Properties Measurement of $H \rightarrow ZZ^* \rightarrow 4\ell$ and $Z \rightarrow 4\ell$ with ATLAS

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LHC mini-Workshop

Zhejiang University, HangZhou, China

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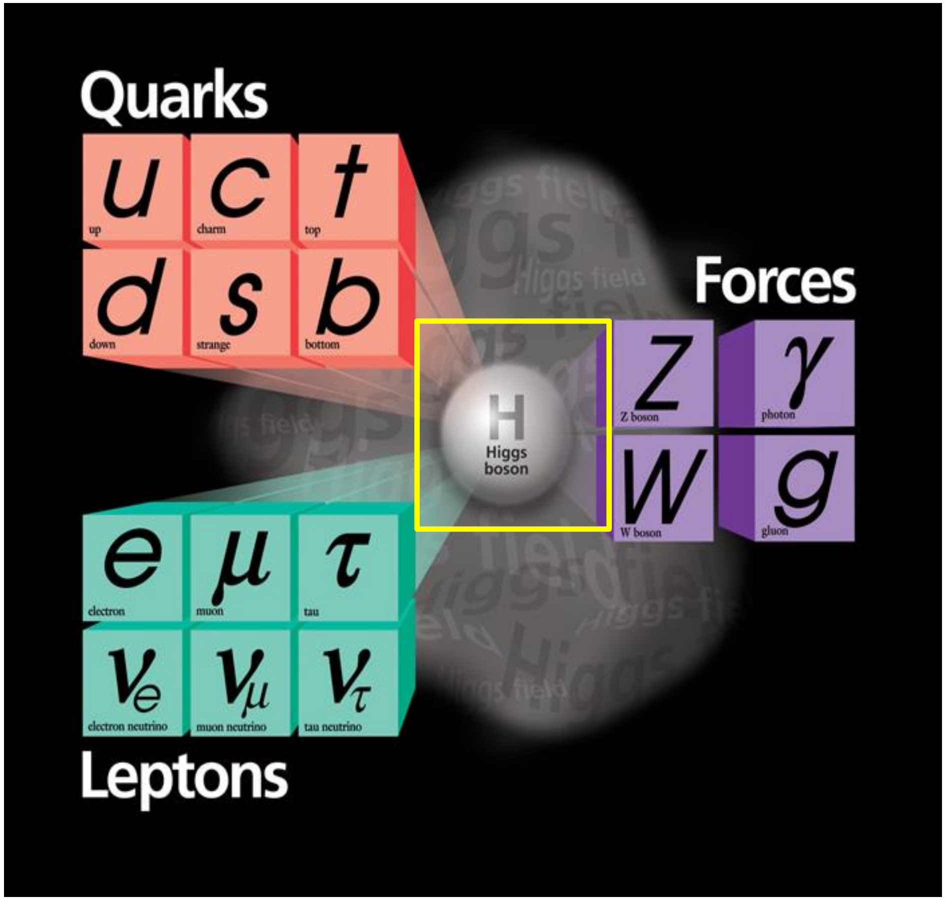
Outline

- Discovery of the Higgs Boson
- Higgs Production and Decays at LHC
- Event Selection of H → ZZ* → 4ℓ
- Higgs Properties : mass, width, spin, parity, couplings
- Analysis of Single Resonance Z→4l: cross section, BR
- Summary

References:

PLB 726 pp.88-119, pp. 120-144 (2013)
PRD 90, 052004 (2014), PRL 112, 231806(2014)
ATLAS-CONF-2013-013, ATLAS-CONF-2013-034
ATLAS-CONF-2014-009, ATL-COM-PHYS-2014-1403

Standard Model and Discovery of the Higgs

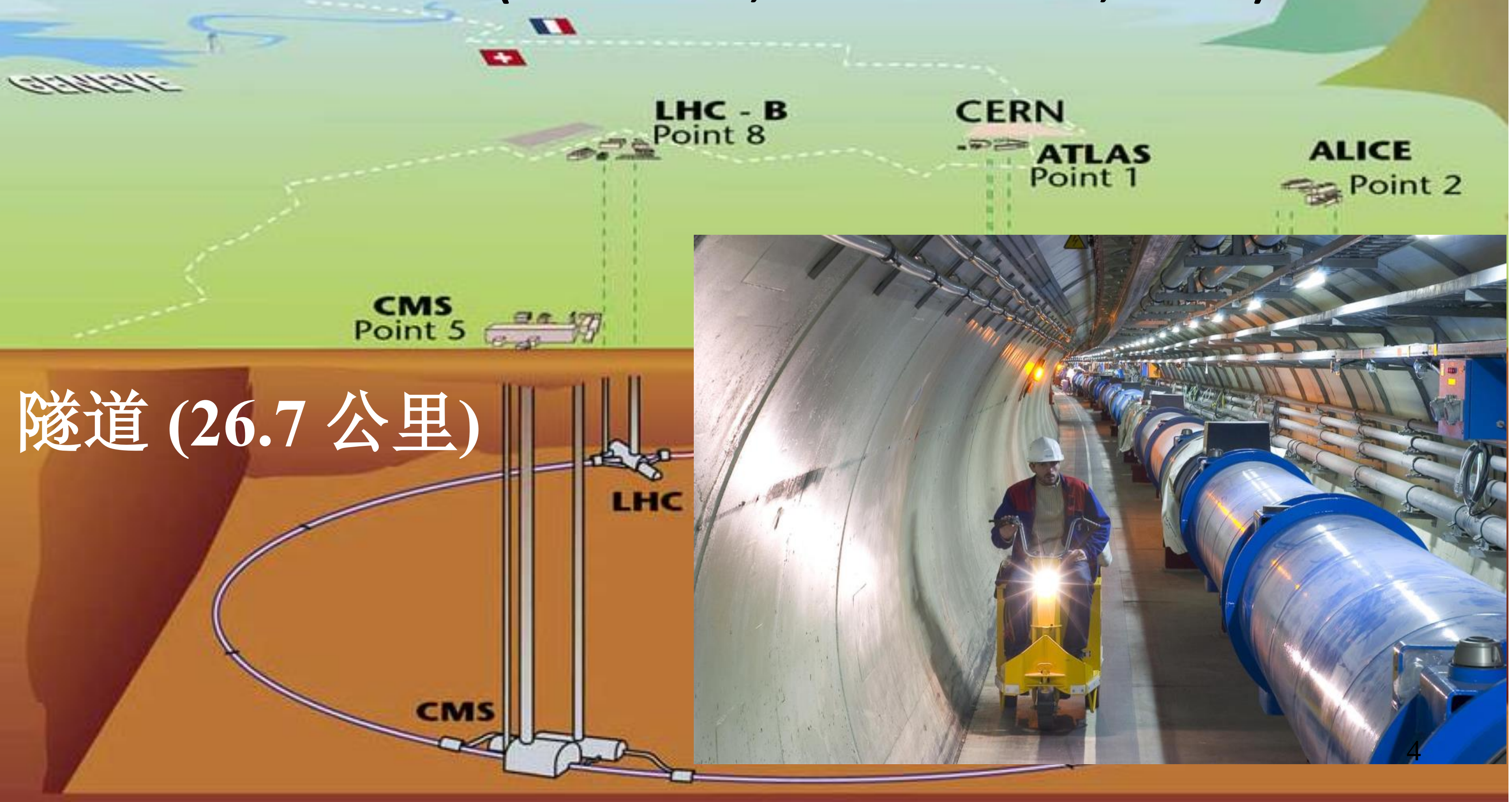


Higgs boson is proposed to responsible for the electroweak symmetry breaking, particles acquire mass when interacting with the Higgs field.

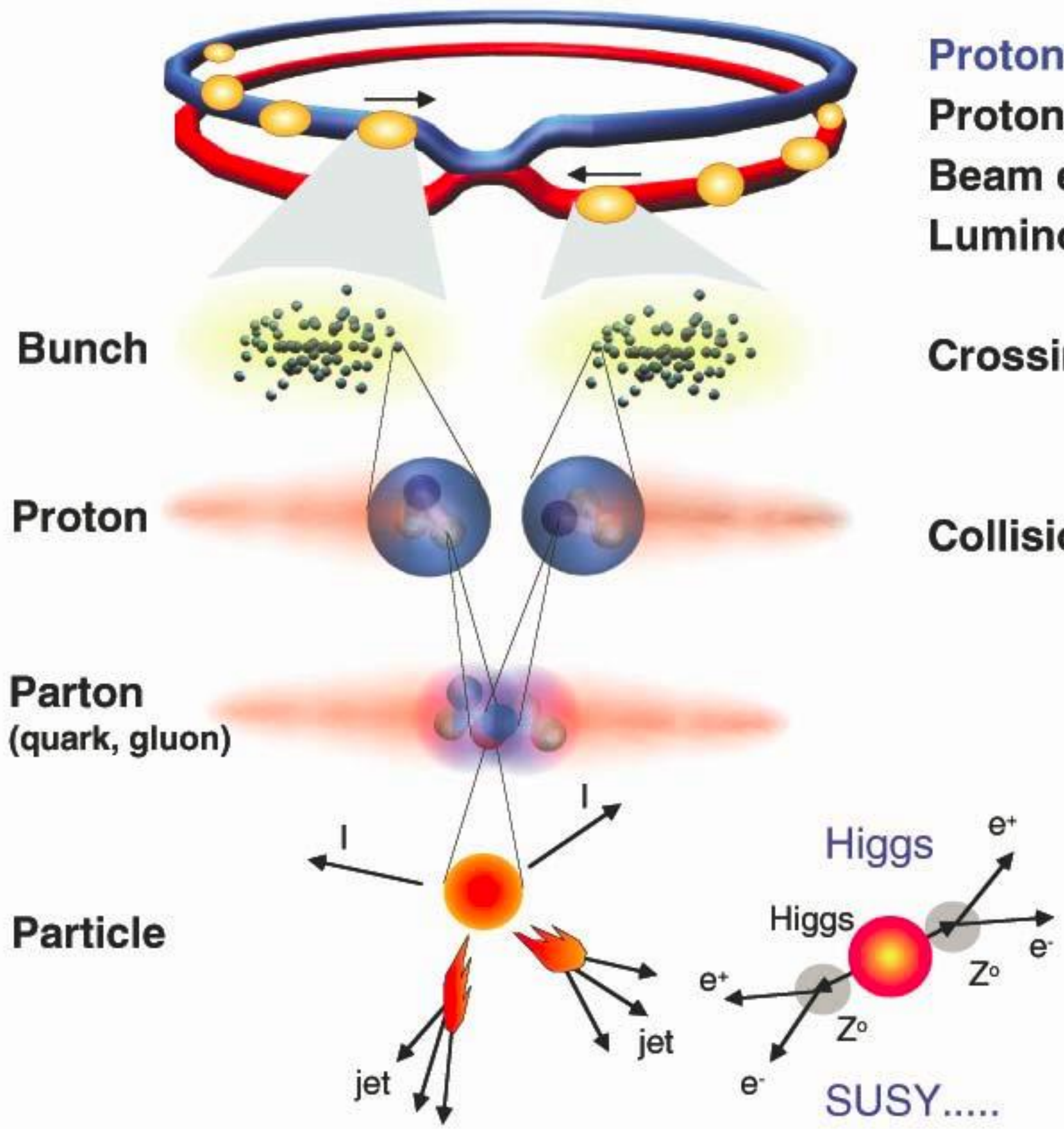
➔ The Higgs boson was discovered by ATLAS and CMS at LHC in July, 2012.
➔ F. Englert and P. Higgs won the Nobel Prize in Physics in 2013.

CERN's Large Hadron Collider (LHC)

LHC is the world's largest collider (7-14 TeV)
ATLAS Collaboration (38 countries, 174 institutions, ~ 3000)
CMS Collaboration (41 counties, 179 institutions, ~3300)



LHC：Proton-Proton Collisions



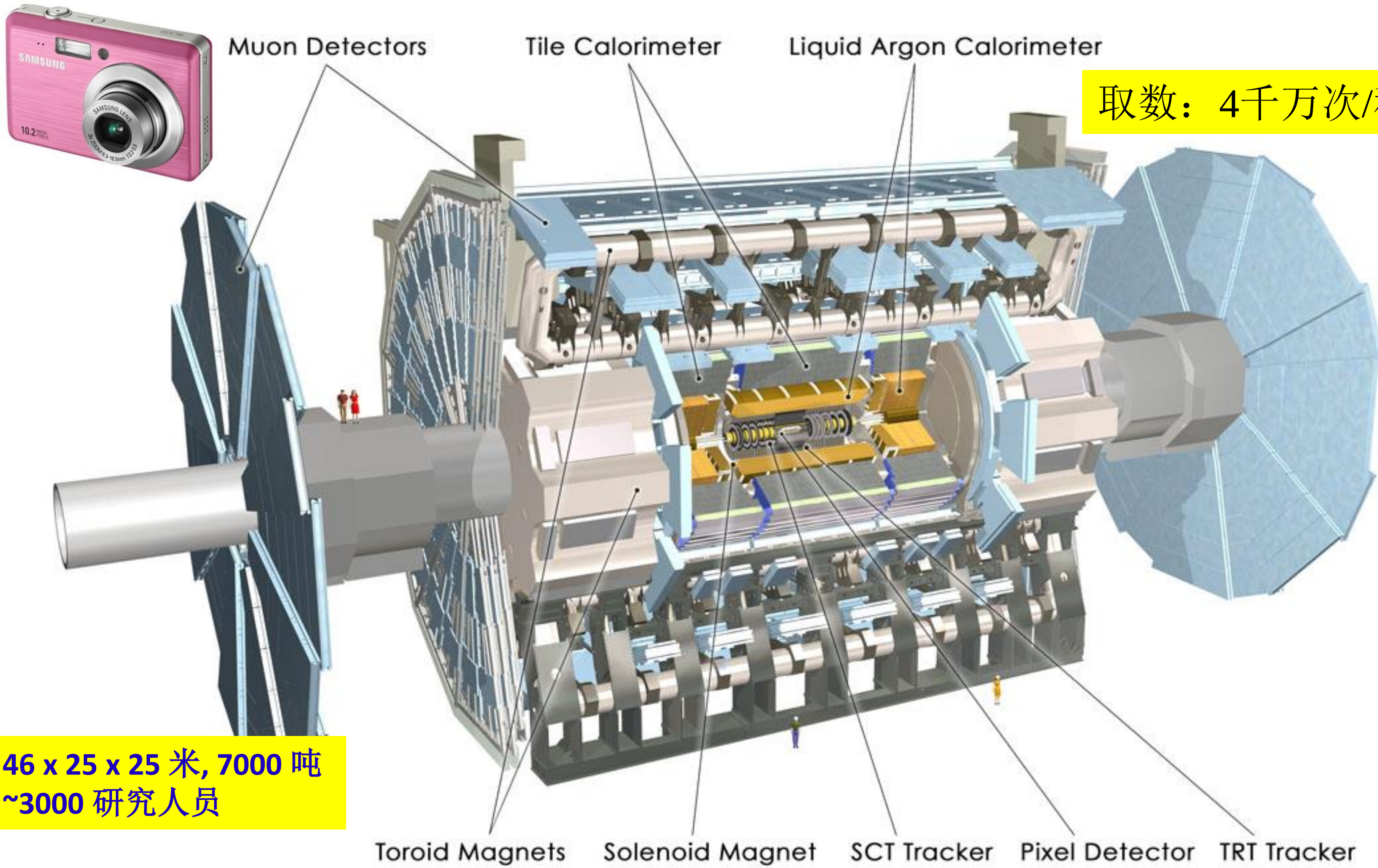
Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV ($7x10^{12}$ eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

Major challenge：

Higgs → ZZ* → 4l 产生几率为10万亿分之一

Selection of 1 in 10,000,000,000,000

The ATLAS Detector: Huge Camera

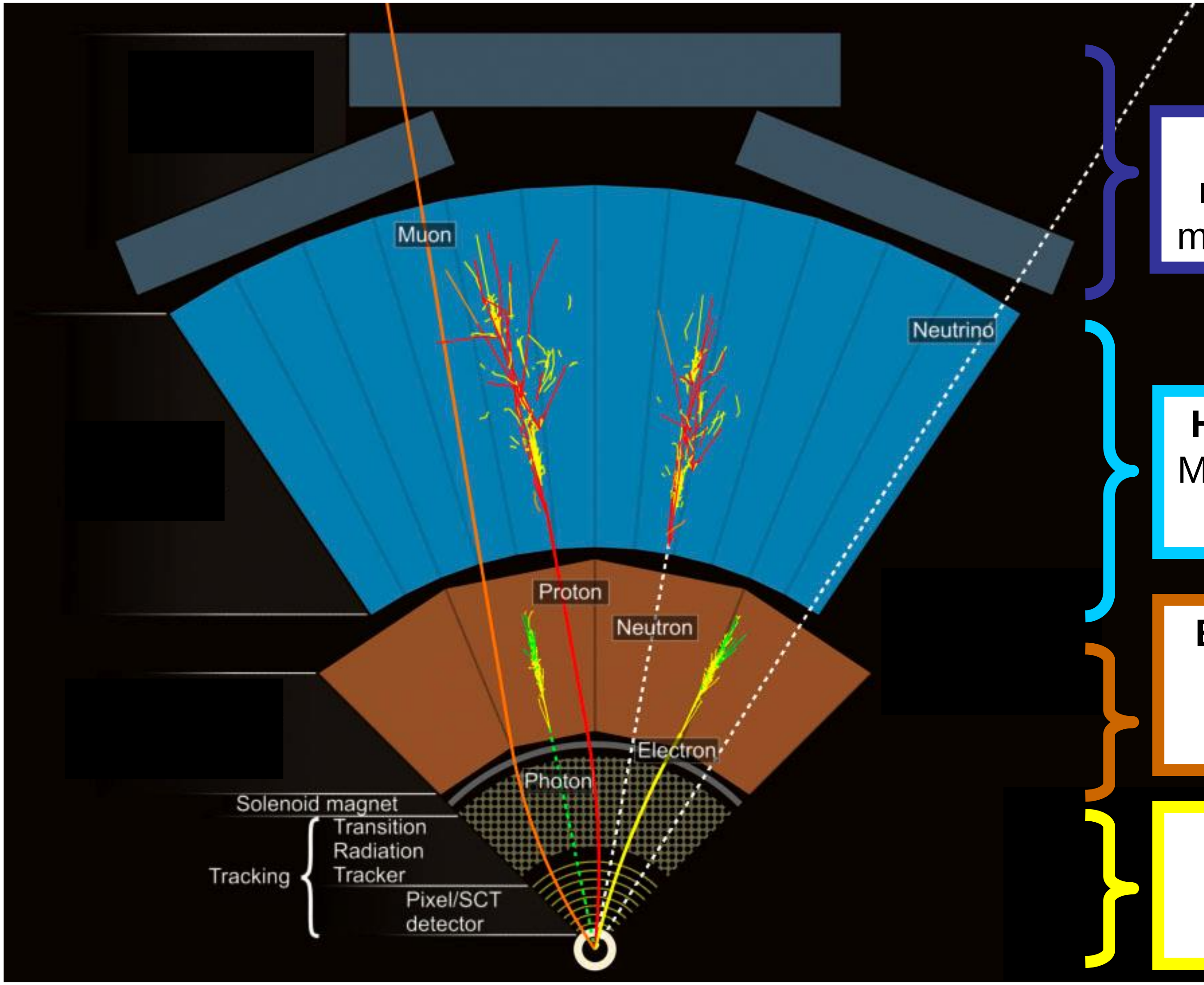


取数：4千万次/秒

46 x 25 x 25 米, 7000 吨
~3000 研究人员

Particle Detection

- Different particles have different signatures in detectors



Muon Spectrometer:
muon identification and momentum measurement

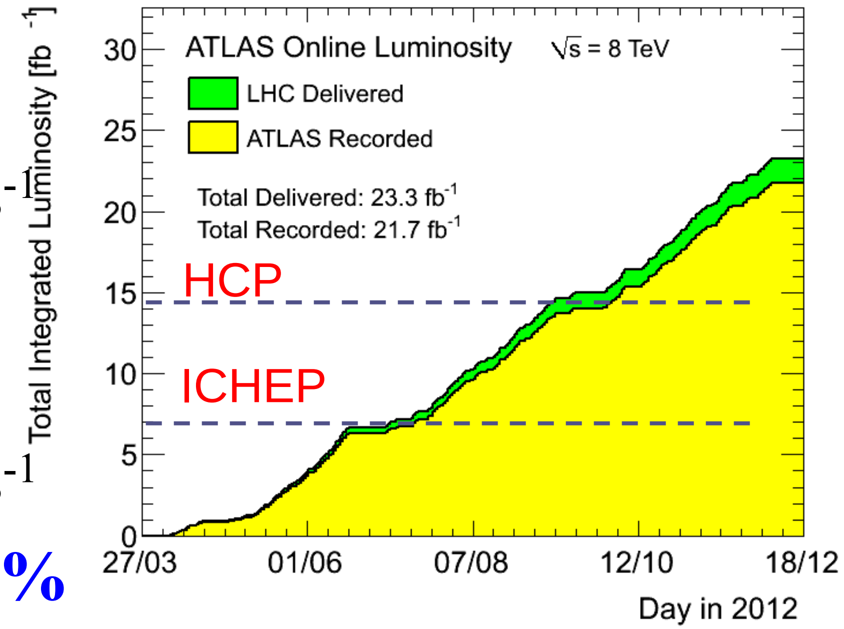
Hadronic calorimeter:
Measurement of jets and missing energy

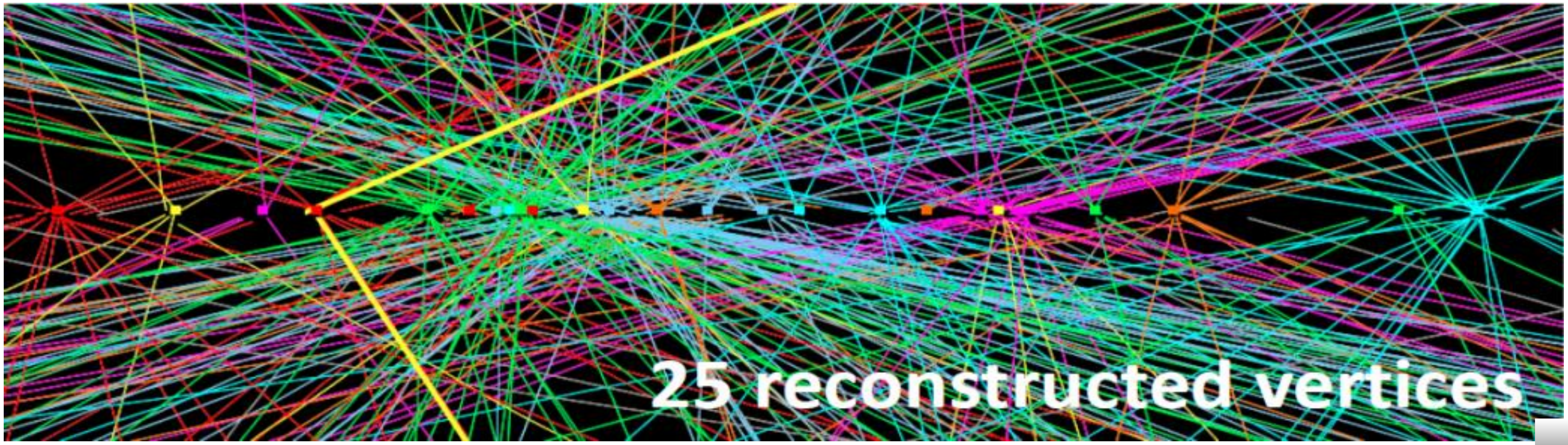
Electromagnetic calo:
e/γ identification and energy measurement

Tracking system:
Charged particle momentum, vertexing

ATLAS Data Samples

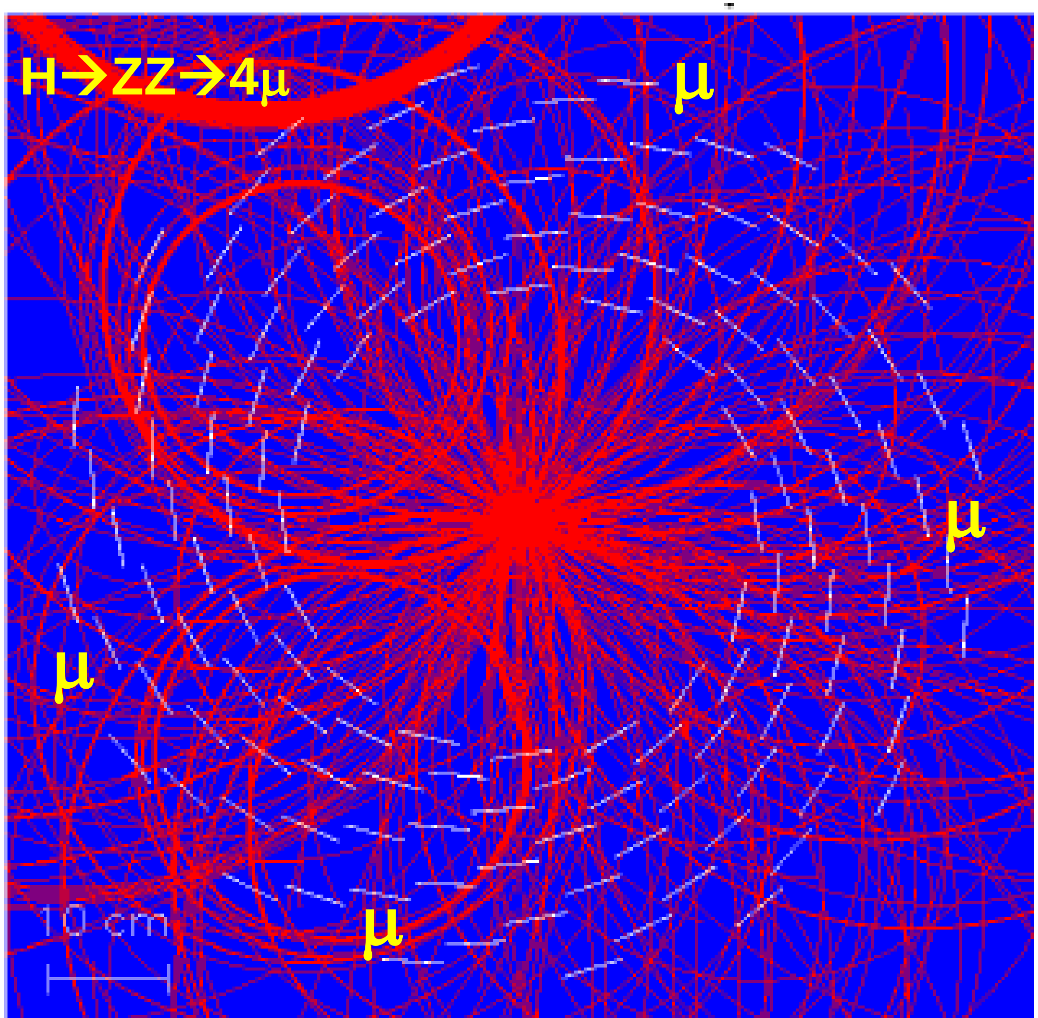
- **7 TeV data samples (2011)**
  - 4.5 fb^{-1} for physics analysis
  - Peak luminosity $3.6\times10^{33}cm^{-2}s^{-1}$
- **8 TeV data samples (2012)**
  - 20.3 fb^{-1} for physics analysis
  - Peak luminosity $7.7\times10^{33}cm^{-2}s^{-1}$
- **Data-taking efficiency: ~95.5%**
- **Significant pileup events**





Major Challenge (Large Pileup)

- Large pileup events result in big challenge to the detector, reconstruction and particle identification (**eg. e, γ, τ, b**) !



Boosted Decision Trees (BDT)

最先 (2004) 提出和应用先进的BDT方法用于粒子鉴别和事例识别。
BDT方法应用于希格斯粒子的寻找，显著提高希格斯粒子发现的灵敏度。

Available online at www.sciencedirect.com
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Nuclear Instruments and Methods in Physics Research A 543 (2005) 577–584
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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Boosted decision trees as an alternative to artificial neural networks for particle identification

Byron P. Roe[a], Hai-Jun Yang[a,*], Ji Zhu[b], Yong Liu[c], Ion Stancu[c], Gordon McGregor[d]

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Studies of boosted decision trees for MiniBooNE particle identification

Hai-Jun Yang[a,c,*], Byron P. Roe[a], Ji Zhu[b]

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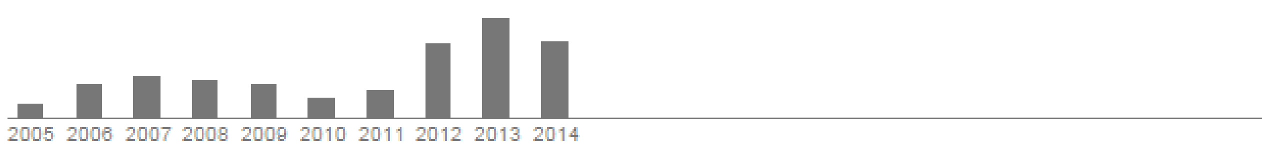
Available online 4 October 2005

BDT 论文在高能物理INSPIRES数据库分别引用113次和45次。
Google scholar 数据库分别引用231次和91次。
BDT方法已收录进CERN TMVA分析软件包，被十几个大型国际合作实验组采用作为主要的方法来提高新物理探测灵敏度。

Total citations　Cited by 231



Scholar articles　Boosted decision trees as an alternative to artificial neural networks for particle identification
BP Roe, HJ Yang, J Zhu, Y Liu, I Stancu, G McGregor - Nuclear Instruments and Methods in Physics Research ..., 2005
Cited by 231 - Related articles - All 13 versions

1. Introduction

The artificial neur... has been widely us... Energy Physics exper... use of the ANN t...

by the LSND experiment [2]. It is a crucial experiment which will imply new physics beyond

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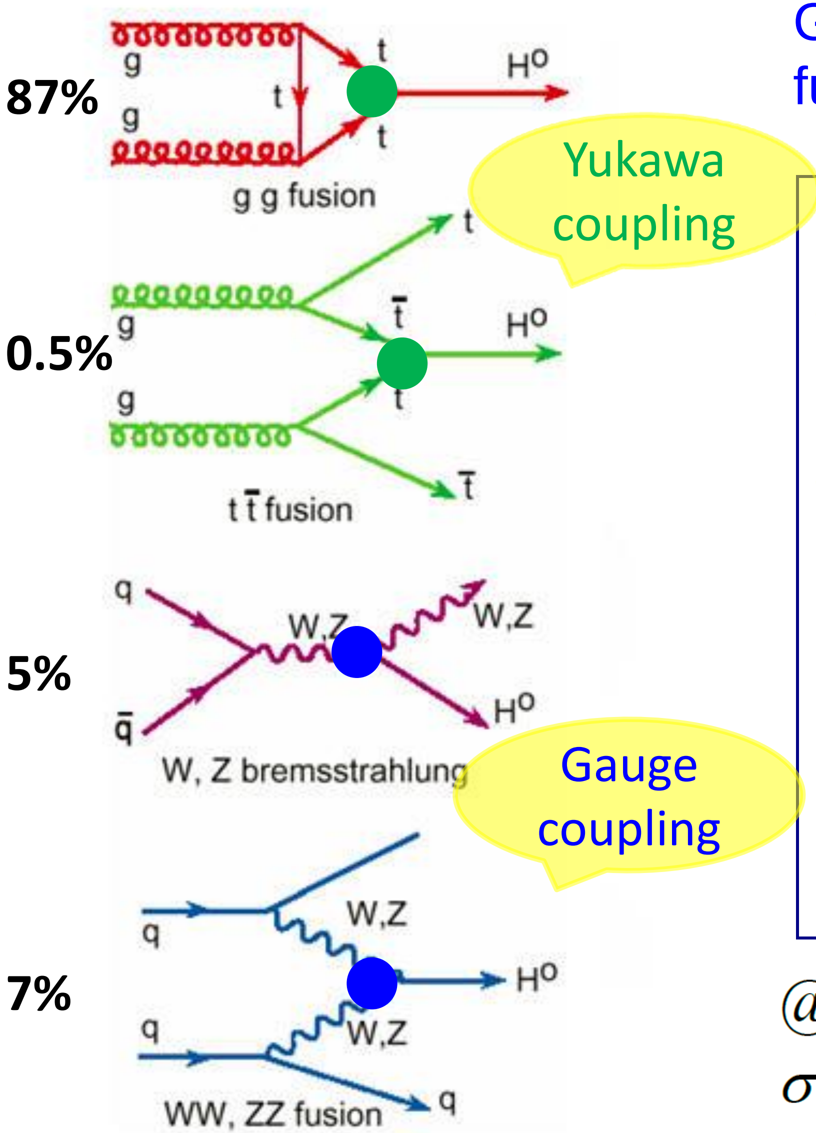
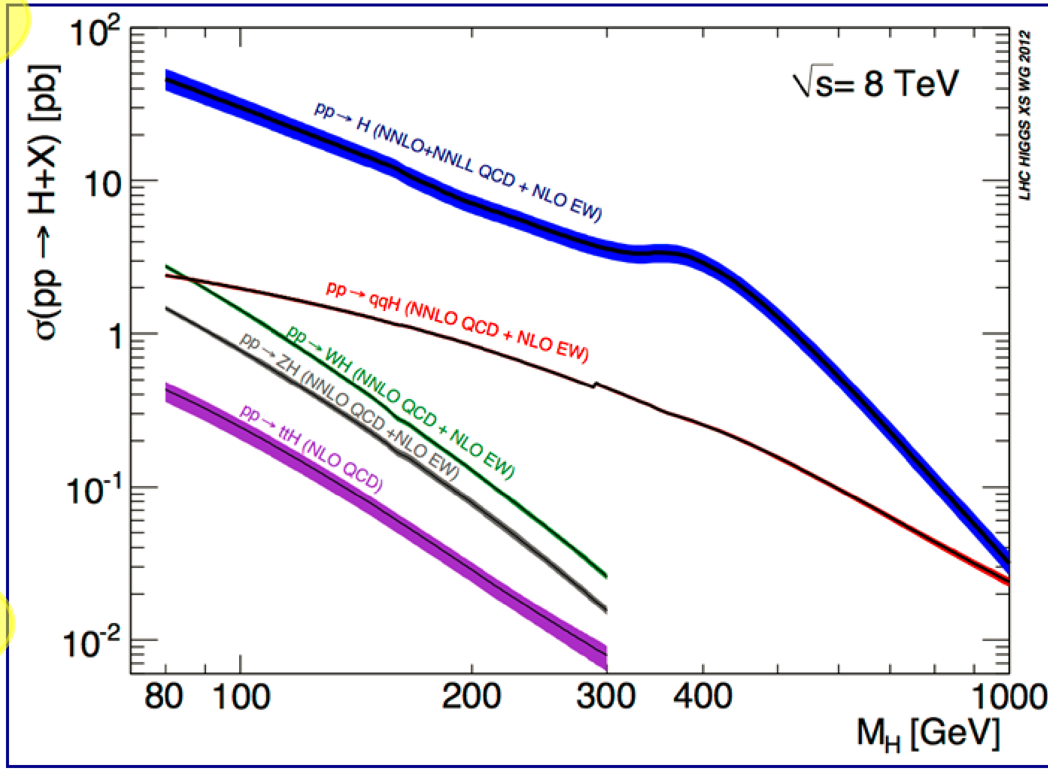
doi:10.1016/j.nima.2005.09.022

Higgs Boson Production at LHC



Gluon-gluon fusion gg→H and vector-boson fusion qq→qqH are dominant

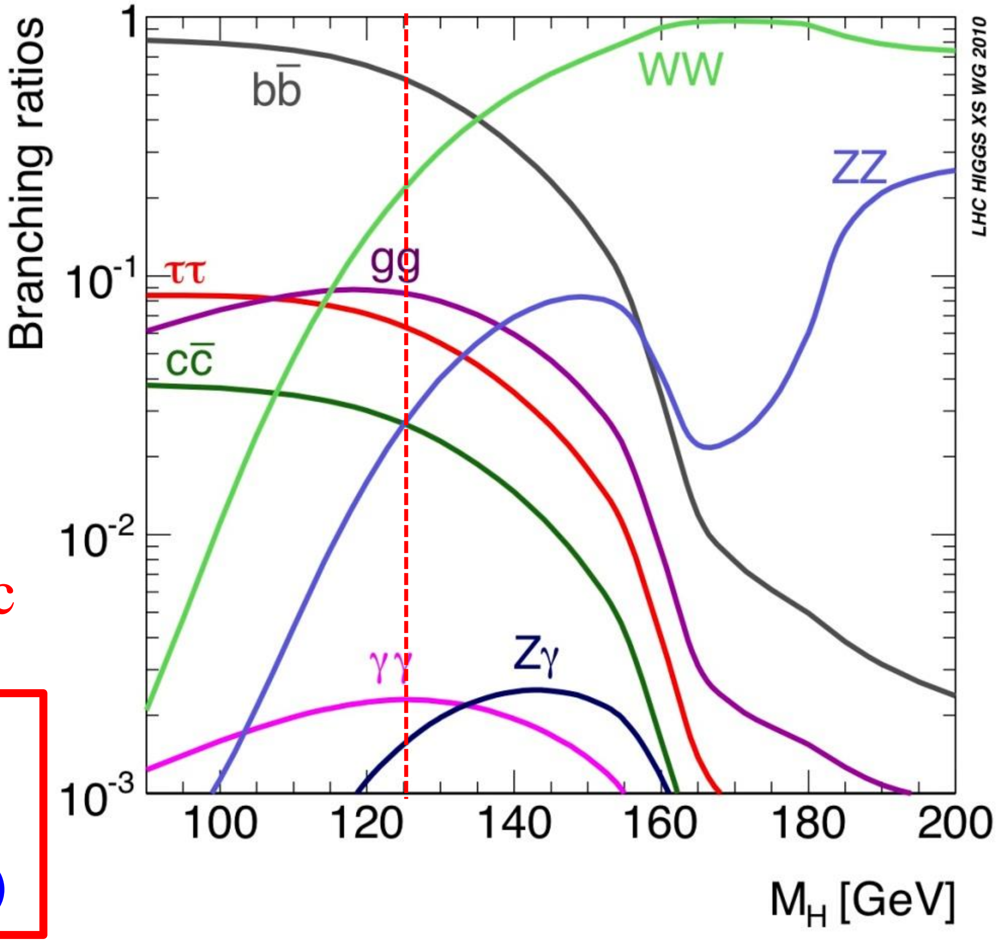


$$@125\text{ GeV: } \sigma_{ggH}=19.5\text{ pb}, \sigma_{VBF}=1.6\text{ pb},$$
$$\sigma_{WH}=0.70\text{ pb}, \sigma_{ZH}=0.39\text{ pb}, \sigma_{ttH}=0.13\text{ pb}$$

Higgs Boson Decay

Higgs decay branching ratio at m_H=125 GeV

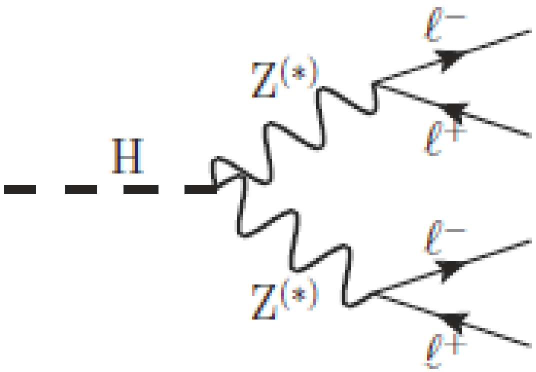
- bb: 57.7% (huge QCD background)
- WW: 21.5% (easy identification in di-lepton mode, complex background)
- ττ: 6.3% (complex final states with τ leptonic and/or hadronic decays)
- ZZ*: 2.6% ("gold-plated", clean signature of 4-lepton, high S/B, excellent mass peak)
- γγ: 0.23% (excellent mass resolution, high sensitivity)



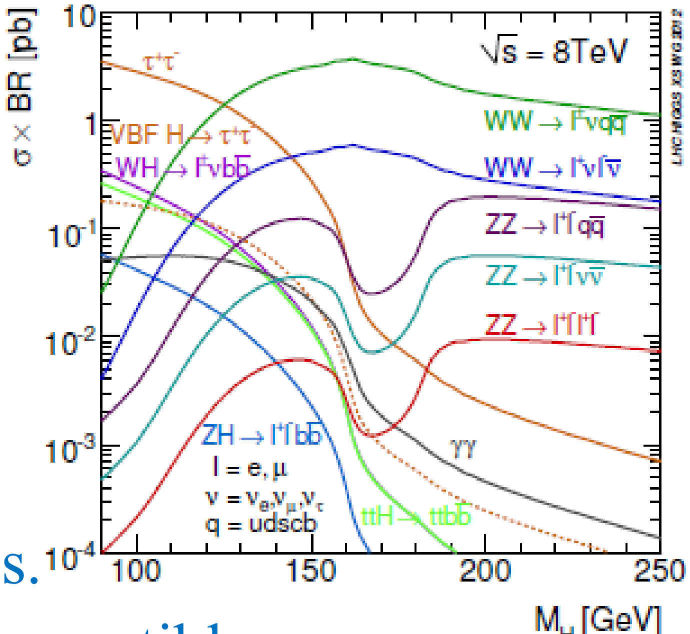
H → ZZ* → 4l production rate: 1 out of 10^{13} collision events

H→ZZ*→4ℓ Overview

- ❑ Extremely clean – "Gold-plated" channel
  - o Fully reconstructed final states
  - o Good mass resolution (~ 1.6-2.4 GeV)
  - o High S/B ratio (~ 1-2)
  - o Low decay branching fraction



- ❑ Currently statistically limited
  - o 4.5 fb^{-1} @ 7 TeV + 20.3 fb^{-1} @ 8 TeV
  - o Expect 68 SM H→ZZ*→4ℓ (e,μ) events



- ❑ Properties measurement
  - o Higgs mass, width, spin, parity, couplings.
  - o Critical to determine whether it is fully compatible with the SM Higgs boson

H→ZZ*→4l Event Selection

- Trigger match with single and/or di-lepton trigger
- Four sub-channels: 4e, 2e2μ, 2μ2e, 4μ

Event Pre-selection	
Electrons	
"MultiLepton" quality GSF electrons with $E_{\mathrm{T}} > 7$ GeV and $\lvert\eta\rvert < 2.47$	
Muons	
combined or segment-tagged muons with $p_{\mathrm{T}} > 6$ GeV and $\lvert\eta\rvert < 2.7$	
Maximum one calo-tagged or standalone muon	
calo-tagged muons with $p_{\mathrm{T}} > 15$ GeV and $\lvert\eta\rvert < 0.1$	
standalone muons with $p_{\mathrm{T}} > 6$ GeV, $2.5 < \lvert\eta\rvert < 2.7$ and $\Delta R > 0.2$ from closest segment-tagged	
Event Selection	
Kinematic Selection	Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons fulfilling the following requirements:
	p_{T} thresholds for three leading leptons in the quadruplet 20, 15 and 10 GeV
	Leading di-lepton mass requirement $50\ \mathrm{GeV} < m_{12} < 106\ \mathrm{GeV}$
	Sub-leading di-lepton mass requirement $m_{threshold} < m_{34} < 115$ GeV
	Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} < 5$ GeV
	$\Delta R(\ell,\ell') > 0.10(0.20)$ for all same (different) flavour leptons in the quadruplet.
Isolation	Lepton track isolation ($\Delta R = 0.20$): $\Sigma p_{\mathrm{T}}/p_{\mathrm{T}} < 0.15$
	Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.20$
	Muon calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.30$
	Stand-Alone muons calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T/E_T < 0.15$
Impact Parameter Significance	Apply impact parameter significance cut to all leptons of the quadruplet.
	For electrons : $d_0/\sigma_{d_0} < 6.5$
	For muons : $d_0/\sigma_{d_0} < 3.5$

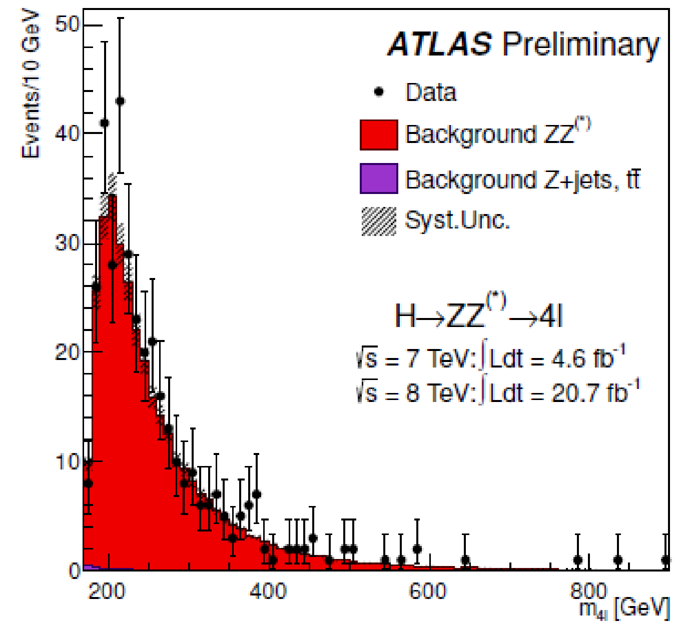
Background Estimation

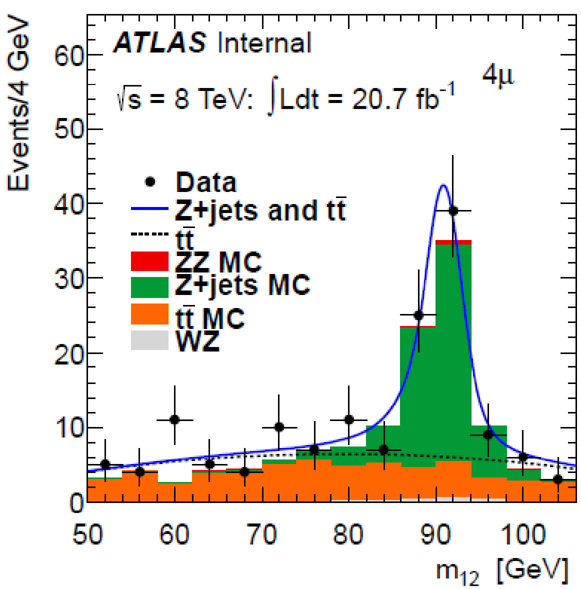
Main background is $ZZ^{(*)}$ production

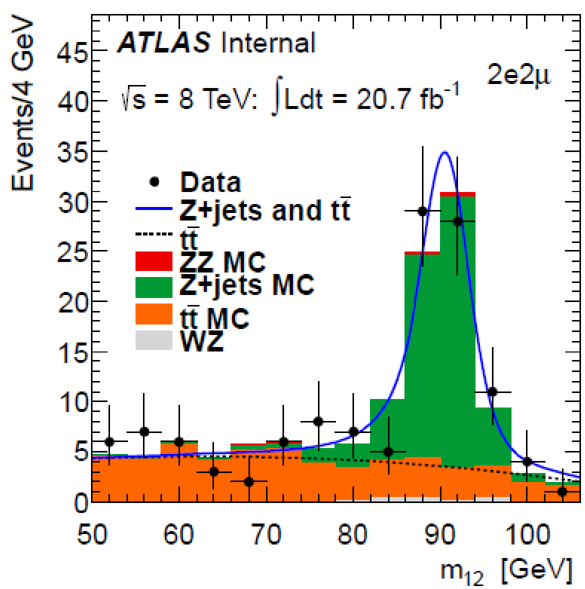
- MC simulation, scaled to theoretical cross section

Reducible backgrounds:

- $Zb\bar{b}$, Z+light jets, $t\bar{t}$
- Estimated using data-driven methods
  - Define background-enriched/signal-depleted control reigions
  - Extrapolate to signal region using transfer factors







- Estimates agree well with data in control region where isolation and d_0 requirements are removed for subleading pair

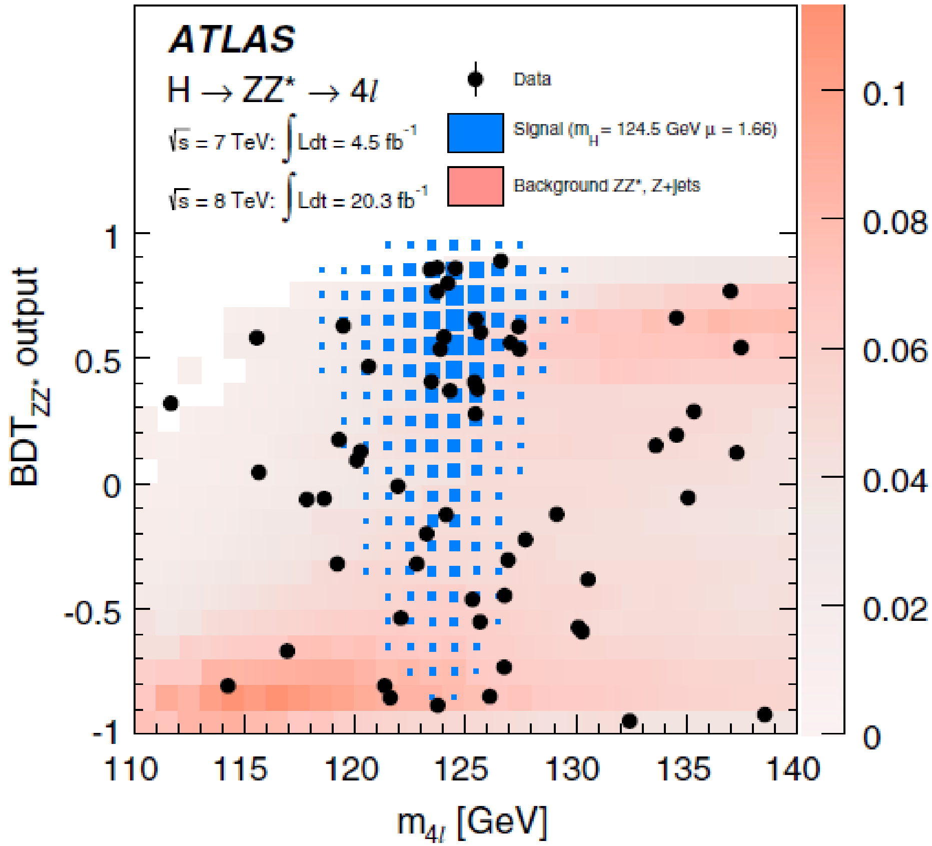
Selected Higgs Candidates

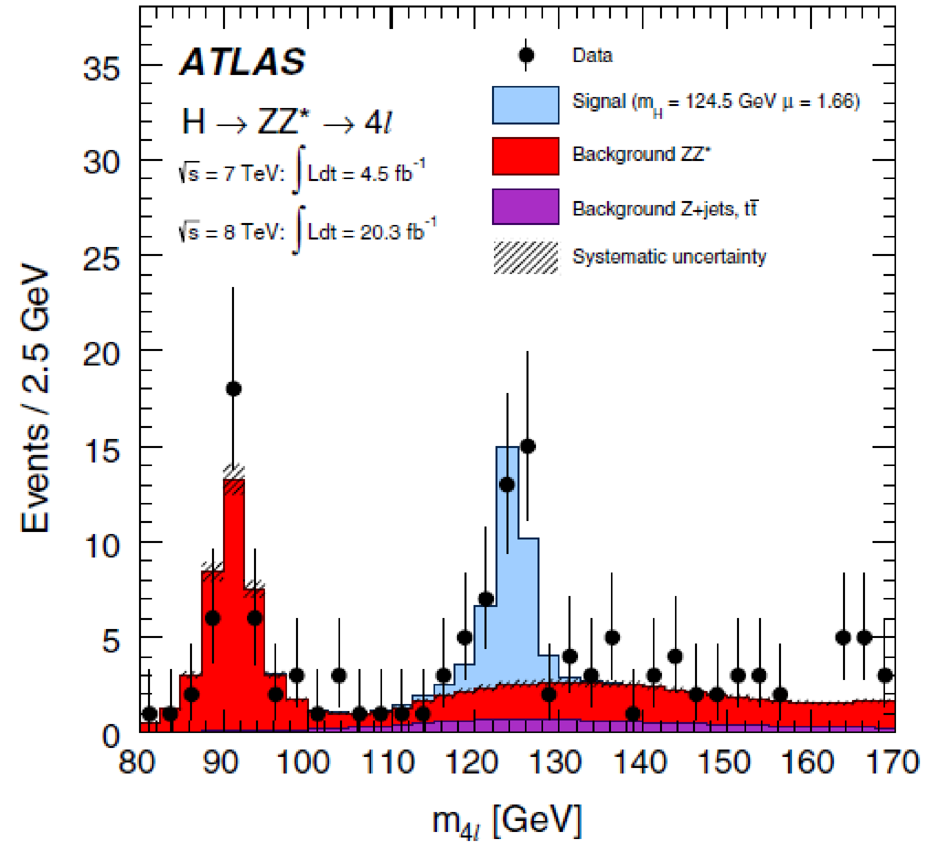
TABLE III. The number of events expected and observed for a $m_H = 125$ GeV hypothesis for the four-lepton final states. The second column shows the number of expected signal events for the full mass range. The other columns show the number of expected signal events, the number of ZZ^* and reducible background events, and the signal-to-background ratio (s/b), together with the numbers of observed events, in a window of $120 < m_{4\ell} < 130$ GeV for 4.5 fb^{-1} at $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV as well as for the combined sample.

Final state	Signal Full mass range	Signal	ZZ^*	$Z+\text{jets}, t\bar{t}$	s/b	Expected	Observed
$\sqrt{s} = 7$ TeV							
4μ	1.00 ± 0.10	0.91 ± 0.09	0.46 ± 0.02	0.10 ± 0.04	1.7	1.47 ± 0.10	2
$2e2\mu$	0.66 ± 0.06	0.58 ± 0.06	0.32 ± 0.02	0.09 ± 0.03	1.5	0.99 ± 0.07	2
$2\mu 2e$	0.50 ± 0.05	0.44 ± 0.04	0.21 ± 0.01	0.36 ± 0.08	0.8	1.01 ± 0.09	1
$4e$	0.46 ± 0.05	0.39 ± 0.04	0.19 ± 0.01	0.40 ± 0.09	0.7	0.98 ± 0.10	1
Total	2.62 ± 0.26	2.32 ± 0.23	1.17 ± 0.06	0.96 ± 0.18	1.1	4.45 ± 0.30	6
$\sqrt{s} = 8$ TeV							
4μ	5.80 ± 0.57	5.28 ± 0.52	2.36 ± 0.12	0.69 ± 0.13	1.7	8.33 ± 0.6	12
$2e2\mu$	3.92 ± 0.39	3.45 ± 0.34	1.67 ± 0.08	0.60 ± 0.10	1.5	5.72 ± 0.37	7
$2\mu 2e$	3.06 ± 0.31	2.71 ± 0.28	1.17 ± 0.07	0.36 ± 0.08	1.8	4.23 ± 0.30	5
$4e$	2.79 ± 0.29	2.38 ± 0.25	1.03 ± 0.07	0.35 ± 0.07	1.7	3.77 ± 0.27	7
Total	15.6 ± 1.6	13.8 ± 1.4	6.24 ± 0.34	2.00 ± 0.28	1.7	22.1 ± 1.5	31
$\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV							
4μ	6.80 ± 0.67	6.20 ± 0.61	2.82 ± 0.14	0.79 ± 0.13	1.7	9.81 ± 0.64	14
$2e2\mu$	4.58 ± 0.45	4.04 ± 0.40	1.99 ± 0.10	0.69 ± 0.11	1.5	6.72 ± 0.42	9
$2\mu 2e$	3.56 ± 0.36	3.15 ± 0.32	1.38 ± 0.08	0.72 ± 0.12	1.5	5.24 ± 0.35	6
$4e$	3.25 ± 0.34	2.77 ± 0.29	1.22 ± 0.08	0.76 ± 0.11	1.4	4.75 ± 0.32	8
Total	18.2 ± 1.8	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37

Candidates of 4-lepton

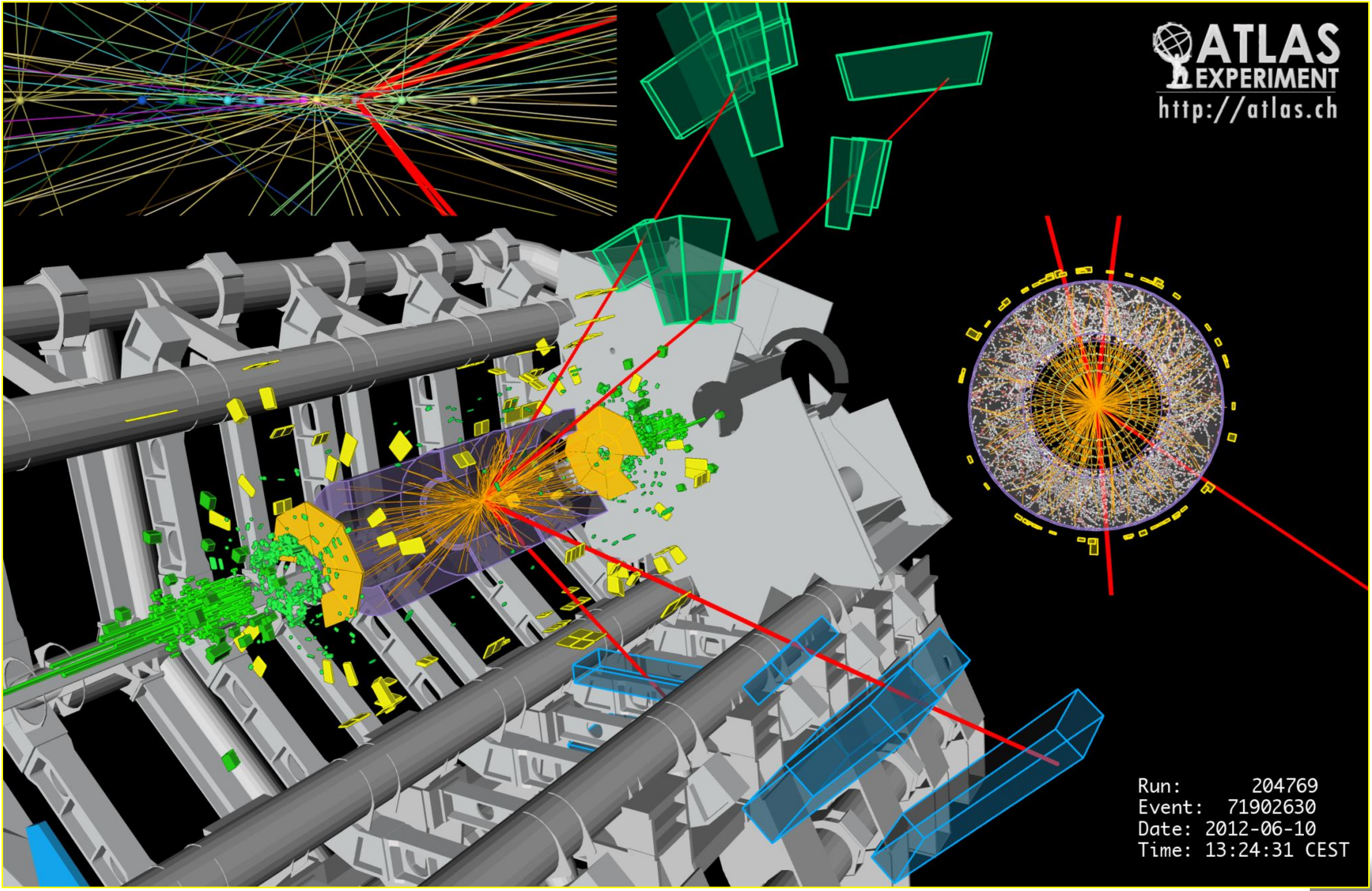
- ➔ BR(H➔ZZ*) = 2.63%, BR(ZZ*➔4l)=0.45%
- ➔ About 68 H➔ ZZ*➔4l events produced
- ➔ Observed 37 candidates with 16 Higgs ➔ ZZ* ➔ 4l signal



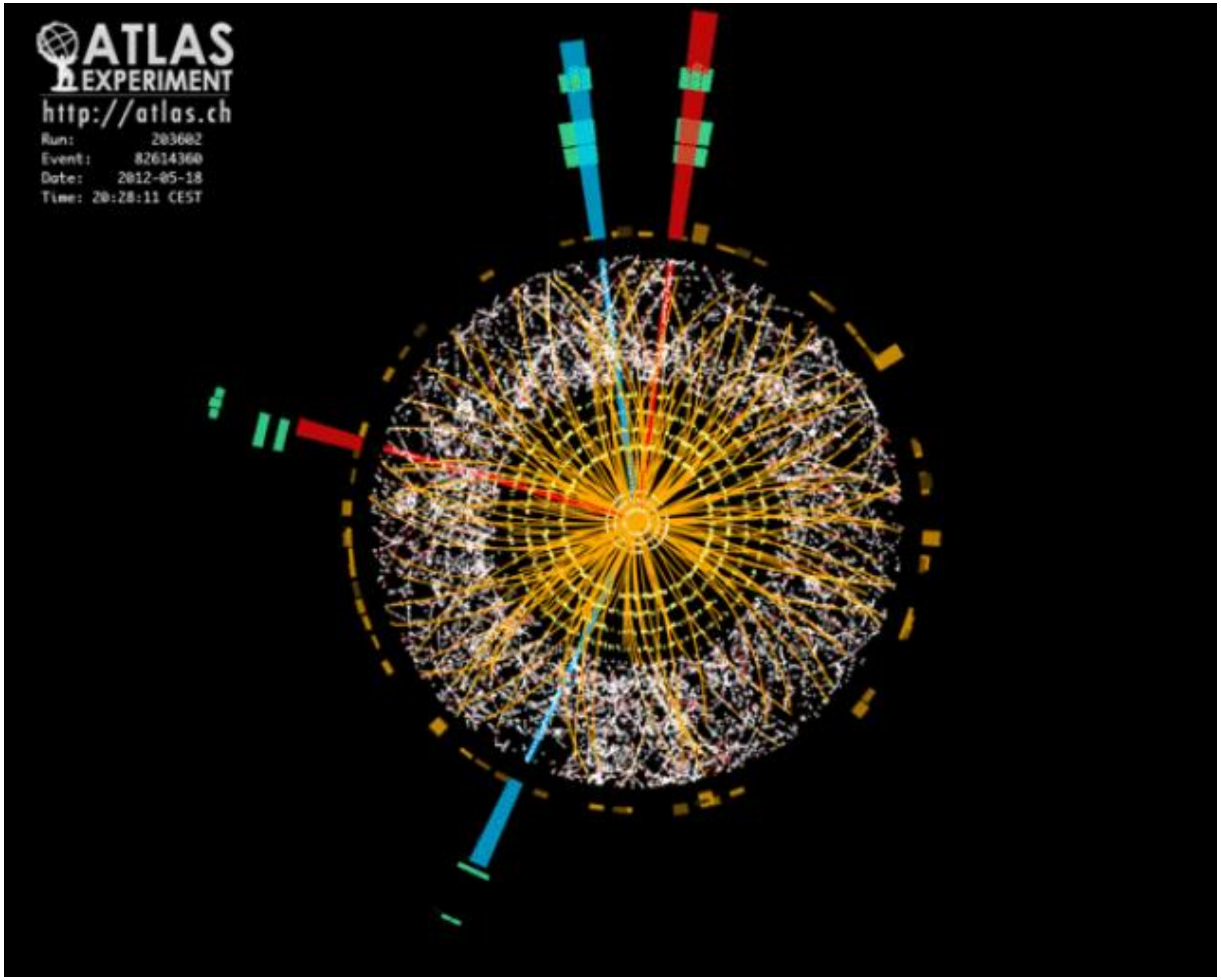


ATLAS H → ZZ* → 4μ Candidate

- $M_{4\mu}$ = 125.1 GeV, M_{12} = 86.3 GeV, M_{34} = 31.6 GeV

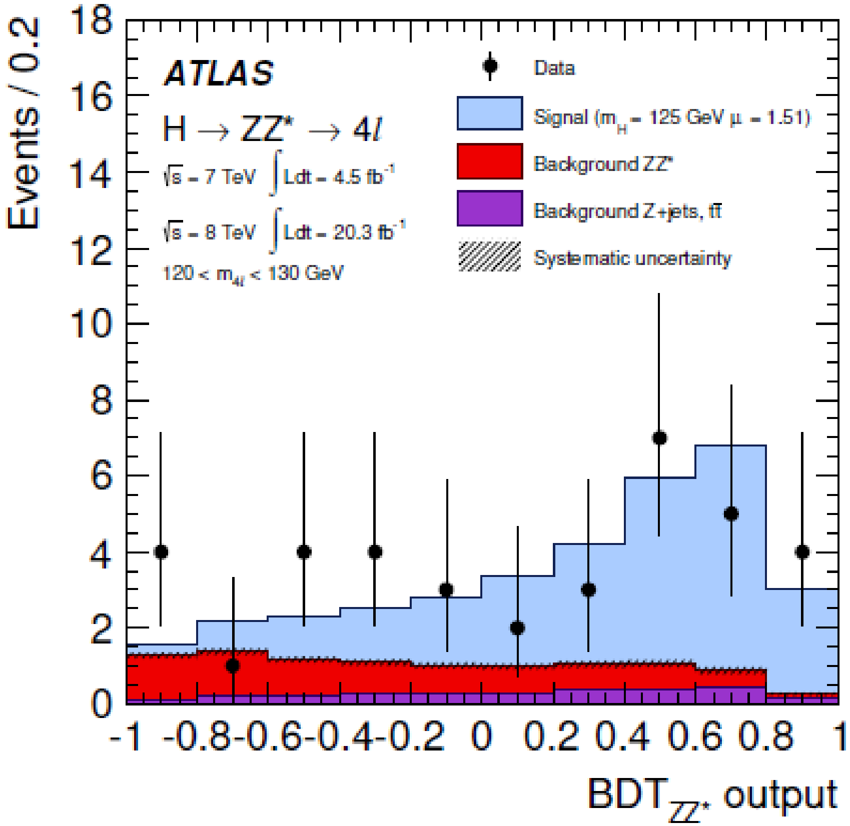


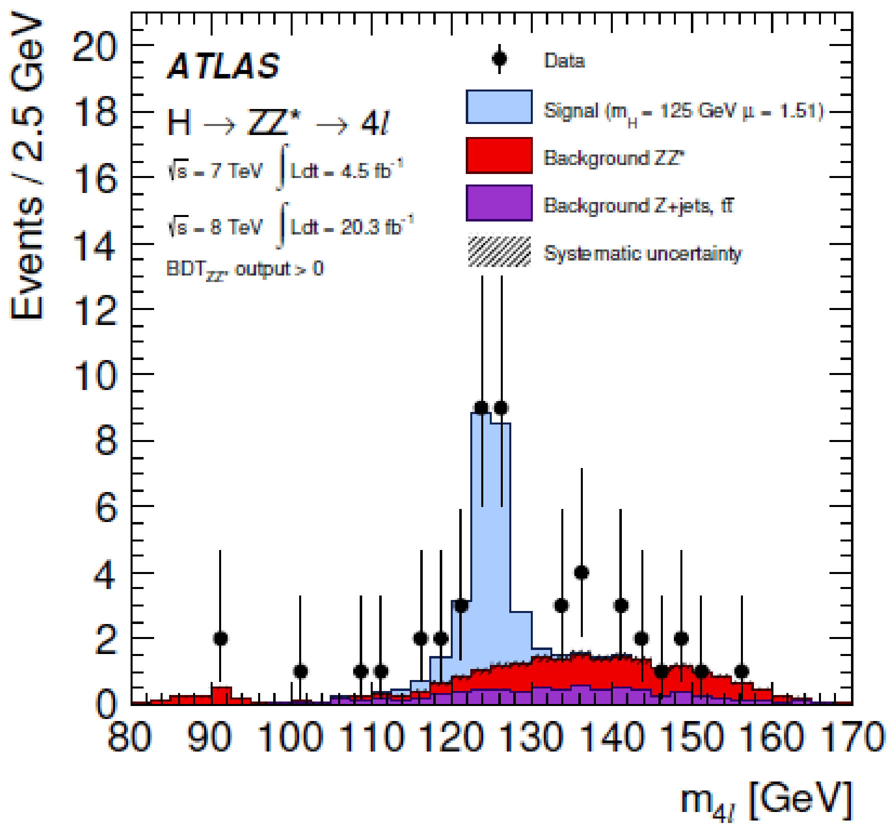
Higgs →ZZ* →4l Candidates Evolution



Candidates of 4-lepton

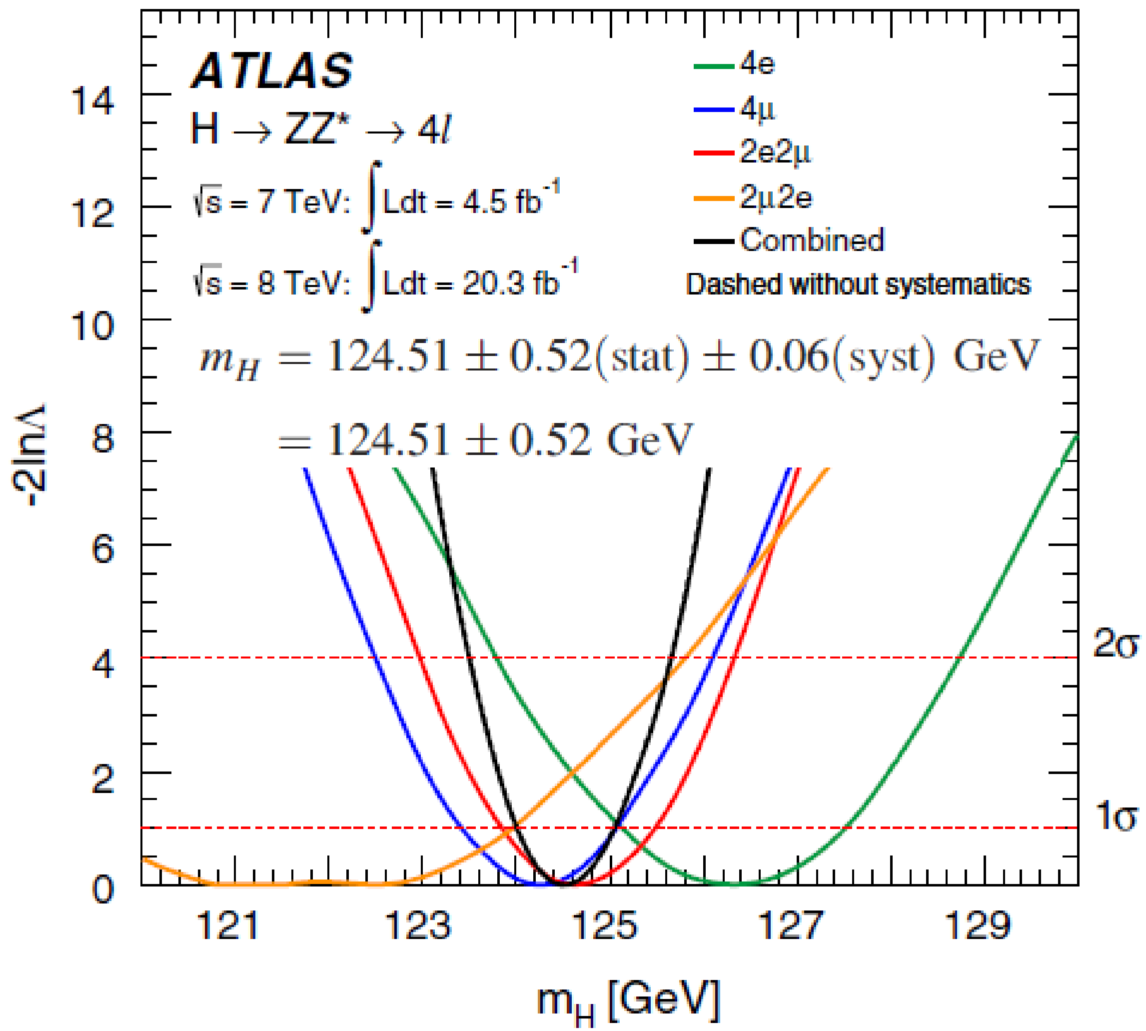
- ➔ Left: BDT_{ZZ} output with requirement of $120 < m_{4l} < 130$ GeV
- ➔ Right: m_{4l} output with requirement of $BDT_{ZZ} > 0$





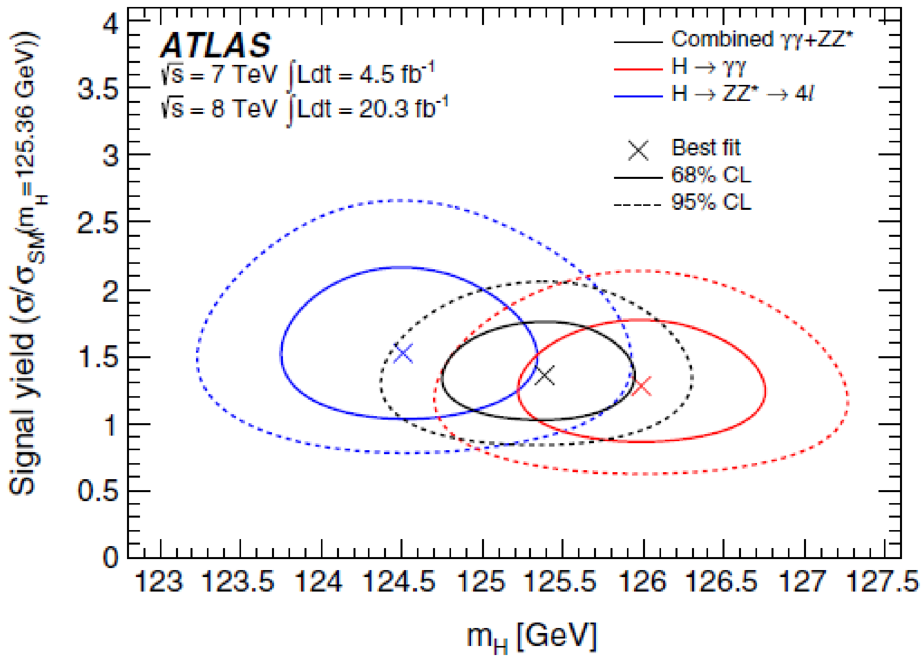
Higgs Mass Measurement

- Two dimensional (2D) fit to m_{4l} and BDT_{ZZ^*} based on profile likelihood method to obtain Higgs mass.

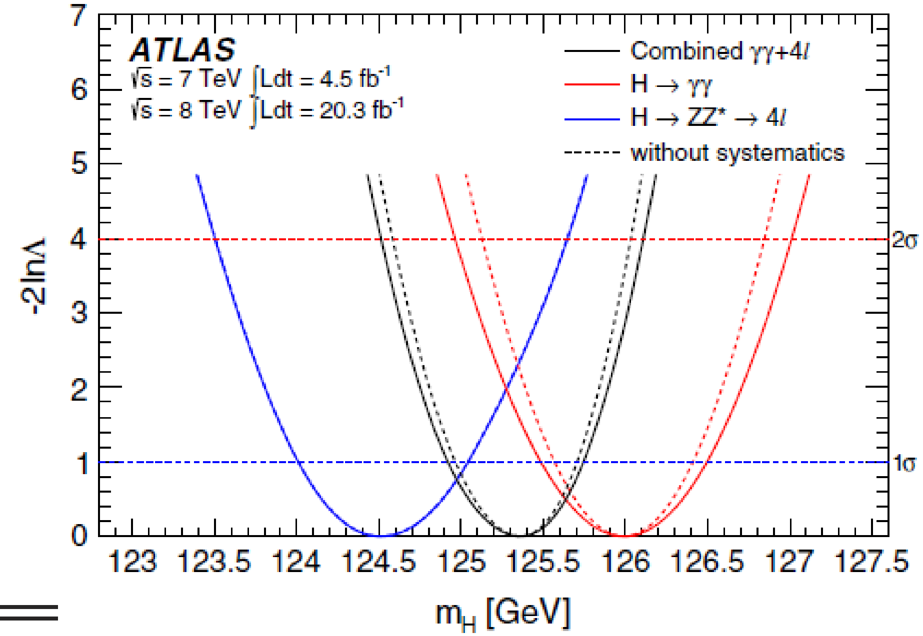


Higgs Mass Measurements

$$\Lambda(\Delta m_H) = \frac{L(\Delta m_H\,,\,\hat{\hat{\mu}}_{\gamma\gamma}(\Delta m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(\Delta m_H)\,,\,\hat{\hat{m}}_H(\Delta m_H)\,,\,\hat{\hat{\theta}}(\Delta m_H))}{L(\hat{\Delta m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{m}_H, \hat{\theta})}$$



$$\Delta m_H = 1.47 \pm 0.67(\text{stat}) \pm 0.28(\text{syst})\ \text{GeV}$$
$$= 1.47 \pm 0.72\ \text{GeV}$$



Fitted Higgs mass

Channel	Mass measurement [GeV]
$H \to \gamma\gamma$	$125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst}) = 125.98 \pm 0.50$
$H \to ZZ^* \to 4\ell$	$124.51 \pm 0.52(\text{stat}) \pm 0.06(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst}) = 125.36 \pm 0.41$

It is compatible with $\Delta M_H = 0$ at the level of 4.8%, 2.0σ

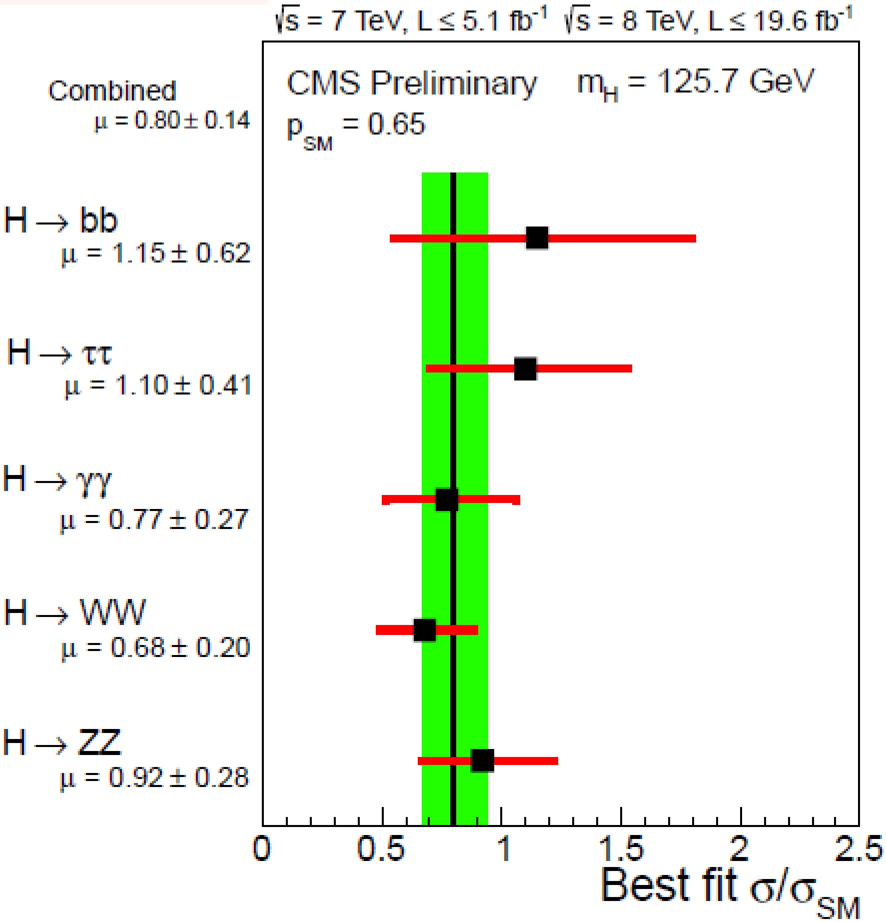
Measurements of Higgs Signal Strength

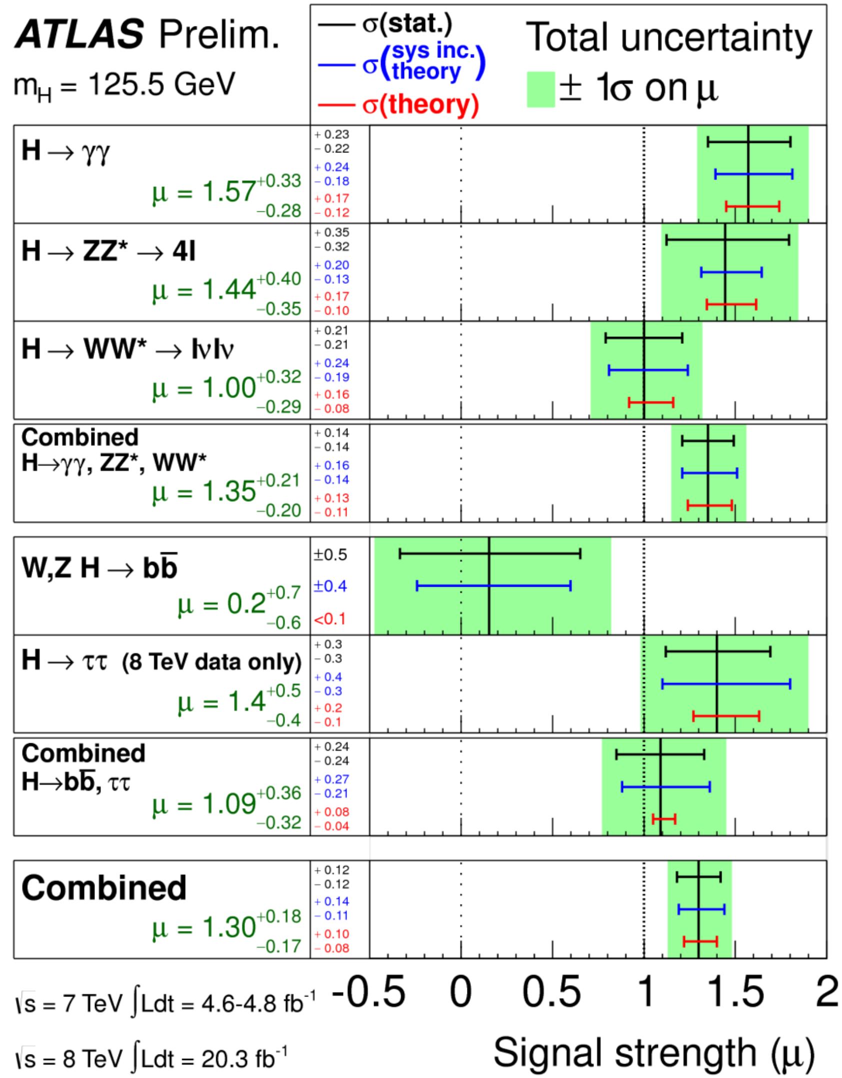
➔ **Signal strength: μ = 1.3±0.2(ATLAS)**
➔ **μ = 0.8 ±0.14 (CMS)**

PLB 726 pp.88-119
ATLAS-CONF-2014-009

$$\mu = \frac{\sigma \times Br}{(\sigma \times Br)_{SM}}$$

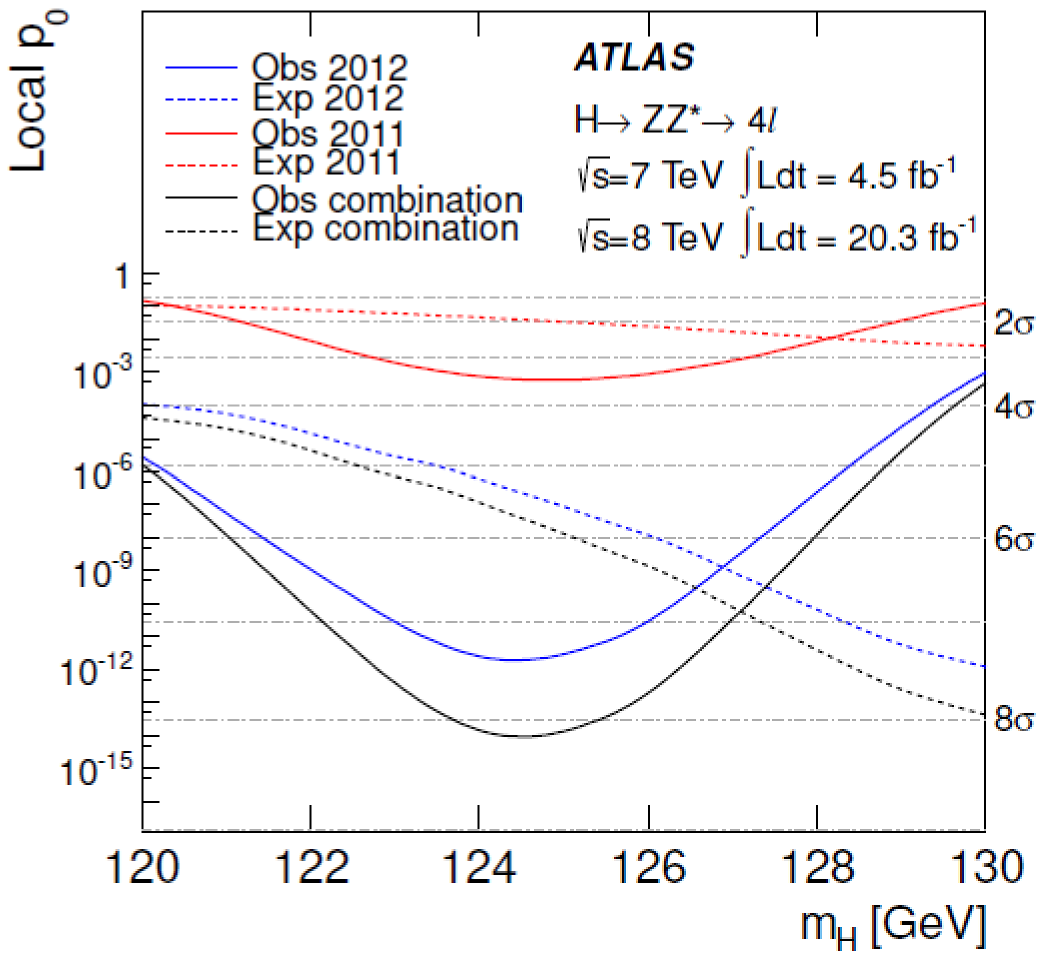
CMS-HIG-13-005





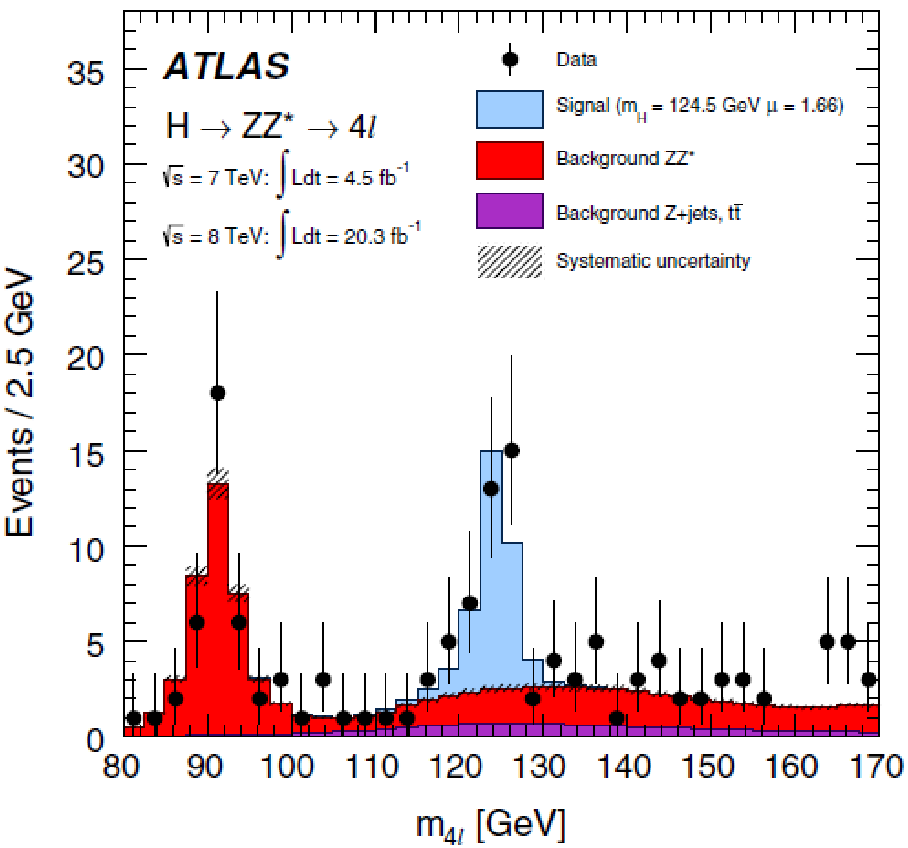
Significance of H→ZZ*→4l

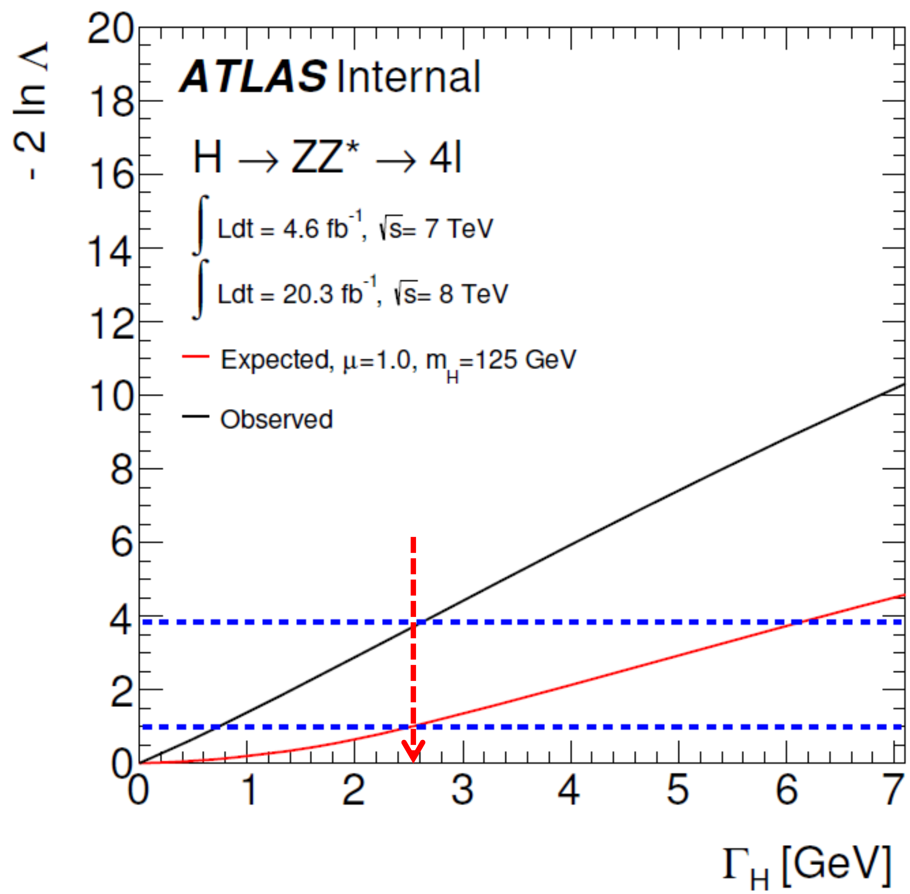
- Higgs mass m_H = 124.51 and 125.36 GeV, Expected significances are 5.8σ and 6.2σ, Observed significances are 8.2σ and 8.1σ.



Direct Measurement of Higgs Width

- Using per-event-error method, direct limit on the total width of the Higgs boson $\Gamma_H < 2.6$ GeV @ 95% C.L.

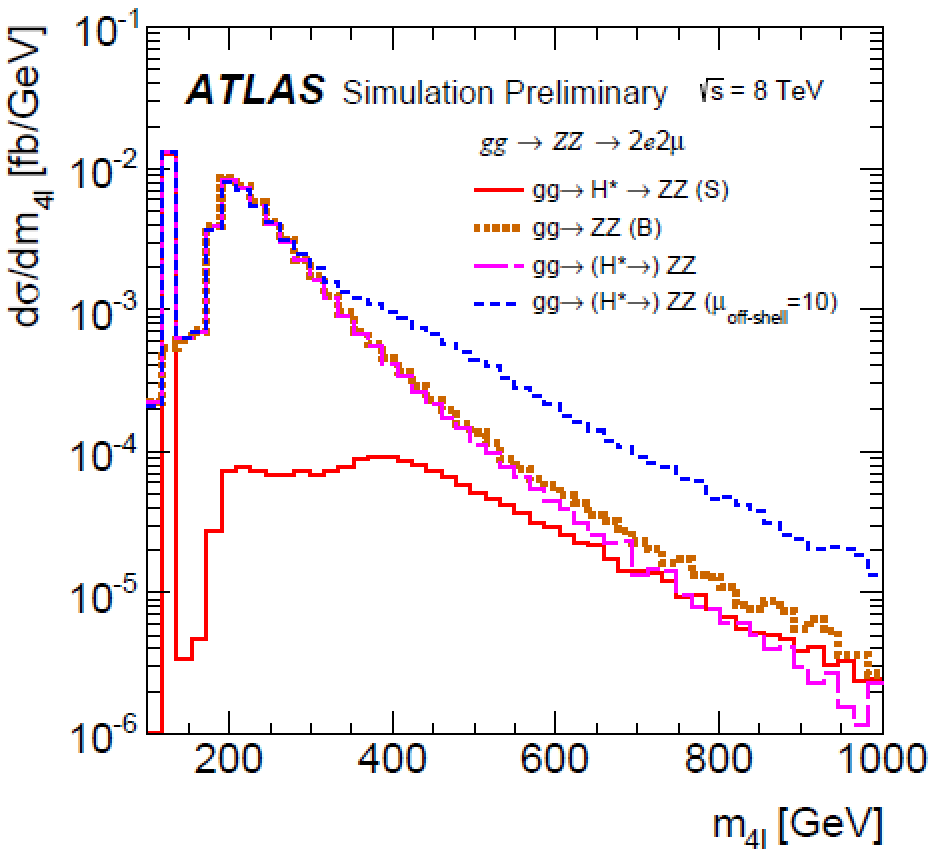




Indirect Measurement of Higgs Width

- High-mass off-peak region of the H→ZZ→4l channel above the $2M_V$ threshold have sensitivity to Higgs production through off-shell and background interference effects.

(Ref: ATL-COM-PHYS-2014-1403)



$$\frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{V,\text{off-shell}}$$

$\mu_{\text{off-shell}}$ is the off-shell signal strength

$$\frac{\sigma^{gg\to H\to VV}_{\text{on-shell}}}{\sigma^{gg\to H\to VV}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

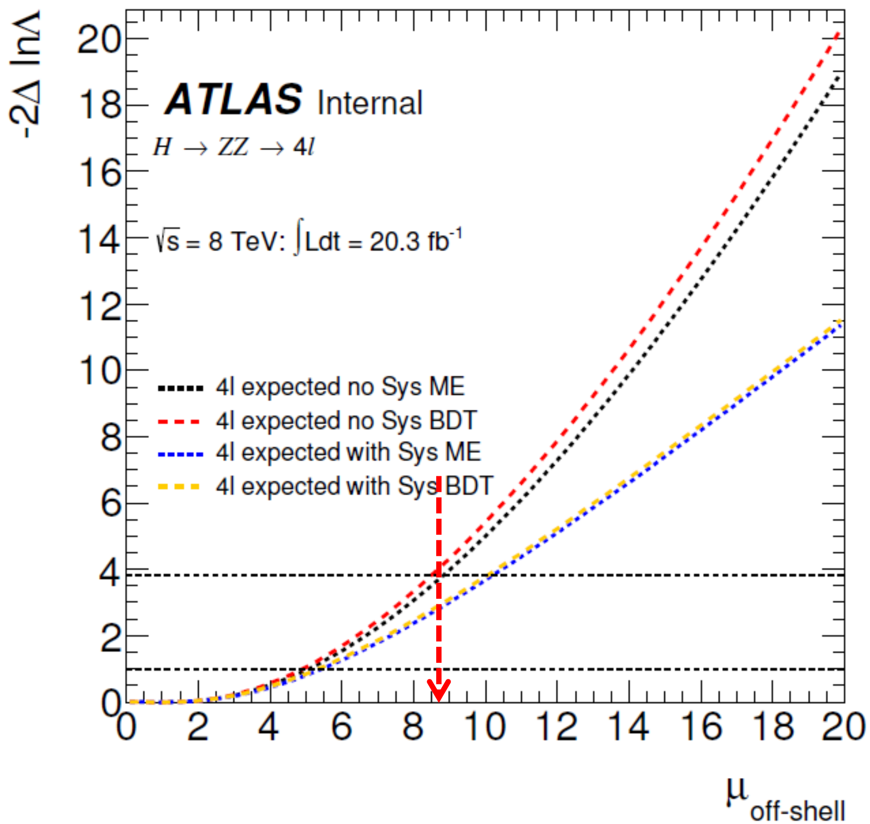
assumption $\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$

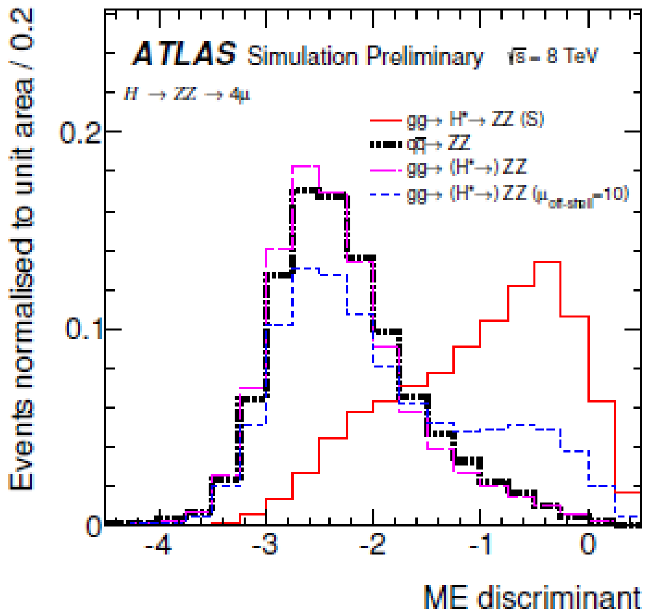
The combination of both on-shell and off-shell measurements of signal strength achieve a significantly higher sensitivity to the total width Γ_H.

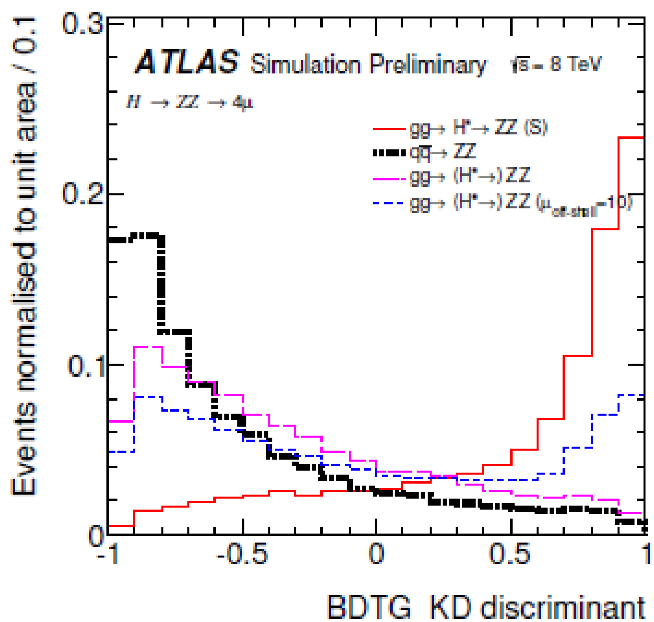
ME and BDT Outputs

- The expected 95% C.L. upper limits on $\mu_{off\text{-}shell}$。

	Without systematics	With systematics
ME	1.00 (8.85)	1.00 (10.23)
BDT	1.00 (8.52)	1.00 (10.08)

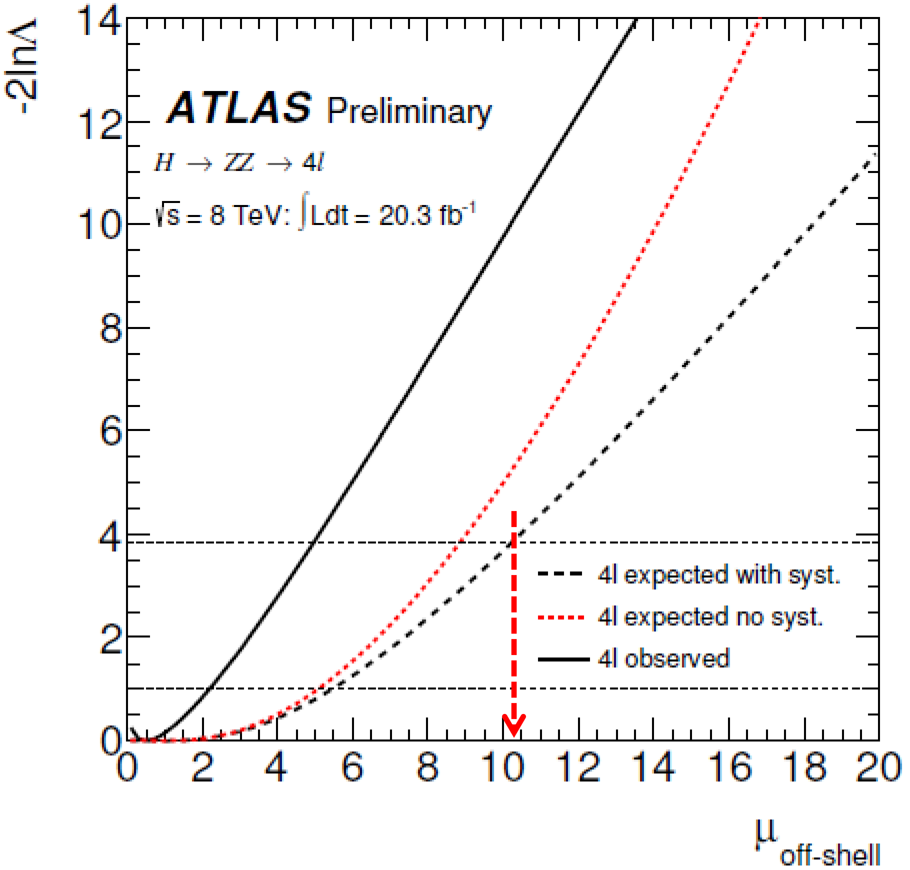


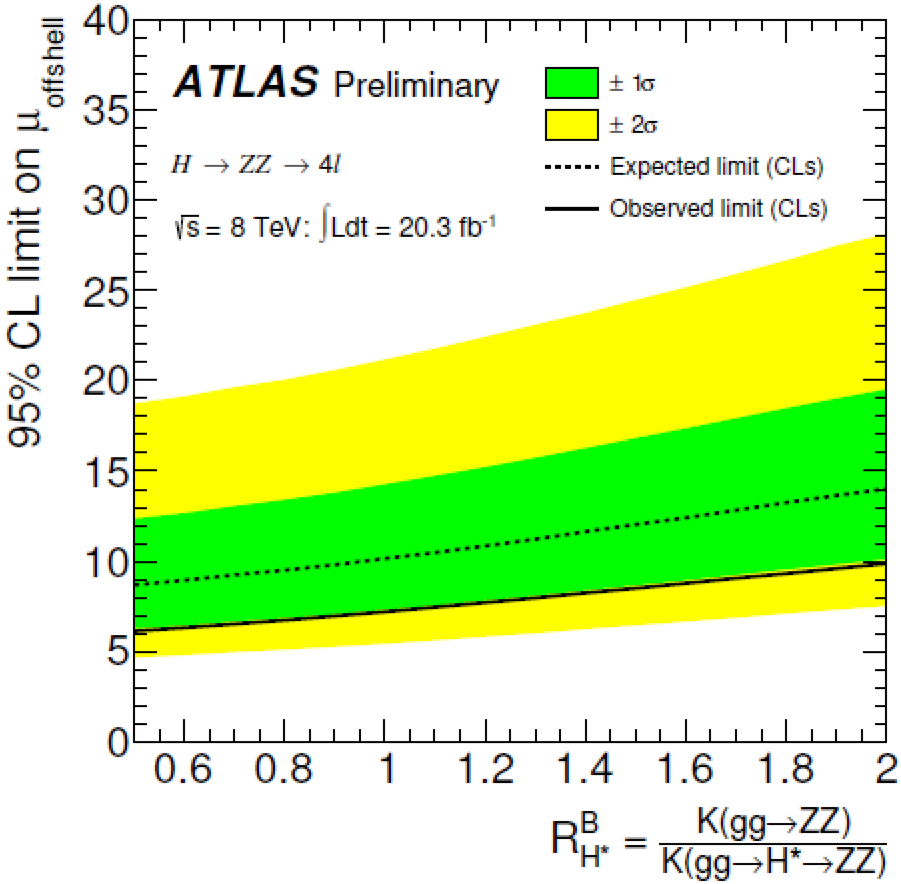




Indirect Measurement of Higgs Width

- The expected 95% C.L. upper limits on $\mu_{\text{off-shell}}$, is 10.1 and the observed limit is 5.

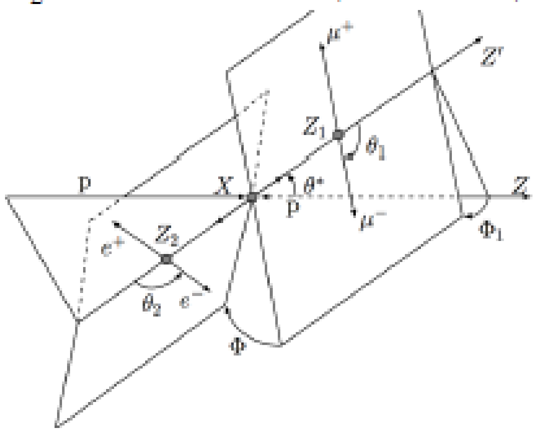


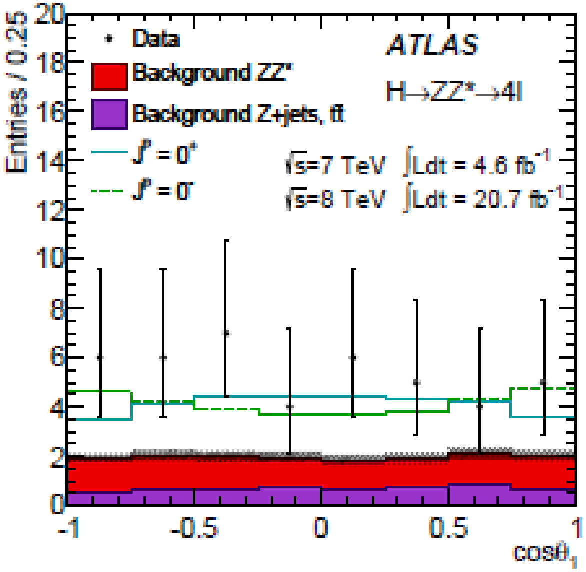


H→ZZ*→4l : Spin and Parity

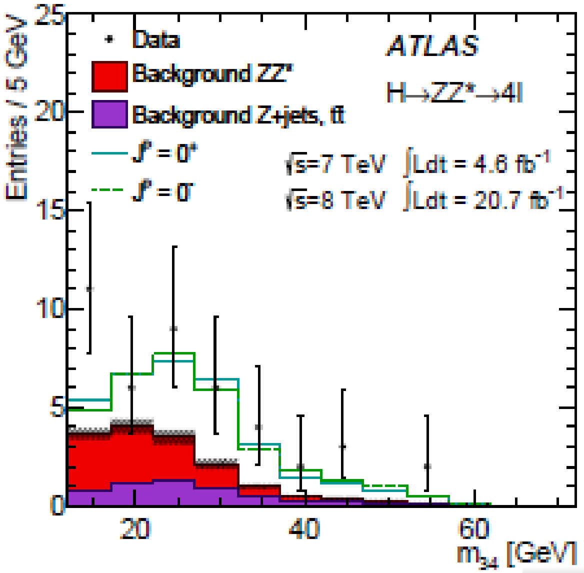
- In $X \to ZZ^{(*)} \to 4\ell$ decays, m_{Z_1}, m_{Z_2} and the production and decay angles are sensitive to the spin-parity of X

$\{m_{4l}, m_{Z_1}, m_{Z_2}, \cos\theta_1, \cos\theta_2, \phi, \cos\theta^*, \phi_1\}$

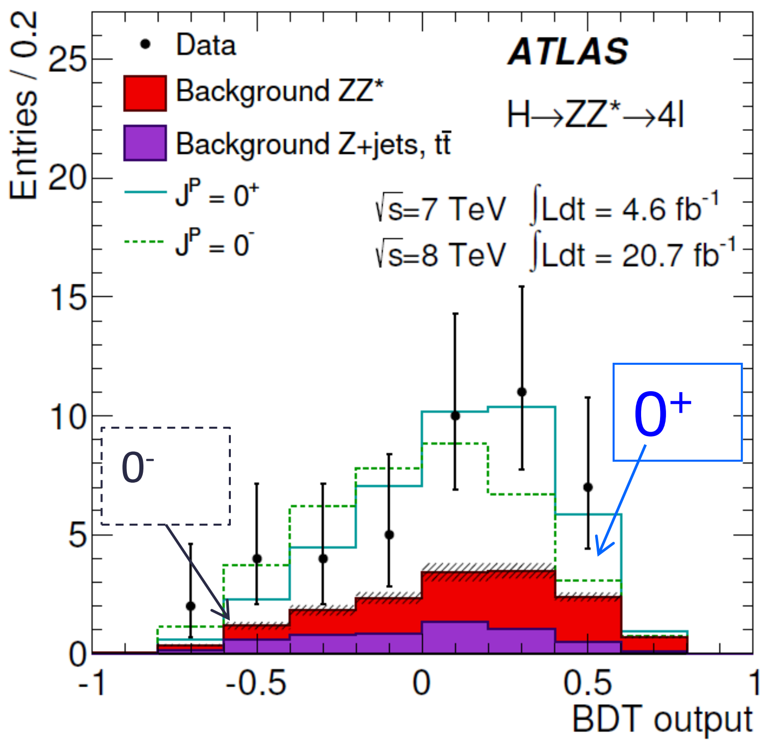


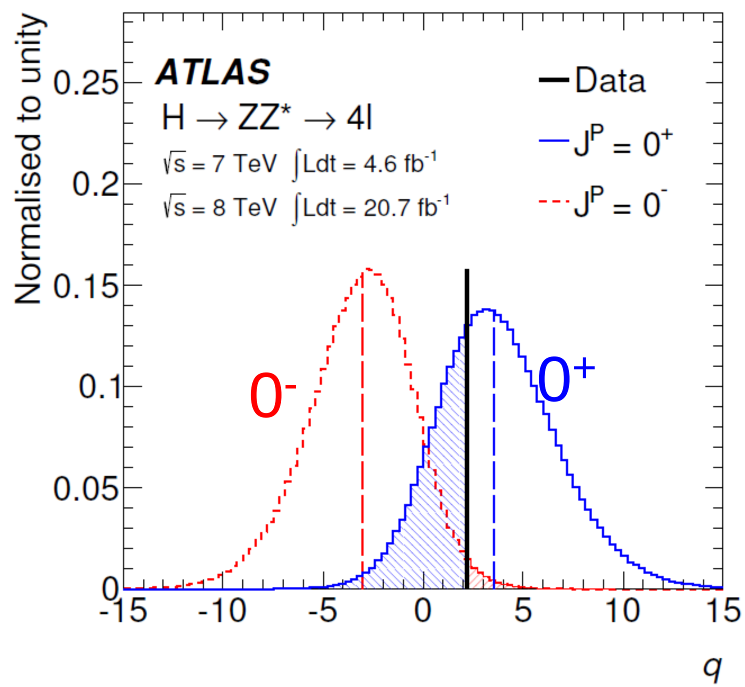


- Construct a discriminant between different hypotheses using two different multivariate techniques:
  - BDT (machine learning)
  - J^P-MELA (use theoretical differential decay rates to construct a matrix element based likelihood ratio)
- Use events in range $115 < m_{4\ell} < 130$ GeV
- Test SM 0^+ hypothesis against alternative hypotheses 0^-, 1^+, 1^-, 2^+_m



H→ZZ*→4l : Spin and Parity





BDT analysis variables:

m_{Z1}, m_{Z2} from Higgs --> ZZ* →4l
+ production and decay angles

Exclusion (1-CL$_s$):

Observed 0^- exclusion 97.8%

Observed 1^+ exclusion 99.8%

Observed 2^+_m exclusion 83.2%

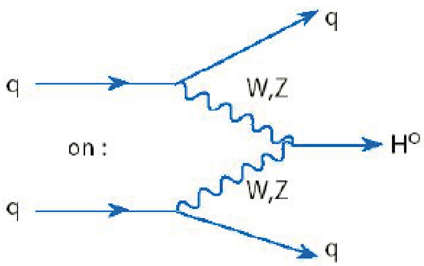
		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

Probing Higgs Production (VBF)

- Event characteristics allow measurement of signal strength from different production modes

σ/σ_{Total}

7%



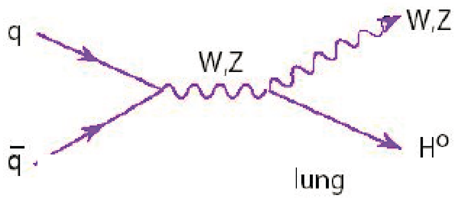
Vector Boson Fusion (VBF)

>= 2 jets with p_T > 25 (30) GeV and
$|\eta|$<2.5 (2.5 < $|\eta|$ <4.5)
$\Delta\eta_{jj}$ > 3; M_{jj} > 350 GeV
8 observed candidates →

One VBF candidate with
$m_{4\ell}$ = 123.5 GeV

In 120-130 GeV:
Expected **N_{signal}** = 0.71 ± 0.10
Expected **N_{VBF}** ~ 0.4
Expected **S/B** ~ 5

5%

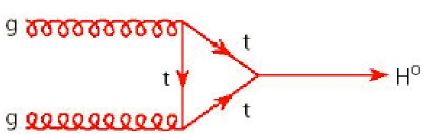


Associated Production (VH)

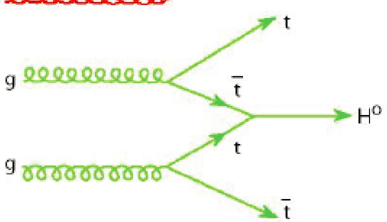
Additional lepton with p_T > 8 GeV
1 observed candidate →

Consistent with expected background

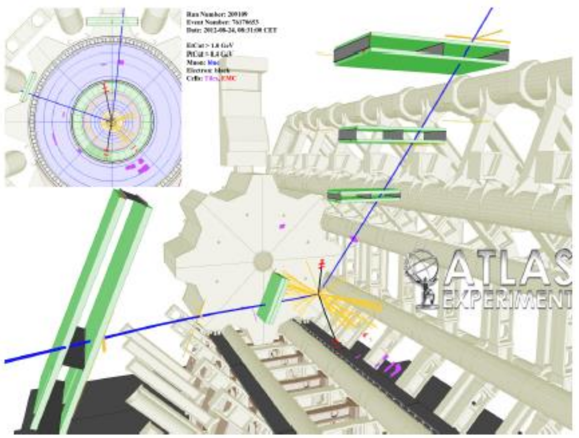
87%



0.5%



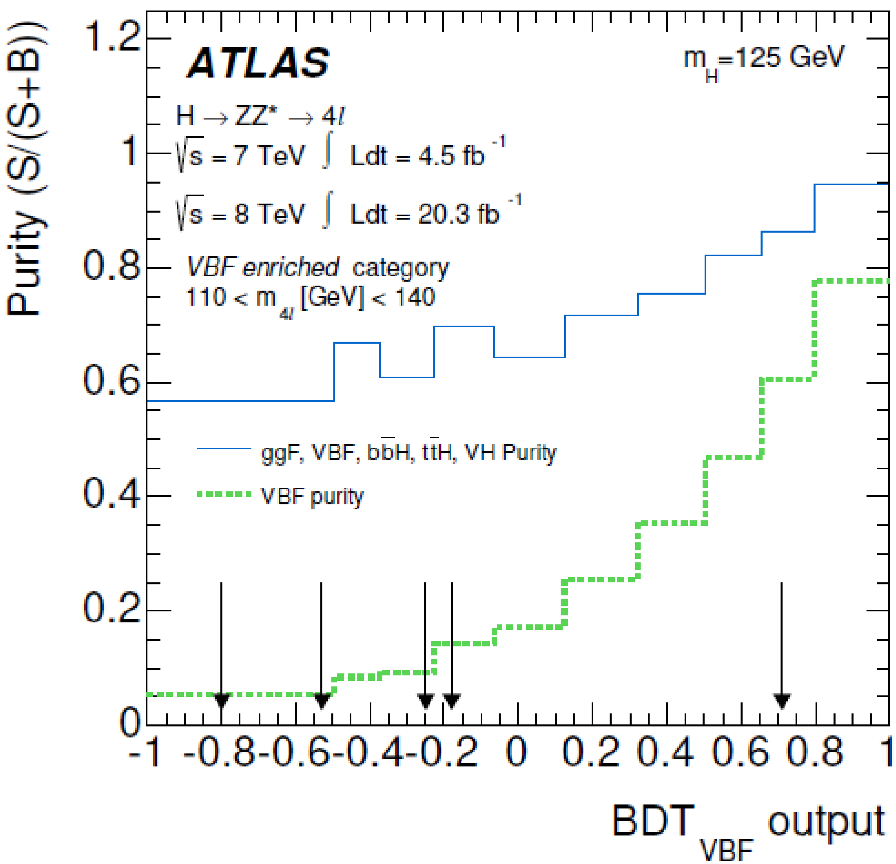
Gluon Gluon Fusion (ggF)
+
tt Fusion (ttH)

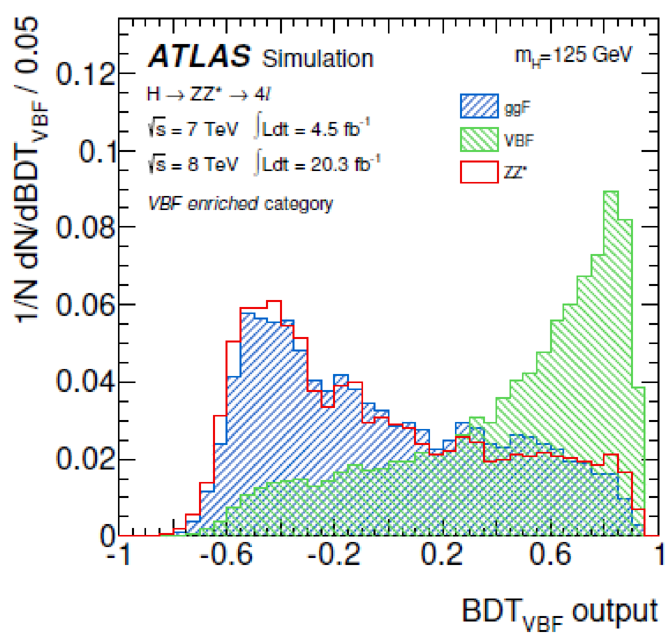


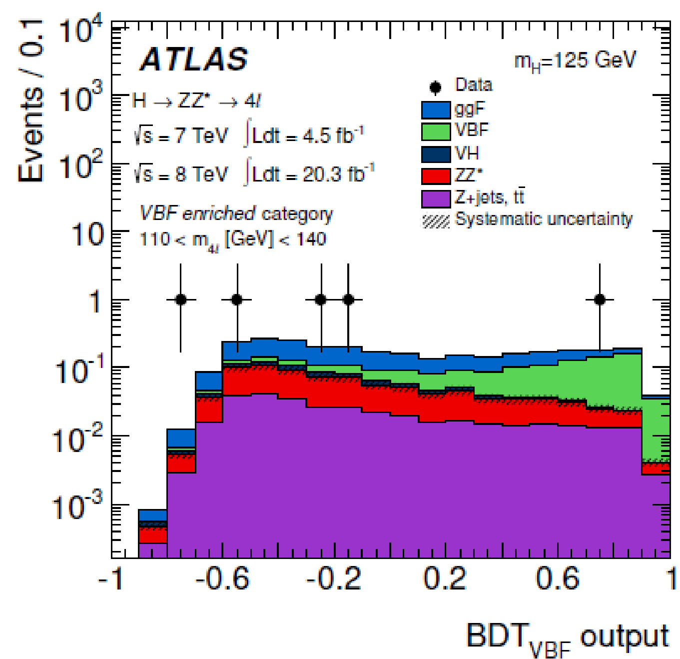
Candidate event with $m_{4\ell}$ = 123.5 GeV in VBF-like category

Probing Higgs Production (VBF)

- BDT_{VBF} based on 5 variables:
  - M_{jj}, η_{jj} , $\eta_{\text{leading jet}}$
  - p_T of leading and subleading jets







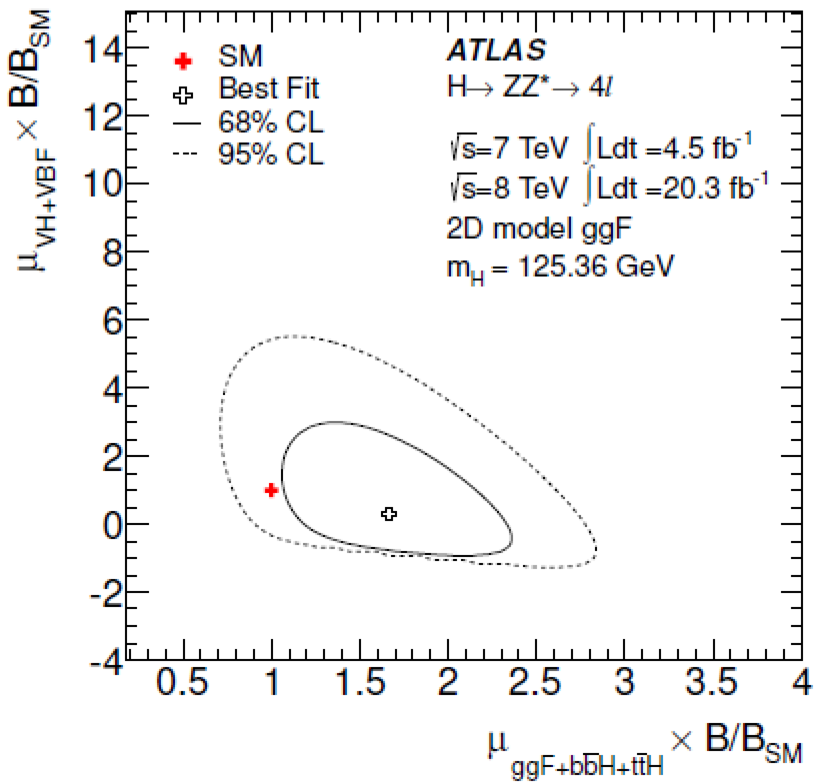
Probing Higgs Production (VBF)

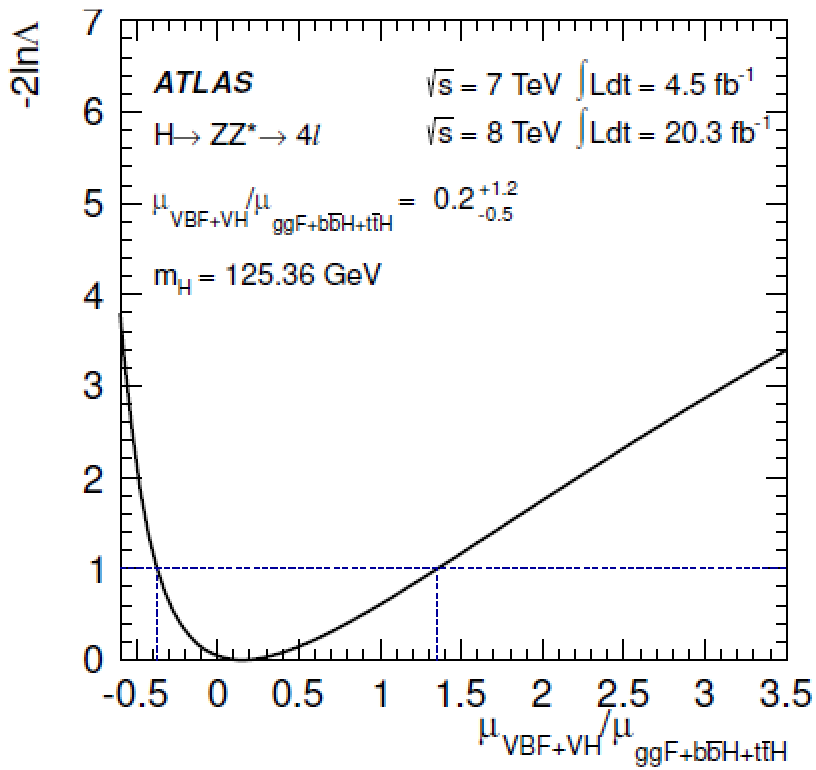
- The compatibility of VBF production with the SM expectation is 30%.

$$\mu_{VBF+VH}/\mu_{ggF+b\bar{b}H+t\bar{t}H} = 0.2^{+1.2}_{-0.5}$$

$$\mu_{ggF+b\bar{b}H+t\bar{t}H} \times B/B_{SM} = 1.66\ ^{+0.45}_{-0.41}\ (\text{stat})\ ^{+0.25}_{-0.15}\ (\text{syst})$$

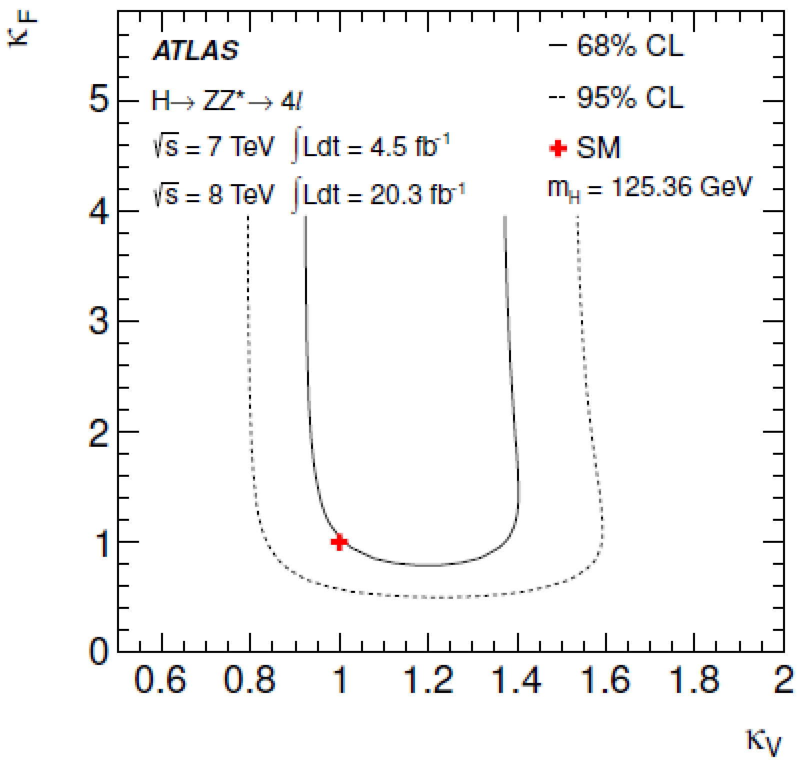
$$\mu_{VBF+VH} \times B/B_{SM} = 0.26\ ^{+1.60}_{-0.91}\ (\text{stat})\ ^{+0.36}_{-0.23}\ (\text{syst})$$

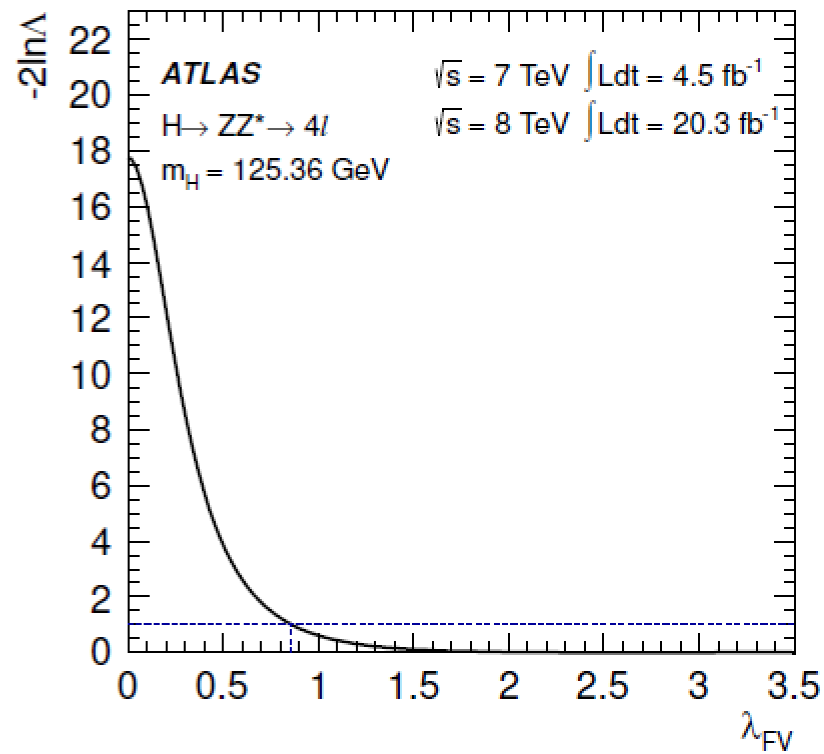




Fermion and Vector Couplings

- The likelihood scan as a function of the ratio of fermion to vector-boson coupling scale factors, $\lambda_{FV} = \kappa_F / \kappa_V$





- **The value of $\lambda_{FV} = 0$ is disfavored at the 4σ level.**

Fermion and Vector Couplings

Coupling scale factors

2-parameter benchmark model:

$\kappa_V = \kappa_W = \kappa_Z$

$\kappa_F = \kappa_t = \kappa_b = \kappa_c = \kappa_\tau = \kappa_g$

(Gluon coupling are related to top, b, and their interference in tree level loop diagrams)

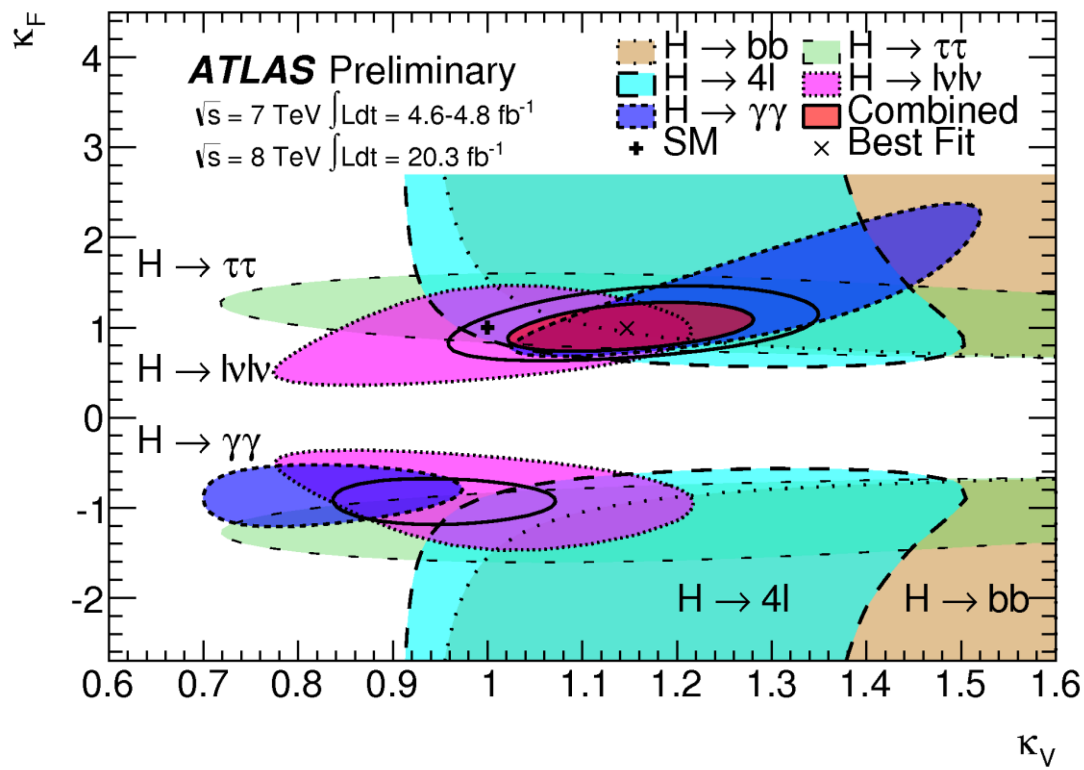
Assume no BSM contributions to loops: gg→ H and no BSM decays (no invisible decays)

$$\kappa_V = 1.15 \pm 0.08$$

$$\kappa_F = 0.99^{+0.17}_{-0.15}.$$

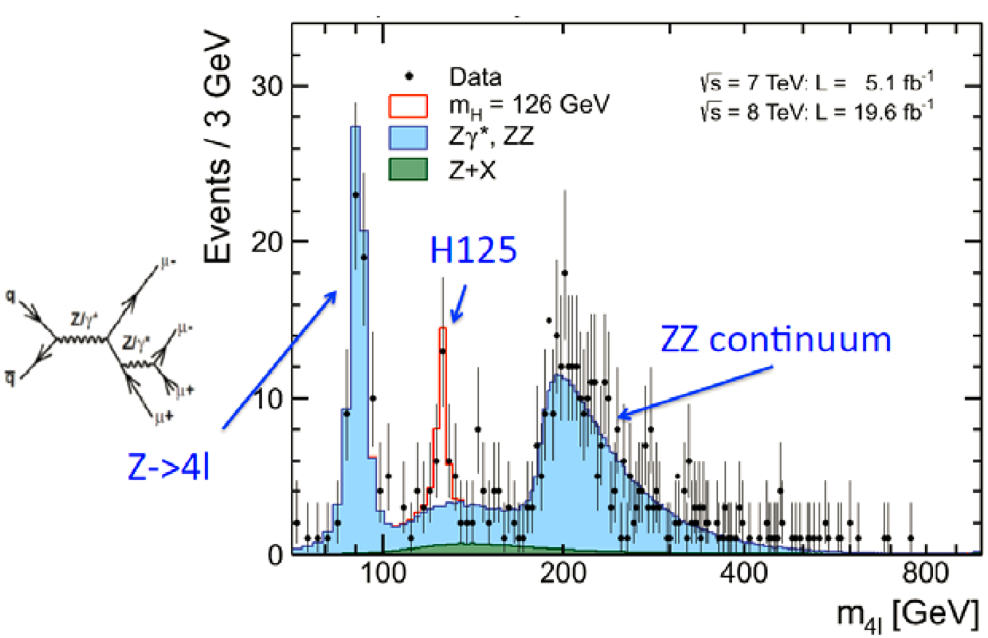
→ κ_F = 0 is excluded (>5σ)

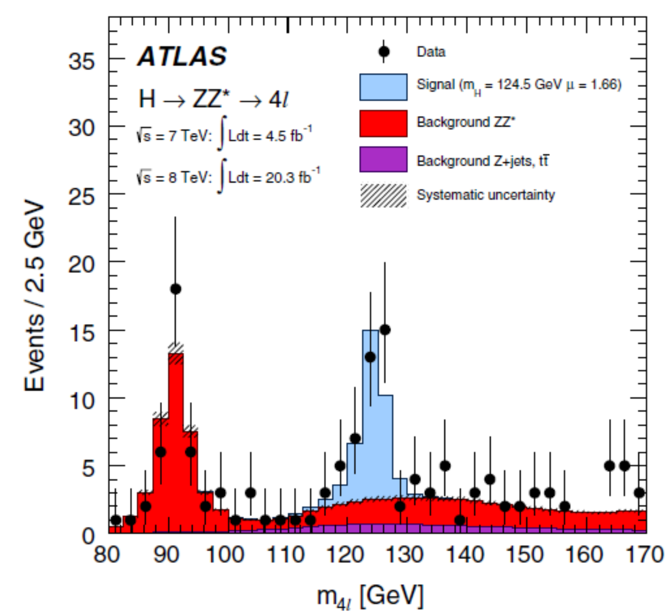
$$\frac{\sigma \cdot B\,(gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot B_{SM}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$



Analysis of Single Resonance Z→4ℓ

- The Z →4l production was first observed at the LHC by ATLAS and CMS along with the Higgs boson discovery in 4l decay channel
- Cross section measurement of the Z → 4l production provides
  - A SM test for a rare decay process, meas. of σ(4l) and BR(Z→4l)
  - A complementary test of the detector response for H → 4l detection

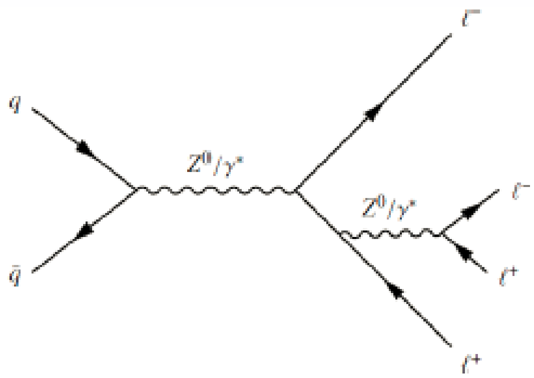




ATLAS: Phys. Rev. Lett. 112, 231806 (2014) arXiv:1403.5657
CMS:JHEP 12 (2012) 034, arXiv:1210.3844

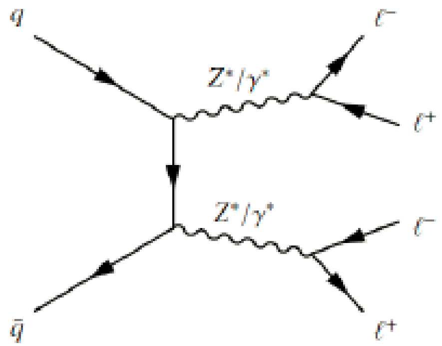
Production of single resonance Z→4l

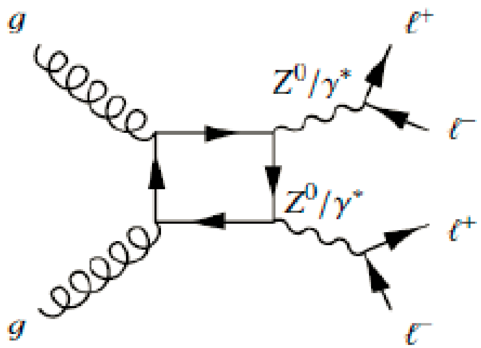
- Four lepton 4l final states: 4e, 4m and 2e2m



- **Resonant 4l production** via an s-channel $Z \to \ell^+\ell^-$ include an additional $\ell^+\ell^-$ from internal conversion of Z^*/γ^*
- > 96% 4l event rate from s-channel at Z resonance (80< m_{4l} < 100 GeV, m_{2l}>5 GeV)

- **Non-resonant 4l production**
  - via t-channel: qq → Z^*/γ^* +Z^*/γ^* →4l including the Z production with ISR internal conversion (< 4% 4l event rate at the Z resonance)
  - via gg → ZZ → 4l (~0.1% 4l event rate at the Z resonance)



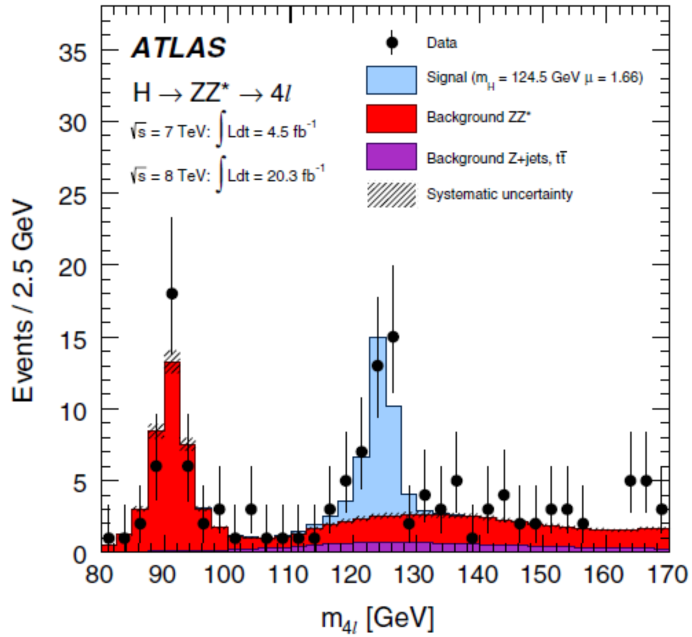


Cuts Optimization

ATLAS Higgs → ZZ*→ 4l selection:

- pT_{min} > 7 (6) GeV for e (μ)
- m_{12} > 50 GeV; m_{34} > 12 GeV

Select 37 Z→4l events in Z mass window

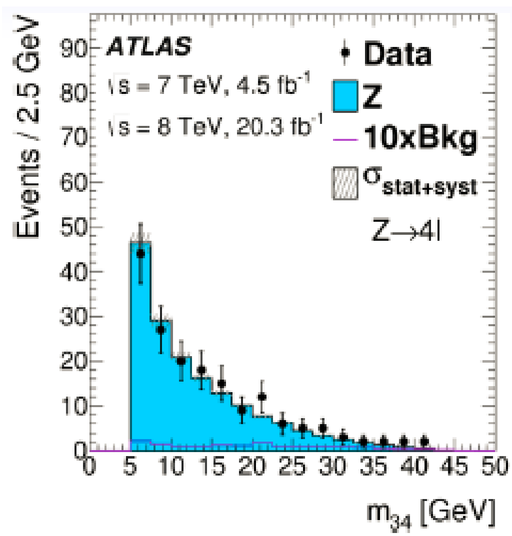


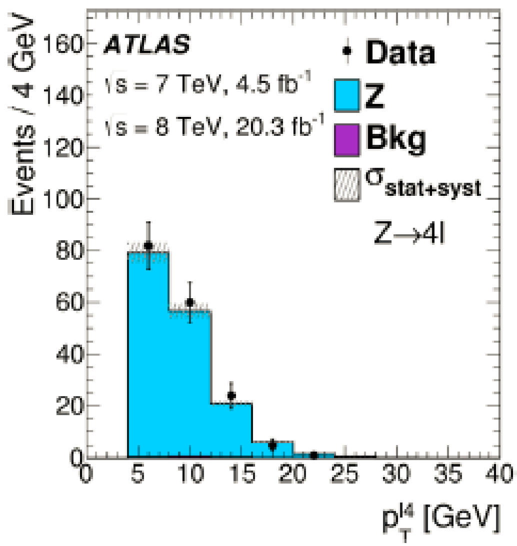
- The Z→4l process is dominant by low mass m34 and low pT leptons (the pT-ordered 4th leptons)
- **Need to detect low pT leptons**

Loosen some Higgs cuts :

e :	p_T > 20, 15, 10, 7 GeV
μ :	p_T > 20, 15, **8**, **4** GeV
	m_{12} > **20** GeV, m_{34} > **5** GeV

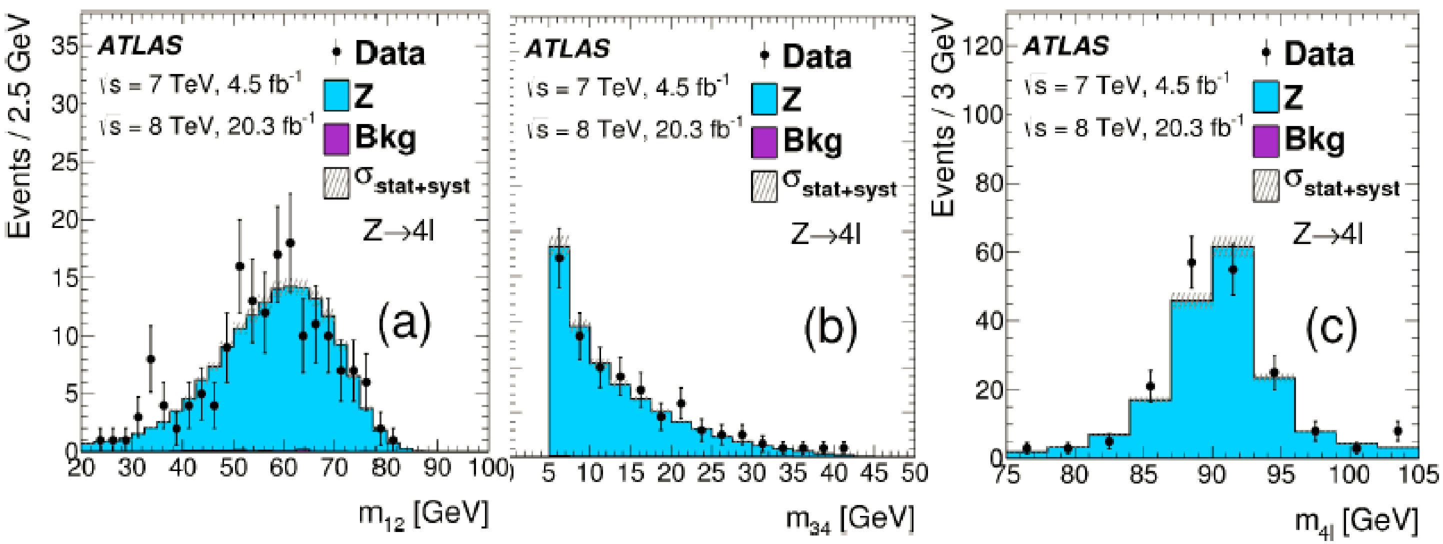
Increase statistics by a factor of 5





ATLAS: Selected Z→4l Events

$\sqrt{s}$	Channel	Data	Total expected	MC signal ($Z/ZZ \to 4\ell$)	Backgrounds
7 TeV	$eeee$	1	1.8 ± 0.3	1.7 ± 0.3	0.12 ± 0.04
	$ee\mu\mu$	7	8.0 ± 0.4	7.7 ± 0.4	0.18 ± 0.09
	$\mu\mu ee$	5	3.3 ± 0.3	3.2 ± 0.3	0.08 ± 0.04
	$\mu\mu\mu\mu$	8	11.3 ± 0.5	11.2 ± 0.3	0.09 ± 0.04
	Combined	21	24.4 ± 1.2	23.8 ± 1.2	0.47 ± 0.11
8 TeV	$eeee$	16	14.4 ± 1.2	14.3 ± 1.2	0.16 ± 0.03
	$ee\mu\mu$	48	43.2 ± 2.3	42.9 ± 2.2	0.36 ± 0.05
	$\mu\mu ee$	16	19.3 ± 1.2	19.1 ± 1.2	0.21 ± 0.04
	$\mu\mu\mu\mu$	71	68.8 ± 3.0	68.4 ± 2.9	0.41 ± 0.05
	Combined	151	145.7 ± 7.7	145 ± 7	1.14 ± 0.13



Acceptance A_{4l} and Correction Factor C_{4l}

- Definition of Fiducial Volume

$p_T^{\ell_1} > 20$ GeV; $p_T^{\ell_2} > 15$ GeV;
$p_T^{\ell_3} > 10$ GeV (if electron), > 8 GeV (if muon);
$p_T^{\ell_4} > 7$ GeV (if electron), > 4 GeV (if muon);
$|\eta^{\mu}| < 2.7$ for all muons; $|\eta^{e}| < 2.5$ for all electrons;
$\Delta R(\ell, \ell') > 0.1$ for all same flavor parings and > 0.2 for different flavor pairings;
$M_{\ell^+\ell^-} > 20$ GeV for at least one SFOS lepton pair;
$M_{\ell^+\ell^-} > 5$ GeV for all SFOS lepton pair;
$80 < M_{4\ell} < 100$ GeV.

$$A_{4l} = \frac{Number\ of\ 4l\ events\ selected\ in\ the\ fiducial\ volume}{Number\ of\ 4l\ events\ in\ the\ phase\ space}$$

$$C_{4l} = \frac{Number\ of\ 4l\ events\ passing\ full\ event\ selection}{Number\ of\ 4l\ events\ selected\ in\ the\ fiducial\ volume}$$

ATLAS: Fiducial Cross Sections

$$\sigma^{fiducial}_{Z\to 4\ell} = \frac{N_{obs} - N_{bkg}}{\mathcal{L} C_{Z\to 4\ell}}$$

ATLAS

$\sqrt{s}$	Final state	$C_{4\ell}$	Measured σ^{Fid} fb
7 TeV	$eeee$	21.5%	$0.910^{+1.39}_{-0.72}$ (stat) $\pm$ 0.14 (syst) $\pm$ 0.02 (lumi) fb
	$\mu\mu\mu\mu$	59.2%	$2.970^{+1.18}_{-0.94}$ (stat) $\pm$ 0.07 (syst) $\pm$ 0.05 (lumi) fb
	$ee\mu\mu$	49.0%	$3.091^{+1.35}_{-1.05}$ (stat) $\pm$ 0.16 (syst) $\pm$ 0.05 (lumi) fb
	$\mu\mu ee$	36.3%	$3.015^{+1.57}_{-1.17}$ (stat) $\pm$ 0.30 (syst) $\pm$ 0.06 (lumi) fb
8 TeV	$eeee$	36.06%	$2.16^{+0.59}_{-0.50}$ (stat) $\pm$ 0.16 (syst) $\pm$ 0.06 (lumi) fb
	$\mu\mu\mu\mu$	71.13%	$4.89^{+0.66}_{-0.56}$ (stat) $\pm$ 0.13 (syst) $\pm$ 0.14 (lumi) fb
	$ee\mu\mu$	55.54%	$4.23^{+0.65}_{-0.59}$ (stat) $\pm$ 0.15 (syst) $\pm$ 0.12 (lumi) fb
	$\mu\mu ee$	46.24%	$1.68^{+0.46}_{-0.39}$ (stat) $\pm$ 0.07 (syst) $\pm$ 0.04 (lumi) fb

ATLAS: Phase-space xsections

$$\sigma^{total}_{Z\to 4\ell} = \frac{\sigma^{fiducial}_{Z\to 4\ell}}{A_{Z\to 4\ell}}$$

ATLAS measurement in final phase space 80 < m_{4l} < 100 GeV and $m_{\ell+\ell-}$ > 5 GeV

$\sqrt{s}$	4ℓ state	$N^{obs}_{4\ell}$	$N^{exp}_{4\ell}$	$N^{bkg}_{4\ell}$	$C_{4\ell}$	$\sigma^{fid}_{Z4\ell}$ [fb]	$A_{4\ell}$		$\sigma_{Z4\ell}$ [fb]
7 TeV	$ee+ee$	1	1.8 ± 0.3	0.12 ± 0.04	21.5%	$0.9^{+1.4}_{-0.7} \pm 0.14 \pm 0.02$	7.5%	$4e$, 4μ	$32 \pm 11 \pm 1.0 \pm 0.6$
	$\mu\mu+\mu\mu$	8	11.3 ± 0.5	0.08 ± 0.04	59.2%	$3.0^{+1.2}_{-0.9} \pm 0.07 \pm 0.05$	18.3%		
	$ee+\mu\mu$	7	7.9 ± 0.4	0.18 ± 0.09	49.0%	$3.1^{+1.4}_{-1.1} \pm 0.16 \pm 0.05$	15.8%	$2e2\mu$	$44 \pm 14 \pm 3.3 \pm 0.9$
	$\mu\mu+ee$	5	3.3 ± 0.3	0.07 ± 0.04	36.3%	$3.0^{+1.6}_{-1.2} \pm 0.30 \pm 0.06$	8.8%		
	combined	21	24.2 ± 1.2	0.44 ± 0.14					$76 \pm 18 \pm 4 \pm 1.4$
8 TeV	$ee+ee$	16	14.4 ± 1.4	0.14 ± 0.03	36.1%	$2.2^{+0.6}_{-0.5} \pm 0.20 \pm 0.06$	7.3%	$4e$, 4μ	$56 \pm 6 \pm 1.8 \pm 1.6$
	$\mu\mu+\mu\mu$	71	68.8 ± 2.7	0.34 ± 0.05	71.1%	$4.9^{+0.7}_{-0.6} \pm 0.13 \pm 0.14$	17.8%		
	$ee+\mu\mu$	48	43.2 ± 2.1	0.32 ± 0.05	55.5%	$4.2^{+0.7}_{-0.6} \pm 0.16 \pm 0.12$	14.8%	$2e2\mu$	$52 \pm 7 \pm 2.4 \pm 1.5$
	$\mu\mu+ee$	16	19.3 ± 1.3	0.18 ± 0.04	46.2%	$1.7^{+0.5}_{-0.4} \pm 0.10 \pm 0.04$	7.9%		
	combined	151	146 ± 7	1.0 ± 0.11					$107 \pm 9 \pm 4 \pm 3.0$

ATLAS	Phase-space Cross Section (fb)
SM NLO Prediction (7 TeV)	90 ± 2.1 fb
Measured (7 TeV)	76 ±18(stat) ±4(syst) ±1.4(lumi) fb
SM NLO Prediction (8 TeV)	104.8 ± 2.5 fb
Measured (8 TeV)	107 ± 9(stat) ± 4(syst) ±3.0(lumi) fb

ATLAS: BR of Z→4l

- Measure the Z→2μ cross section and take the known Br(Z→2m) to get inclusive cross section of Z from pp collisions
- Cancels luminosity uncertainty and theoretical uncertainty of σ(pp→Z）
- Derive the BR（Z→4l) as below

$$\mathrm{BR}(Z \to 4\ell) = \mathrm{BR}(Z \to 2\mu)(1-f_t)\frac{\left(N_{\text{obs.}} - N_{\text{bkg.}}\right)^{4\ell}(C \times A)^{2\mu}}{\left(N_{\text{obs.}} - N_{\text{bkg.}}\right)^{2\mu}(C \times A)^{4\ell}}$$

Uncertainty on $\mathrm{BR}(Z \to 2\mu)$ is small. f_t = fraction of t-channel in phase-space.

- Cancel luminosity uncertainty: 2.8% （8 TeV）
- Cancel NLO σ(Z) calculation uncertainties (Scales, PDF, NNLO correction): 4%

Branching Ratio of Z→4l

Branching fraction result uses an error weighted combination of the 7 and 8 TeV results. For (m_{2l} > 5 GeV, 80 < m_{4l} < 100 GeV)

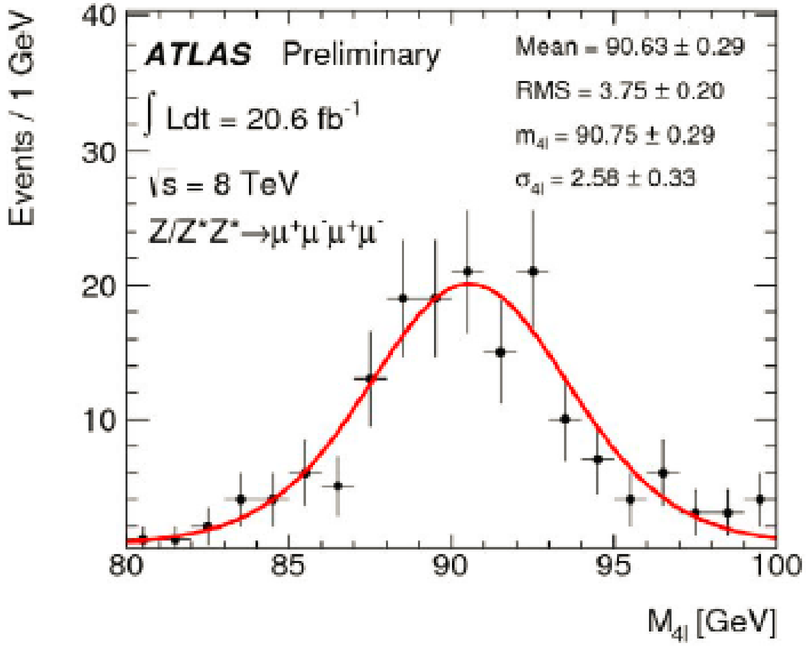
Quantity	$\sqrt{s}$	Value **ATLAS**
Measured	7 TeV	$(2.67 \pm 0.62\ \text{(stat)} \pm 0.14\ \text{(syst)}) \times 10^{-6}$
	8 TeV	$(3.33 \pm 0.27\ \text{(stat)} \pm 0.11\ \text{(syst)}) \times 10^{-6}$
	Combined	$(3.20 \pm 0.25\ \text{(stat)} \pm 0.13\ \text{(syst)}) \times 10^{-6}$
Expected		$(3.33 \pm 0.01) \times 10^{-6}$

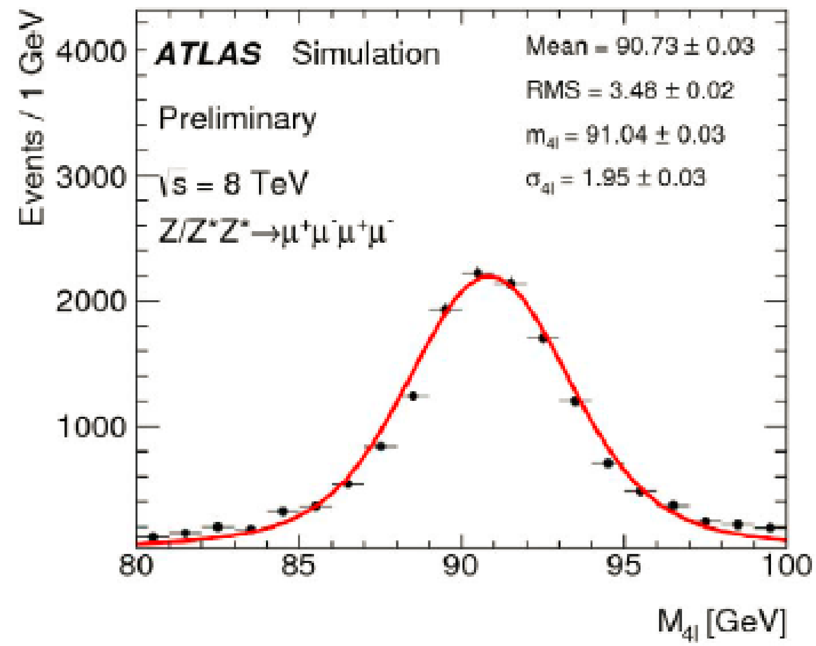
For $M_{\ell\ell} > 4$ GeV

- We observe $(4.31 \pm 0.34\ \text{(stat)} \pm 0.16\ \text{(syst)}) \times 10^{-6}$ and expect $(4.50 \pm 0.01) \times 10^{-6}$, (ATLAS combining 7 & 8 TeV measurements)
- CMS observes $\left(4.2^{+0.9}_{-0.8}\ \text{(stat)} \pm 0.2\ \text{(syst)}\right) \times 10^{-6}$ and expects 4.45×10^{-6}.

ATLAS: 4-lepton Mass Scale

- 4-lepton mass fitted with the convolution of a Breit-Wigner and a Gaussian distributions for 4 channels
- Fitted results show good consistence with MC predictions
- Example of 4μ mass fit for data and MC





Summary

- With 2011 (4.5 fb^{-1} @ 7TeV) and 2012 (20.3 fb^{-1} @ 8 TeV) datasets, the Higgs boson is observed in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel with local significance of 8.1σ.
- The best fit mass of the Higgs boson from $H \rightarrow ZZ^* \rightarrow 4\ell$

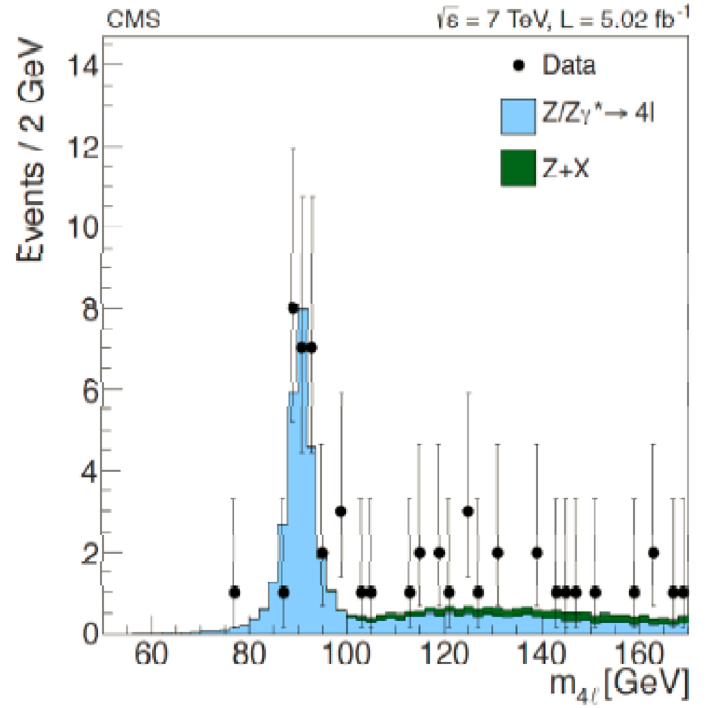
Channel	Mass measurement [GeV]
$H \rightarrow \gamma\gamma$	$125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst}) = 125.98 \pm 0.50$
$H \rightarrow ZZ^* \rightarrow 4\ell$	$124.51 \pm 0.52(\text{stat}) \pm 0.06(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst}) = 125.36 \pm 0.41$

- The ratio of signal strength for bosonic (VBF+VH) and fermionic (ggF+ttH) production modes are measured, the compatibility of VBF production with SM expectation is 30%.
- The SM Higgs boson with $J^P = 0^+$ hypothesis is favored.
- The Higgs mass width $\Gamma_H < 2.6$ GeV / 42 MeV @ 95% C.L. for direct / indirect measurements.
- BR of $Z \rightarrow 4\ell$ is 4.3×10^{-6} which agree with SM prediction.

Backup

CMS: Z→4l Analysis

Final state channels	4e	4μ	$2e2\mu$	4ℓ
Irreducible background ($pp \to Z\gamma^* \to 4\ell$)	0.07	0.25	0.14	0.46 ± 0.05
Other (reducible) backgrounds	0.01	0.01	0.05	0.07 ± 0.1
Expected signal ($pp \to Z \to 4\ell$)	3.8	13.6	12.0	29.4 ± 2.6
Total expected (simulation)	3.9	13.9	12.2	30.0 ± 2.6
Observed events	2	14	12	28
Yield from fit to the observed mass distribution	-	13.6 ± 3.8	11.5 ± 3.1	27.3 ± 5.4



Phase space cuts

$80 < M_{4l} < 100$ GeV; $M_{2l} > 4$ GeV

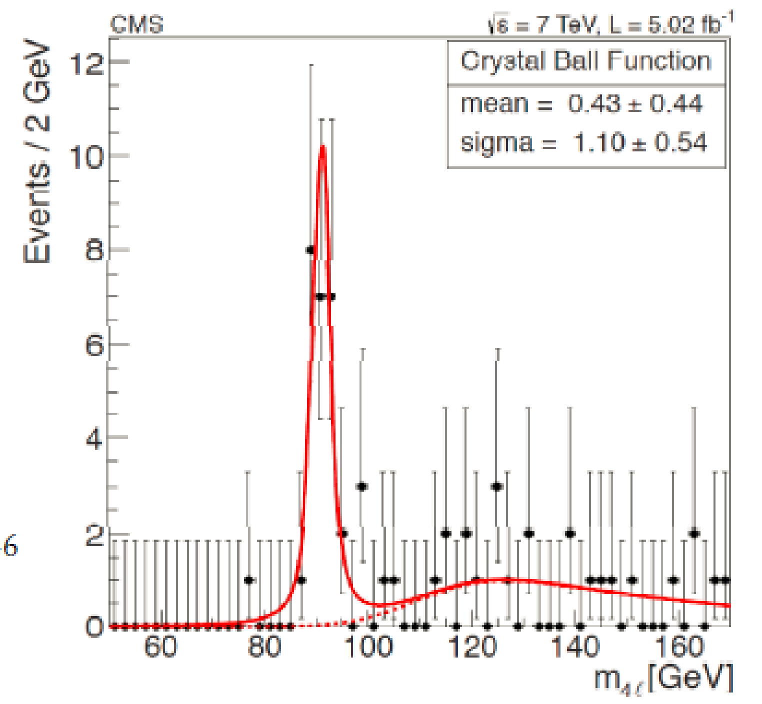
SM prediction (FEWZ @ NNLO):

$\sigma(pp \to Z \to 4l) = 120 \pm 5$ fb

$BR(Z \to 4l) = 4.45 \times 10^{-6}$ (LO CalcHEP)

$$\sigma(pp \to Z)\,\mathcal{B}(Z \to 4\ell) = 112^{+23}_{-20}\,(\text{stat.})^{+7}_{-5}(\text{syst.})^{+3}_{-2}\,(\text{lum.})\,\text{fb},$$

$$\mathcal{B}(Z \to 4\ell) = \left(4.2^{+0.9}_{-0.8}\,(\text{stat.}) \pm 0.2\,(\text{syst.})\right) \times 10^{-6}$$



Categories of H→ZZ*→4l Events

Table 12: Expected and observed yields in the *VBF enriched*, *VH-hadronic enriched*, *VH-leptonic enriched* and *ggF enriched* categories. The yields are given for the different production modes and the ZZ^* and reducible background for 4.6 fb^{-1} at $\sqrt{s}$ = 7 TeV and 20.3 fb^{-1} at $\sqrt{s}$ = 8 TeV. The estimates are given for both the $m_{4\ell}$ mass range 120–130 GeV and the mass range above 110 GeV.

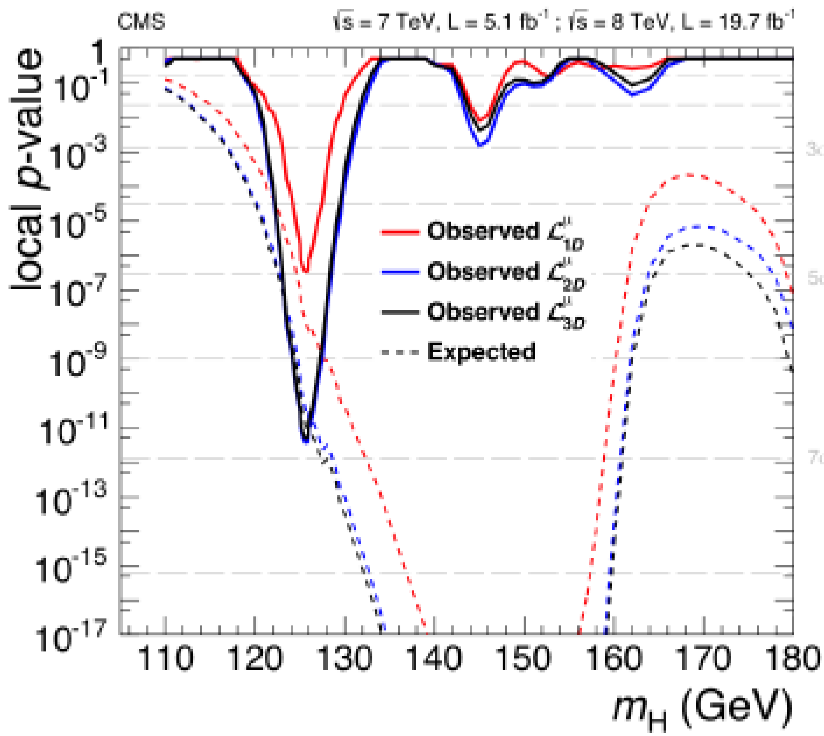
Enriched category	Signal $ggF + b\bar{b}H + t\bar{t}H$	VBF	VH-hadronic	VH-leptonic	Background ZZ^*	Z + jets, $t\bar{t}$	Total expected	Observed
				$120 < m_{4\ell} < 130$ GeV				
VBF	1.18 ± 0.37	0.75 ± 0.04	0.083 ± 0.006	0.013 ± 0.001	0.17 ± 0.03	0.25 ± 0.14	2.4 ± 0.4	3
($BDT_{VBF} > 0$)	0.48 ± 0.15	0.62 ± 0.04	0.023 ± 0.002	0.004 ± 0.001	0.06 ± 0.01	0.10 ± 0.05	1.26 ± 0.15	1
VH-hadronic	0.40 ± 0.12	0.034 ± 0.004	0.20 ± 0.01	0.009 ± 0.001	0.09 ± 0.01	0.09 ± 0.04	0.80 ± 0.12	0
VH-leptonic	0.013 ± 0.002	< 0.001	< 0.001	0.069 ± 0.004	0.015 ± 0.002	0.016 ± 0.019	0.11 ± 0.02	0
ggF	12.8 ± 1.3	0.57 ± 0.02	0.24 ± 0.01	0.11 ± 0.01	7.1 ± 0.2	2.7 ± 0.4	23.5 ± 1.4	34
				$m_{4\ell} > 110$ GeV				
VBF	1.4 ± 0.4	0.82 ± 0.05	0.092 ± 0.007	0.022 ± 0.002	20 ± 4	1.6 ± 0.9	$24. \pm 4.$	32
($BDT_{VBF} > 0$)	0.54 ± 0.17	0.68 ± 0.04	0.025 ± 0.002	0.007 ± 0.001	8.2 ± 1.6	0.6 ± 0.3	10.0 ± 1.6	12
VH-hadronic	0.46 ± 0.14	0.038 ± 0.004	0.23 ± 0.01	0.015 ± 0.001	9.0 ± 1.2	0.6 ± 0.2	10.3 ± 1.2	13
VH-leptonic	0.026 ± 0.004	< 0.002	< 0.002	0.15 ± 0.01	0.63 ± 0.04	0.11 ± 0.14	0.92 ± 0.16	1
ggF	14.1 ± 1.5	0.63 ± 0.02	0.27 ± 0.01	0.17 ± 0.01	$351. \pm 20$	16.6 ± 2.2	$383. \pm 20$	420

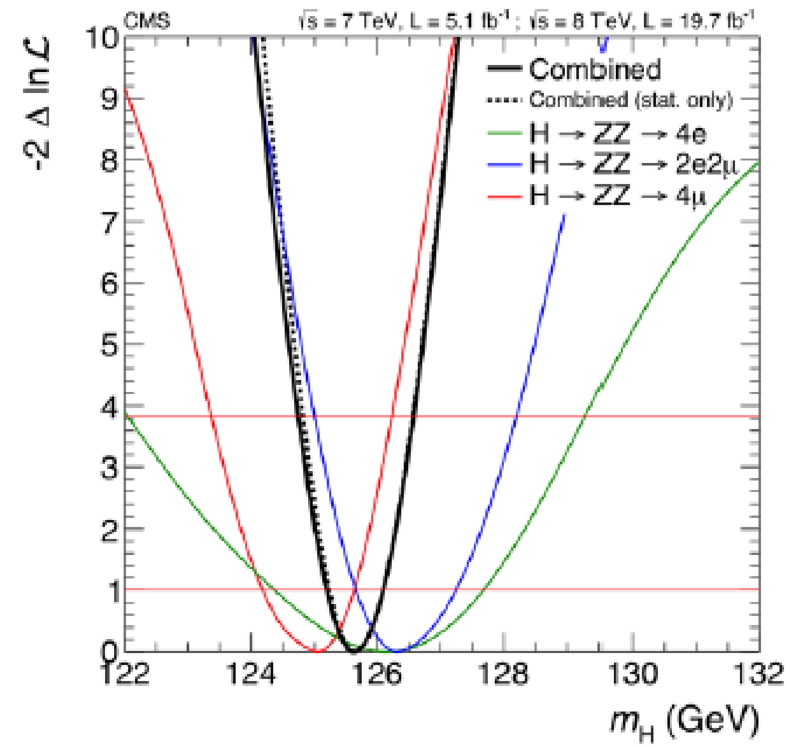
CMS: H→ZZ*→4l

- The observed and expected Higgs significance is 6.8σ and 6.7σ, respectively.
- $m_{4l} = 125.6$ GeV

$$\mu = 0.93^{+0.26}_{-0.23}(stat.)^{+0.13}_{-0.09}(syst.)$$

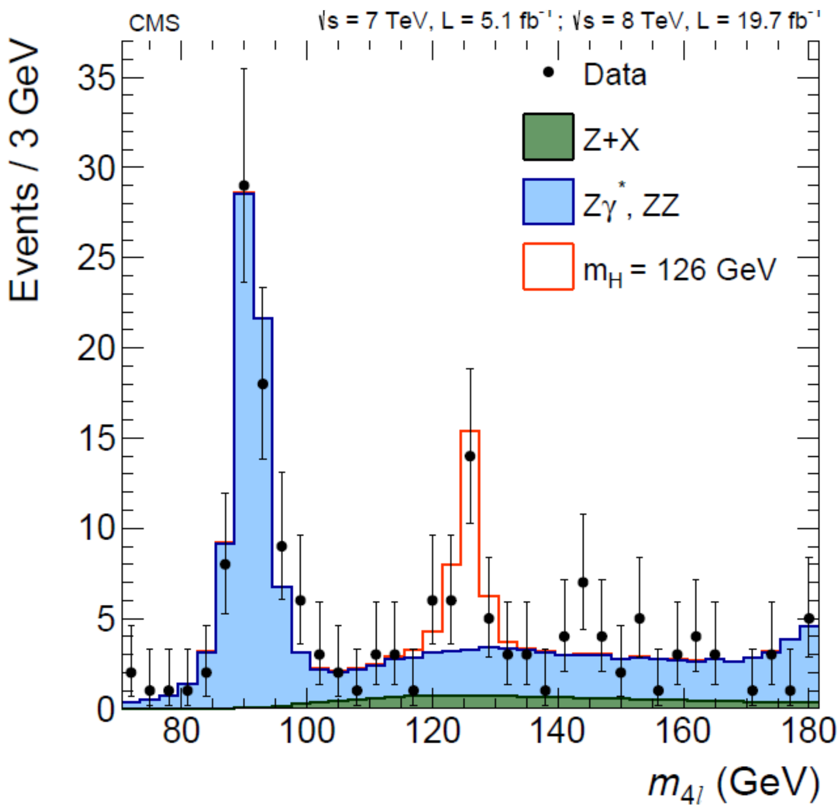
Channel	Measured mass (GeV)
4e	$126.2^{+1.5}_{-1.8}$
$2e2\mu$	$126.3^{+0.9}_{-0.7}$
4μ	$125.1^{+0.6}_{-0.9}$
4ℓ	$125.6 \pm 0.4\,(\text{stat.}) \pm 0.2\,(\text{syst.})$



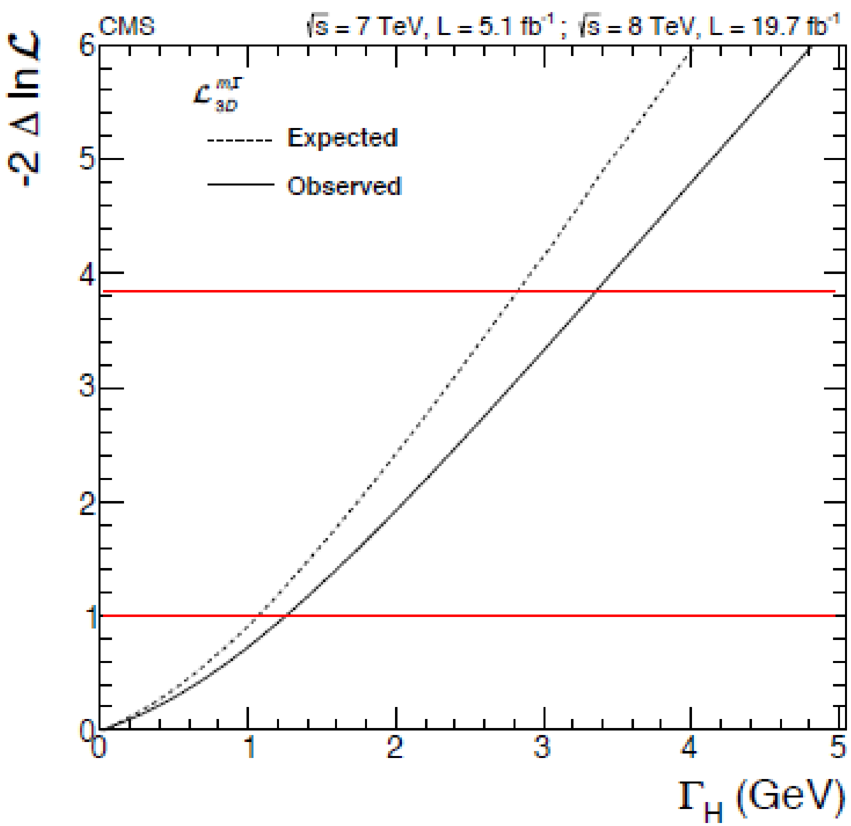


CMS: Higgs mass width

Category	0/1-jet	Dijet
ZZ background	6.4 ± 0.3	0.38 ± 0.02
Z + X background	2.0 ± 0.3	0.5 ± 0.1
All backgrounds	8.5 ± 0.5	0.9 ± 0.1
ggH	15.4 ± 1.2	1.6 ± 0.3
$t\bar{t}H$	—	0.08 ± 0.01
VBF	0.70 ± 0.03	0.87 ± 0.07
WH	0.28 ± 0.01	0.21 ± 0.01
ZH	0.21 ± 0.01	0.16 ± 0.01
All signal, $m_H = 126$ GeV	16.6 ± 1.3	3.0 ± 0.4
Observed	20	5



- The expected upper limit of Higgs mass width is 2.8 GeV and the observed upper limit is 3.4 GeV, at a 95% CL.



Higgs Width (CMS)

- https://cds.cern.ch/record/1670066/files/HIG-14-002-pas.pdf

The production cross section as a function of m_{ZZ} can be written as:

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g^2_{ggH} g^2_{HZZ} \frac{F(m_{ZZ})}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}, \quad (1)$$

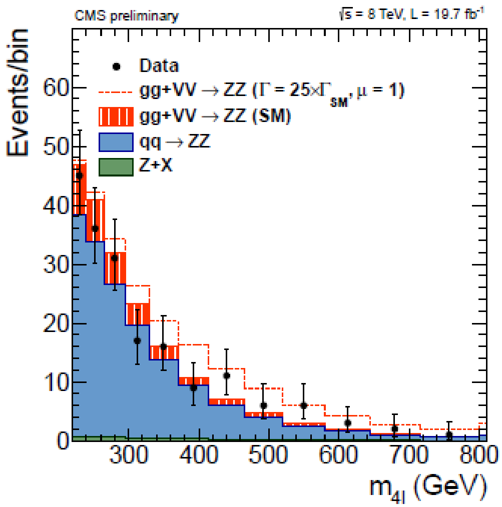
where g_{ggH} (g_{HZZ}) is the coupling constant of the Higgs boson to gluons (to Z bosons), and $F(m_{ZZ})$ is a function which depends on the (virtual) Higgs and Z boson production and decay dynamics. In the resonant and off-shell regions, the integrated cross sections are

$$\sigma^{on-peak}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}, \qquad \sigma^{off-peak}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}. \quad (2)$$

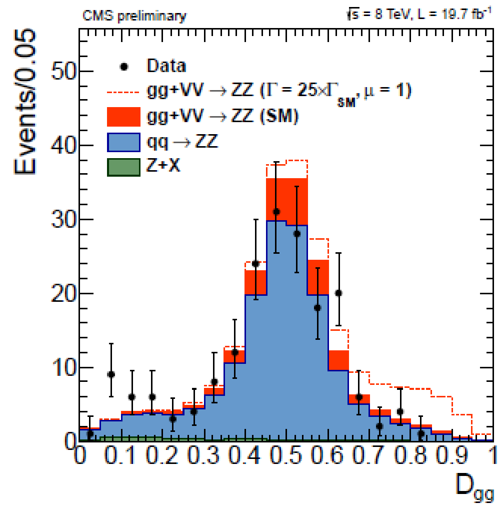
	4ℓ	$2\ell 2\nu$	Combined
Expected 95% CL limit, r	11.5	10.7	8.5
Observed 95% CL limit, r	6.6	6.4	4.2
Observed 95% CL limit, Γ_H (MeV)	27.4	26.6	17.4
Observed best fit, r	$0.5^{+2.3}_{-0.5}$	$0.2^{+2.2}_{-0.2}$	$0.3^{+1.5}_{-0.3}$
Observed best fit, Γ_H (MeV)	$2.0^{+9.6}_{-2.0}$	$0.8^{+9.1}_{-0.8}$	$1.4^{+6.1}_{-1.4}$

Higgs Width (CMS)

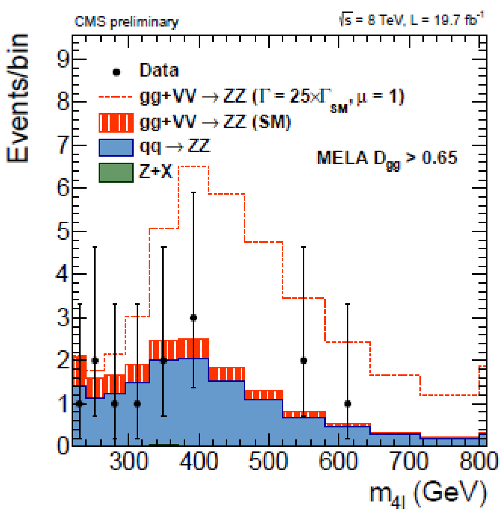
- https://cds.cern.ch/record/1670066/files/HIG-14-002-pas.pdf



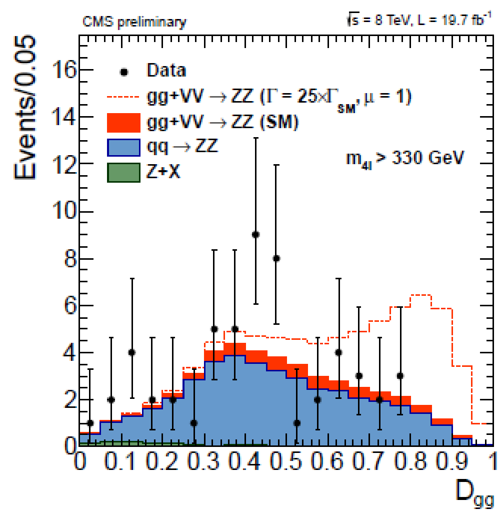
(a)



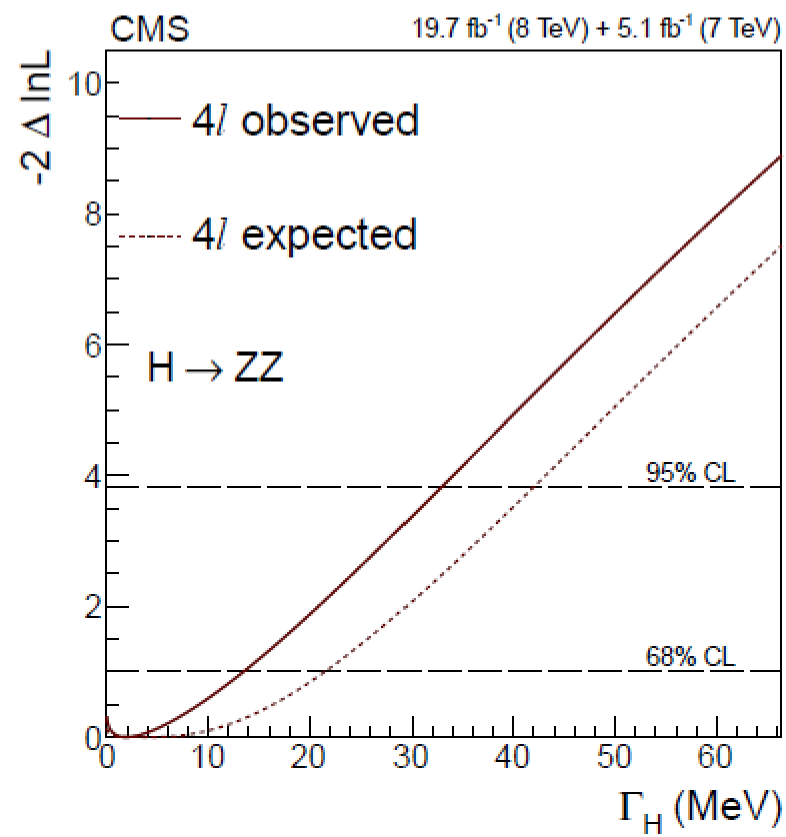
(b)



(c)



(d)

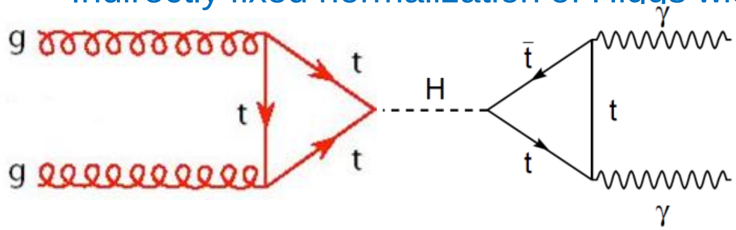


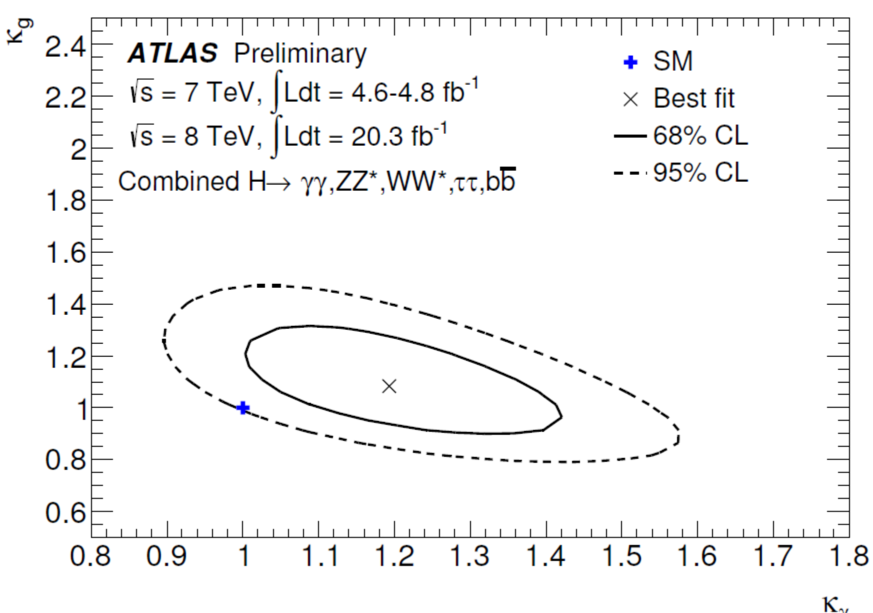
$\Gamma_H < 33$ MeV (42 MeV) at 95% C.L.

Constraints on BSM

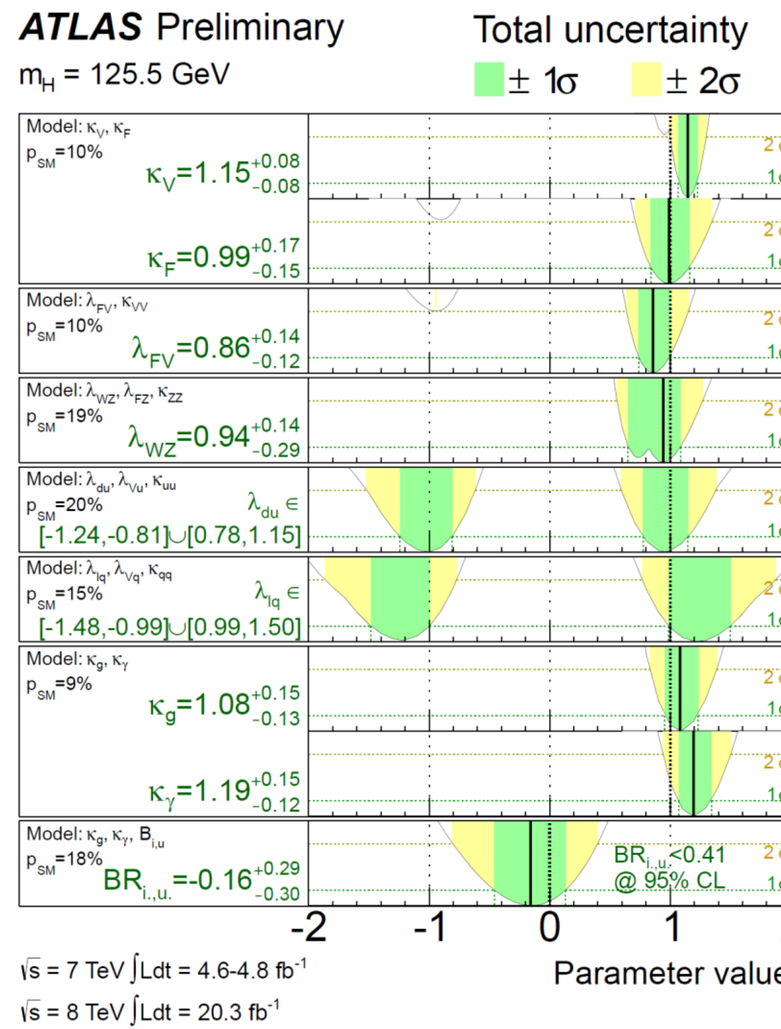
New heavy particles may contribute to loops

- Introduce effective κ_g, κ_γ to allow heavy BSM particles contribute to the loops
- Tree-level couplings: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b$, κ_τ etc set to 1
  - Absorb all difference into loop couplings
  - Indirectly fixed normalization of Higgs width





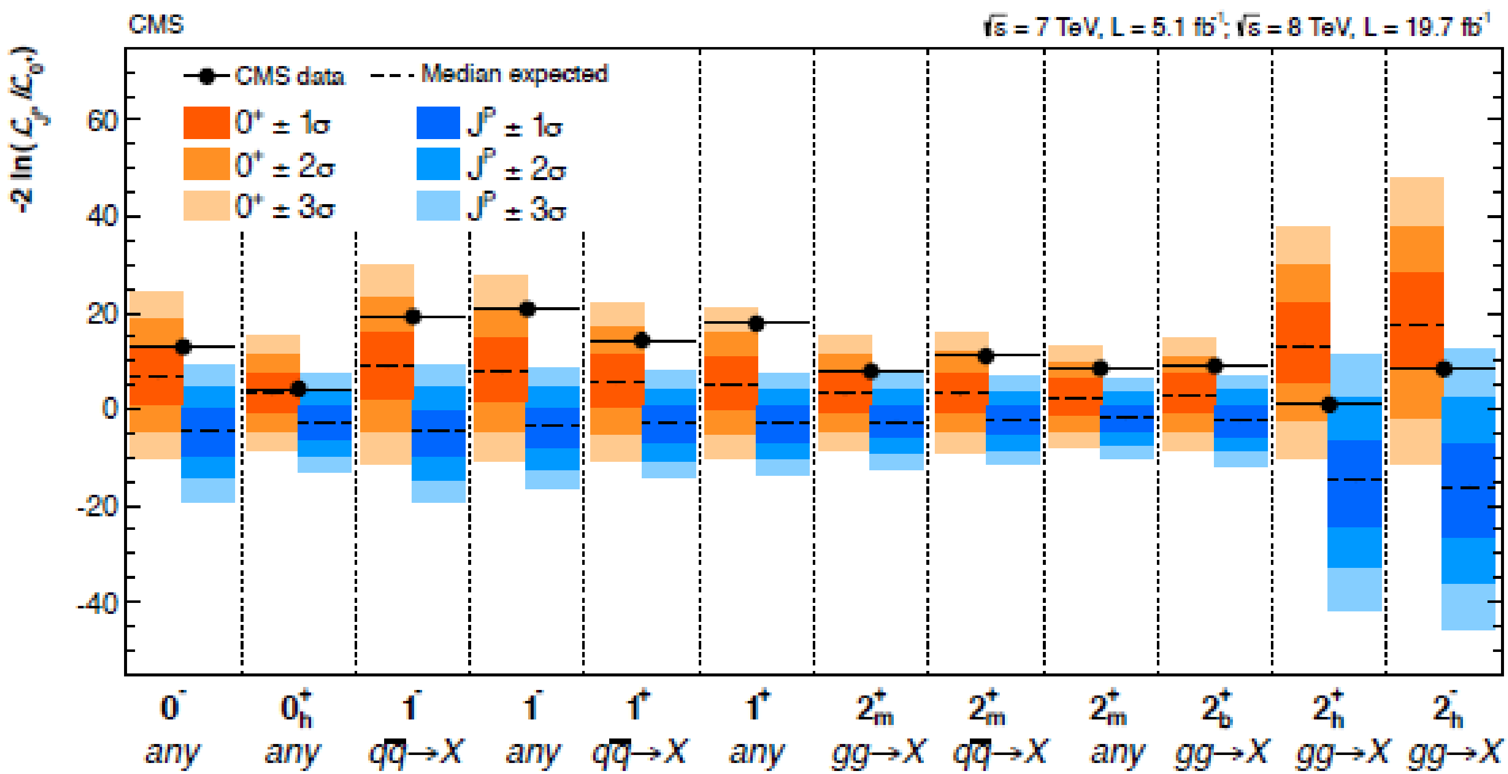
3D Compatibility with SM: 18%



Couplings tested for anomalies w.r.t. fermion and boson, W/Z & vertex loop contributions at ±10%-15% precision

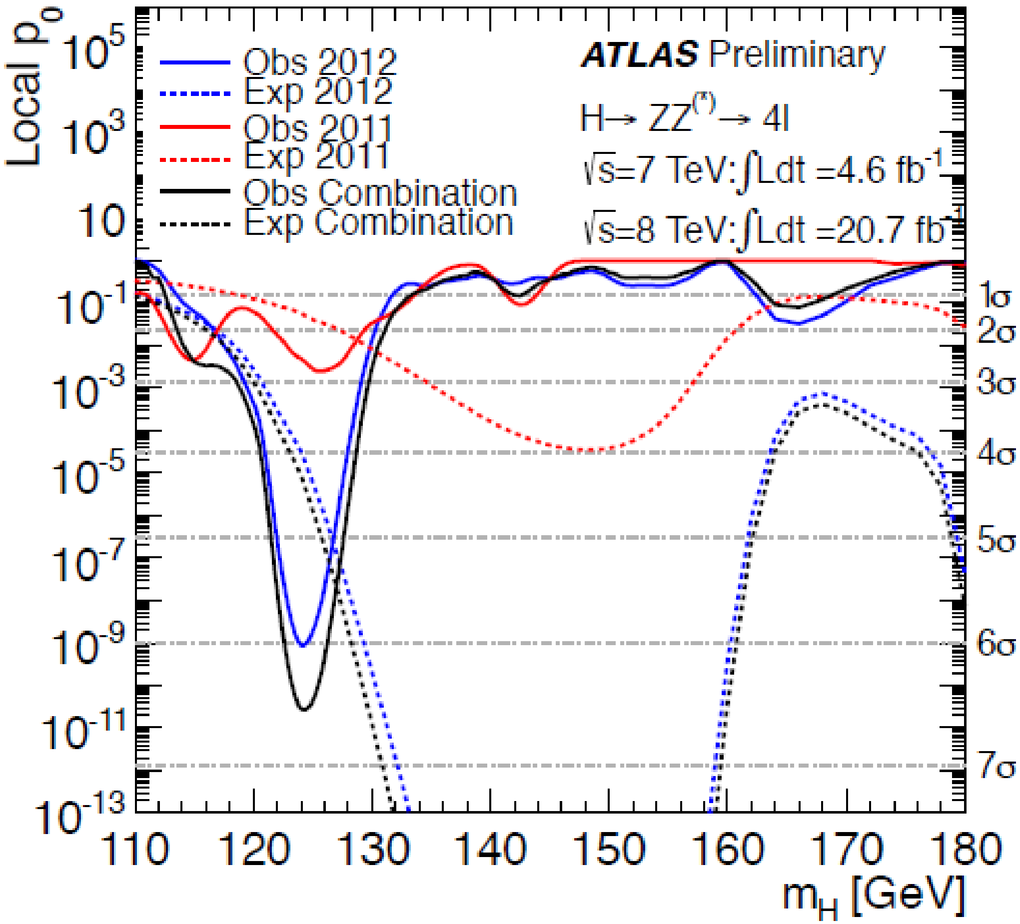
Higgs Spin and Parity with CMS

- The data disfavor the hypotheses JP with a CLs value in the range of 0.001% - 10%.



Higgs Detection Significance

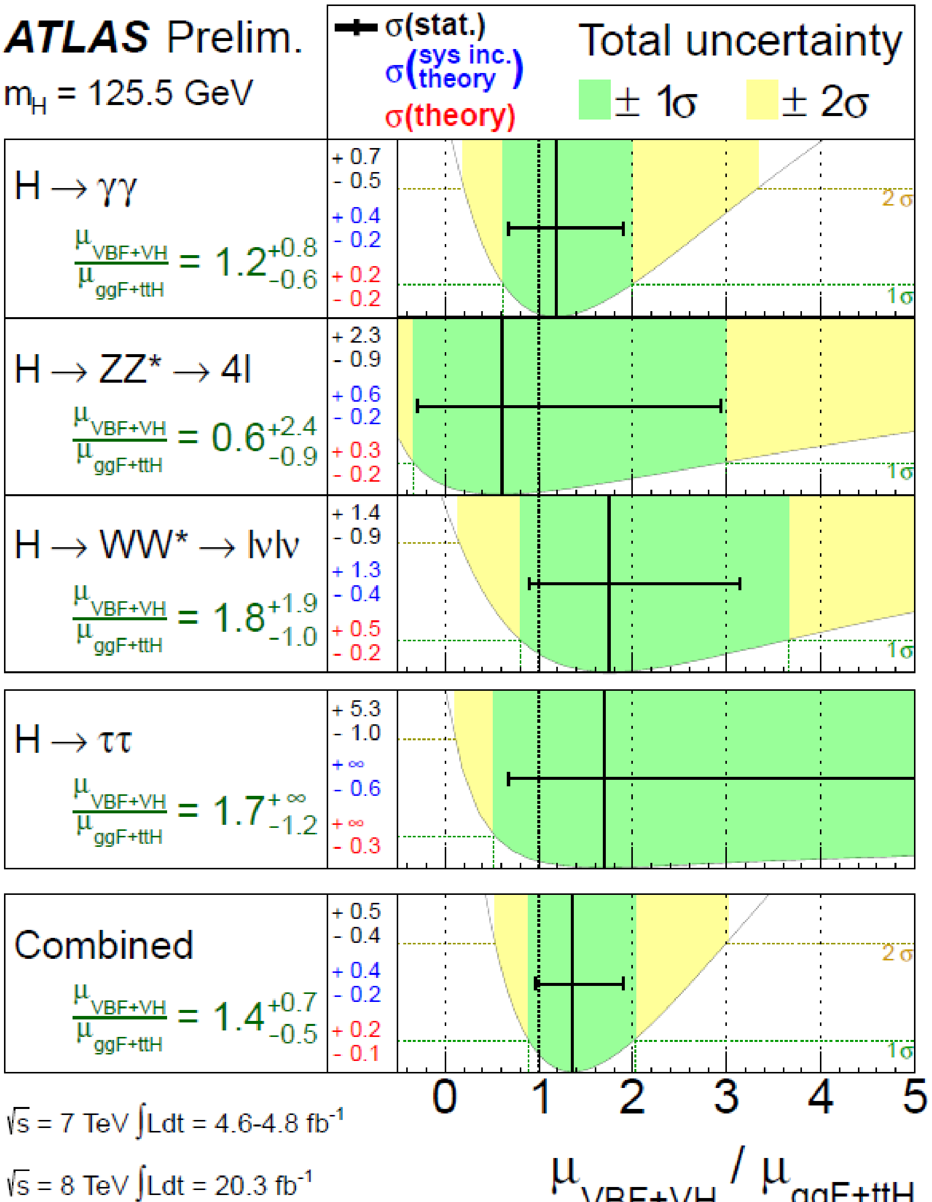
data set	observed			expected	
	min p_0	significance $[\sigma]$	$m_H(p_0)$	min $p_0(m_H)$	significance $[\sigma]$
$\sqrt{s} = 7$ TeV	2.5×10^{-3}	2.8	125.6 GeV	3.5×10^{-2}	1.8
$\sqrt{s} = 8$ TeV	8.8×10^{-10}	6.0	124.1 GeV	2.8×10^{-5}	4.0
combined	2.7×10^{-11}	6.6	124.3 GeV	5.7×10^{-6}	4.4



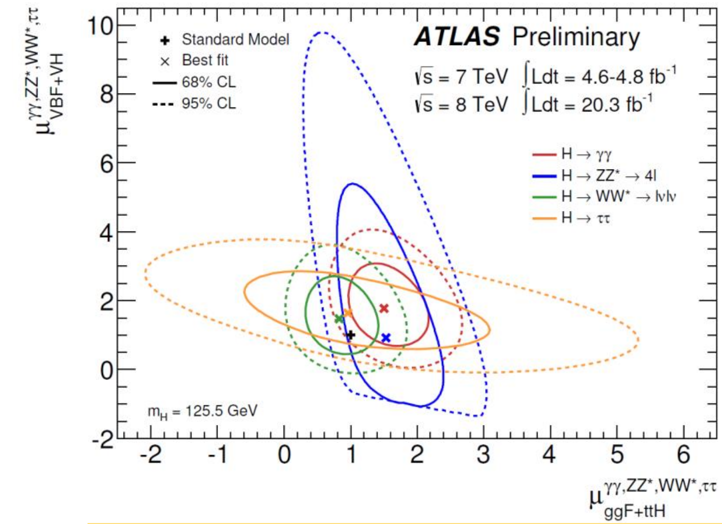
- **Signal significance**
  6.6 σ (Measured)
  4.4 σ (Expected)

➔ **> 5σ discovery in H➔ZZ*➔4ℓ channel**

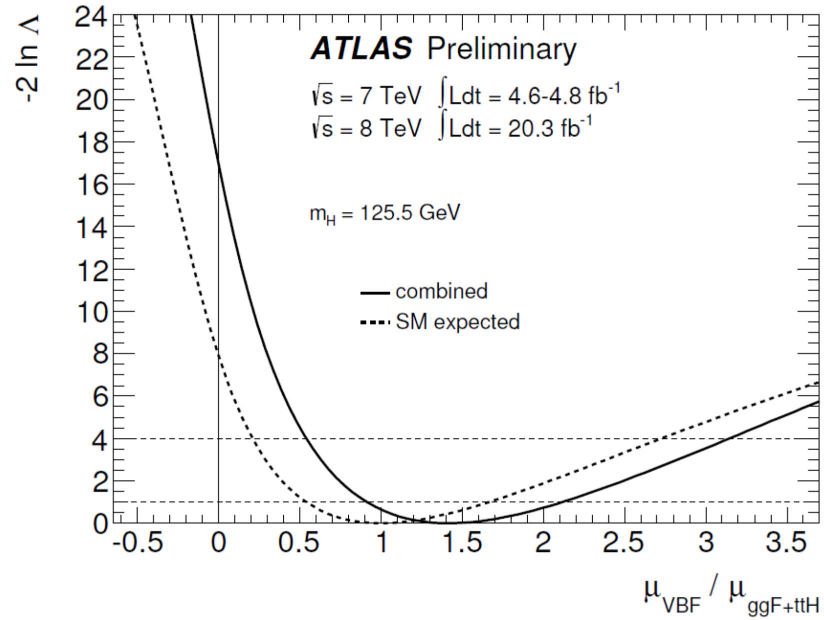
Higgs Production: ggF vs.VBF



μ_{VBF+VH} vs $\mu_{ggF+ttH}$ potentially modified by B/B_{SM}

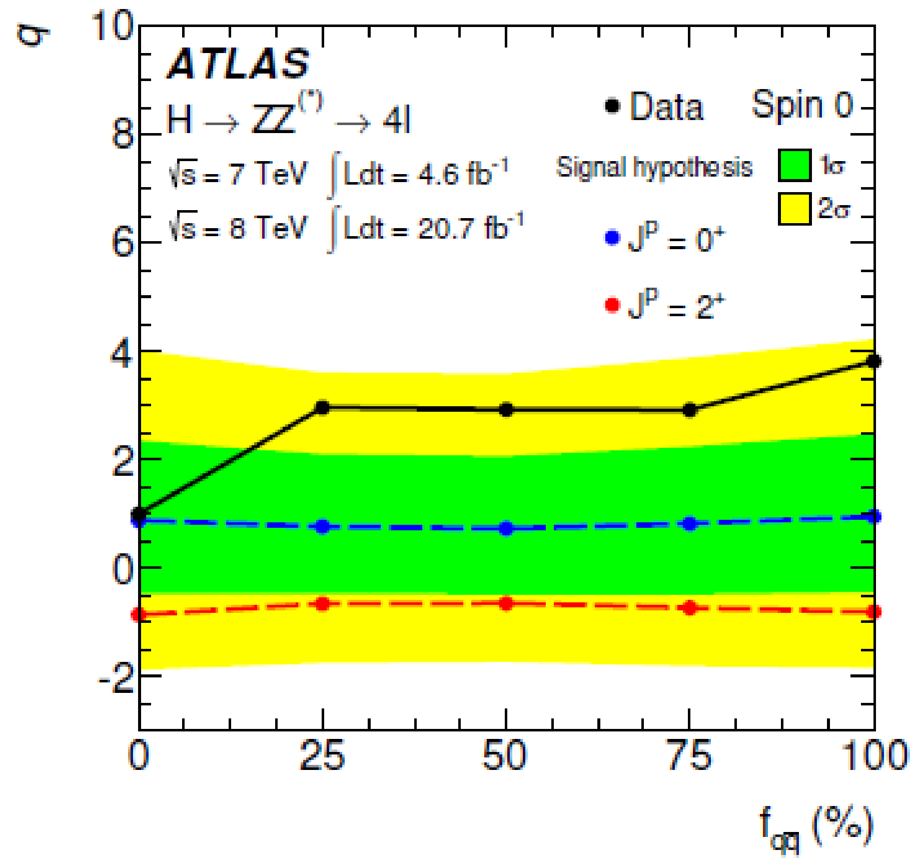


Compatibility with $\mu_{VBF}=0 \rightarrow 4.1\sigma$



H→ZZ*→4l : Spin and CP

- For $J^P = 2^+_m$ model:
  - Graviton-like tensor with minimal couplings to SM particles
  - See Phys. Rev. D81 (2010) 075022
  - Production via *gg* or *qq*
- Scan fraction of *qq* production between 0 and 100%
- Sensitivity is stable as a function of $q\bar{q}$ fraction
- Observed exclusion (0^+ vs 2^+_m) at 83.2 CL for 100% ggF produced state



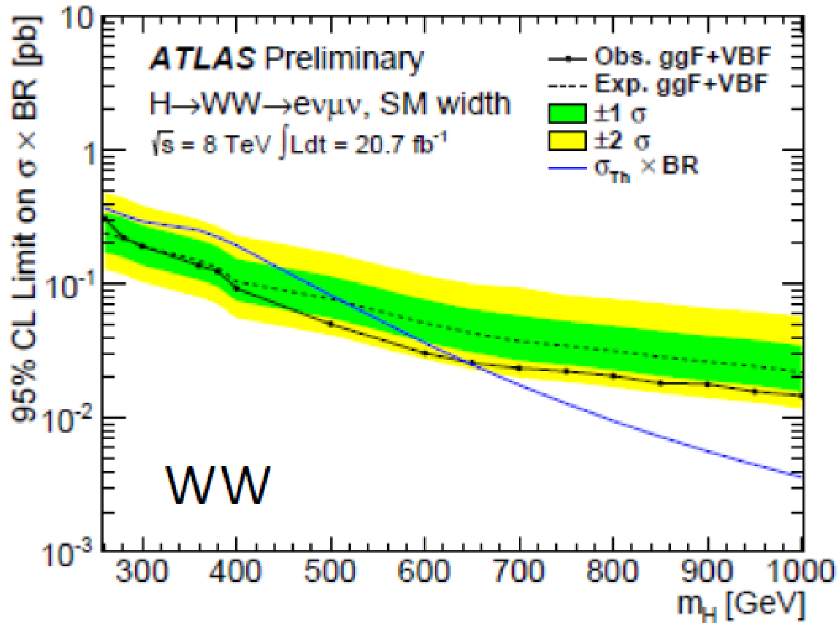
Value of test statistic, q, as a function of the $q\bar{q}$ production fraction, $f_{q\bar{q}}$

Search for High Mass H→ ZZ, WW

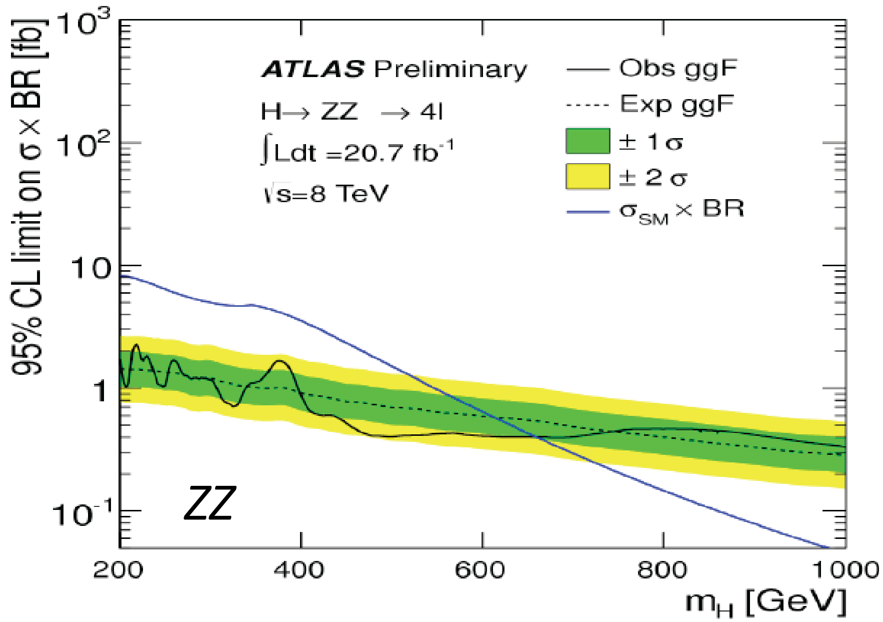
ATLAS-CONF-2013-067

Extend the Higgs search to high mass assume SM-like width, and decay to WW/ZZ

WW → lνlν*

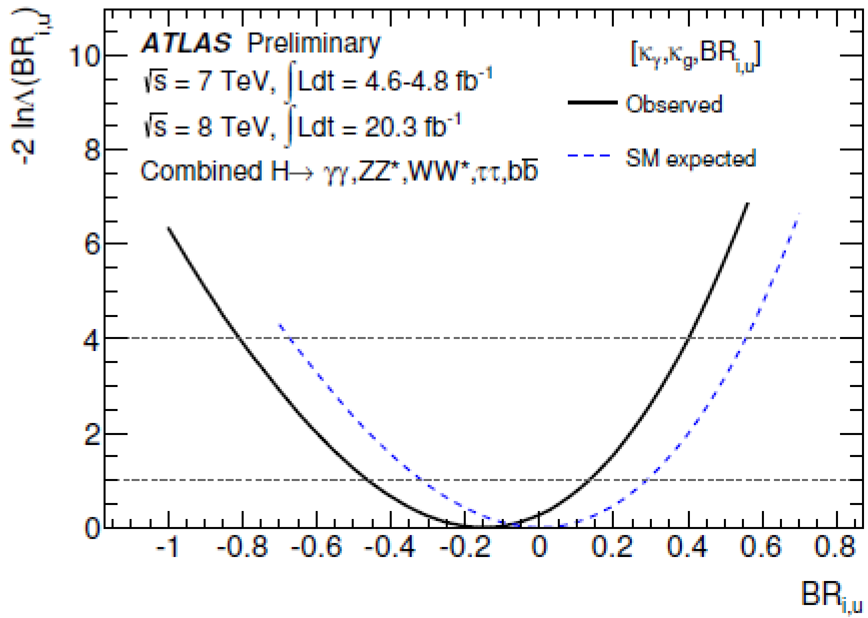


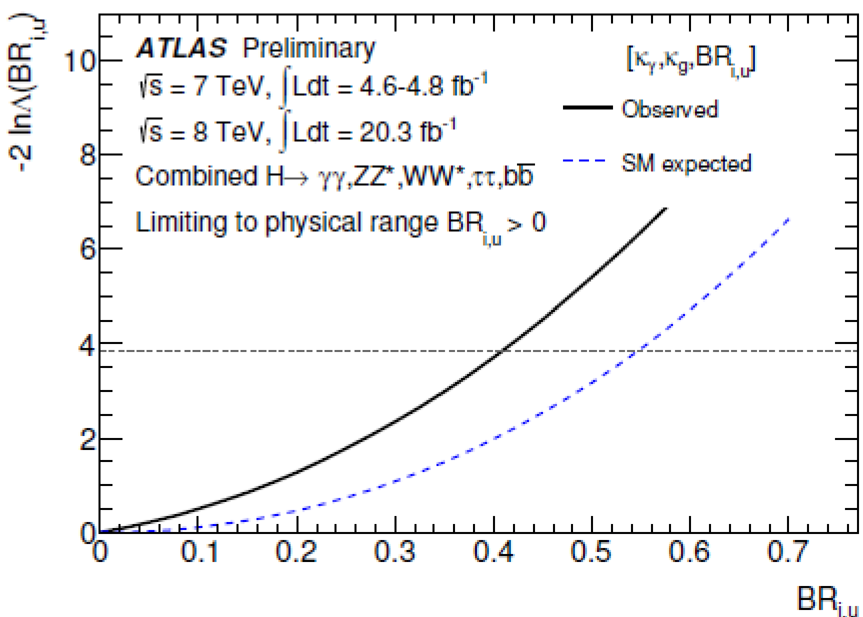
ZZ → 4l*



95% C.L. exclusion of a SM-like heavy Higgs up to ~ 650 GeV

Constraints on BSM Loops





New particles may contribute to loops

- Introduce effective κ_g, κ_γ to allow heavy BSM particles contribute to the loops
- Tree-level couplings: $\kappa_W,\kappa_Z,\kappa_t,\kappa_b,\kappa_\tau$ set to 1
  - Absorb all difference into loop couplings
  - Indirectly fixed normalization of Higgs width

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1-BR_{i.,u.})}\Gamma_H^{SM}$$

$$\kappa_g = 1.00^{+0.23}_{-0.16}$$

$$\kappa_\gamma = 1.17^{+0.16}_{-0.13}$$

$$BR_{i.,u.} = -0.16^{+0.29}_{-0.30}$$

ATLAS Trigger

Table 9: Summary of the triggers that are used during the 2012 data taking for the three analysis channels. When multiple chains are indicated, it is intended that the OR among them is requested.

Channel	Single-lepton	Di-lepton
4e	e24vhi_medium1, e60_medium1	2e12Tvh_loose1, 2e12Tvh_loose1_L2StarB(only data)
4μ	mu24i_tight, mu36_tight	2mu13, mu18_mu8_EFFS
$2e2\mu$	4μ OR $4e$ OR e12Tvh_medium1_mu8 OR e24vhi_loose1_mu8	

Table 10: Summary of the triggers that are used during the 2011 data taking. In each data taking period, the OR of single and di-lepton triggers is used to select each signature.

Single-lepton triggers				
Period	B-I	J	K	L-M
4μ	EF_mu18_MG	EF_mu18_MG_medium	EF_mu18_MG_medium	EF_mu18_MG_medium
$4e$	EF_e20_medium	EF_e20_medium	EF_e22_medium	EF_e22vh_medium1
$2e2\mu$	4μ OR $4e$			
Di-lepton triggers				
Period	B-I	J	K	L-M
4μ	EF_2mu10_loose	EF_2mu10_loose	EF_2mu10_loose	EF_2mu10_loose
$4e$	EF_2e12_medium	EF_2e12_medium	EF_2e12T_medium	EF_2e12Tvh_medium
$2e2\mu$	4μ OR $4e$ OR EF_e10_medium_mu6			

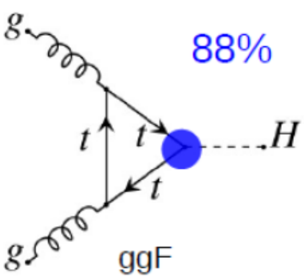
Higgs Production and Decays

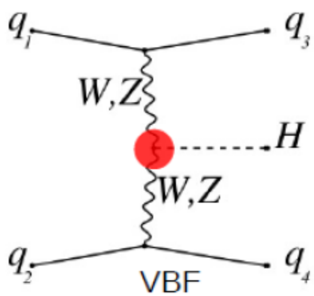
Table 2: Higgs boson production cross sections for gluon fusion, vector-boson fusion and associated production with a W or Z boson in pp collisions at $\sqrt{s}$ of 7 TeV and 8 TeV [11]. The quoted uncertainties correspond to the total theoretical systematic uncertainties with linear sum of QCD scale and PDF+α_s uncertainties. The production cross section for the associated production with a W or Z boson is negligibly small for $m_H > 300$ GeV. The decay branching ratio for $H \to 4\ell$, with $\ell = e$ or μ, is reported in the last column [11].

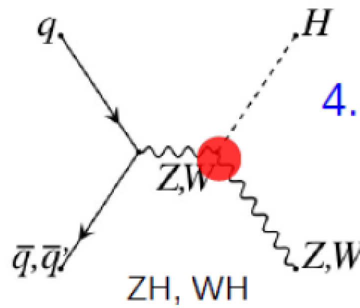
m_H [GeV]	$\sigma(gg \to H)$ [pb]	$\sigma(qq' \to Hqq')$ [pb]	$\sigma(q\bar{q} \to WH)$ [pb]	$\sigma(q\bar{q} \to ZH)$ [pb]	BR $\left(H \to ZZ^{(*)} \to 4\ell\right)$ [10^{-3}]
			$\sqrt{s} = 7$ TeV		
123	$15.8^{+2.3}_{-2.4}$	1.25 ± 0.03	$0.60^{+0.02}_{-0.03}$	0.33 ± 0.02	0.103
125	15.3 ± 2.3	1.22 ± 0.03	0.57 ± 0.02	0.32 ± 0.02	0.125
127	14.9 ± 2.2	1.20 ± 0.03	0.54 ± 0.02	0.30 ± 0.02	0.148
			$\sqrt{s} = 8$ TeV		
123	20.2 ± 3.0	1.61 ± 0.05	0.73 ± 0.03	0.42 ± 0.02	0.103
125	19.5 ± 2.9	$1.58^{+0.04}_{-0.05}$	0.70 ± 0.03	0.39 ± 0.02	0.125
127	18.9 ± 2.8	1.55 ± 0.05	$0.66^{+0.02}_{-0.03}$	0.37 ± 0.02	0.148

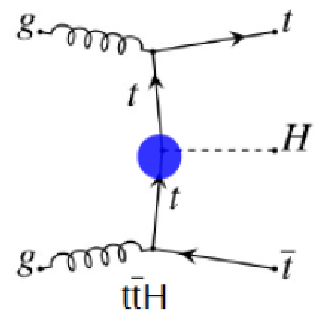
Is it the SM Higgs Boson?

❖ **Higgs production (m_H = 125 GeV)**

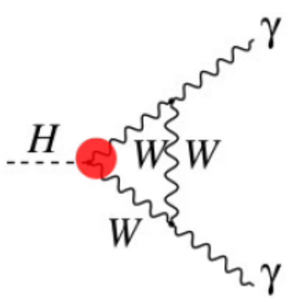


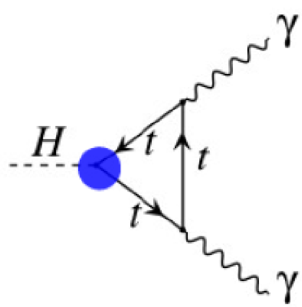


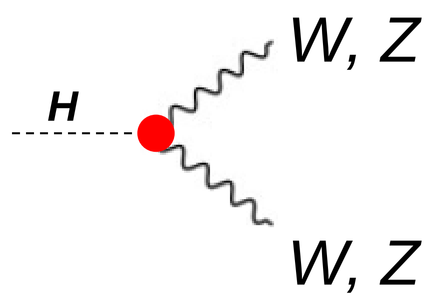


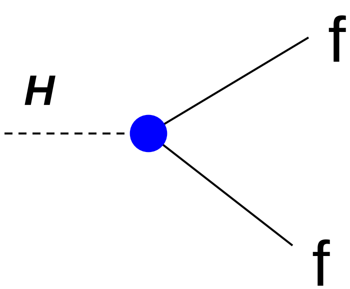


❖ **Higgs decays**









❖ **Couplings (new force!)**

● : fermions

● : vector bosons

g_F (Yukawa coupling) $=\sqrt{2} \times m_F/\nu$

g_V (Gauge coupling) $= 2m_V^2/\nu$

(ν is the vacuum expectation value)

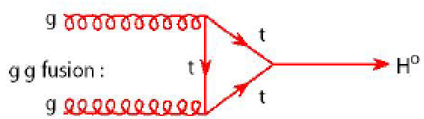
❖ **Spin and Parity**

Coupling Measurements

Coupling strengths κ_i & ratio: $\kappa_F = g_F/g_{F,SM}$, $\kappa_V = g_V/g_{V,SM}$, $\lambda_{ij} = \kappa_i / \kappa_j$

Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $gg \to H \to \gamma\gamma$
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)/\kappa_H^2(\kappa_F, \kappa_V)$
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, \lambda_{FV}, \lambda_{FV}, 1)$
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{\gamma Z}^2$
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma)$

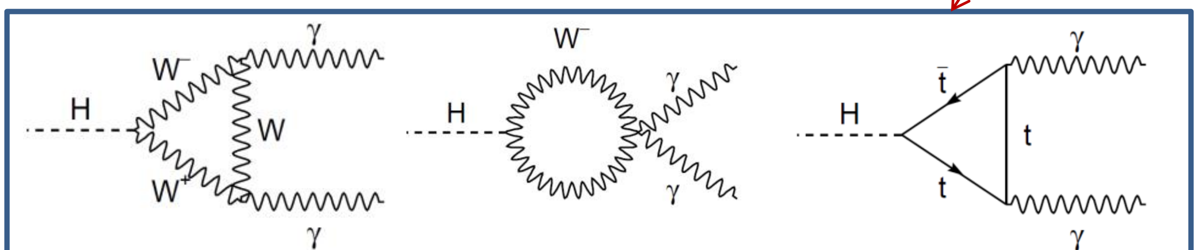
Example $H \to \gamma\gamma$



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

κ_g , κ_γ: loop coupling scale factors

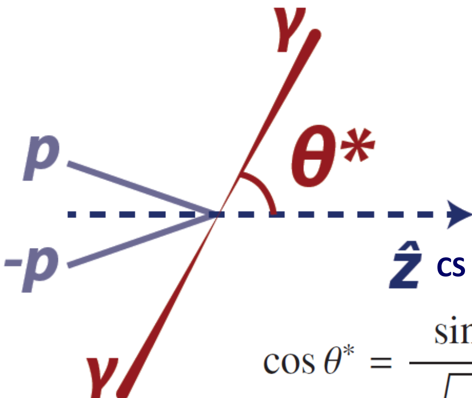
κ_H is the total Higgs width scale factor



$$\kappa_\gamma^2 = |1.28\,\kappa_W - 0.28\,\kappa_t + \ldots|^2$$

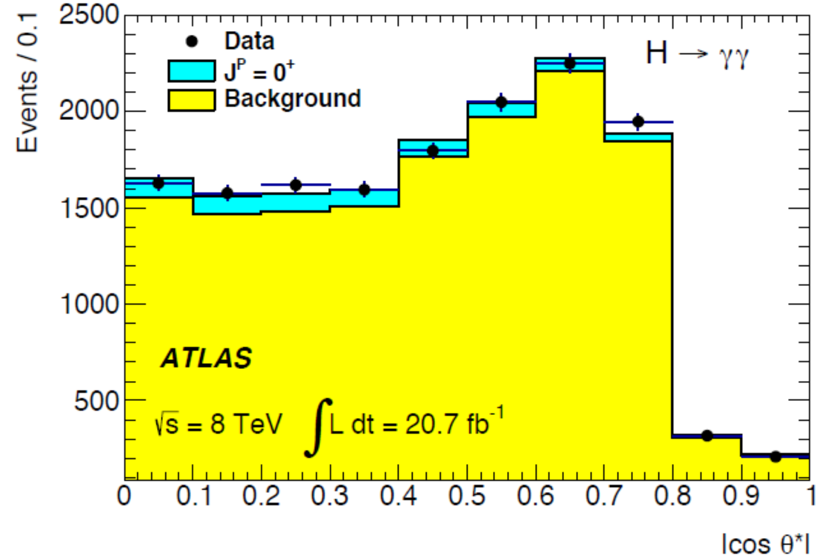
Spin Analysis with H→ γγ

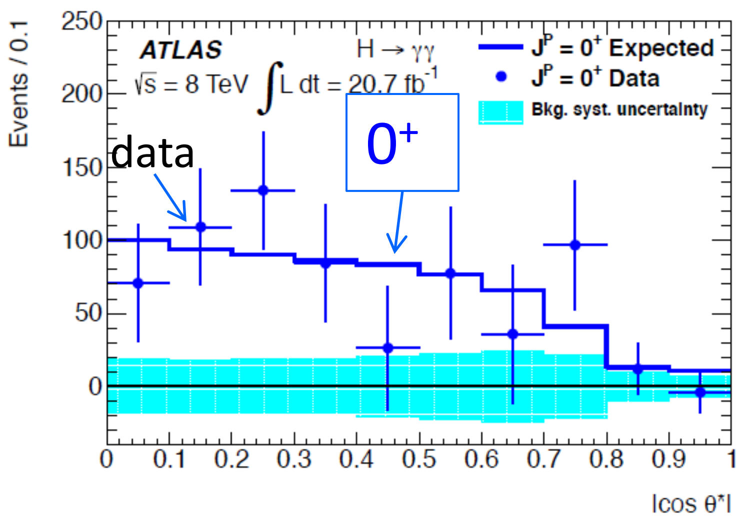
Polar angle θ* of the photon decay in Collines-Soper frame, along with $m_{\gamma\gamma}$

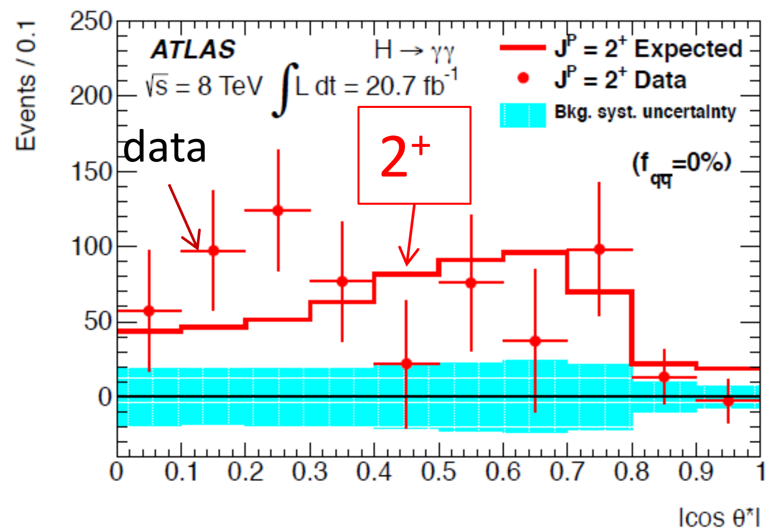


Z_{CS} bisects angle between the momenta of colliding hadrons

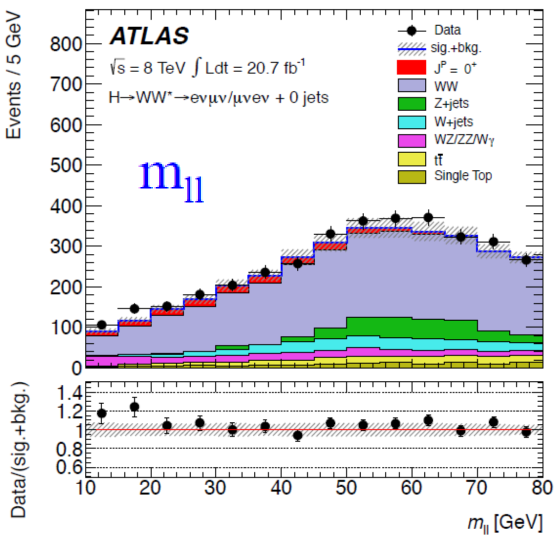
$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

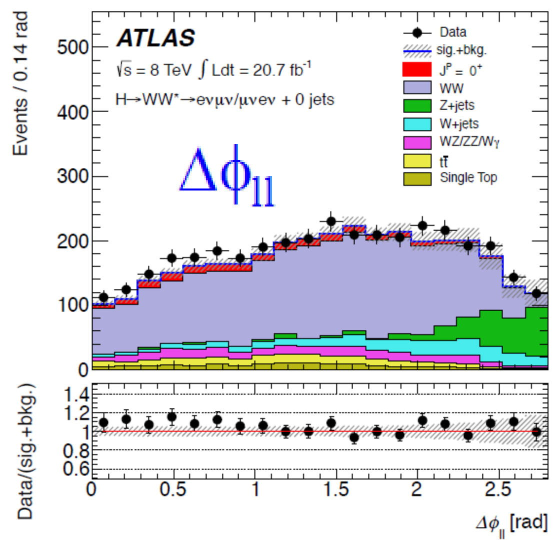


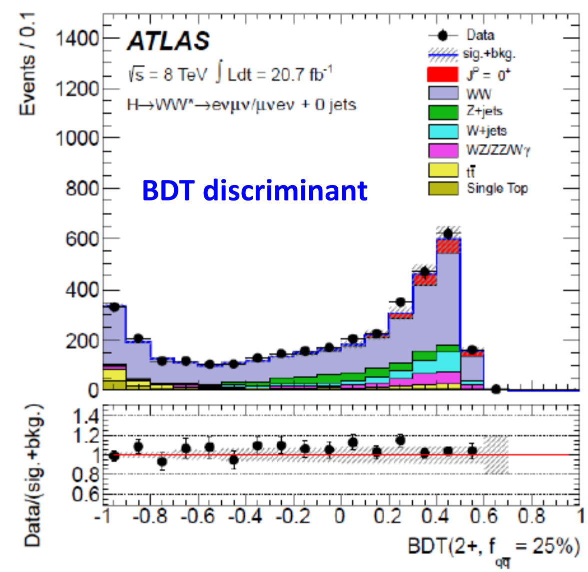




Spin Analysis With H→ WW*

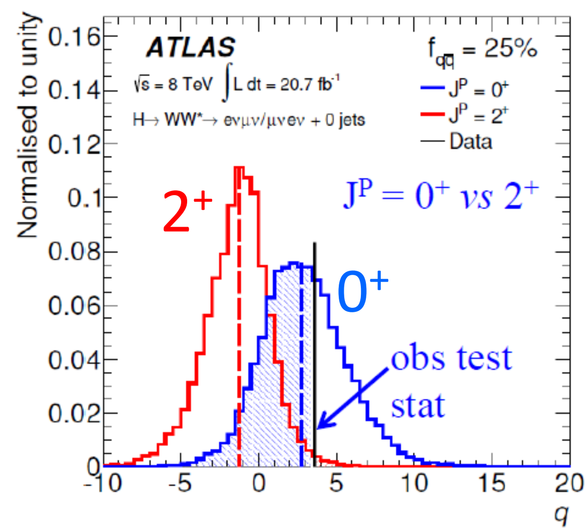






$J^P = 0^+ \; vs \; 2^+$

$f_{q\bar{q}}$	2⁺ assumed Exp. $p_0(J^P = 0^+)$	0⁺ assumed Exp. $p_0(J^P = 2^+)$	Obs. $p_0(J^P = 0^+)$	Obs. $p_0(J^P = 2^+)$	$CL_s(J^P = 2^+)$
100%	0.013	$3.6 \cdot 10^{-4}$	0.541	$1.7 \cdot 10^{-4}$	$3.6 \cdot 10^{-4}$
75%	0.028	0.003	0.586	0.001	0.003
50%	0.042	0.009	0.616	0.003	0.008
25%	0.048	0.019	0.622	0.008	0.020
0%	0.086	0.054	0.731	0.013	0.048



Exclusion **($1-CL_s$):**

Observed 2⁺ (qq=100%) exclusion 99.96%

Observed 2⁺ (qq = 0%) exclusion 95.2%

MVA Discriminant: Higgs Spin and CP