

# Measuring the Higgs boson properties with the Higgs to 4-lepton final state

Run Number: 18279  
Event Number: 74566644  
Date: 2011-05-30, 06:54:29 CET

EtCut > 0.3 GeV  
PtCut > 2.0 GeV  
Vertex Cuts:  
Z direction < 1cm  
Rphi < 1cm

Muon: blue  
Electron: pink  
Cells: Fill



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S**

**BROOKHAVEN**  
NATIONAL LABORATORY

**Eleni Mountricha**

**Brookhaven National Laboratory**

US LHC Users Organization Annual Meeting  
November 6-8, 2013

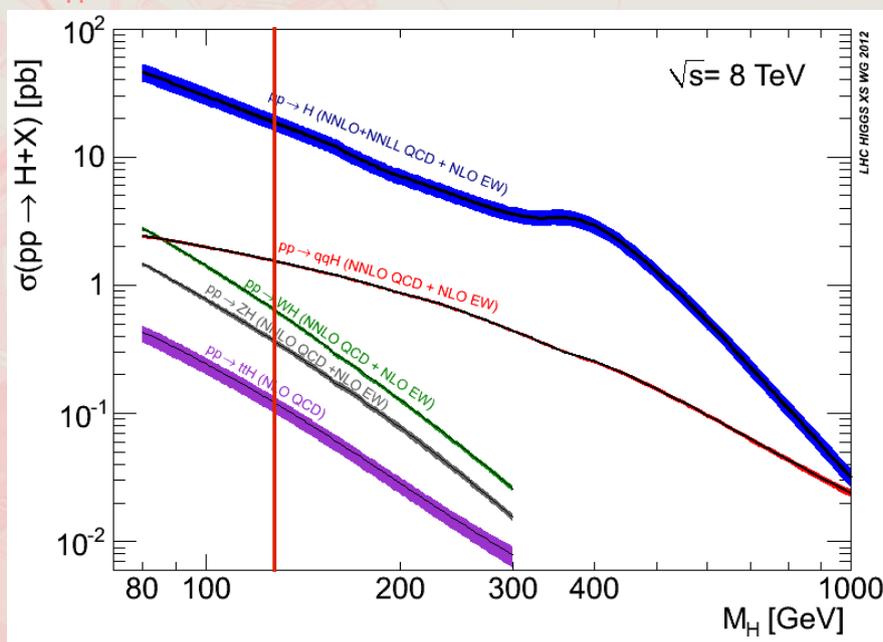
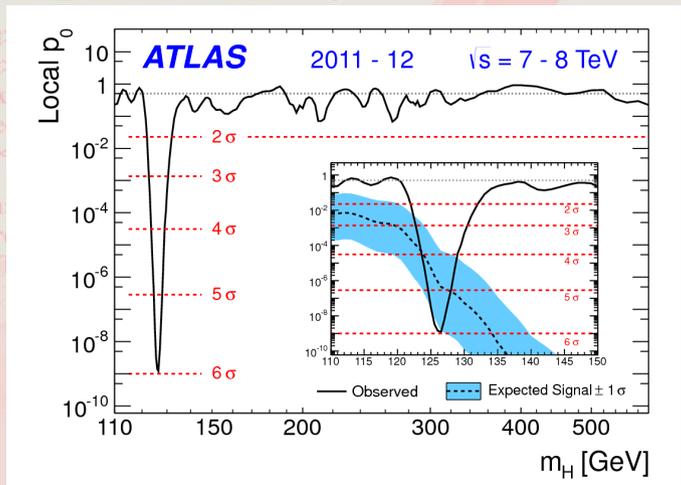
# Introduction

PLB 716(2012) 1-29

<http://arxiv.org/abs/1207.7214>

Discovery of the Higgs boson at the LHC  
Study properties to validate the SM “title”

$[m_H = 125.5 \text{ GeV}, 21.8 \text{ pb} @ 8 \text{ TeV}]$



ggF: 19 pb

VBF: 1.6 pb

VH: 1.1 pb

ttH: 0.1 pb

## Properties studies

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

✓ Mass

✓ Couplings

✓ Spin/CP

<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections>

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

$\sigma \times \text{BR} \sim 2.5 \text{ fb} (m_H = 125.5 \text{ GeV})$

**110 < m<sub>H</sub> < 1000 GeV**

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

Run Number: 182796,  
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**H → Z(l)Z(l'):**  
2 OS SF isolated lepton (e/μ) pairs  
[p<sub>T</sub>(l<sub>1</sub>, l<sub>2</sub>, l<sub>3</sub>, l<sub>4</sub>) > 20, 15, 10, 7/6 GeV]

EtCut > 0.3 GeV  
PtCut > 2.0 GeV  
Vertex Cuts:  
Z direction < 1cm  
Rphi < 1cm

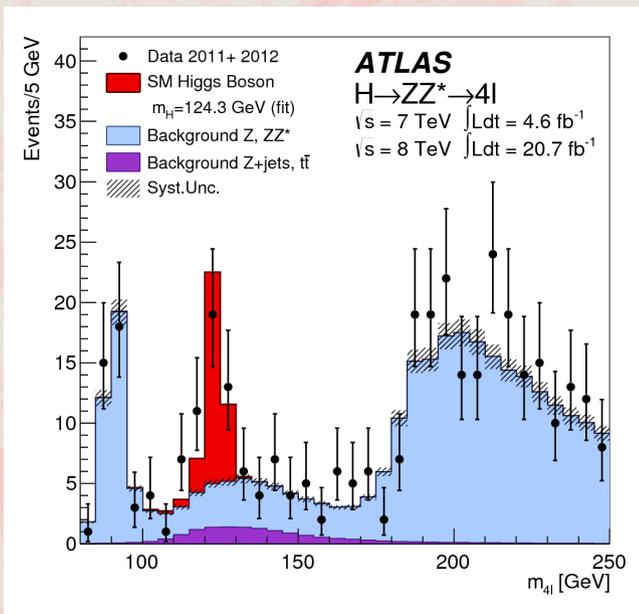
Discriminant: m<sub>4l</sub>

S/B: 1.4 for  
m<sub>H</sub> = 125 GeV;  
mass resolution:  
1.6 - 2.4 GeV

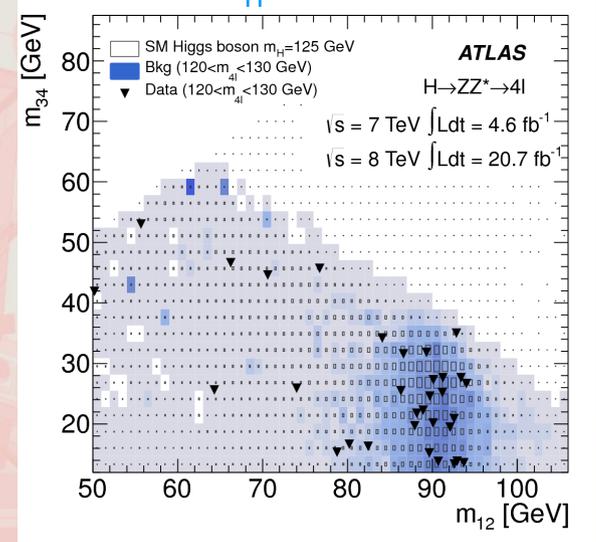
Background:  
ZZ, Z-jets, tt̄

Background  
estimated from control regions and data

Categories in lepton flavor  
[4μ, 2μ2e, 2e2μ, 4e]



**120 < m<sub>H</sub> < 130 [GeV]**



**32 observed events**  
**15.9 ± 2.1 expected [m<sub>H</sub> = 125 GeV]**  
**11.1 ± 1.3 background expected**

# Mass measurement

For a given  $m_H$ , properties are well defined

Resolution improvements:

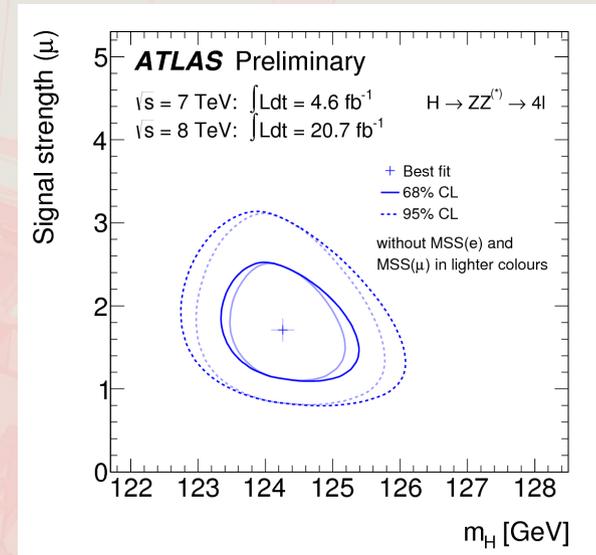
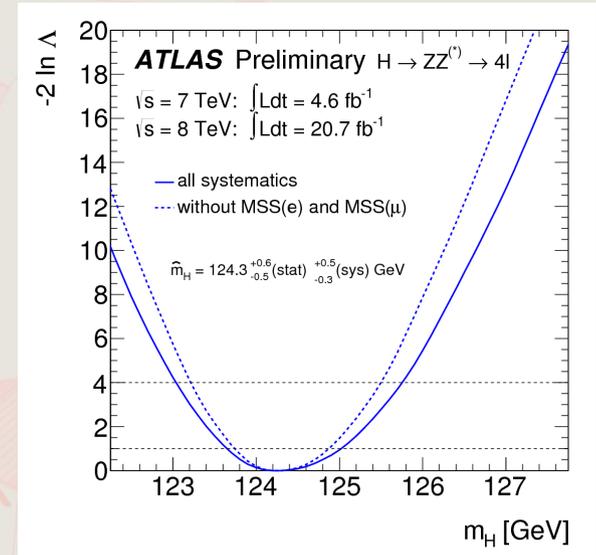
- Final State Radiation (FSR) photon correction on leading  $\mu$  pairs (~4% of  $4\mu$  events with 85% purity and 70% efficiency)
- Z-mass constrained kinematic fit on leading pairs (12 - 19% improvement on resolution)

Best fit mass:

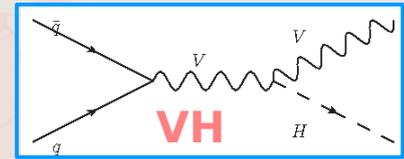
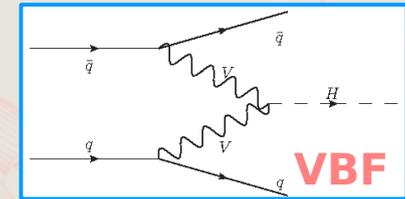
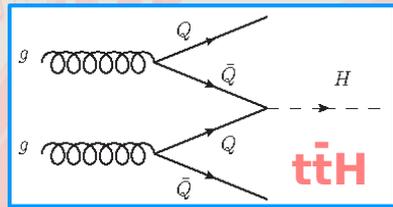
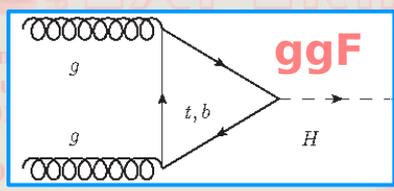
**$124.3^{+0.6}_{-0.5}$  (stat)  $^{+0.5}_{-0.3}$  (syst) GeV**

Signal strength:  **$1.7^{+0.5}_{-0.4}$** , for  $m_H = 124.3$  GeV  
 **$[1.5 \pm 0.4]$** , for  $m_H = 125.5$  GeV

Dominant contribution to the systematic uncertainty from theory (up to 20%) and electron ID/reconstruction ( $\leq 4\%$ )



# Couplings



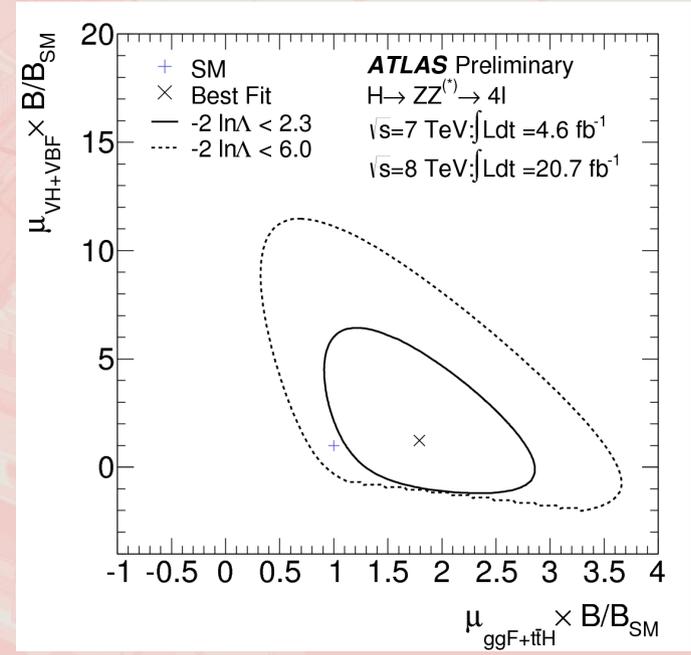
Run Num:  
Event Num:  
Date: 20  
EtCut>0  
PtCut>2.0 GeV  
Vertex Cuts:  
Z direction  
Rphi <1cm  
Muon: blue  
Electron: Black  
Cells: T1, T2, T3

Disentangle production mechanisms: probe fermion vs vector boson couplings; ratio probes production only (BR cancels out)

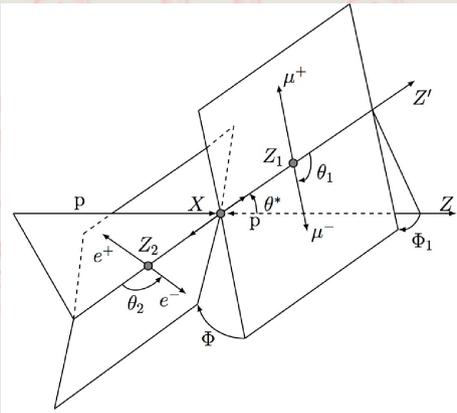
3 production-enriched categories:

- VBF-like  
two jets [ $p_T > 25/30 \text{ GeV}$ ,  $m_{jj} > 350 \text{ GeV}$ ]  
with large  $\eta$  separation  
**1 event** [ $125 \pm 5 \text{ GeV}$ ]
- VH-like  
additional leptons [ $p_T > 8 \text{ GeV}$ ]
- and ggF-like  
the rest  
**31 events** [ $125 \pm 5 \text{ GeV}$ ]

Rates consistent with SM expectation within  $2\sigma$



# Spin/CP



Run Number: 18  
Event Number: 7  
Date: 2011-05-30

EtCut > 0.3 GeV  
PtCut > 2.0 GeV  
Vertex Cuts:  
Z direction < 1 cm  
Rphi < 1 cm  
Muon: blue  
Electron: red  
Cell: 1 cm, 1 cm

## Ideal channel to study spin/CP

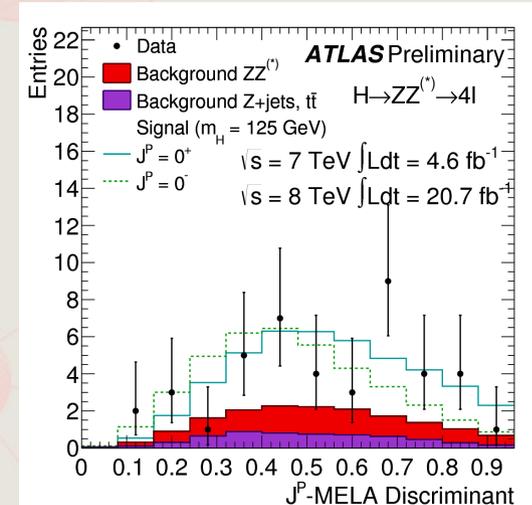
- Complete reconstruction of the event topology
- High S/B ratio
- Several discriminants: five production and decay angles,  $m_{12}$ ,  $m_{34}$

## Two approaches:

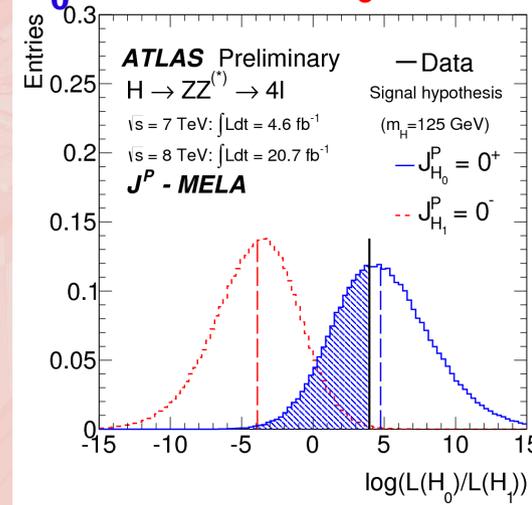
- BDT for each hypothesis
- ME corrected for acceptance and pairing ( $J^P$  MELA)

Compare SM spin- $0^+$  hypothesis to spin- $0^-$ , spin- $1^\pm$ , spin- $2_m^+$  (“graviton-like” model with minimal couplings).

[ $115 < m_H < 130$  GeV]



$p_0 = 40.0\%$     $p_0 = 0.2\%$



Compatibility with SM spin- $0^+$ ; spin- $0^-$  and spin- $1^+$  states are excluded at the 97.8% CL or higher using  $CL_s$  in favour of spin- $0^+$

# Conclusions

Studies on the properties of the Higgs boson in the  $H \rightarrow ZZ^{(*)} \rightarrow 4l$  channel in ATLAS

Run Number: 261123  
 Event Number: 74566644  
 Date: 2011-09-01

EtCut > 0.3 GeV  
 PtCut > 2.0 GeV  
 Vertex Cuts:  
 Z direction < 1cm  
 Rphi < 1cm

Muon: blue  
 Electron: Black  
 Cells: Tiles, EMC

- Mass measurement: limited by statistics and systematics; more work and data needed

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

- Couplings: categories enriched in exclusive production mechanisms; rates within  $2\sigma$  the SM expectation
- Spin/Parity: SM spin- $0^+$  hypothesis has been compared to alternative models; the results favour  $J^P = 0^+$

ATLAS combination on Higg boson properties measurements:

<http://arxiv.org/abs/1307.1432>

<http://arxiv.org/abs/1307.1427>



# Backup

Run Number: 182796,  
Event Number: 74566644  
Date: 2011-05-30, 06:54:29 CET

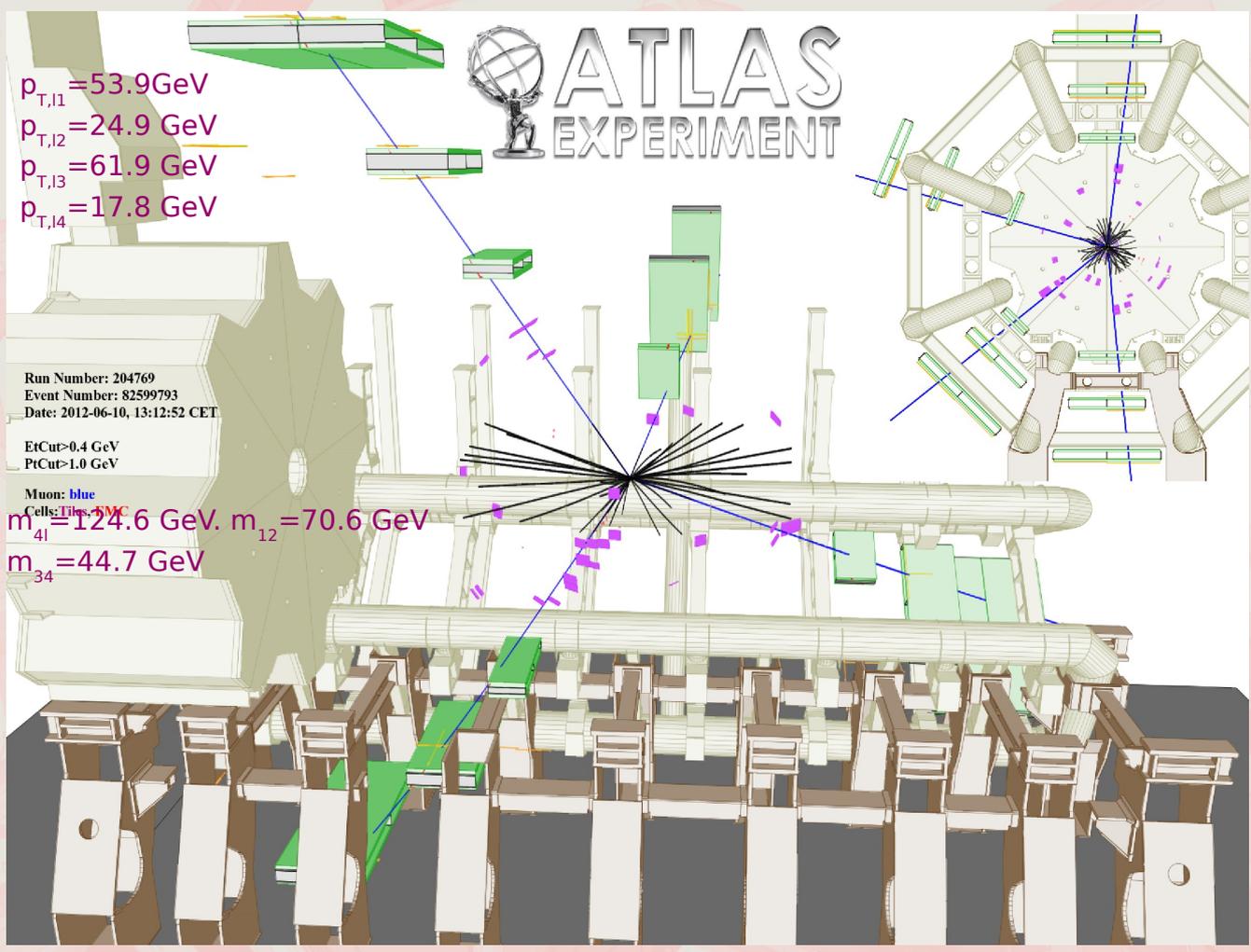
EtCut > 0.3 GeV  
PtCut > 2.0 GeV  
Vertex Cuts:  
Z direction < 1cm  
Rphi < 1cm

Muon: blue  
Electron: Black  
Cells: Tiles, EMC

## Event display

Run Number: 182796,  
Event Number: 74566644  
Date: 2011-05-30, 06:54:29 CET

EtCut>0.3 GeV  
PtCut>2.0 GeV  
Vertex Cuts:  
Z direction <1cm  
Rphi <1cm  
  
Muon: blue  
Electron: Black  
Cells: Tiles, EMC



$p_{T,11} = 53.9 \text{ GeV}$   
 $p_{T,12} = 24.9 \text{ GeV}$   
 $p_{T,13} = 61.9 \text{ GeV}$   
 $p_{T,14} = 17.8 \text{ GeV}$

Run Number: 204769  
Event Number: 82599793  
Date: 2012-06-10, 13:12:52 CET

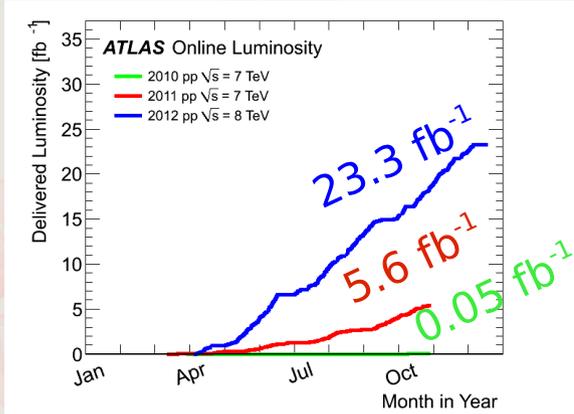
EtCut>0.4 GeV  
PtCut>1.0 GeV

Muon: blue  
Cells: Tiles, EMC

$m_{41} = 124.6 \text{ GeV}$ ,  $m_{12} = 70.6 \text{ GeV}$   
 $m_{34} = 44.7 \text{ GeV}$

# LHC and ATLAS performance

## Outstanding LHC performance



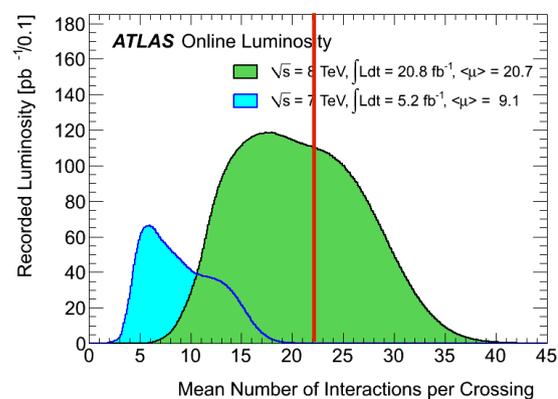
Peak  $L_{inst} : 7.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

## Excellent ATLAS performance

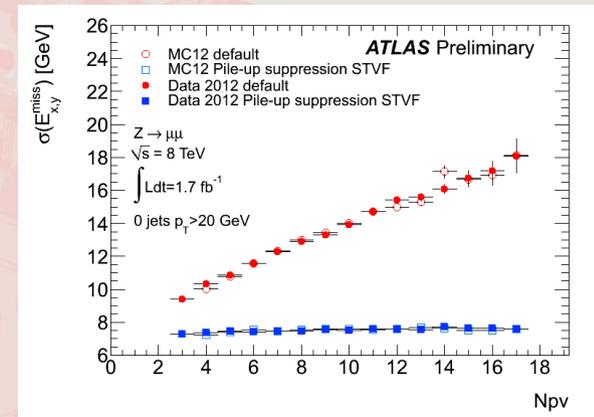
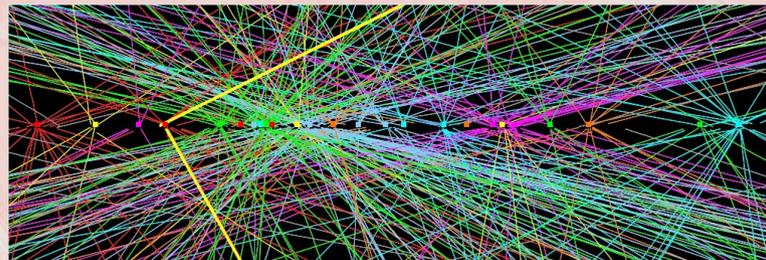
Data-taking efficiency: 93%

Good quality data fraction used for analysis: 95.8%

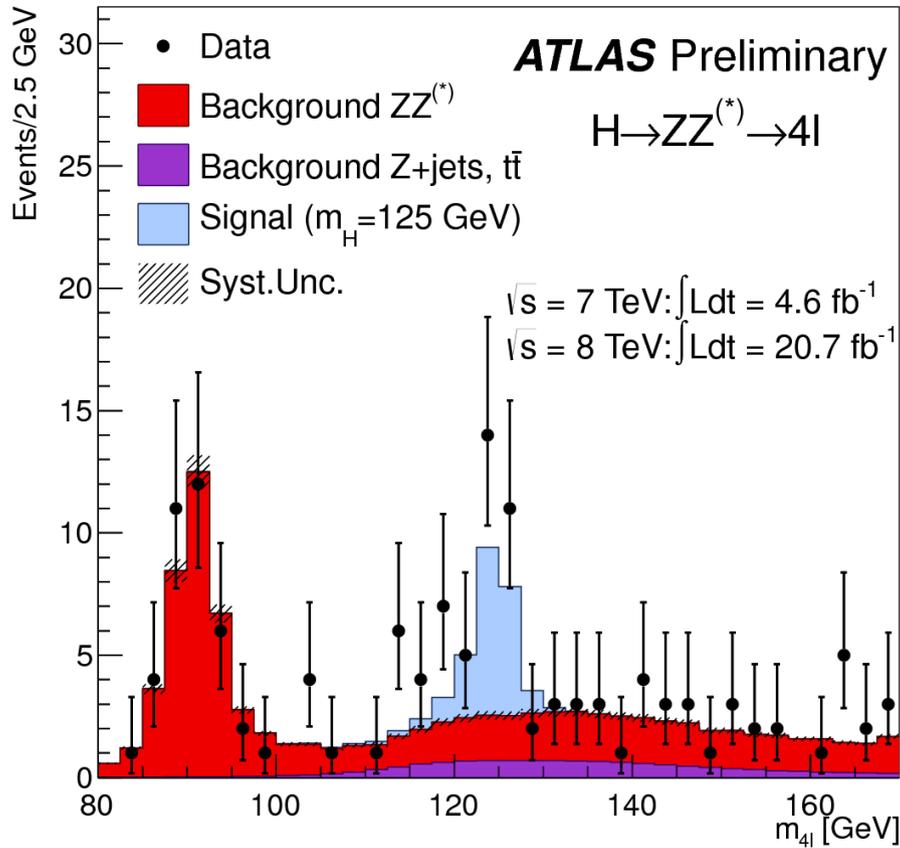
Challenge: harsh pile-up conditions  
[trigger, computing, reconstruction of physics objects]



## Z → μμ event with 25 reconstructed vertices

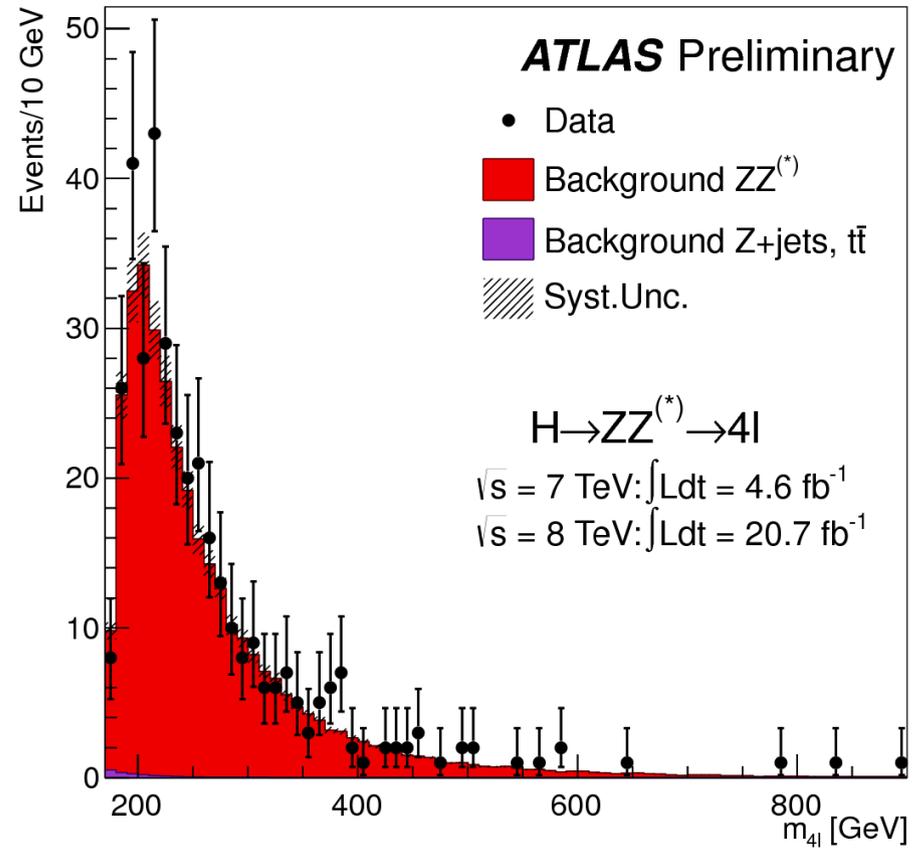


# ATLAS EXPERIMENT $H \rightarrow ZZ^{(*)} \rightarrow 4l$ $m_{4l}$ distribution



$100 < m_{4l} < 160$  GeV

expected total bkg	$53.1 \pm 2.2$
expected signal (125 GeV)	$18.2 \pm 2.4$
data	83



$m_{4l} > 160$  GeV

expected total bkg	$344.0 \pm 13.8$
expected signal (125 GeV)	-
data	376

# H $\rightarrow$ ZZ<sup>(\*)</sup> $\rightarrow$ 4l yields

	4 $\mu$		2 $\mu$ 2e/2e2 $\mu$		4e	
	low mass	high mass	low mass	high mass	low mass	high mass
$\sqrt{s} = 8 \text{ TeV}$ integrated luminosity 20.7 fb <sup>-1</sup>						
ZZ <sup>(*)</sup>	12.4 $\pm$ 0.6	92.6 $\pm$ 6.7	14.7 $\pm$ 0.9	144 $\pm$ 11	5.4 $\pm$ 0.5	55.9 $\pm$ 4.5
Z, Zbb $\bar{\bar{}}$ , and t $\bar{t}$	2.0 $\pm$ 0.6	0.5 $\pm$ 0.2	6.1 $\pm$ 1.5	1.5 $\pm$ 0.4	2.5 $\pm$ 0.6	0.6 $\pm$ 0.2
total Background	14.3 $\pm$ 0.8	92.0 $\pm$ 6.6	20.8 $\pm$ 1.7	143 $\pm$ 11	7.9 $\pm$ 0.8	55.8 $\pm$ 4.4
data	27	93	28	169	13	55
$m_H = 123 \text{ GeV}$	4.4 $\pm$ 0.6		5.4 $\pm$ 0.8		2.2 $\pm$ 0.4	
$m_H = 125 \text{ GeV}$	5.8 $\pm$ 0.7		7.0 $\pm$ 0.9		2.9 $\pm$ 0.4	
$m_H = 127 \text{ GeV}$	6.7 $\pm$ 0.9		8.4 $\pm$ 1.2		3.4 $\pm$ 0.5	
$\sqrt{s} = 7 \text{ TeV}$ integrated luminosity 4.6 fb <sup>-1</sup>						
ZZ <sup>(*)</sup>	2.2 $\pm$ 0.1	16.8 $\pm$ 1.2	2.5 $\pm$ 0.2	26.6 $\pm$ 2.0	0.8 $\pm$ 0.1	9.4 $\pm$ 0.8
Z, Zbb $\bar{\bar{}}$ , and t $\bar{t}$	0.2 $\pm$ 0.1	0.05 $\pm$ 0.02	2.4 $\pm$ 0.5	0.6 $\pm$ 0.1	2.0 $\pm$ 0.5	0.53 $\pm$ 0.1
total Background	2.4 $\pm$ 0.1	16.7 $\pm$ 1.2	4.9 $\pm$ 0.6	26.8 $\pm$ 2.0	2.8 $\pm$ 0.5	9.7 $\pm$ 0.7
data	8	23	5	23	2	13
$m_H = 123 \text{ GeV}$	0.7 $\pm$ 0.1		0.8 $\pm$ 0.1		0.3 $\pm$ 0.1	
$m_H = 125 \text{ GeV}$	1.0 $\pm$ 0.1		1.1 $\pm$ 0.2		0.4 $\pm$ 0.1	
$m_H = 127 \text{ GeV}$	1.0 $\pm$ 0.2		1.2 $\pm$ 0.2		0.4 $\pm$ 0.1	

low mass:  
100 < m<sub>4l</sub> < 160 GeV  
high mass:  
m<sub>4l</sub> > 160 GeV

# H $\rightarrow$ ZZ<sup>(\*)</sup> $\rightarrow$ 4l expectation yields

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EtCut > 0.3 GeV  
 PtCut > 2.0 GeV  
 Vertex Cuts:  
 Z direction < 1cm  
 Rphi < 1cm

Muon: blue  
 Electron: black  
 Cells: Tiles, EMC

category	$gg \rightarrow H, q\bar{q}/gg \rightarrow t\bar{t}H$	$qq' \rightarrow Hqq'$	$q\bar{q} \rightarrow W/ZH$	ZZ <sup>(*)</sup>
$\sqrt{s} = 8 \text{ TeV}$				
ggF-like	13.5	0.79	0.65	320.4
VBF-like	0.28	0.43	0.01	3.58
VH-like	0.06	-	0.14	0.69
$\sqrt{s} = 7 \text{ TeV}$				
ggF-like	2.20	0.14	0.11	57.5
VBF-like	0.03	0.06	-	0.44
VH-like	0.01	-	0.03	0.25

# A Toroidal LHC Apparatus

## Inner Detector

( $|\eta| < 2.5$ ,  $B=2T$ ):  
Si Pixels, Si strips,  
Transition Radiation  
Tracker.  
Precise tracking and  
vertexing,  
 $e/\pi$  separation.  
 $\sigma(p_t)/p_t$ :  
 $\sim 0.05\% p_t(\text{GeV}) \pm 1\%$

## EM calorimeter:

Pb-LAr Accordion.  
 $e/\gamma$  trigger,  
identification and  
measurement.  
 $\sigma(E)/E$ :  
 $\sim 10\%/\sqrt{E} \pm 0.7\%$

## Hadronic calorimeter ( $|\eta| < 4.9$ ):

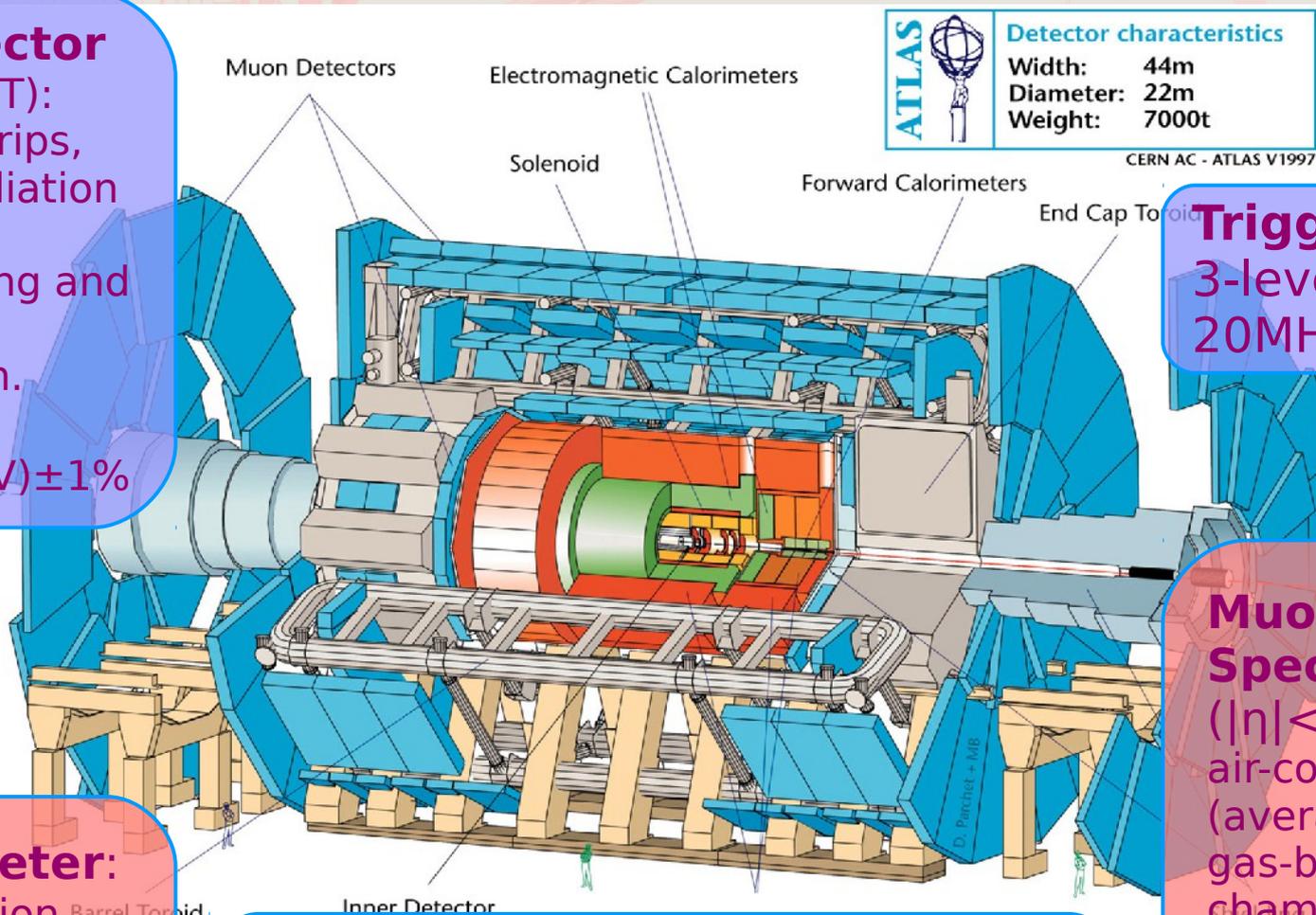
Fe/scintillator Tiles (central), Cu/W-LAr.  
Trigger and measurement of jets and  
missing  $E_T$ .  
 $\sigma(E)/E$ :  $\sim 50\%/\sqrt{E} \pm 3\%$

## Trigger:

3-level, rate:  
 $20\text{MHz} \rightarrow \sim 400\text{Hz}$

## Muon Spectrometer

( $|\eta| < 2.7$ ):  
air-core toroids  
(average 0.5T) with  
gas-based muon  
chambers. Muon  
trigger and  
measurement  
 $\sigma(p_t)/p_t$ :  
 $< 10\%$  up to  $\sim 1\text{ TeV}$

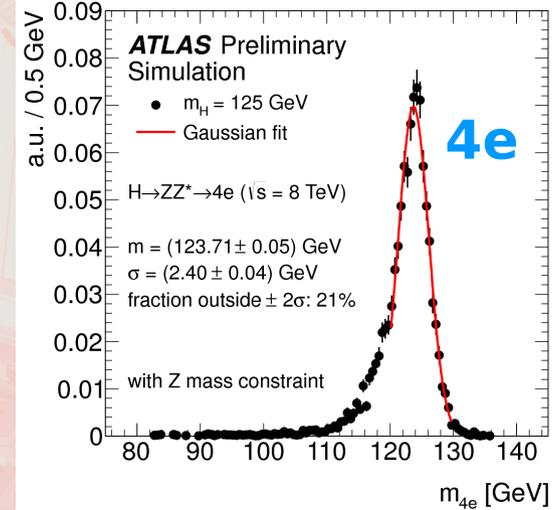
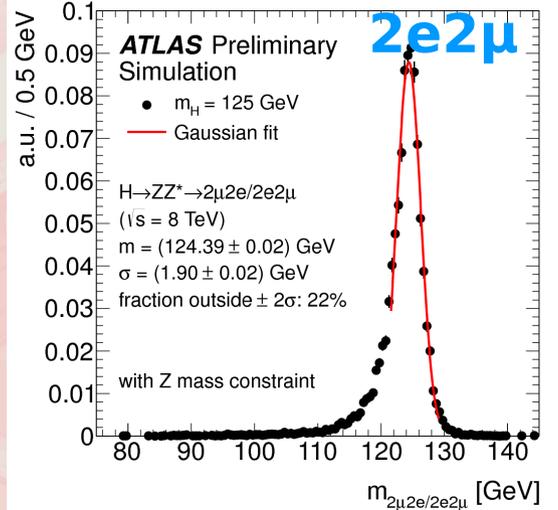
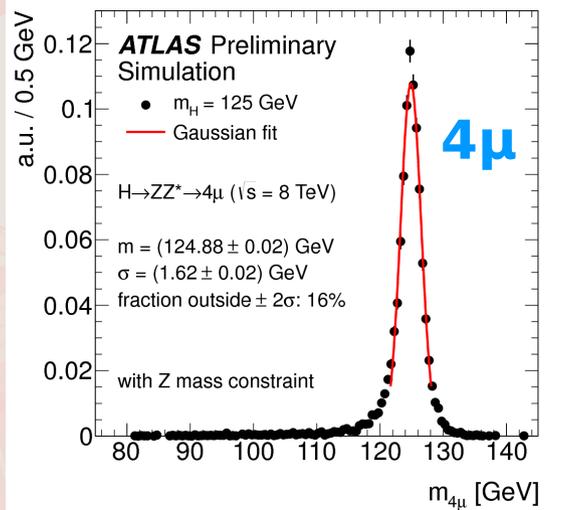
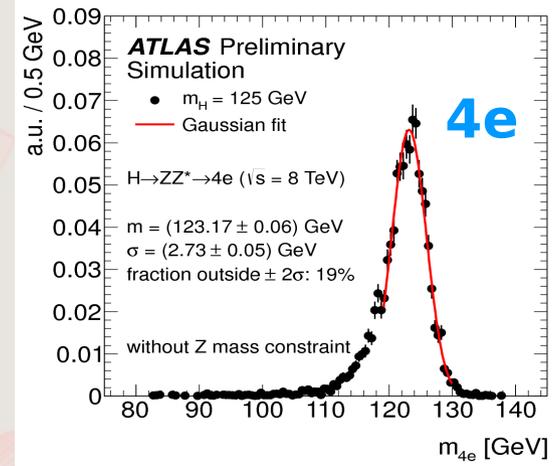
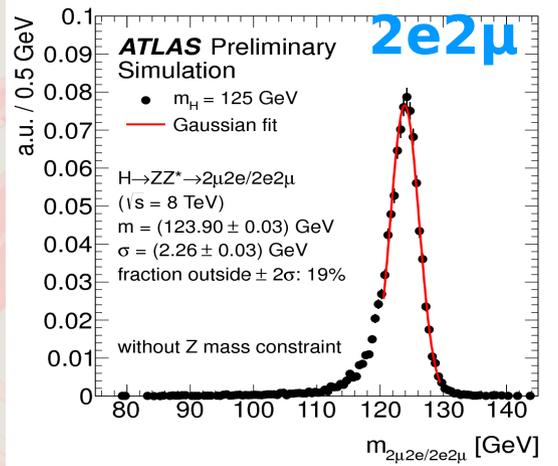
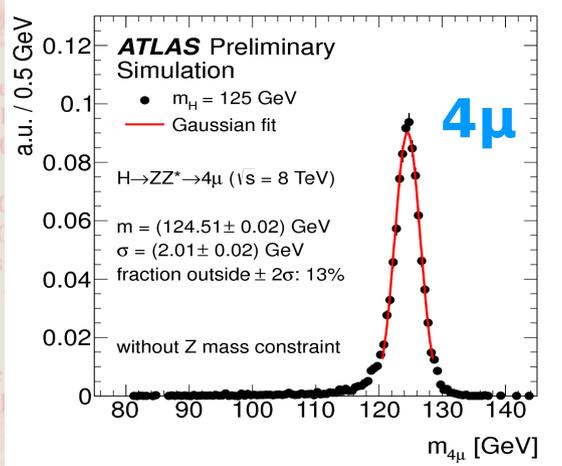


### Detector characteristics

Width: 44m  
Diameter: 22m  
Weight: 7000t

CERN AC - ATLAS V1997

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



$m_{4l}$ : main discriminant;  
 resolution crucial for sensitivity;  
 dominated by detector resolution  
 for low  $m_H$

channel	$m$ (GeV)	$\sigma$ (GeV)
4 $\mu$	124.9	1.62
2e2 $\mu$	124.4	1.90
4e	123.7	2.40

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

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normalized

- ZZ

- ✓ main background
- ✓ irreducible

- ttbar

- ✓ leptons from b jets

- Z+heavy flavor jets (Zbb)

- ✓ leptons from b jets

- Z+light jets

- ✓ misidentified jets

- WZ

- Data-driven estimation:

- ✓ Control regions by relaxing/inverting selection
- ✓ Extrapolate to signal region using data or MC x-checked with data

ll+μμ

ll+ee

normalized data driven

# H $\rightarrow$ ZZ<sup>(\*)</sup> $\rightarrow$ 4l reducible background summary

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Z direction < 1cm  
Rphi < 1cm

Muon: blue  
Electron: black  
Cells: Fides, EMC

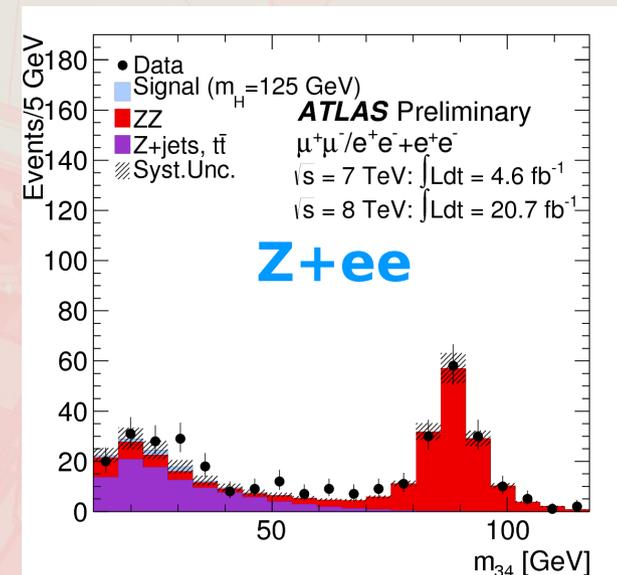
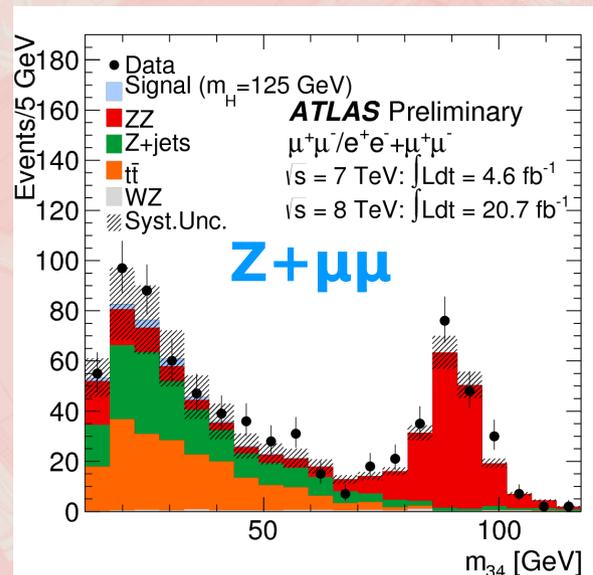
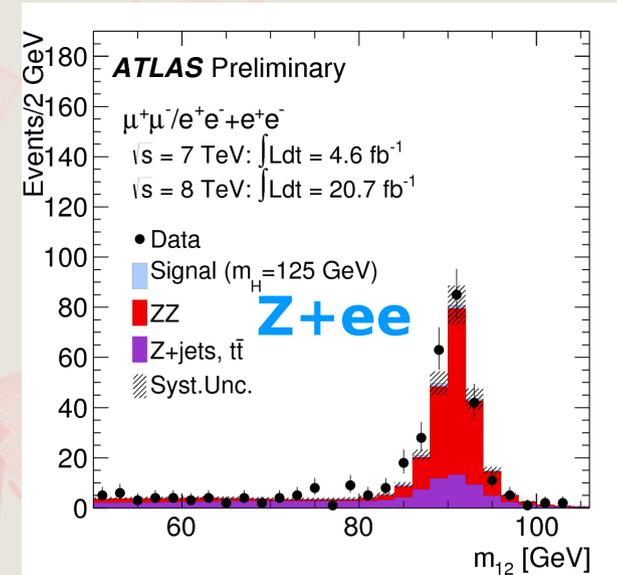
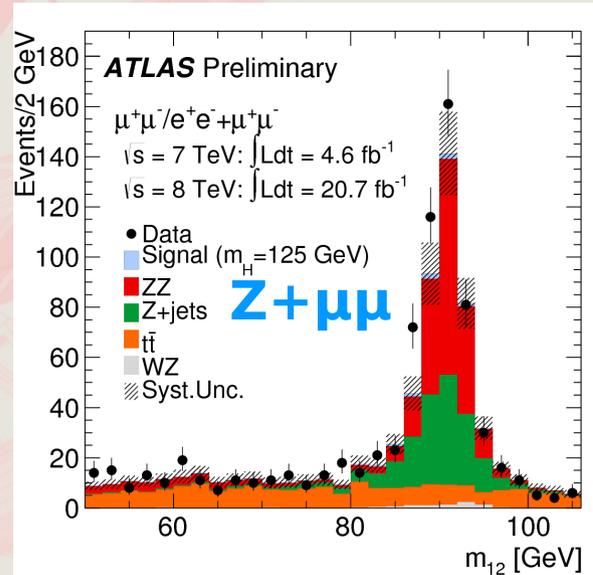
method	estimate at $\sqrt{s} = 8 \text{ TeV}$	estimate at $\sqrt{s} = 7 \text{ TeV}$
	$4\mu$	$4\mu$
$m_{12}$ fit: Z + jets contribution	$2.4 \pm 0.5 \pm 0.6^\dagger$	$0.22 \pm 0.07 \pm 0.02^\dagger$
$m_{12}$ fit: $t\bar{t}$ contribution	$0.14 \pm 0.03 \pm 0.03^\dagger$	$0.03 \pm 0.01 \pm 0.01^\dagger$
$t\bar{t}$ 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 $e\mu + \mu\mu$	$0.12 \pm 0.07 \pm 0.005$	-
	$2\mu2e$	$2\mu2e$
$ll + e^\pm e^\mp$ relaxed cuts	$5.2 \pm 0.4 \pm 0.5^\dagger$	$1.8 \pm 0.3 \pm 0.4$
$ll + e^\pm e^\mp$ inverted cuts	$3.9 \pm 0.4 \pm 0.6$	-
$3l + l$ (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
	$4e$	$4e$
$ll + e^\pm e^\mp$ relaxed cuts	$3.2 \pm 0.5 \pm 0.4^\dagger$	$1.4 \pm 0.3 \pm 0.4$
$ll + e^\pm e^\mp$ inverted cuts	$3.6 \pm 0.6 \pm 0.6$	-
$3l + l$ (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

# H $\rightarrow$ ZZ<sup>(\*)</sup> $\rightarrow$ 4l control plots

Run Number: 182796,  
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 Date: 2011-05-28 06:54:39 CET

EtCut > 0.3 GeV  
 PtCut > 2.0 GeV  
 Vertex Cuts:  
 Z direction < 0.05  
 Rphi < 1cm  
 Muon: blue  
 Electron: Black  
 Cells: Tiles, E

- Control region: isolation/IP requirements relaxed in the subleading dileptons
- Data-driven normalization of the background MC expectation



# H $\rightarrow$ ZZ<sup>(\*)</sup> $\rightarrow$ 4l systematics

- On the measurement of the signal rate

Run Number: 182796,  
Event Number: 74566644  
Date: 2011-05-30, 06:54:21 CERN  
✓ Luminosity [1.8%/3.6% 2011/2012]

EtCut > 0.3 GeV  
PtCut > 2.0 GeV  
Vertex Cuts:  
Z direction < 1cm  
Rphi < 1cm  
✓ Signal cross section [8%/8%/4% QCD scale/PDF gg/PDF qq]

✓ ZZ<sup>(\*)</sup> cross section & shape [5%/8%/4% QCD scale/PDF gg/PDF qq]

✓ Reducible background estimation & shape

✓ Electron ID and reconstruction efficiency

[signal: 9.4%/8.7%/2.4 4e/2 $\mu$ 2e/2e2 $\mu$  @125 GeV; ZZ<sup>(\*)</sup>: shape]

✓ Muon ID and reconstruction eff [<1%]

- On the mass measurement

✓ Electron energy scale and resolution [<0.4%]

✓ Muon momentum scale and resolution [<0.1%]

- Categories

✓ VBF: JES <14%; Underlying event <19%; theory <35%

✓ VH: VH-specific cuts <8%; theory <30%

# H $\rightarrow$ ZZ<sup>(\*)</sup> $\rightarrow$ 4l yields [120-130]

Run Number: 2026  
 Event Number: 74566644  
 Date: 2011-05-30 06:54:29 CET

**120 < m<sub>4l</sub> < 130 GeV**

EtCut > 0.3 GeV  
 PtCut > 2.0 GeV  
 Vertex Cuts:  
 Z direction < 1cm  
 Rphi < 1cm

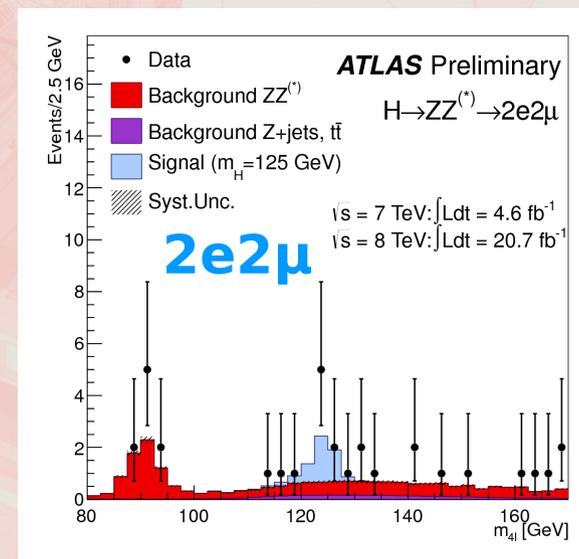
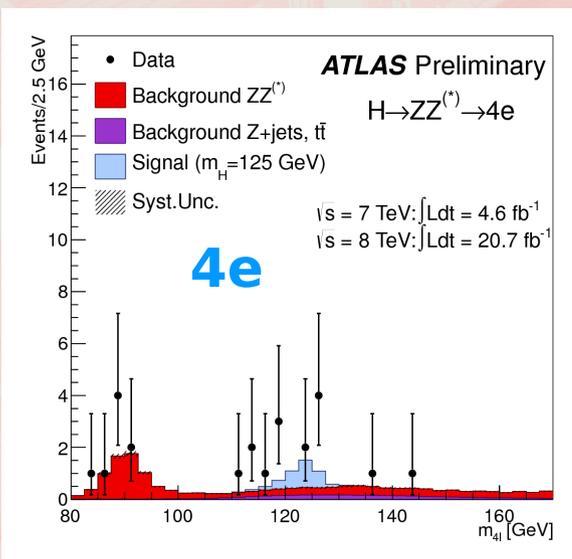
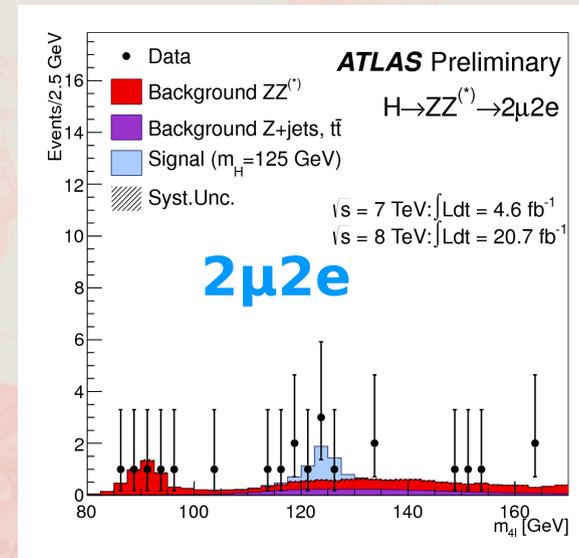
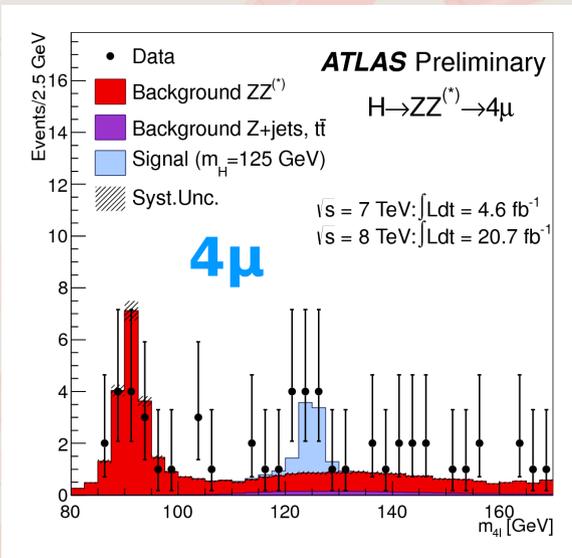
Muon: blue  
 Electron: black  
 Cells: Fides, EMC

$\sqrt{s} = 8 \text{ TeV}$							
	total signal	signal (in window)	ZZ <sup>(*)</sup>	Z + jets, $t\bar{t}$	S/B	expected	observed
4 $\mu$	5.8 $\pm$ 0.7	5.3 $\pm$ 0.7	2.3 $\pm$ 0.1	0.50 $\pm$ 0.13	1.9	8.1 $\pm$ 0.9	11
2 $\mu$ 2e	3.0 $\pm$ 0.4	2.6 $\pm$ 0.4	1.2 $\pm$ 0.1	1.01 $\pm$ 0.21	1.2	4.8 $\pm$ 0.7	4
2e2 $\mu$	4.0 $\pm$ 0.5	3.4 $\pm$ 0.4	1.7 $\pm$ 0.1	0.51 $\pm$ 0.16	1.5	5.6 $\pm$ 0.7	6
4e	2.9 $\pm$ 0.4	2.3 $\pm$ 0.3	1.0 $\pm$ 0.1	0.62 $\pm$ 0.16	1.4	3.9 $\pm$ 0.6	6
total	15.7 $\pm$ 2.0	13.7 $\pm$ 1.8	6.2 $\pm$ 0.4	2.62 $\pm$ 0.34	1.6	22.5 $\pm$ 2.9	27
$\sqrt{s} = 7 \text{ TeV}$							
4 $\mu$	1.0 $\pm$ 0.1	0.97 $\pm$ 0.13	0.49 $\pm$ 0.02	0.05 $\pm$ 0.02	1.8	1.5 $\pm$ 0.2	2
2 $\mu$ 2e	0.4 $\pm$ 0.1	0.39 $\pm$ 0.05	0.21 $\pm$ 0.02	0.55 $\pm$ 0.12	0.5	1.0 $\pm$ 0.1	1
2e2 $\mu$	0.7 $\pm$ 0.1	0.57 $\pm$ 0.08	0.33 $\pm$ 0.02	0.04 $\pm$ 0.01	1.6	0.9 $\pm$ 0.1	2
4e	0.4 $\pm$ 0.1	0.29 $\pm$ 0.04	0.15 $\pm$ 0.01	0.49 $\pm$ 0.12	0.5	0.9 $\pm$ 0.1	0
total	2.5 $\pm$ 0.4	2.2 $\pm$ 0.3	1.17 $\pm$ 0.07	1.12 $\pm$ 0.17	1.0	4.3 $\pm$ 0.5	5
$\sqrt{s} = 8 \text{ TeV and } \sqrt{s} = 7 \text{ TeV}$							
4 $\mu$	6.8 $\pm$ 0.8	6.3 $\pm$ 0.8	2.8 $\pm$ 0.1	0.55 $\pm$ 0.15	1.9	9.6 $\pm$ 1.0	13
2 $\mu$ 2e	3.4 $\pm$ 0.5	3.0 $\pm$ 0.4	1.4 $\pm$ 0.1	1.56 $\pm$ 0.33	1.0	6.0 $\pm$ 0.8	5
2e2 $\mu$	4.7 $\pm$ 0.6	4.0 $\pm$ 0.5	2.1 $\pm$ 0.1	0.55 $\pm$ 0.17	1.6	6.6 $\pm$ 0.8	8
4e	3.3 $\pm$ 0.5	2.6 $\pm$ 0.4	1.2 $\pm$ 0.1	1.11 $\pm$ 0.28	1.2	4.8 $\pm$ 0.8	6
total	18.2 $\pm$ 2.4	15.9 $\pm$ 2.1	7.4 $\pm$ 0.4	3.74 $\pm$ 0.93	1.6	27.0 $\pm$ 3.4	32

# H $\rightarrow$ ZZ(\*) $\rightarrow$ 4l $m_{4l}$ distribution in the final states

Run Number: 182796,  
 Event Number: 74566644  
 Date: 2011-05-30, 06:54:29 C

EtCut > 0.3 GeV  
 PtCut > 2.0 GeV  
 Vertex Cuts:  
 Z direction < 1cm  
 Rphi < 1cm  
 Muon: blue  
 Electron: black  
 Cells: FHCs, EMC

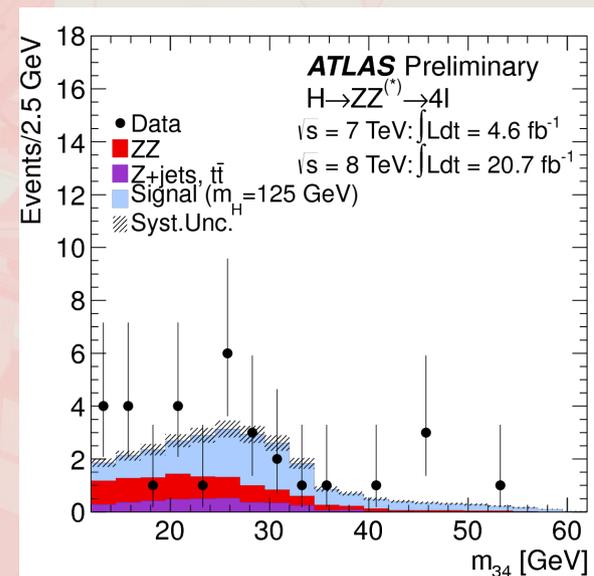
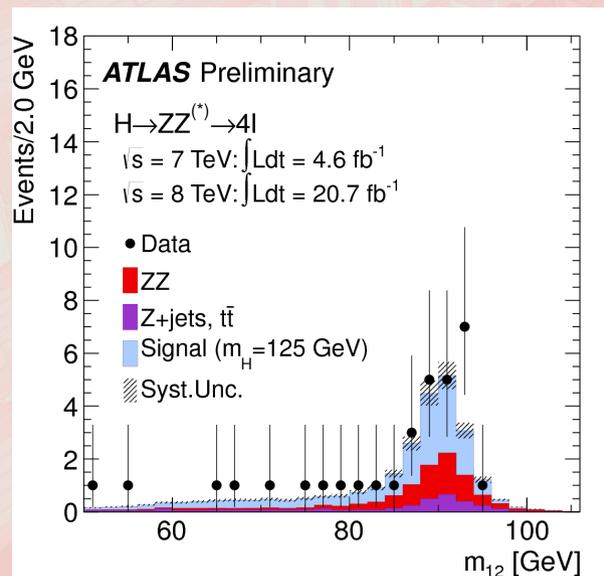
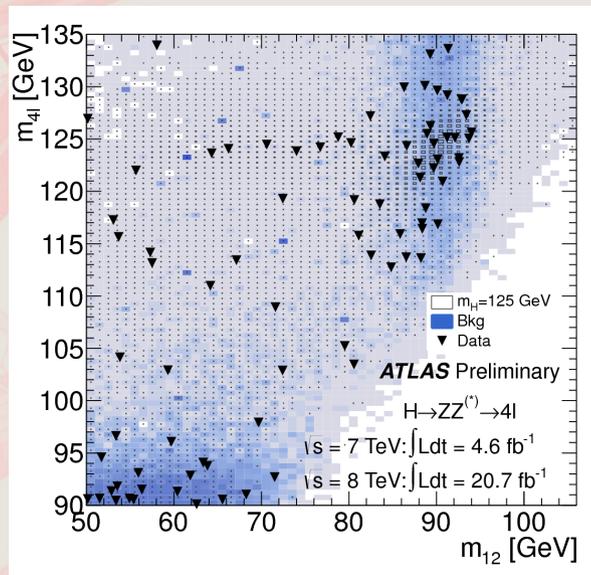


# ATLAS EXPERIMENT $H \rightarrow ZZ^{(*)} \rightarrow 4l$ invariant mass distributions

Run Number: 182796,  
 Event Number: 74566644  
 Date: 2011-05-30, 06:54:29 CET

EtCut > 0.3 GeV  
 PtCut > 2.0 GeV  
 Vertex Cuts:  
 Z direction < 1cm  
 Rphi < 1cm

Muon: blue  
 Electron: black  
 Cells: Tiles, EMC

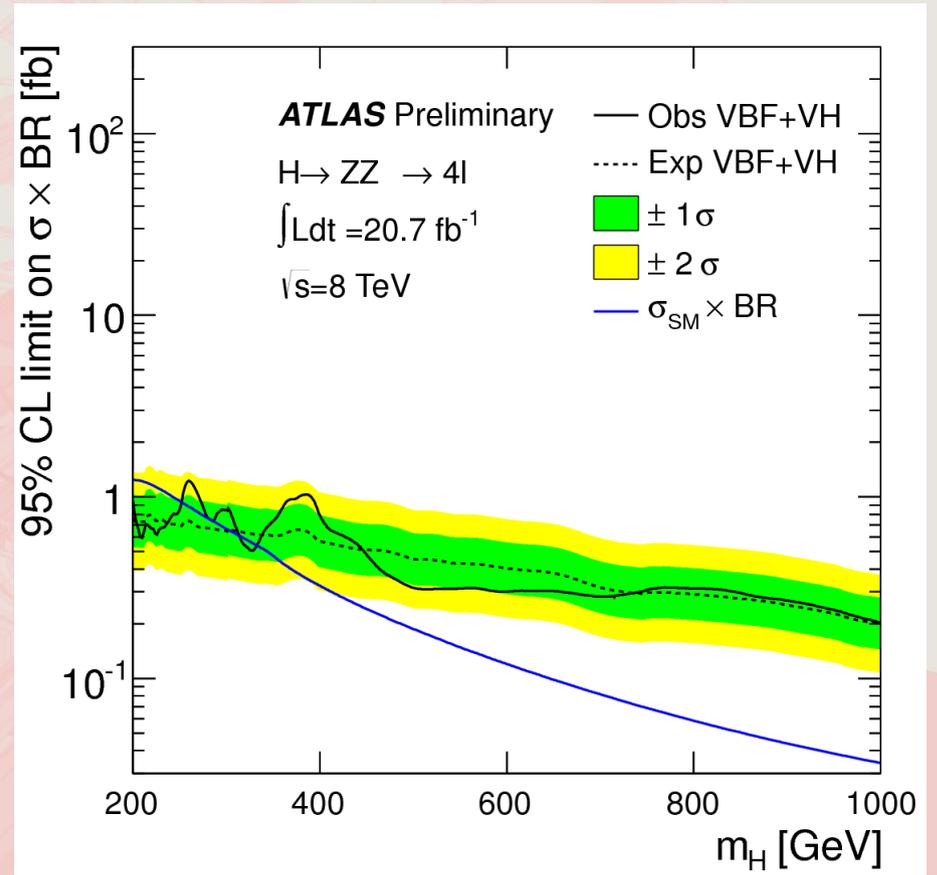
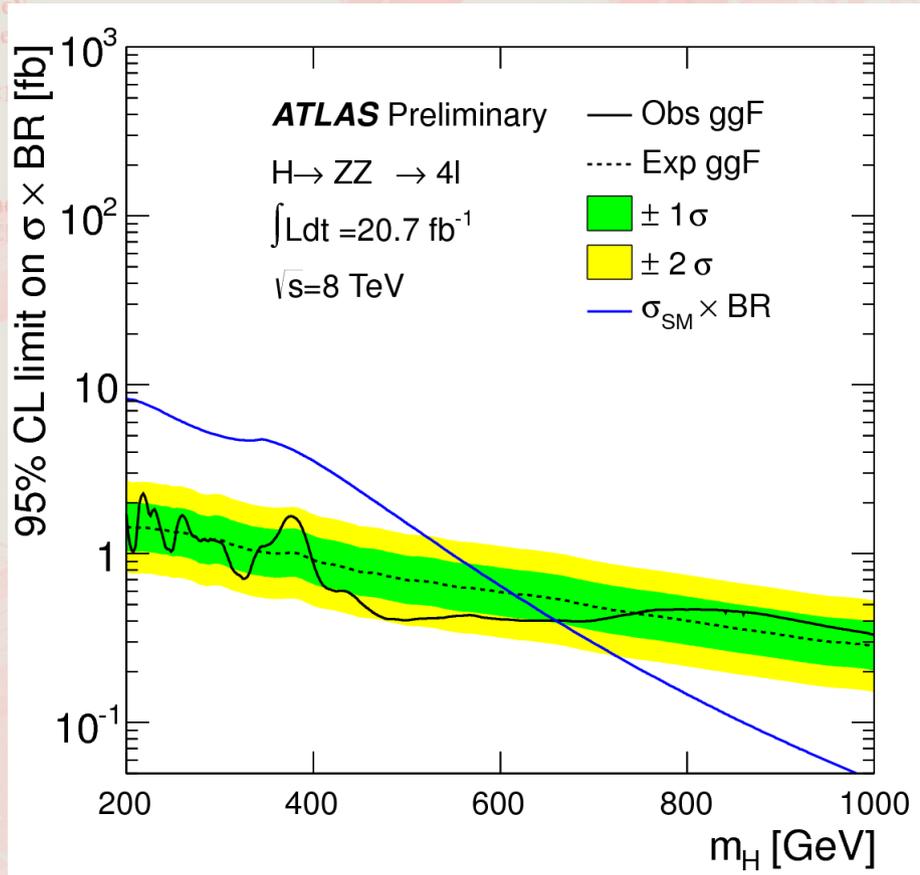


$120 < m_{4l} < 130 \text{ GeV}$

# H $\rightarrow$ ZZ<sup>(\*)</sup> $\rightarrow$ 4l limits in high mass

Run Number: 182796,  
 Event Number: 74566644  
 Date: 2011-05-30, 06:54:29 CET

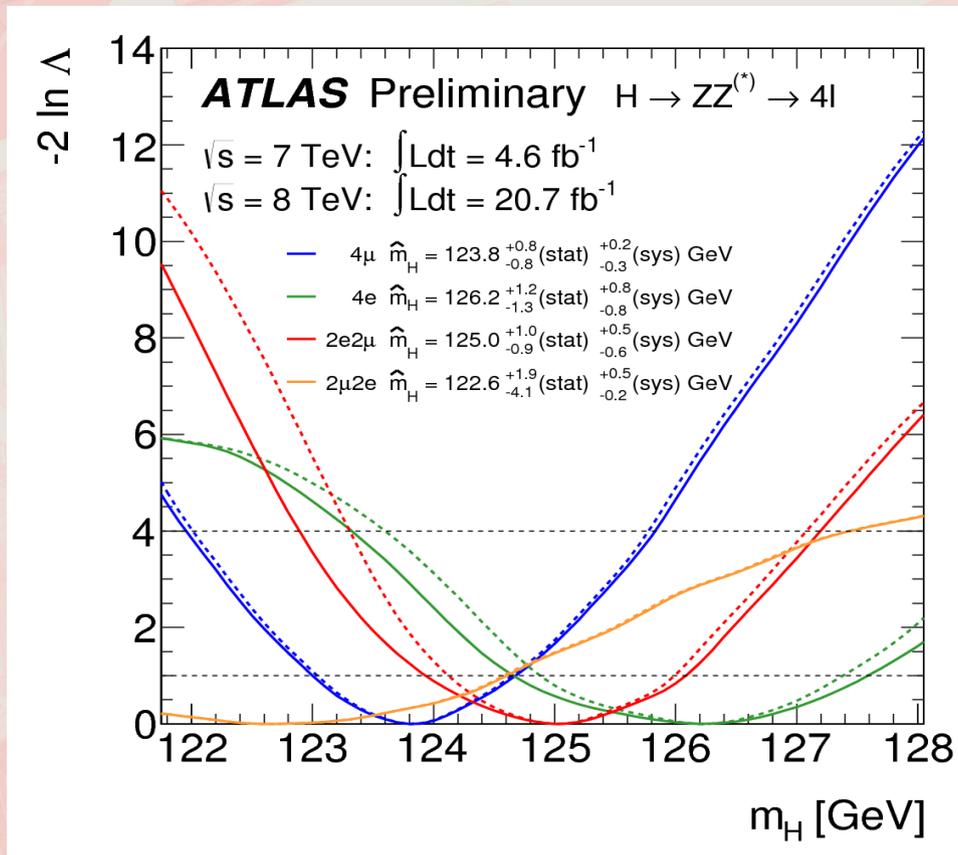
EtCut>0.3 GeV  
 PtCut>2.0 GeV  
 Vertex Cuts:  
 Z direction <  
 Rphi <1cm  
 Muon: blue  
 Electron: Bla  
 Cells:Files, E



# H $\rightarrow$ ZZ<sup>(\*)</sup> $\rightarrow$ 4l mass per channel

Run Number: 182796,  
Event Number: 74566644  
Date: 2011-05-30, 06:54:29 CET

EtCut > 0.3 GeV  
PtCut > 2.0 GeV  
Vertex Cuts:  
Z direction < 1cm  
Rphi < 1cm  
  
Muon: blue  
Electron: Black  
Cells: Tiles, EMC

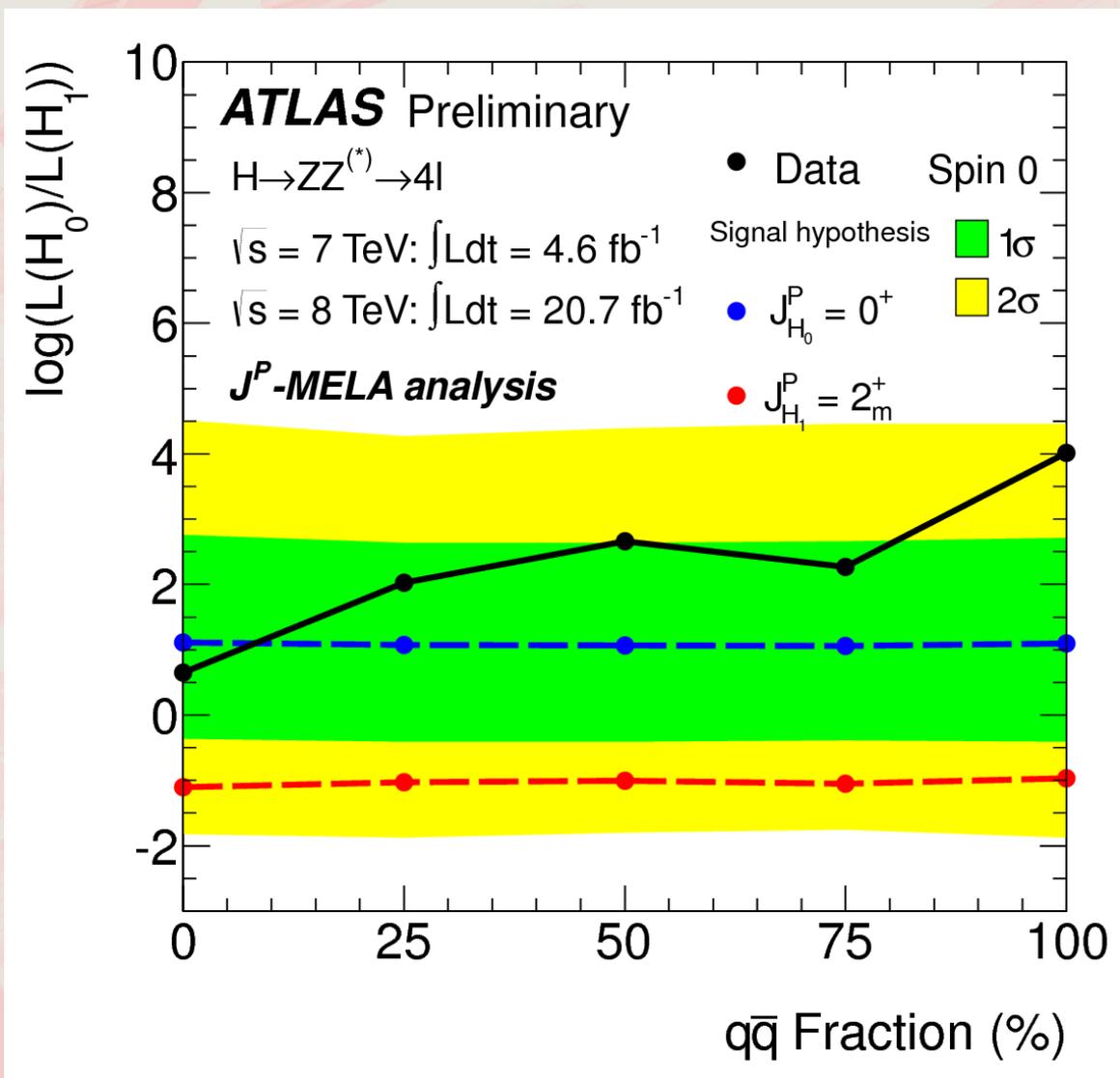


# $H \rightarrow ZZ^{(*)} \rightarrow 4l$ $f_{qq}$ scan

Run Number: 182796,  
 Event Number: 74566644  
 Date: 2011-05-30, 06:54:29 CET

EtCut > 0.3 GeV  
 PtCut > 2.0 GeV  
 Vertex Cuts:  
 Z direction < 1cm  
 Rphi < 1cm

Muon: blue  
 Electron: Black  
 Cells: Tiles, EMC



# Prospects for HL-LHC

Run Number: 182796,  
Event Number: 74566644  
Date: 2011-05-30, 06:54:29 CET

EtCut>0.3 GeV  
PtCut>2.0 GeV  
Vertex Cuts:  
Z direction <1cm  
Rphi <1cm  
Muon: blue  
Electron: Blue  
Cells: Full

<https://cds.cern.ch/record/1611186>

Expected number of events for each category [3000 fb<sup>-1</sup>]

Category	True Origin					
	ggF	VBF	WH	ZH	ttH	Background
ttH-like	3.1 ±1.0	0.6 ±0.1	0.6 ±0.1	1.1 ±0.2	30 ±6	1.6 ±1.0
ZH-like	0.0	0.0	0.01 ±0.01	4.4 ±0.3	1.3 ±0.3	0.06 ±0.06
WH-like	22 ±7	6.6 ±0.4	25 ±2	4.4 ±0.3	8.8 ±1.8	13 ±0.8
VBF-like	41 ±14	54 ±6	0.7 ±0.1	0.4 ±0.1	1.0 ±0.2	4.2 ±1.5
ggF-like	3380 ±650	274 ±17	77 ±5	53 ±3	25 ±4	2110 ±50

Expected relative uncertainties on the  $\mu$

$\Delta\mu/\mu$	Total	Stat.	Expt. syst.	Theory
Production mode	300 fb <sup>-1</sup>			
ggF	0.152	0.066	0.053	0.124
VBF	0.625	0.545	0.233	0.226
WH	1.074	1.064	0.061	0.085
ttH	0.535	0.516	0.038	0.120
Combined	0.125	0.042	0.044	0.108
	3000 fb <sup>-1</sup>			
ggF	0.131	0.025	0.040	0.124
VBF	0.371	0.187	0.225	0.226
WH	0.390	0.375	0.061	0.085
ZH	0.532	0.526	0.038	0.073
ttH	0.224	0.184	0.034	0.120
Combined	0.100	0.016	0.036	0.093

The exclusion limits on the non-SM CP-even coupling  $g_2$  and CP-odd coupling  $g_4$ , given the SM Higgs boson signal

Luminosity	$f_{g_4}$	$f_{g_2}$
300 fb <sup>-1</sup>	0.15	0.43
3000 fb <sup>-1</sup>	0.037	0.20

<https://cds.cern.ch/record/1611123>