Search for the SM Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4l$ in ATLAS

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On behalf of the ATLAS Collaboration

Higgs Hunting 2012
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Introduction

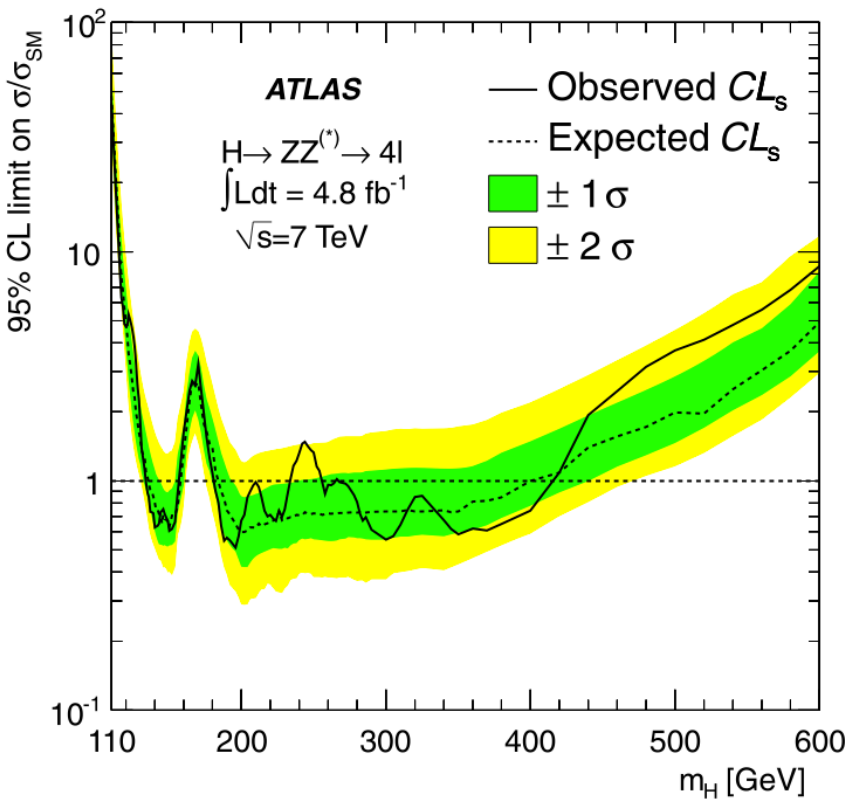
- Signature: $H \rightarrow ZZ^{(*)} \rightarrow 4l$ ($l = e, \mu$)
- The "golden channel":
  - Small rates, but high S/B
  - Can be fully reconstructed; mass resolution ~2% at 130 GeV
- Cross section times branching ratio (at m_H=125 GeV):

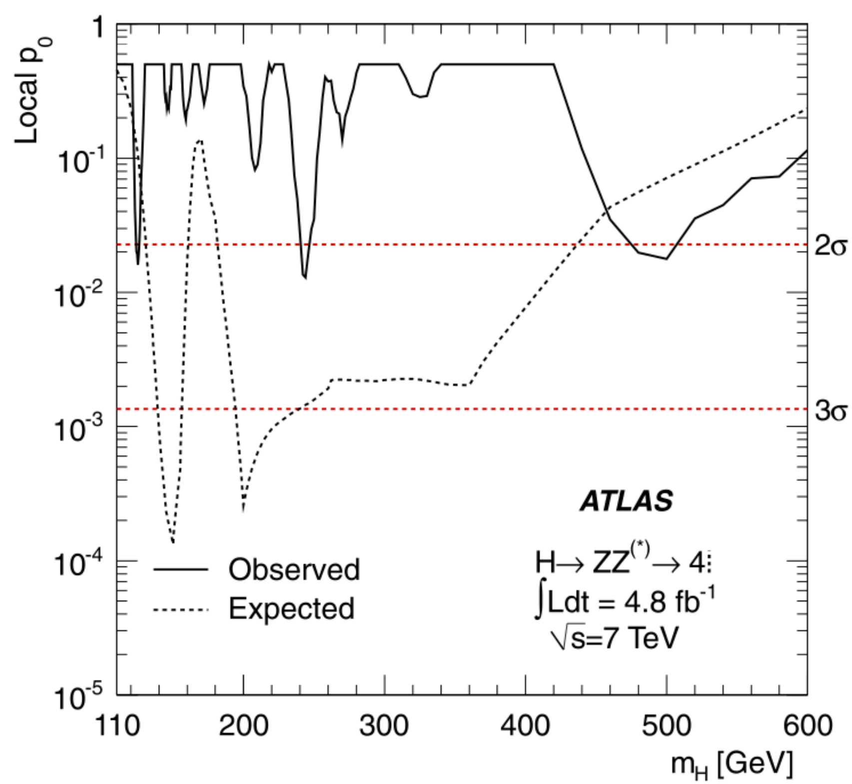
  ~ 4 fb at $\sqrt{s}$=7 TeV

  ~ 5 fb at $\sqrt{s}$=8 TeV
- Backgrounds:
  - Irreducible: $pp \rightarrow ZZ^{(*)} \rightarrow 4l$
  - Reducible: *Z+jets*, *Zbb*, *ttbar* (sizeable at low Higgs masses)
- Mass range under consideration: **110 GeV to 600 GeV**
- Four final states: ***4e, 4μ, 2e2μ, 2μ2e***

Previous ATLAS results

- February 2012 (Phys. Lett. B710 (2012) 383-402):
  - Complete 2011 dataset (4.8 fb^{-1})
  - Excluded: 134-156, 182-233, 256-265, 268-415 GeV
  - Observed excesses at 125, 244, 500 GeV (2.1σ, 2.2σ, 2.1σ, local)

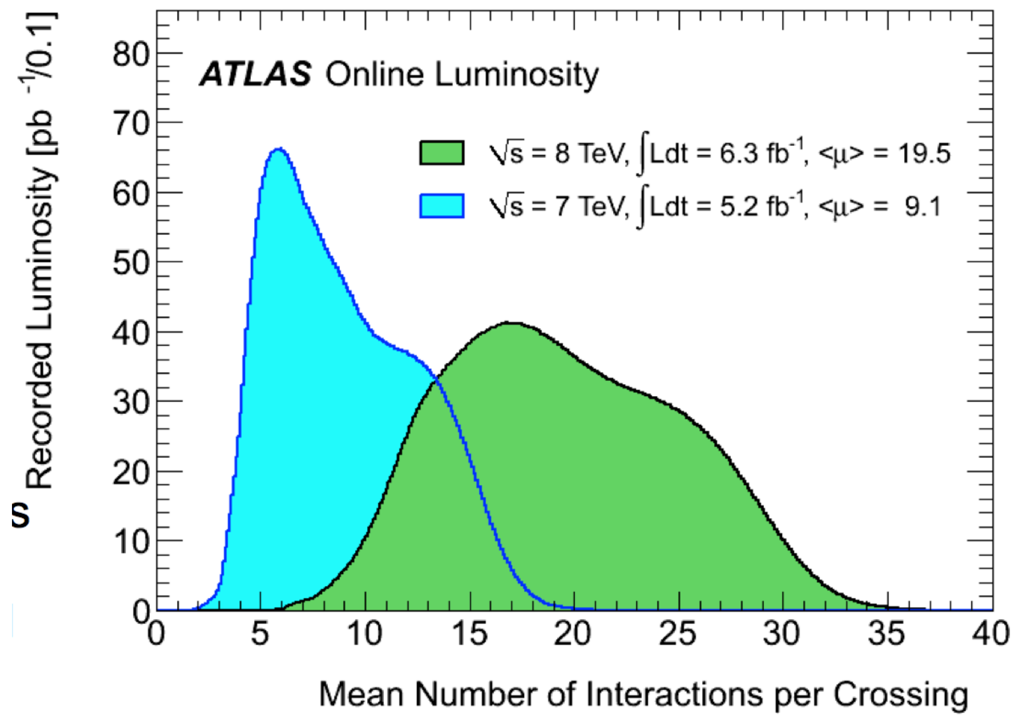




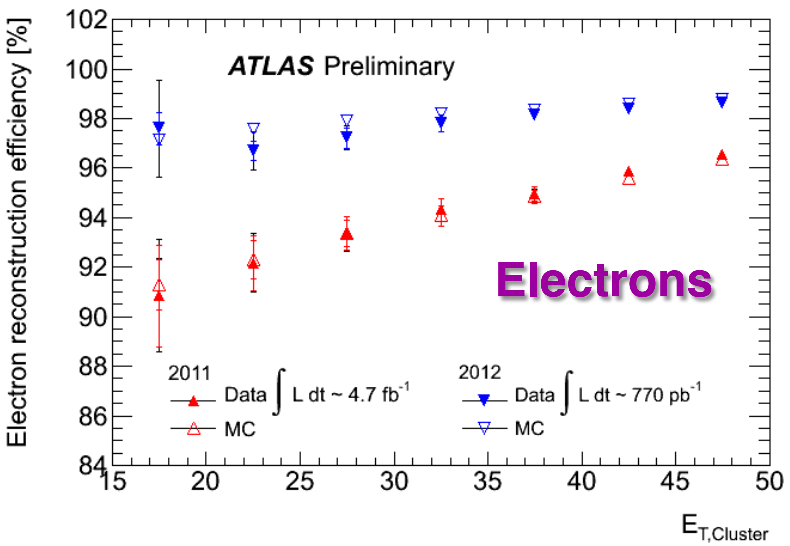
Dataset

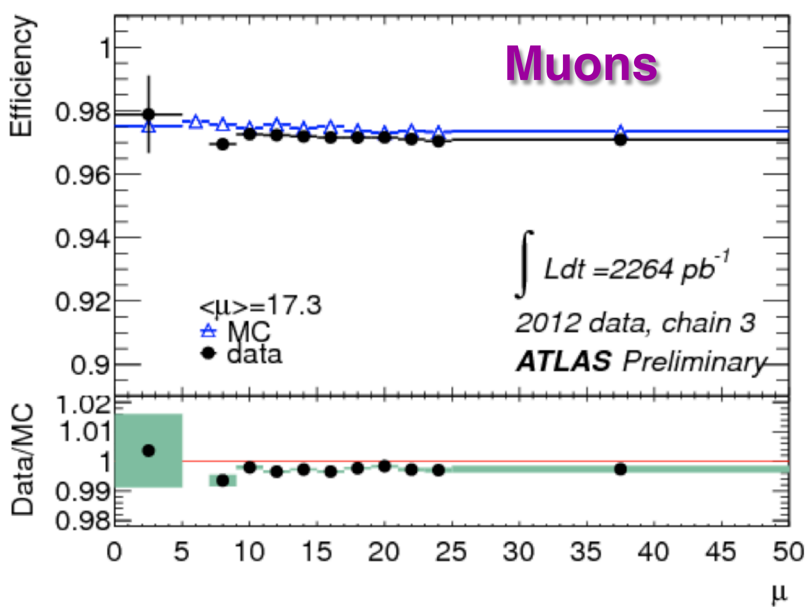
- 7 TeV dataset (2011):
  - 5.3 fb^{-1} recorded, 4.8 fb^{-1} for physics
  - Peak stable luminosity 3.6×10^{33} $cm^{-2}s^{-1}$
- 8 TeV dataset (2012):
  - 6.3 fb^{-1} recorded, 5.8 fb^{-1} for physics
  - Peak stable luminosity 6.8×10^{33} $cm^{-2}s^{-1}$

- Substantially more pileup in 2012; need to
  - maintain level of detector performance
  - ensure proper modeling in simulation



Lepton reconstruction and identification





Electrons

- Improved reconstruction
  - New pattern finding/track fit
- Improved identification
  - Pile-up robust
  - Higher rejection and efficiency than in 2011

Muons

- Combine Inner Detector (ID) tracks with tracks in Muon Spectrometer (MS)
- Extended coverage:
  - ID tracks + energy deposits in calorimeter ($|\eta|<0.1$, $p_T>15$GeV)
  - MS stand-alone ($2.5<|\eta|<2.7$)

Updated analysis, selection

Updated analysis for 2011 and 2012 data

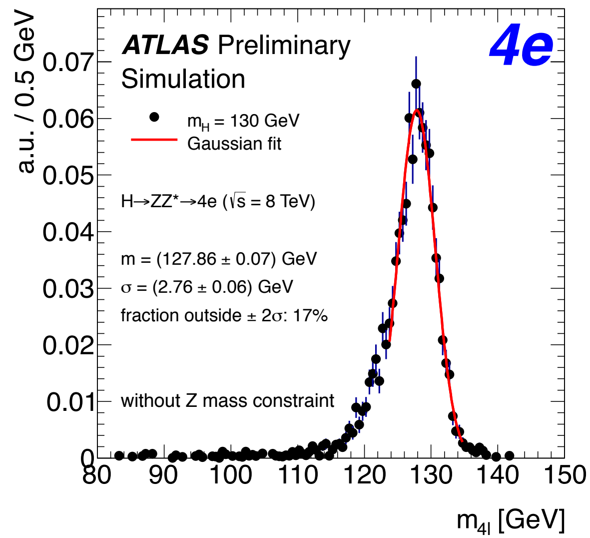
- Improved expected sensitivity for low m_H
- Estimate backgrounds using data (sidebands, control regions)
- Development based only on 2011 data and 2012 control regions

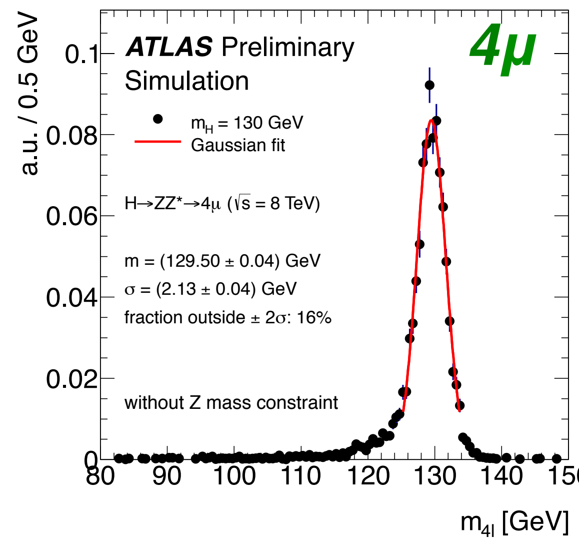
Selection

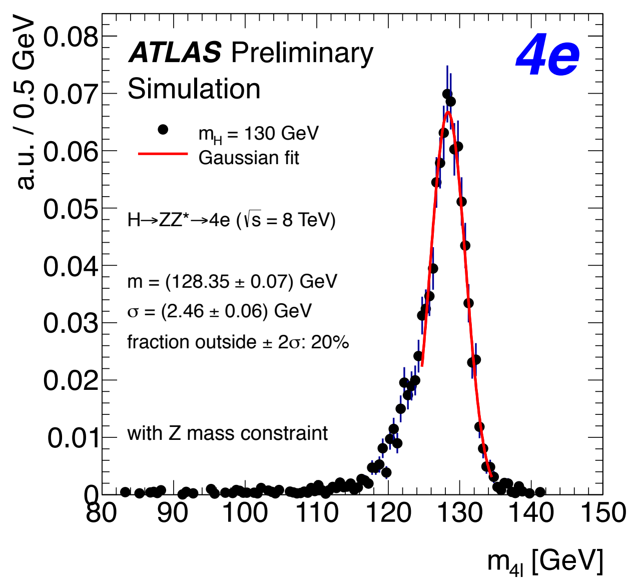
- Single lepton and di-lepton triggers
- At least two pairs of opposite-charge, same-flavor leptons (e,mu)
- p_T thresholds: 20, 15, 10, 7 GeV (6 GeV for muons)
- $50 < m_{12} < 106$ GeV, m_{4l}-dependent cut on m_{34}, $m_{34} < 115$ GeV
- All same-flavor, opposite-sign pairs m_{ll}>5 GeV (J/Psi veto)
- $\Delta R(l,l') < 0.1$ (0.2) for all same (different)-flavor
- Tracking and calorimeter isolation:
  Ptcone20/p_T<0.15, Etcone20/E_T<0.3 (0.15 for muons outside the acceptance of the tracker)
- $|d_0/\sigma(d_0)|< 3.5$ (6.5 for electrons)

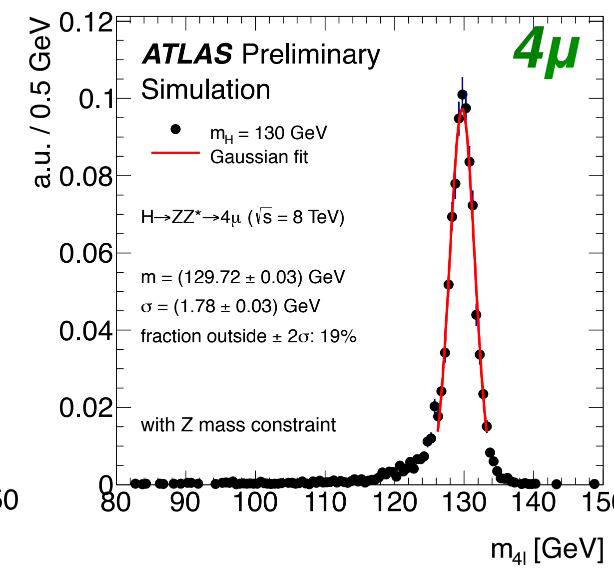
Mass resolution

- Main discriminant variable:
  4-lepton invariant mass
- Resolution crucial for sensitivity
- At low m_H, detector resolution dominates width
- Z-mass constraint improves resolution
  - From 1.6 - 2.1%
    to 1.3 - 1.9%
  (for m_H=130 GeV)









Background estimation

Irreducible ($ZZ^{(*)}$): MC simulation normalized to theory cross section [both gg and qq production (PowHeg, qq2ZZ), MCFM NLO xs]

Reducible (ll+jets and tt):

- Comparable to ZZ in the low mass region
- Estimated using data-driven methods
- Background composition depends on flavor of subleading lepton pair → different approaches for *ll+μμ* and *ll+ee*:

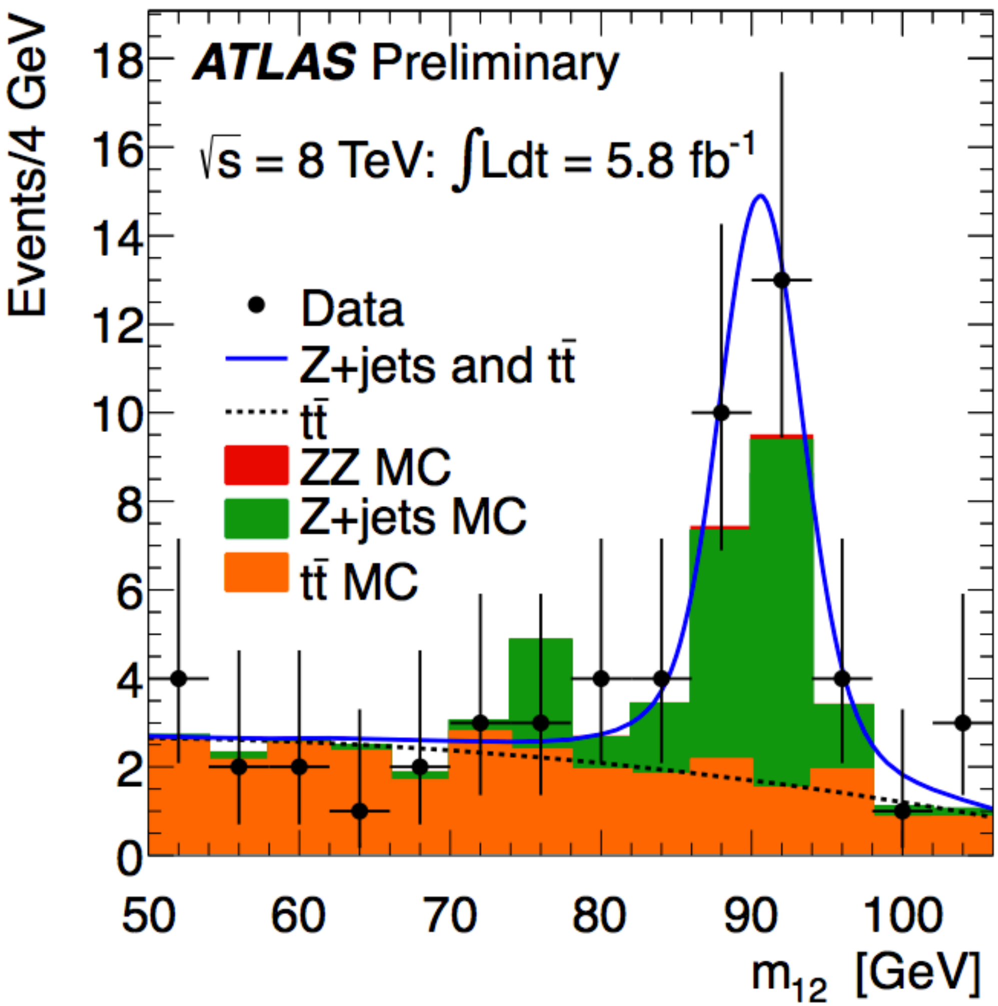
  ll+μμ *(4μ, 2e2μ)*:
  - ttbar and Zbb from a fit to m12 (nominal)
  - ttbar from *eμ+μμ* (cross check)

  ll+ee *(2e2μ, 4e)*:
  - Z+XX control samples (nominal)
  - 3l + l (same-sign) (cross check)
- **General strategy**: **Loosen or revert selection, obtain composition, extrapolate to signal region**

Background estimation

Fit to m_{12}

- Loosened selection on sub-leading leptons (enhance tt, reduce ZZ):
  - No isolation cuts
  - At least one should fail the impact parameter cut
- tt and Z+jets estimated via a fit
  Chebychev +
  BreitWigner⊗CrystalBall
- Extrapolate to signal region via MC-based efficiency (validated in Z+μ control region)



Background estimation

$ll+\mu\mu$

[cross-check]

tt yield cross check using eμ+μμ

Requirements:

- Leading **$e^+\mu^-$** pair with $50<m_{e\mu}<106$ GeV + two muons (done independently for same-sign and opposite-sign muons)
- As main analysis, but no isolation or IP cuts on subleading muons
- Veto events with a Z

	7 TeV	8 TeV
Expected	11.0 ± 0.6	18.9 ± 1.1
Observed	8	16

- Extrapolated to signal region
- Results compatible with the m_{12} fit (nominal method)

Background estimation $ll+ee$

[nominal]

Z+XX control samples

X: **E**lectrons from heavy flavor,
Electrons from photon **C**onversions,
jets misidentified as electrons ("**F**akes")

The idea

- Loosen requirements on the two subleading electrons
- Classify each of the two as (E)lectron, (C)onversion or (F)ake
  Nine types of events (EE, EC, EF, CE, CC, CF, FE, FC, FF) [p_T-ordered]
- Using MC-based efficiencies, determine how many of each type is expected in the signal region

- Classification as **E**lectron, **C**onversion or **F**ake based on
  - Transition radiation hits,
  - Number of hits in the innermost pixel layer (the *b*-layer),
  - Fraction of energy deposited in first layer of the EM calorimeter,
  - Lateral containment along φ in the 2nd layer of the EM calorimeter

Z+XX control samples

- Events on each class (based on reconstruction quantities) are a mixture of *true* ee, ec, ef, …

	ee	ec	ef	ce	…
EE					
EC					
EF					
…					

- Composition fractions from MC are used to obtain the expected true composition of each class
  - Limited Z+XX MC; efficiencies obtained from Z+X MC
  - Reweighted to Z+XX p_T spectrum
  - Verified good agreement w/data after isolation, IP and all cuts.
- Final estimate:
  expected true composition * efficiency (true class → signal region)
  $\Sigma_j\ \Sigma_i$ (true type i)*(efficiency of true i to be reco'd as j in the signal region)
- Low event numbers; toy MC used to obtain central value and uncertainty

Background estimation

$ll+ee$

[nominal]

Data/MC comparison

	$4e$		$2\mu2e$	
	Data	MC	Data	MC
EE	32	22.7±4.8	31	24.9±5.0
EC	6	6.0±2.5	2	1.9±1.4
EF	18	19.0±4.4	26	15.3±3.9
CE	4	8.8±3.0	6	5.1±2.3
CC	1	5.3±2.3	6	4.2±2.0
CF	12	8.8±3.0	15	15.3±3.9
FE	16	5.7±2.4	12	8.4±2.9
FC	6	6.5±2.6	7	4.3±2.1
FF	12	17.4±4.2	16	33.6±5.8
Total	107	100±10	121	113±11

(8 TeV data)

- **Opposite-sign subleading electrons**
- **Estimate based on same-sign subleading electrons also obtained as cross check**

Background estimation *ll+ee*

[cross-check]

3l + l

Three highest p_T leptons pass all analysis cuts

Last electron passes good track and basic electron id cuts (nSiHits≥7, nPixel≥1, R_η).

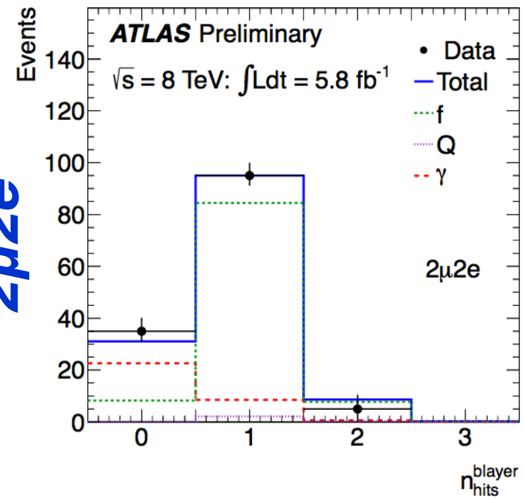
2D fit using MC templates for

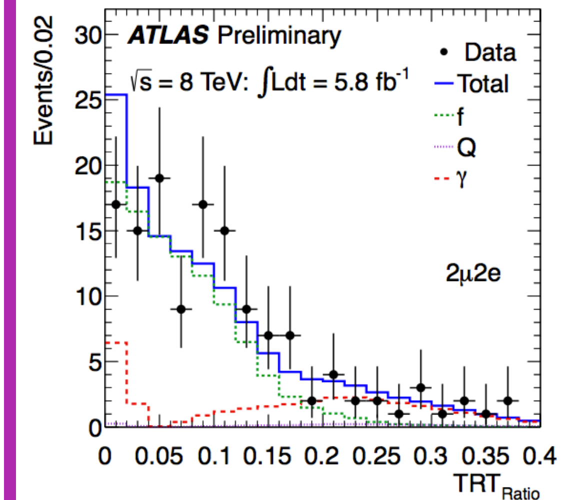
- Number of *b*-layer hits
- Transition radiation hits

(in the calorimeter endcap, the latter is replaced by an energy fraction)

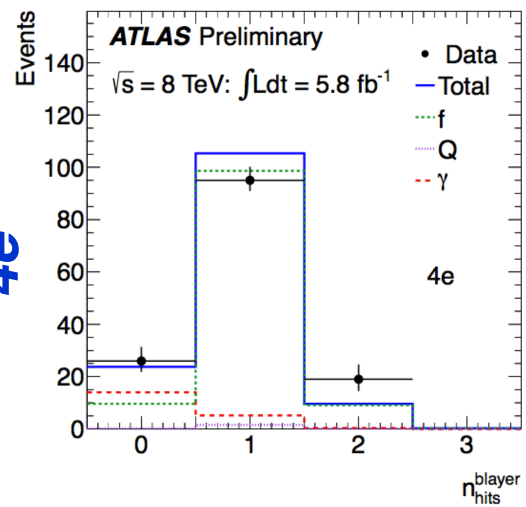
N B-layer | **TRT ratio**

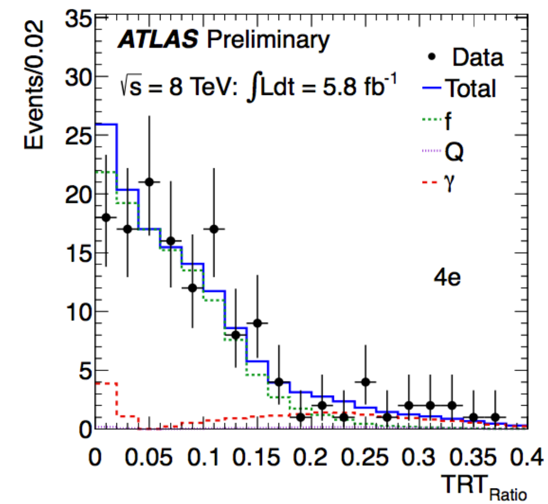
2μ2e





4e



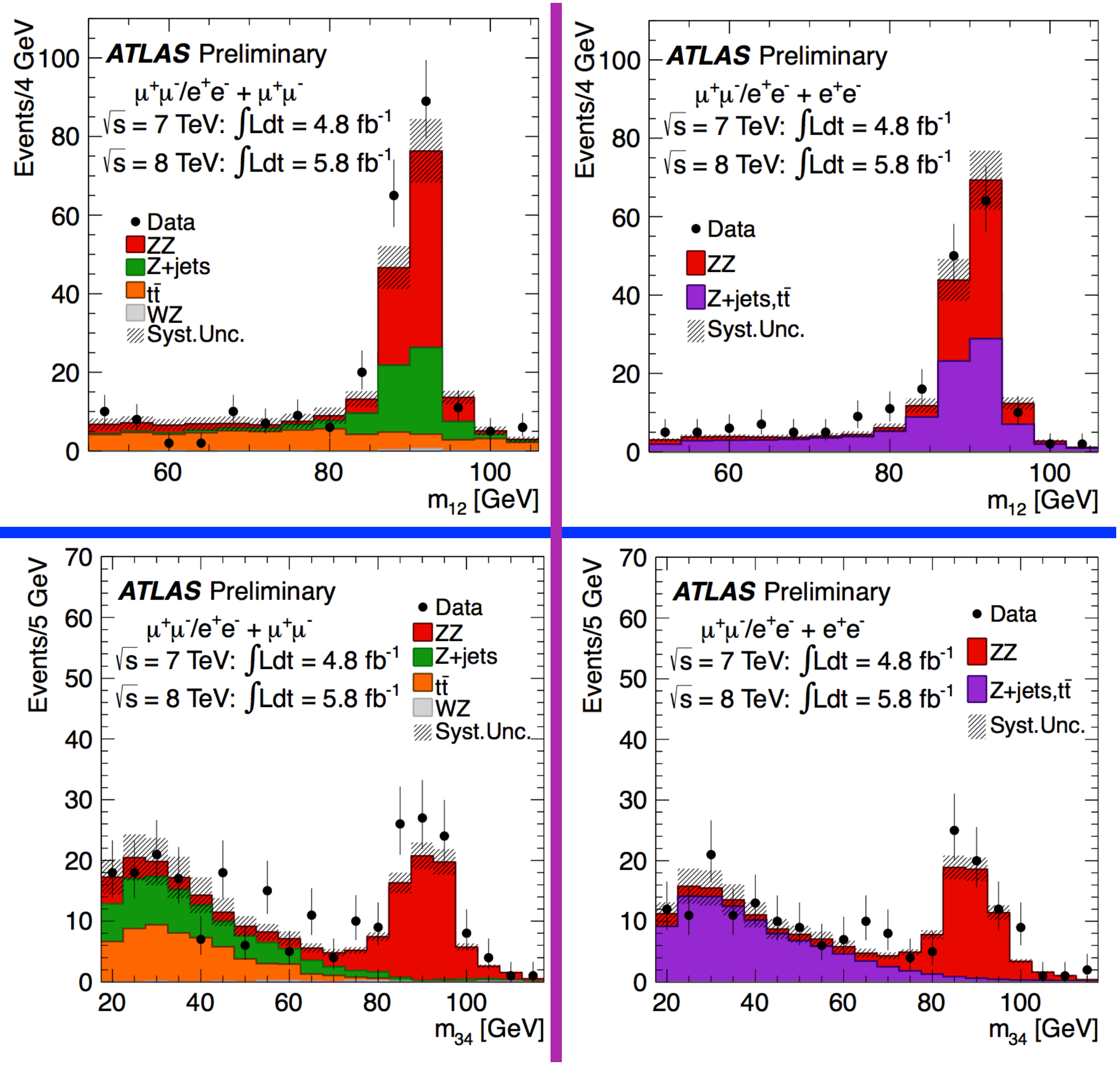


Control Regions

Z+mm Z+ee

On-shell Z

Subleading Z



- Isolation and impact parameter cuts not applied to sub-leading di-lepton
- Normalized to data-driven estimates
- Good data/MC agreement in shape and normalization

Summary of background estimations

8 TeV

Method	Estimated number of events
4μ	
m_{12} fit: $Z+$jets contribution	$0.51\pm 0.13 \pm 0.16^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.044\pm 0.015\pm 0.015^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp}+\mu^{\pm}\mu^{\mp}$	$0.058\pm 0.015\pm 0.019$
$2e2\mu$	
m_{12} fit: $Z+$jets contribution	$0.41\pm 0.10 \pm 0.13^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.040\pm 0.013\pm 0.013^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp}+\mu^{\pm}\mu^{\mp}$	$0.051\pm 0.013\pm 0.017$
$2\mu 2e$	
$\ell\ell+e^{\pm}e^{\mp}$	$4.9\pm 0.8 \pm 0.7^{\dagger}$
$\ell\ell+e^{\pm}e^{\pm}$	$4.1\pm 0.6 \pm 0.8$
$3\ell+\ell$ (same-sign)	$3.5\pm 0.5 \pm 0.5$
$4e$	
$\ell\ell+e^{\pm}e^{\mp}$	$3.9\pm 0.7 \pm 0.8^{\dagger}$
$\ell\ell+e^{\pm}e^{\pm}$	$3.1\pm 0.5 \pm 0.6$
$3\ell+\ell$ (same-sign)	$3.0\pm 0.4 \pm 0.4$

7 TeV

Method	Estimated number of events
4μ	
m_{12} fit: $Z+$jets contribution	$0.25\pm 0.10 \pm 0.08^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.022\pm 0.010\pm 0.011^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp}+\mu^{\pm}\mu^{\mp}$	$0.025\pm 0.009\pm 0.014$
$2e2\mu$	
m_{12} fit: $Z+$jets contribution	$0.20\pm 0.08 \pm 0.06^{\dagger}$
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$t\bar{t}$ from $e^{\pm}\mu^{\mp}+\mu^{\pm}\mu^{\mp}$	$0.024\pm 0.009\pm 0.014$
$2\mu 2e$	
$\ell\ell+e^{\pm}e^{\mp}$	$2.6\pm 0.4 \pm 0.4^{\dagger}$
$\ell\ell+e^{\pm}e^{\pm}$	$3.7\pm 0.9 \pm 0.6$
$3\ell+\ell$ (same-sign)	$2.0\pm 0.5 \pm 0.3$
$4e$	
$\ell\ell+e^{\pm}e^{\mp}$	$3.1\pm 0.6 \pm 0.5^{\dagger}$
$\ell\ell+e^{\pm}e^{\pm}$	$3.2\pm 0.6 \pm 0.5$
$3\ell+\ell$ (same-sign)	$2.2\pm 0.5 \pm 0.3$

More than one method per channel, compatible results

Uncertainties 20%-70% depending on background and data sample

Summary of background estimations

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$\ell\ell+e^{\pm}e^{\pm}$	$3.1\pm 0.5 \pm 0.6$
$3\ell+\ell$ (same-sign)	$3.0\pm 0.4 \pm 0.4$

7 TeV

Method	Estimated number of events
4μ	
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m_{12} fit: $t\bar{t}$ contribution	$0.022\pm 0.010\pm 0.011^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp}+\mu^{\pm}\mu^{\mp}$	$0.025\pm 0.009\pm 0.014$
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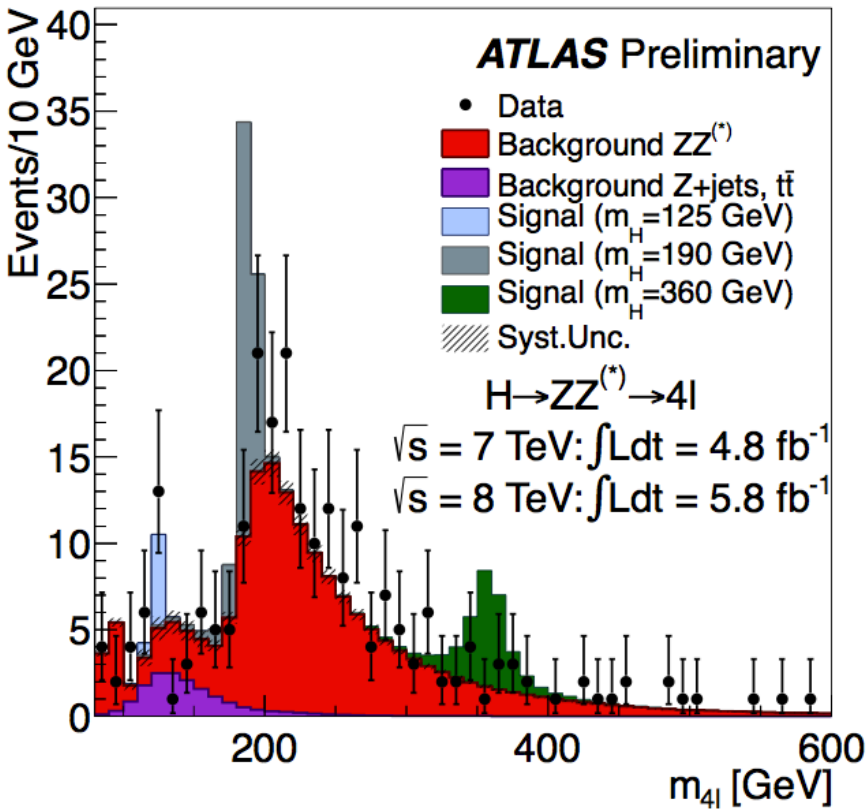
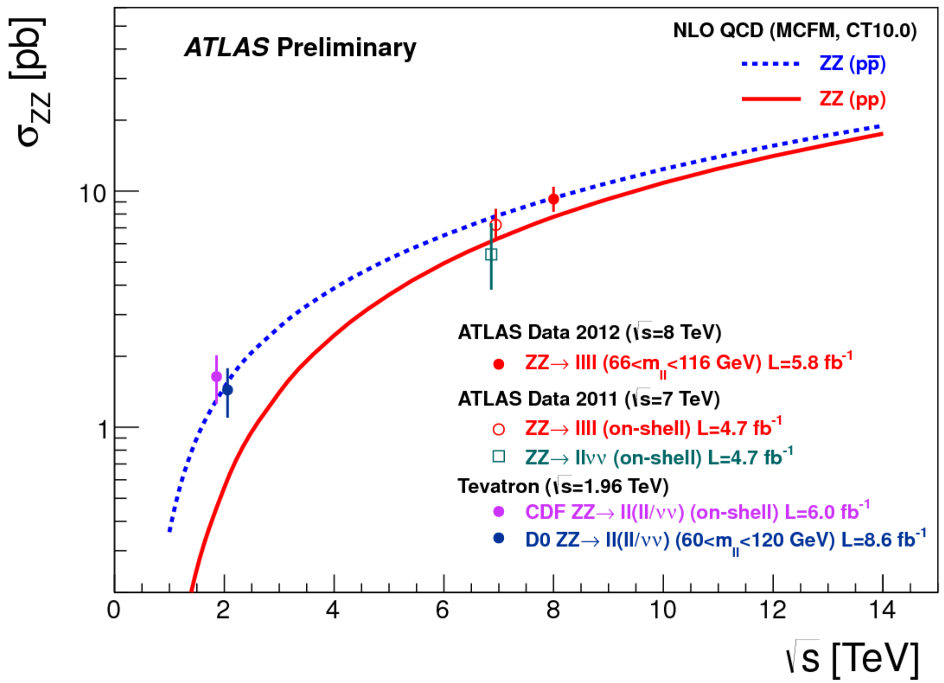
$4e$	
$\ell\ell+e^{\pm}e^{\mp}$	$3.1\pm 0.6 \pm 0.5^{\dagger}$
$\ell\ell+e^{\pm}e^{\pm}$	$3.2\pm 0.6 \pm 0.5$
$3\ell+\ell$ (same-sign)	$2.2\pm 0.5 \pm 0.3$

More than one method per channel, compatible results

Uncertainties 20%-70% depending on background and data sample

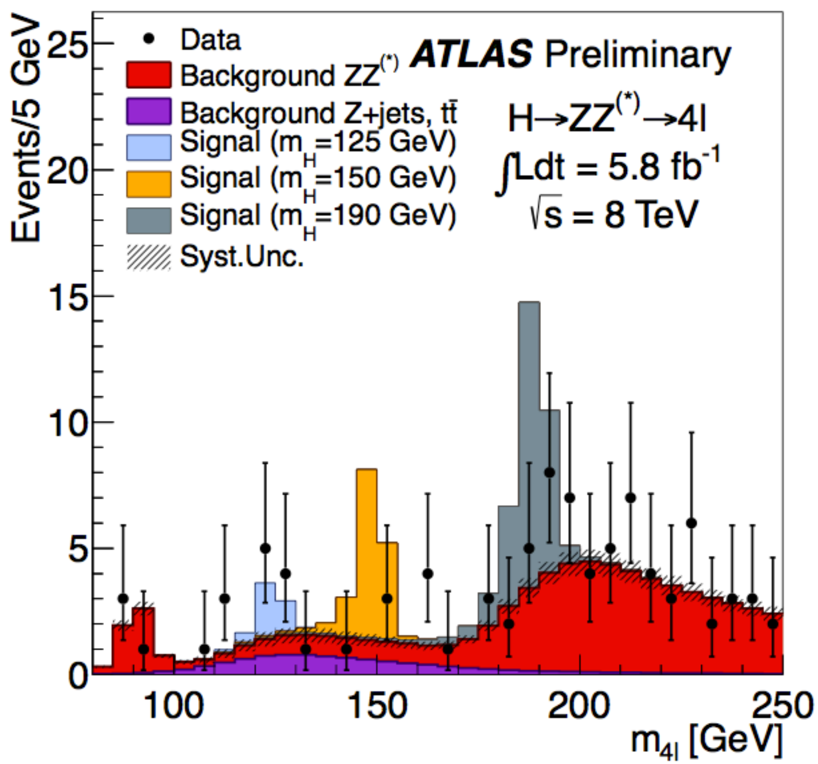
Results of event selection

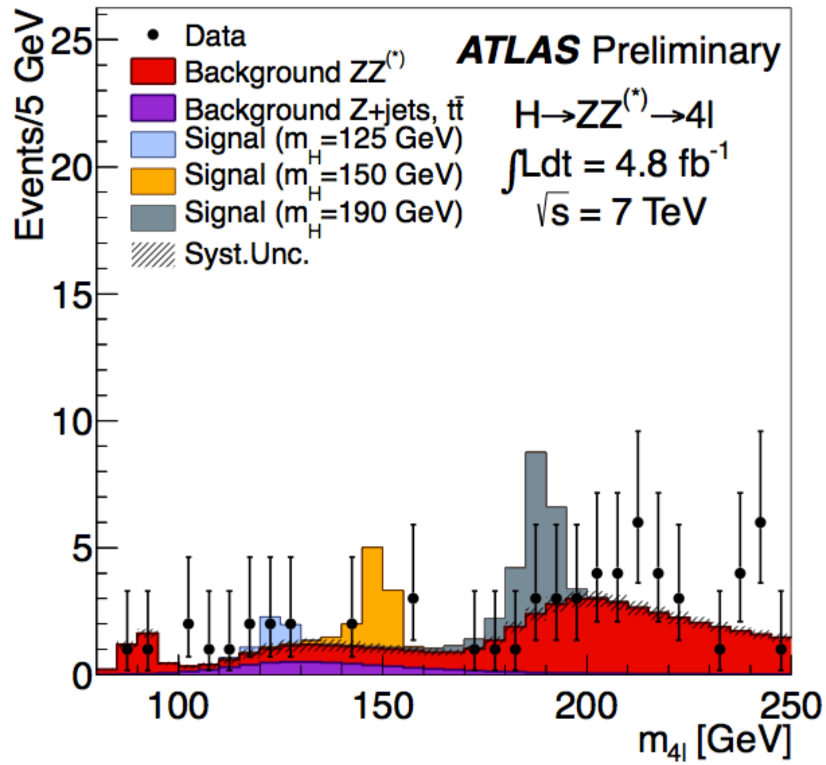




- For m_{4l}>160 GeV, data 20-30% above MC-expected in 2011 and 2012
- Events consistent with ZZ production
- Reflected in the ATLAS ZZ production cross-section measurement

Results of event selection





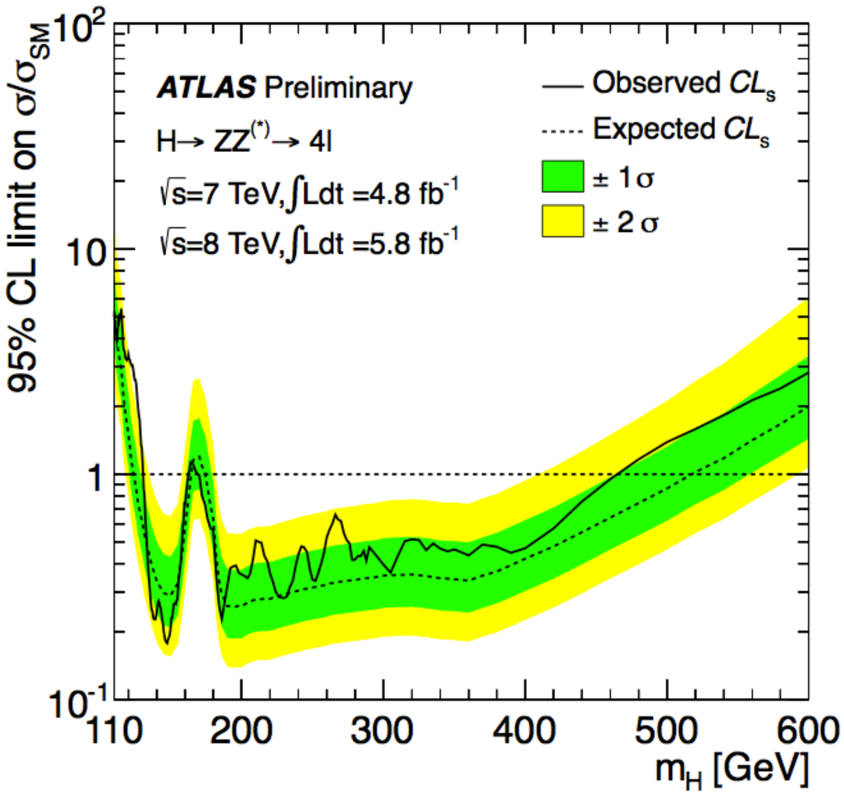
	2011	2012	Combined
Exp. bg	2.1±0.3	2.9±0.4	5.1±0.8
Exp. sig	2.0±0.3	3.3±0.5	5.3±0.8
Observed	4	9	13

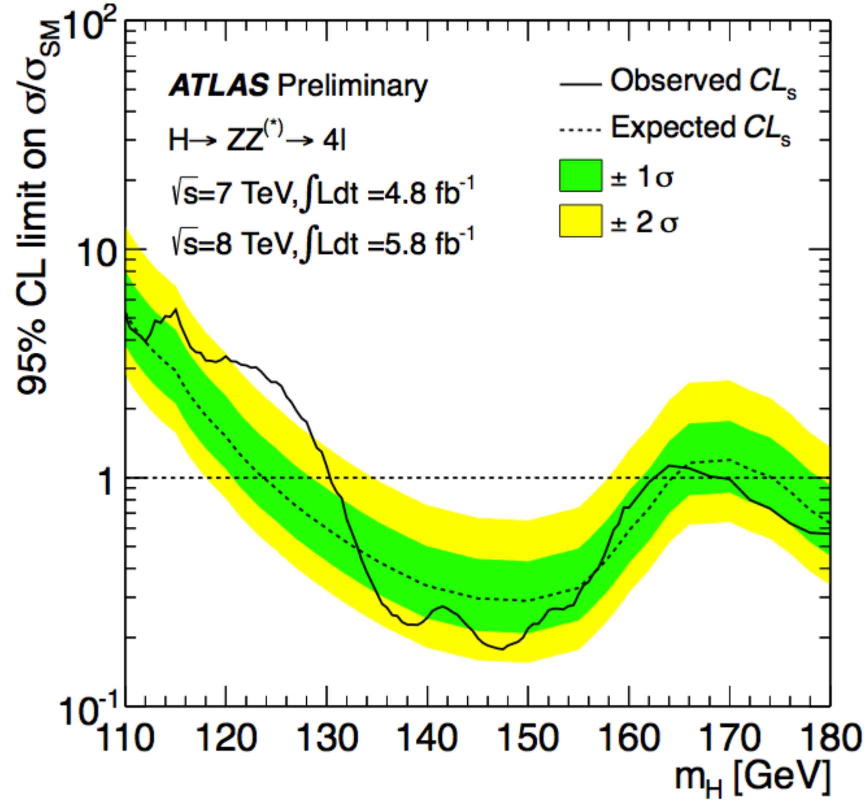
(m_{4l} in 125±5 GeV)

Expected S/B (m_H=125 GeV)

4mu	~ 1.6
2e2mu/2mu2e	~ 1.0
4e	~ 0.6

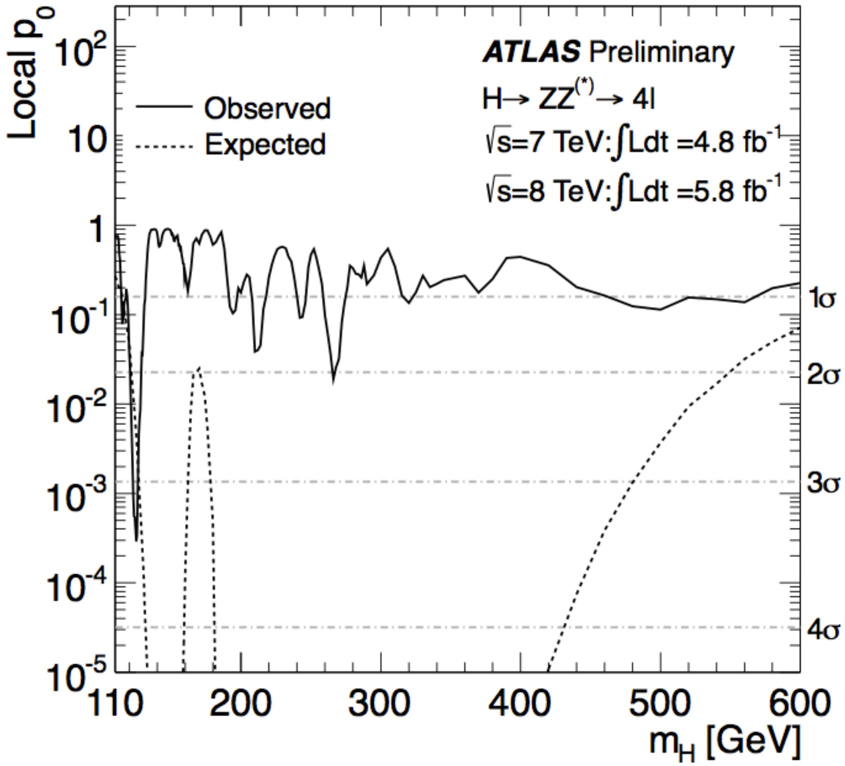
Exclusion limits

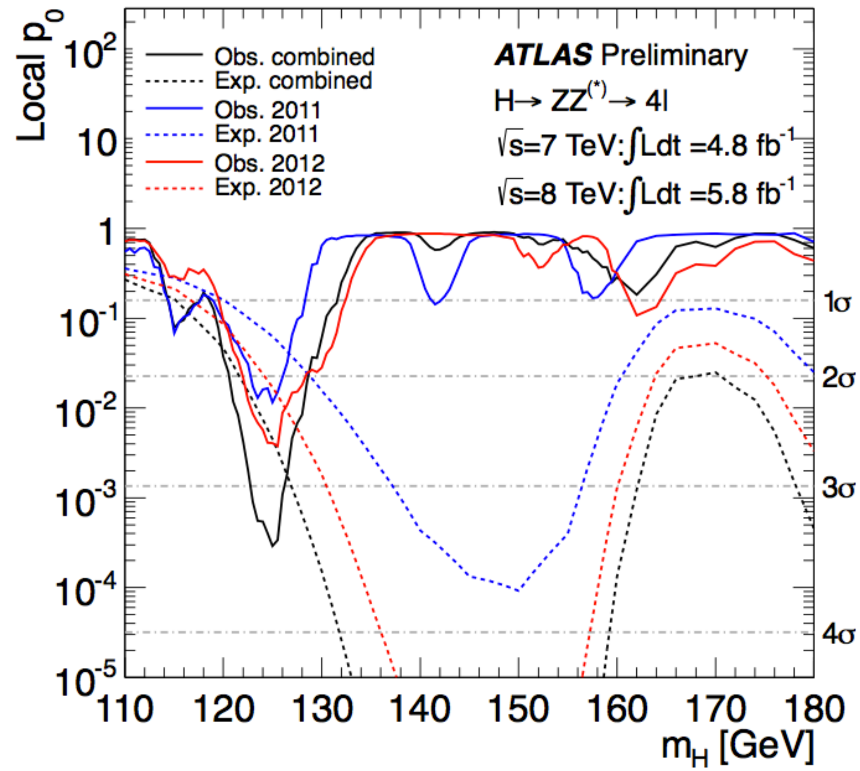




- Exclusion limits using CLs, profile likelihood ratio
- Exclusion: Expected: 124-164 and 176-500 [GeV]
  Observed: 131-162 and 170-460 [GeV]
- Much weaker than expected at 120-130 GeV

Significance of excess



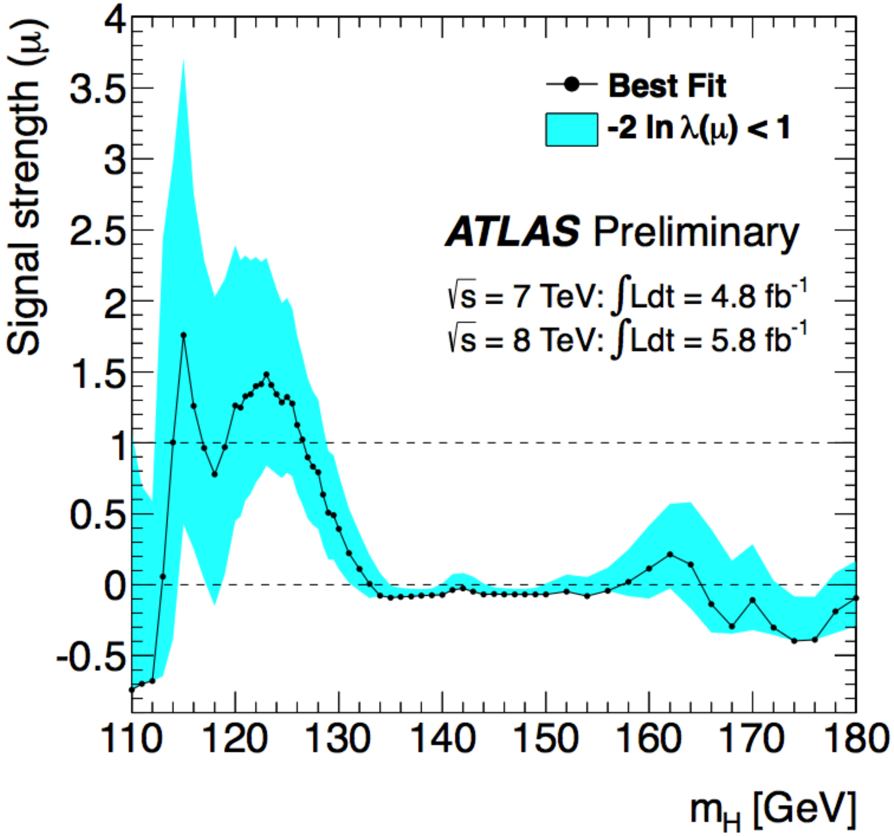


- At high m_H, small fluctuations from bg
- Consistent excesses in 2011 and 2012
- Combined: 3.4σ @ 125 GeV
  (with LEE for the range 100-141 GeV: 2.5σ)

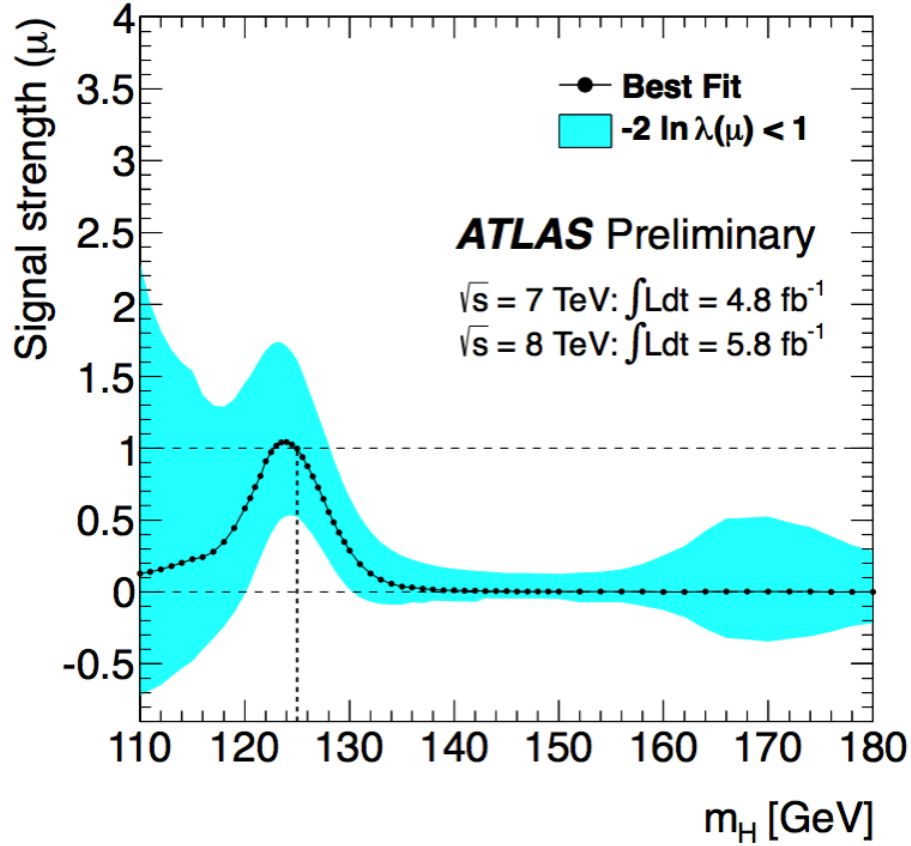
	m_H [GeV]	Obs	Exp
2012	125.0	2.7σ	2.1σ
2011	125.5	2.3σ	1.7σ
Combined	125.0	3.4σ	2.6σ

Signal Strength

DATA



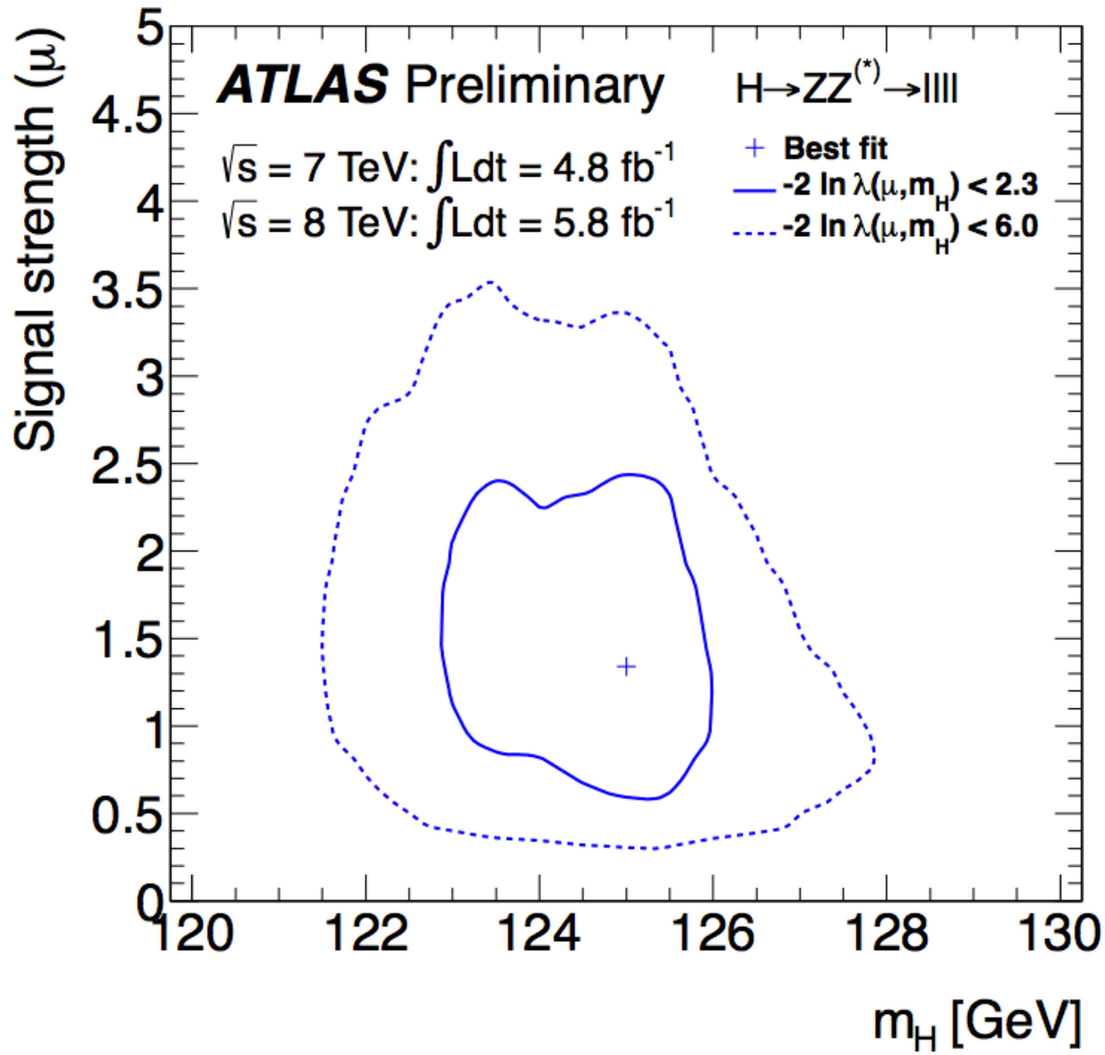
Signal injection at m_H=125 GeV



- μ = (best fit signal rate at m_H)/(expected SM rate at m_H)
- Best fit value at m_H=125 GeV (lowest p_0): 1.3 ± 0.6

Likelihood contours

- Signal strength (μ) vs m_H
- 2D likelihood fit; approximate 68% and 95% CL contours



Summary

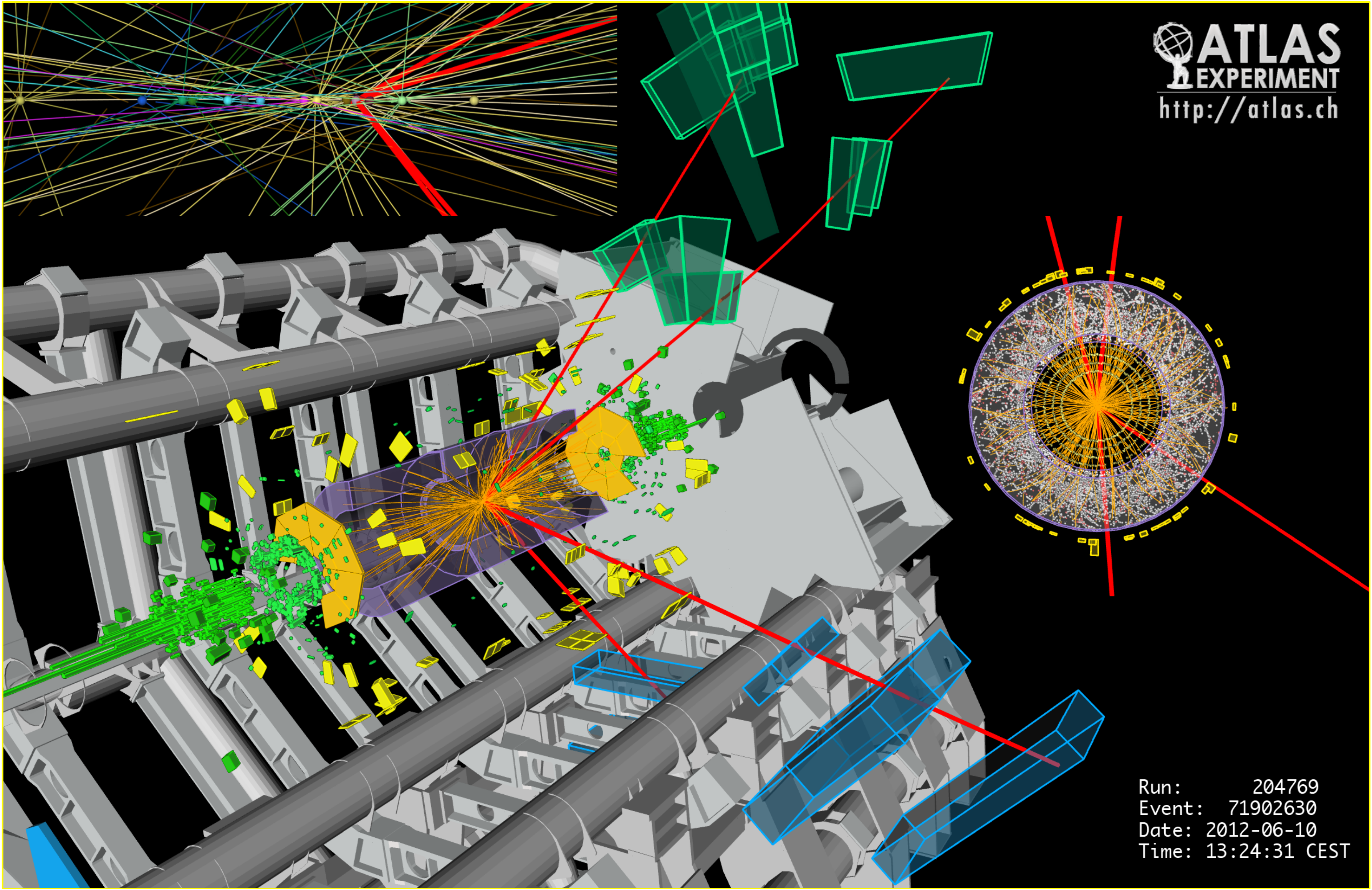
- **Updated analysis**
  - Progress on lepton performance and pile-up robustness
  - Improved sensitivity in the low mass region
  - Multiple, robust background estimation methods

- **An excess of events is observed at m_H~125 GeV**
  - Size and position consistent between 2011 and 2012 data
  - Combining the two datasets, local significance of **3.4σ**
    2.5σ global significance in the range 110-141 GeV

Backup slides

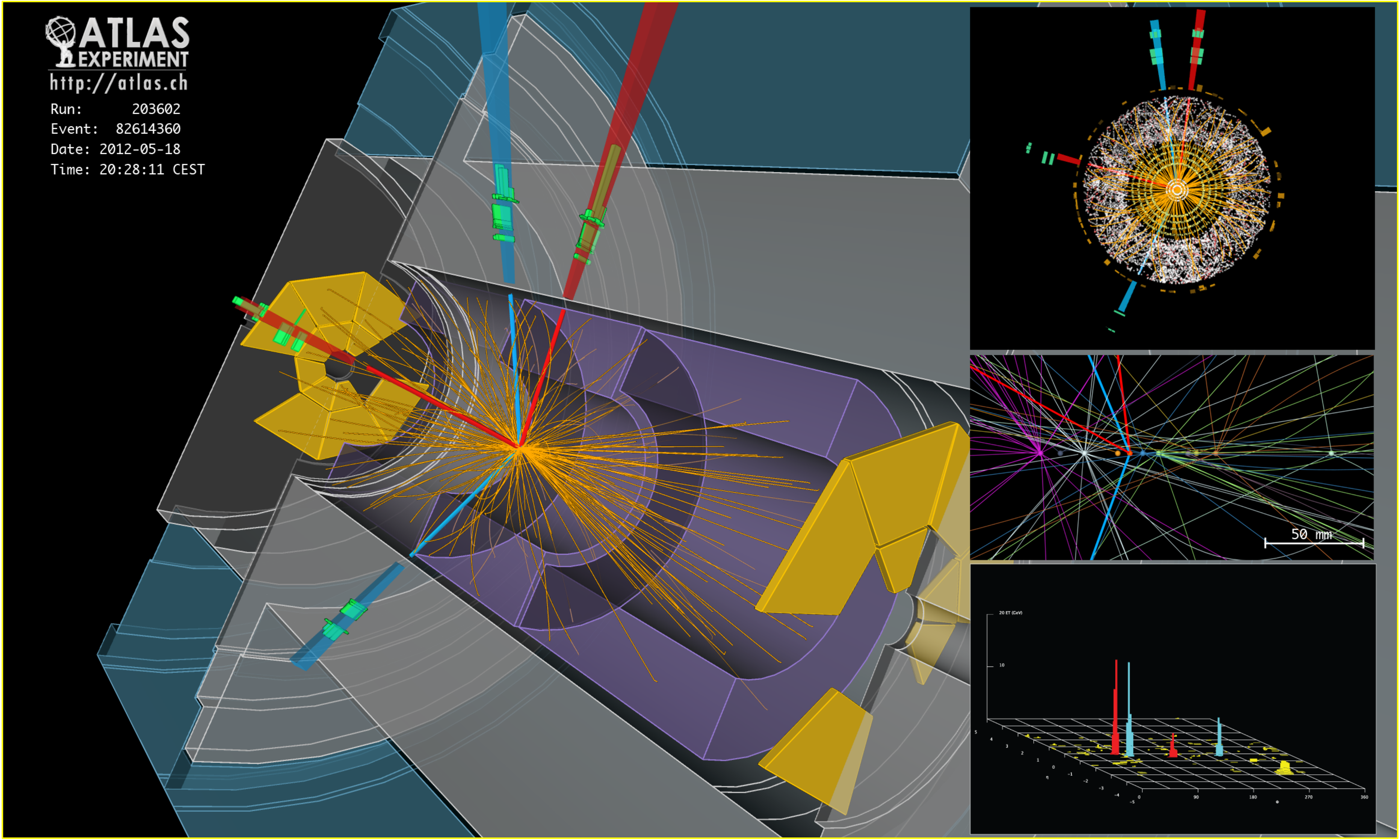
$m_{4\mu}$ = 125.1 GeV

p_T (muons)= 36.1, 47.5, 26.4, 71 .7 [GeV]
m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
15 reconstructed vertices



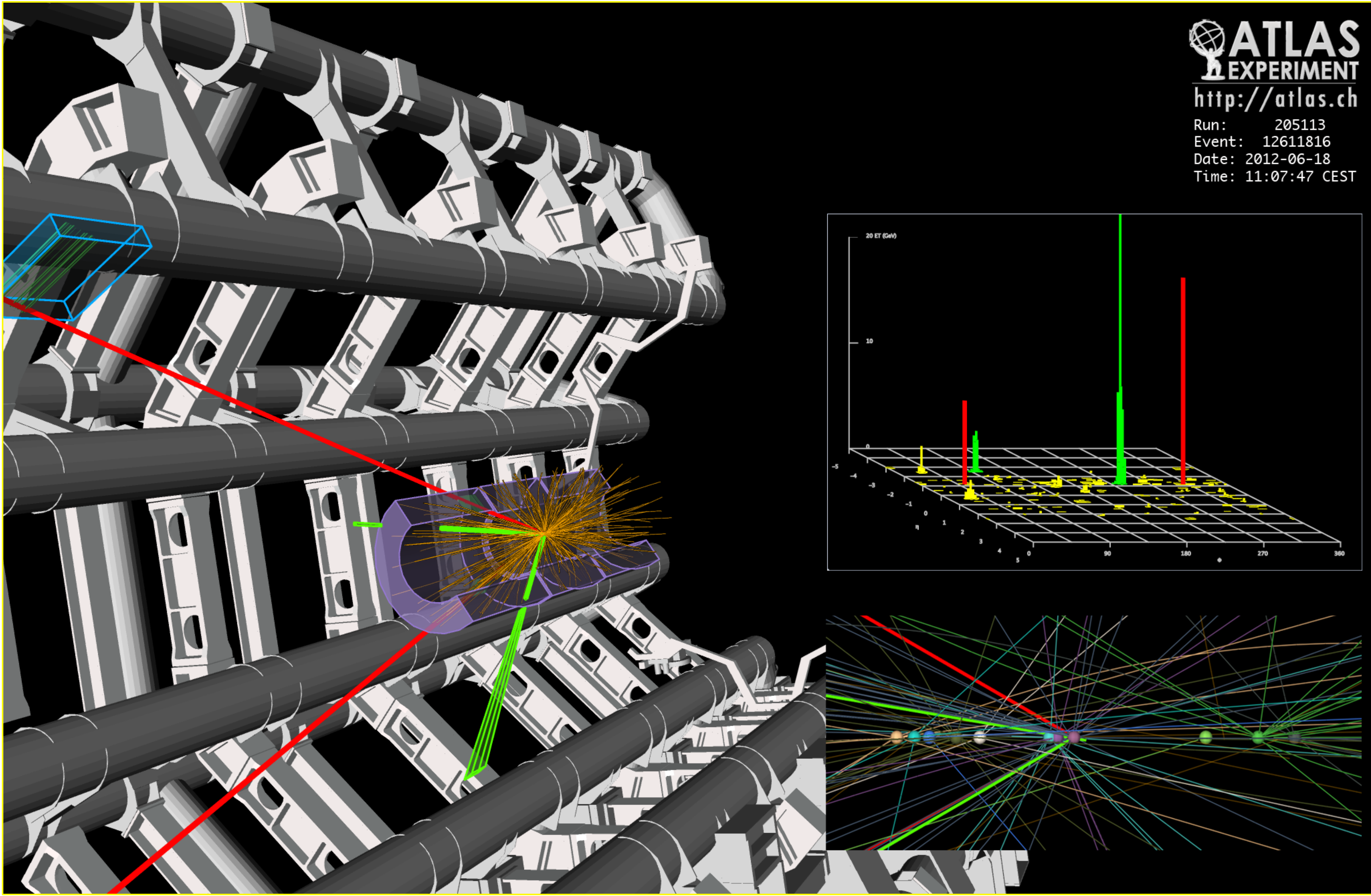
m_{4e} = 124.6 GeV

p_T (electrons)= 24.9, 53.9, 61.9, 17.8 [GeV]
m_{12}= 70.6 GeV, m_{34}= 44.7 GeV
12 reconstructed vertices

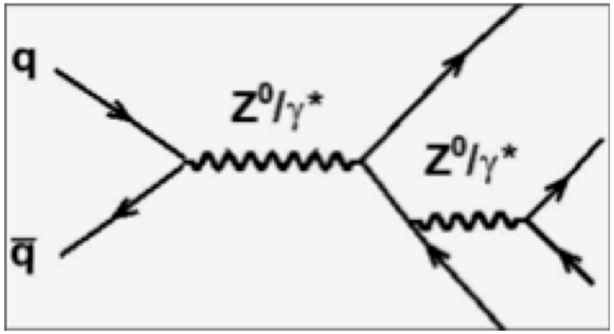


$m_{2e2\mu}$ = 123.9 GeV

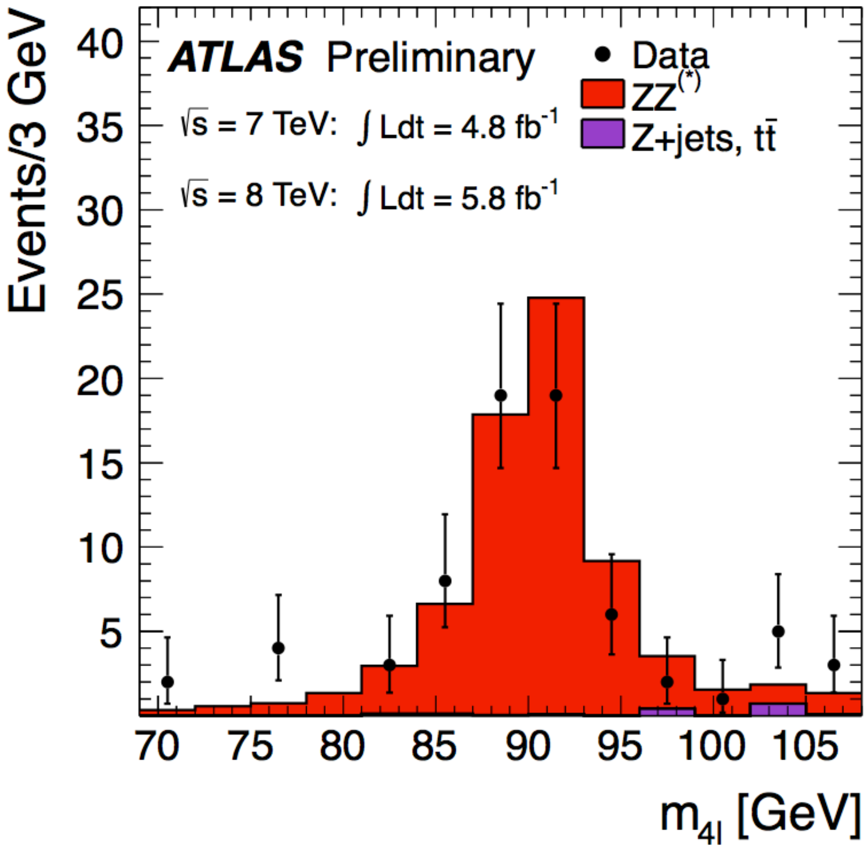
p_T (eeμμ)= 18.7, 76, 19.6, 7.9 [GeV]
m_{ee}= 87.9 GeV, $m_{\mu\mu}$= 19.6 GeV
12 reconstructed vertices



$pp \to Z \to 4l$



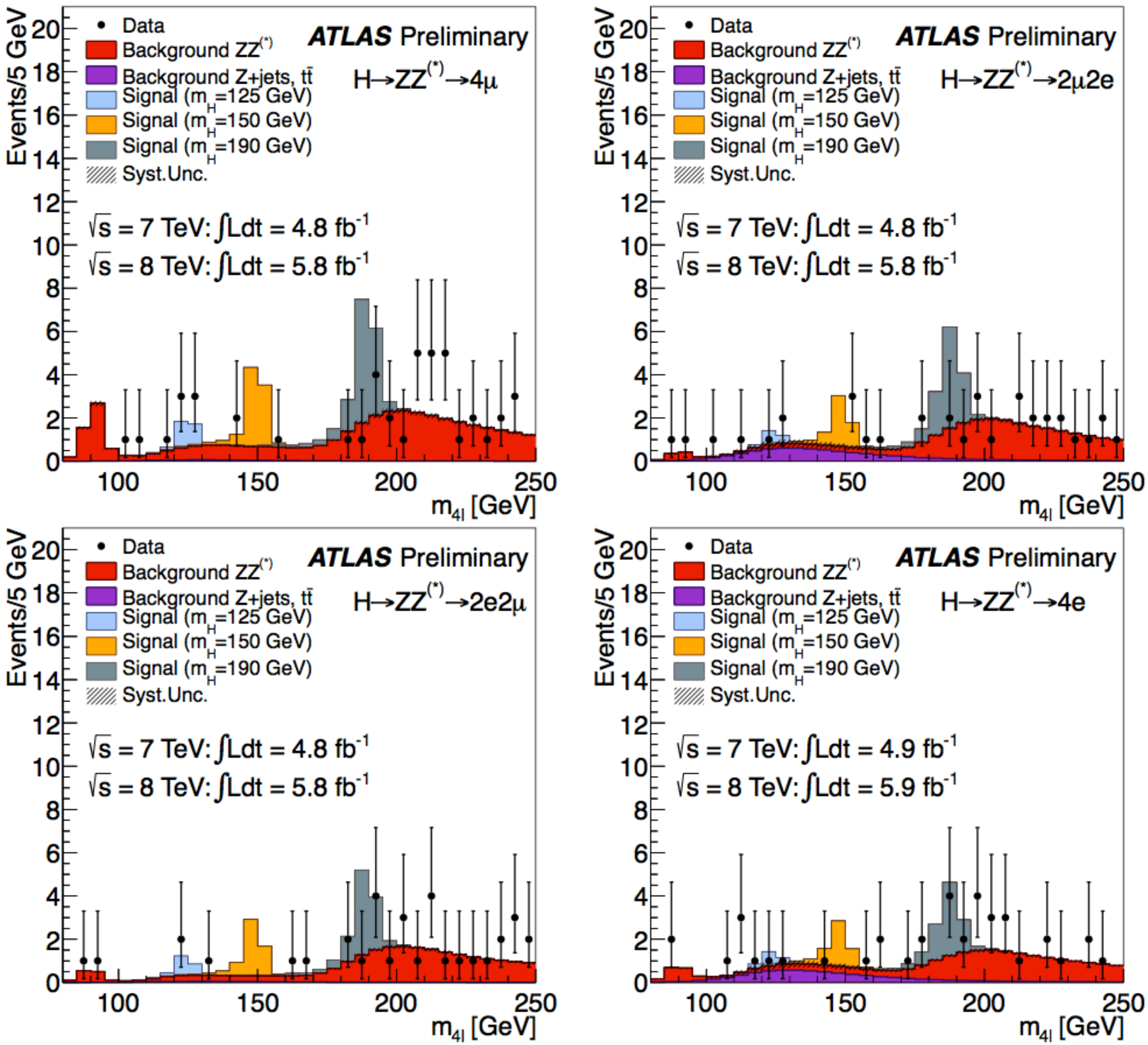
- Relax selection
  - m_{12}>30 GeV, m_{34}>5GeV
  - pT(muons) > 4 GeV
- Cross check of analysis configuration
- Indicates reasonable performance of lepton reconstruction and identification



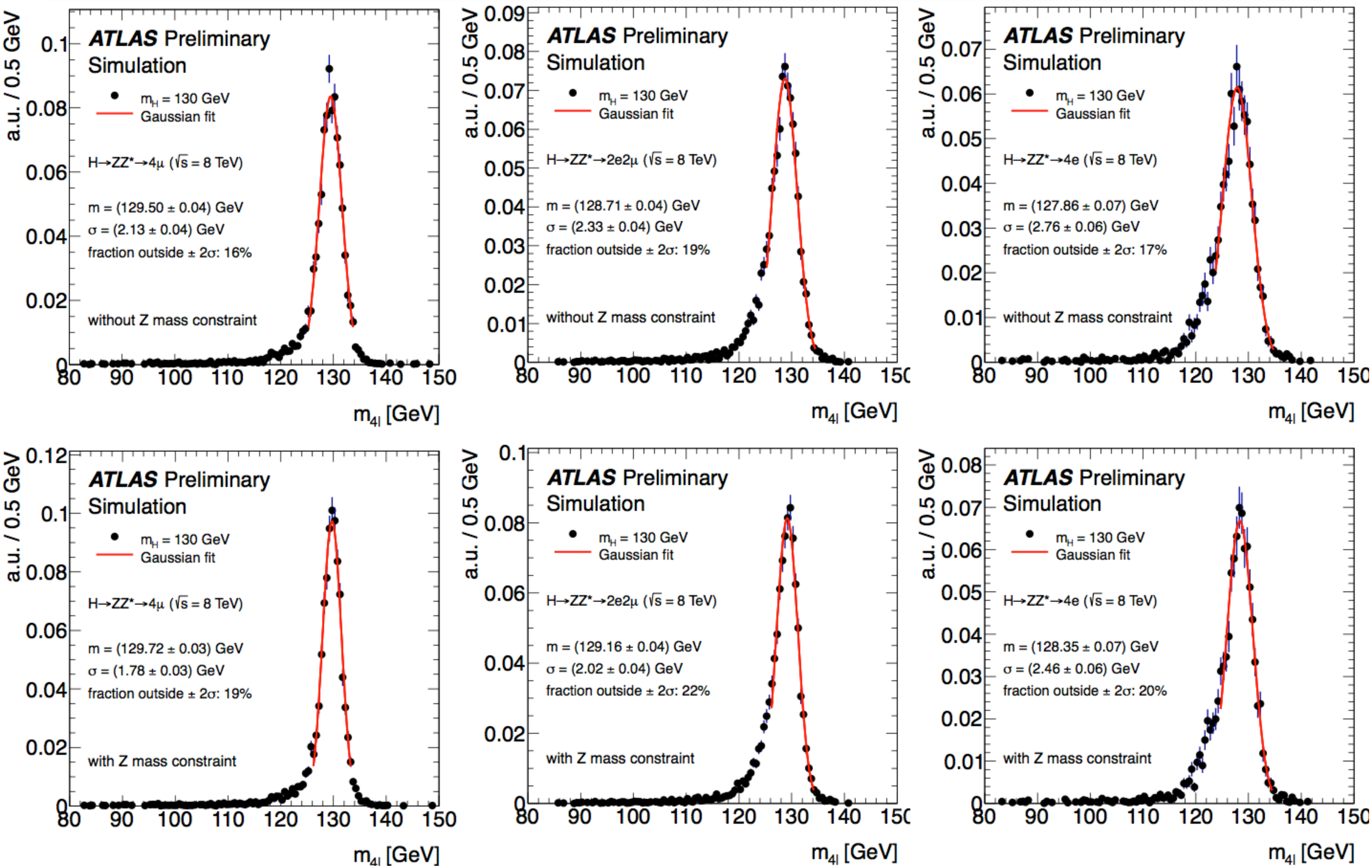
In m_Z±10 GeV:

- Expected: **65±5**
- Observed: **57**

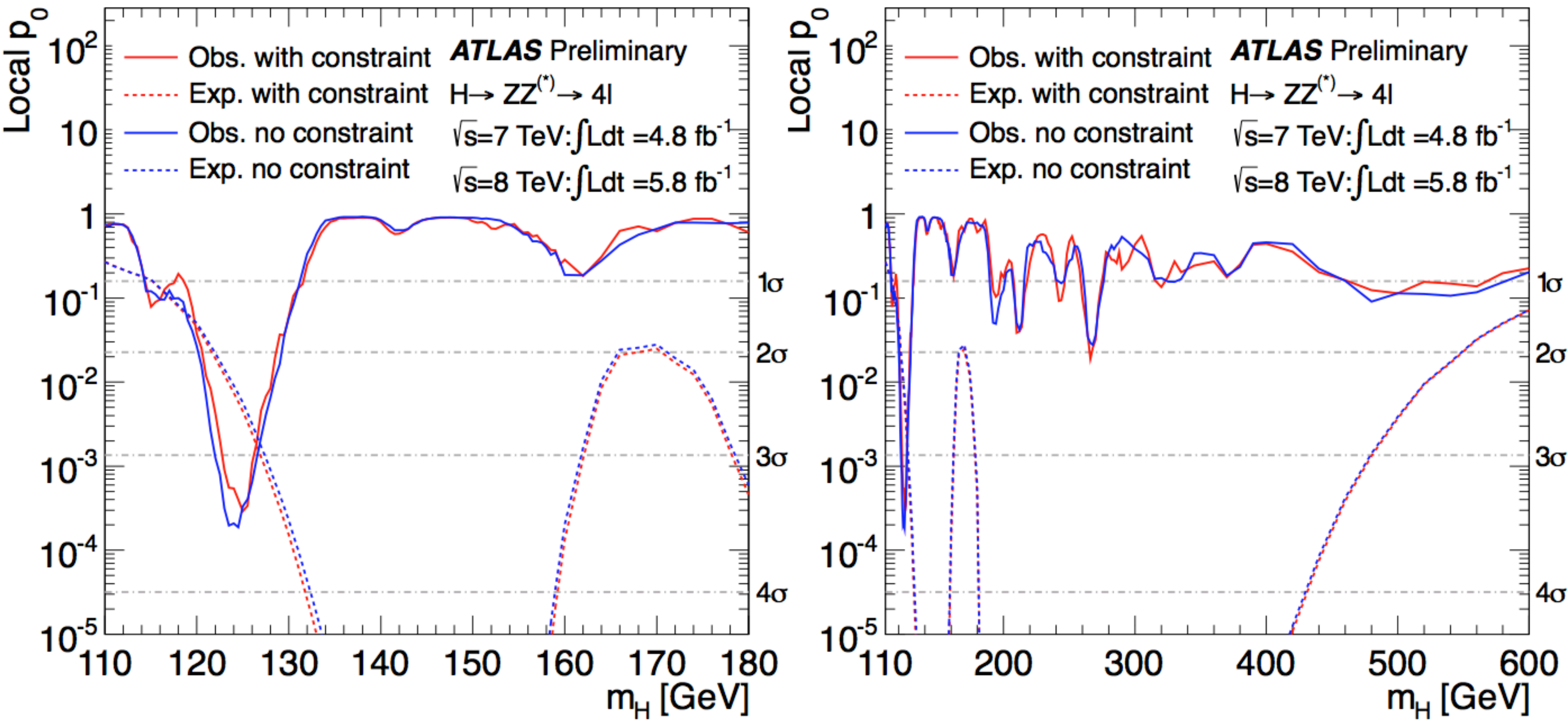
Per channel


Data
Background ZZ$^{(*)}$
Background Z+jets, $t\bar{t}$
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
Syst.Unc.
ATLAS Preliminary
$H\rightarrow ZZ^{(*)}\rightarrow 4\mu$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8 fb^{-1}
$H\rightarrow ZZ^{(*)}\rightarrow 2\mu 2e$
$H\rightarrow ZZ^{(*)}\rightarrow 2e2\mu$
$H\rightarrow ZZ^{(*)}\rightarrow 4e$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.9 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.9 fb^{-1}
Events/5 GeV
m_{4l} [GeV]

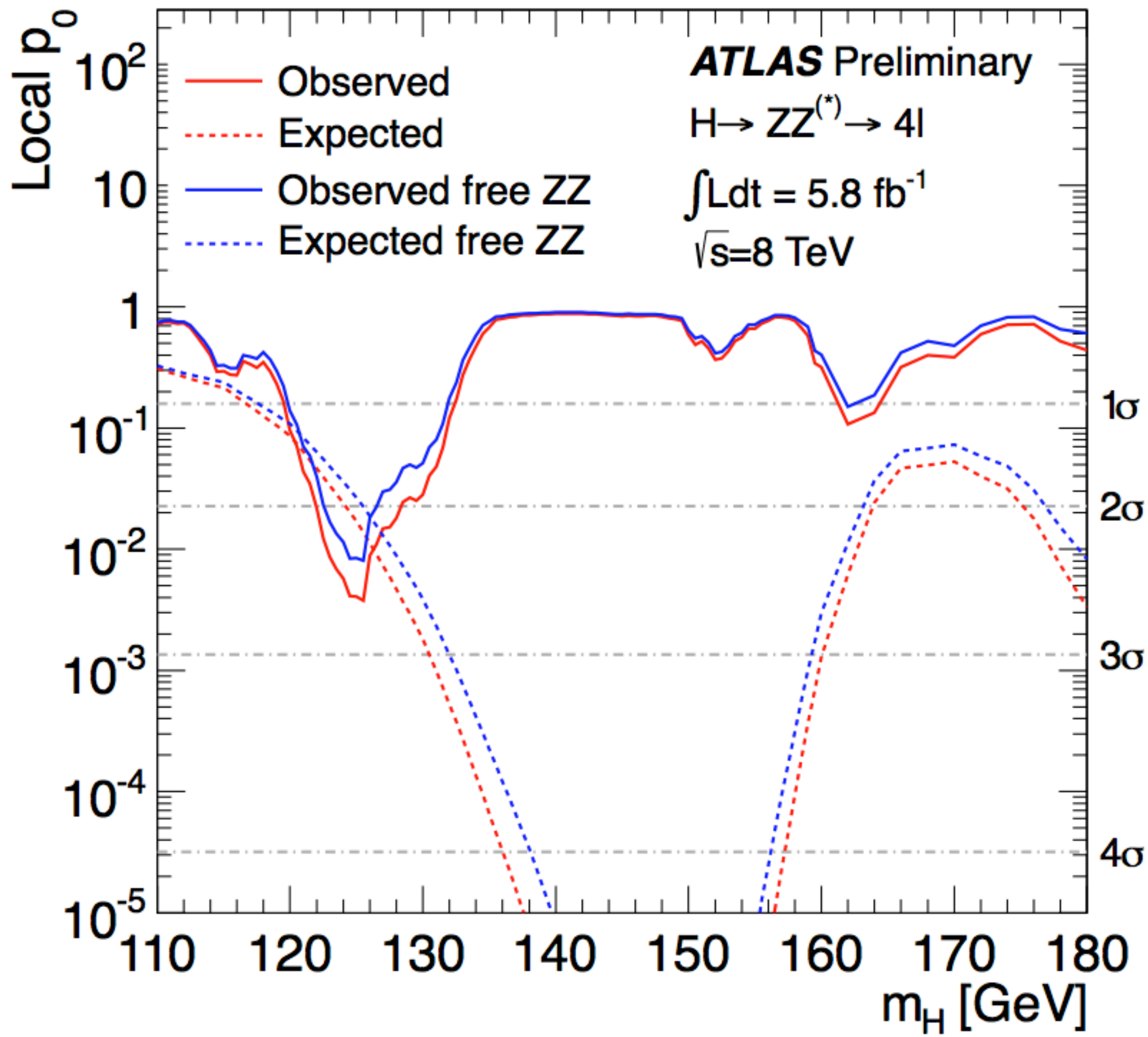
Mass resolution



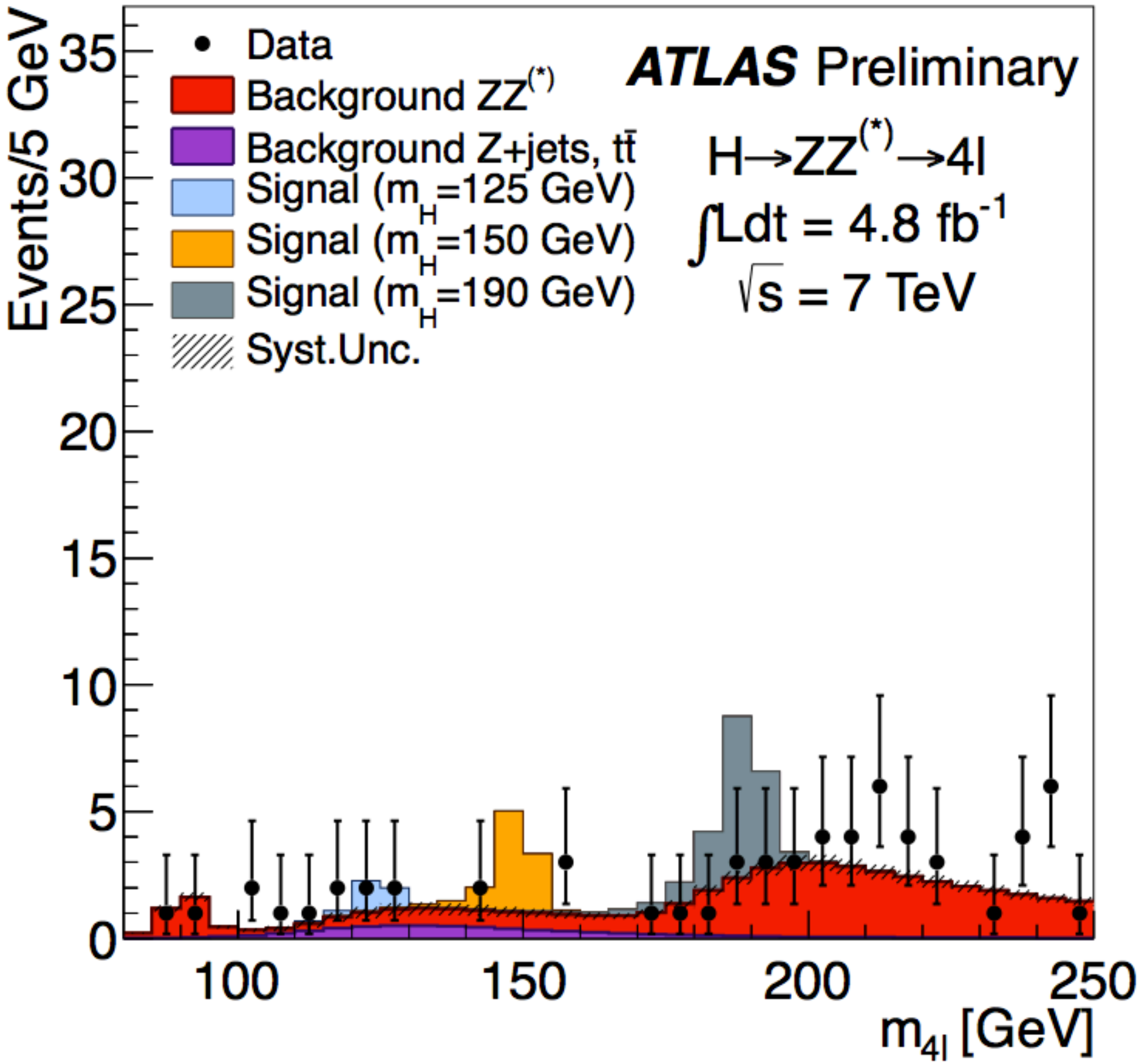
Effect of the Z mass constraint



ZZ normalization from data

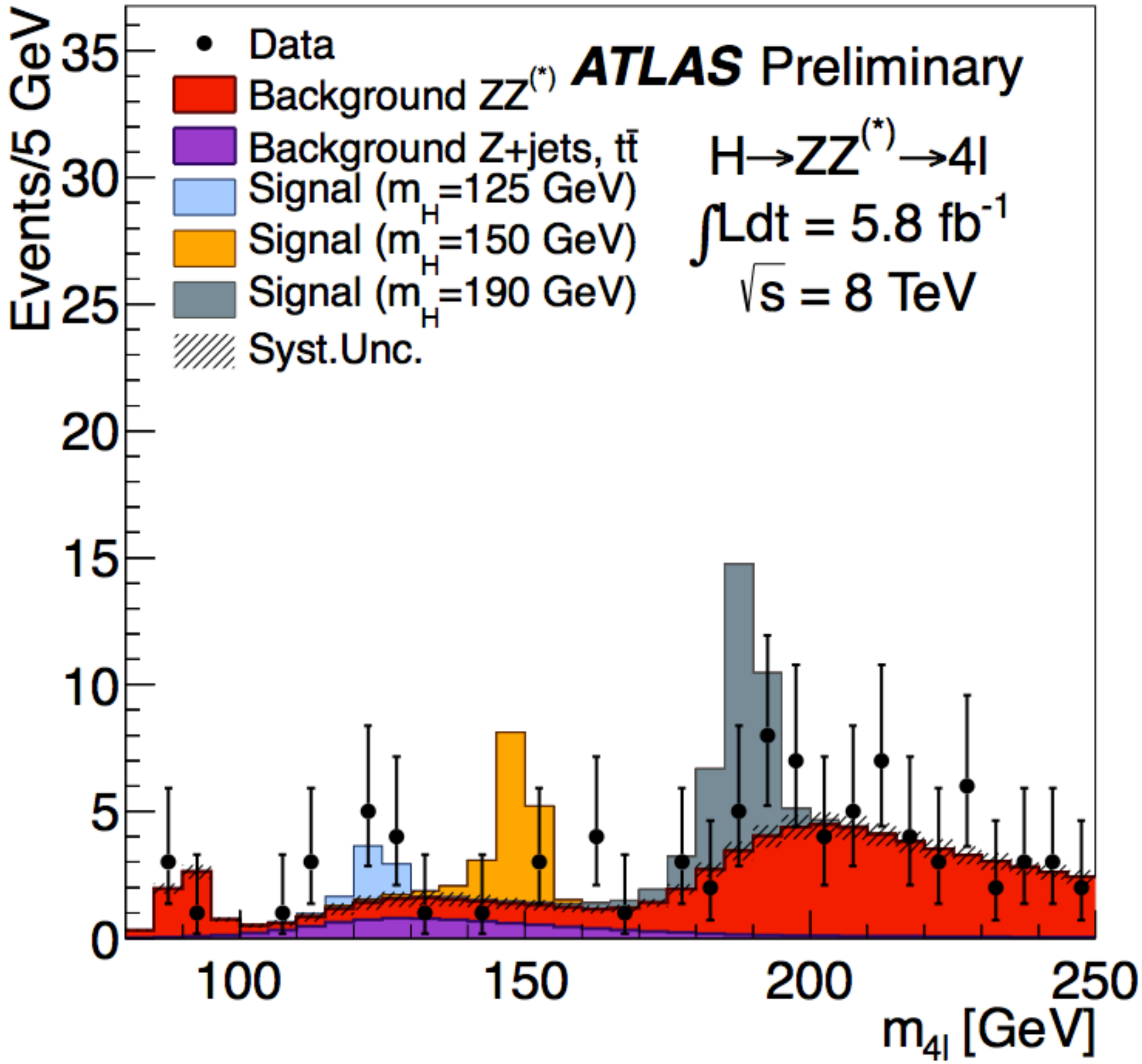


2011 data



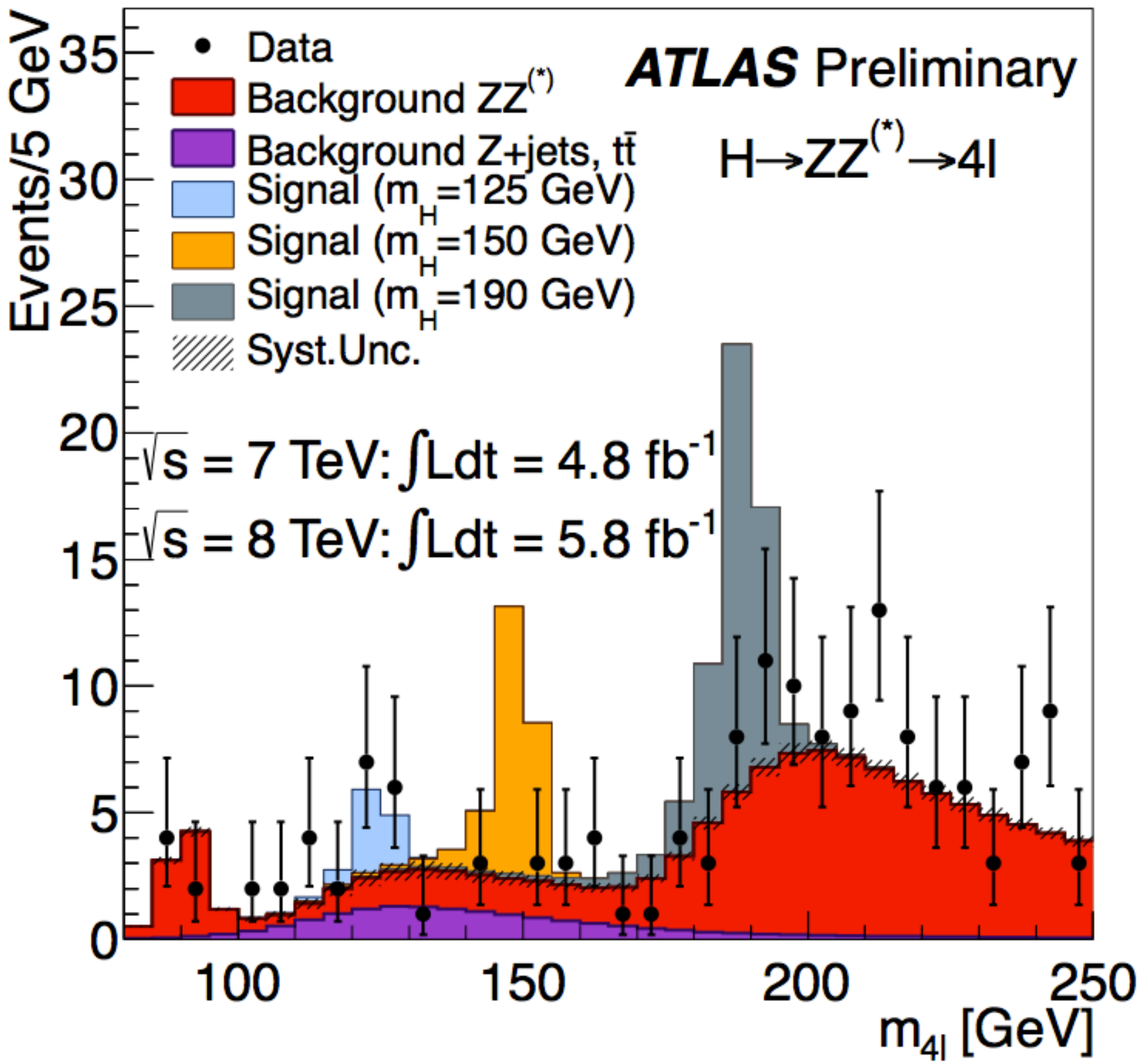
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (mH=125 GeV)
Signal (mH=150 GeV)
Signal (mH=190 GeV)
Syst.Unc.
ATLAS Preliminary
H→ZZ(*)→4l
∫Ldt = 4.8 fb-1
√s = 7 TeV
Events/5 GeV
0
5
10
15
20
25
30
35
100
150
200
250
m4l [GeV]

2012 data



Events/5 GeV
Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
Syst.Unc.
ATLAS Preliminary
H→ZZ(*)→4l
∫Ldt = 5.8 fb-1
√s = 8 TeV
0
5
10
15
20
25
30
35
100
150
200
250
m4l [GeV]

2011 data



Data
Background ZZ(*)
Background Z+jets, tt̄
Signal (m_H=125 GeV)
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
Syst.Unc.
ATLAS Preliminary
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Events/5 GeV
0
5
10
15
20
25
30
35
100
150
200
250
m4l [GeV]