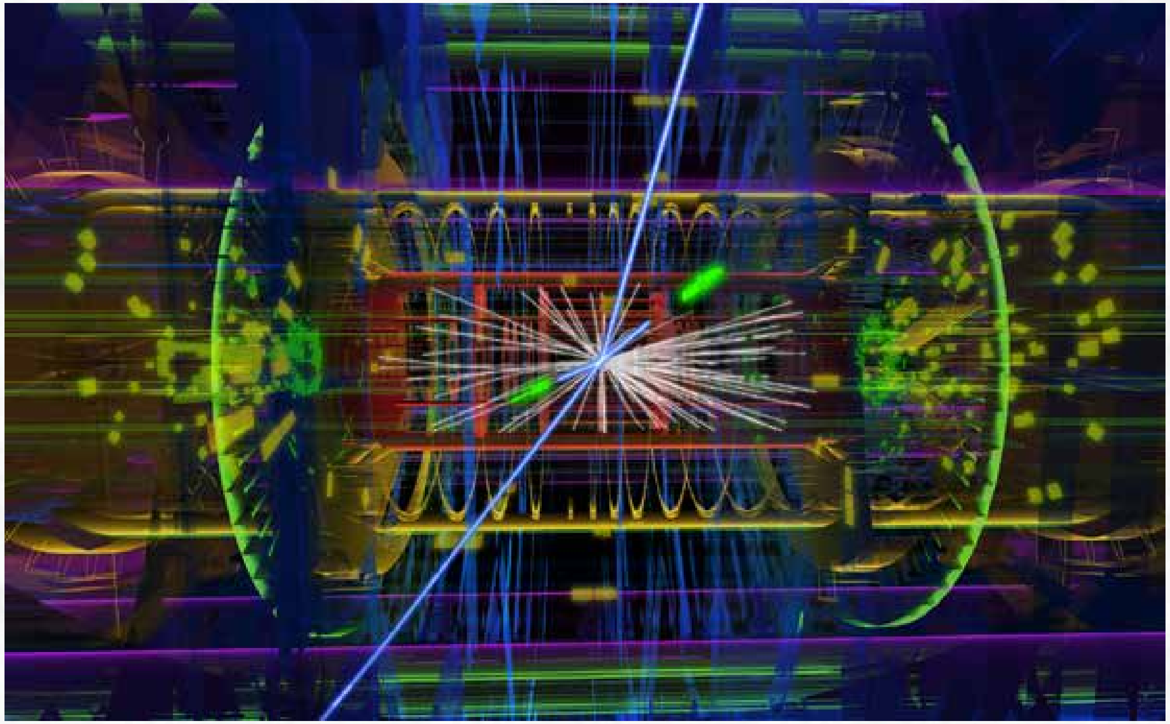
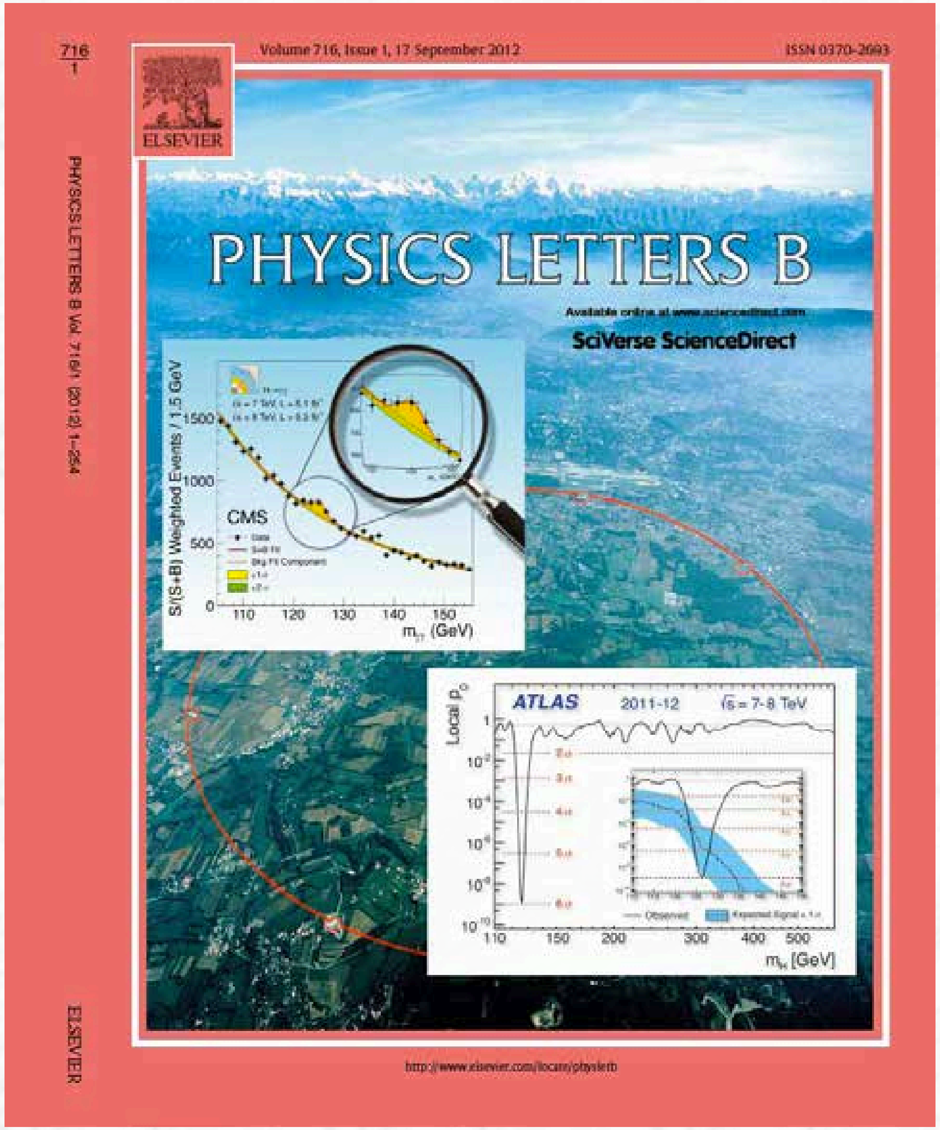
Higgs boson physics at ATLAS



Karl Jakobs, University of Freiburg

-On behalf of the ATLAS Collaboration-



Outline

- LHC and ATLAS
- Higgs boson studies

    - Di-boson decays
      H → γγ, H → ZZ*, H → WW*

    - Decays into fermions

    - Search for rare decays

- Higgs boson parameters
- Spin / parity

Publication in Phys. Lett. B (2012)

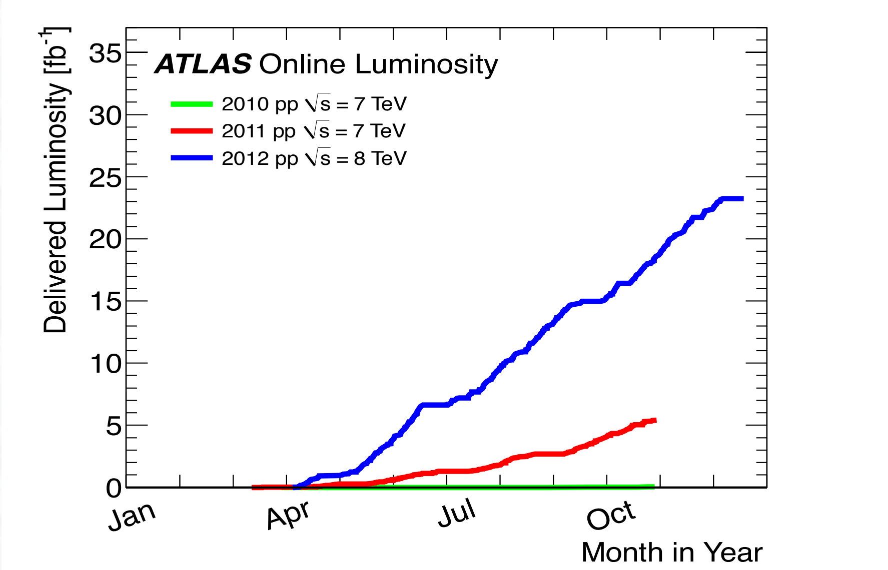
The Large Hadron Collider

Steve Myers PLHC 2012:

"The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics."

Key ingredients to this success story

1. The accelerator

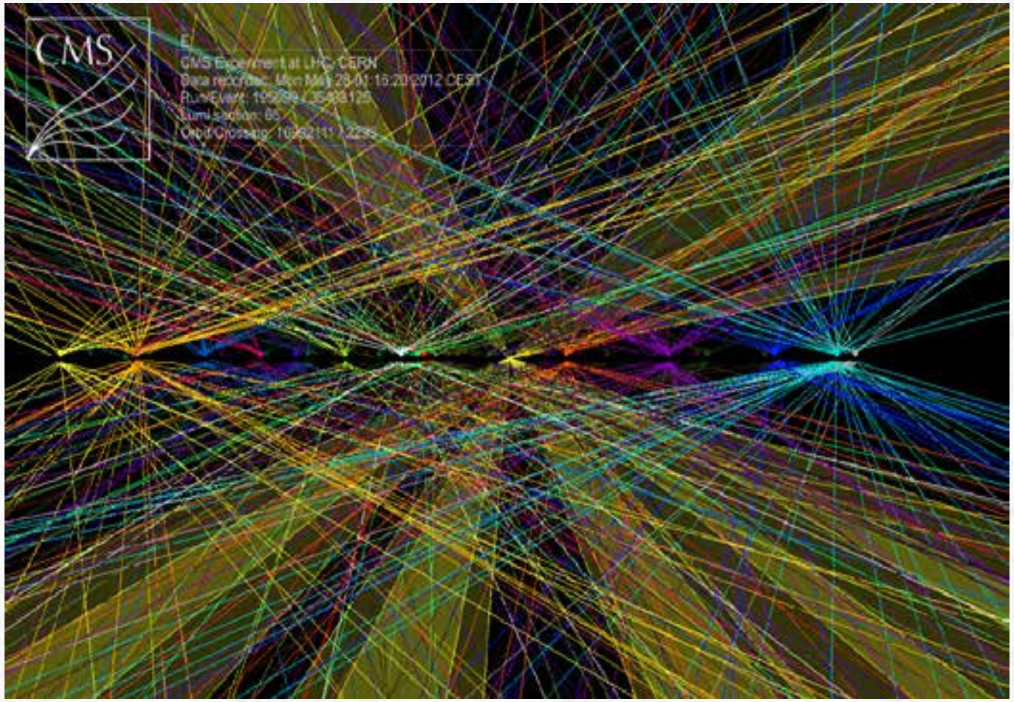


- World record on instantaneous luminosity on 22. April 2011: 4.7 10^{32} cm^{-2} s^{-1} (Tevatron record: 4.0 10^{32} cm^{-2} s^{-1})
- 2012: regularly above 6 10^{33} $cm^{-2}s^{-1}$

The key ingredients to this success story

1. The accelerator

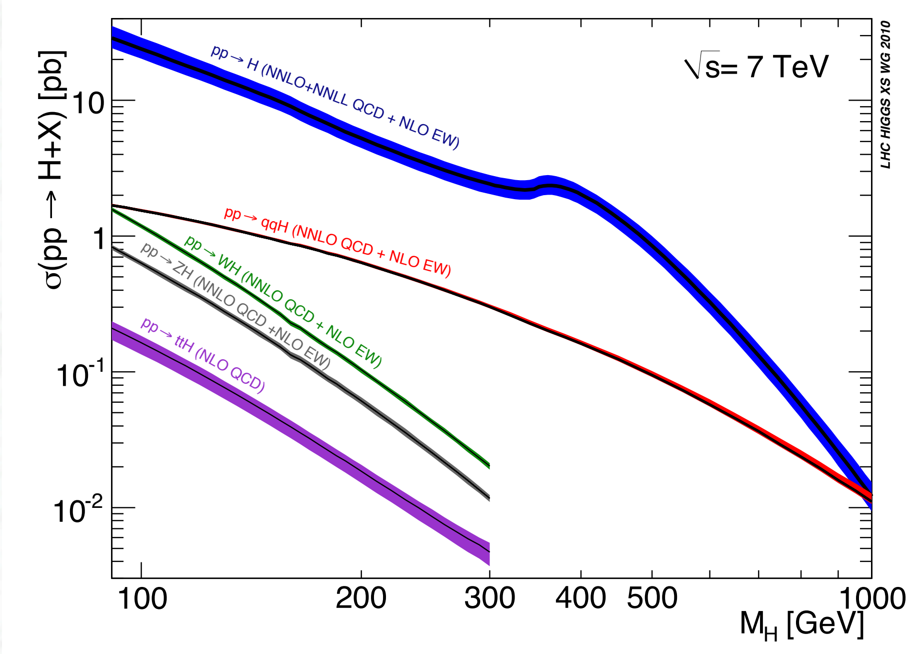
2. The detectors



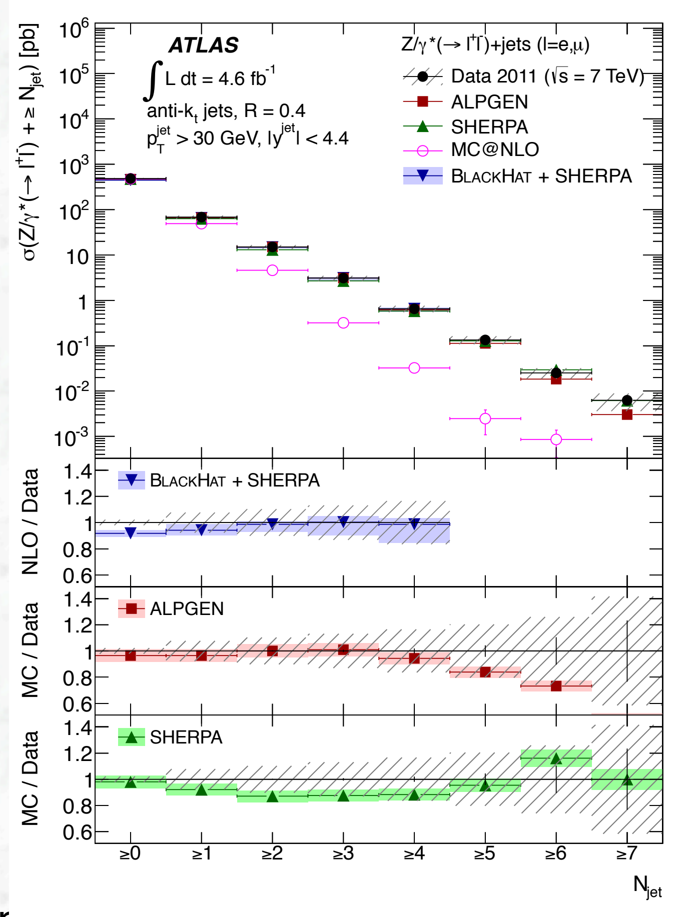
- Working channels > 99%
- Data recording efficiency ~93-94%
- Data quality
- Speed of data analysis
- Had to cope with high luminosity

The key ingredients to this success story

1. The accelerator
2. The detectors
3. Theory, including advances in Monte Carlo simulation



- The overwhelming progress in (N)NLO calculations for signal and background processes



- Improved Monte Carlos simulations

  ALPGEN, MC@NLO, POWHEG, SHERPA, …

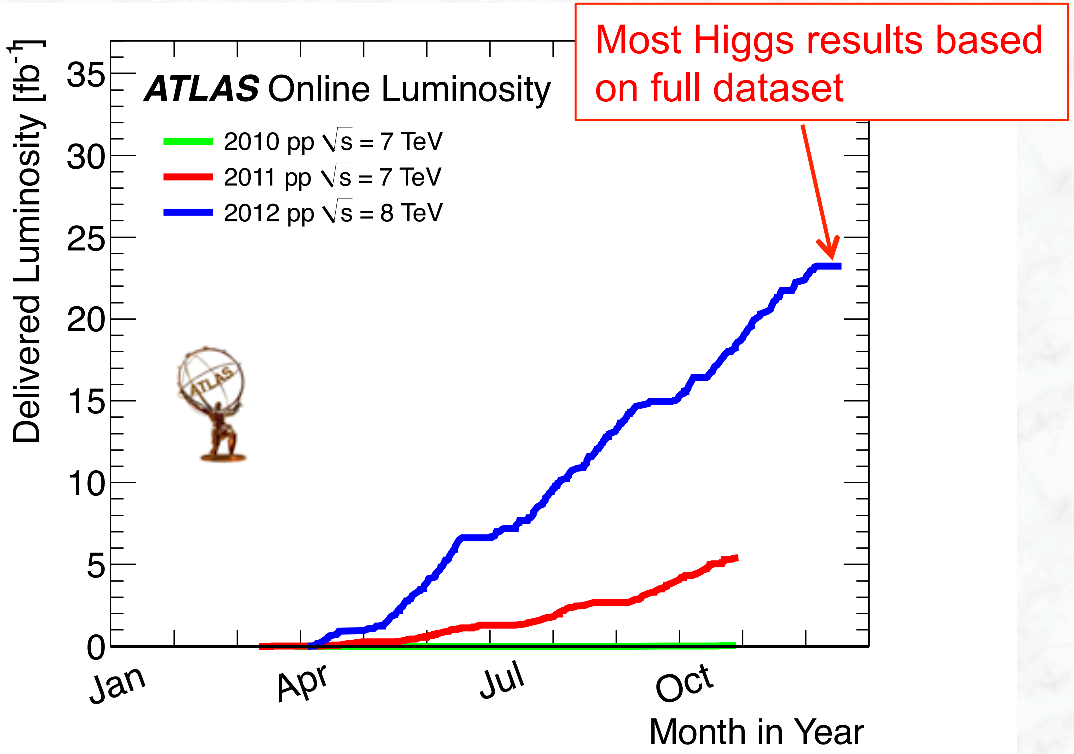
- The "Higgs *cross section group*"

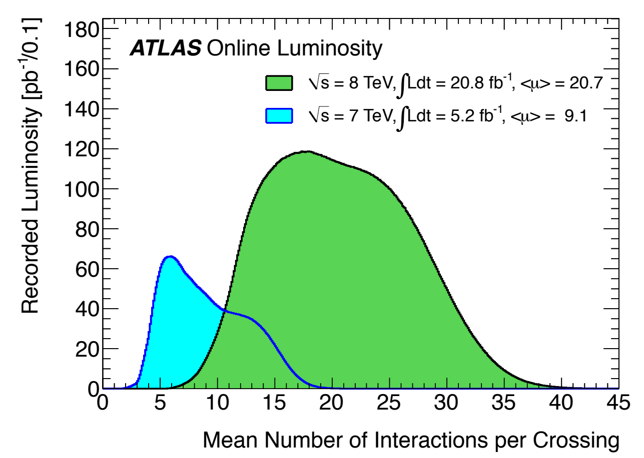
  A big success story !!

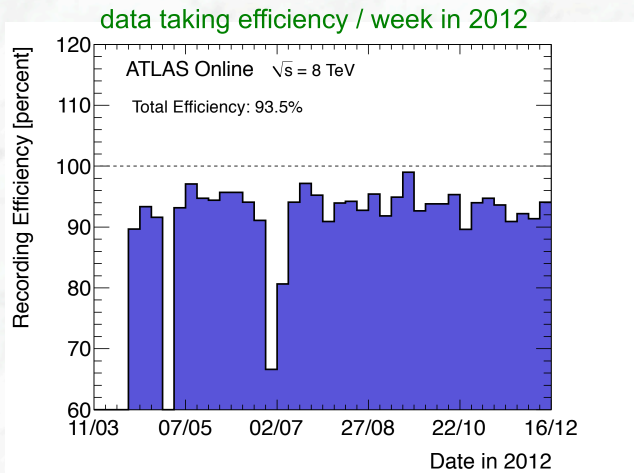
  HXSWG

  * Central values for the production processes
  * Theoretical uncertainties
  * Differential distributions
  * Guidance / benchmark scenarios on coupling measurements
  * Guidance in spin/CP measurements

Summary of LHC and ATLAS performance

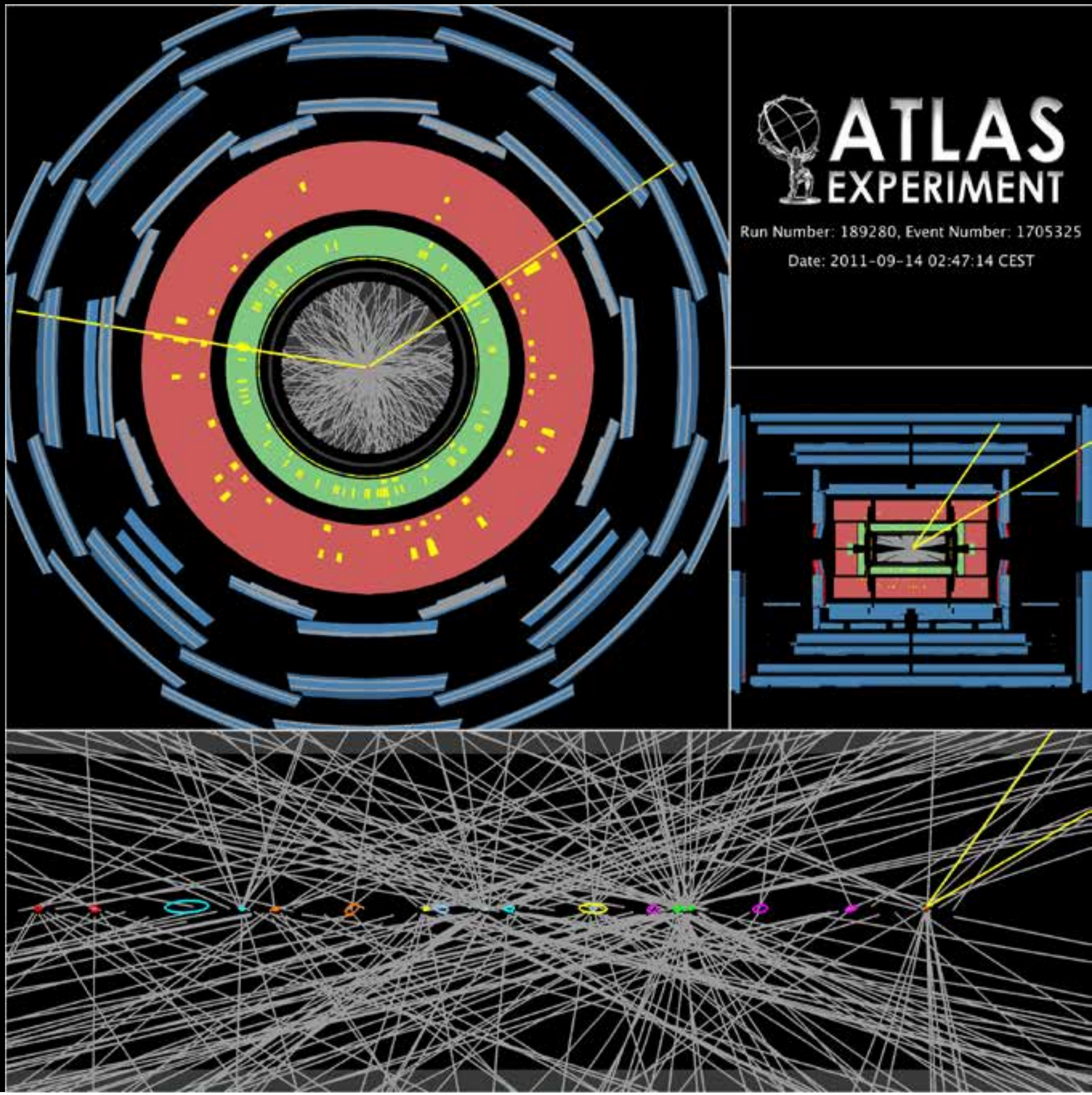




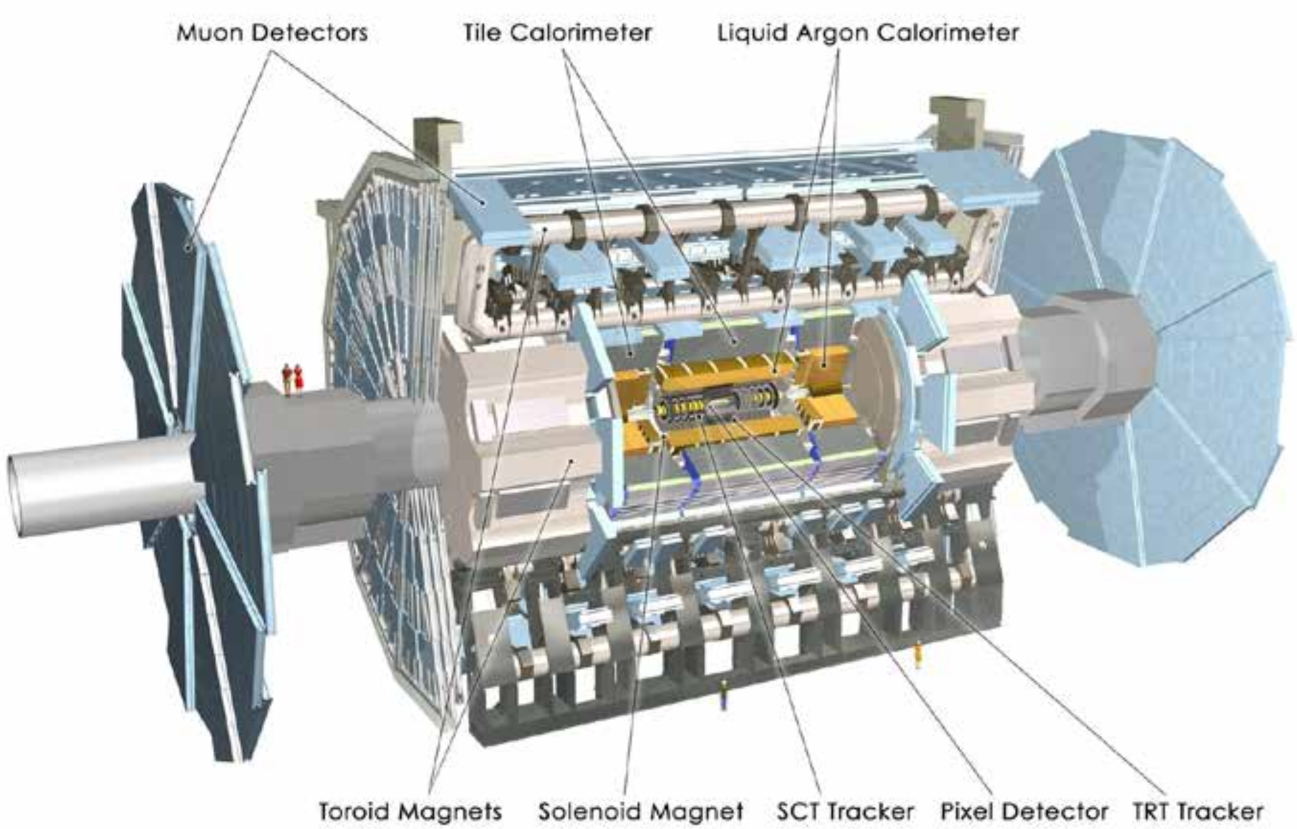


- Excellent LHC performance in 2011 and 2012
- Peak luminosities > 7 10^{33} cm^{-2} s^{-1}
- High level of pileup: mean of ~21 interactions / beam crossing in 2012
- Excellent performance of the ATLAS experiment: (Data recording efficiency: ~93.5%, working detector channels >99 % for most sub-detectors, high data quality, speed of the data analysis)

$Z \rightarrow \mu^{+} \mu^{-}$ with 20 reconstructed pp vertices



The ATLAS experiment

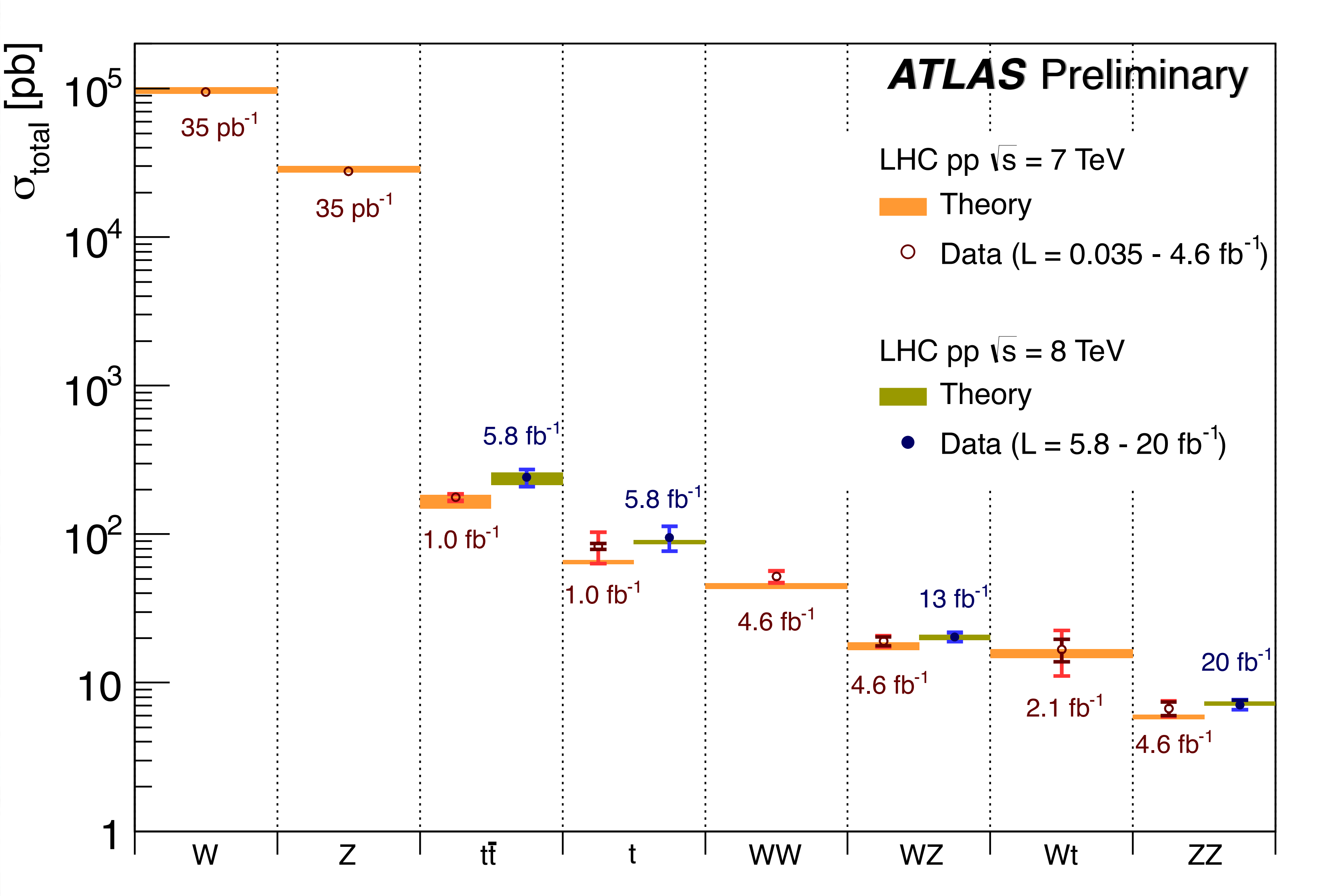


- Solenoidal magnetic field (2T) in the central region (momentum measurement)
- Independent muon spectrometer (supercond. toroid system)
- High resolution silicon detectors:
  - 6 Mio. channels (80 µm x 12 cm)
  - 100 Mio. channels (50 µm x 400 µm)

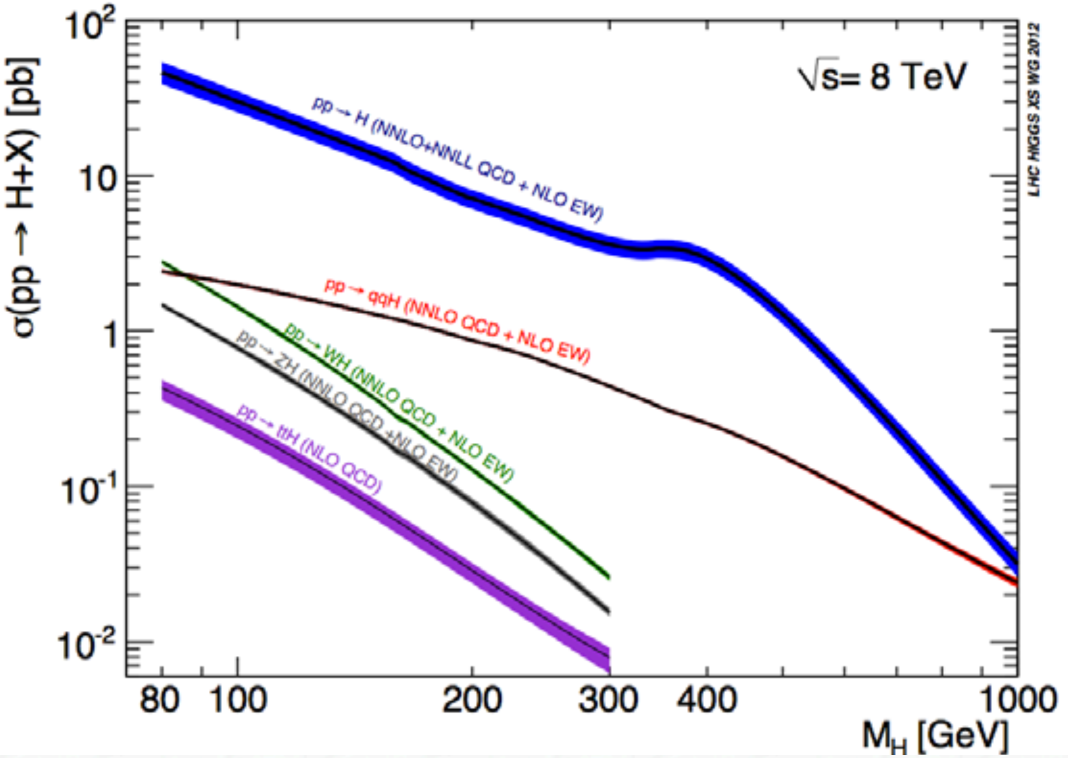
  space resolution: ~ 15 µm
- Liquid argon el. magn. calorimeter (high granularity, long. segmentation); Energy measurement down to 1° to the beam line

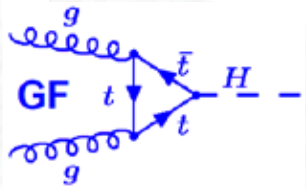
Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

Standard Model processes at the LHC

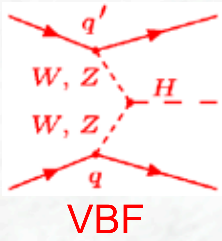


Higgs Boson Production

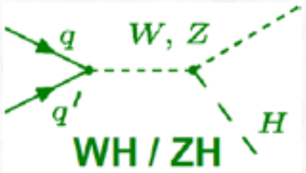




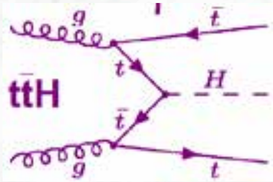
Gluon fusion



Vector boson fusion



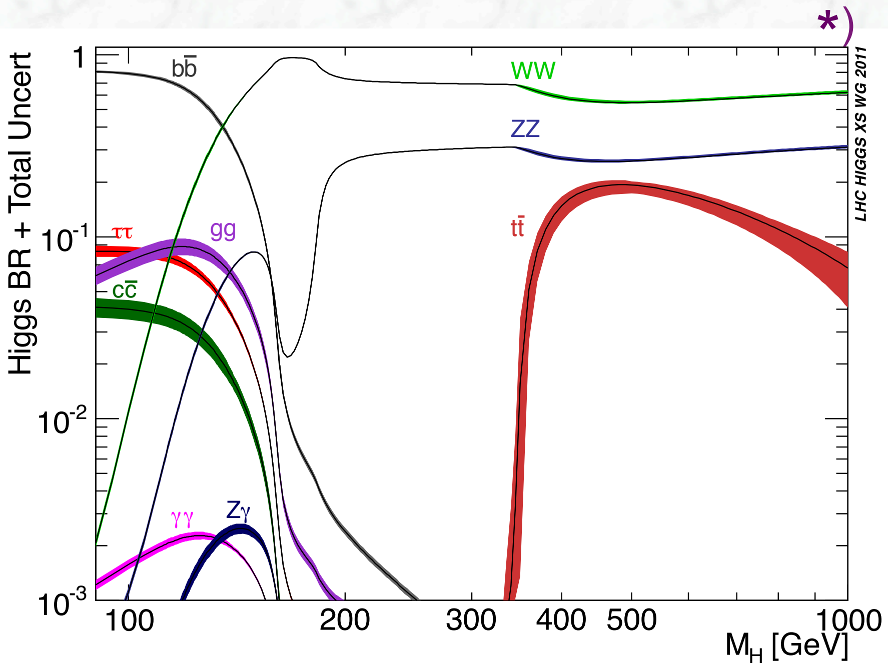
WH/ZH associated production



tt associated production

*) LHC Higgs cross-section working group
Large theory effort

Higgs Boson Decays



Useful decays at a hadron collider:

- Final states with leptons via WW and ZZ decays
- γγ final states (despite small branching ratio)
- ττ final states (more difficult)
- In addition: H → bb decays via associated lepton signatures (VBF, VH or ttH production)

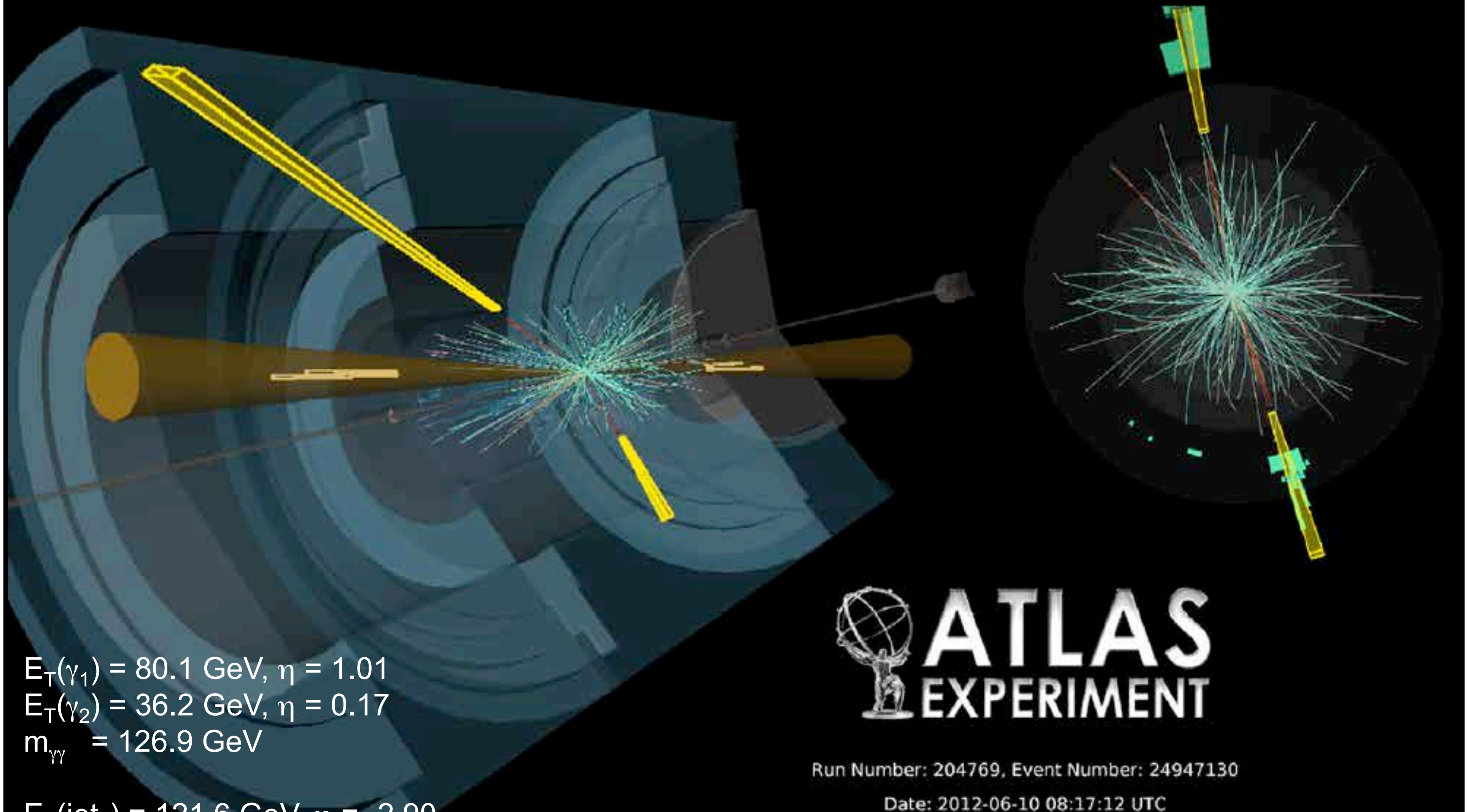
SM predictions (m_H = 125.5 GeV):

BR (H→ WW) = 22.3%	BR (H → bb) = 56.9%
BR (H → ZZ) = 2.8%	BR (H → ττ) = 6.2%
BR (H → γγ) = 0.24%	BR (H →μμ) = 0.022%

→ at 125 GeV: only ~11% of decays not observable (gg, cc)

*) LHC Higgs cross-section working group

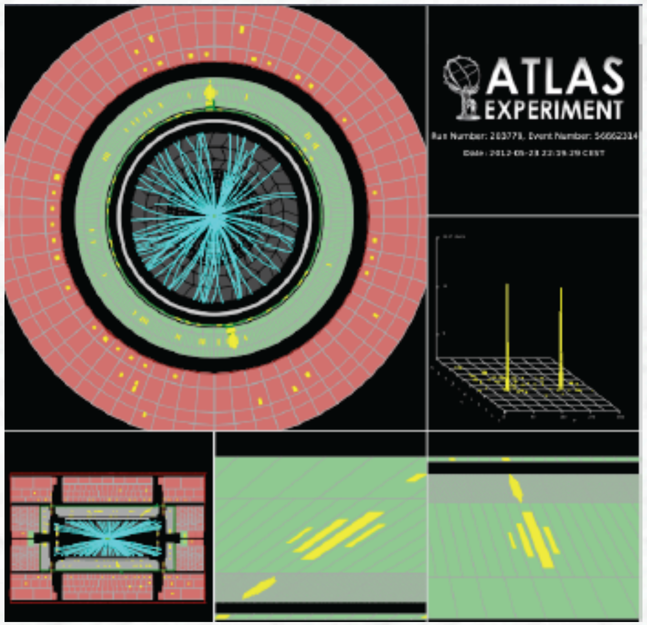
$H \rightarrow \gamma\gamma$ VBF candidate event



$E_T(\gamma_1)$ = 80.1 GeV, η = 1.01
$E_T(\gamma_2)$ = 36.2 GeV, η = 0.17
$m_{\gamma\gamma}$ = 126.9 GeV

$E_T(jet_1)$ = 121.6 GeV, η = -2.90
$E_T(jet_2)$ = 82.8 GeV, η = 2.72
m_{jj} = 1.67 TeV

Result of the ATLAS search for H → $\gamma\gamma$

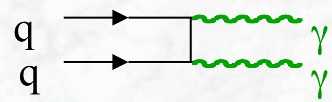


- Two photons (isolated) with large transverse momentum (P_T > 40, 30 GeV)

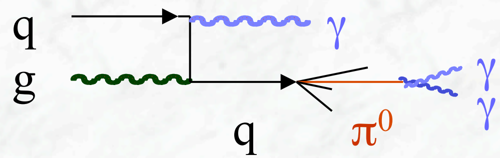
- Mass of the Higgs boson can be reconstructed $m_{\gamma\gamma}$

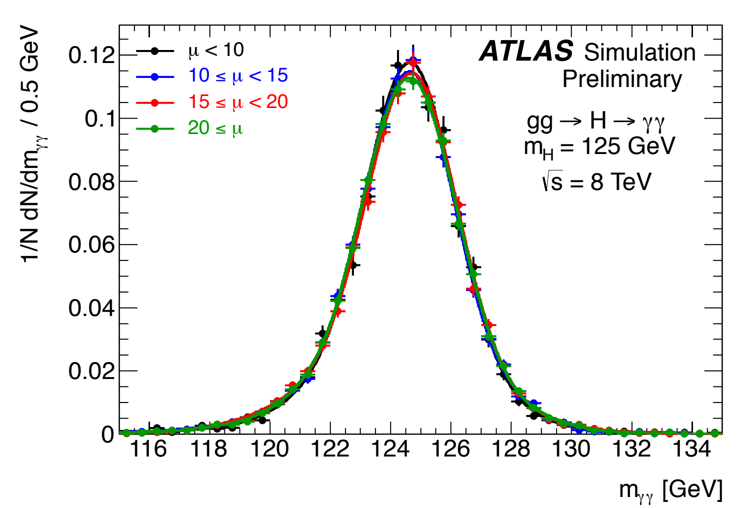
  Good mass resolution: ~1.7 GeV for m_H ~120 GeV - LAr el. magn. calorimeter (high granularity)
  - Direction measurement in fine-segmented calorimeter

- Challenge: signal-to-background ratio
  - irreducible $\gamma\gamma$ background



  - reducible backgrounds from γj and jj (several orders of magnitude larger than the irreducible one, before selections / isolation)

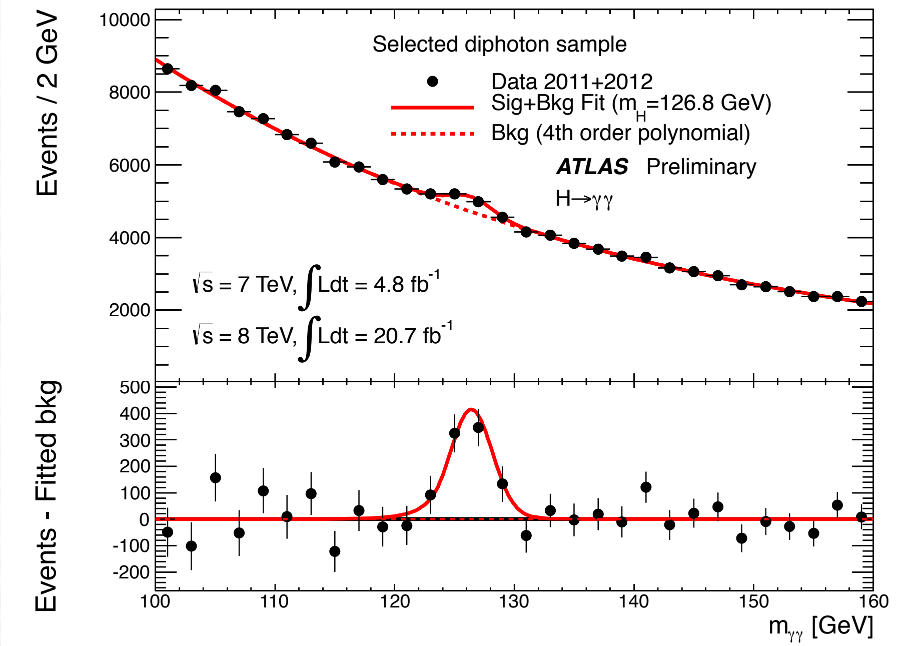




pile-up-robust mass reconstruction

Result of the ATLAS search for H → γγ

Full dataset ATLAS-CONF-2013-012



100 GeV < $m_{\gamma\gamma}$ < 160 GeV:

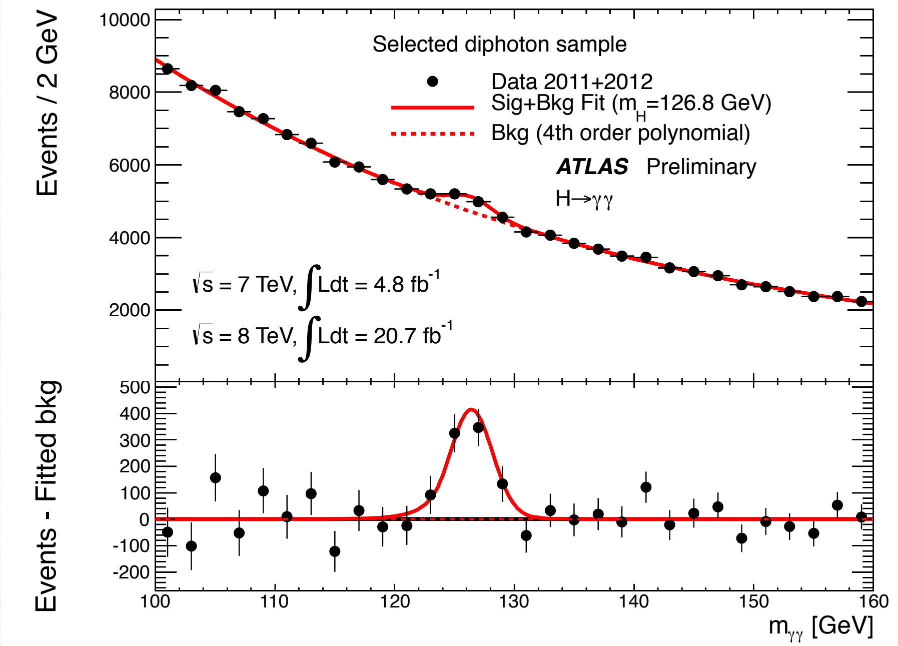
$\sqrt{s}$ = 7 TeV 23 788 events

$\sqrt{s}$ = 8 TeV 118 893 events

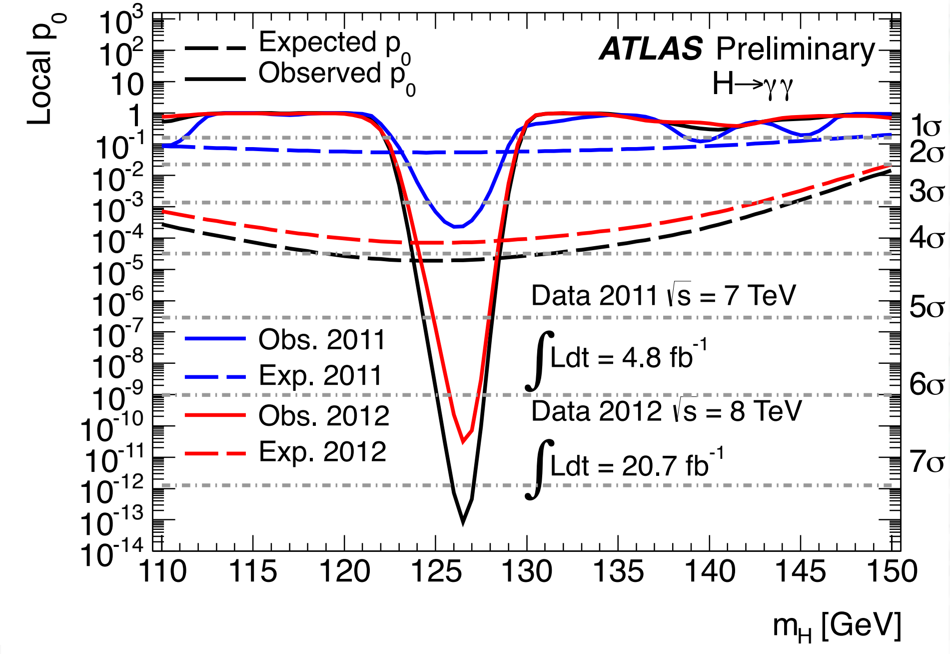
- Background interpolation in the region of the excess (obtained from sidebands)
- Reducible γ-jet and jet-jet background at the level of 25%

Result of the ATLAS search for H → γγ

Full dataset ATLAS-CONF-2013-012



ATLAS-CONF-2013-012

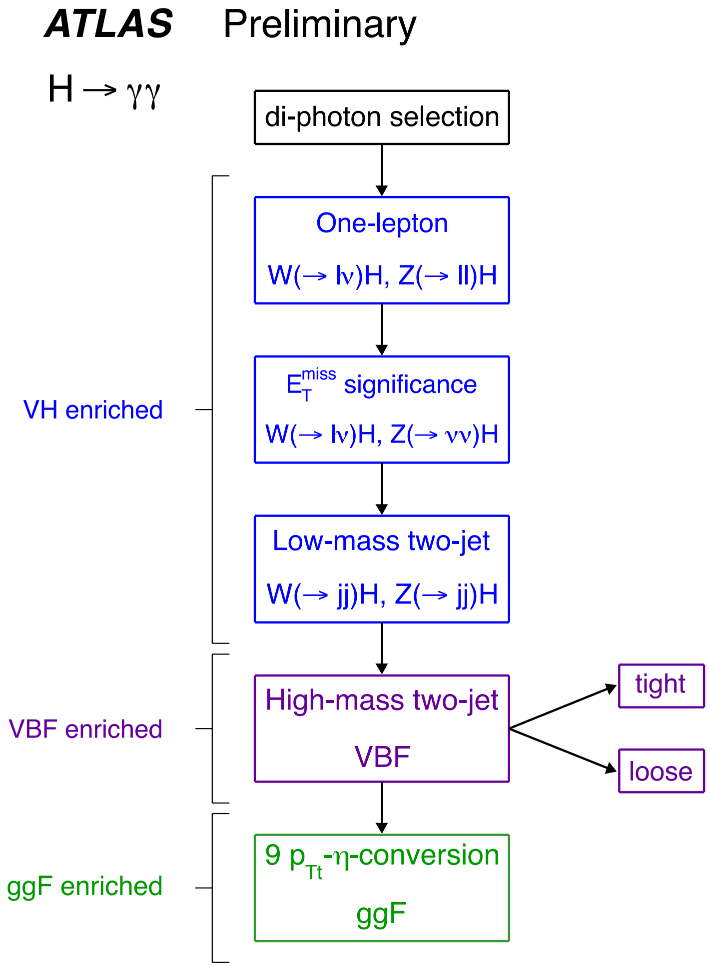


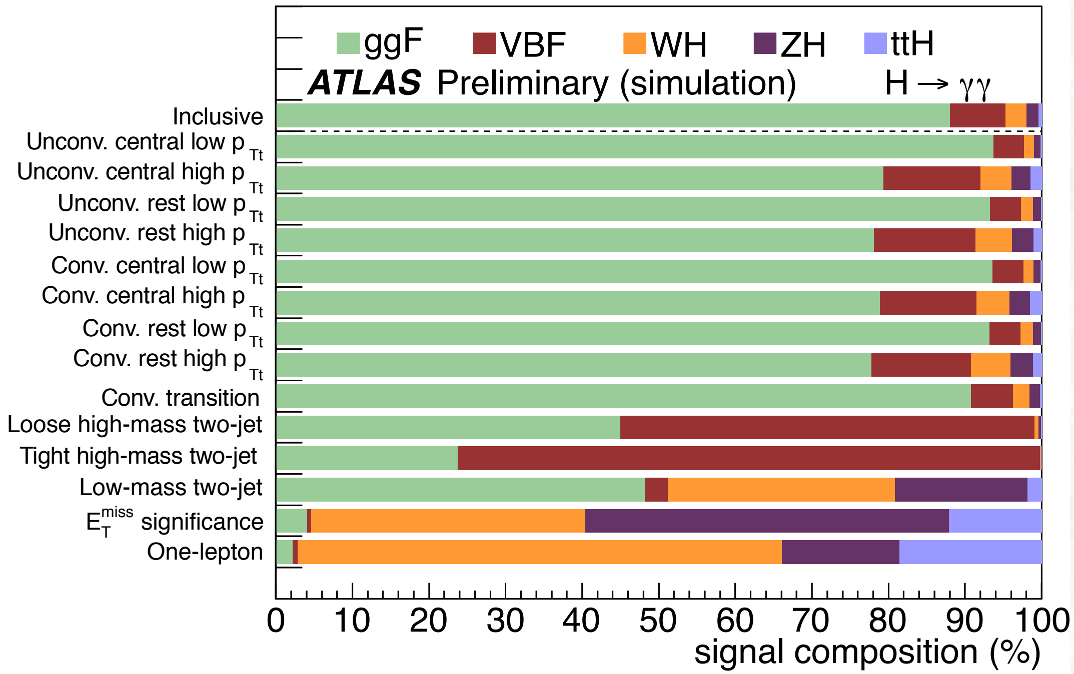
- p_0 value for consistency of data with background-only: $\sim 10^{-13}$ (7.4σ observed) for the combined 7 TeV and 8 TeV data; (4.3σ expected) (minimum found at $m_{\gamma\gamma}$ = 126.5 GeV)
- Establishes the discovery of the new particle in the γγ channel alone

Categorisation of H → γγ candidate events

ATLAS-CONF-2013-012

Categorisation: to increase overall sensitivity and sensitivity to different production modes (VBF, VH)

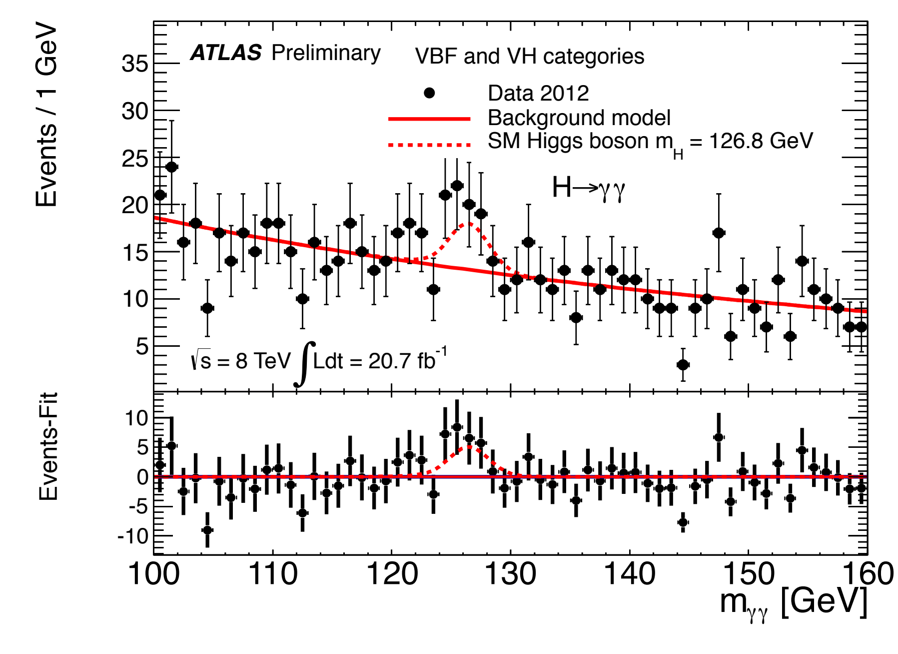


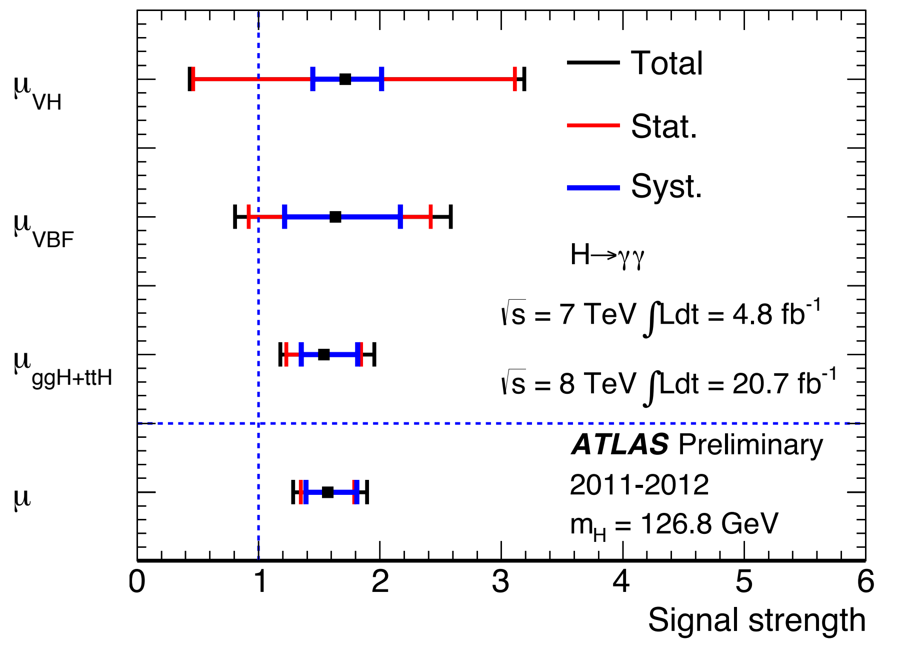


- VH enriched: one-lepton, E_T^{miss}, low-mass di-jets
- VBF enriched (tag-jet configuration, $\Delta\eta$, m_{jj})
- gluon fusion: 9 categories, exploit different mass resolution for different detector regions, γγ conversion status and p_{Tt}

Mass and signal strength for H → γγ

VBF + VH categories

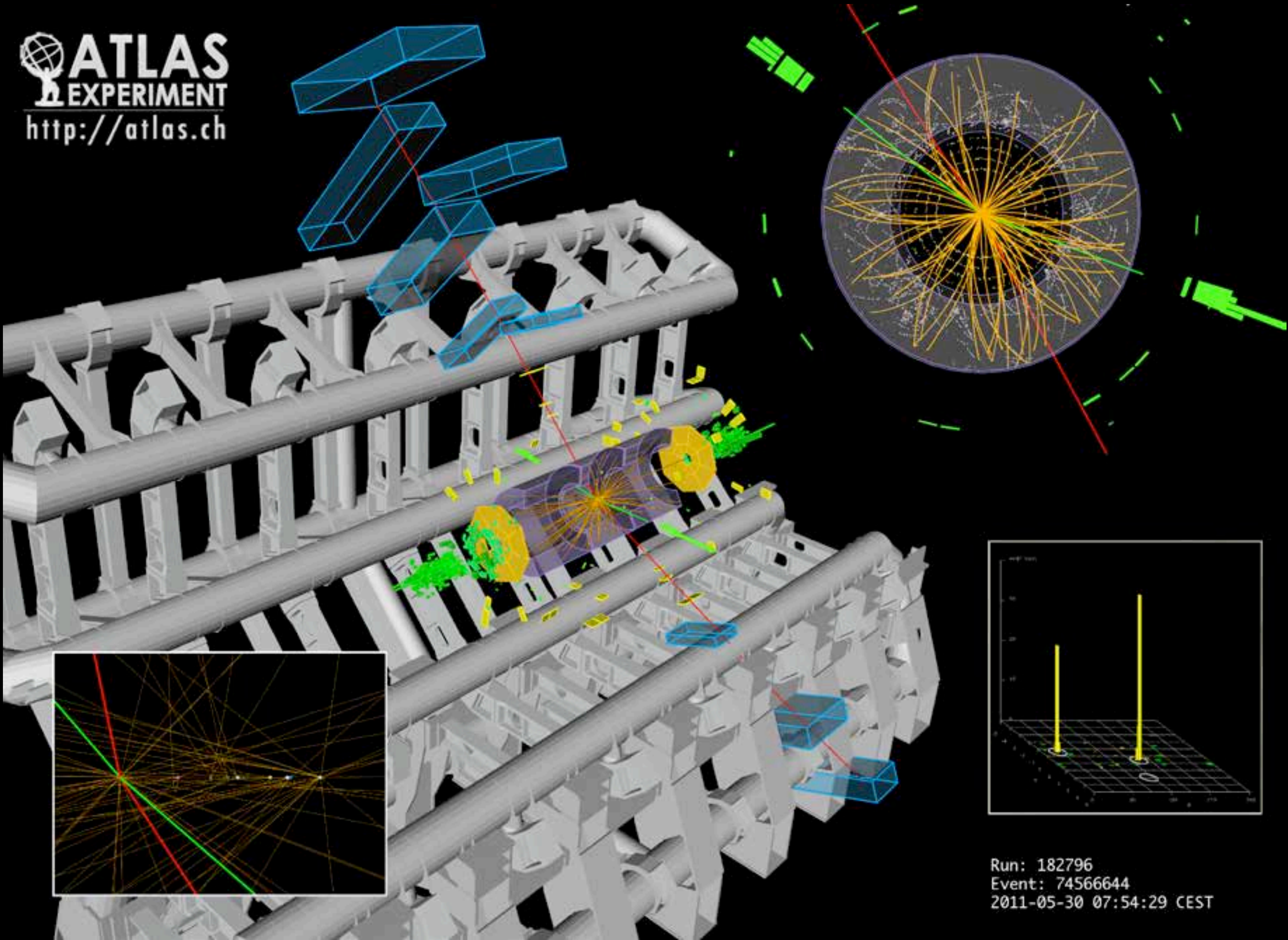




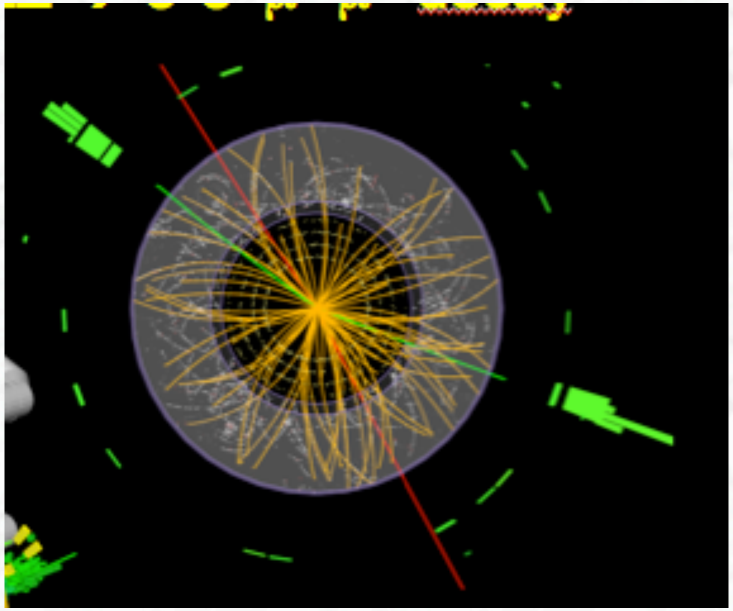
Mass: $m_H = 126.8 \pm 0.2\,(\text{stat}) \pm 0.7\,(\text{syst})$ GeV

Signal strength: $\mu := \sigma / \sigma_{SM} = 1.57 \pm 0.22(\text{stat})\,^{+0.24}_{-0.18}(\text{syst})$
(m_H = 126.8 GeV)

H → ZZ → $e^+e^- \mu^+ \mu^-$ candidate event



Search for the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- \ell^+\ell^-$ decay

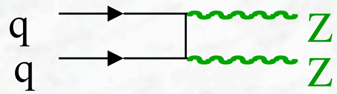


- The "golden mode": 4 isolated leptons
  e: $P_T > 20$, 15, 10, 7 GeV, $|\eta| < 2.47$
  μ: $P_T > 20$, 15, 10, 6 GeV, $|\eta| < 2.7$
  One pair consistent with Z mass (m_{12})
  Mass of other pair: $m_{min} < m_{34} < 115$ GeV

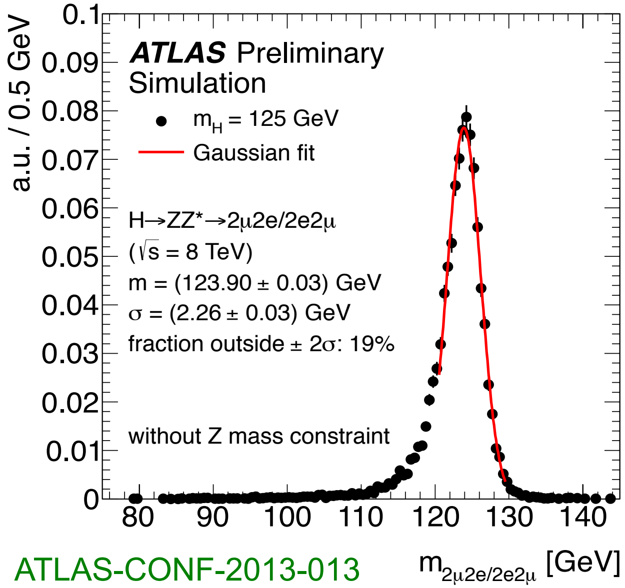
- Mass of the Higgs boson can be reconstructed $m_{4\ell}$

  Good mass resolution $m_{4\ell}$; For $m_H = 125$ GeV:
  4e: ~2.7 (2.4) GeV without (with) Z mass constraint
  4μ: ~2.0 (1.6) GeV without (with) Z mass constraint

- Low signal rate, but also low background
  - Mainly from ZZ continuum

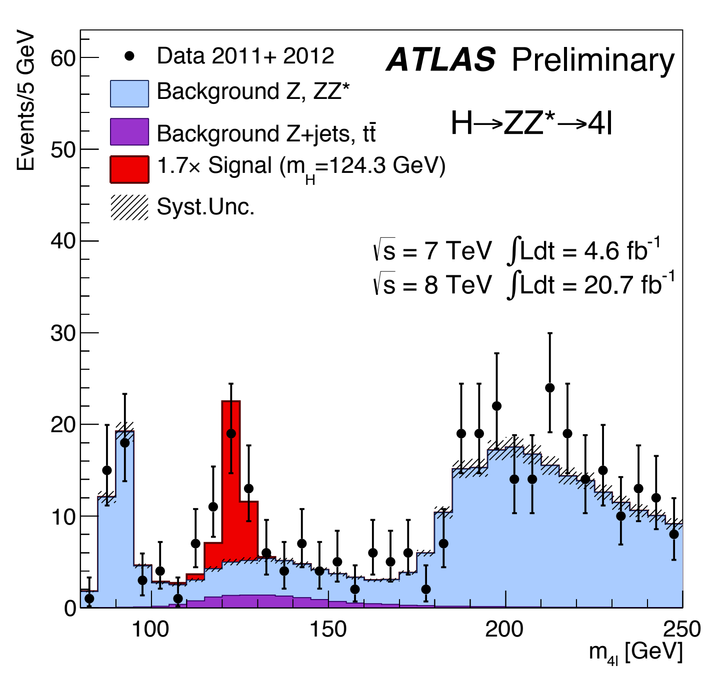


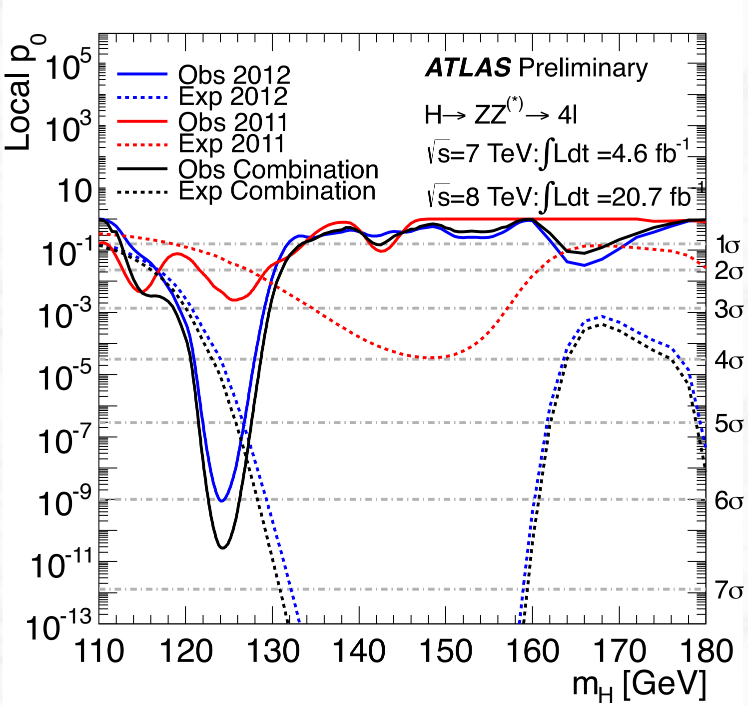
  - In addition from tt and Z+jet production:
    (two prompt leptons from W / Z decays and two leptons from (heavy) quark decays)



ATLAS-CONF-2013-013

4ℓ invariant mass spectra



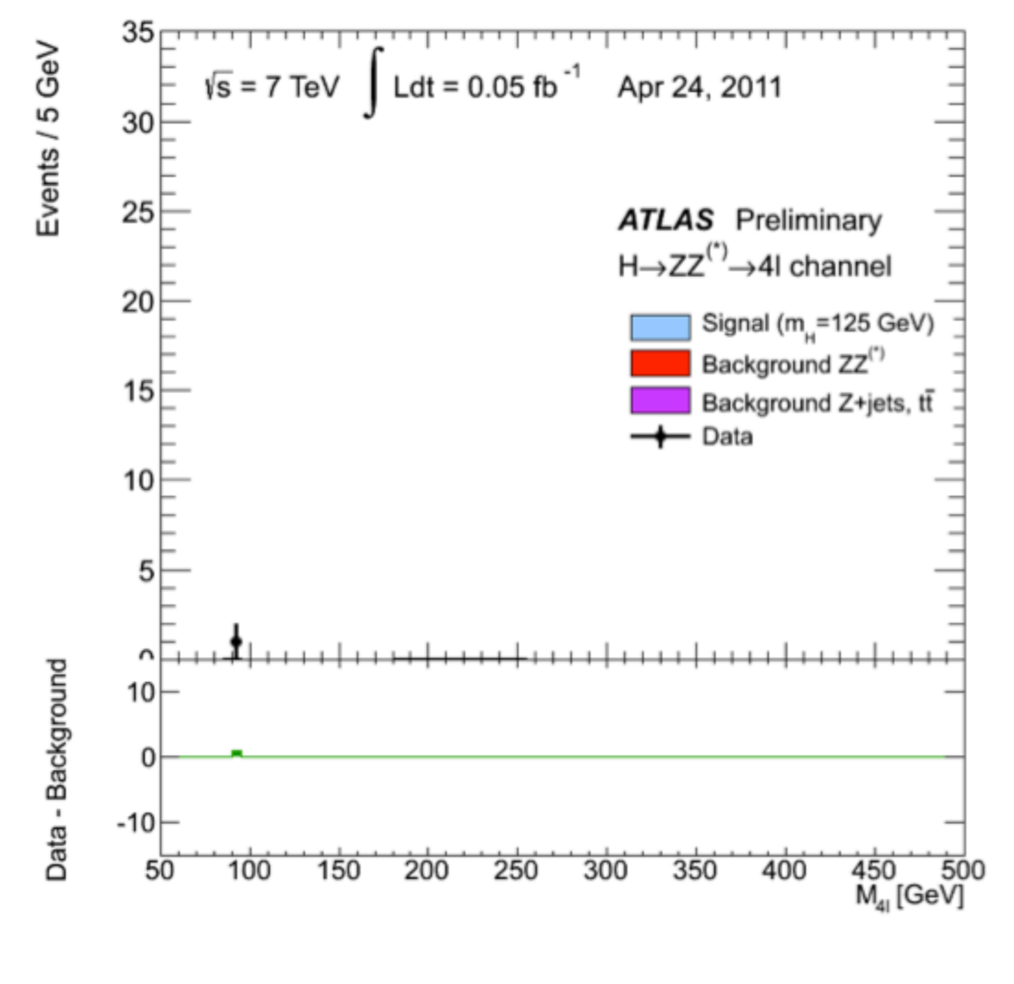


Mass range 120 – 130 GeV	Expected signal	Background	Data
√s = 7 TeV	2.2	2.3	5
√s = 8 TeV	13.7	8.8	27

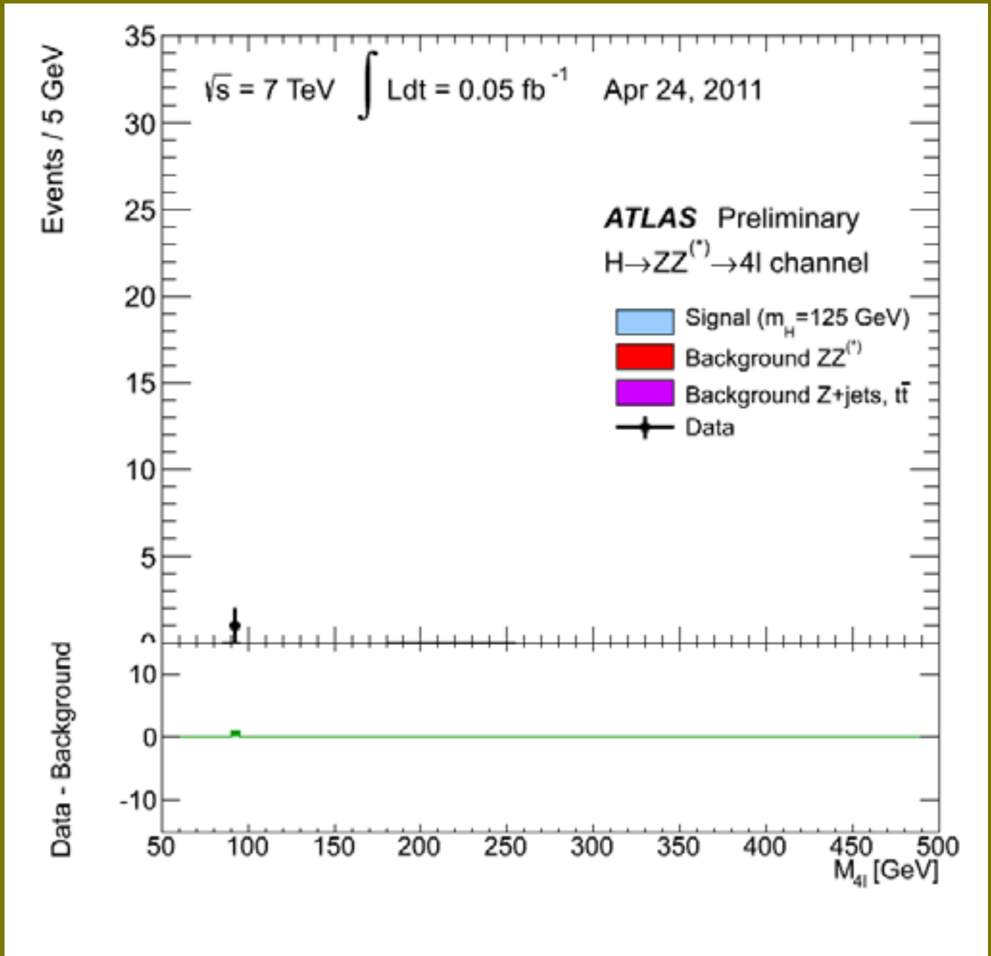
$m_{4\ell}$ > 160 GeV: 376 events observed
348 ± 26 expected from
√s = 7 + 8 TeV background (mainly ZZ)

- maximum deviation at 124.3 GeV
  p_0 value: ~2.7 10^{-11} (6.6σ obs.)
  (4.4σ exp.)
- Independent discovery-level observation

Time evolution of the H → ZZ → 4ℓ signal

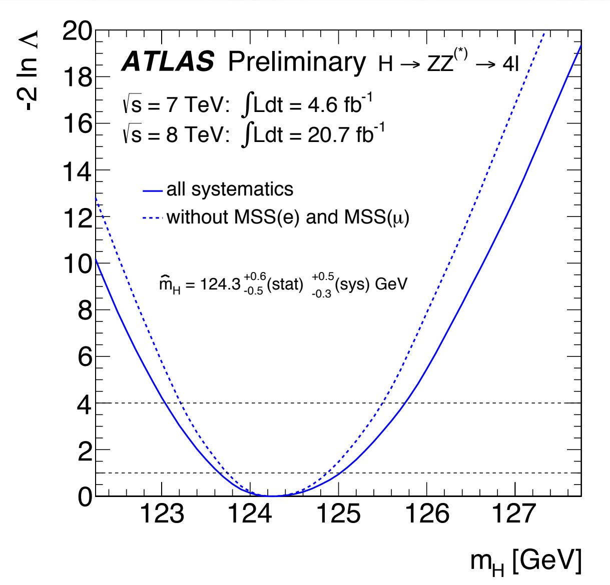


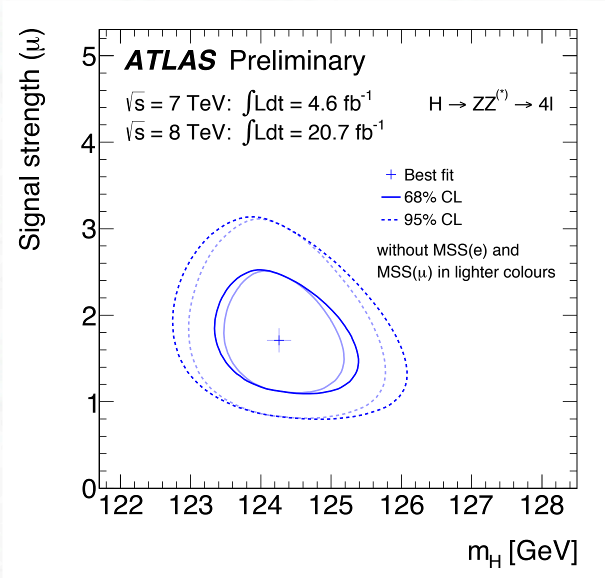
Time evolution of the H → ZZ → 4ℓ signal

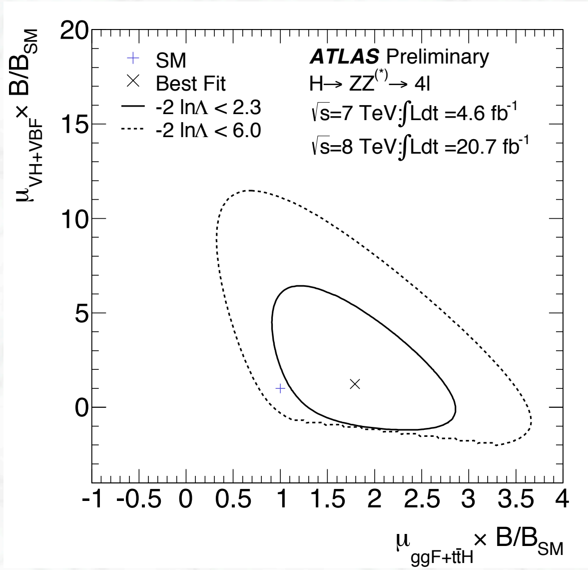


Mass and signal strength for H → ZZ*

ATLAS-CONF-2013-013







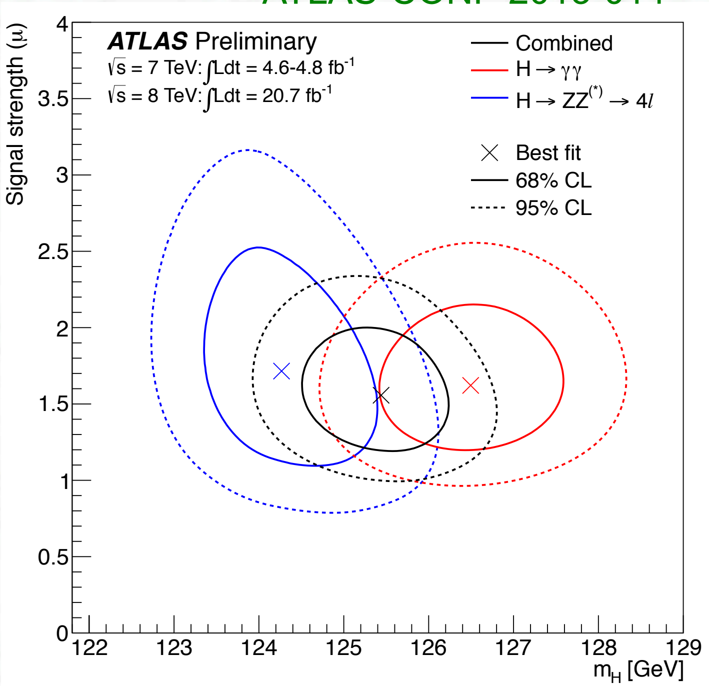
Mass: $m_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\ \text{GeV}$

Signal strength: $\mu = 1.7 \pm 0.5$

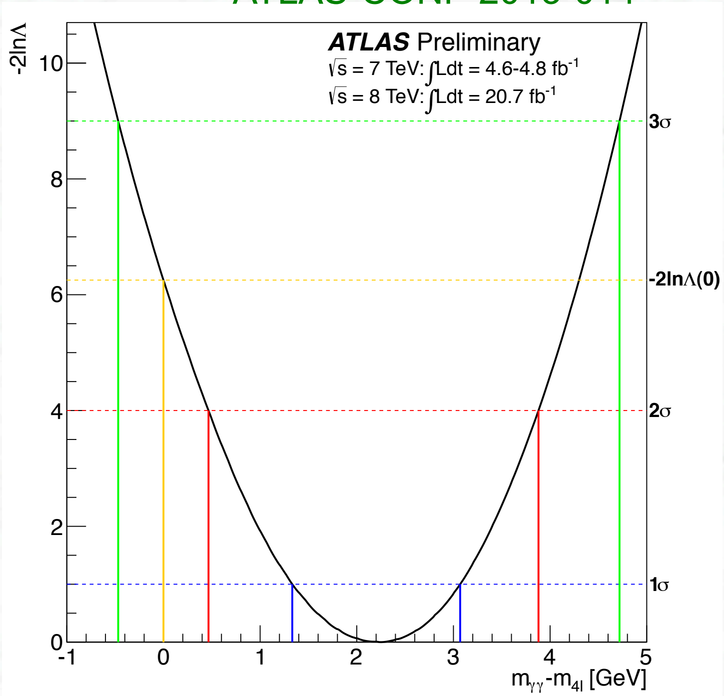
(m_H = 124.3 GeV)

Determination of the mass, compatibility of channels

ATLAS-CONF-2013-014



ATLAS-CONF-2013-014



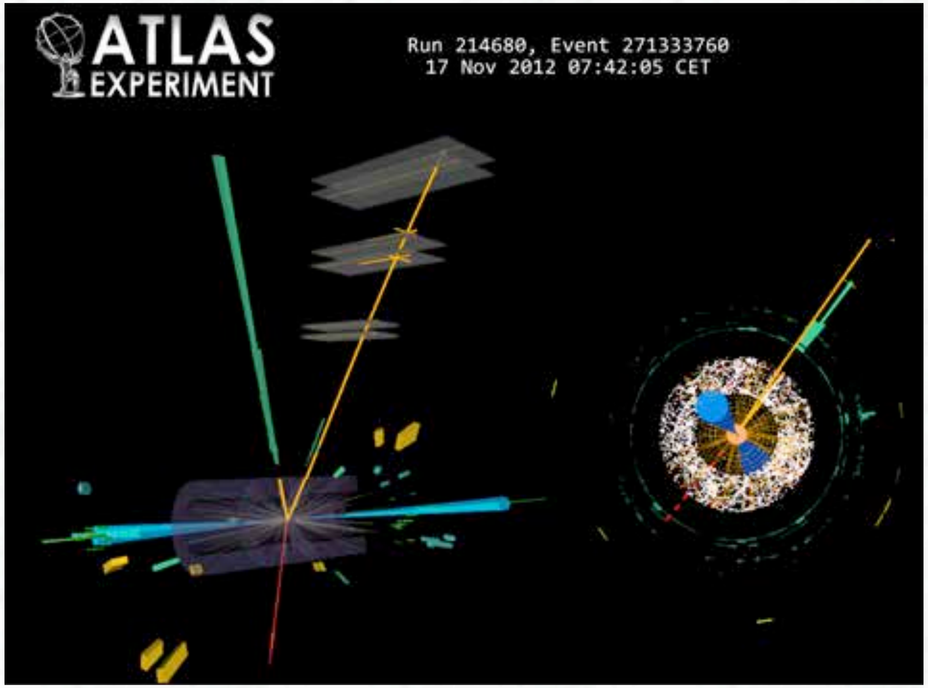
$$m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})\ \text{GeV}$$

Consistency between the fitted masses from likelihood value for Δm = 0 w.r.t. best fit value for Δm.

$$\Delta m = 2.3^{+0.6}_{-0.7}(\text{stat}) \pm 0.6\ (\text{syst})\ \text{GeV}$$

- Probability for disfavoring the Δm = 0 hypothesis by more than observed: 1.5% (2.4σ)
- Increases to 8%, by fixing the three principle sources contributing to the e/γ energy scale uncertainty (material, pre-samples energy scale, calibration procedure) to their ±1σ values

Search for H → WW → ℓν ℓν decay



- Two high p_T leptons (e or μ)

  Leptons from Higgs boson decay (spin-0 particle) are expected to have a small angular separation

- Neutrinos: → use transverse mass

- Perform analysis in bins of jet multiplicity

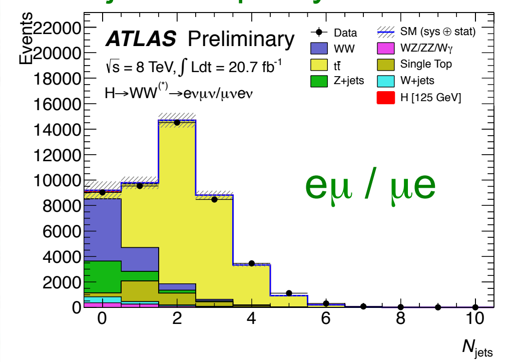
  - Different background composition
  - Sensitivity to VBF component

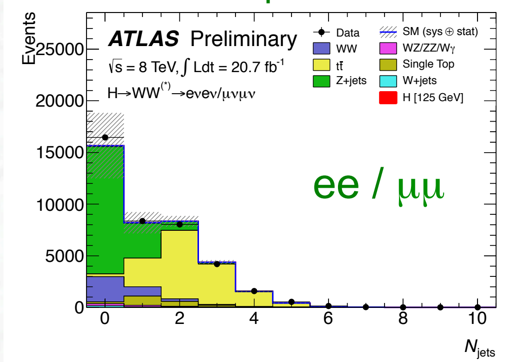
Major backgrounds:
(normalization in control regions)

- WW pair production (0 jet)
- tt background (2 jets)
- Z+jets (for ee/μμ pairs)

ATLAS-CONF-2013-030

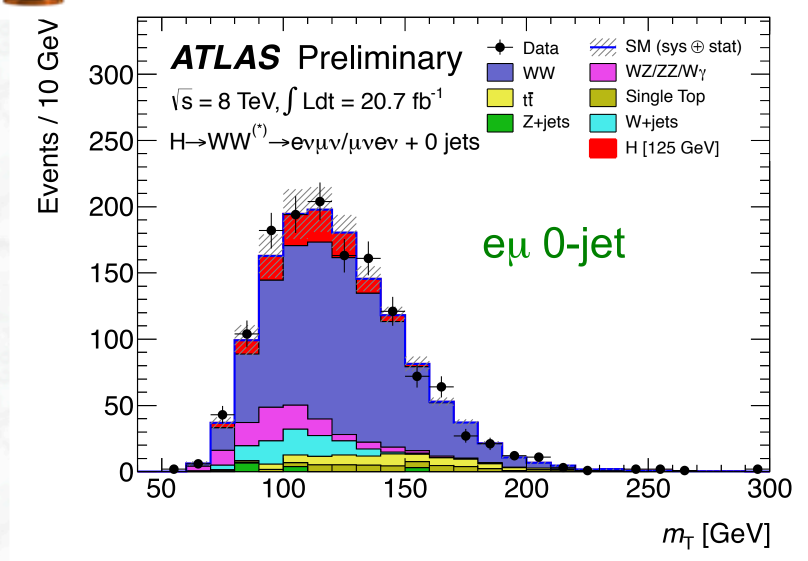
jet multiplicity distr. after basic selection requirements

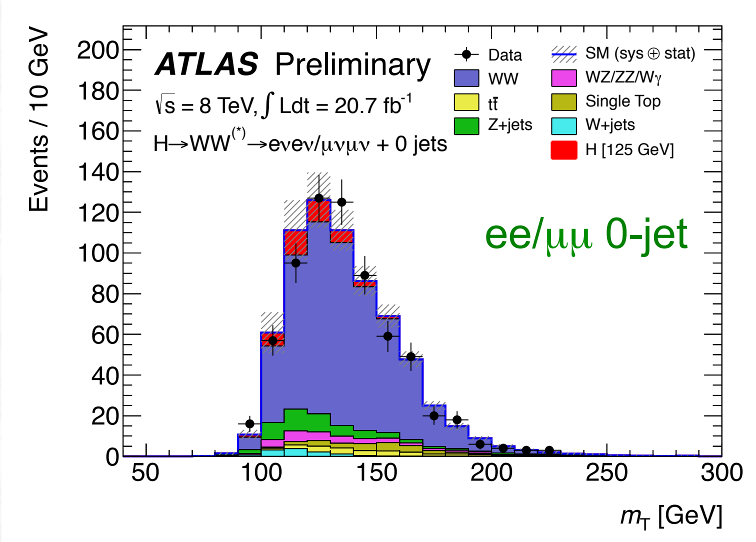


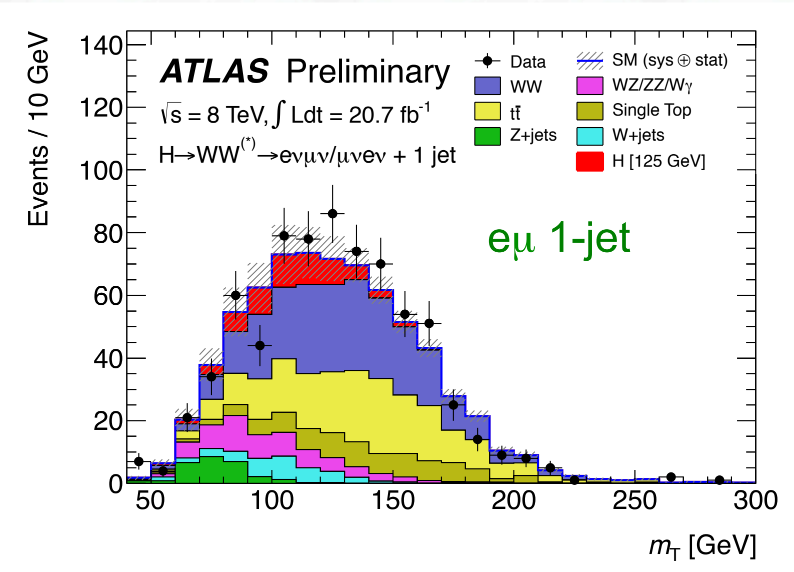


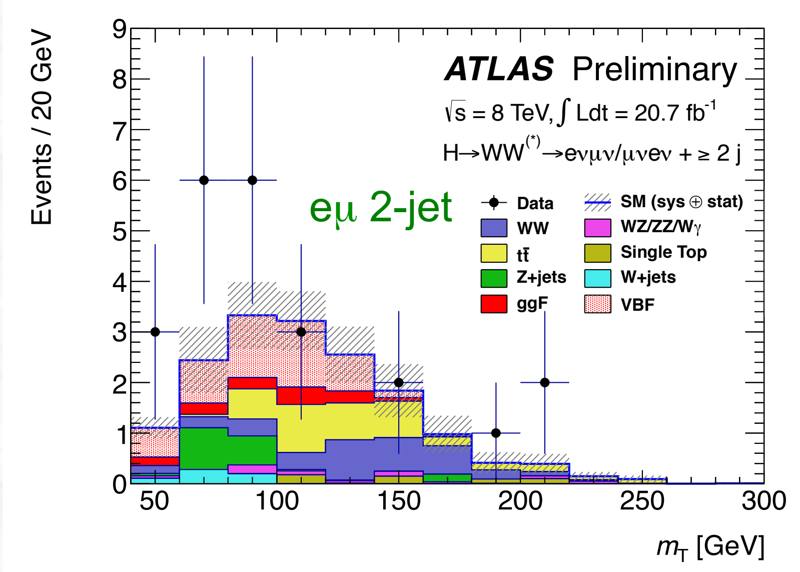
Transverse mass distributions

ATLAS-CONF-2013-030





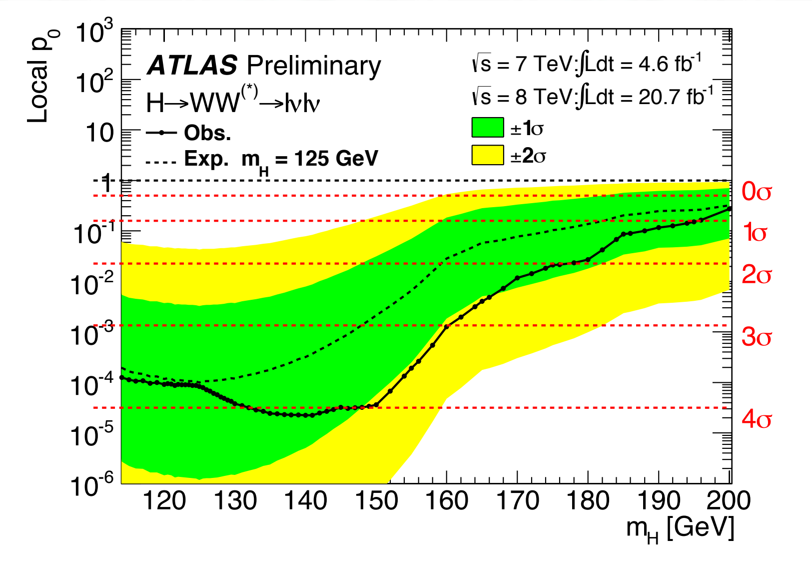




Clear excess above backgrounds in all sub-channels (jet multiplicities)

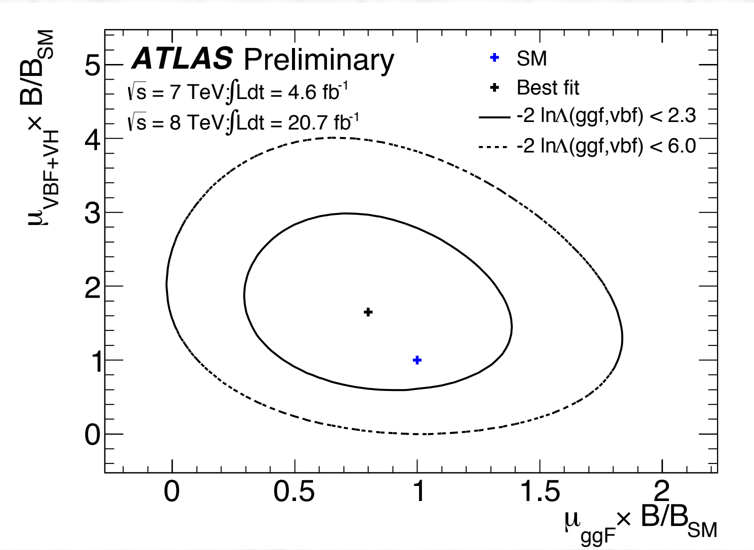
Results on the search for H → WW → ℓν ℓν decays

ATLAS-CONF-2013-030



Shallow minimum of p_0 value at 140 GeV

p_0 (125 GeV) = 8 10^{-5} (3.8σ observed)
(3.7σ expected)



Signal strength:
(combination of 7 TeV and 8 TeV data, at 125 GeV)

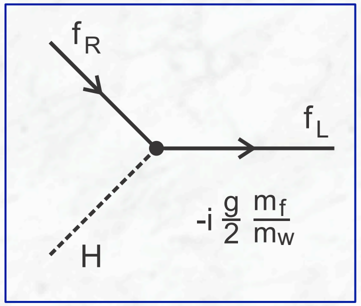
μ = 1.01 ± 0.21 (stat) ± 0.12 (syst) ± 0.19 (theo)

μ_{VBF} = 1.66 ± 0.79

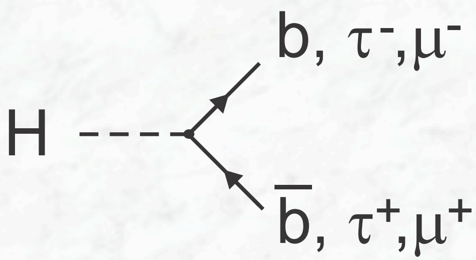
μ_{ggF} = 0.82 ± 0.36

Couplings to quarks and leptons ?

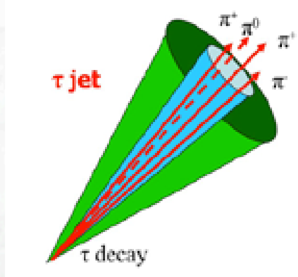
- Search for H → ττ and H → bb decays



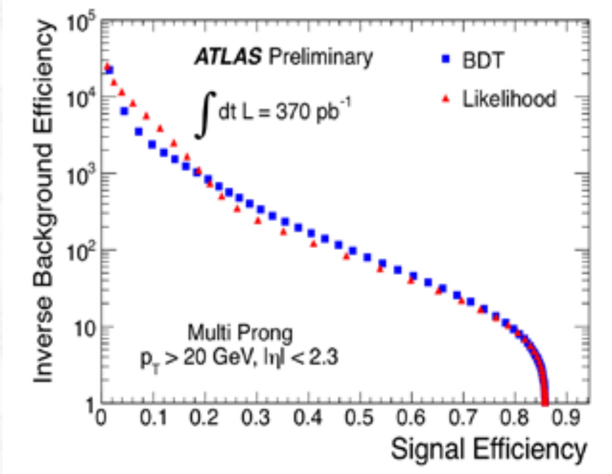
- Search for the rare H → μμ decay



Search for H → ττ decays



- Hadronic τ decays (challenging signature)
  Use multivariate technique to separate τ decays from jets from QCD production



- 2-4 neutrinos in final state, mass reconstruction difficult;
  Using "Missing mass calculation" *)

- Major background: Z → ττ decays;
  Modelled using data:
  "Embedding technique" replace muons in real Z → μμ events by simulated taus

- Signal-to-background ratio improves for
  VBF-topology or high-p_T Higgs ("boosted" category)

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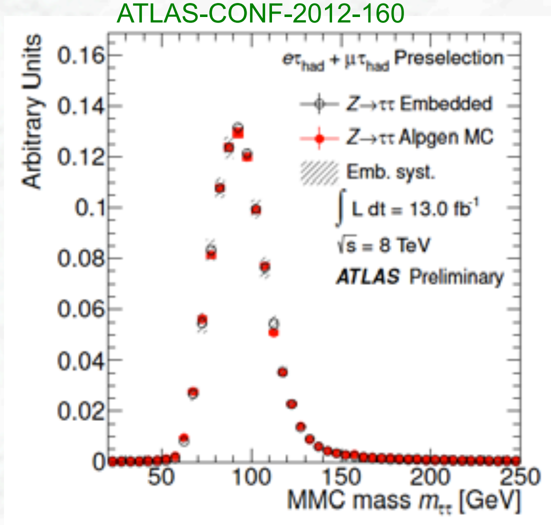


- Analysis is split into three sub-channels:

  - H → ττ → ℓ νν   ℓ νν
  - H → ττ → ℓ νν   had ν
  - H → ττ → had ν   had ν

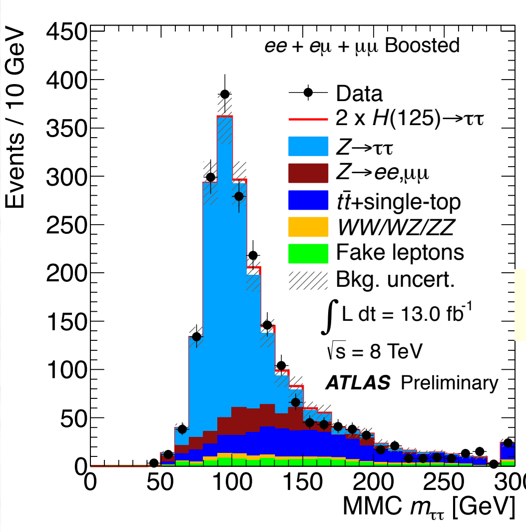
*) Nucl. Instrum. Methods A654 (2011) 481

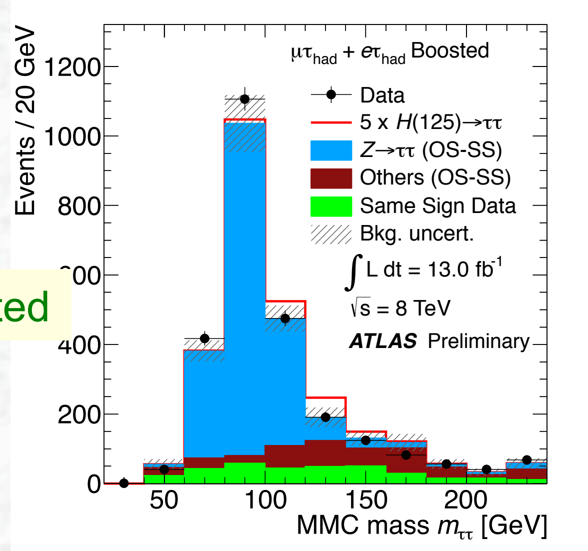
Reconstructed mass distributions

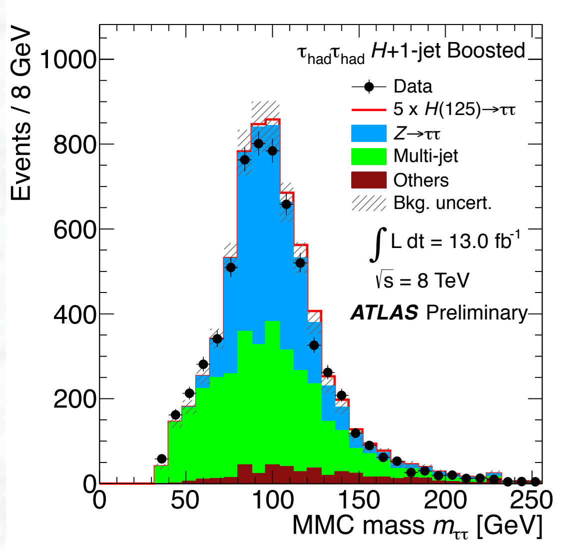
L = 13 fb^{-1} (2012)

lepton-lepton | e/μ – hadron | hadron – hadron

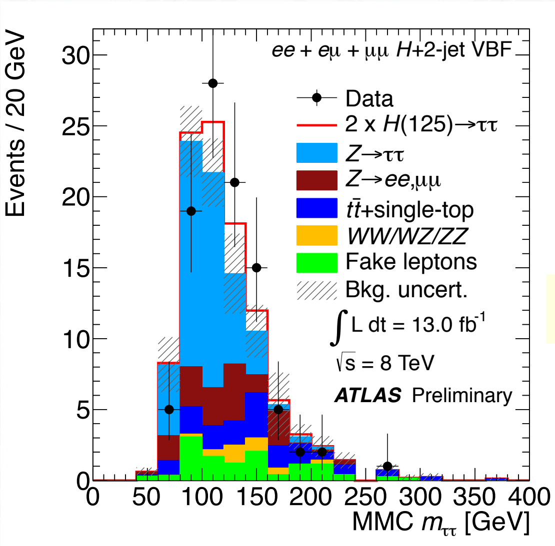
Boosted

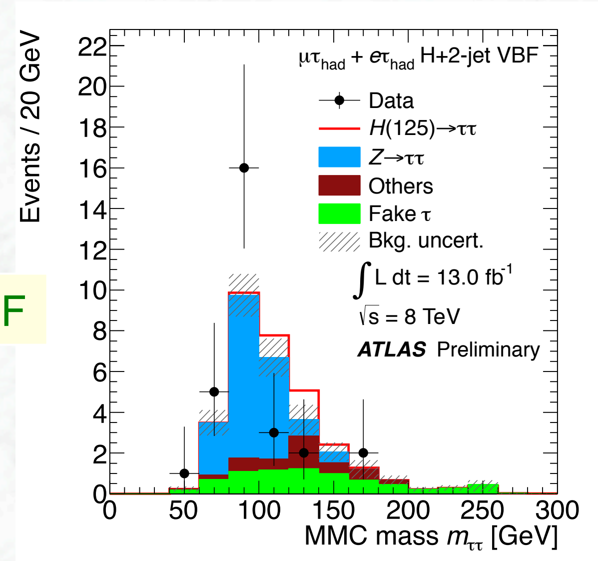


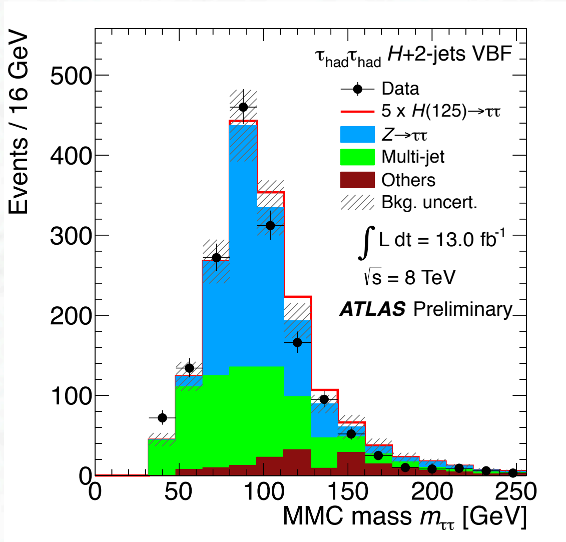




VBF







SM Higgs signal (multiplied by factors)

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Results on the search for H → ττ decays

- Discovery sensitivity for a signal not yet reached

- → 95% C.L. limits on cross section
  (normalized to SM cross sections)

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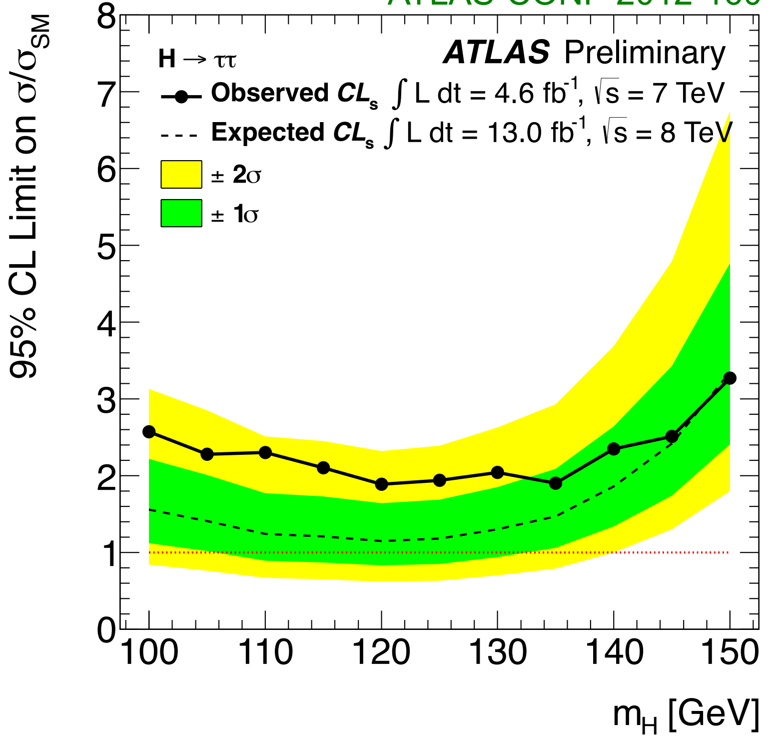


m_H = 125 GeV:

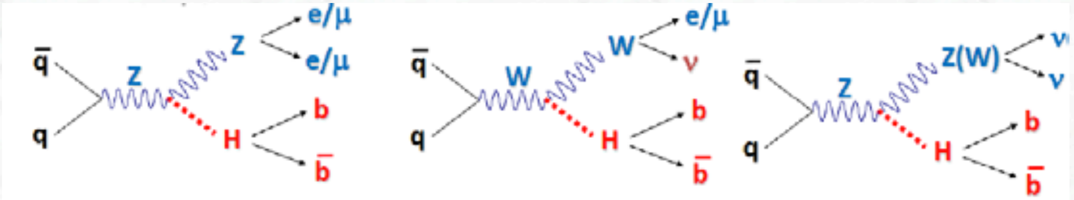
Observed 95% CL: $1.9\ \sigma_{SM}$
Expected (no Higgs): $1.2\ \sigma_{SM}$

Fitted signal strength
(all sub-channels):

$\mu = 0.7 \pm 0.7$

Updated analysis, including the full data sample, expected soon

Search for VH production with H → bb decays



- Exploit three leptonic vector boson decay modes
  → split analysis in 0, 1, and 2-lepton categories

- Require 2 b-tagged jets
  (working point for 70% efficiency)

- Major background: W/Z bb, W+jets, tt

- Signal-to-background ratio improves for
  “boosted Higgs boson”,
  split analysis in bins of $p_T(V)$

  in total: 15 categories (0,1,2 jets × p_T bins)

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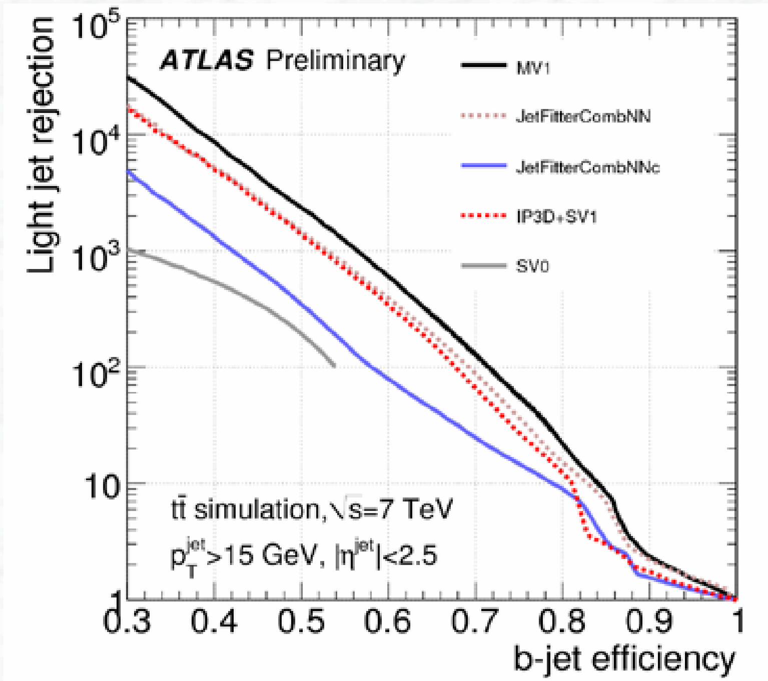
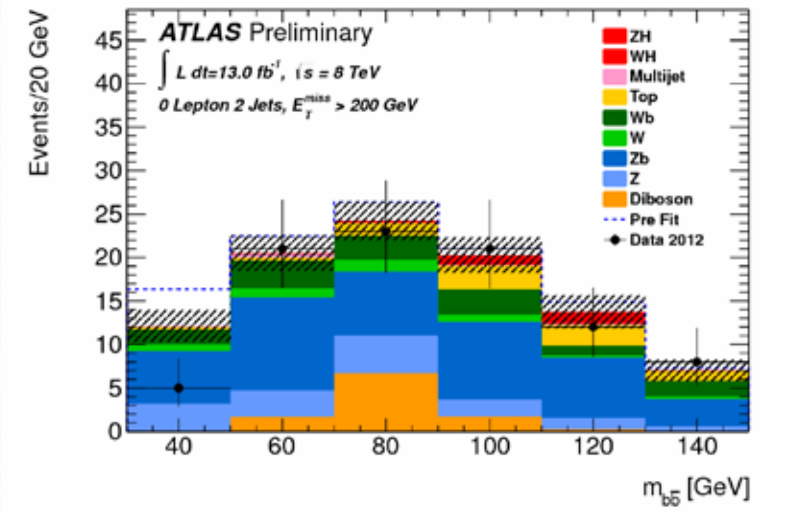


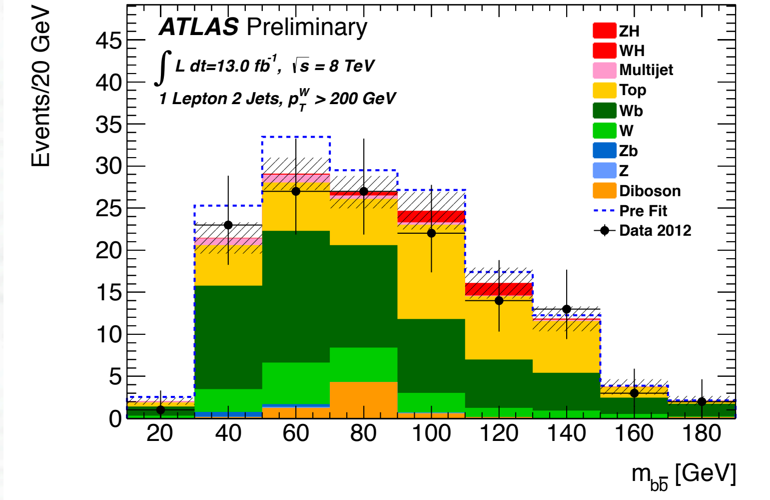
Reconstructed mass distributions

-8 TeV, L = 13 fb^{-1} (a selection, high p_T bins)-

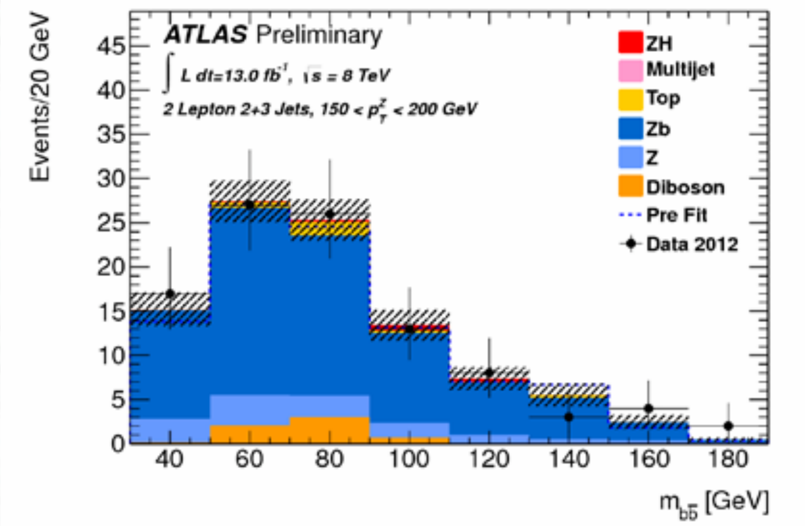
0 lepton



1 lepton



2 leptons



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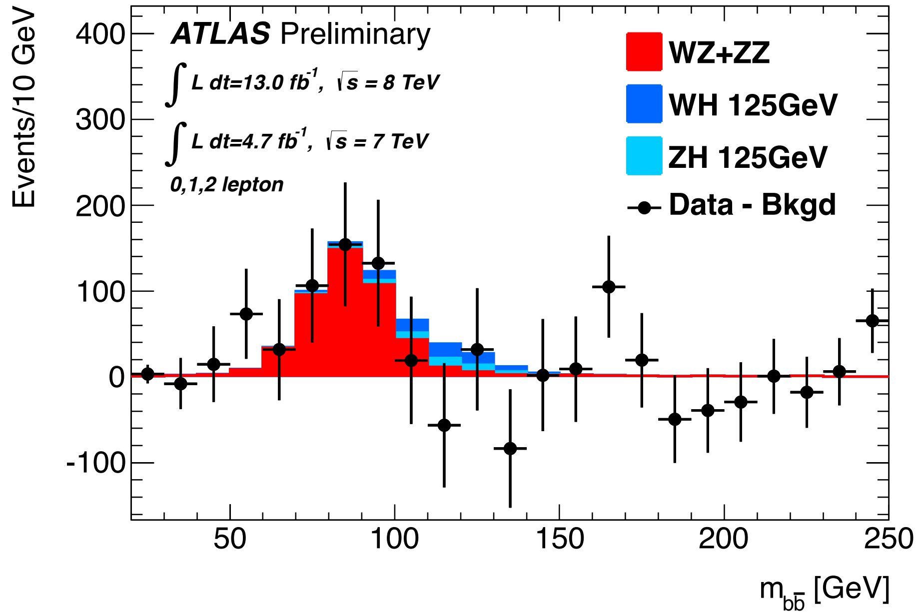
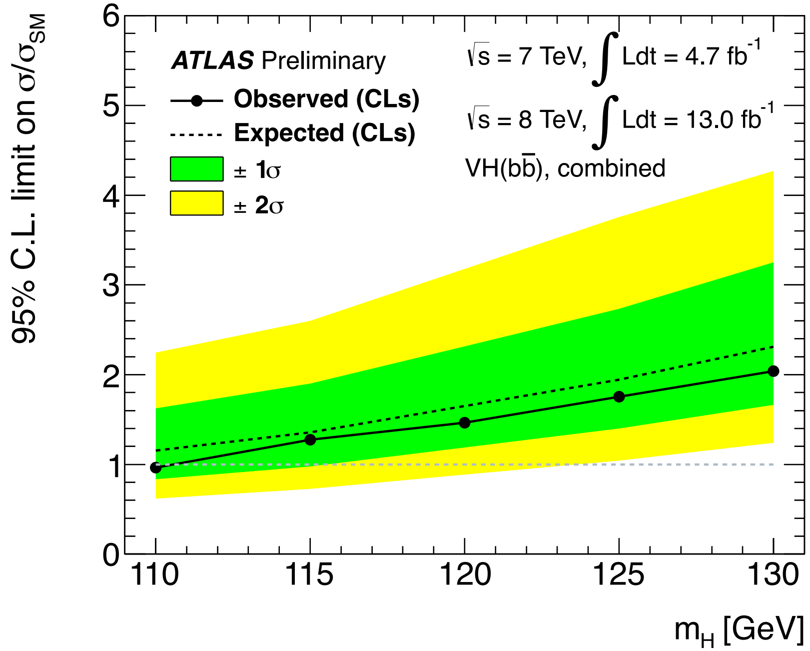
Results on the search for H → bb decays

combination: data - background



ATLAS-CONF-2012-161



Di-boson signal established
(important “calibration” signal)

Significance 4.0σ

m_H = 125 GeV:

Observed 95% CL: 1.8 σ_{SM}
Expected (no Higgs): 1.9 σ_{SM}

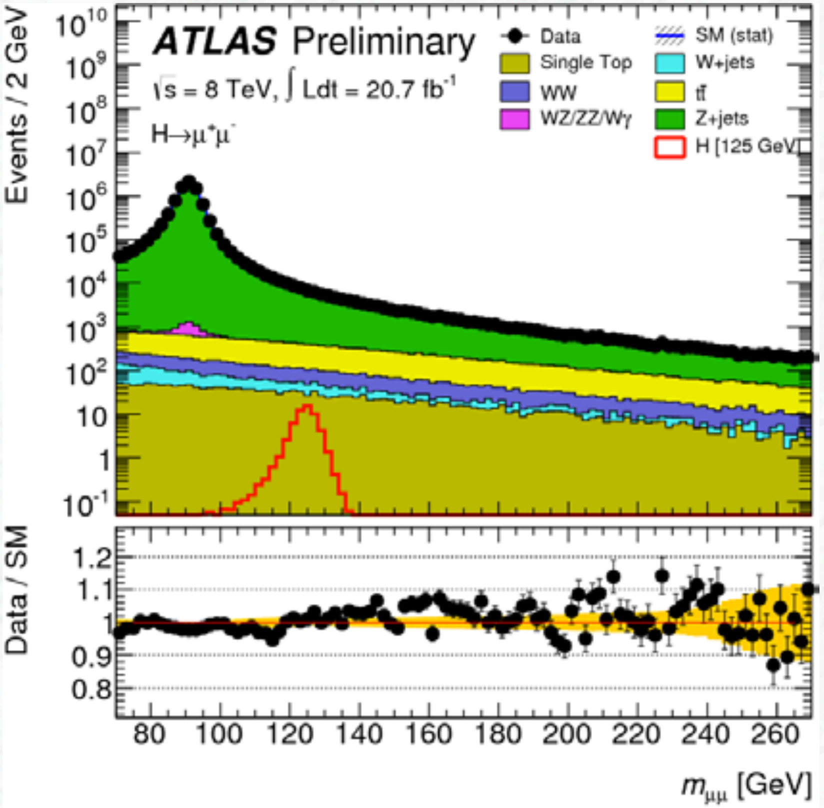
μ_{WZ+WW} = 1.09 ± 0.20 (stat) ± 0.22 (syst)

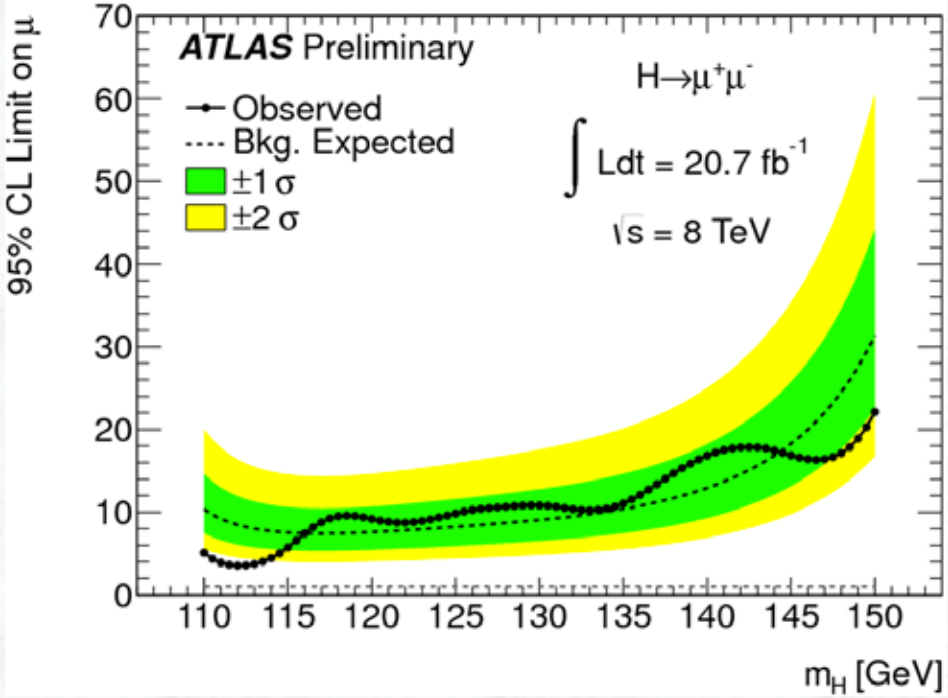
μ_H = -0.4 ± 0.7 (stat) ± 0.8 (syst)

Updated analysis, including the full data sample, expected soon

Results on the search for H→ μμ

ATLAS-CONF-2013-010



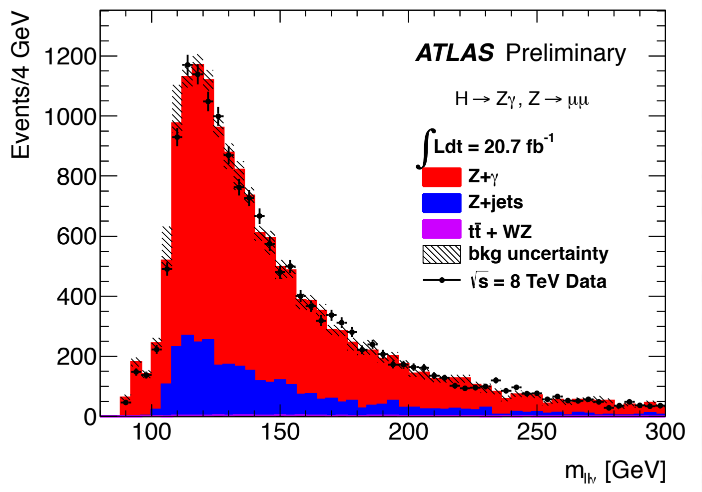


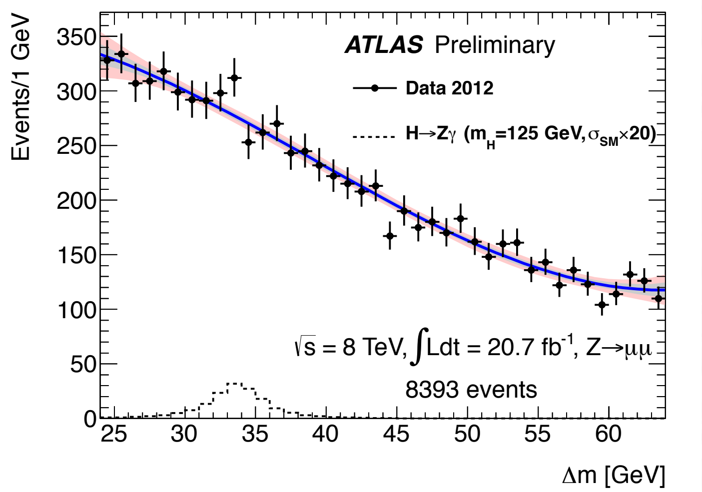
m_H = 125 GeV:

Observed 95% CL: $9.8\ \sigma_{SM}$
Expected (no Higgs): $8.2\ \sigma_{SM}$

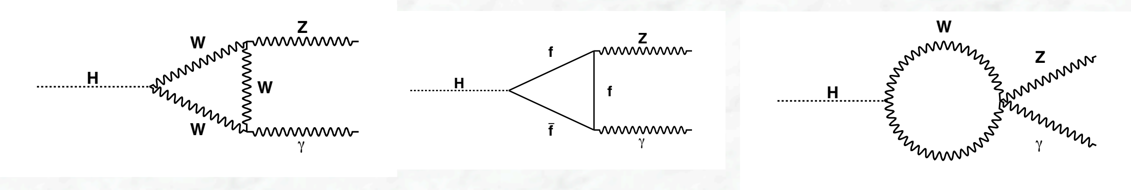
Results on the search for H→ Zγ, Z → ℓℓ

ATLAS-CONF-2013-009

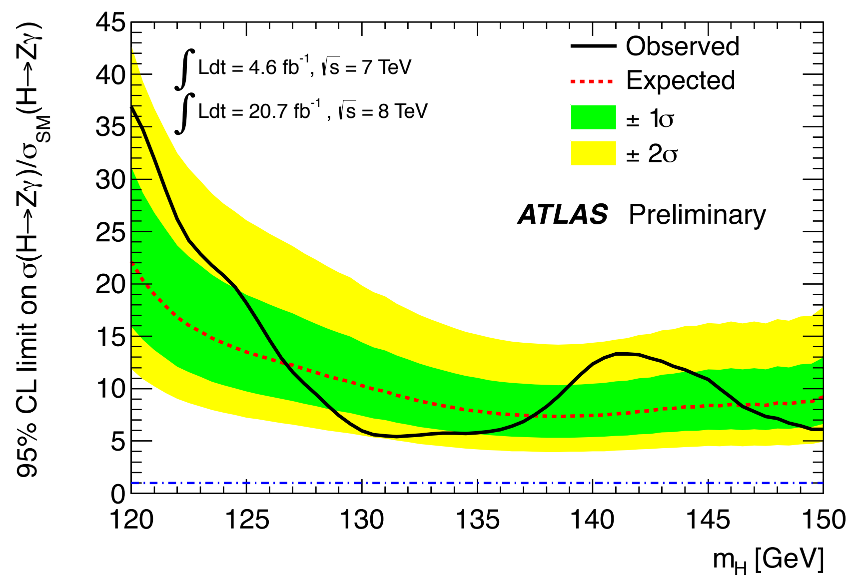




Mass difference Δm between $m_{\ell\ell\gamma}$ and $m_{\ell\ell}$



Expected BR = 1.54 10^{-3}, decays via loop diagrams;
Measurement / limits can constrain BSM models

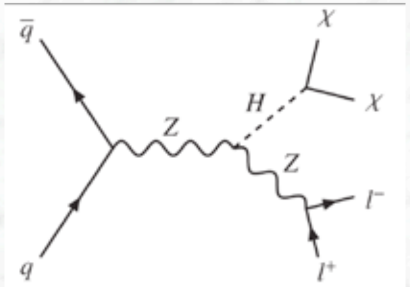


m_H = 125 GeV:

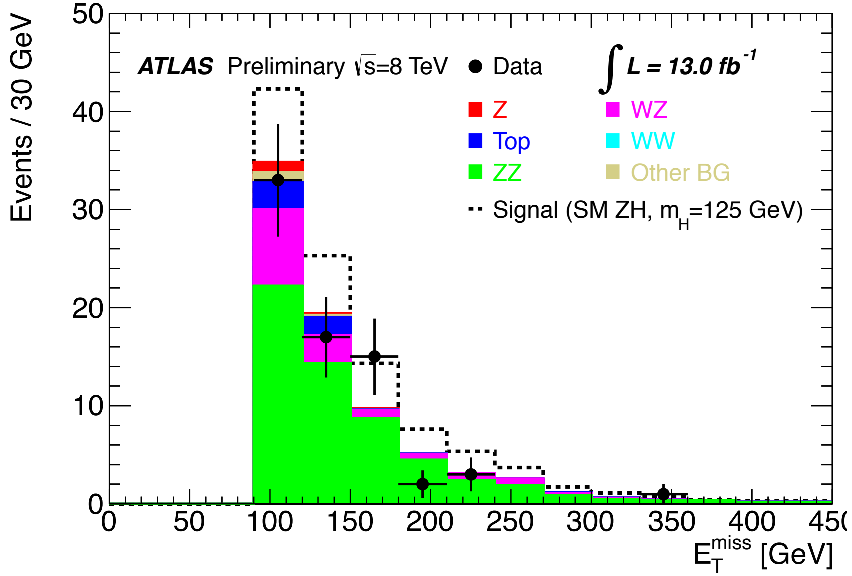
Observed 95% CL:	18.2 σ_{SM}
Expected (no Higgs):	13.5 σ_{SM}

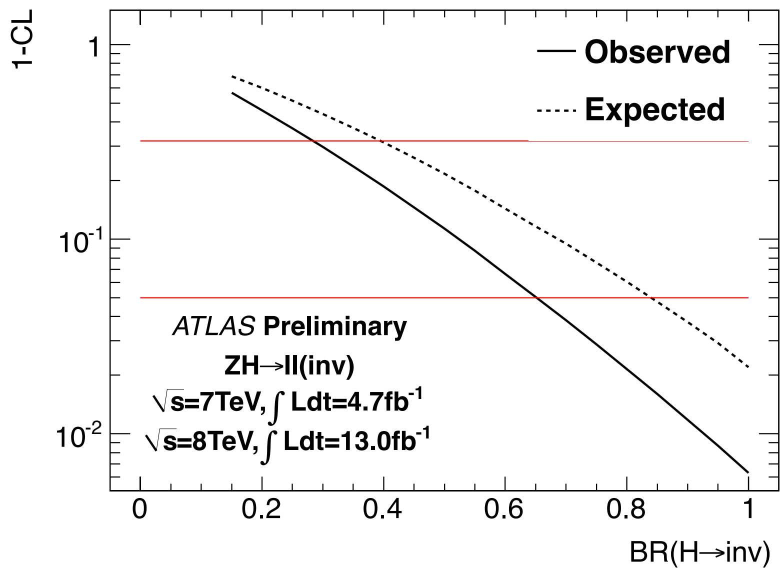
Search for invisible Higgs boson decays

- Some extensions of the Standard Model allow a Higgs boson to decay to stable or long-lived particles
- Search for excess in ZH associated production



ATLAS-CONF-2013-011

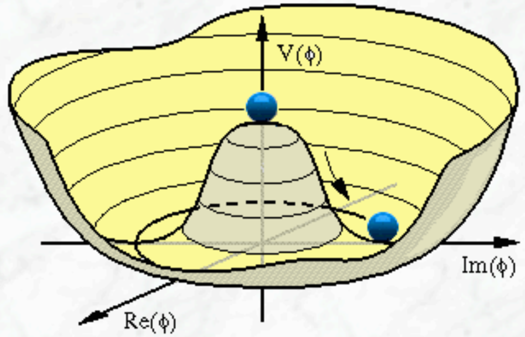




Assuming the ZH production rate for m_H = 125 GeV:

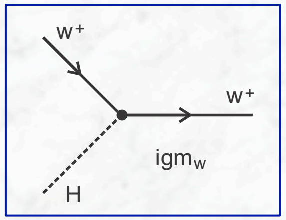
BR (H → inv.) > 65% can be excluded

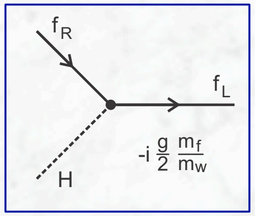
Is the new particle the Higgs Boson ?



- Production rates ?

  Couplings to bosons and fermions

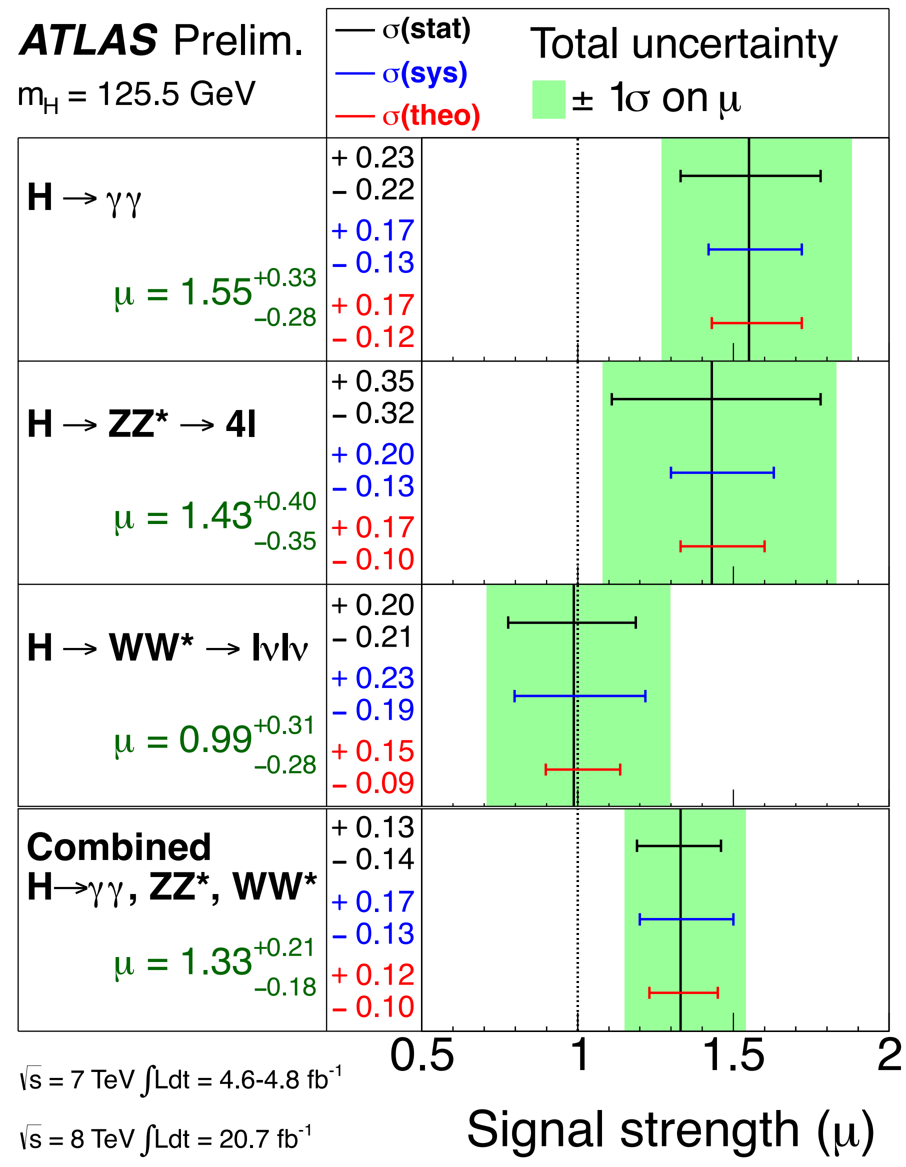




- Spin, J^P quantum number

Signal strength in di-boson decay modes

-including full data set-



- Data are consistent with the hypothesis of a Standard Model Higgs boson:

$$\mu = 1.33^{+0.21}_{-0.18}$$

- Experimental uncertainties are still too large to get excited about "high" γγ signal strength

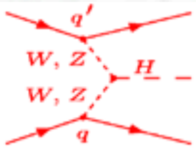
- Signal strengths in fermionic decay modes have large uncertainties, but are compatible with SM value of 1;

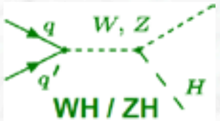
  If preliminary H → ττ and H → bb results are included:

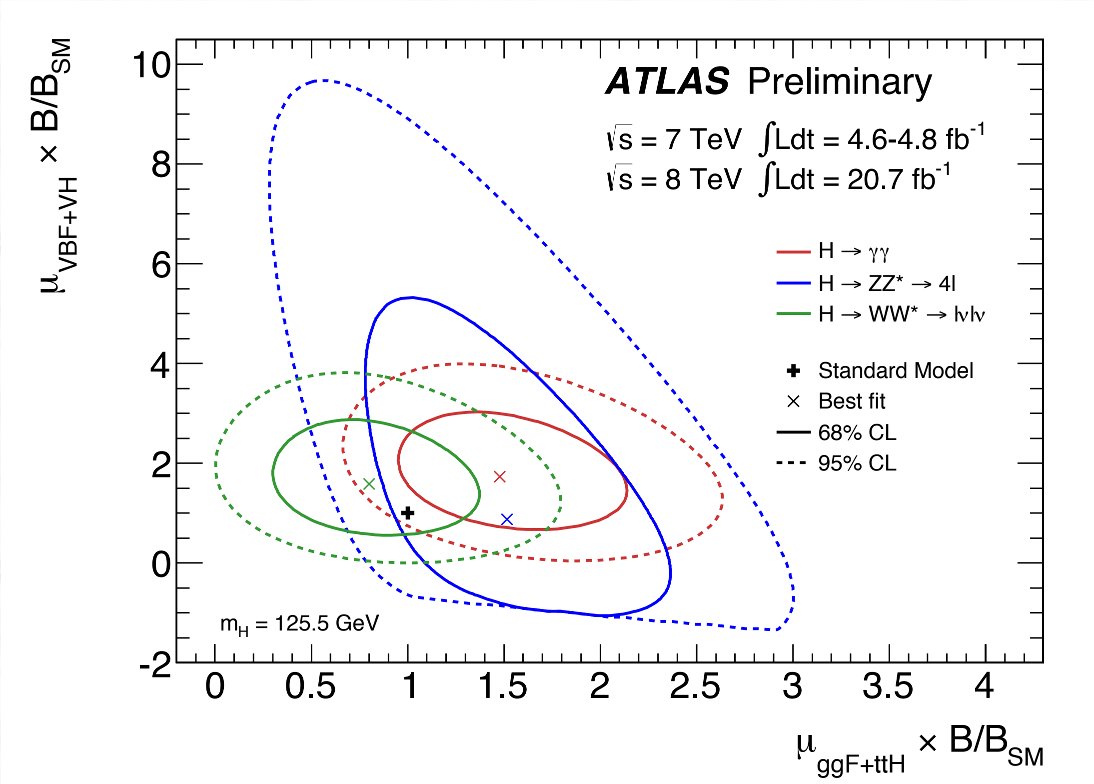
$$\mu = 1.23 \pm 0.18$$

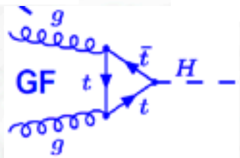
Ratios of production cross sections for the various processes (ggF, VBF,..) fixed to SM values

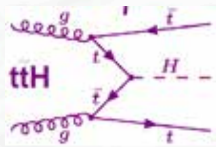
Gluon fusion versus vector-boson fusion





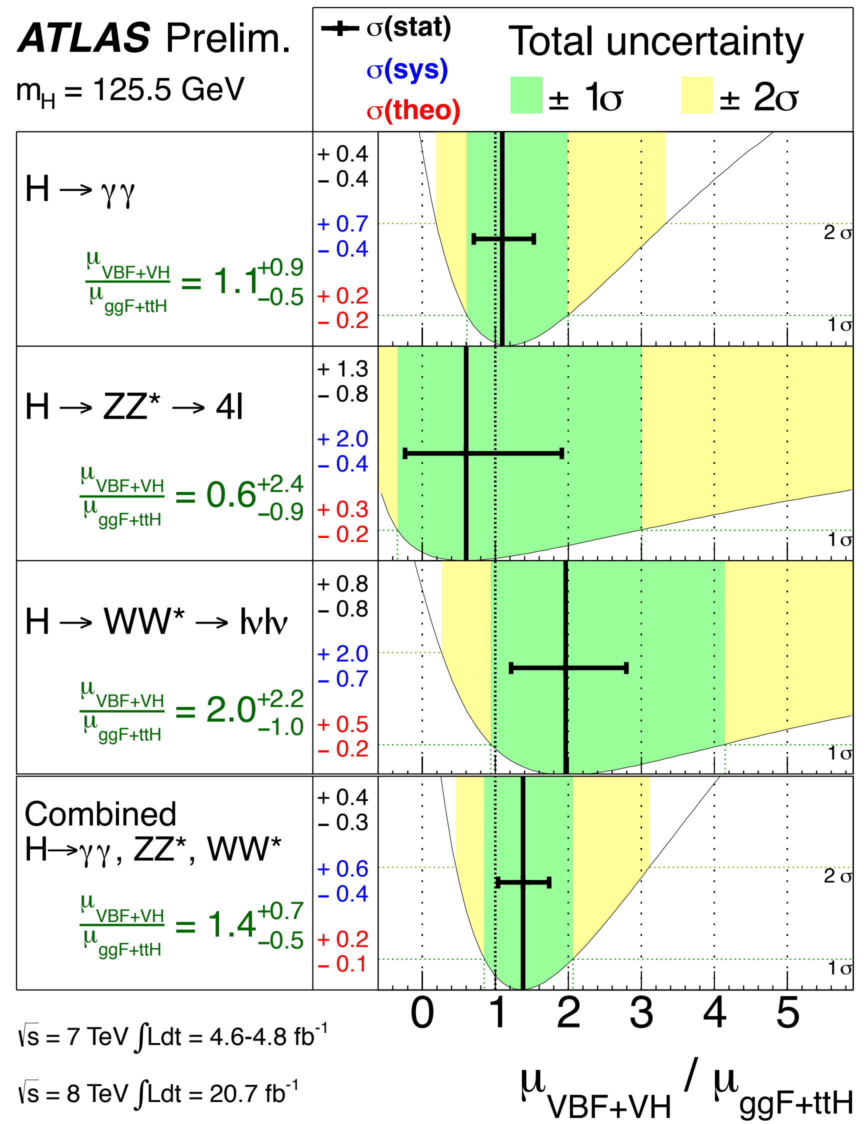




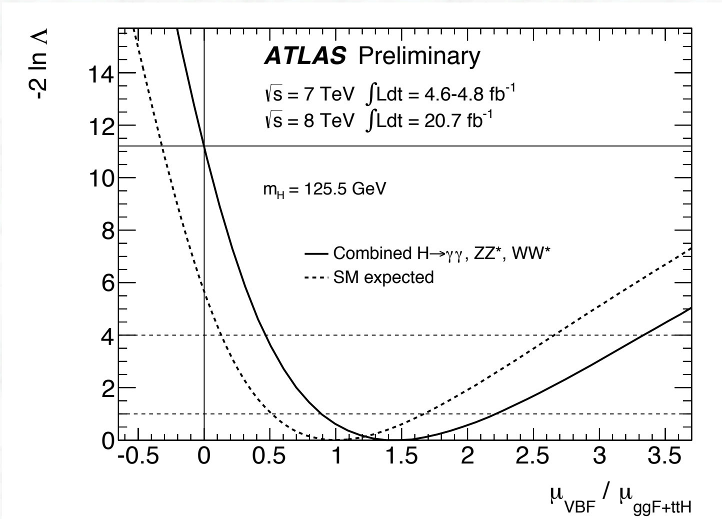


Sensitivity to (ggF + ttH) and (VBF+VH) production fractions,
modulo branching ratio factors B/B_{SM}

Evidence for production via vector boson fusion



- Fit for the ratio of μ_{VBF+VH} / $\mu_{ggF+ttH}$ for the individual channels (model independent)
- Results can be combined
- Good agreement with SM expectation for individual channels and the combination)



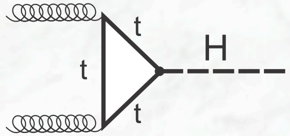
$\mu_{VBF} / \mu_{ggF+ttH} = 1.4^{+0.4}_{-0.3}\,(stat)\,^{+0.6}_{-0.4}\,(syst)$

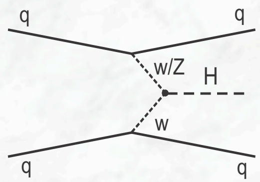
3.3σ evidence for VBF production

Higgs boson couplings

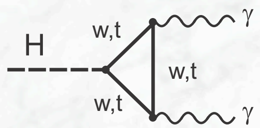
- Production and decay involve several couplings

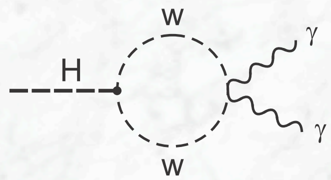
Production:





Decays: e.g H → γγ (best example)
(Decay widths depends on W and top-coupling,
destructive interference)





- Benchmarks defined by LHC cross section working group (leading-order tree-level framework):

  - Signals observed originate from a single resonance;
    (mass assumed here is 125.5 GeV)

  - Narrow width approximation: → rates for given channels can be decomposed as:

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

i, f = initial, final state
Γ_f, Γ_H = partial, total width

  - Modifications to coupling strength are considered (coupling scale factors κ), tensor structure of Lagrangian assumed as in Standard Model