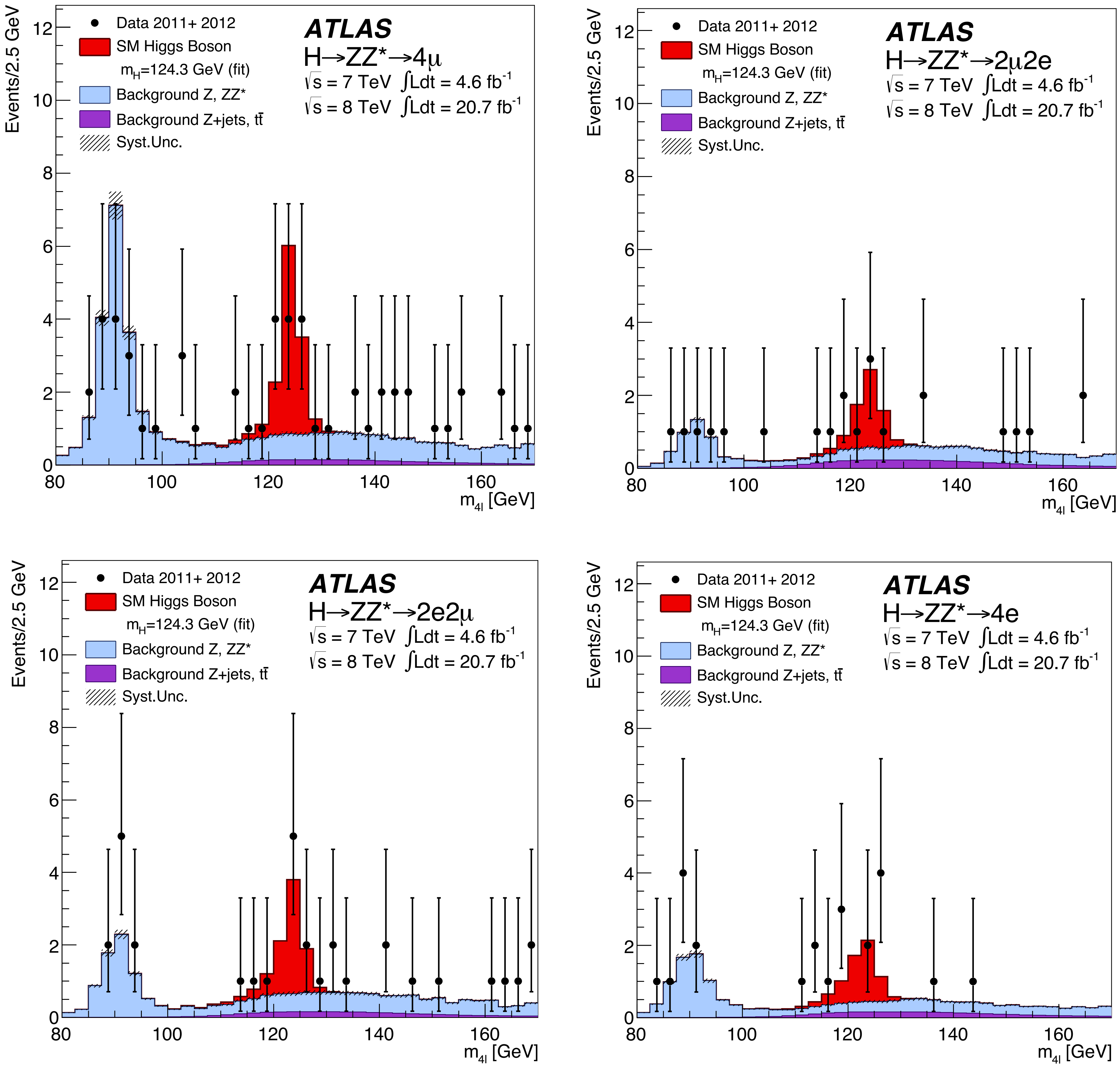
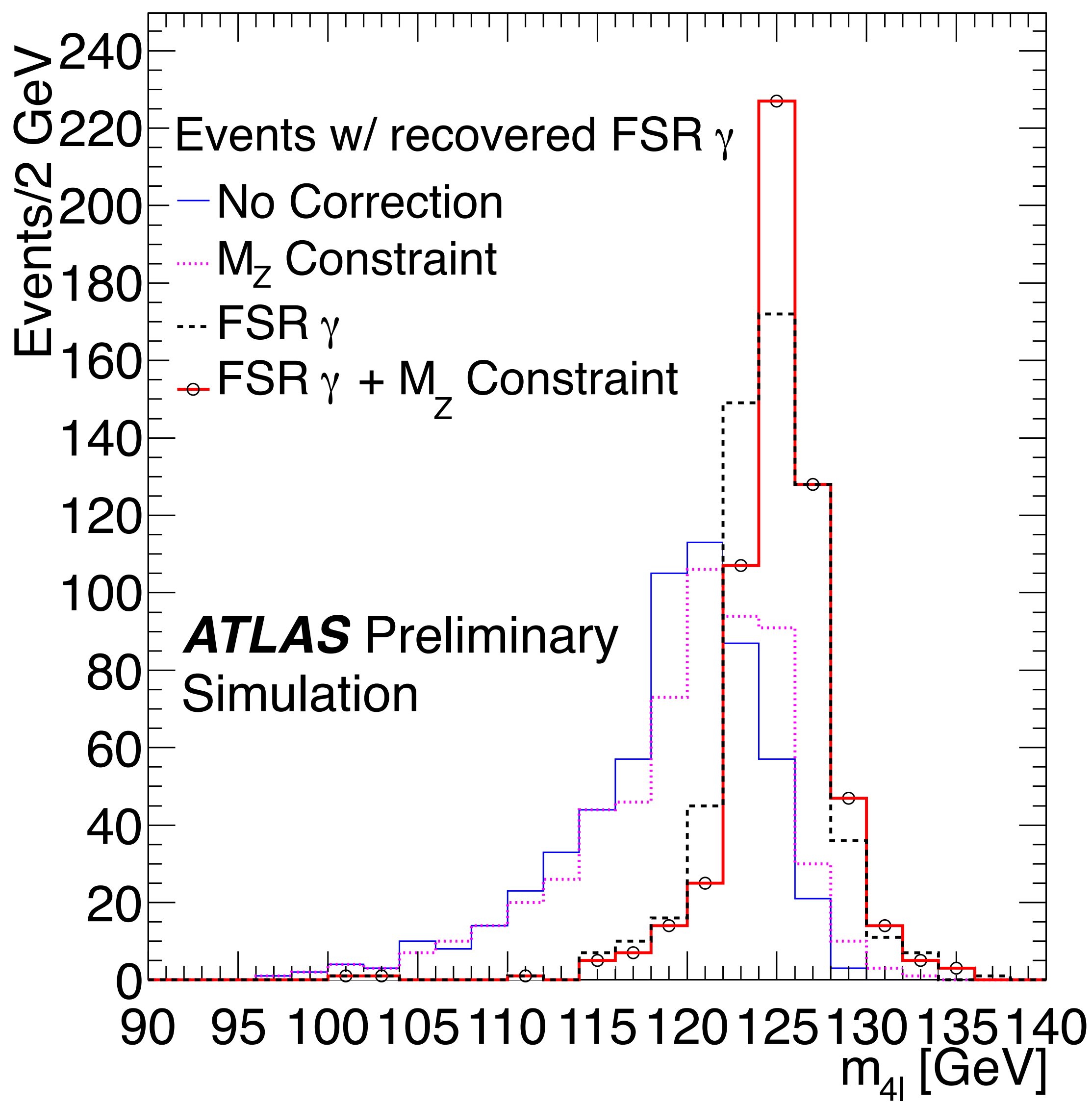
W, Z bremsstrahlung


Data 2011+ 2012
SM Higgs Boson
m_H=124.3 GeV (fit)
Background Z, ZZ*
Background Z+jets, $t\bar{t}$
Syst.Unc.
ATLAS
$H \rightarrow ZZ^* \rightarrow 4\mu$
$\sqrt{s}$ = 7 TeV $\int Ldt$ = 4.6 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int Ldt$ = 20.7 fb^{-1}
$H \rightarrow ZZ^* \rightarrow 2\mu 2e$
$H \rightarrow ZZ^* \rightarrow 2e 2\mu$
$H \rightarrow ZZ^* \rightarrow 4e$
Events/2.5 GeV
m_{4l} [GeV]

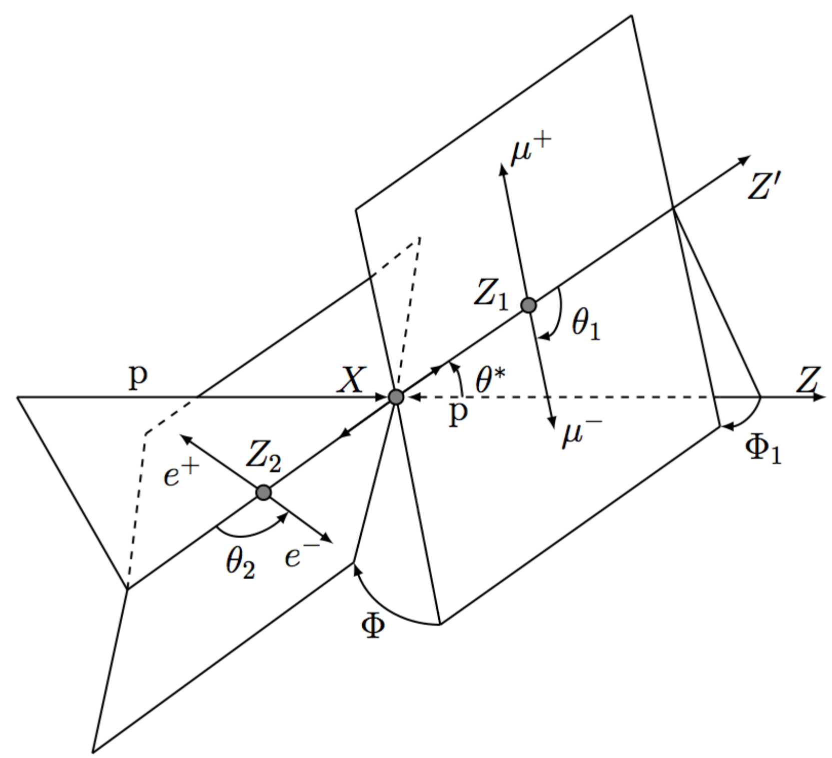
FSR+MassConstraint



reducible background summary

method	estimate at $\sqrt{s} = 8$ TeV	estimate at $\sqrt{s} = 7$ TeV
	4μ	4μ
m_{12} fit: Z + jets contribution	$2.4 \pm 0.5 \pm 0.6^{\dagger}$	$0.22 \pm 0.07 \pm 0.02^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.14 \pm 0.03 \pm 0.03^{\dagger}$	$0.03 \pm 0.01 \pm 0.01^{\dagger}$
$t\bar{t}$ from $e\mu + \mu\mu$	$0.10 \pm 0.05 \pm 0.004$	-
	$2e2\mu$	$2e2\mu$
m_{12} fit: Z + jets contribution	$2.5 \pm 0.5 \pm 0.6^{\dagger}$	$0.19 \pm 0.06 \pm 0.02^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.10 \pm 0.02 \pm 0.02^{\dagger}$	$0.03 \pm 0.01 \pm 0.01^{\dagger}$
$t\bar{t}$ from $e\mu + \mu\mu$	$0.12 \pm 0.07 \pm 0.005$	-
	$2\mu 2e$	$2\mu 2e$
$\ell\ell + e^{\pm}e^{\mp}$ relaxed cuts	$5.2 \pm 0.4 \pm 0.5^{\dagger}$	$1.8 \pm 0.3 \pm 0.4$
$\ell\ell + e^{\pm}e^{\mp}$ inverted cuts	$3.9 \pm 0.4 \pm 0.6$	-
$3\ell + \ell$ (same-sign)	$4.3 \pm 0.6 \pm 0.5$	$2.8 \pm 0.4 \pm 0.5^{\dagger}$
sub-leading same sign full analysis events	4	0
	$4e$	$4e$
$\ell\ell + e^{\pm}e^{\mp}$ relaxed cuts	$3.2 \pm 0.5 \pm 0.4^{\dagger}$	$1.4 \pm 0.3 \pm 0.4$
$\ell\ell + e^{\pm}e^{\mp}$ inverted cuts	$3.6 \pm 0.6 \pm 0.6$	-
$3\ell + \ell$ (same-sign)	$4.2 \pm 0.5 \pm 0.5$	$2.5 \pm 0.3 \pm 0.5^{\dagger}$
sub-leading same sign full analysis events	3	2

Definitions of angular variables



- θ_1 (θ_2) is the angle between the negative final state lepton and the direction of flight of Z_1 (Z_2) in the Z rest frame.
- Φ is the angle between the decay planes of the four final state leptons expressed in the four lepton rest frame.
- Φ_1 is the angle defined between the decay plane of the leading lepton pair and a plane defined by the vector of the Z_1 in the four lepton rest frame and the direction of the parton following the positive z axis.
- θ^* is the production angle of the Z_1 defined in the four lepton rest frame.[2]