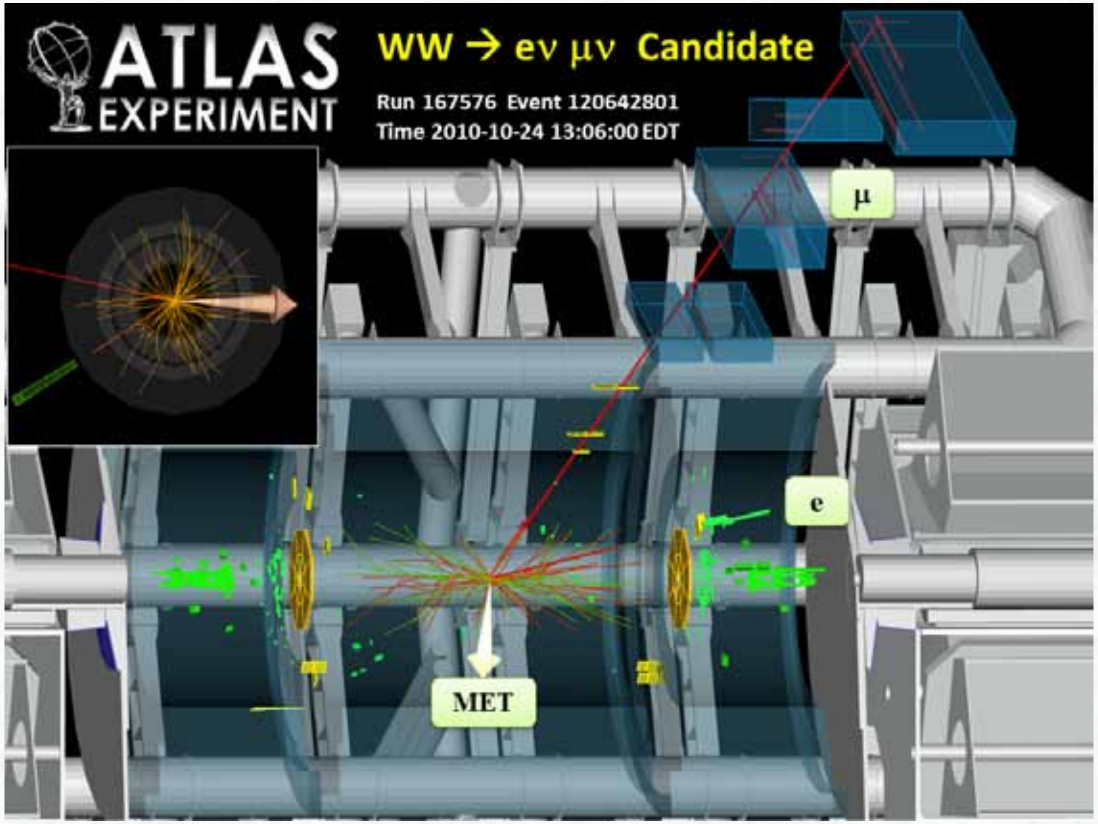
Higgs boson searches in the ATLAS experiment
- Recent results-



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Outline:

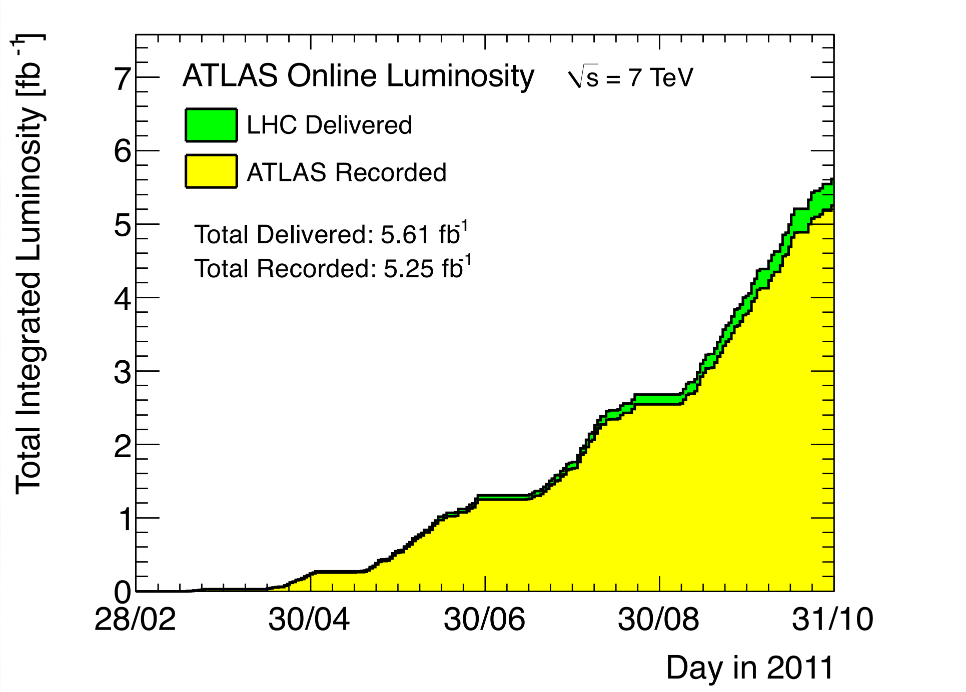
1. Introduction, Data taking, ATLAS performance

2. Search for the Standard Model Higgs boson
   - Focus on important channels in the low mass region
   - Summary of searches in the high mass region

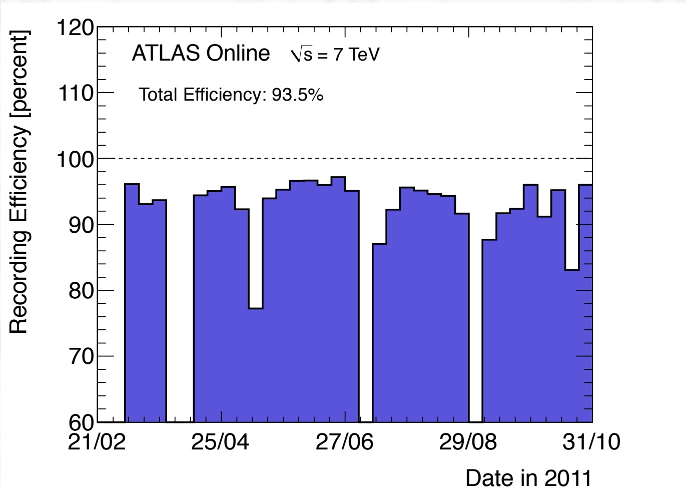
3. Combination of results

4. A few examples on recent searches for non-Standard Model Higgs bosons

ATLAS data taking in 2011

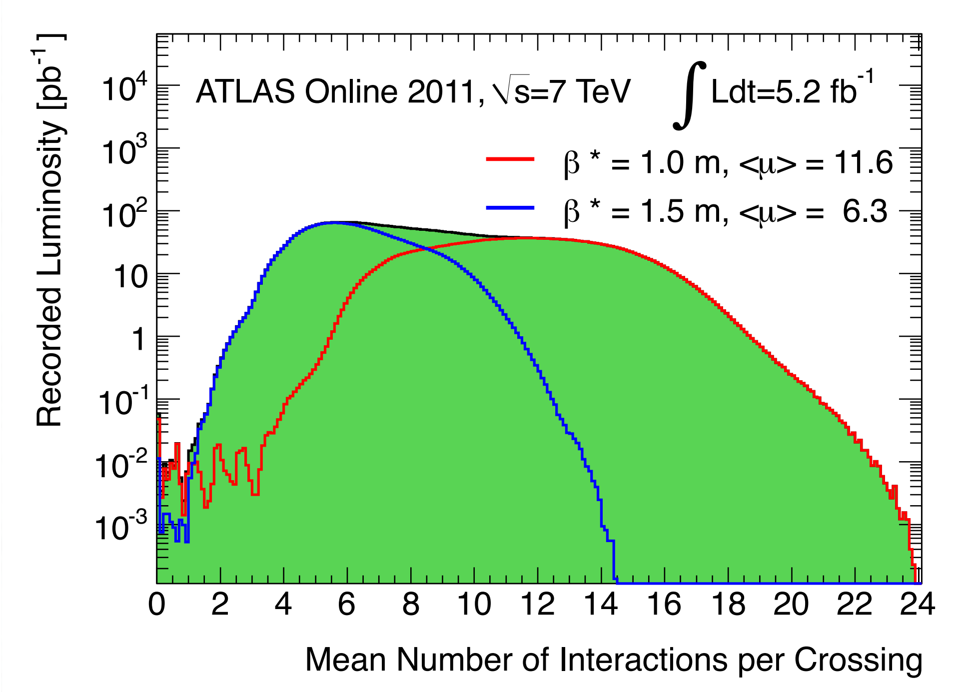


- Excellent LHC performance in 2011 (far beyond expectations)
- Peak luminosity seen by ATLAS: $3.6\ 10^{33}\ cm^{-2}\ s^{-1}$
- 1 fb^{-1} line passed in June 2011



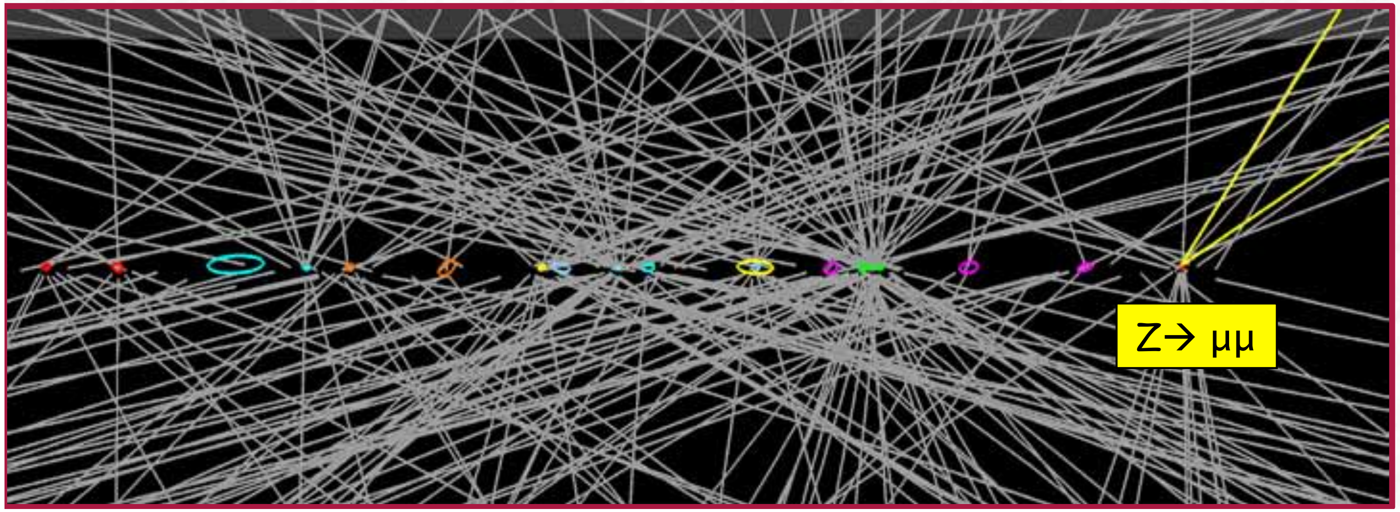
- Excellent performance of ATLAS
- Small fraction of non-working detector channels (few per mille → 3.5%)
- Data taking efficiency is high: ~93.5%
- High fraction (90-96%) used for analysis (good quality, depends on analysis)

ATLAS running conditions in 2011



- High peak luminosity and 50 ns bunch spacing → high pile-up
- Two running periods with different machine settings

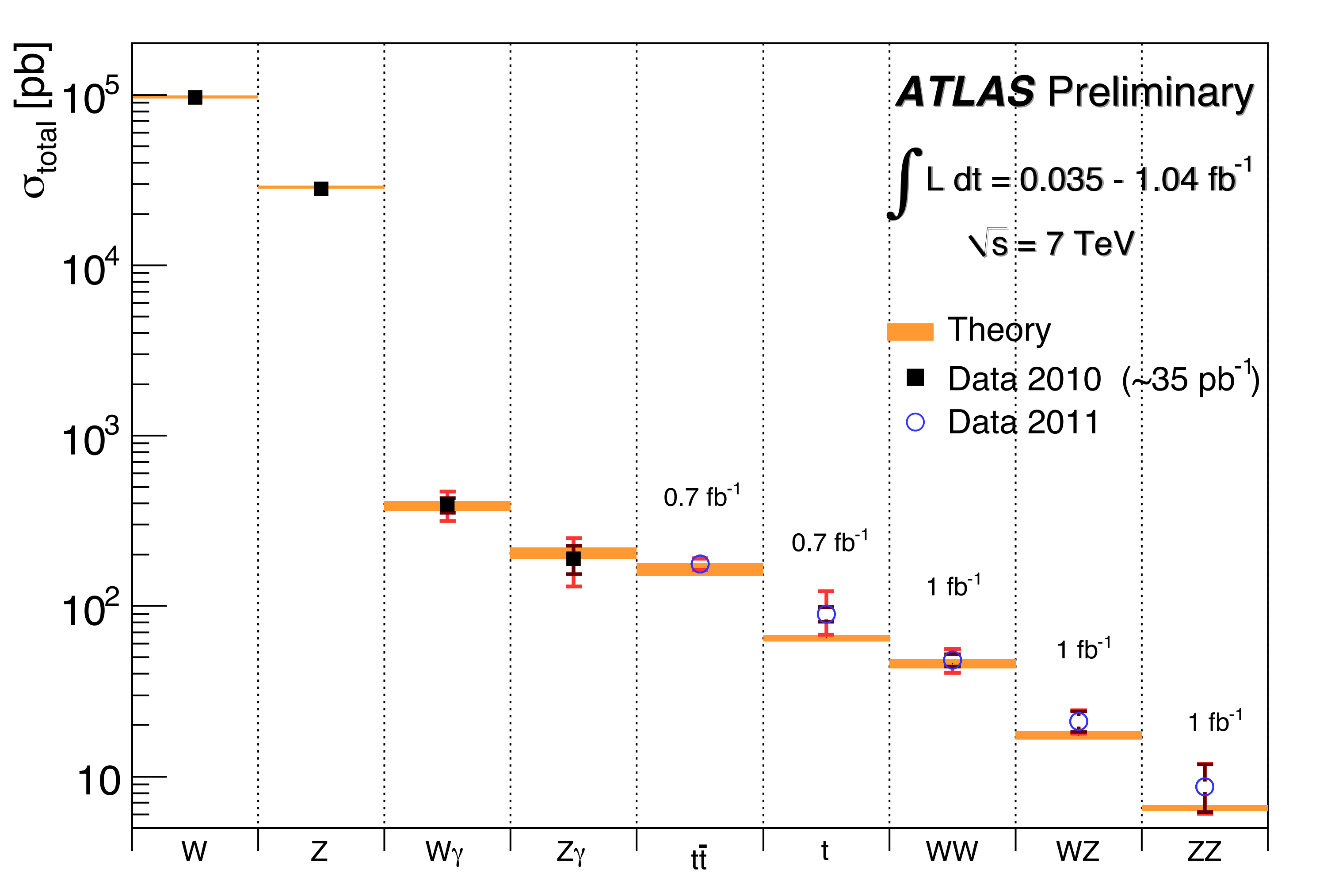
  (period A (Mar - July): μ = 6.3,
  period B (Aug. - Oct): μ = 11.6,
  with tails beyond 20 interactions / beam crossing, ~ design luminosity)
- Very challenging for trigger, computing, reconstruction of physics objects,…



An event with 20 reconstructed vertices

(error ellipses are scaled up by a factor of 20 for visibility reasons)

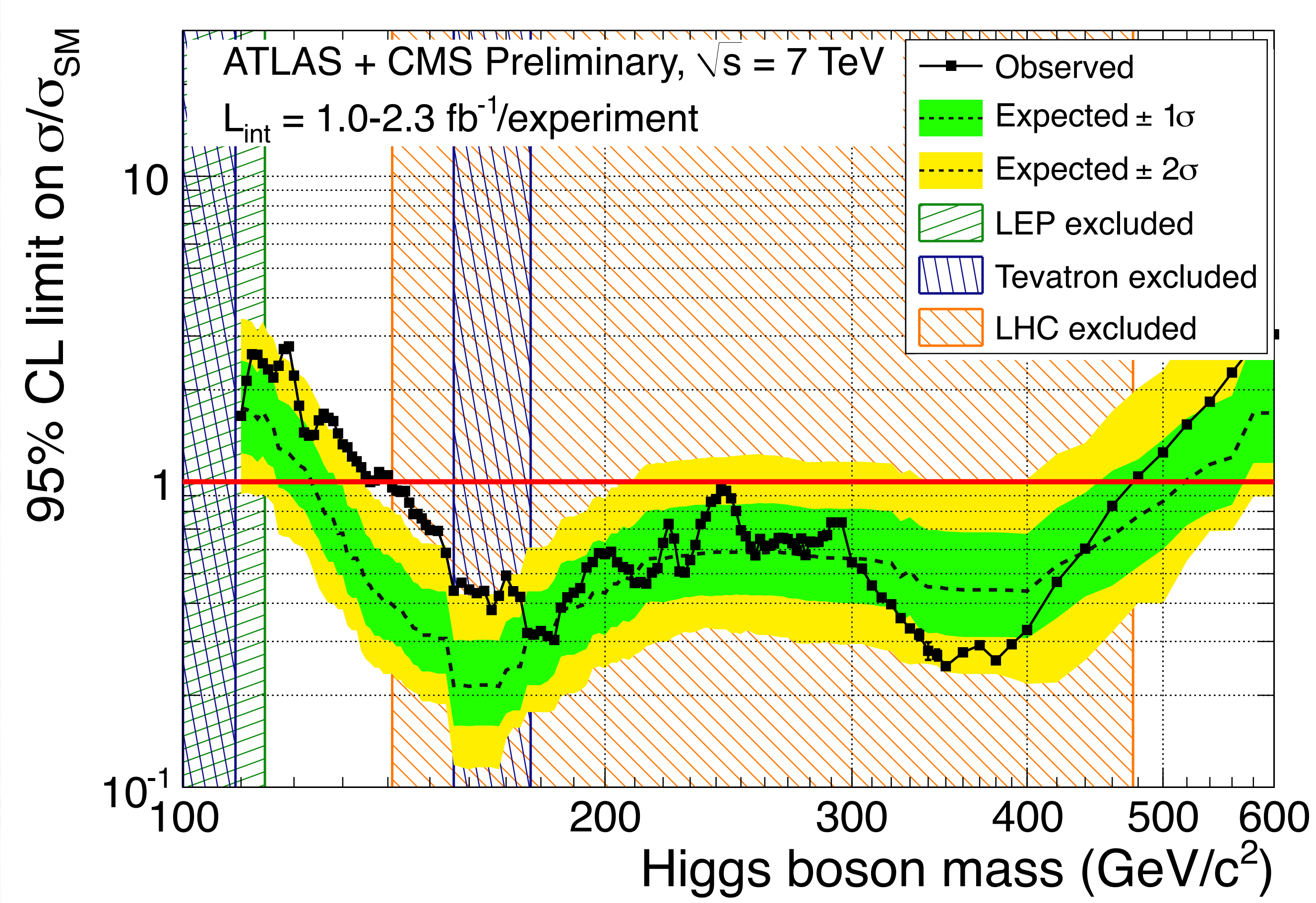
An impressive number of processes have already been measured



- Excellent agreement with the Standard Model predictions
- Important for background estimates in Higgs boson searches

Status of Higgs Boson searches

- based on results presented at the Summer Conferences 2011-



Higgs boson mass constraints: 114.4 < m_H < 141 GeV
(at 95% C.L.) .or. m_H > 476 GeV

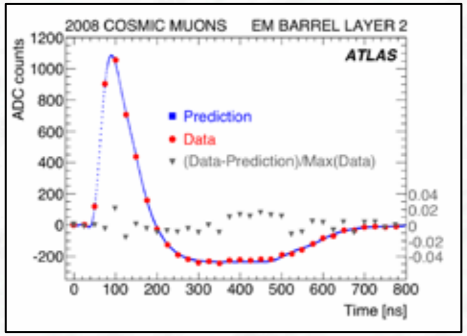
Updates on the analyses (since the Summer Conferences)

- More data: analyses of some channels are based on the full 2011 data set (up to 4.9 fb^{-1})

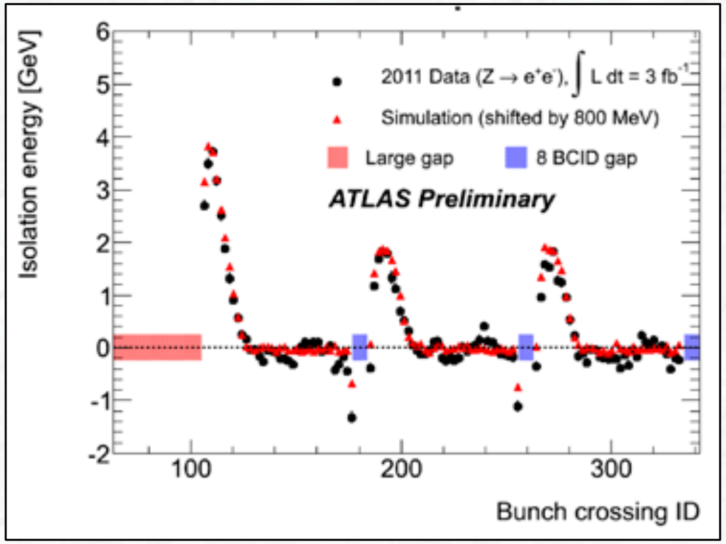
- Huge effort to improve the understanding of the detector performance
  - 2011 data recorded with very different conditions compared to 2010

  - Improved knowledge (of many subtle effects) propagated to the simulation and reconstruction, e.g.
    * in- and out-of-time pile-up, including bunch train structure (see below)
    * new detector alignment
    * better material description
    * …

- Example: pile-up energy in a cone around e/γ candidates (isolation energy) depends on the position in the bunch train

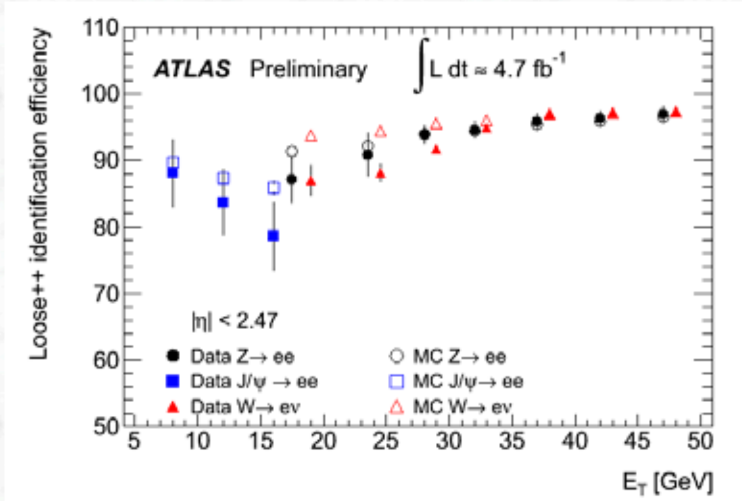


Calorimeter bipolar pulse shape: average pile-up is zero over ~ 600 ns (~12 bunches)



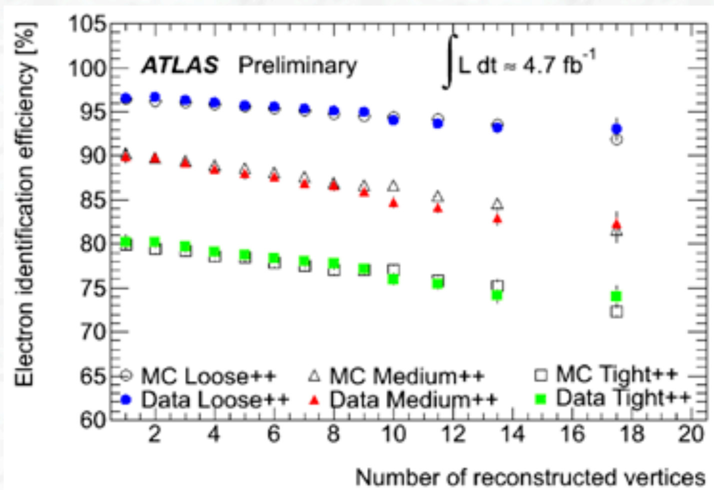
A few performance figures: (i) electrons

- Electron identification efficiencies:
  (based on measurements from Z → ee,
  W → eν and J/ψ→ ee in data,
  using the so-called "tag-and-probe" method)



Systematic uncertainty: ±6% (p_T ~7 GeV)
< ±2% (p_T ~50 GeV)

- Variation of the electron efficiency with pile-up
  is well modelled in the simulation
  (Z → ee data vs. simulation, cuts not yet re-tuned)

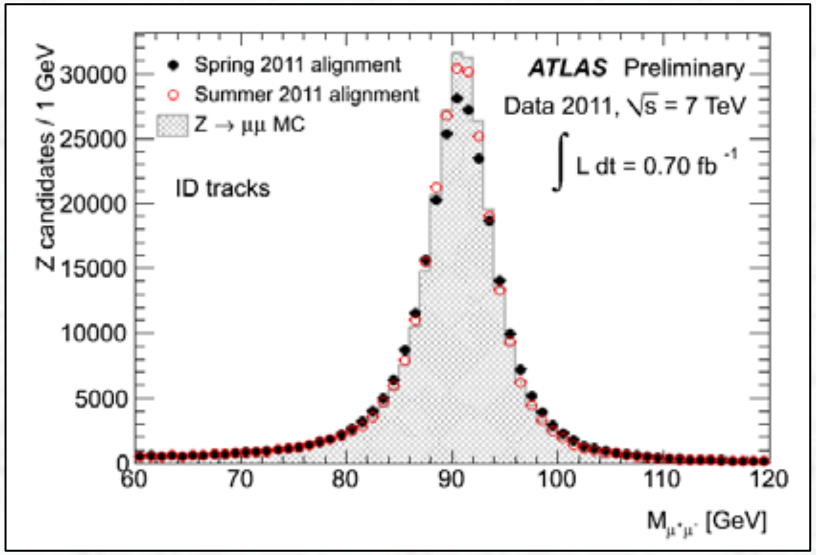


- Electron calorimeter energy scale:
  (based on Z → ee, W → eν, J/ψ→ ee in data)

  - Energy scale at m_Z known to ~0.5%
  - Linearity better than 1% (over few GeV → few 100 GeV)
  - "Uniformity" (constant term of resolution): 1% (barrel) -1.7 % (end-cap)

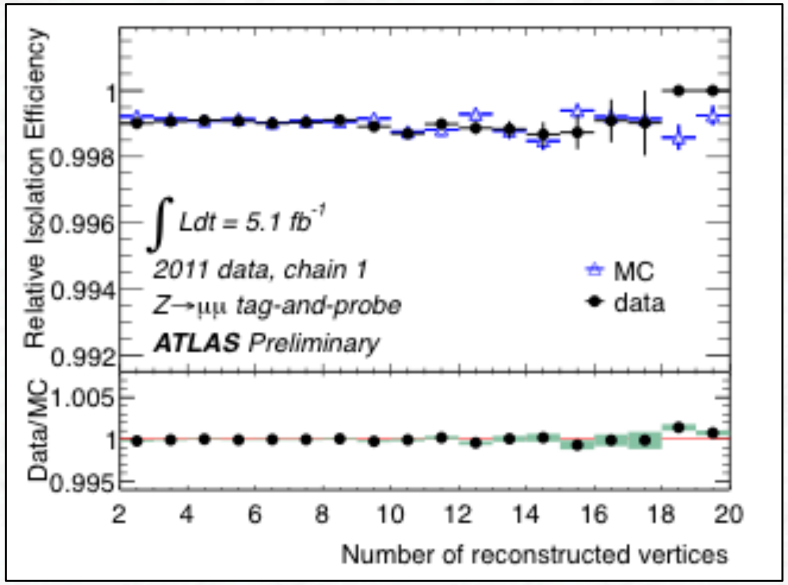
A few performance figures: (ii) muons

Improved Z → μμ mass resolution via improved alignment

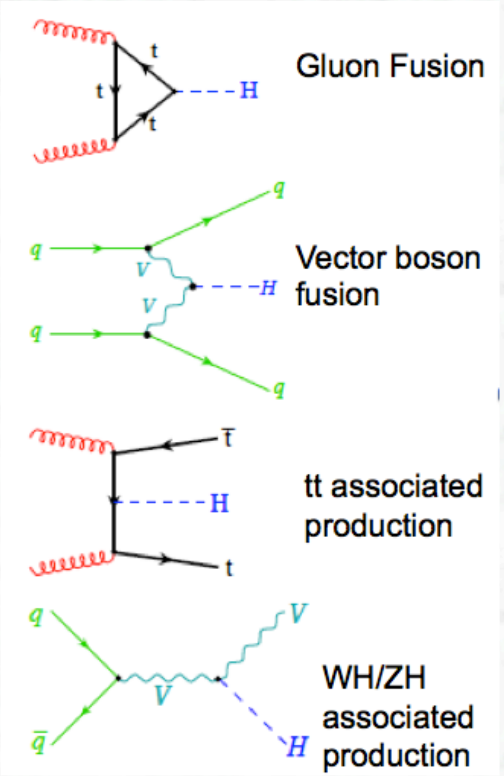


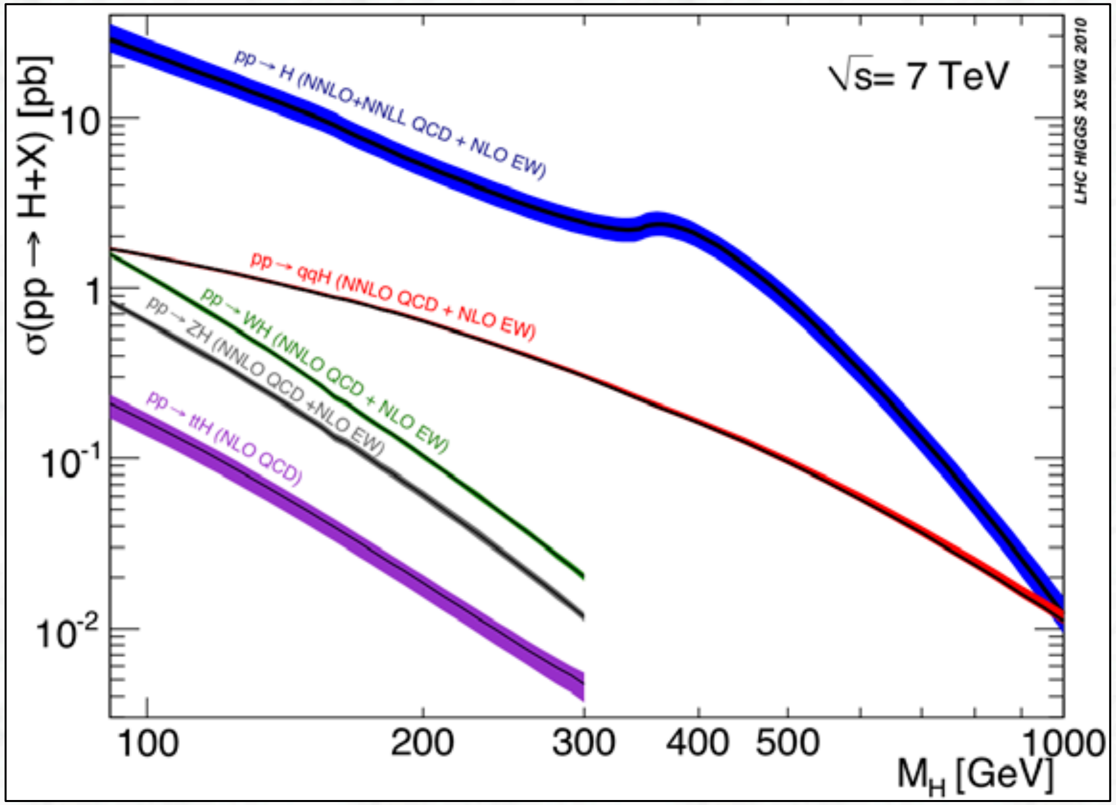
MC (perfect):	2.31 ± 0.01 GeV
Data Spring 2011 :	2.89 ± 0.01 GeV
Data Summer 2011:	2.45 ± 0.01 GeV

Muon isolation efficiency (in calorimeter), measured from Z → μμ events in data and Monte Carlo simulation



Higgs boson production cross sections





LHC Higgs cross-section working group, 2010, arXiv: 1101.0593

ATLAS Higgs boson signal simulation:

- POWHEG Monte Carlo + PYTHIA for showering and hadronization
- Cross sections normalized to calculations of LHC Higgs cross-section working group (NNLO+NNLL for gg, NNLO for VBF and VH processes)
- Reweighting of Higgs boson p_T spectrum in gg process (De Florian et al, arXiv:1109.2109)
- Uncertainties according to the recommendations of the LHC Higgs cross-section group

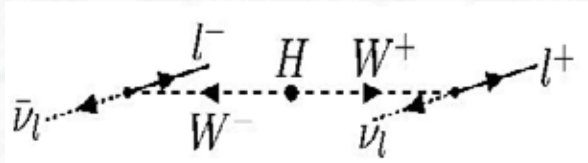
Overview on ATLAS analyses

Channel	Mass range (GeV)	L_{int} (fb^{-1})	Main backgrounds
Low mass:			
H → $\gamma\gamma$	110 – 150	4.9	$\gamma\gamma$, γj, jj
H → ZZ*→ 4ℓ	110 - 180	4.8	ZZ*, tt, Zbb
H → $WW^{(*)}$ → ℓν ℓν	110 – 180	2.1	WW, tt, Z+jets
H → ττ → ℓℓ + … → ττ → $\ell\tau_{had}$ + ..	110 – 140 100 - 150	1.1 1.1	Z → ττ, tt Z → ττ, tt
W(Z) H → ℓν(ℓℓ) bb	110 – 130	1.1	W(Z) + jets, tt ,..
High mass:			
H → WW → ℓν ℓν → ℓν qq	180 – 300 240 - 600	2.1 1.1	WW, tt, Z+jets W+jet, tt, jets (QCD)
H → ZZ → 4ℓ → ℓℓ νν → ℓℓ qq	180 – 600 200 – 600 200 – 600	4.8 2.1 2.1	ZZ ZZ, tt, Z+jets Z+jets, tt

- Searches in $\gamma\gamma$ and 4ℓ final states are based on the full data set
- Updates of the other channels expected for Moriond 2012
  (requires a solid understanding of more complex signatures at high luminosity, e.g. E_T^{miss})

Search for H → WW → ℓν ℓν

- Most sensitive channel over ~130 – 180 GeV (large H → WW branching ratio around 160 GeV)



- Clean signature of two isolated leptons, large E_T^{miss}, Topological cuts against the "irreducible" WW background ($\Delta\phi_{\ell\ell}$, $p_T(\ell\ell)$, $m_{\ell\ell}$ -due to spin-0 of Higgs boson-)

- However, two neutrinos in final state, no mass peak → counting experiment

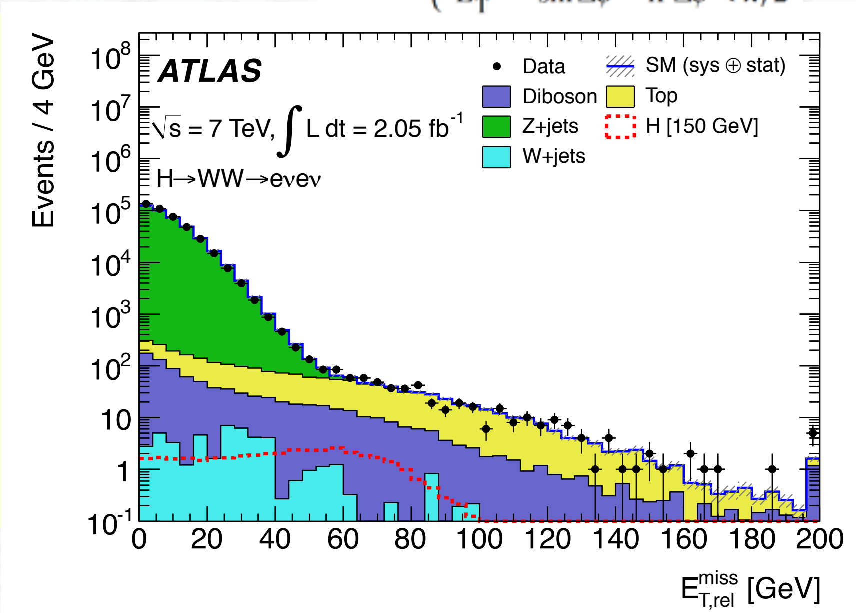
Important: - understanding of missing transverse energy and
- backgrounds in the signal region (transverse mass)

$$E_{T,rel}^{miss} = \begin{cases} E_T^{miss} & \text{if } \Delta\phi \geq \pi/2 \\ E_T^{miss} \cdot \sin\Delta\phi & \text{if } \Delta\phi < \pi/2 \end{cases}$$

E_T^{miss} distribution after basic lepton requirements: p_T > 25 / 15 GeV
$m_{\ell\ell}$ > 15 GeV

- well described (several components), dominated by real E_T^{miss} above ~50 GeV;

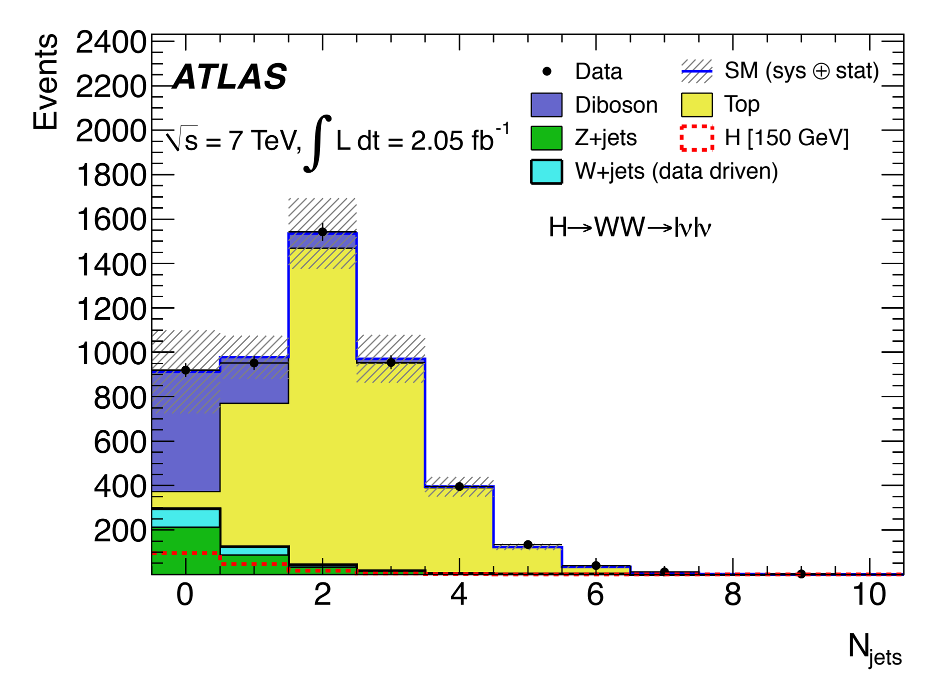
(no large tails from fake E_T^{miss} visible)



Search for H → WW → ℓν ℓν (cont.)

- Additional cuts: Z-mass veto: $|m_{\ell\ell} - m_Z| < 15$ GeV (ee, μμ)
  $E_{T,rel}^{miss} > 40$ GeV (ee,μμ), > 25 GeV (eμ)

- Split according to jet multiplicity ($E_T > 25$ GeV)
  → multiplicity distribution well described
  → background composition depends on # jets



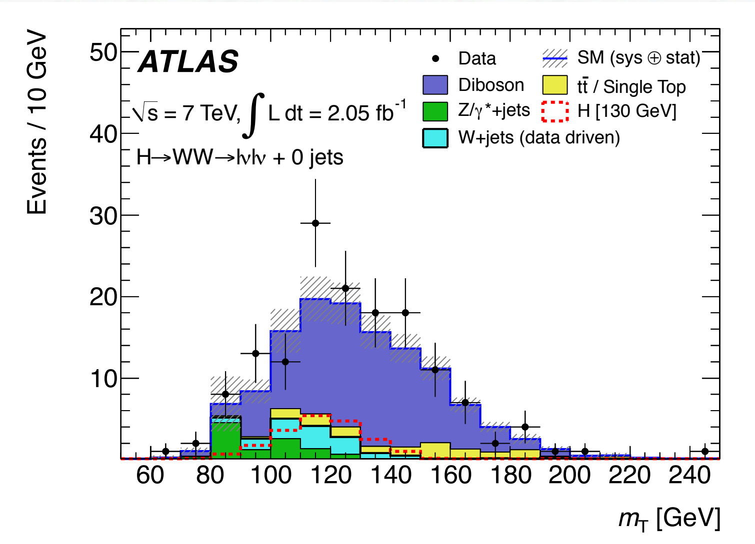
- Use control regions with small signal contamination in data to constrain the backgrounds
- Use Monte Carlo to extrapolate into the signal region

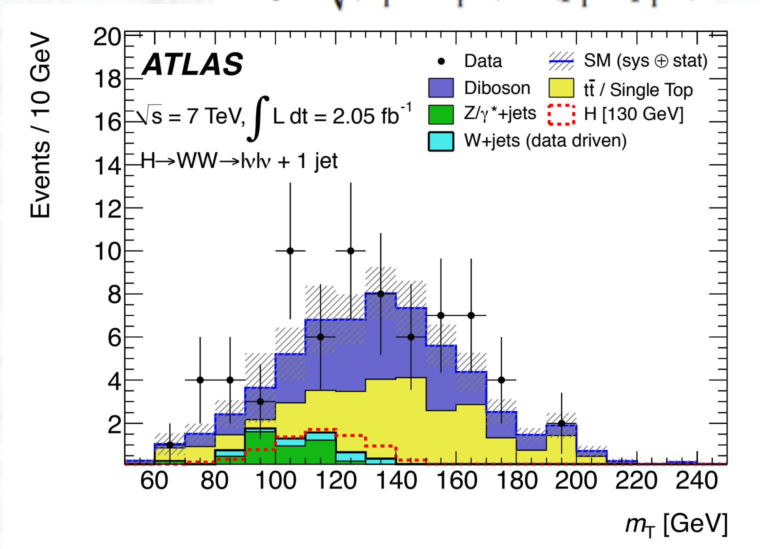
Control region	MC expectation	Observed in data
WW 0-jet	296±36	296
WW 1-jet	171±21	184
Top 1-jet	270±69	249

Search for H → WW → ℓν ℓν (cont.)

- Transverse mass distributions for the 0- and 1-jet events after additional topological cuts ($\Delta\phi_{\ell\ell} < 1.3$, $m_{\ell\ell} < 50$ GeV)

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{miss})^2}$$





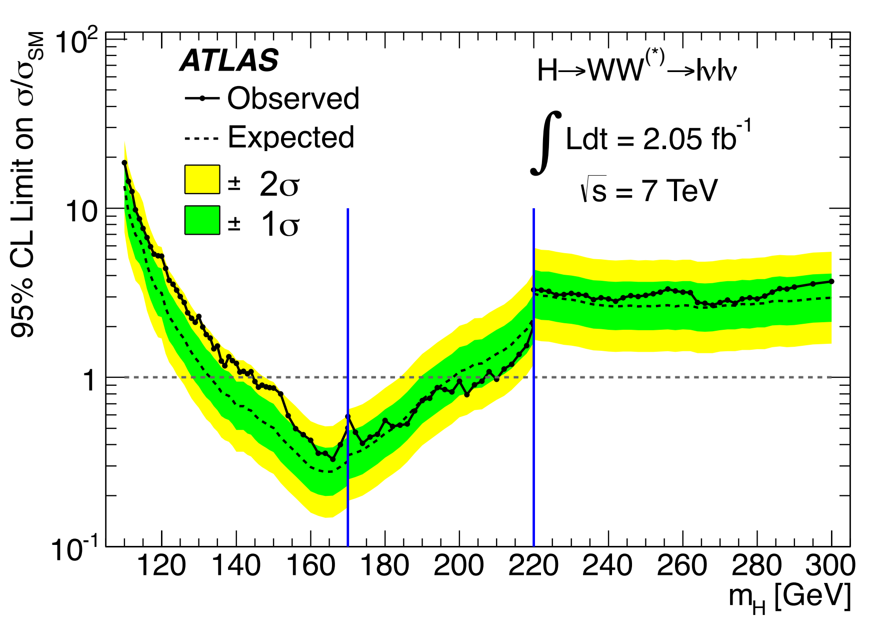
- Number of events after final cuts: $0.75\ m_H < m_T < m_H$

m_H = 130 GeV	0-jet	1-jet
Observed in data	67	27
Expected background	56 ± 10	20 ± 3
Expected signal	14 ± 3	4.9 ± 1.1

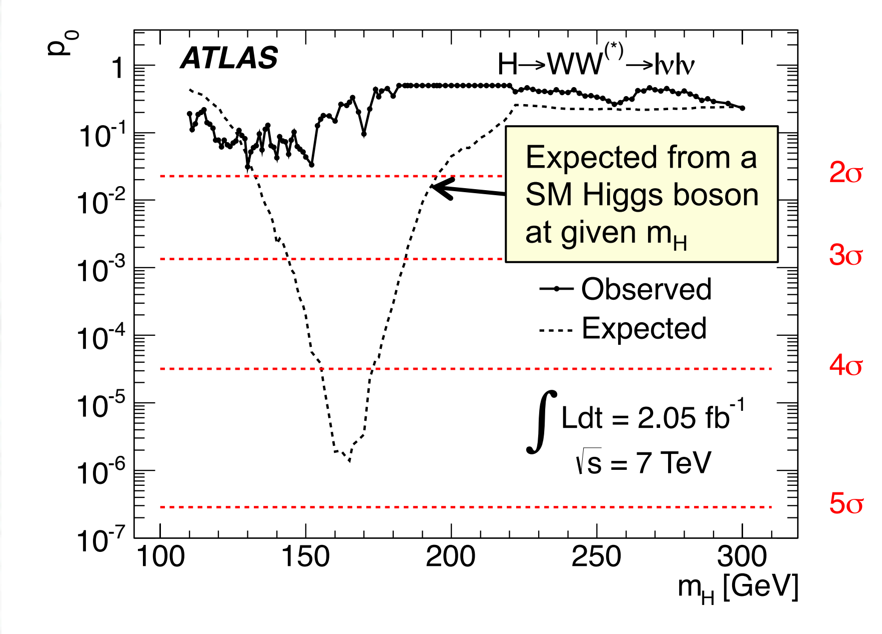
Dominant syst. uncertainties:
- background normalization (statistics in control regions)
- cross sections, pdfs
- energy scales, E_T^{miss}

H → WW → ℓν ℓν: sensitivity and exclusion

Cross sections σ_{95} that can be excluded with a C.L. of 95%, normalized to the Standard Model cross sections



p_0: consistency of the data with the background-only hypothesis



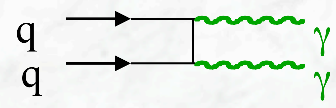
Excluded mass regions (95% C.L.): $145 < m_H < 206$ GeV
(Expected exclusion: $134 < m_H < 200$ GeV)

Observed limit within 2σ of expected, maximal deviation: 1.9σ for a mass around 130 GeV

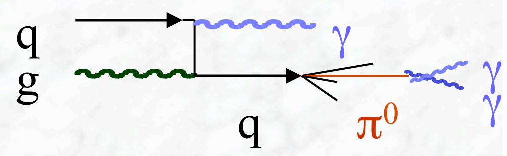
The observed limits at neighboring mass points are highly correlated due to the limited mass resolution in this final state. The discontinuities in the expected and observed limits at 170 and 220 GeV are caused by a change of the selection cuts at these points

Search for H → γγ

- One of the important discovery channels at low mass
- Mass reconstruction possible, needs good γγ mass resolution and direction measurement of photons
- Challenges:
  - signal-to-background ratio
    (small, but smooth irreducible γγ background)

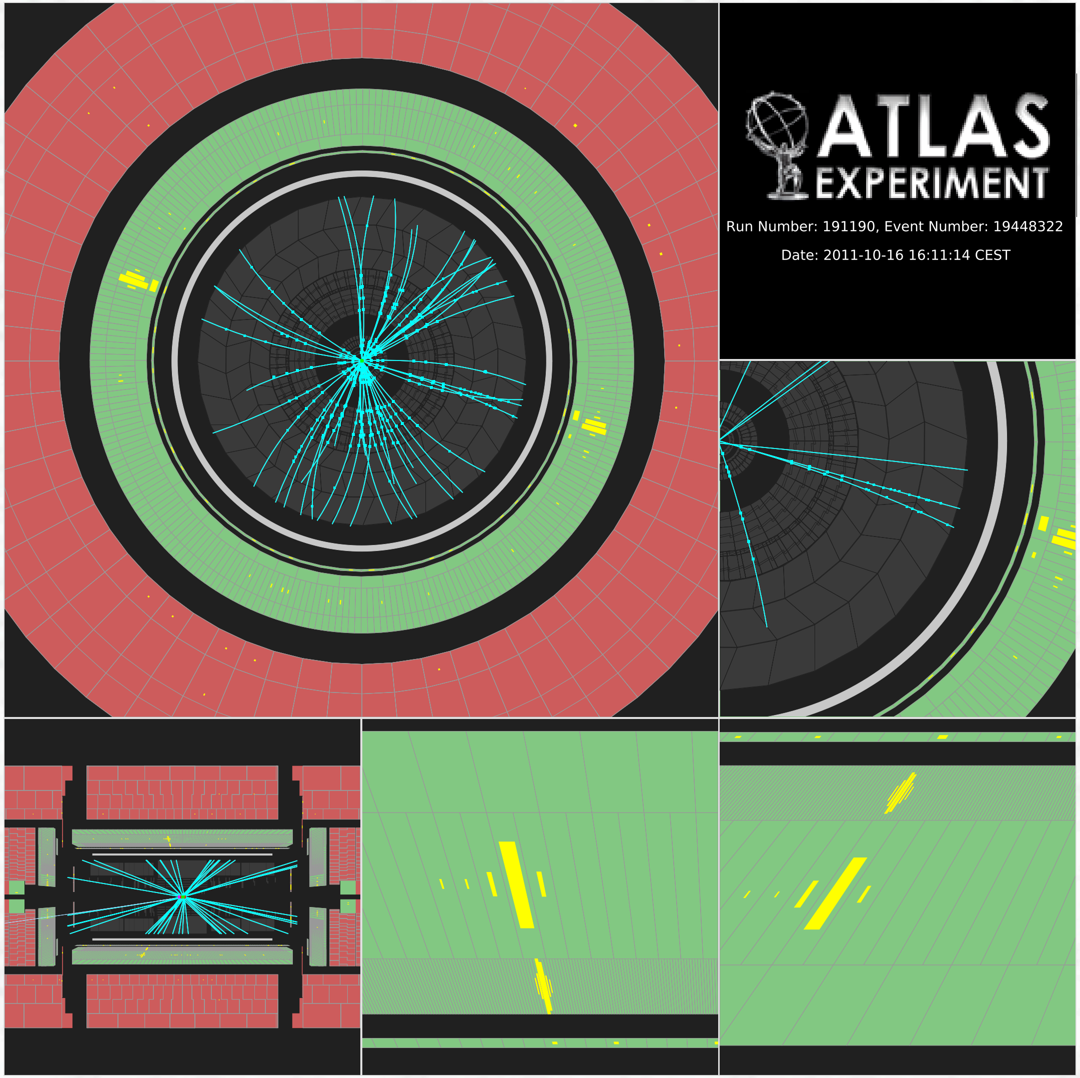


  - reducible backgrounds from γj and jj
    (several orders of magnitude larger than irreducible one)



- Large amount of material in the LHC trackers;
  requires the reconstruction of converted photons

A γγ event in ATLAS



Event selection:

- 2 photons within $|\eta| < 2.4$ and $E_T(\gamma_1, \gamma_2) > 40, 25$ GeV
  (exclude transition region between barrel and endcap calorimeters)

- Isolation criteria in tracker and calorimeters
  (calo: < 5 GeV in $\Delta R < 0.4$)

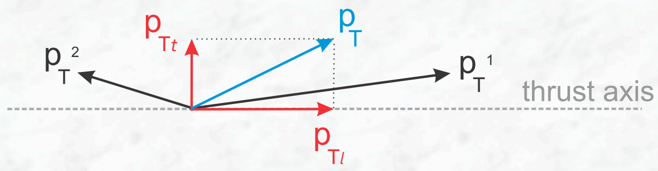
Important detector features:

- longitudinal (and lateral) segmentation of the EM calorimeter is used to measure the photon polar angle θ (important at high pile-up)

- reconstruction of conversions in silicon detectors and transition radiation tracker

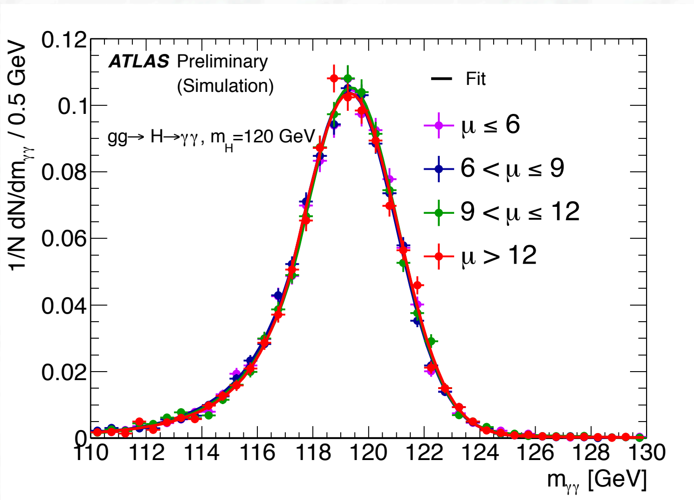
A few $\gamma\gamma$ performance figures

- Di-photon events are classified in 9 categories, based on η, conversion status and di-photon momentum component (P_{Tt}) transverse to the di-photon thrust axis



m_H=120 GeV	σ ($m_{\gamma\gamma}$) GeV	Event fraction in $\pm$ 1.4 σ ($m_{\gamma\gamma}$)
All	1.7	80 %
Best category (unconverted central)	1.4	84%
Worst category (~10%) ($\geq$ 1 γ converted, $\geq$ 1 γ near barrel/end-cap transition)	2.3	70%

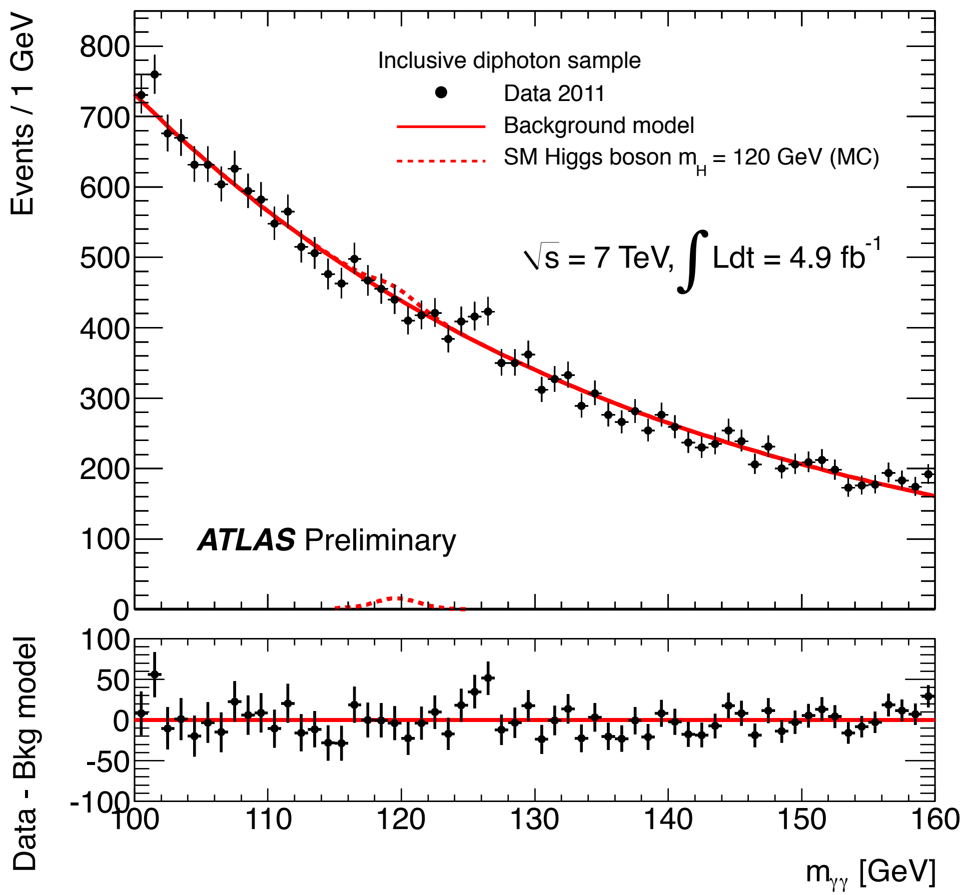
Photon energy scale and resolution transported from electron studies using Monte Carlo simulation
(main systematics due to material effects)



- Signal description by a Crystal ball function + a Gaussian for tails
- Mass resolution shows no sensitivity to pile-up

Measured γγ mass spectrum

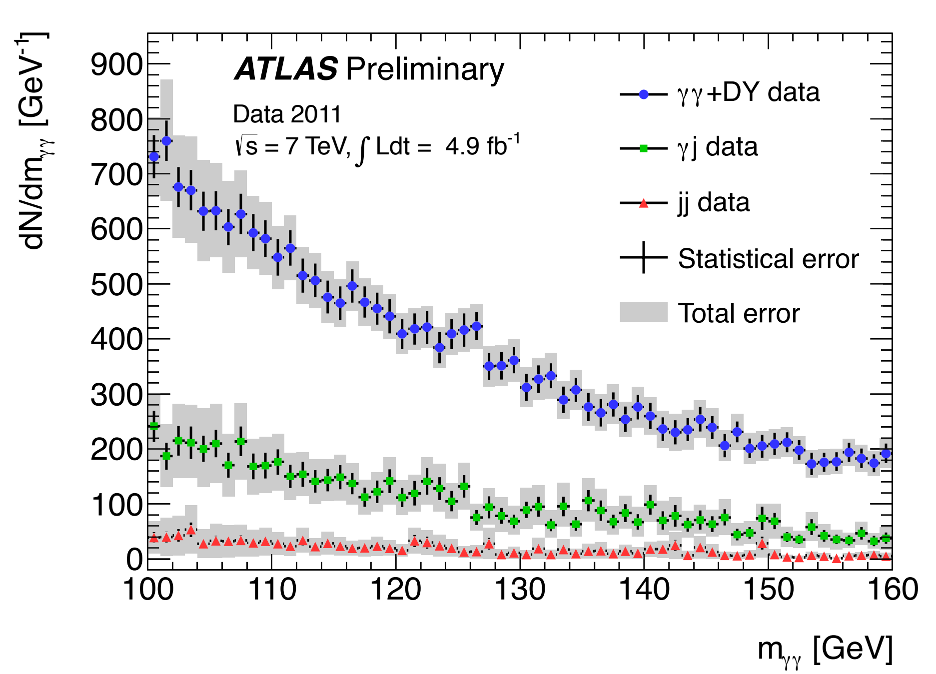
-after all selection cuts, summed over 9 categories-

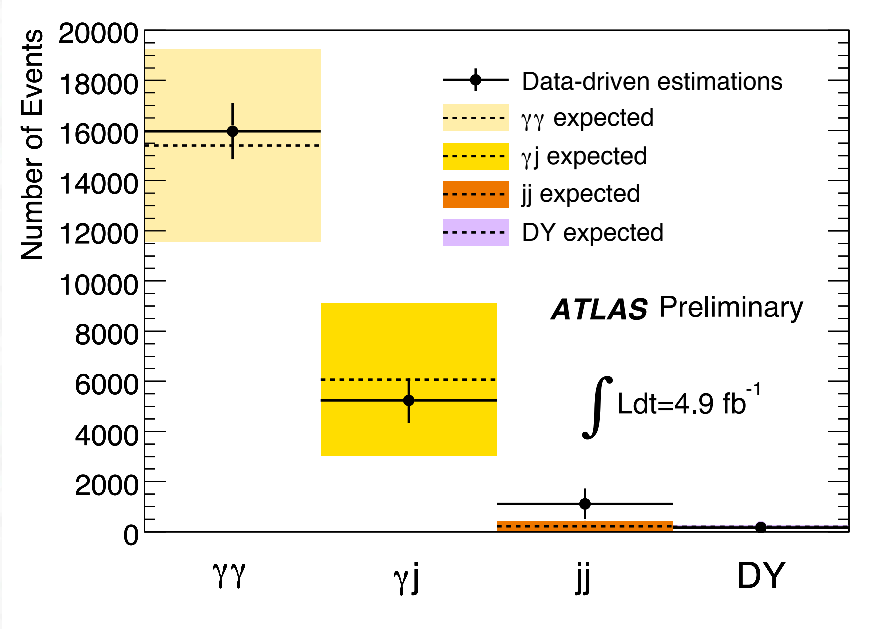


- Background model: exponential function, determined directly from data (different models have been used → systematics)
- Excess of events seen around $m_{\gamma\gamma}$ ~126 GeV
- Use statistical analysis to quantify excess incl. systematic uncertainties on background and signal modelling

  (γγ mass resolution, γγ p_T modelling, …)

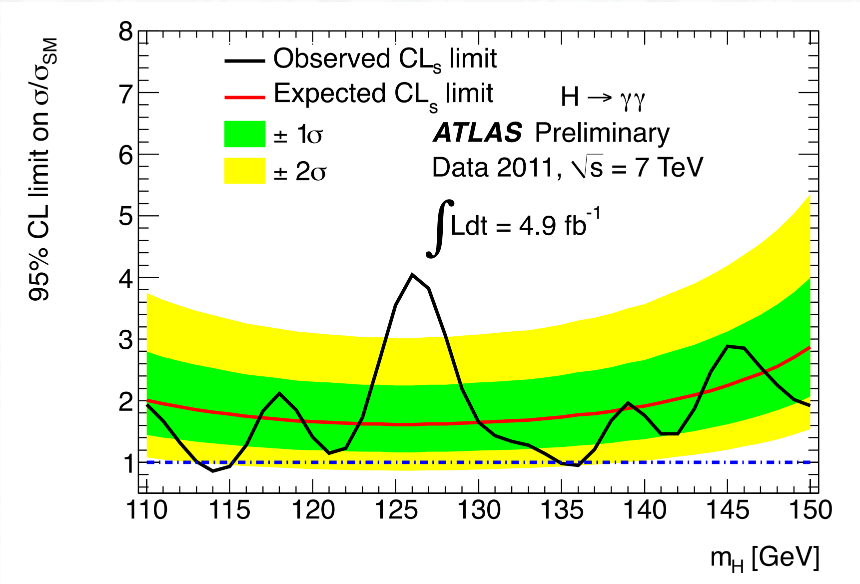
H → γγ : composition of the γγ continuum background

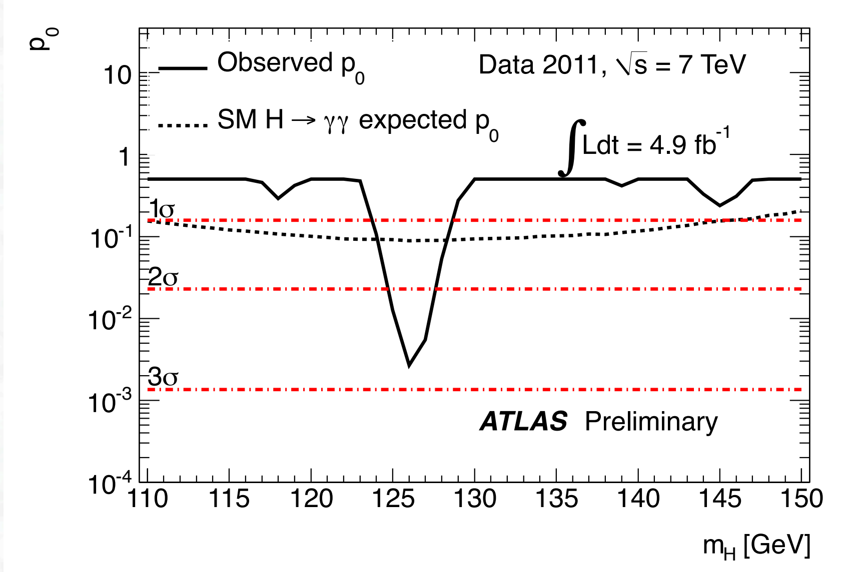




	Number of events	Fraction
γγ	16000 ± 1120	71 ± 5%
γj	5200 ± 890	23 ± 4%
jj	1130 ± 600	5 ± 3%
Z/γ*	165 ± 8	0.7 ± 0.1%

$H \rightarrow \gamma\gamma$: sensitivity and exclusion

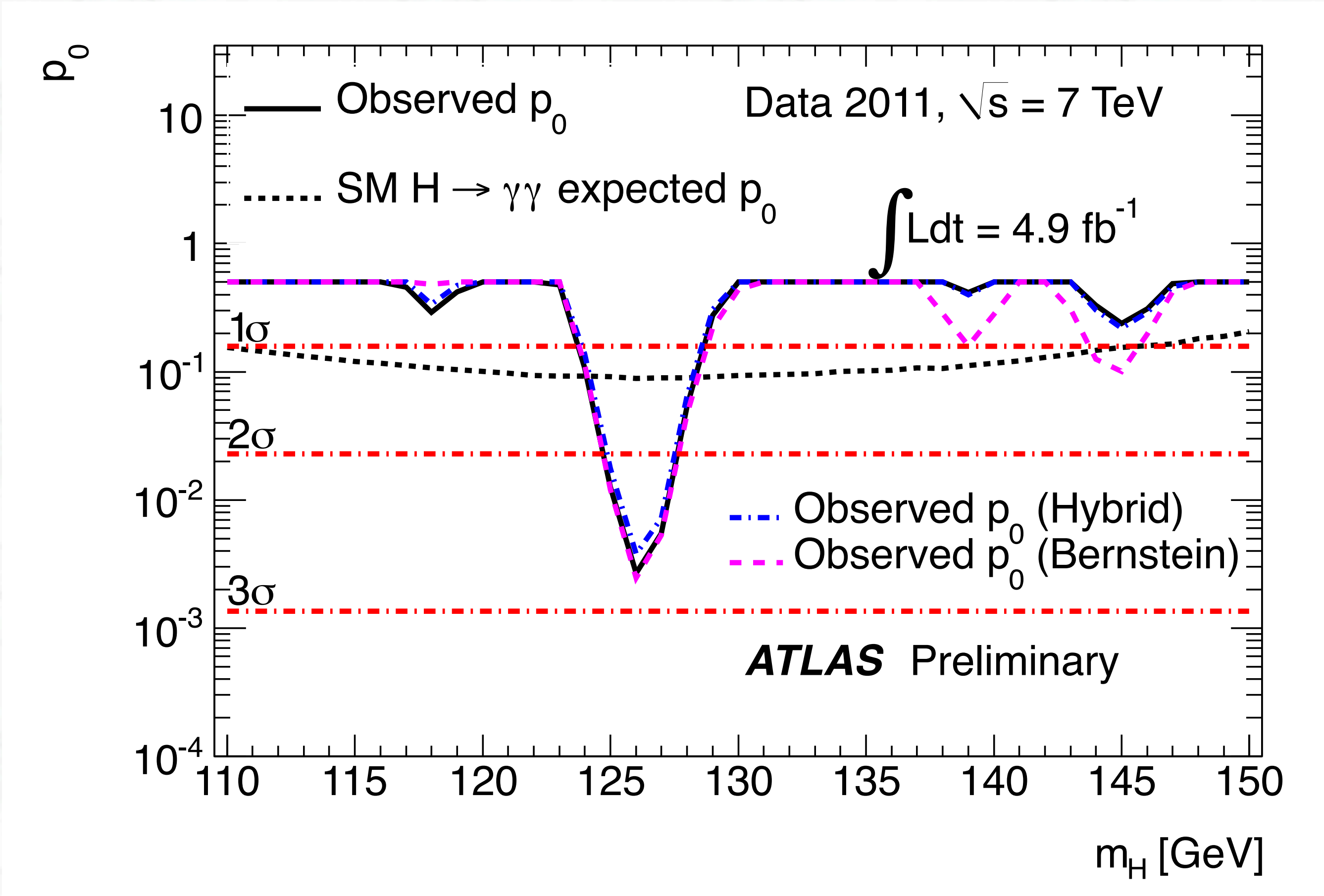




- Maximum deviation from background-only expectation observed for m_H~126 GeV:
  - local p_0-value: 0.27% or 2.8σ (expect 1.4σ from SM Higgs boson)
  - global p_0-value*: ~7% or 1.5σ
- Small mass ranges from 114 – 115 GeV and 135 – 136 GeV excluded

* The global p_0 value takes into account the probability that such an excess can appear anywhere in the investigated mass range from 110 to 150 GeV ("Look-Elsewhere Effect", LEE)

$H \rightarrow \gamma\gamma$: p_0 values for different background models



Hybrid: high P_{Tt} categories are fitted with 2nd order Bernstein polynomials, the other categories with a single exponential;

Bernstein: all categories are fitted with the Bernstein function

Search for H → ZZ$^{(*)}$ → 4ℓ

- "Golden channel" over a large mass range;
  Starts to get sensitivity with the present integrated luminosity

- Mass reconstruction possible, need good lepton identification and measurement down to low p_T (to maximize the acceptance for low m_H)

- Low signal rate, but also small backgrounds
  - $ZZ^{(*)}$ continuum as irreducible background
  - Top and Zbb production as reducible backgrounds (at low mass)
    (suppressed via lepton isolation and impact parameter cuts)

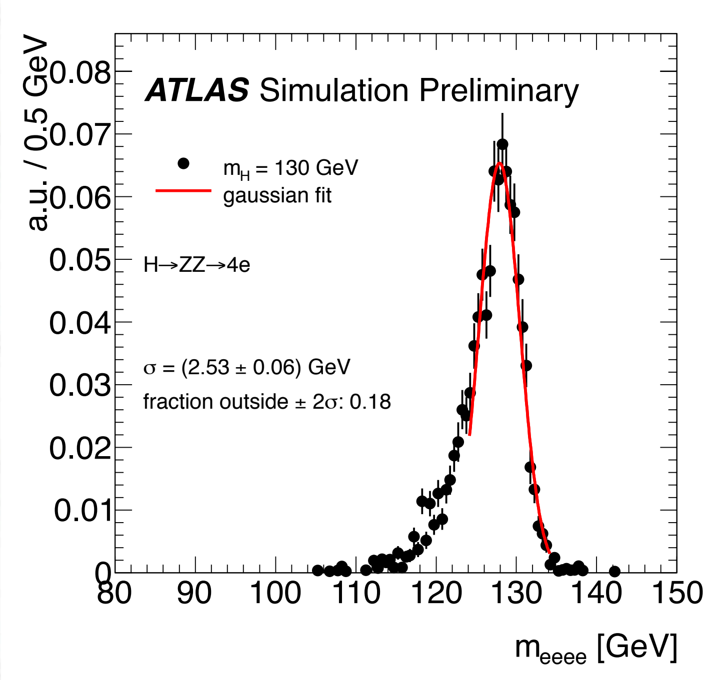
- ATLAS selection cuts: require 4 identified leptons (4e, 2e2μ or 4μ) with:

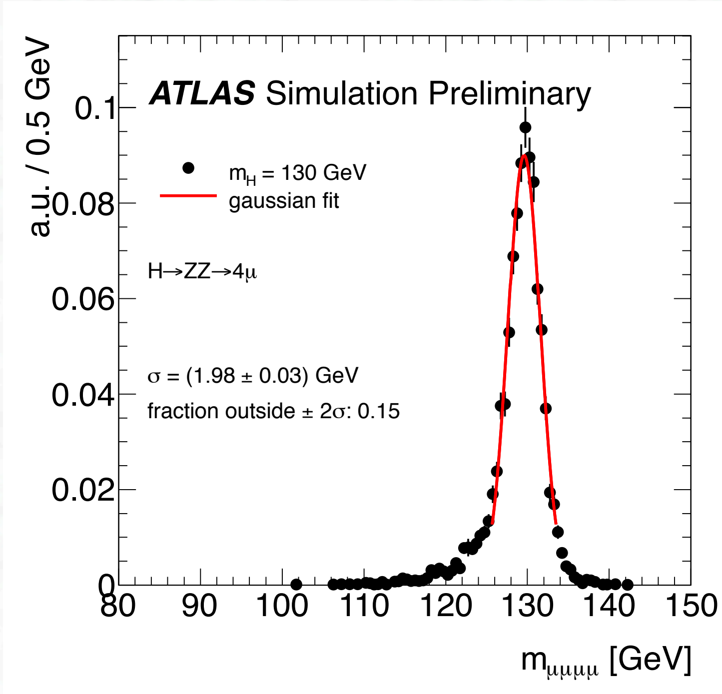
P_T (1,2) > 20 GeV (high trigger acceptance)
P_T (3,4) > 7 GeV
$|\eta|$ < 2.47 (e) and ~2.5 (μ)
Isolation and impact parameter requirements
on the two softest leptons

$m_{12} = m_Z \pm 15$ GeV
m_{34} > 15 – 60 GeV (for m_H in the range 120 - 200 GeV)

Signal acceptance x efficiency ~15% (m_H = 125 GeV)

Expected mass resolutions (for m_H = 130 GeV):

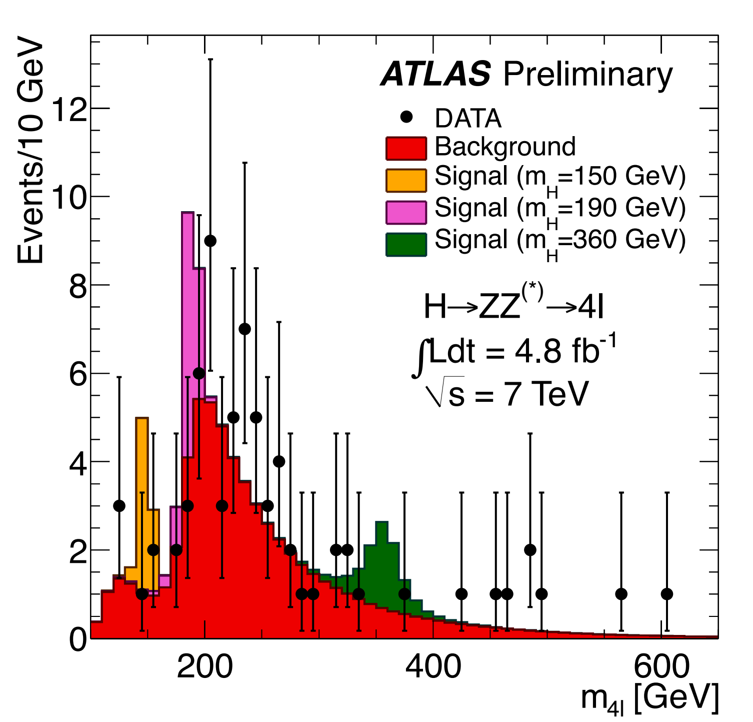


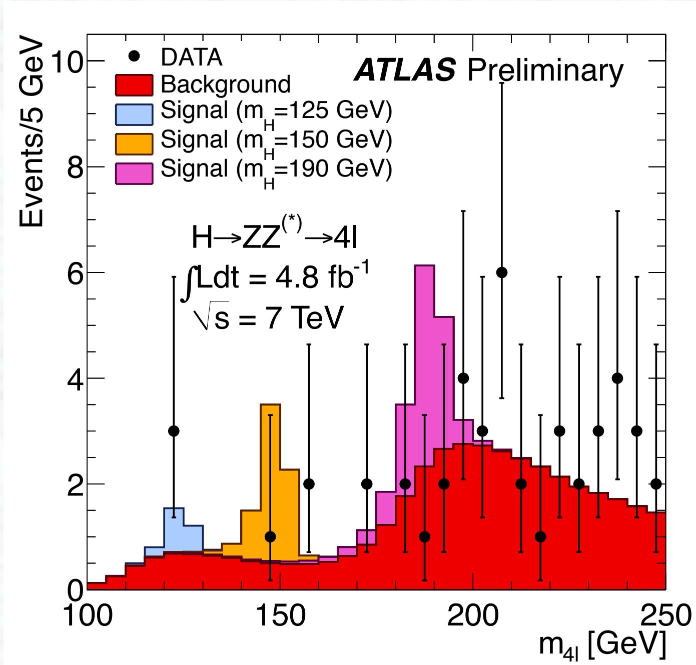


- Width dominated by experimental resolution: ~2.5 GeV for 4e
~2.0 GeV for 4μ
(no Z mass constraints used in the fit)

- Event fractions outside ±2σ at the level of 15-18%

Measured 4ℓ mass spectra



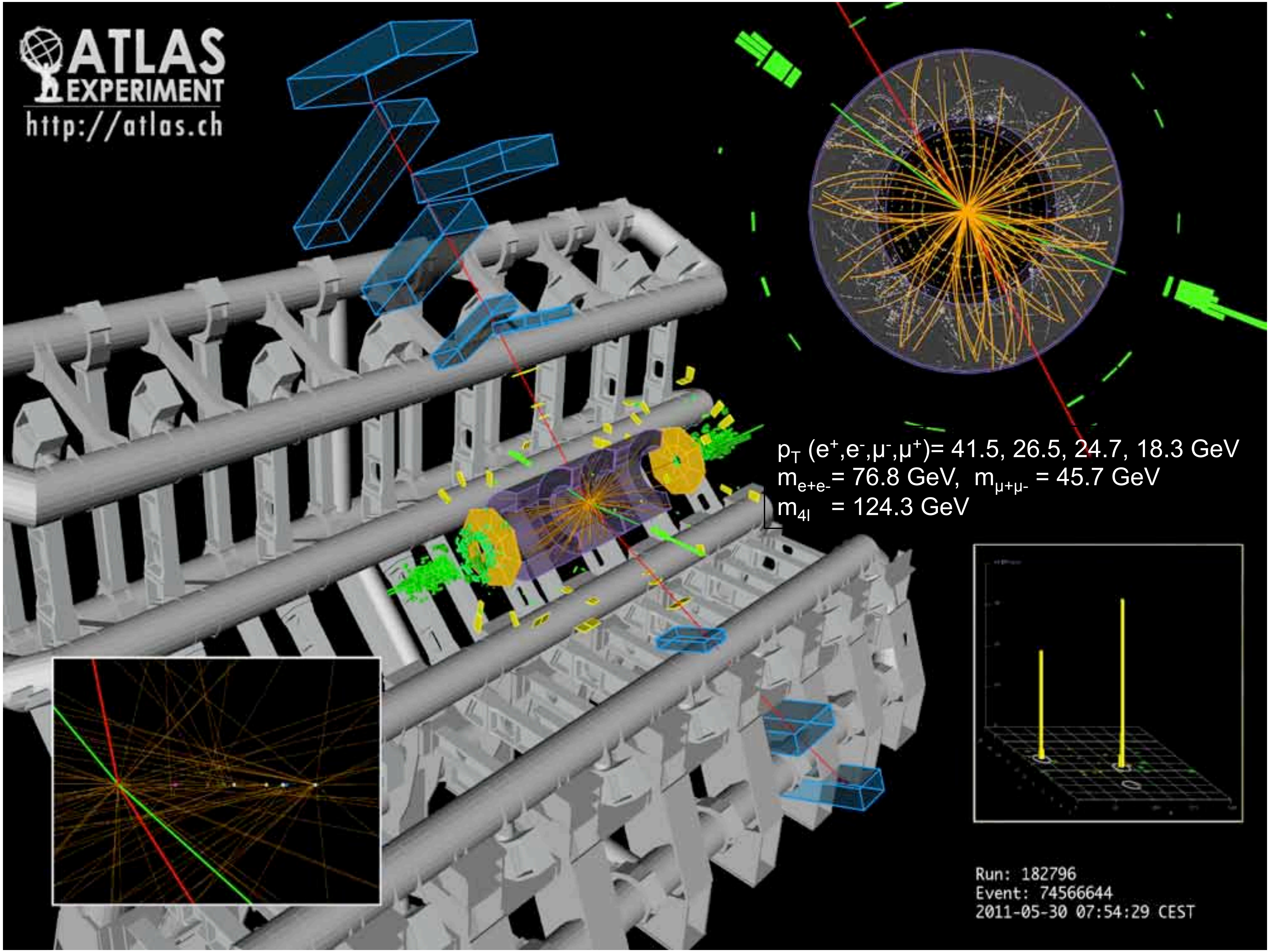


Mass range	Full	< 180 GeV	117 – 128 GeV
Observed in data	71	8	3
Expected background	62 ± 9	9.3 ± 1.5	1.5 ± 0.3

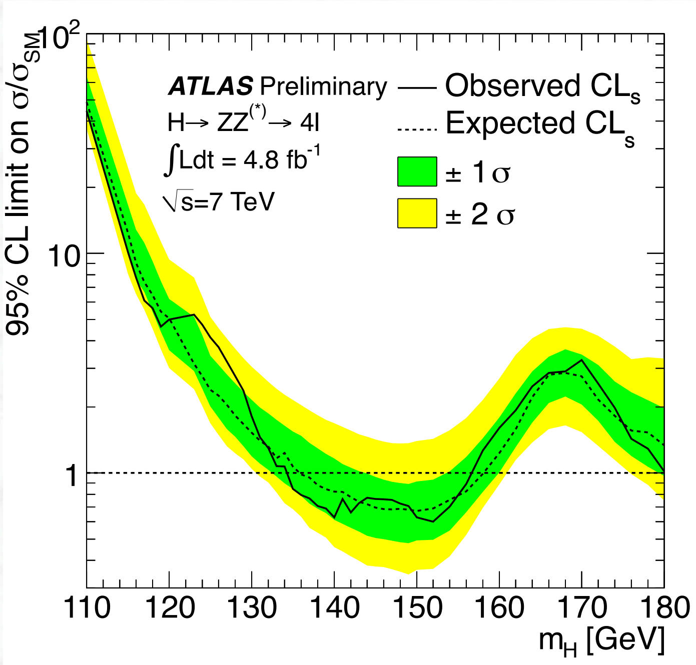
Main systematic uncertainties

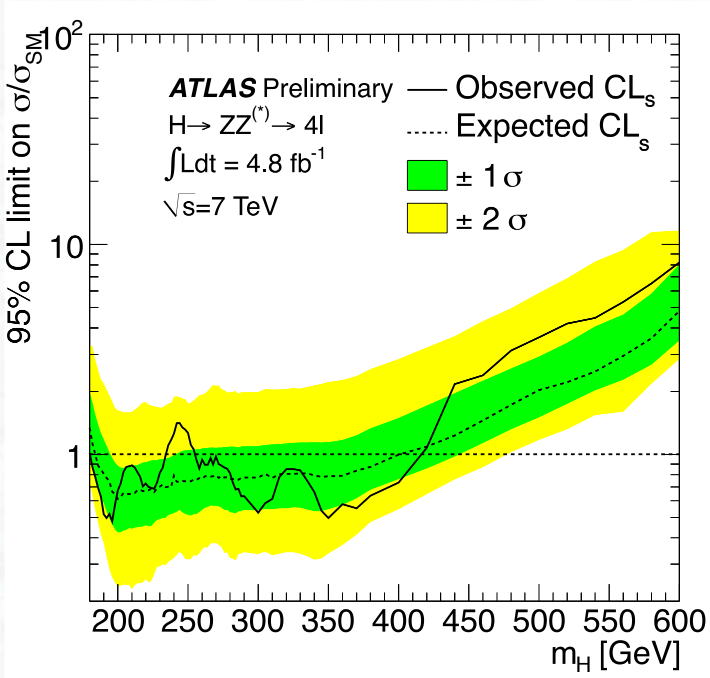
Higgs cross-section : ~ 15%
Electron efficiency : ~ 2-8%
ZZ* background : ~ 15%
Zbb, +jets backgrounds : ~ 40%

Expected signal contribution for m_H=125 is ~1.5 events
Three events observed around 124 GeV: 2 (2e2μ)− and 1 (4μ)-event


ATLAS EXPERIMENT
http://atlas.ch
p_T (e^+,e^-,μ^-,μ^+)= 41.5, 26.5, 24.7, 18.3 GeV
m_{e+e-}= 76.8 GeV, $m_{\mu+\mu-}$ = 45.7 GeV
m_{4l} = 124.3 GeV
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$: sensitivity and exclusion

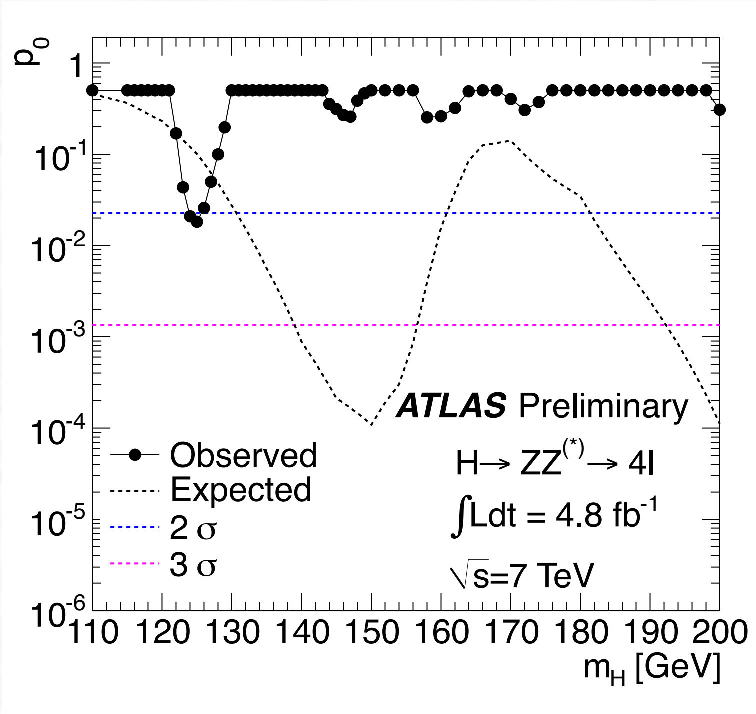


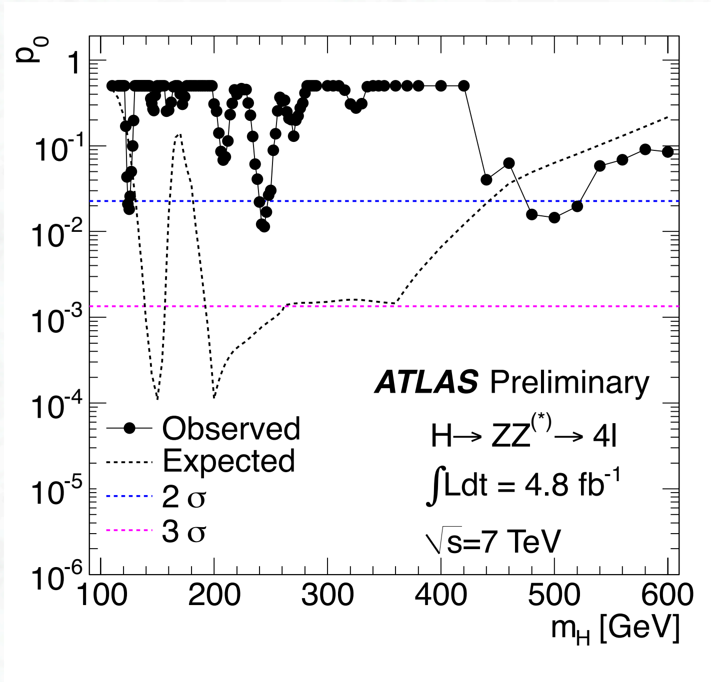


Excluded mass regions (95% C.L.): [135-156], [181-234] and [255-415] GeV

(Expected exclusion: $137 < m_H < 158$ GeV and $185 < m_H < 400$ GeV)

Test of background-only hypothesis for the 4ℓ channel





Small probabilities for background-only hypothesis observed for:

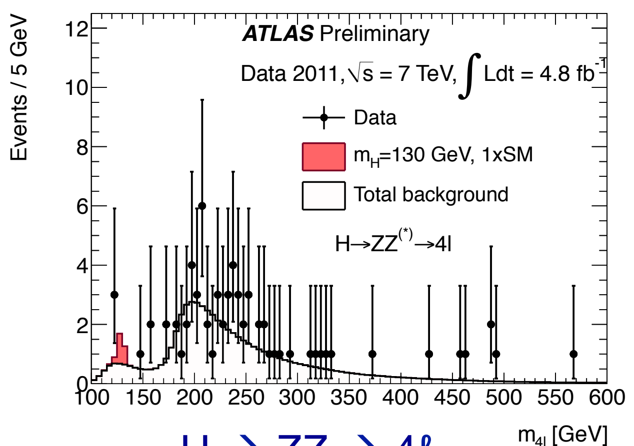
m_H (GeV)	local (global) p_0	Local significance	Expected signif. from SM Higgs
125	1.8% (~50%)**	2.1 σ	1.4 σ
244*	1.1% (~50%)	2.3 σ	3.2 σ
500	1.4% (~50%)	2.2 σ	1.5 σ

*) already excluded by the ATLAS + CMS combination

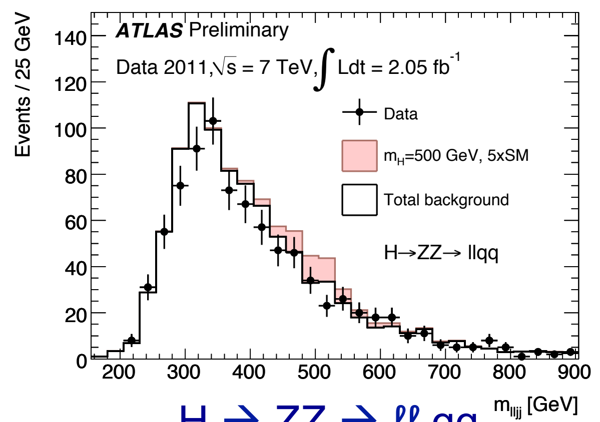
**) Look-elsewhere-effect evaluated over the mass range 110 – 600 GeV

Summary of Search Results in the High Mass Region

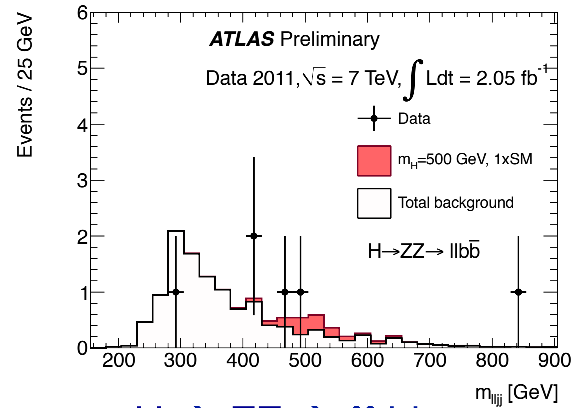
Results from ATLAS on various high mass search channels: L = 1.04 – 4.8 fb^{-1}



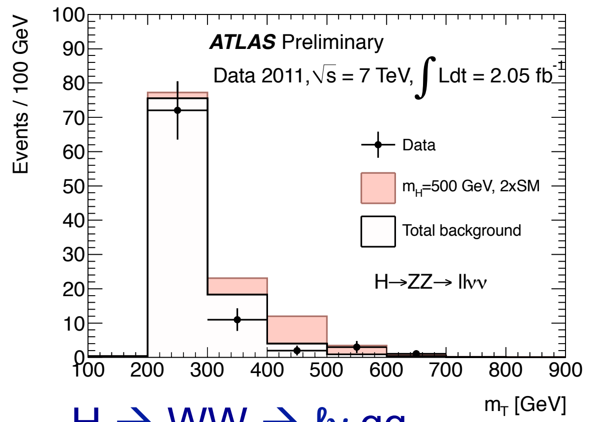
H → ZZ → 4ℓ



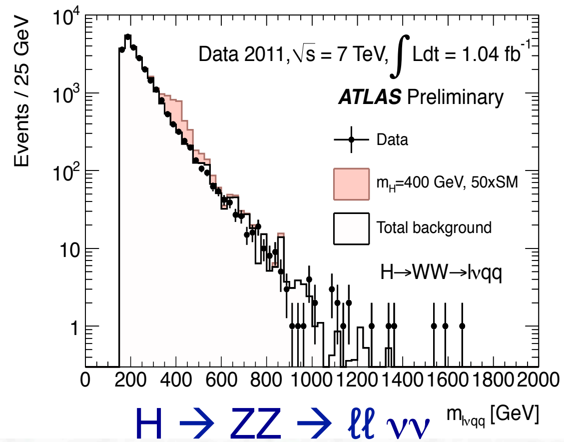
H → ZZ → ℓℓ qq



H → ZZ → ℓℓ bb



H → WW → ℓν qq

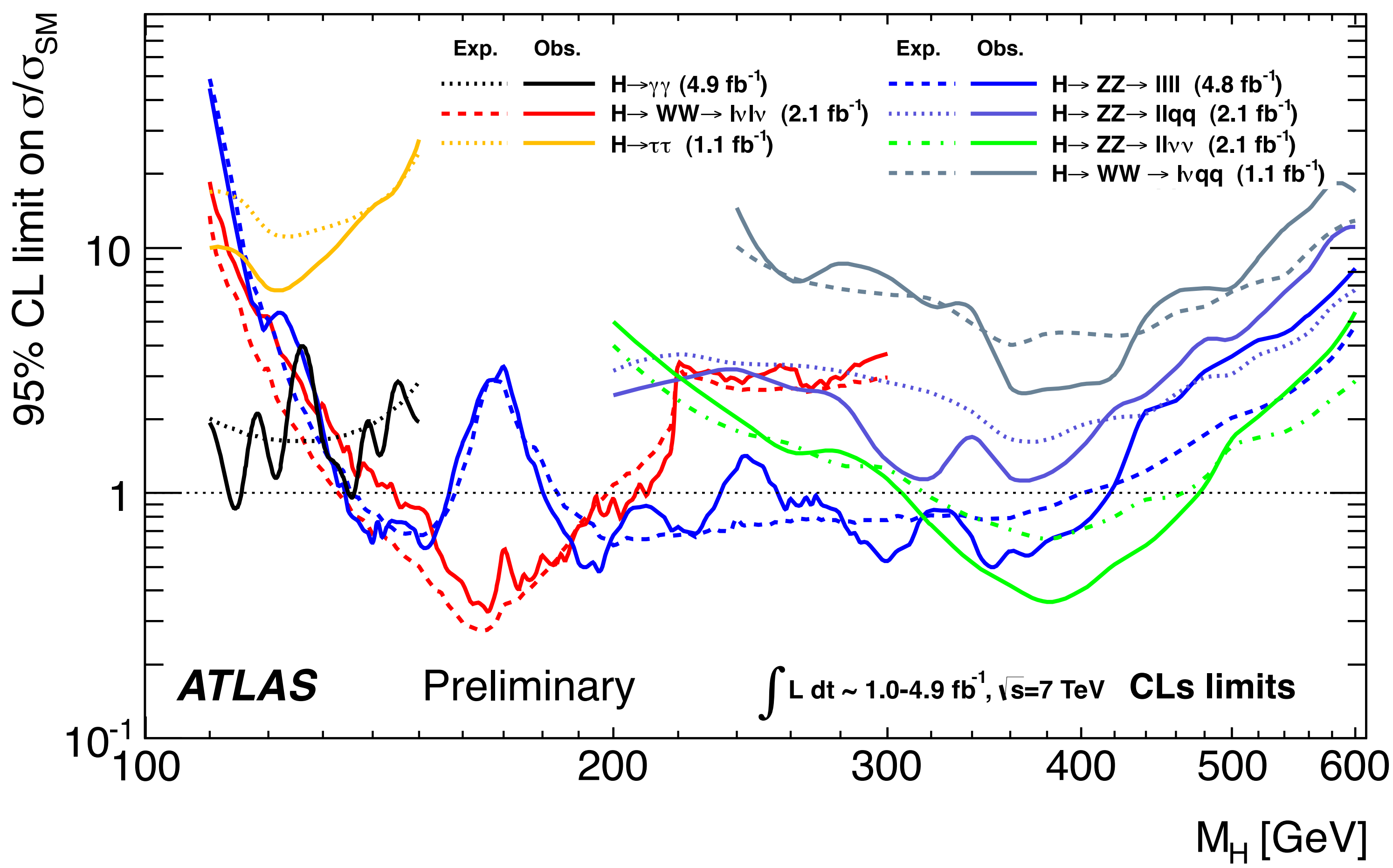


H → ZZ → ℓℓ νν

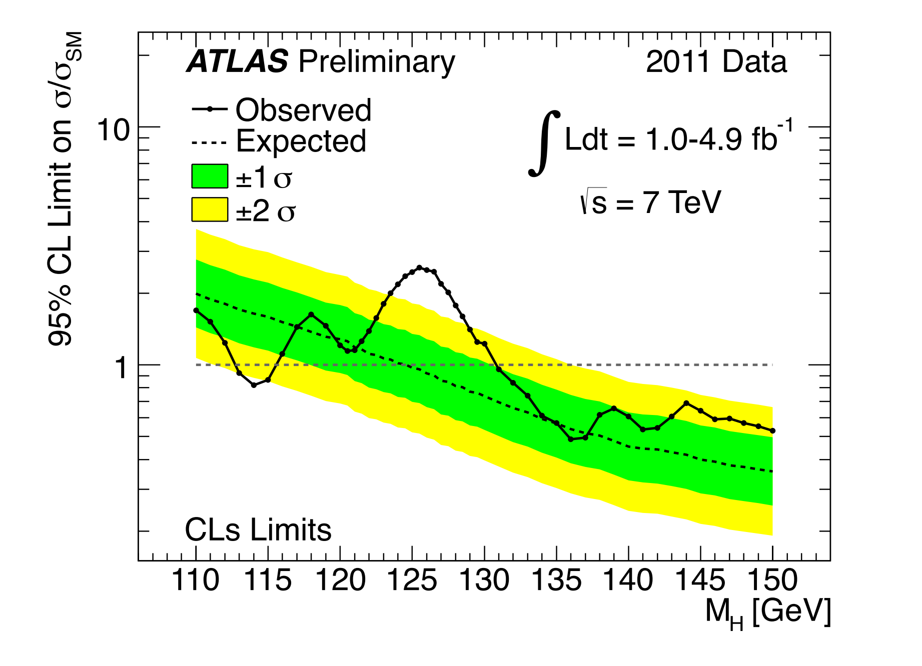
Also in these channels: data are consistent with expectations from Standard Model background processes → work out significances / statistics

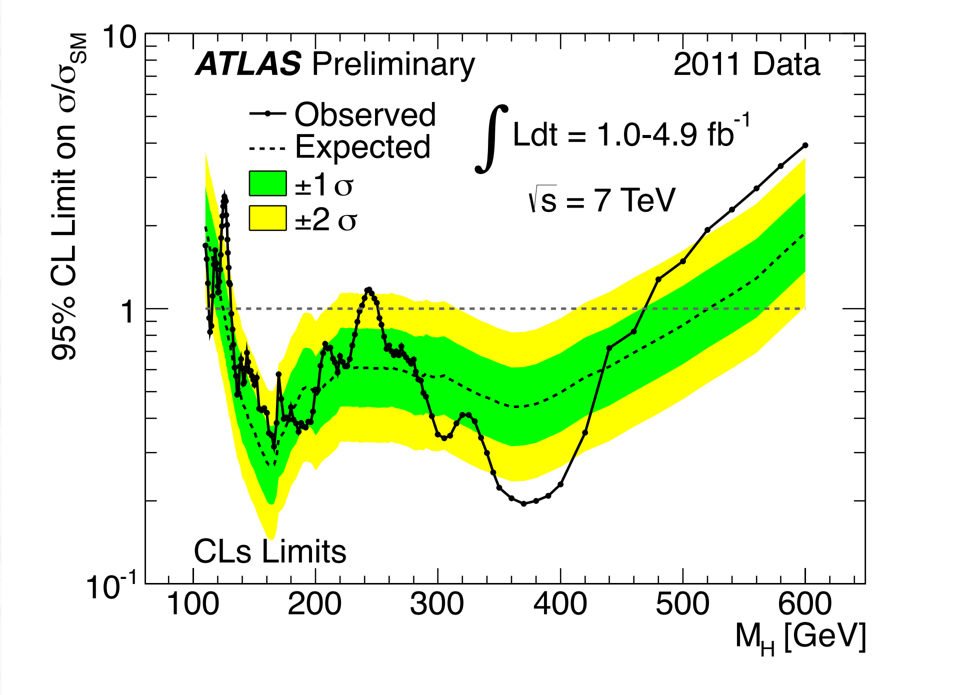
Summary of the current status of the Higgs boson search in ATLAS

- excluded cross sections by individual channels -



The grand combination





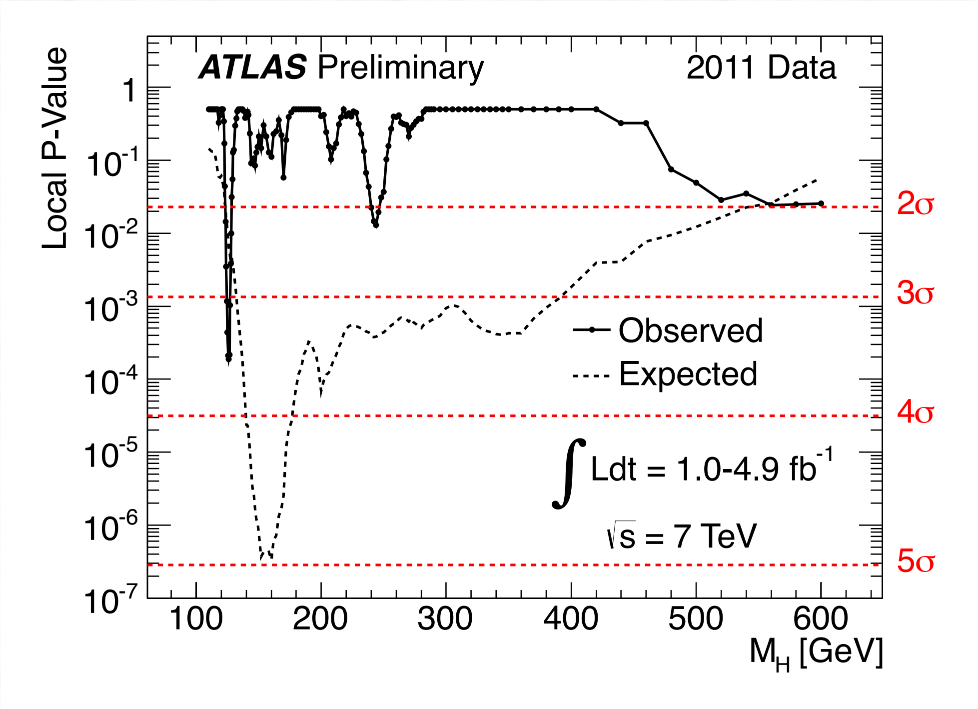
Channels included:
$H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\, \ell\nu$
$H \rightarrow WW \rightarrow \ell\nu\, qq$
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$,
$H \rightarrow ZZ \rightarrow \ell\ell\, \nu\nu$
$H \rightarrow ZZ \rightarrow \ell\ell\, qq$,
$H \rightarrow WW \rightarrow \ell\nu\, qq$

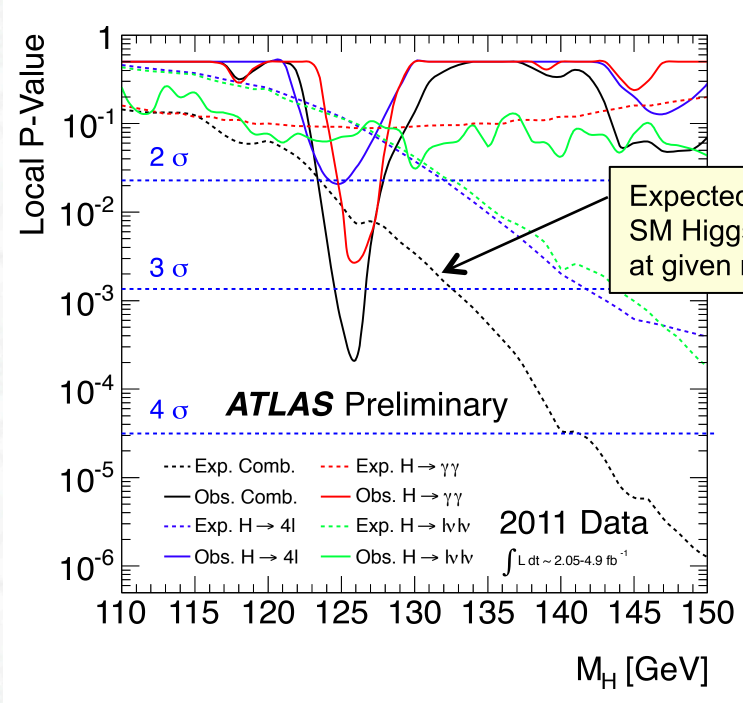
Not included:
$W/ZH \rightarrow \ell bb+X$

Excluded mass regions:	
95 % C.L.	**99 % C.L.**
112.7 – 115.5 GeV	
131 – 237 GeV	133 – 230 GeV
251 – 468 GeV	260 – 437 GeV

95% C.L. expected exclusion: 124.6 – 520 GeV

Consistency of the data with the background-only expectation

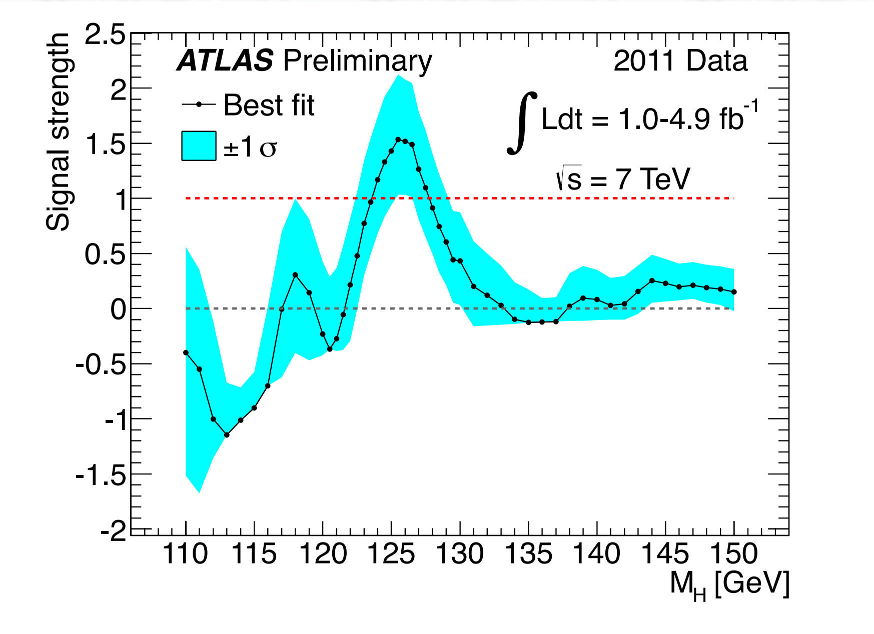


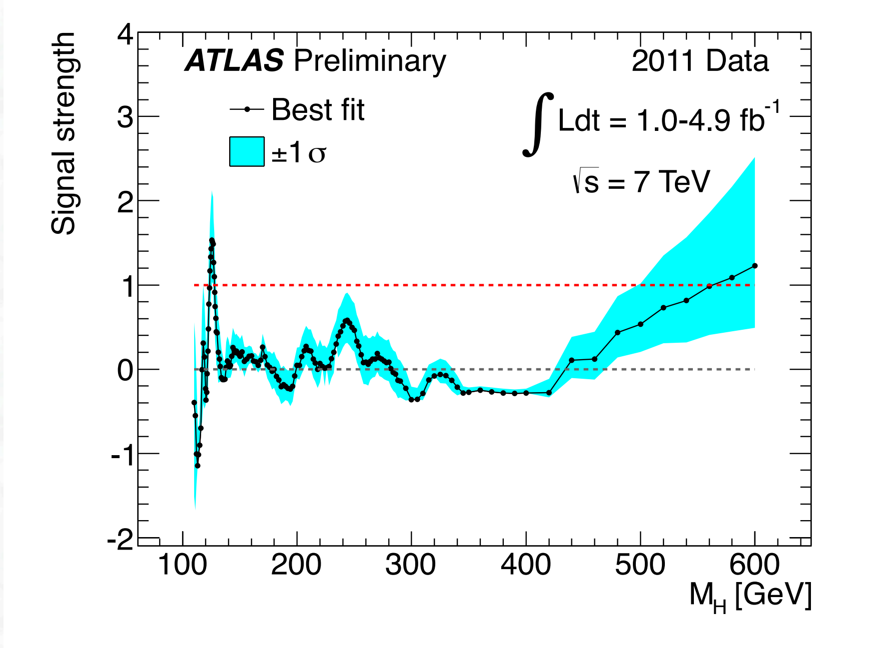


- Lowest probability (p_0 = 1.9 10^{-4}) for background-only expectation observed for m_H ~126 GeV
- Local significance of excess: 3.6σ (2.8σ H → γγ, 2.1σ H → 4ℓ, 1.4σ H → ℓν ℓν)
- Global significances: 2.5σ (p = 0.6%) Look-elsewhere-effect over 110 – 146 GeV
  2.2σ (p = 1.4%) Look-elsewhere-effect over 110 – 600 GeV

Compatibility of the observation with the expected strength of a Standard Model Higgs boson (combination of $\gamma\gamma$, 4ℓ, $\ell\nu\ell\nu$)

Signal strength: $\mu = \sigma / \sigma_{SM}$ (fit value)

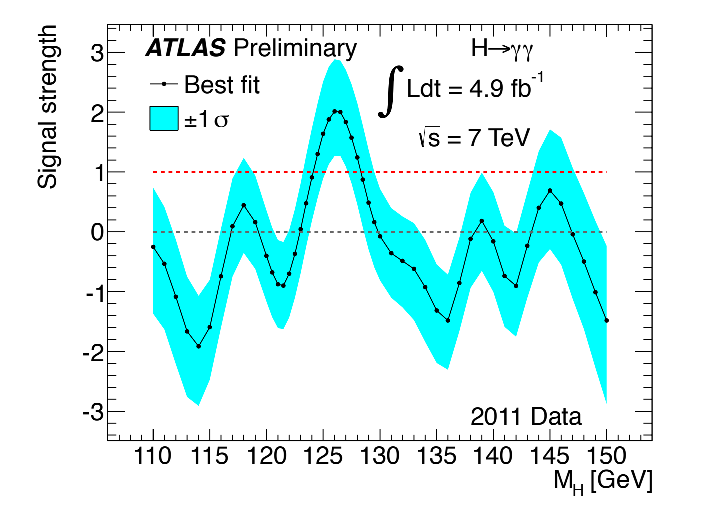


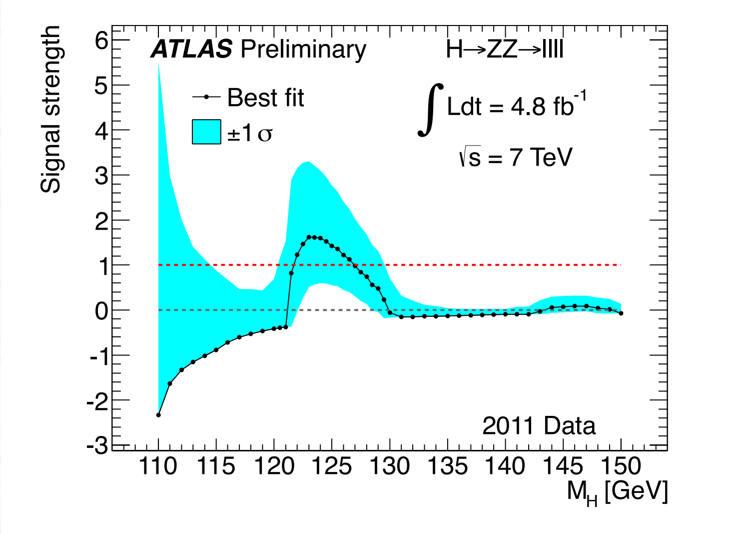


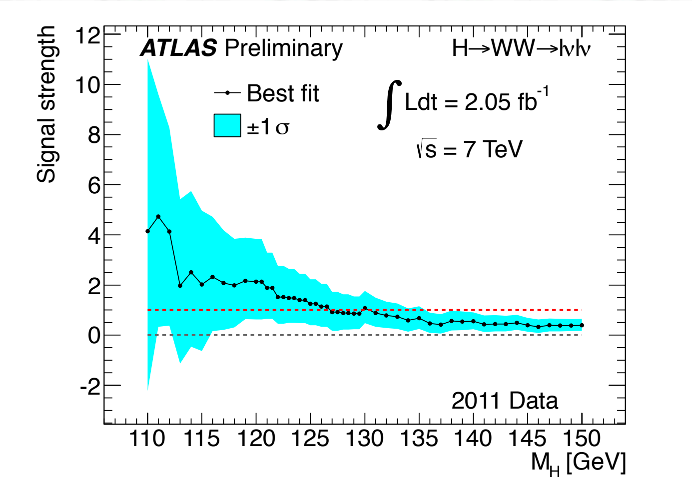
- Observed signal strength is compatible with the expectation from a Standard Model Higgs boson, within errors
- These best fit values do not account for energy scale systematic uncertainties

Compatibility of the observation with the expected strength of a Standard Model Higgs boson (individual channels)

Signal strength: $\mu = \sigma / \sigma_{SM}$ (fit value)







- The observed excess in the γγ channel is a factor of (2 ± 0.8) larger than expected
- Excess in the 4ℓ and ℓν ℓν channels, as well as for the combination are compatible within 1σ

A short summary of recent results on searches for non-Standard Model Higgs bosons

- Search for MSSM Higgs bosons in $\tau\tau$ final states
- Search for fermiophobic Higgs bosons

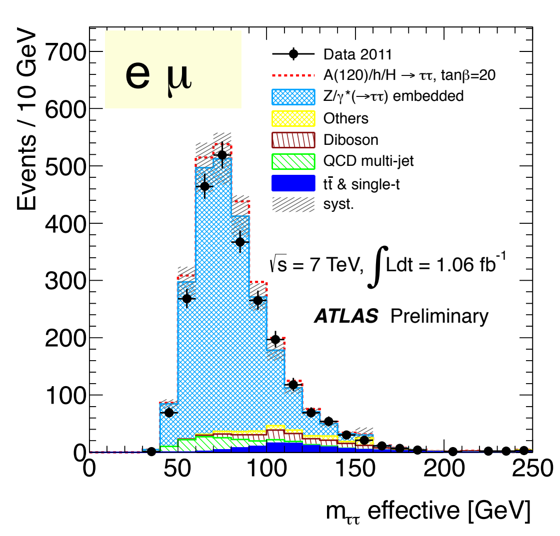
Search for A/H → τ τ

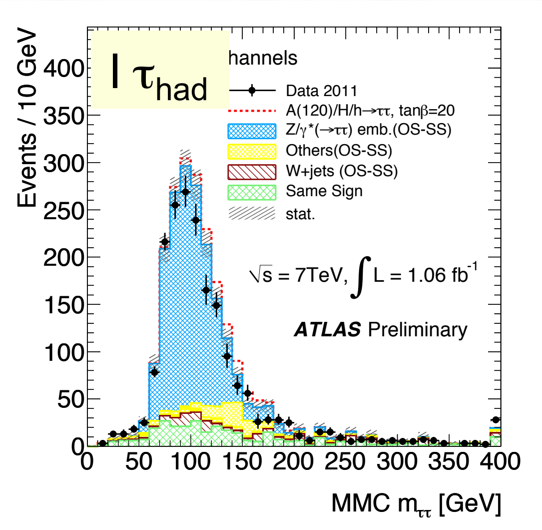
- The production of neutral Higgs bosons A/H is enhanced at large tanβ in the MSSM

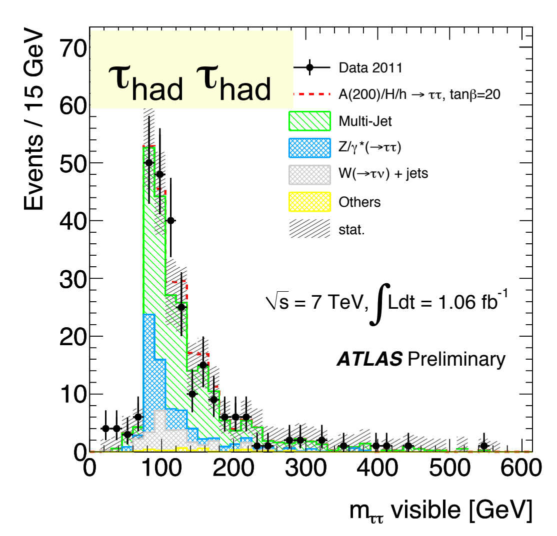
- Search for A/H → τ τ decays in four final states, characterized by the τ decays:
  - A/H → ττ → eνν μνν
  - → ττ → eνν $\tau_{had}\nu$ and μνν $\tau_{had}\nu$
  - → ττ → $\tau_{had}\nu$ $\tau_{had}\nu$

- Good τ identification required, $m_{\tau\tau}$ reconstructed via visible mass or using the missing mass calculation technique

L = 1.06 fb^{-1}

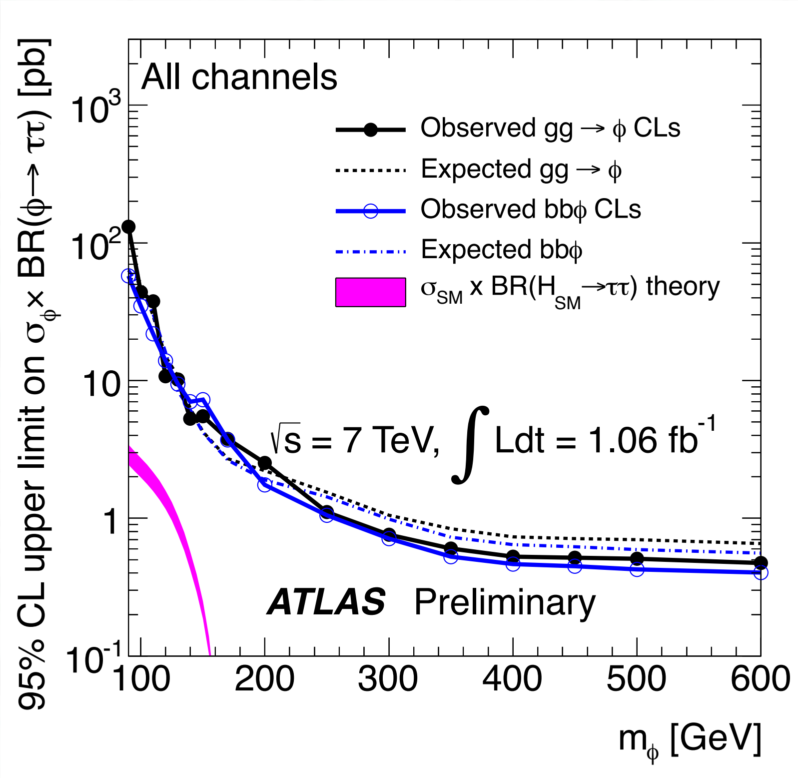




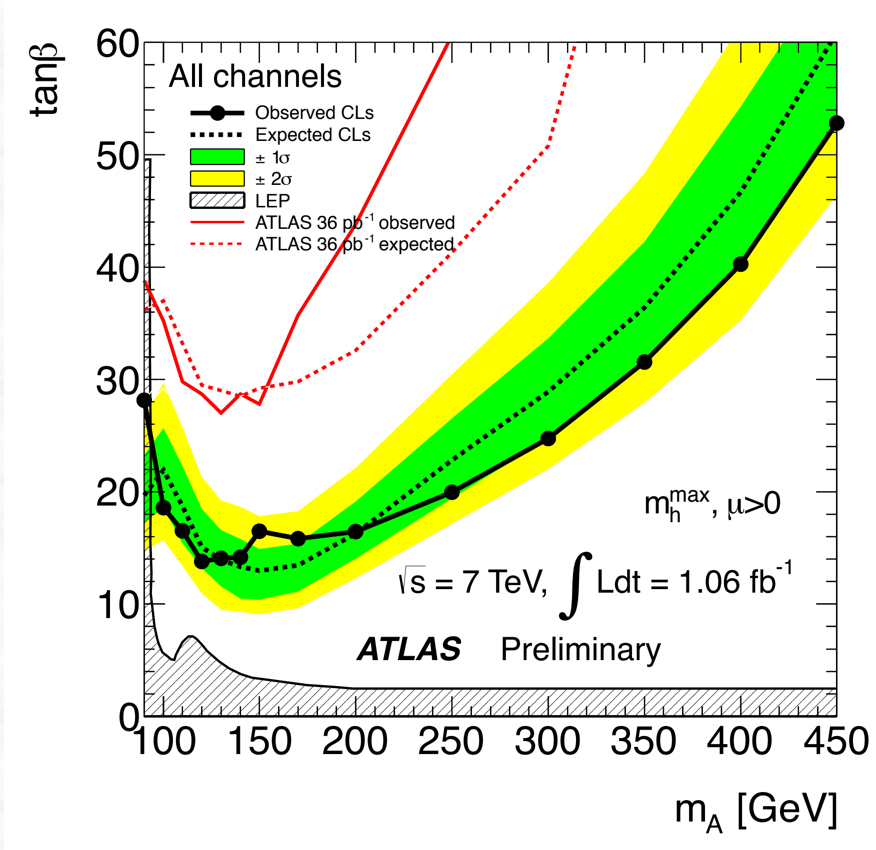


- Select 4630 events in data
- Expectation from SM background sources: 4900 ± 600

Cross section limits and excluded mass regions in the MSSM parameter space



Expected and observed limits on $\sigma \cdot BR(\phi \rightarrow \tau\tau)$ for a generic Higgs boson ϕ



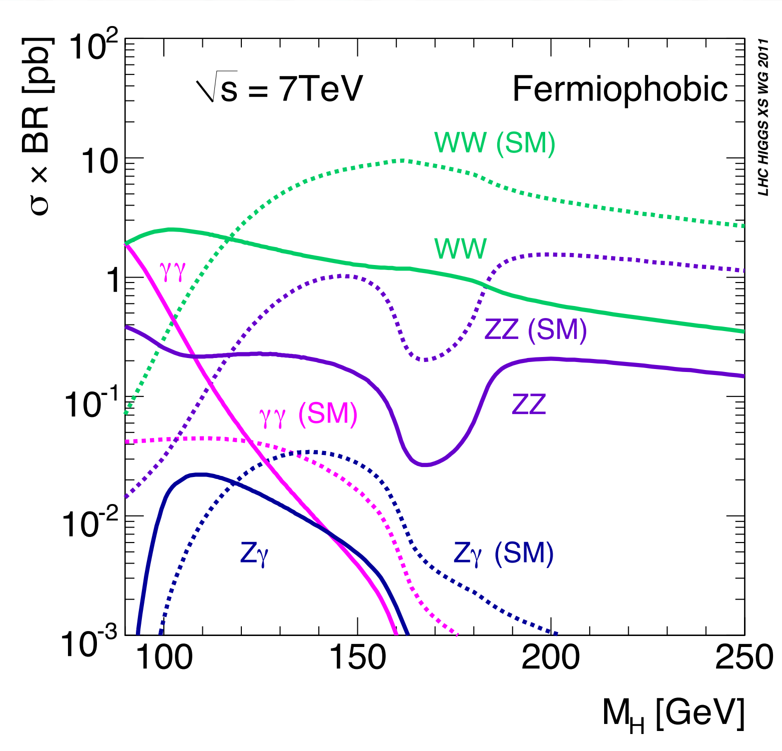
Expected and observed exclusion limits in the MSSM (m_A – $\tan\beta$) plane

m_h^{max} scenario

Search for a fermiophobic Higgs boson in the γγ decay mode

- Benchmark model considered: - all fermion couplings set to 0
  - bosonic couplings kept at the SM values

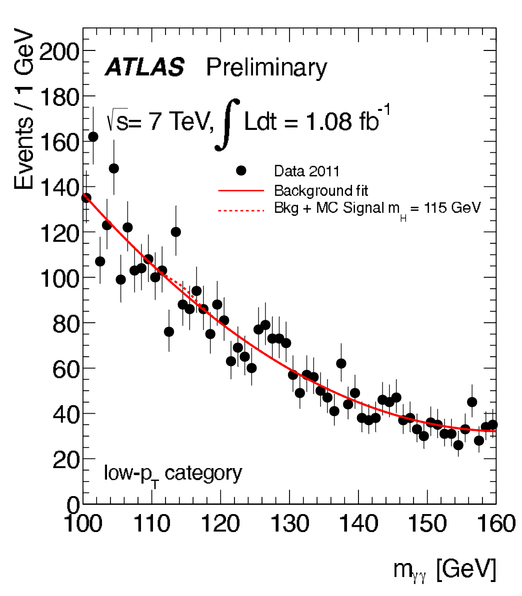
→ modified Higgs production and decay branching ratios,
e.g. no contributions from the gluon-fusion and ttH associated production modes

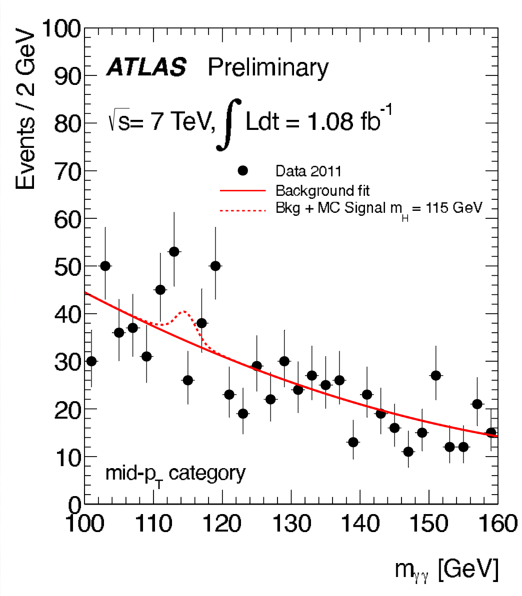


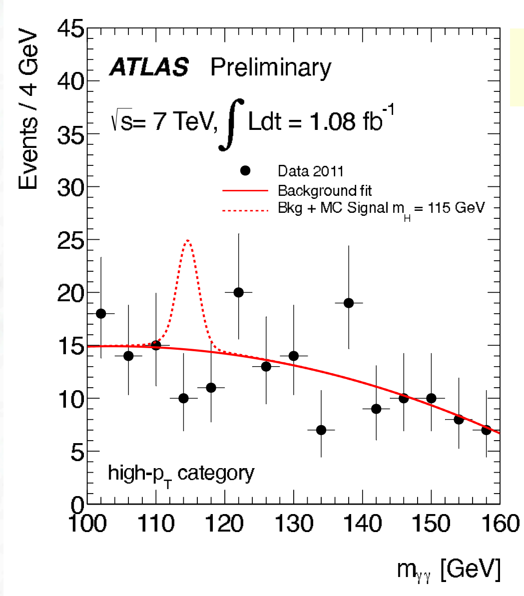
Higgs production with decays to γγ is larger than in the SM for m_H < 120 GeV

Perform analysis similar to SM H → γγ search

VBF and VH production → higher transverse momentum due to recoiling jets or vector bosons

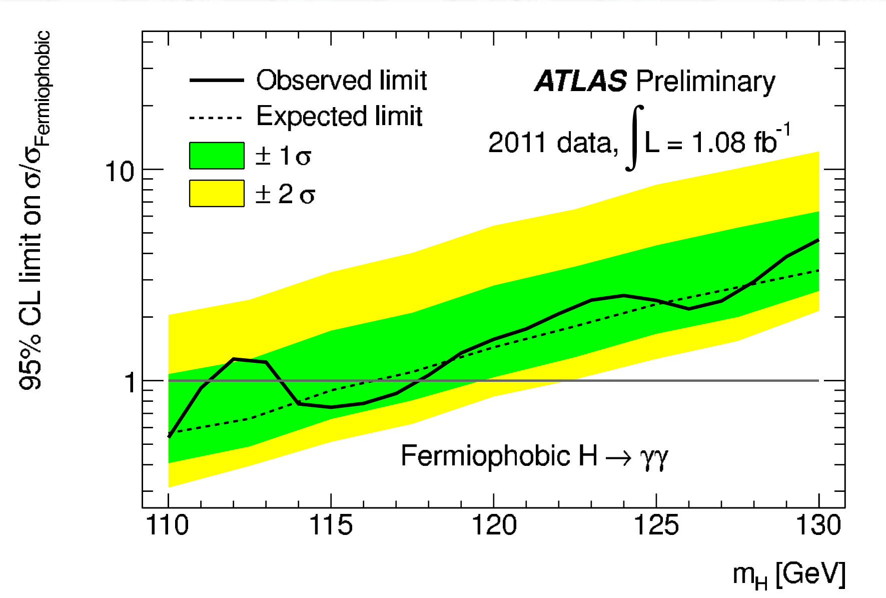






$L = 1.08\ fb^{-1}$

- No excess of events above Standard Model background (for different p_T categories) → exclusion limits



Excluded mass regions:
- 110 – 111 GeV and
- 113.5 – 117.5 GeV

Expected exclusion: 110 – 116 GeV

Summary and conclusions

- The operation of the LHC and of the ATLAS experiment in 2011 was superb
- LHC has reached sensitivity for the Standard Model Higgs boson and first exclusions beyond the LEP and Tevatron limits have been presented by ATLAS and CMS
- The ATLAS experiment has restricted the allowed mass range for the Standard Model Higgs boson to three regions (with 95% C.L.):

  $115.5 < m_H < 131$ GeV .or. $237 < m_H < 251$ GeV .or. $m_H > 468$ GeV

- The data are consistent with the expectations from Standard Model background processes, however, a low background-only probability of 0.6% (2.5σ), after correcting for the look-elsewhere-effect, is found for $m_H \sim 126$ GeV
- The fitted signal strength for a signal + background hypothesis at that mass in the three most important channels ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow WW \rightarrow \ell\nu\,\ell\nu$) is consistent with the Standard Model value, within errors.
- More data and a combination with the CMS experiment are needed to draw definite conclusions
- 2012 is going to be an exciting year for all of us !!

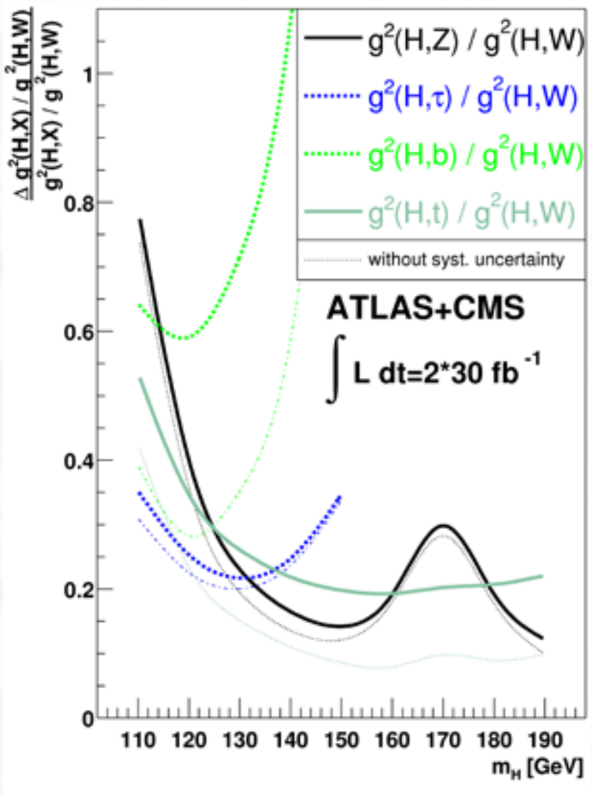
124-126 GeV would be a nice Higgs mass to have !

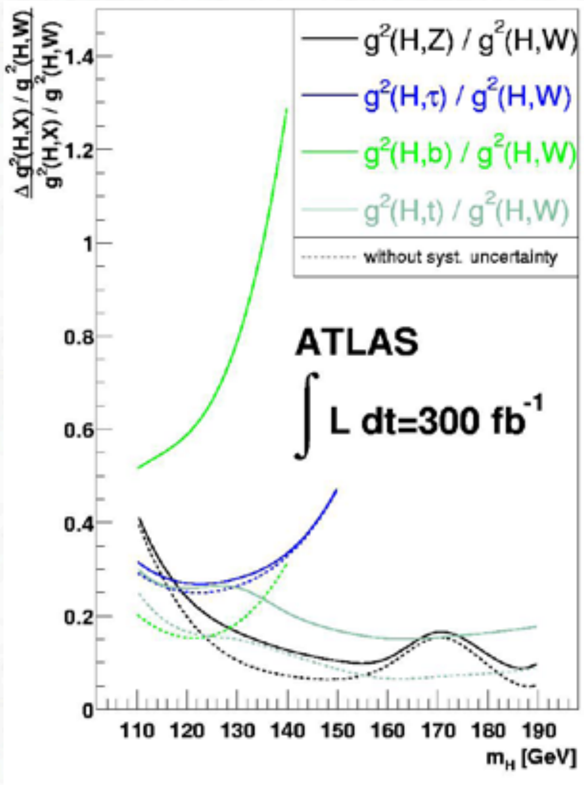
→ Zürich Higgs workshop 2009

Step 2: measurement of ratios of couplings:

<u>Additional assumption</u>: particle content in the gg- and γγ-loops are known;

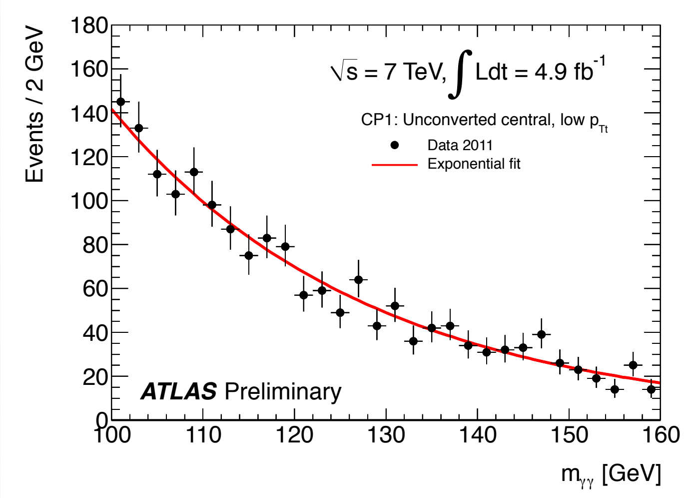
Information from Higgs production is now used as well;
Important for the determination of the top-Yukawa coupling

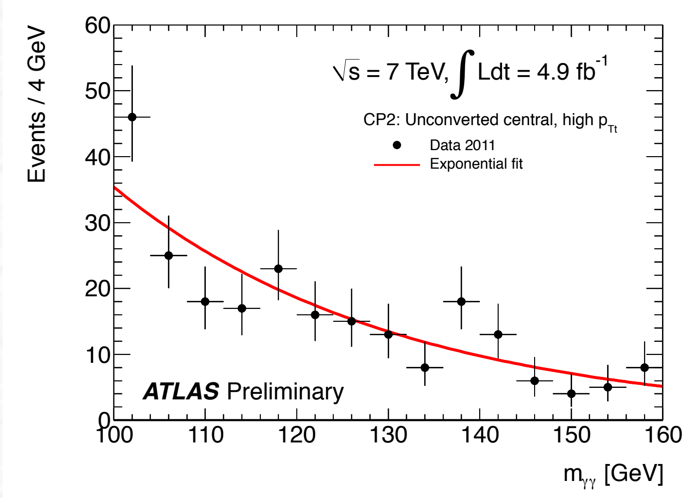


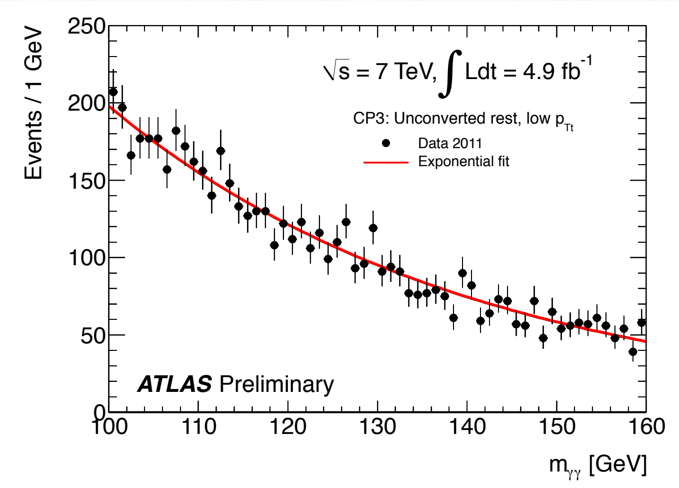


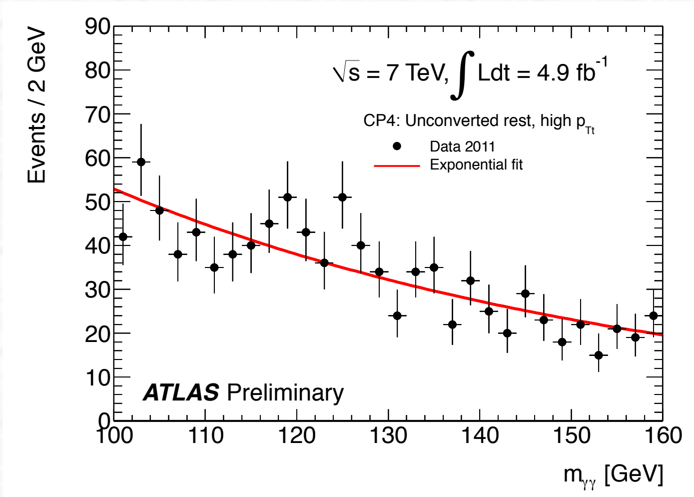
Backup Slides

γγ mass spectra for the nine categories
-unconverted-

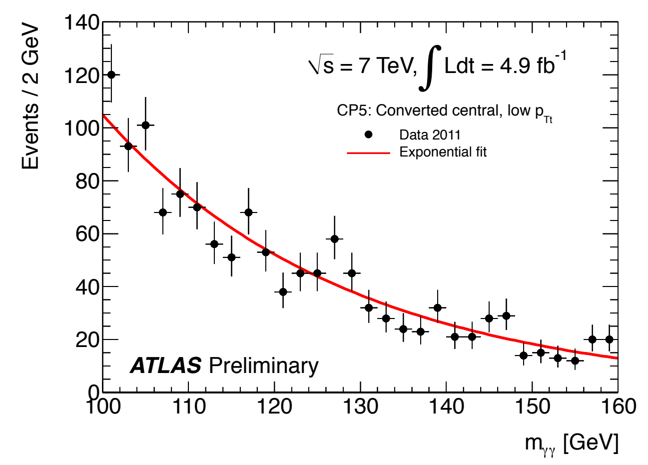


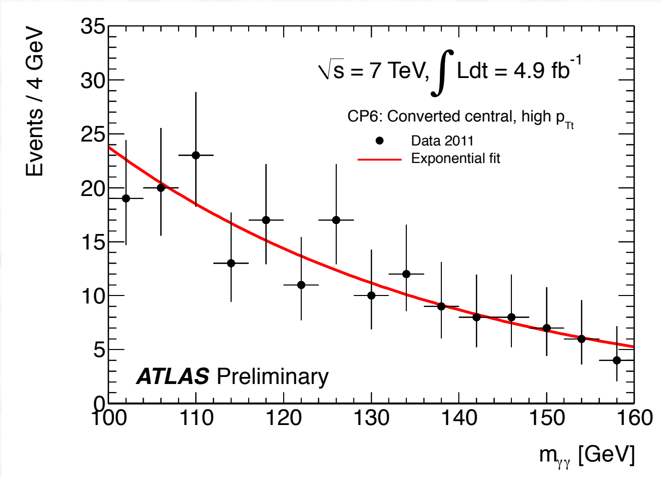


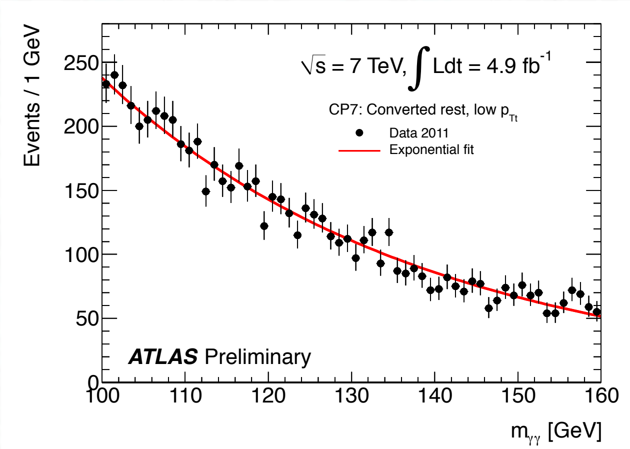


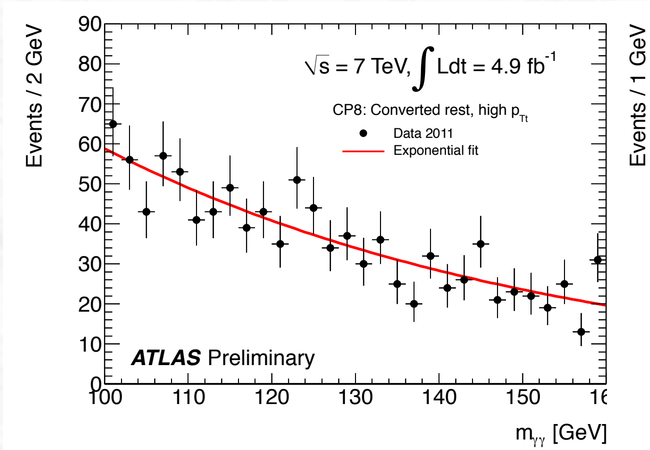


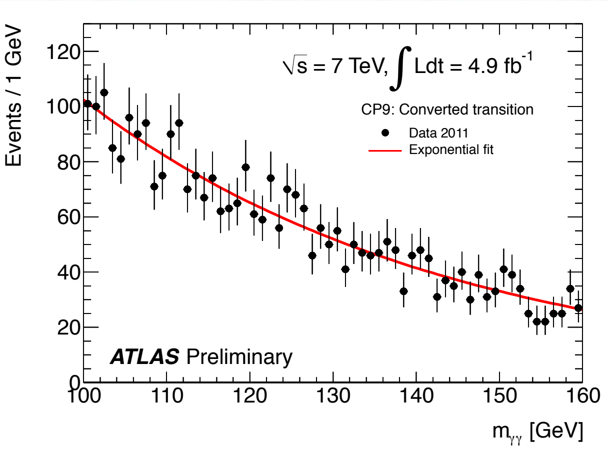
$\gamma\gamma$ mass spectra for the nine categories (cont.) -converted-







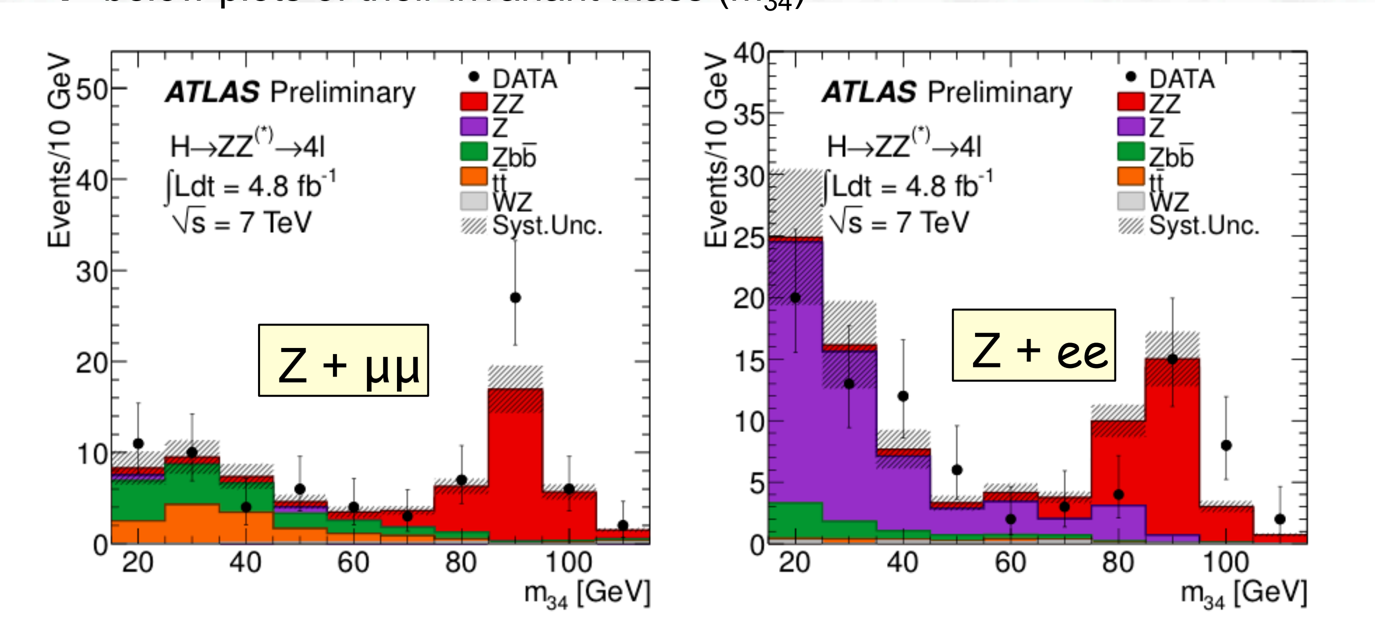




Reducible backgrounds from Zbb, Z+jets, tt giving 2 genuine + 2 fake leptons measured using background-enriched and signal-depleted control regions in data (chose a compromise between statistics and "purity")

Zbb+Z+jets control regions:

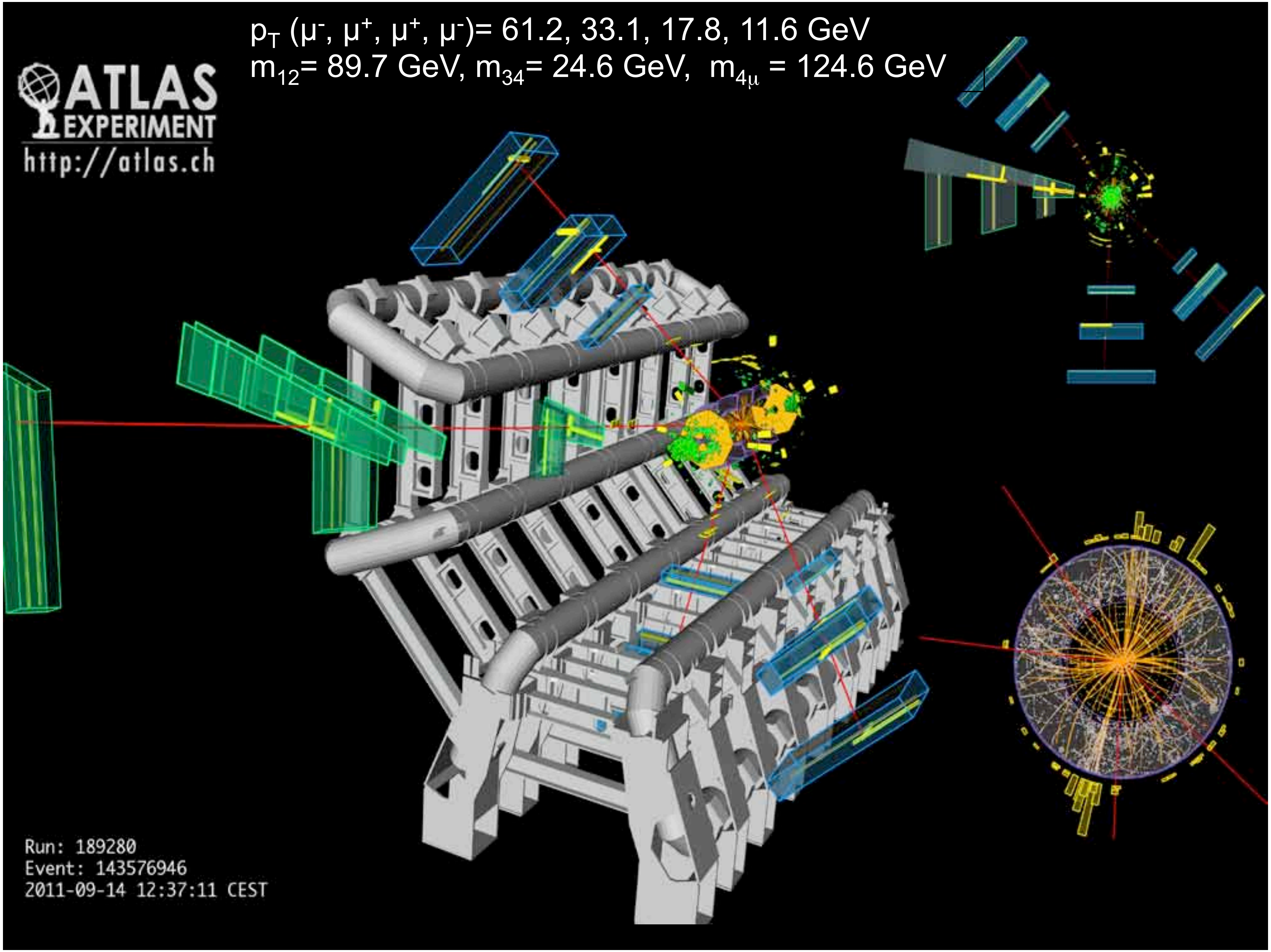
- Select events with 2 opposite-sign same-flavour leptons, $m_{ll}=m_Z \pm 15$ GeV
- 2 additional same-flavour leptons passing all cuts but isolation and impact parameter → below plots of their invariant mass (m_{34})



- Low-mass regions dominated by Zbb (Z+$\mu^+\mu^-$ sample) and Z+jet (Z+e^+e^- sample)
- Data well reproduced by MC (within uncertainties)
- Samples of Z+μ and Z+e then used to compare efficiencies of isolation and impact parameter cuts between data and MC → Good agreement

→ MC used to estimate background contamination in signal region

	Data	MC
Z+μ	20±1%	20.3± 0.4%
Z+e	29.9±0.6%	30.4± 0.4%


p_T (μ^-, μ^+, μ^+, μ^-)= 61.2, 33.1, 17.8, 11.6 GeV
m_{12}= 89.7 GeV, m_{34}= 24.6 GeV, $m_{4\mu}$ = 124.6 GeV
ATLAS EXPERIMENT
http://atlas.ch
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST

p_T (μ^-,μ^+,e^-,e^+) = 43.9, 43.5, 11.2, 9.9 GeV

$m_{\mu+\mu-}$ = 89.3 GeV, m_{e+e-} = 30 GeV, m_{4l} = 123.6 GeV