

Recent Higgs $\rightarrow ZZ^{()} \rightarrow 4l$ Results*

*Latest results from the search for the
Standard Model Higgs Boson with
the ATLAS experiment at LHC*

Antonio Salvucci ¹

on behalf of the ATLAS collaboration

¹ *Radboud University Nijmegen & Nikhef*



La Thuile, 24 February - 2 March 2013

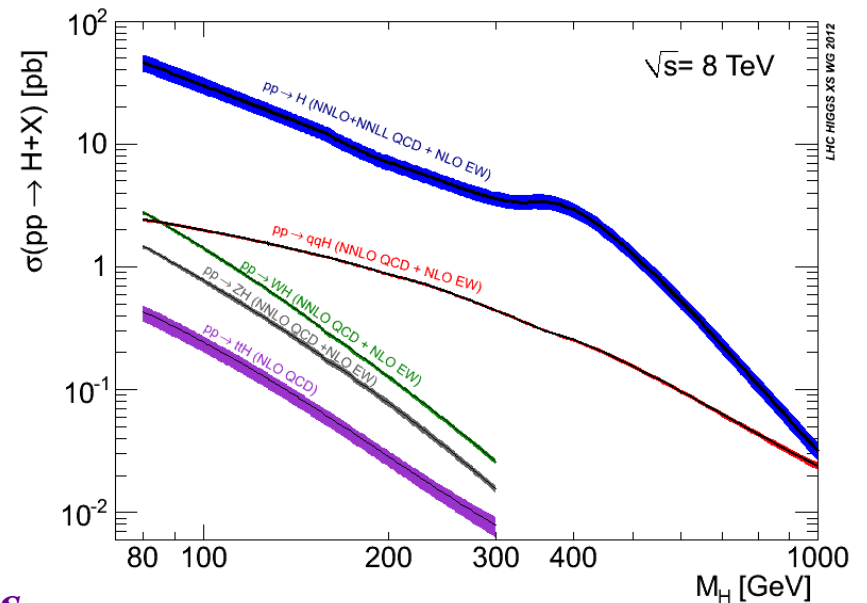
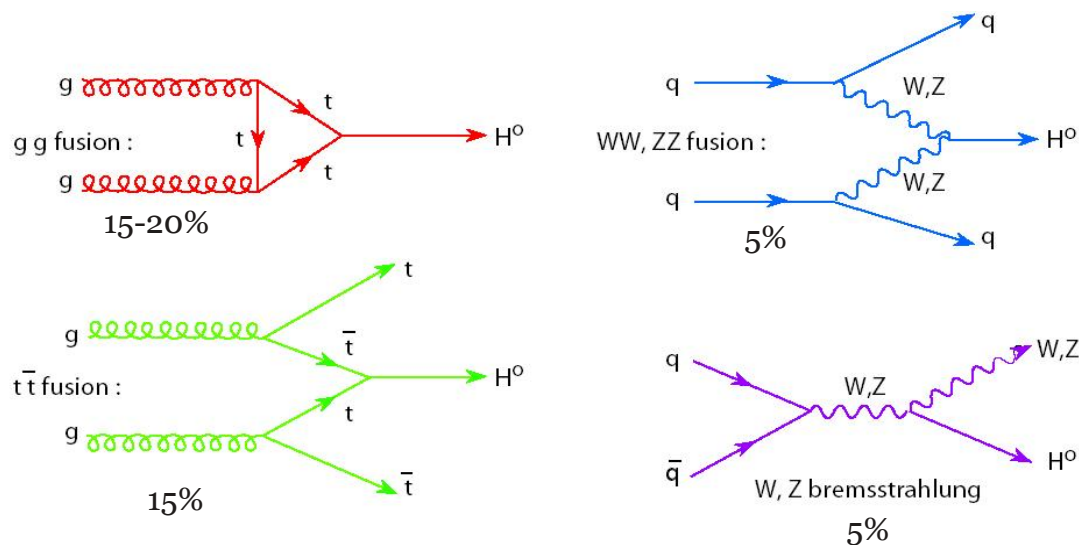
- **Higgs @ LHC**
 - *Standard Model (SM) production mechanism and decays*
 - *Higgs discovery*

- **Higgs $\rightarrow ZZ^{(*)} \rightarrow 4l$: The 'Golden Channel'**
 - *Production and Backgrounds*
 - *Event Selection*

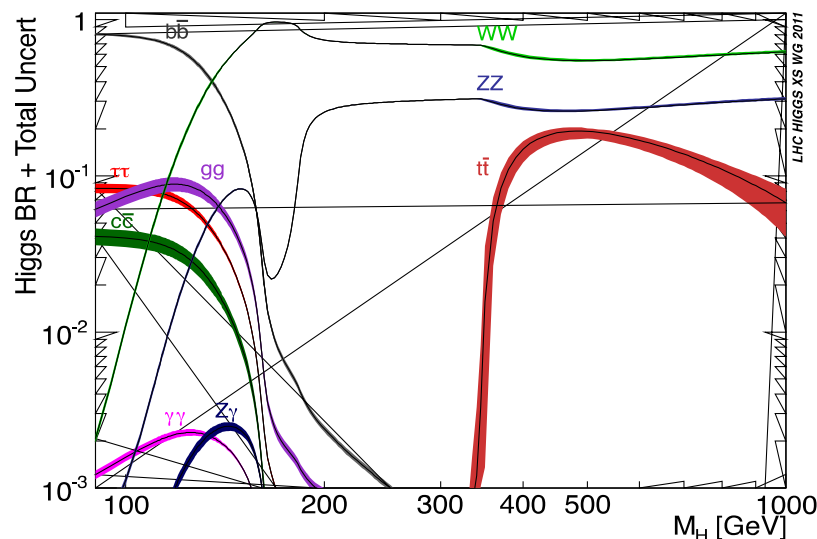
- **Latest Results**
 - *Significance, Mass*
 - *Spin/CP*

- **Conclusions**

Production Mechanism



Decay Modes



● $H \rightarrow \gamma\gamma$

low mass, high background and mass resolution

● $H \rightarrow ZZ^{(*)} \rightarrow 4l$

full mass range, low BR, high purity and mass resolution

● $H \rightarrow WW^{(*)} \rightarrow lv lv$

full mass range

● $H \rightarrow \tau\tau$

low mass

● $VH \rightarrow V + bb$

associated production VH, $V = Z, W$

Higgs Discovery



4th July 2012, the ATLAS [1] and the CMS [2] collaborations announced the observation of a new particle.

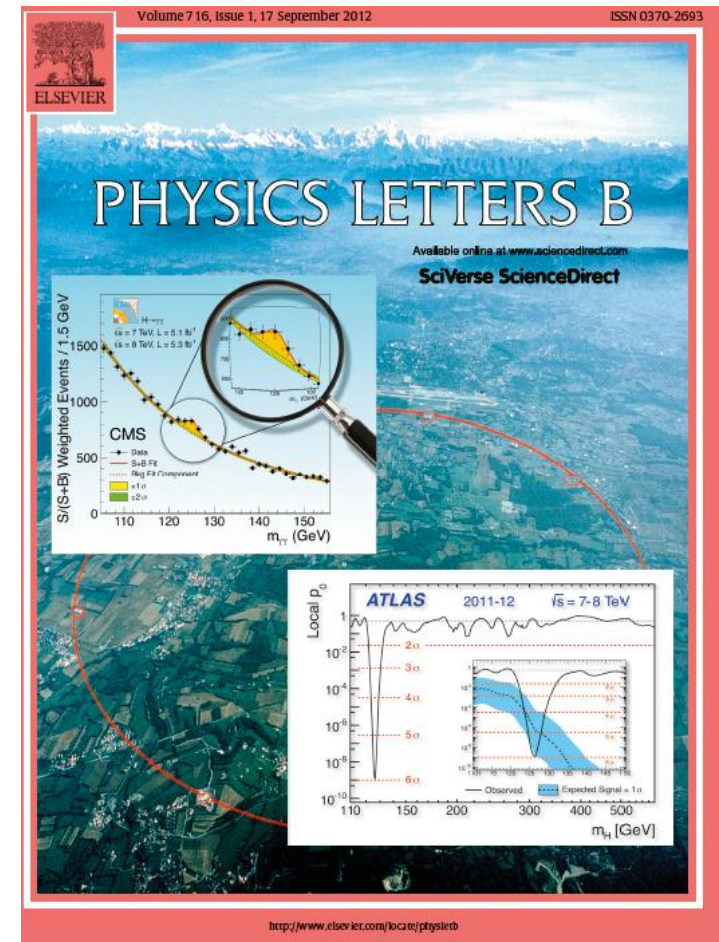
ATLAS channels

(4.8 fb⁻¹ @ 7 TeV and 5.8 fb⁻¹ @ 8 TeV)

$$H \rightarrow \gamma\gamma$$

$$H \rightarrow ZZ^{(*)} \rightarrow 4l$$

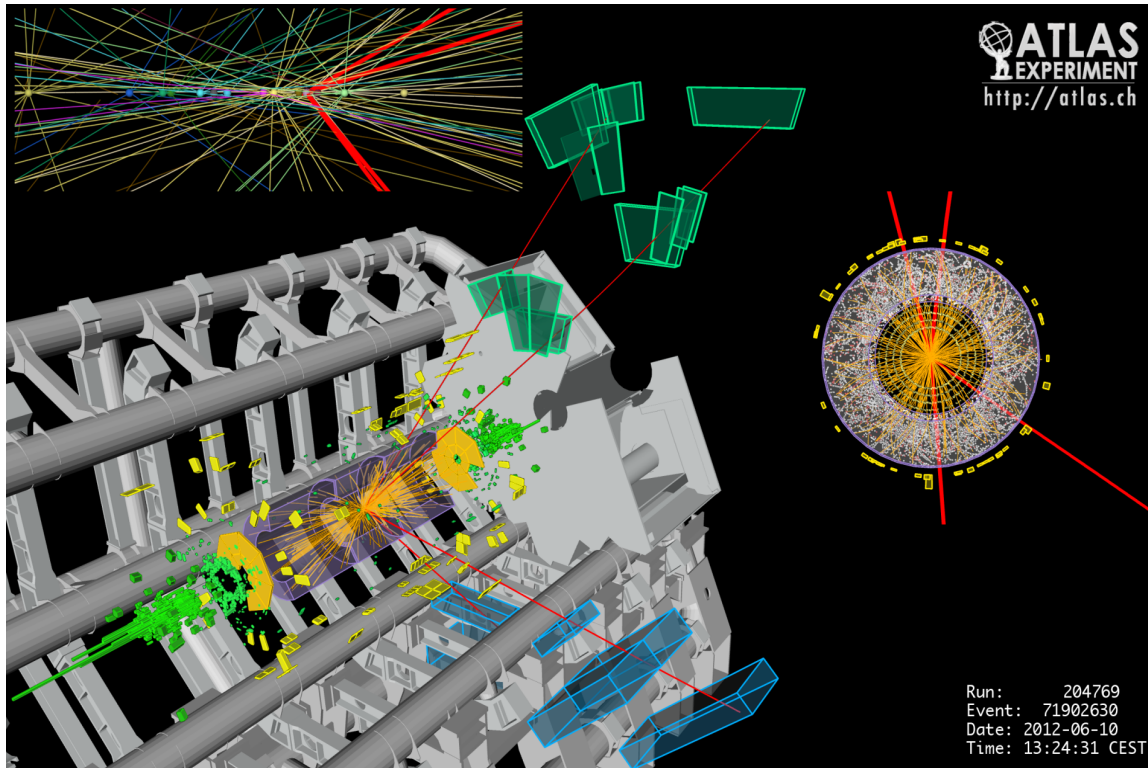
$$H \rightarrow WW \rightarrow lv lv$$



[1] ATLAS Collaboration, 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, arXiv:1207.7214 [hep-ex].

[2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B 716 (2012) 30–61, arXiv:1207.7235 [hep-ex].

$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Production



Signal purity (S/B) ~ 1

Production inclusive;

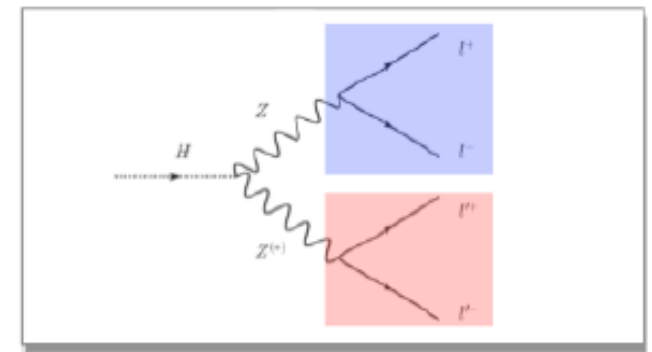
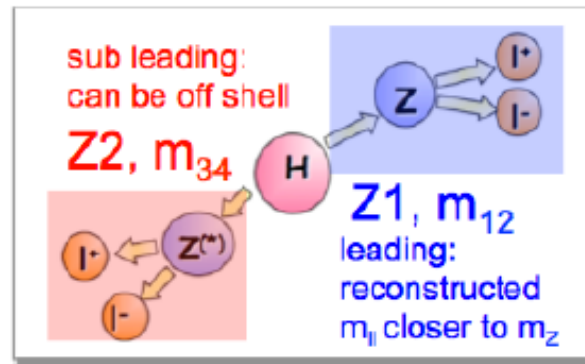
Luminosity:

$4.8 \text{ fb}^{-1} @ 7 \text{ TeV} + 13 \text{ fb}^{-1} @ 8 \text{ TeV}$
(December 2012)

Signal

production mode

gg, VBF, ZH, WH



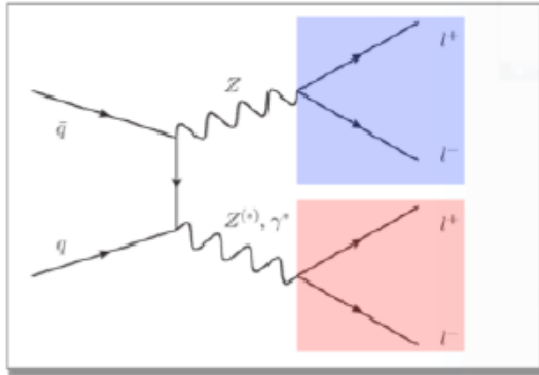
$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Backgrounds



Irreducible bkg \rightarrow $pp \rightarrow ZZ$ (~ 90 % total bkg)

Rejection \rightarrow kinematic cuts e.g. m_{12} and m_{34}

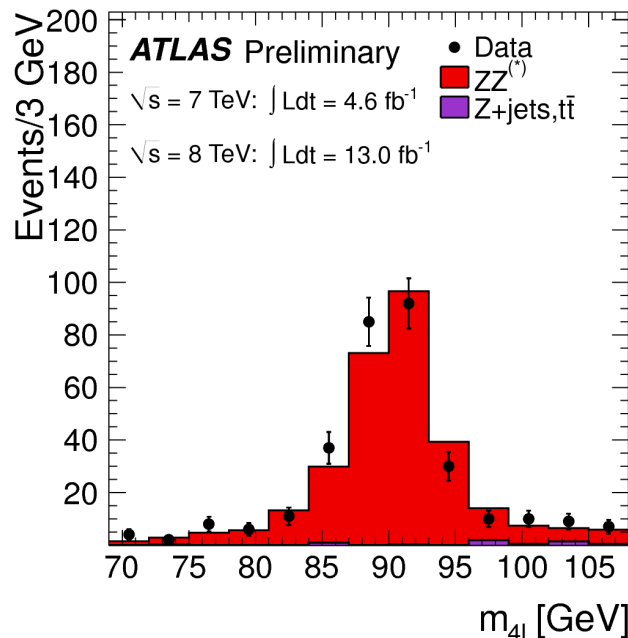
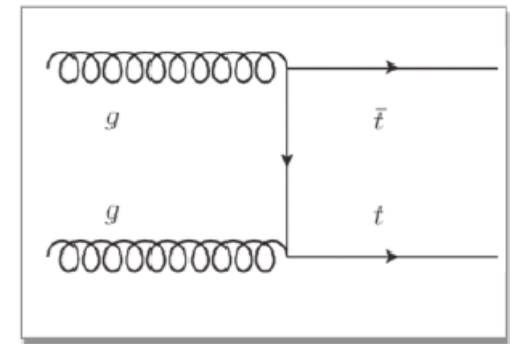
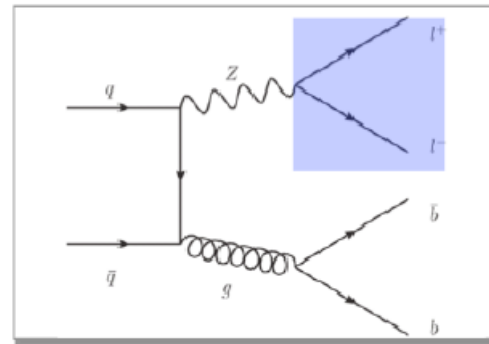
Shape and normalization from MC



Reducible bkg \rightarrow $pp \rightarrow Z$ +jet, $t\bar{t}$...

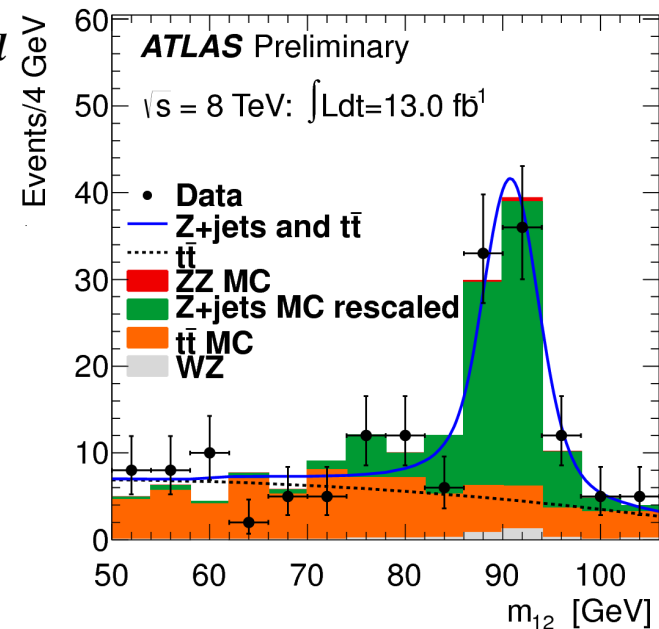
Rejection \rightarrow isolation of leptons, ...

Z+jet from control region, Zbb shape from MC and normalization from data



Reducible background estimation from data

m_{4l} distribution at Z peak
for the combined $\sqrt{s} = 7$ TeV
and $\sqrt{s} = 8$ TeV data



$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Event Selection



Selection:

- 4 leptons $\rightarrow p_T^{1,2,3,4} = 20, 15, 10, 7-6$ (e- μ) GeV
- $50 < m_{12} < 106$ GeV
- $m_{34} > 17.5$ GeV
- track Isolation $< 15\%$
- calorimetric isolation $< 20\%$ (e), 30% (μ)
- Impact parameter significance < 6.5 (e), 3.5 (μ)

details in
backup slides

Overall acceptance
 $M_{\text{higgs}} 125$ GeV



4 μ : 36%
2 μ 2e: 22%
4e: 20%

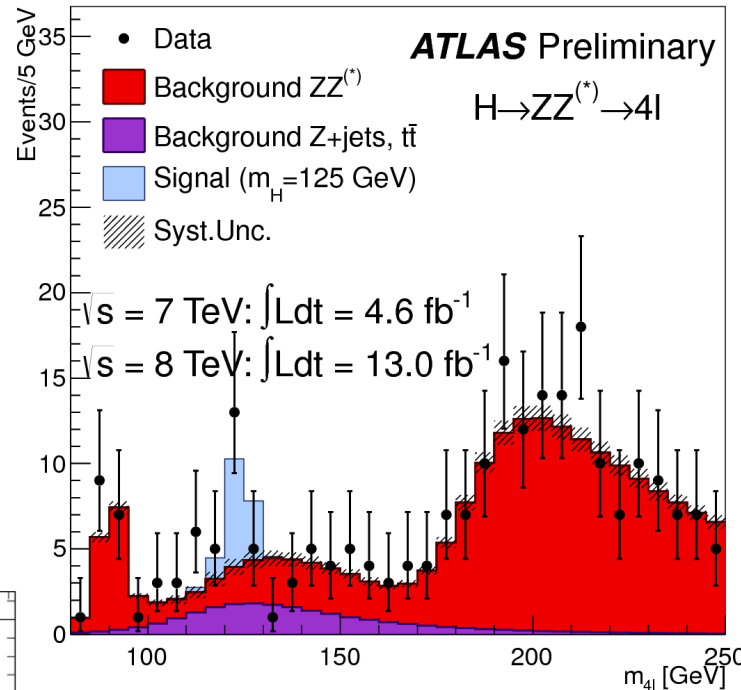
$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Latest Results



arXiv:1207.7214 [hep-ex], ATLAS-CONF-2012-169

Events in the signal region 125 ± 5 GeV

- Observed $\rightarrow 18$
- Expected Bkg $\rightarrow 8.3 \pm 0.3$
- Expected Sig $\rightarrow 9.9 \pm 1.3$

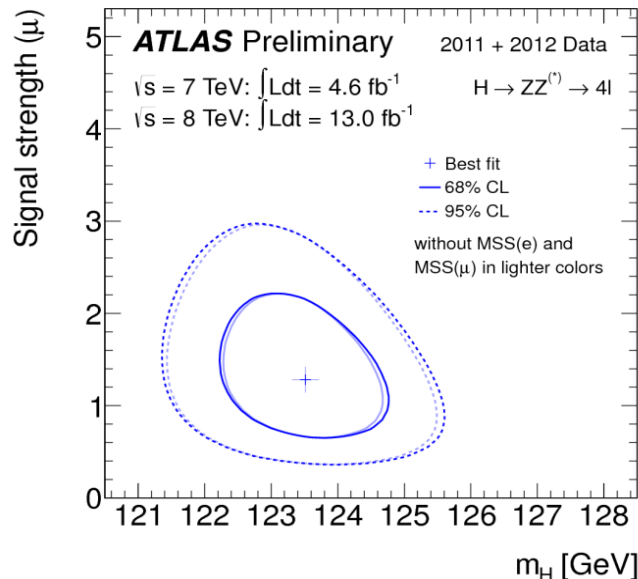


Expected local significance (123.5 GeV)

3.1σ

Observed local significance

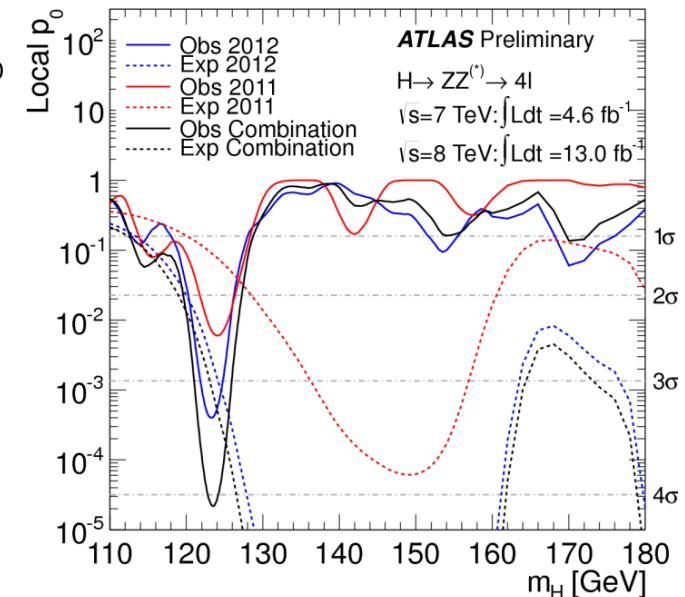
4.1σ @ $m_H = 123.5$ GeV



Signal Strength

1.3 ± 0.5

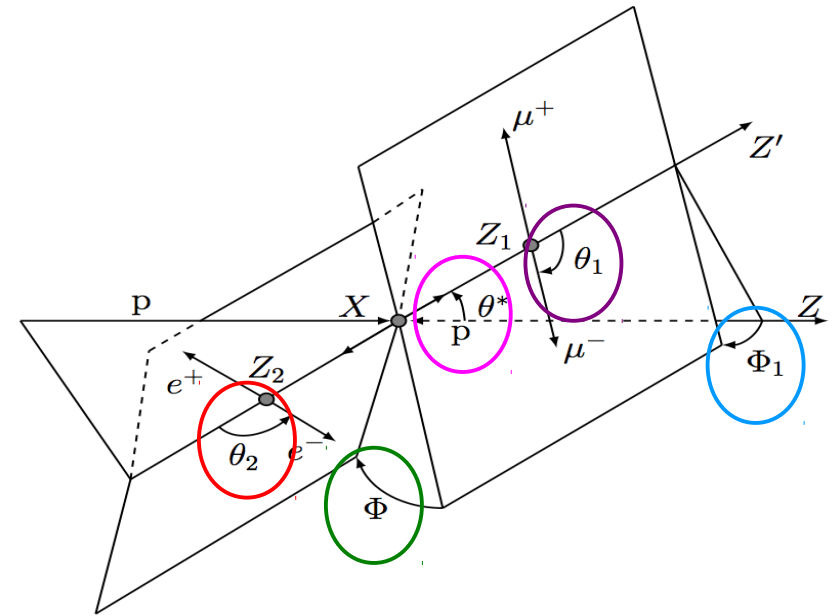
$m_H = 123.5 \pm 0.9$ GeV



$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Spin/CP

Spin/CP could be measured using :

- i. production and decay angles: $\vartheta_1, \vartheta_2, \varphi, \varphi_1, \vartheta^*$
 - ii. m_{12} and m_{34}
- 1) $\vartheta_1, \vartheta_2 \rightarrow$ angles between negative final state leptons and the direction of their respective Z bosons (in the Z rest frame)
 - 2) $\varphi \rightarrow$ angle between the decay planes of the 4 final state leptons (in the leptons rest frame)
 - 3) $\varphi_1 \rightarrow$ angle between the decay plane of the 1st lepton pair and a plane defined by the vector of Z1 (in the 4 lepton rest frame) and the positive direction of the collision axis
 - 4) $\vartheta^* \rightarrow$ production angle of the Z1 (4 lepton rest frame)

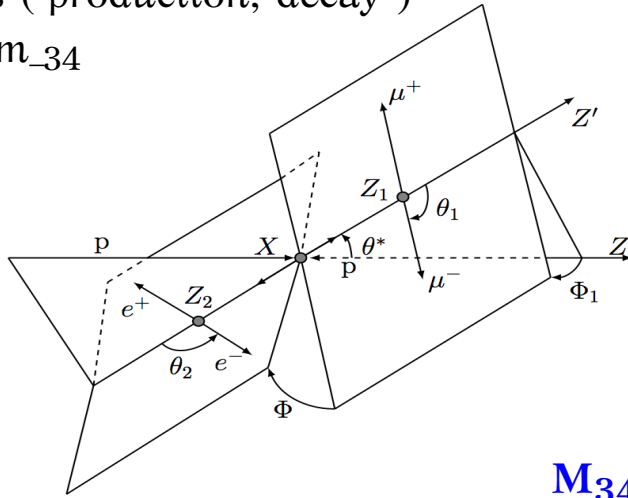


$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Spin/CP



Spin/CP could be measured using :

- i. 5 angles (production, decay)
- ii. m_{12} , m_{34}

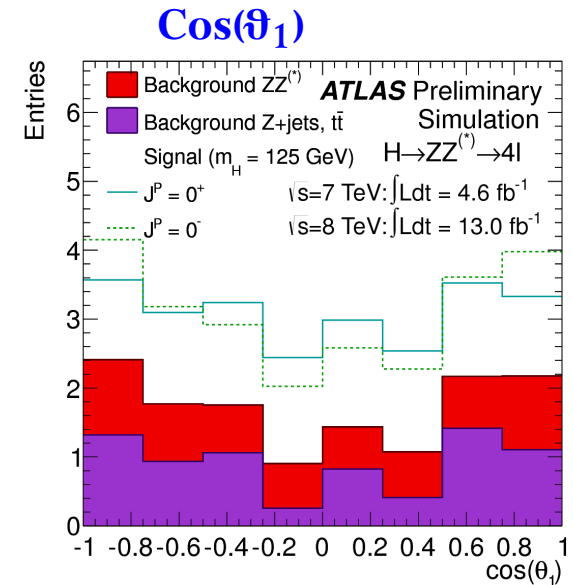
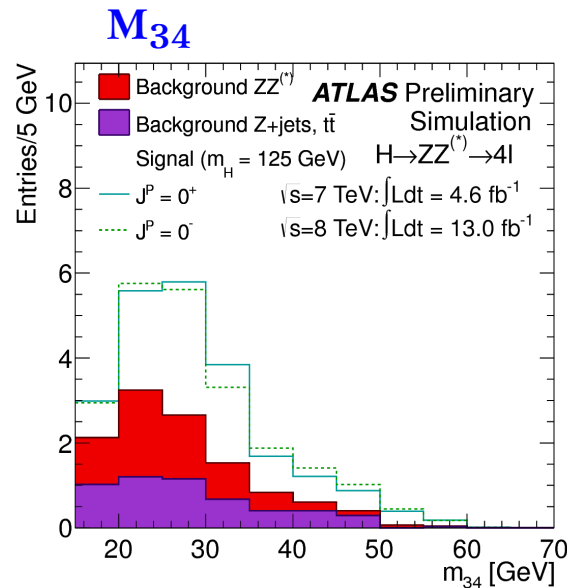
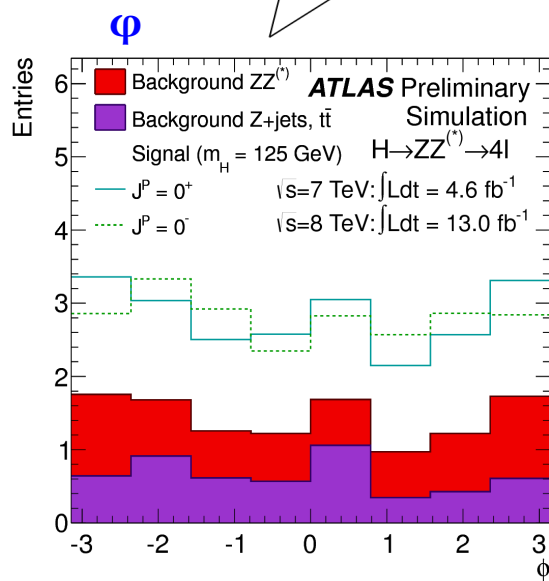


Discriminate 0^+ (SM) hypothesis against:

- i. 0^- ,
- ii. 2^+m (graviton-like tensor with minimal couplings)
- iii. 2^- (pseudo-tensor)

Two Multi-Variate discriminants used:

- i. Boosted Decision Tree (BDT);
- ii. Matrix-Element-Likelihood-Analysis (JP-MELA).

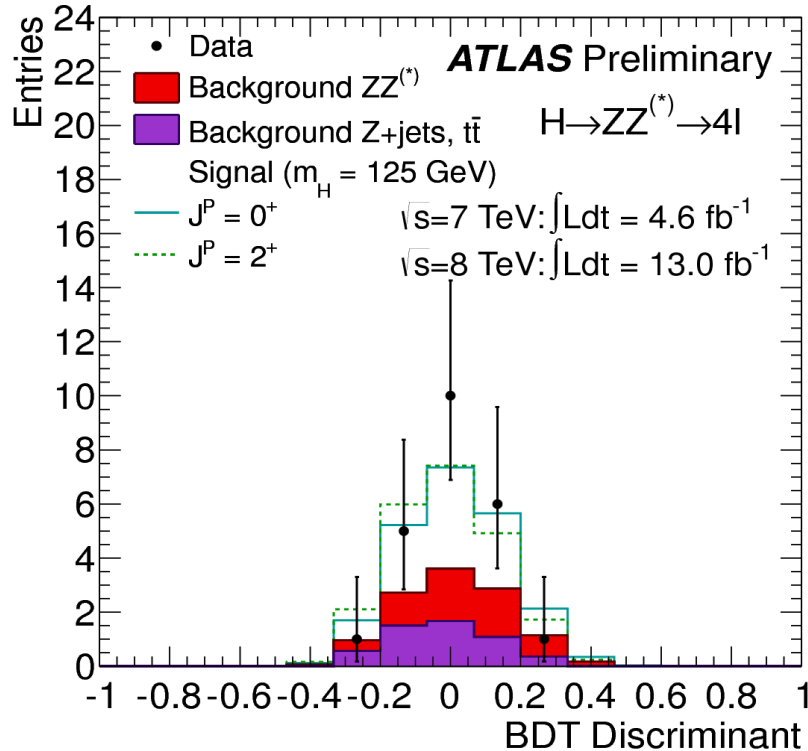


Expected distributions for 0^+ and 0^- hypothesis of ϕ , $\cos \theta_1$ and m_{34} for the combined $\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV data

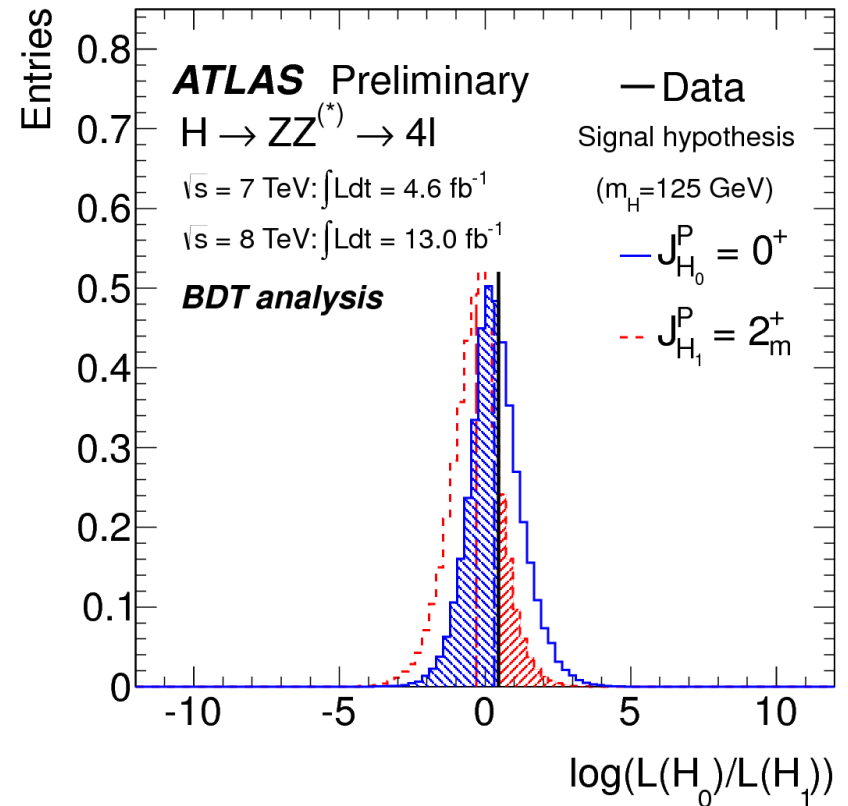
$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Spin Results



arXiv:1207.7214 [hep-ex], ATLAS-CONF-2012-169



$0^+ \text{ vs } 2^+$



► (Low) **Expected** Exclusion of spin 2^+ at the **80% of CL**

► **Observed** Exclusion of spin 2^+ at the **85% of CL**

**BDT and JP-MELA
consistent results**

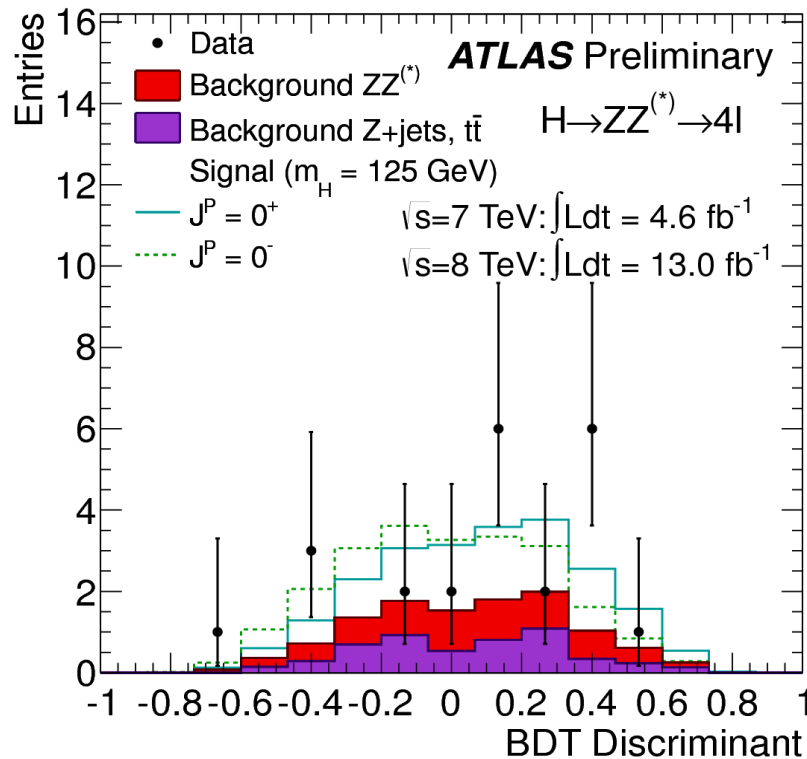
details in backup slides

Observation fully compatible with Spin 0 (within 0.18σ)

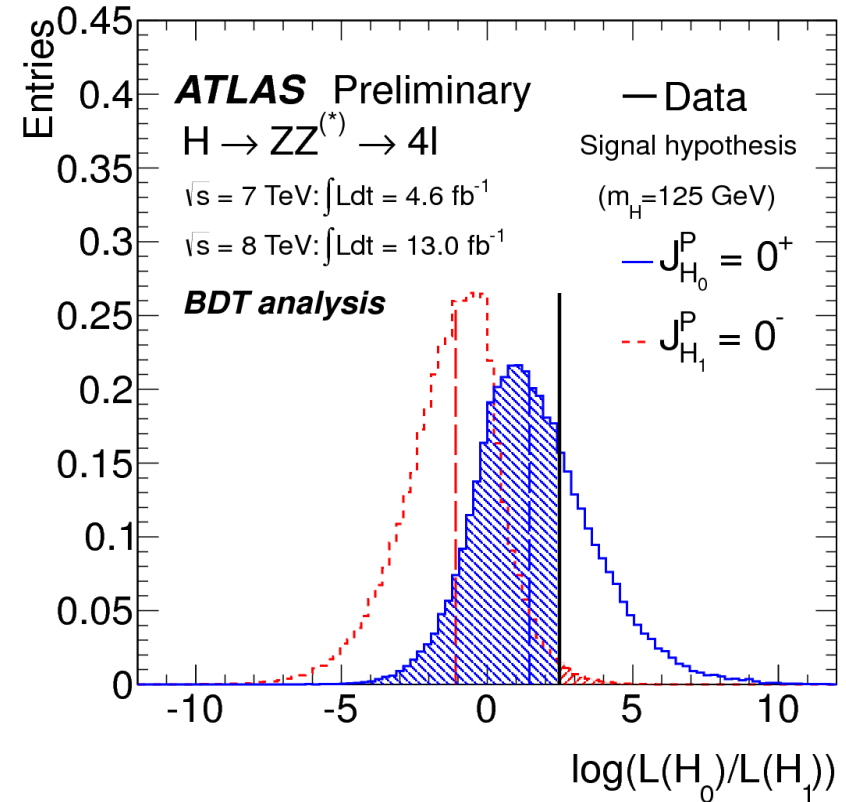
$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Parity Results



arXiv:1207.7214 [hep-ex], ATLAS-CONF-2012-169



$0^+ \text{ VS } 0^-$



► **Expected** exclusion of spin 0^- at the **96% of CL**

► **Observed** exclusion of spin 0^- at the **99% of CL**

**BDT and JP-MELA
consistent results**

details in backup slides

Observation fully compatible with Spin 0^+ (within 0.5σ)

- *The first LHC run has ended:*

ATLAS has recorded in total $\sim 27 \text{ fb}^{-1}$ of pp data!

- *We discovered a new particle:*

- *The discovery is **confirmed** in all most sensitive channels*

- *In the 4 lepton channel, 'observation' at 123.5 GeV with 4.1σ*

- *First measurements of its properties:*

- *The 4l lepton channel it's very important for the spin/CP measurement*

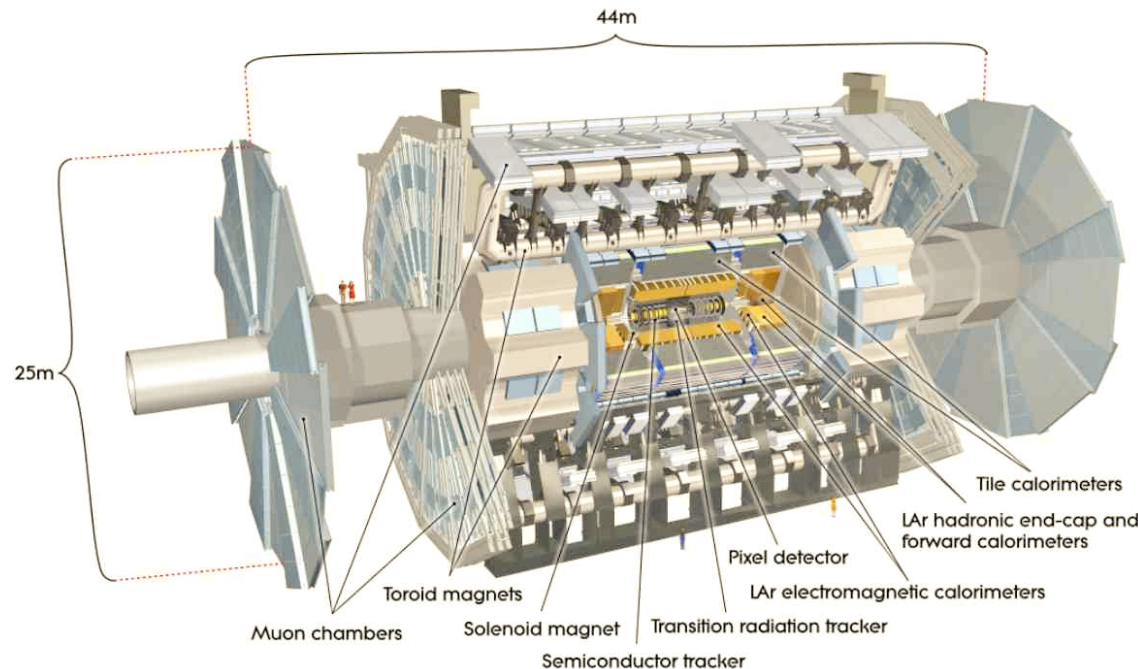
- *First indications that a **spin 2** scenario is **disfavored** (85% exclusion) by angular analysis, as well **as 0⁻** scenario (99% exclusion)*

BACKUP

The ATLAS experiment



It has been designed to study a large range of phenomena, from Higgs boson to beyond standard model searches.



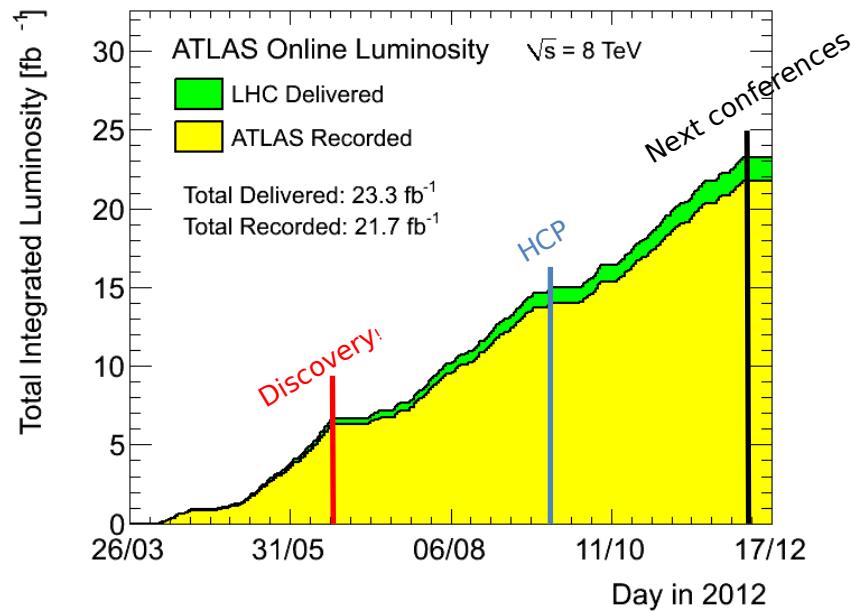
LHC is providing pp collisions since March 2010 at 7 TeV and March 2012 at 8 TeV.

The total integrated luminosity collected is

5 fb⁻¹ at 7 TeV

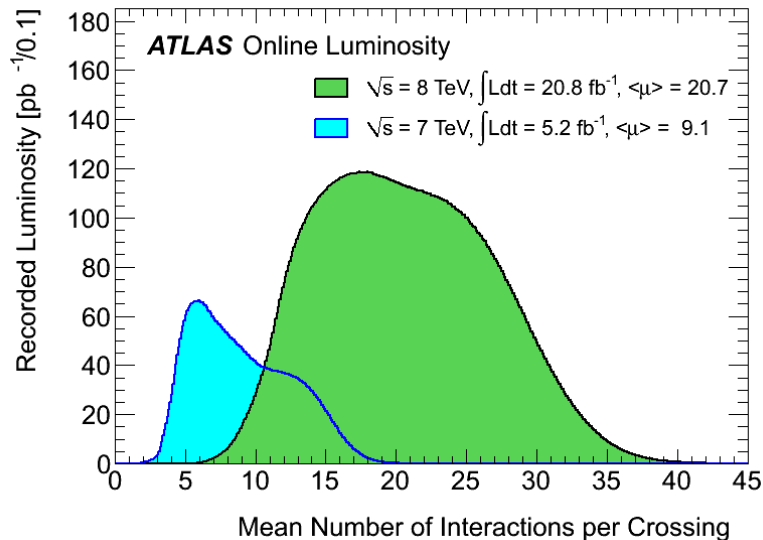
23 fb⁻¹ at 8 TeV

- **Inner Detector (ID)** → measures the momentum of charged particle
- **Calorimetric system** → measure the energy released by particles
- **Muon Spectrometer (MS)** → identifies and measures the momentum of muons

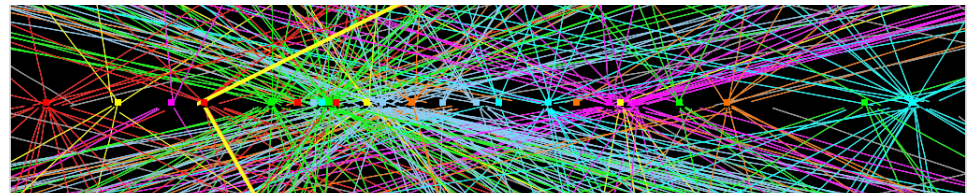


Performance of LHC:

- Proton-proton collider
@ $\sqrt{s} = 7$ (2011) and 8 (2012) TeV;
- Peak luminosity $7.7 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$;
- Integrated lumi delivered:
 $\sim 23 \text{ fb}^{-1}$ at 8 TeV and $\sim 5 \text{ fb}^{-1}$ at 7 TeV;
- Bunch crossing 50 ns.



A candidate Z boson event in the dimuon decay with **25 reconstructed vertices**:



$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Production and backgrounds

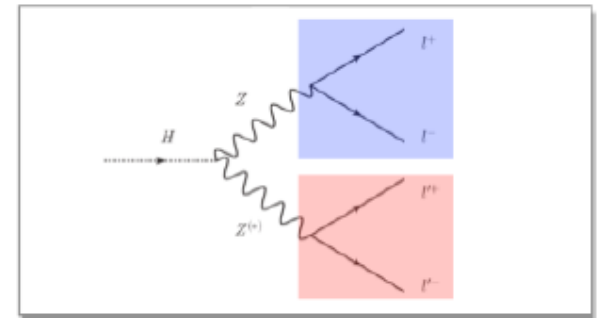
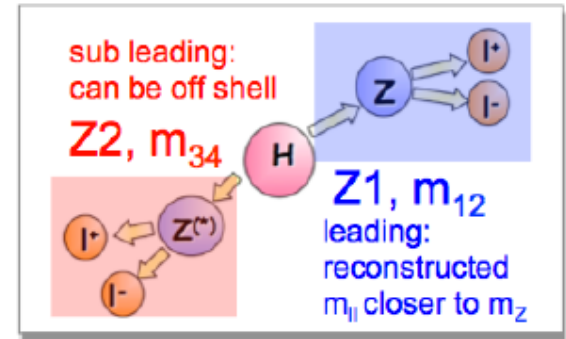
Signal:

- Production mode: gg , VBF , VH , WH

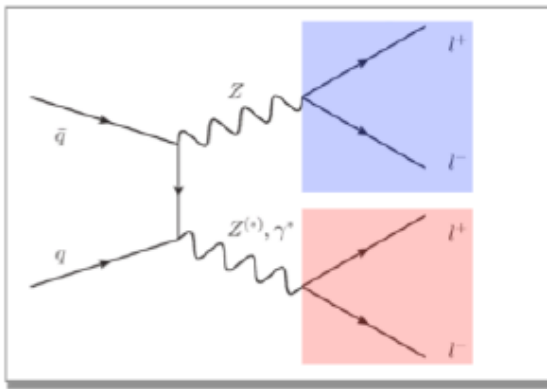
Backgrounds:

- Irreducible: $ZZ^{(*)}$
- Reducible for $m_{4l} < 2 \times m_Z$:
 - Zbb , $Z+jets$ and tt (reducible)
 - Suppressed with isolation and impact parameter cuts

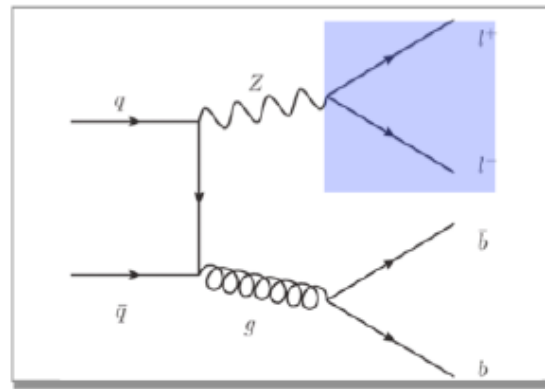
$$H \rightarrow ZZ^{(*)} \rightarrow 4l$$



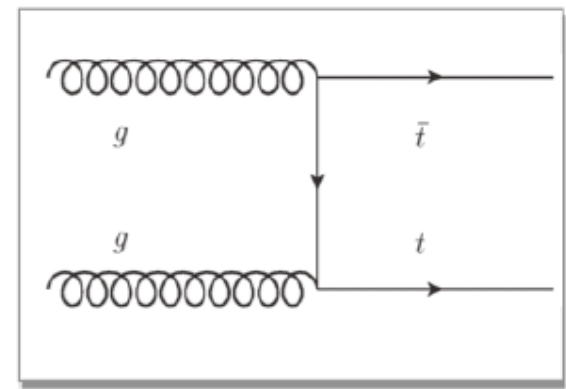
$ZZ^{(*)}$ background



$Z+jets$ background



tt background



$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Event Selection

Event Pre-selection

Electrons

“MultiLepton” quality GSF electrons with $E_T > 7$ GeV and $|\eta| < 2.47$

Muons

combined or segment-tagged muons with $p_T > 6$ GeV and $|\eta| < 2.7$

Maximum one calo-tagged or standalone muon

calo-tagged muons with $p_T > 15$ GeV and $|\eta| < 0.1$

standalone muons with $p_T > 6$ GeV, $2.5 < |\eta| < 2.7$ and $\Delta R > 0.2$ from closest segment-tagged

Event Selection

Kinematic Selection	<p>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 $50 \text{ GeV} < m_{12} < 106 \text{ GeV}$ Sub-leading di-lepton mass requirement $m_{\text{threshold}} < m_{34} < 115 \text{ GeV}$ Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} < 5 \text{ GeV}$ $\Delta R(\ell, \ell') > 0.10(0.20)$ for all same (different) flavour leptons in the quadruplet.</p>
Isolation	<p>Lepton track isolation ($\Delta R = 0.20$): $\Sigma p_T / p_T < 0.15$ 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 ($\Delta R = 0.20$): $\Sigma E_T / E_T < 0.15$</p>
Impact Parameter	<p>Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $d_0 / \sigma_{d_0} < 6.5$</p>
Significance	<p>For muons : $d_0 / \sigma_{d_0} < 3.5$</p>

M4l [GeV]	< 140	>190
M ₃₄ cut [GeV]	12.0	50.0

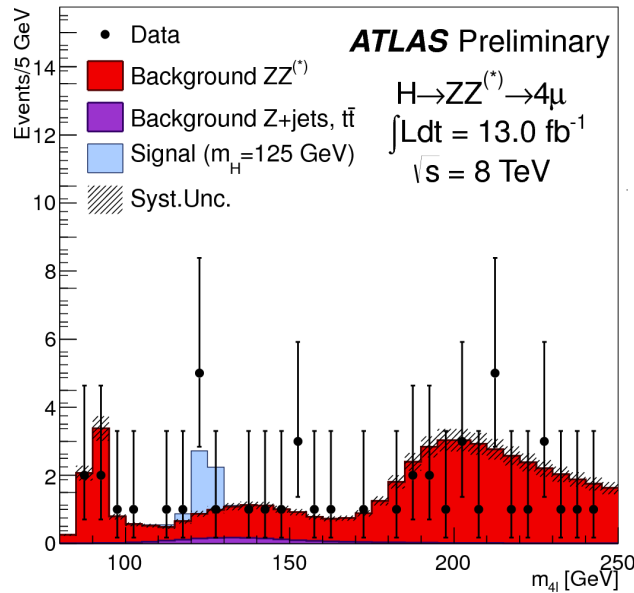
Overall acceptance
 $M_{\text{higgs}} \text{ 125 GeV}$



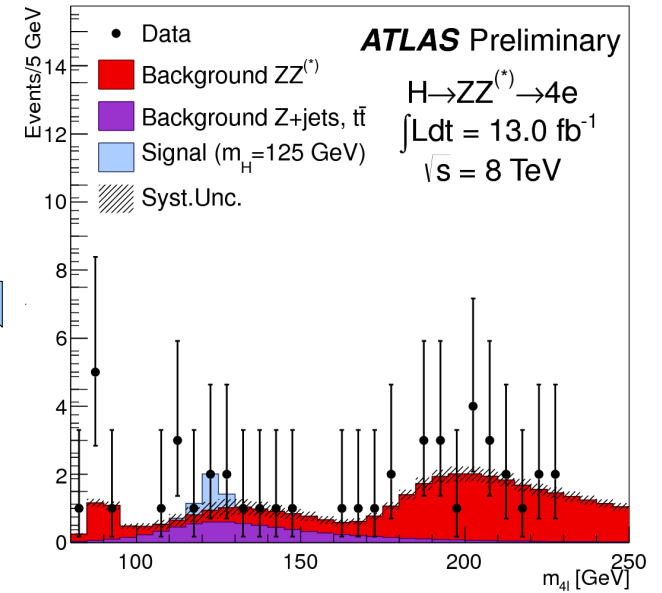
36% / 22% / 20%

4 μ / 2 μ 2e / 4e

$H \rightarrow ZZ^{(*)} \rightarrow 4l: M_{4l}, \text{ single channel}$

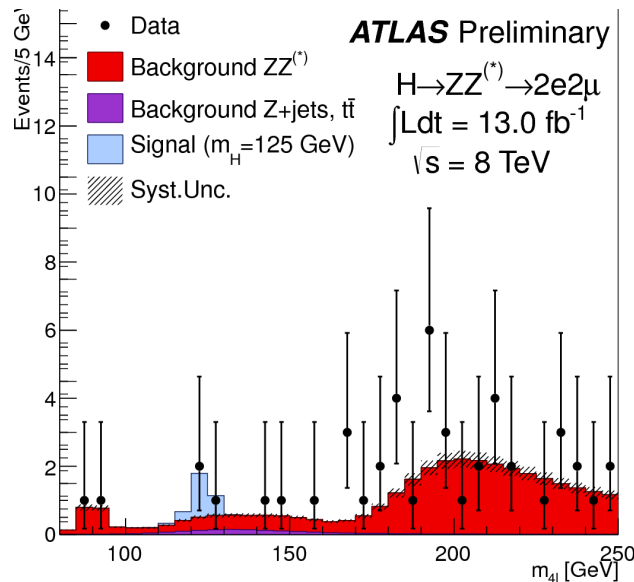


4μ channel

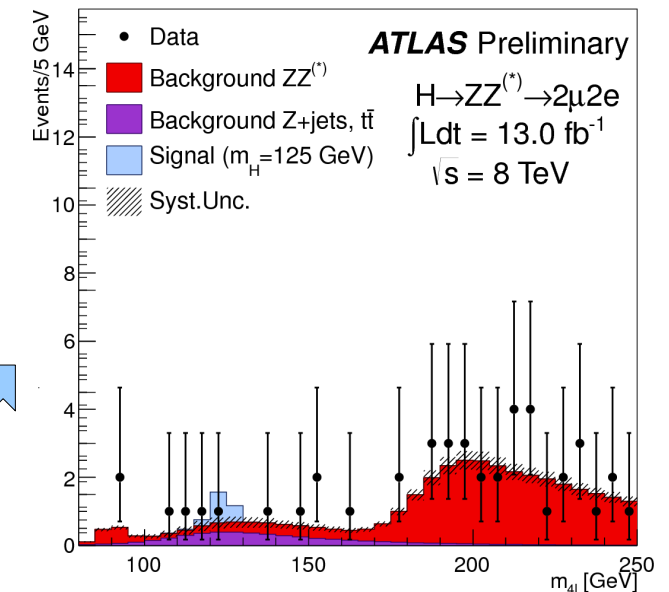


$4e$ channel

ZZ bkg
Z+jets, $t\bar{t}$ bkg
H (125) signal
Data 2012

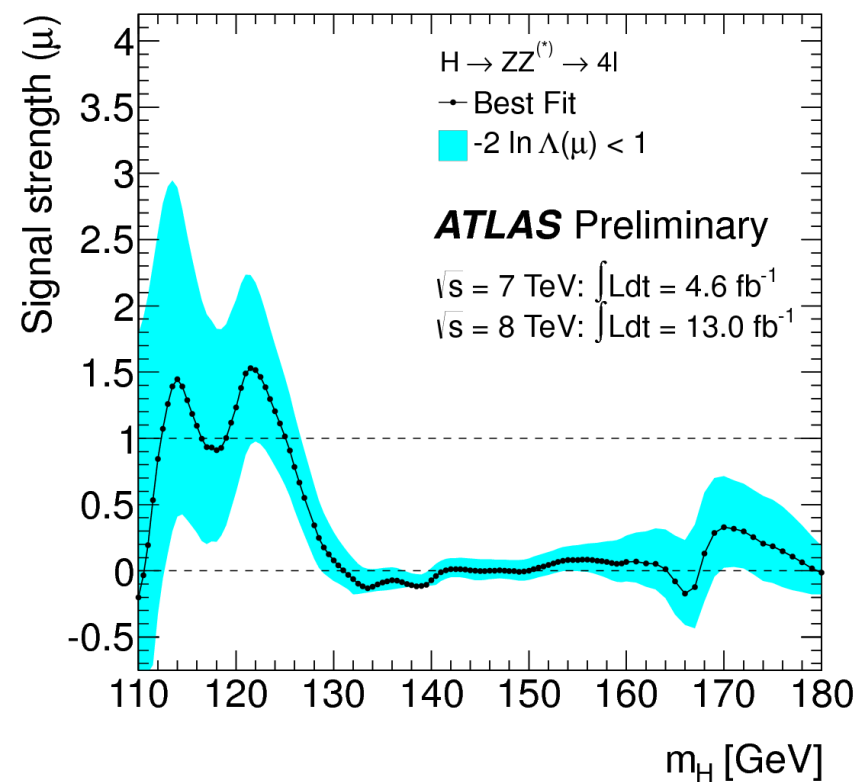
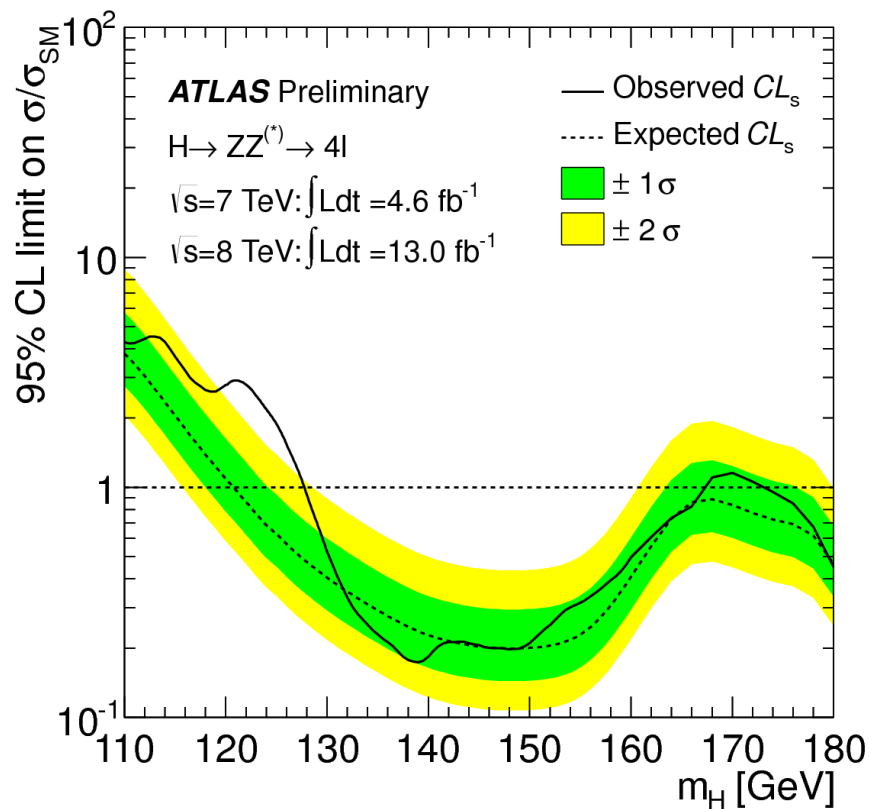


$2e2\mu$ channel

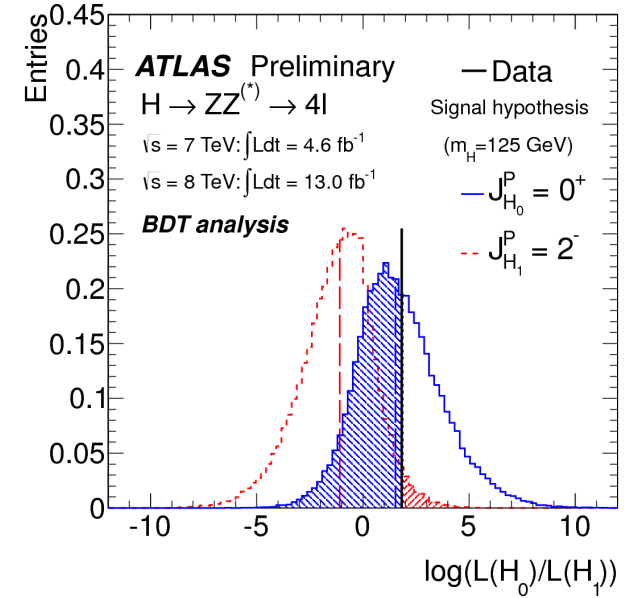
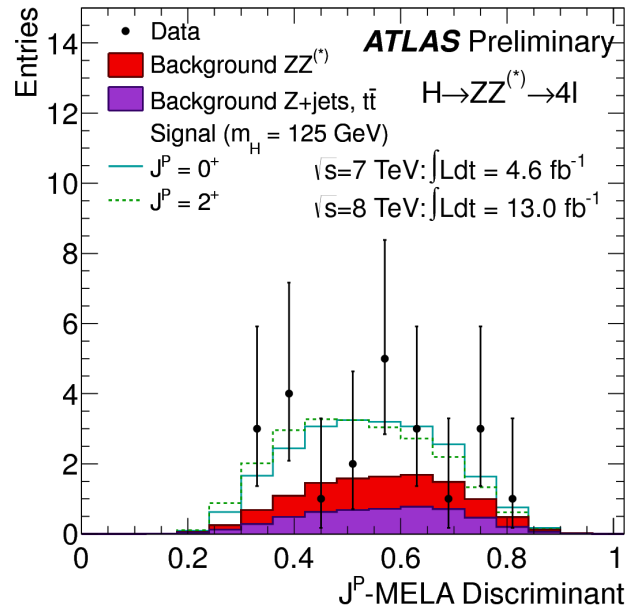
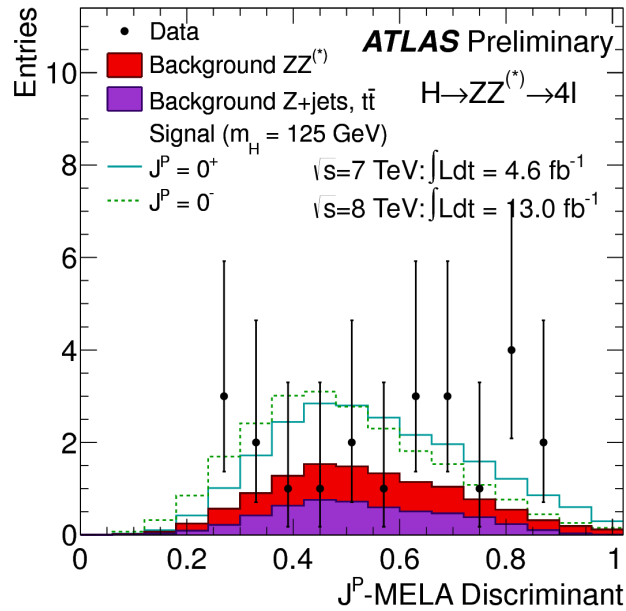


$2\mu2e$ channel

$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Local Significance



$H \rightarrow ZZ^{(*)} \rightarrow 4l$: Spin/CP Results



Tested J^P hypotheses for an assumed 0^+									
	0^-			2_m^+			2^-		
	expected	observed	obs 0^+	expected	observed	obs 0^+	expected	observed	obs 0^+
BDT analysis									
p_0 -value	0.041	0.011	0.69	0.20	0.16	0.57	0.046	0.029	0.56
σ	1.7	2.3	-0.50	0.84	0.99	-0.18	1.7	1.9	-0.15
J^P -MELA analysis									
p_0 -value	0.031	0.0028	0.76	0.18	0.17	0.53	0.04	0.025	0.56
σ	1.9	2.7	-0.72	0.91	0.97	-0.08	1.7	2.0	-0.15