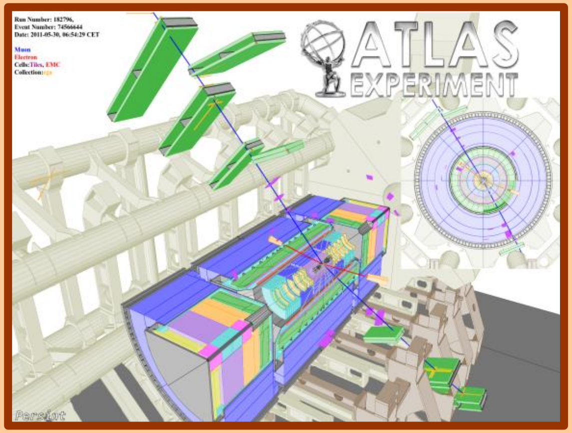
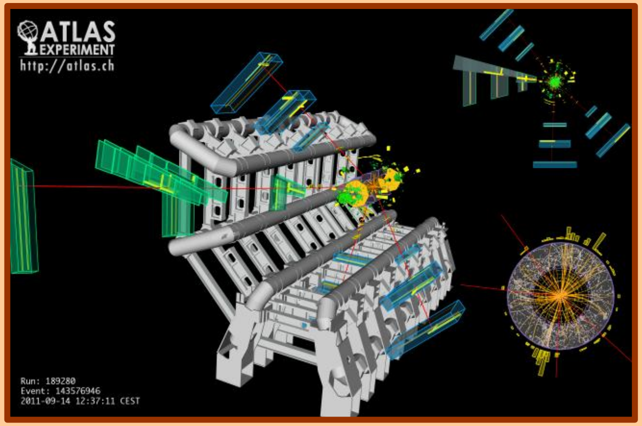
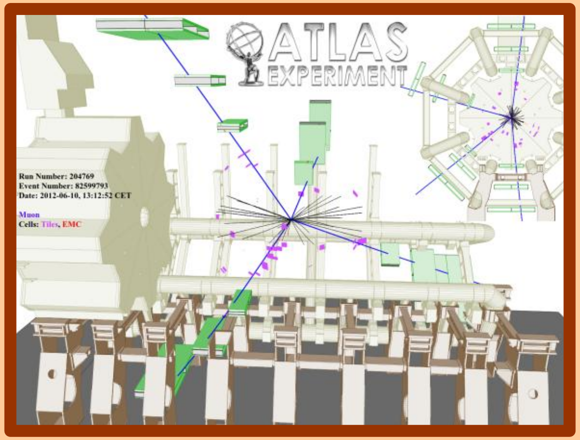
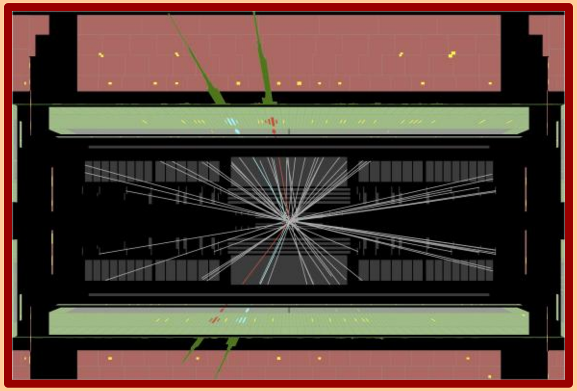


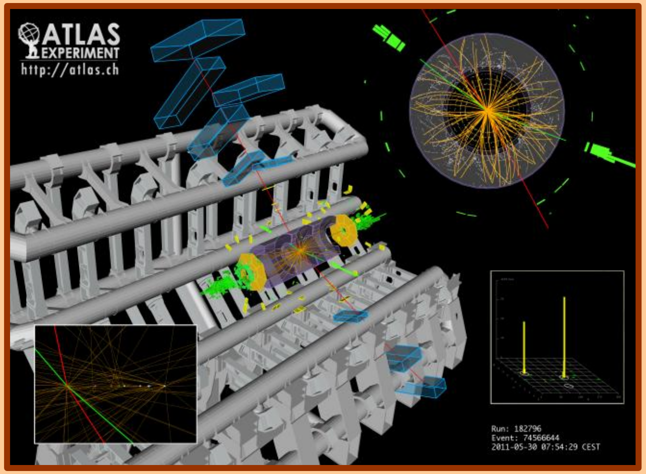


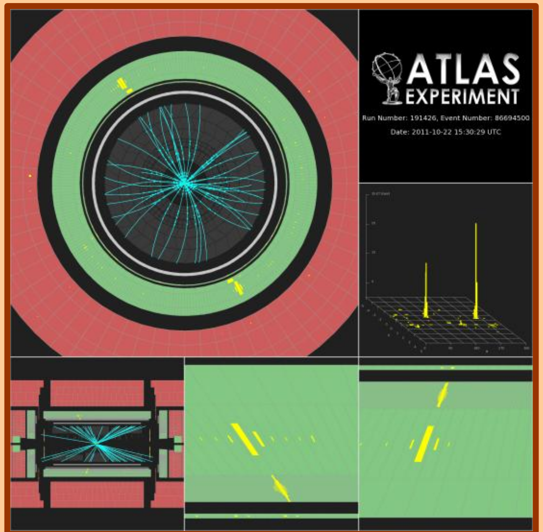


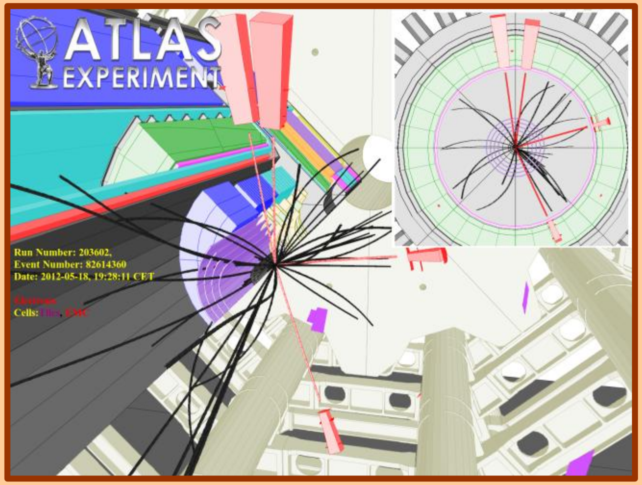
Status of Standard Model Higgs searches in ATLAS



Fabiola Gianotti (CERN)







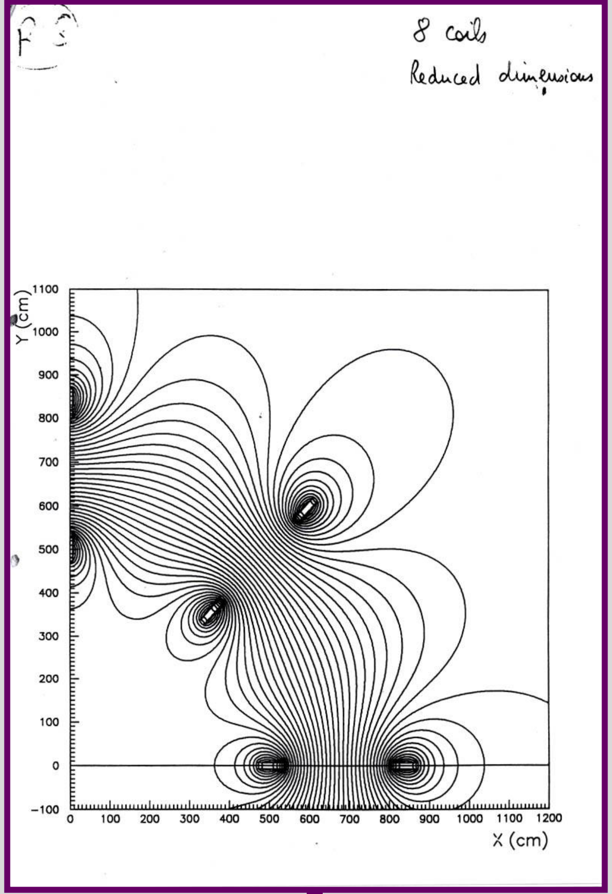
An historical day : 4th July 2012

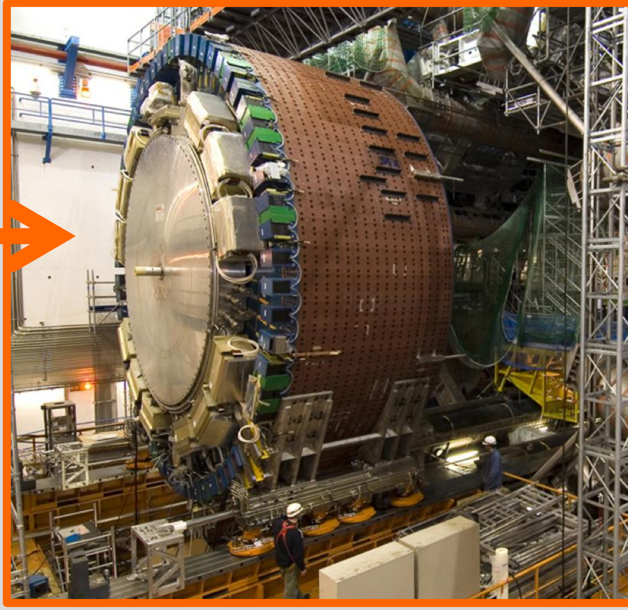
Few milestones of a long path …

1984 : First studies for a high-energy pp collider in the LEP tunnel
1989 : Start of SLC and LEP e^+e^- colliders
1993 : SSC is cancelled → US physicists join the LHC
1994 : LHC approved by the CERN Council
1995 : Top-quark discovered at the Tevatron
1996 : Construction of LHC machine and experiments start
2000 : End of LEP2
2003 : Start of LHC machine and experiments installation
2009 : 23 November: first LHC collisions ($\sqrt{s}$ = 900 GeV)
2010 : 30 March: first collisions at $\sqrt{s}$ = 7 TeV
→ Inauguration of a (~ 20-year ?) long physics programme
2012 : 1st May: first collisions at $\sqrt{s}$ = 8 TeV
2012 : 4th July: discovery of a Higgs-like boson

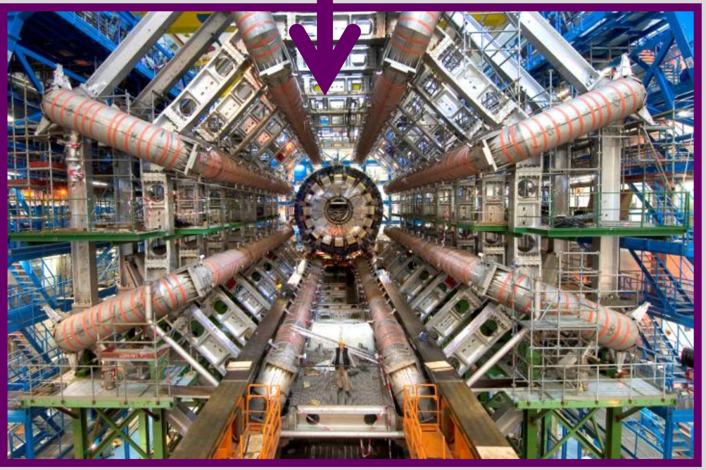
A ~ 40-year project: > > 20 years from conception to start of operation
~ 20 ? years of physics exploitation

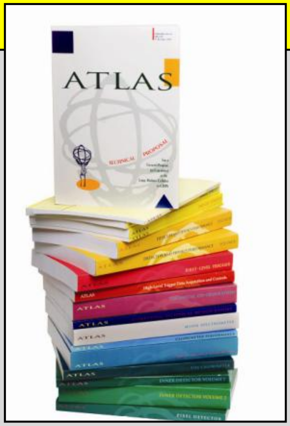
The LHC has required:
- most innovative technologies (superconducting magnets, cryogenics, electronics, data transfer and storage, etc…)
- new concepts, a lot of ingenuity to address challenges and solve problems
- huge efforts of the worldwide community (ideas, technology, people, money)

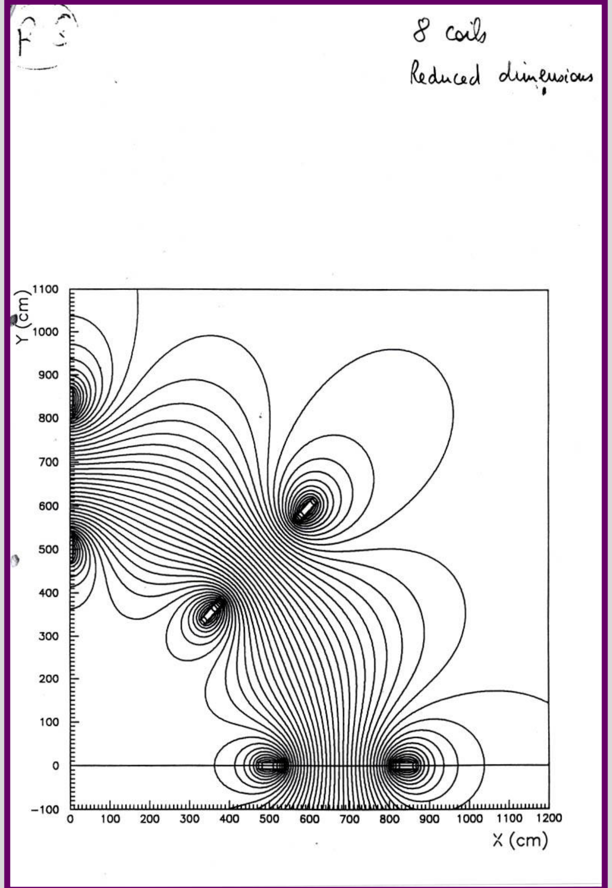


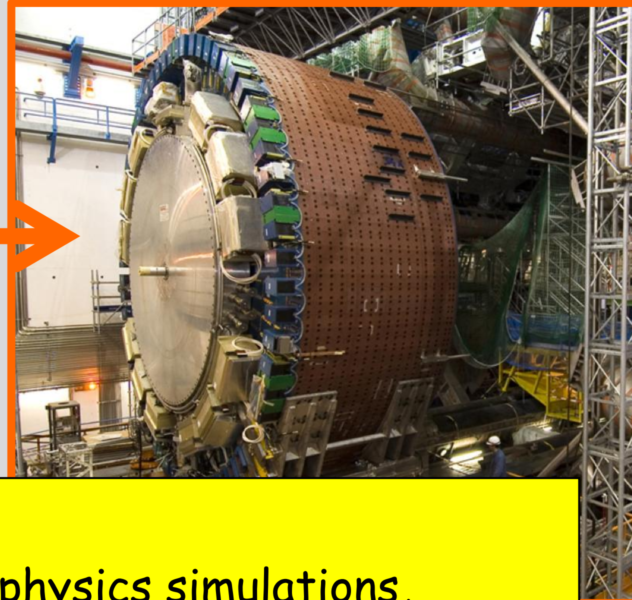


15 years of test beams,
20 years of detector and physics simulations,
8 years of world-wide computing data challenges,
17 Technical Design Reports,
Dozens of agreements and MoU ..









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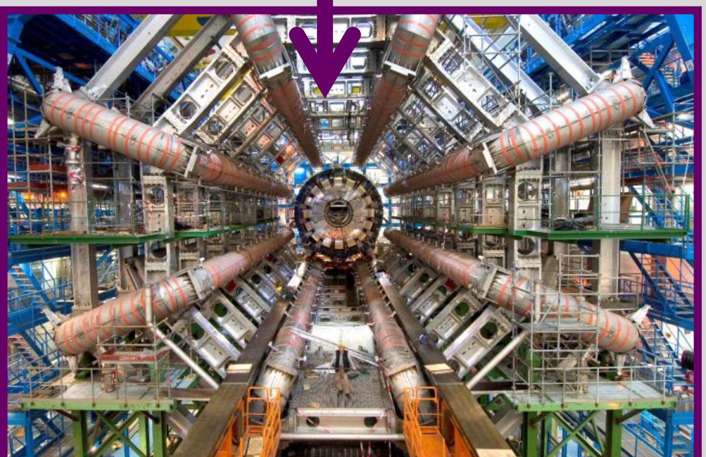


And a lot of parties !

Signing of US-CERN agreement, Dec. 1997

Higgs searches have guided conception, design and technological choices of ATLAS and CMS:

- one of the primary LHC goals
- among the most challenging processes → have set some of the most stringent performance (hence technical) requirements: lepton identification and energy/momentum resolution, b-tagging, E_T^{miss} measurement, forward-jet tagging, etc.

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid 4 magnets Calorimeters in field-free region	Solenoid 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\times10^{-4}\, p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\times10^{-4}\, p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeVstandalone	Fe → $\sigma/p_T \sim 5$% at 1 TeV combining with tracker

CMS: excellent μ momentum resolution (H→ 4μ !) but B=4T solenoid constrains HCAL radius

H→ γγ:
CMS: E-resolution
ATLAS: γ "pointing" and γ/jet separation

ATLAS: excellent HCAL → jets and E_T^{miss} (H→ lνlν)

Since 4th July

On 31st July ATLAS "Higgs discovery" paper submitted (now accepted) for publication in Physics Letters B (together with CMS, to be published side by side)

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP-2012-218

Submitted to: Physics Letters B

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

The ATLAS Collaboration

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Results presented here are those in the paper:

- ❑ H→ $\gamma\gamma$, 4l: full $\sqrt{s}$=7 TeV dataset (~4.9 fb^{-1}) and $\sqrt{s}$ = 8 TeV dataset up to CERN seminar/ICHEP (~5.9 fb^{-1}) → total: ~10.7 fb^{-1}
- ❑ NEW compared to CERN seminar and ICHEP: H→ WW→ e$\nu\mu\nu$ updated with 8 TeV data (~5.9 fb^{-1}) ← NEW
- ❑ New overall combination (H→ $\tau\tau$ and W/ZH→ W/Zbb based on 7 TeV data)

Stepping stones toward a discovery

Superb performance of the LHC

Excellent ATLAS detector performance in terms of data-taking efficiency and data quality

Experience gained with the 2011 data propagated to reconstruction and simulation (improved detector understanding, alignment and calibration, pile-up, …)

Huge amount of work to understand and mitigate the impact of pile-up on the reconstruction and identification of physics objects → sizeable gain in efficiency for e/γ/μ, pile-up dependence minimized, smaller systematic uncertainties

Detailed studies of Standard Model processes and control of the (numerous) backgrounds

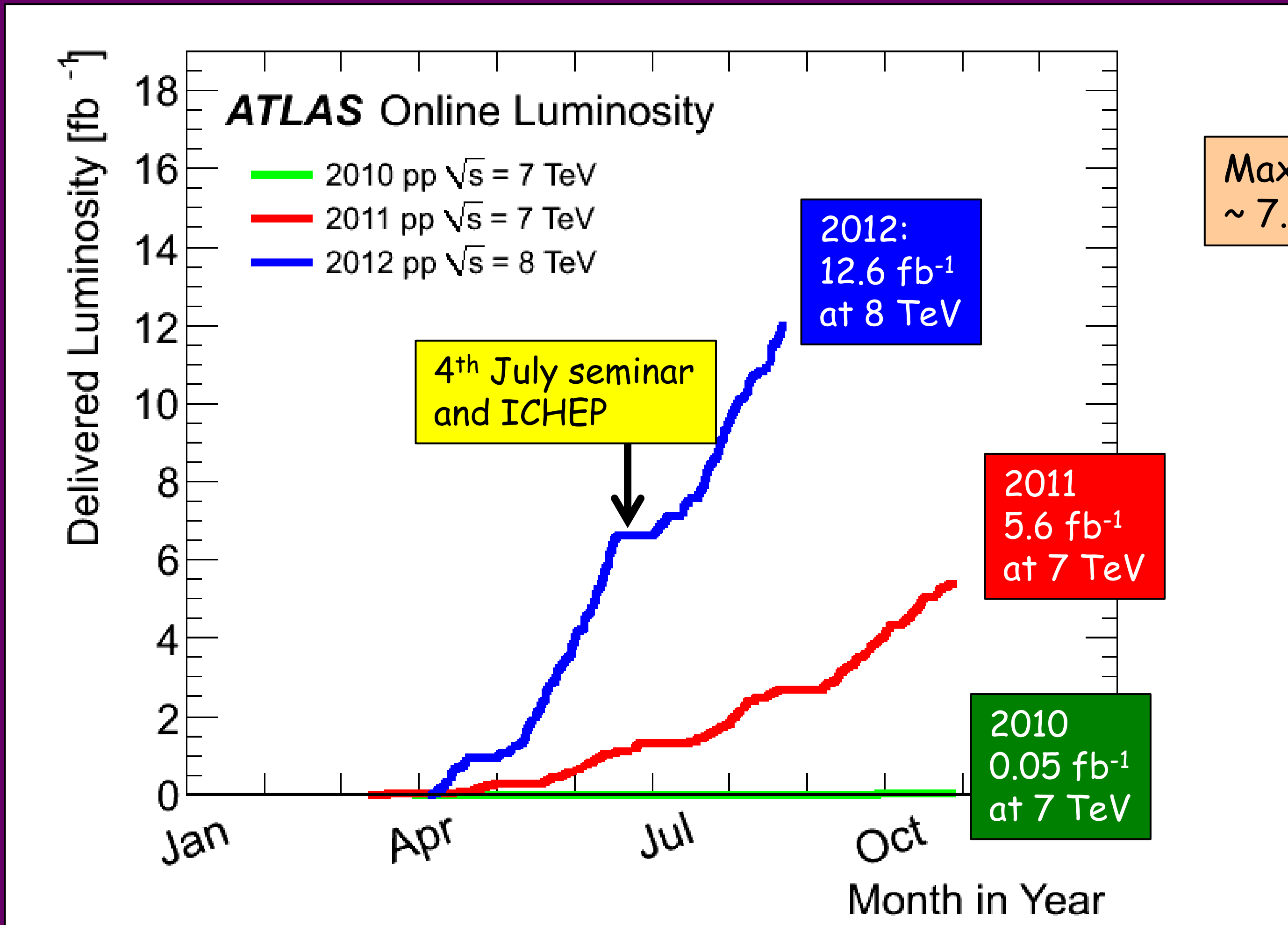
Sensitivity of H → γγ, H → 4l, H→ lνlν analyses improved using the following procedure:

- ❑ optimization only done on MC simulation
- ❑ then looked at 2012 data in signal sidebands and background control regions (note: large and sometimes not well-known backgrounds estimated mostly with data-driven techniques using background-enriched-signal-depleted control regions) → validate MC simulation
- ❑ signal region inspected only after above steps satisfactory

Improved analyses applied also to 2011 data → updated H→ γγ, 4l, lνlν results at 7 TeV

→ Huge amount of painstaking foundation work !

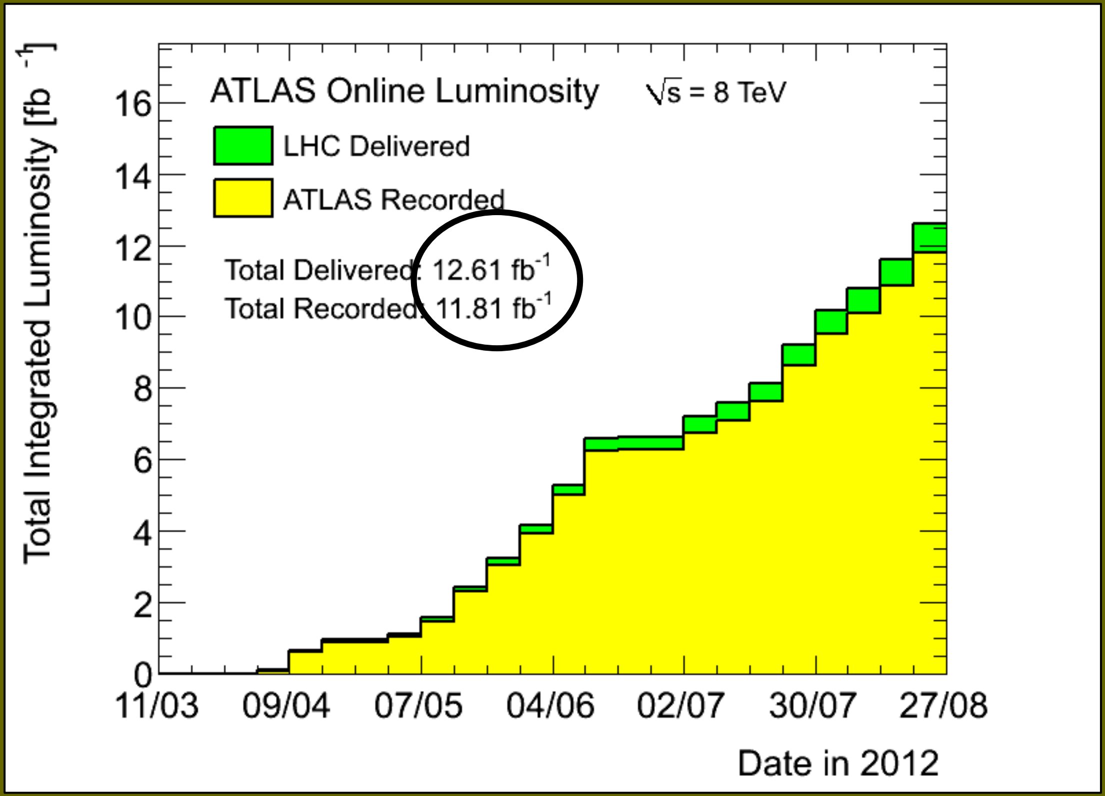
Luminosity delivered to ATLAS since the beginning



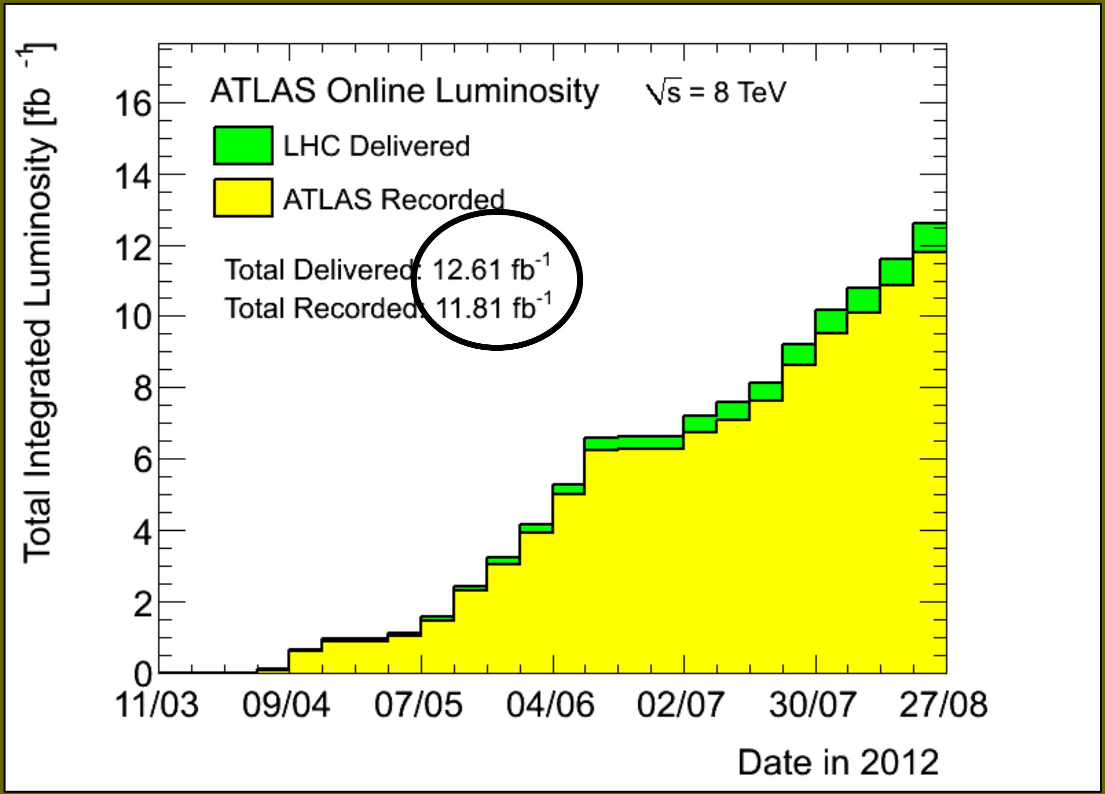
Max luminosity: ~ 7.7 x10^{33} cm^{-2} s^{-1}

BIG THANKS to the LHC team

Detector operation, data-taking efficiency, data quality



Fraction of non-operational detector channels: (depends on the sub-detector)	few permil (most cases) to 4%
Data-taking efficiency = (recorded lumi)/(delivered lumi):	~ 93.7%
Good-quality data fraction, used for analysis : (will increase further with data reprocessing)	~ 93 %



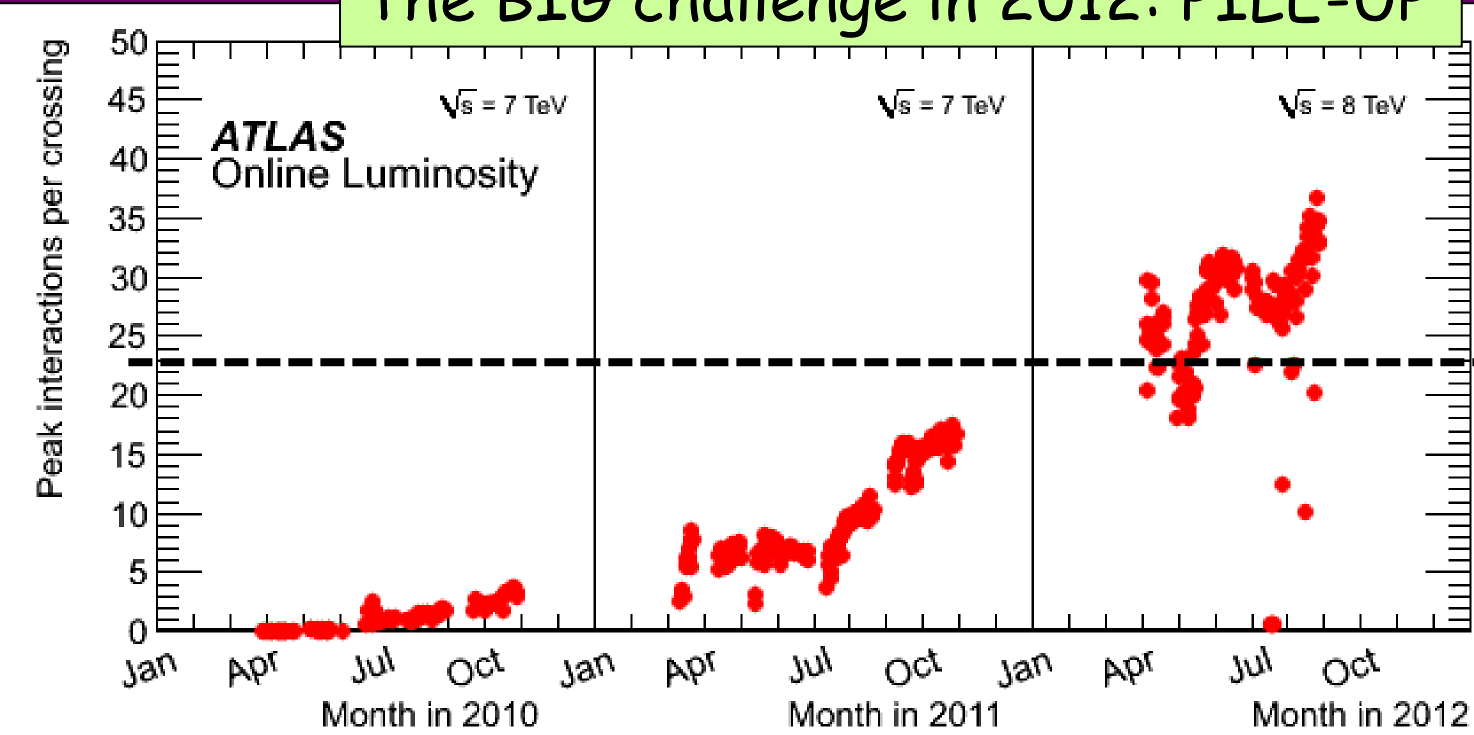
~ 90%

<u>of the delivered luminosity used for these results</u>

(slightly larger fraction than in 2011):

- in spite of the very fresh data
- in spite of the harsher conditions

The BIG challenge in 2012: PILE-UP

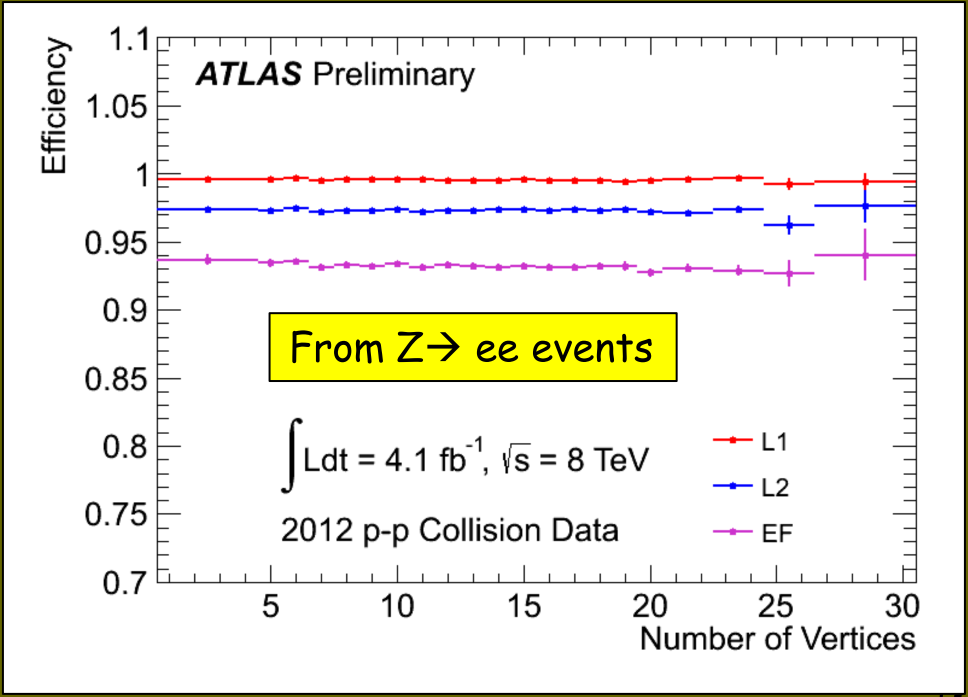


Experiment's design value (expected to be reached at L=10^{34} !)

Huge efforts since Fall 2011 to prepare for 2012 conditions and mitigate impact of pile-up on trigger, reconstruction of physics objects (in particular E_T^{miss}, soft jets, ..), computing resources (CPU, event size)

- Pile-up robust, fast trigger and offline algorithms developed
- Reconstruction and identification of physics objects (e, γ, μ, τ, jet, E_T^{miss}) optimised to be ~independent of pile-up → similar (better in some cases!) performance as with 2011 data
- Precise modeling of in-time and out-of-time pile-up in simulation
- Flexible computing model to accommodate x2 higher trigger rates and event size as well as physics and analysis demands

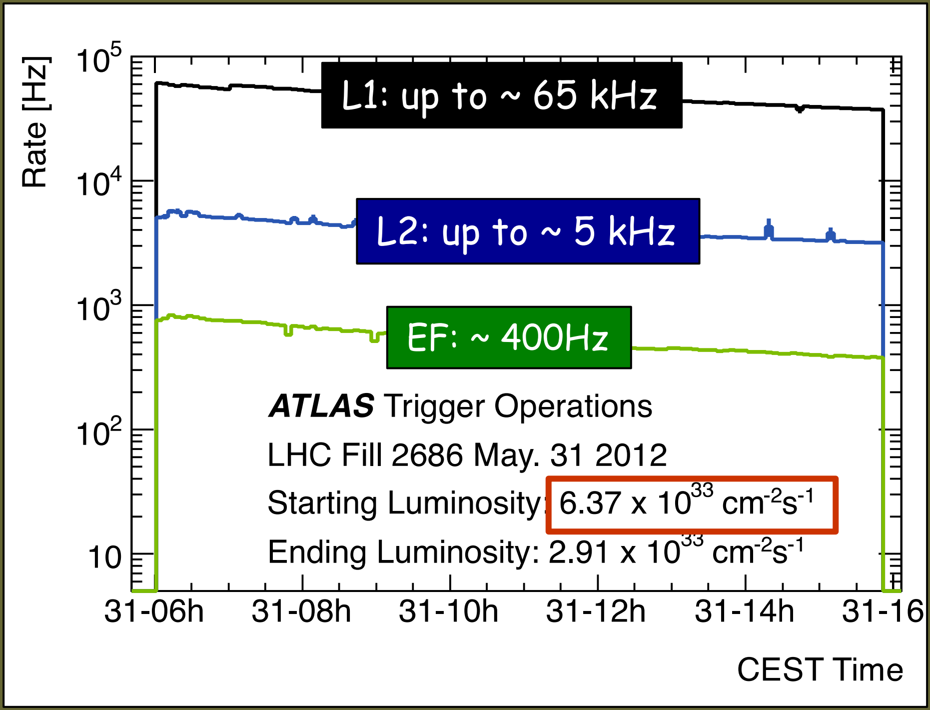
Efficiency of inclusive electron trigger (E_T thresholds as low as 24 GeV) as a function of "pile-up"



Note: number of reconstructed primary vertices is ~ 60% number of interactions per crossings

Results from 2012 operation show trigger is coping very well (in terms of rates, efficiencies, robustness, ..) with harsh conditions while meeting physics requirements

- Optimization of selections (e.g. object isolation) to maintain low un-prescaled thresholds (e.g. for inclusive leptons) in spite of projected x2 higher L and pile-up than in 2011
- Pile-up robust algorithms developed (minimize CPU usage, ...)



Lowest un-prescaled thresholds (examples)

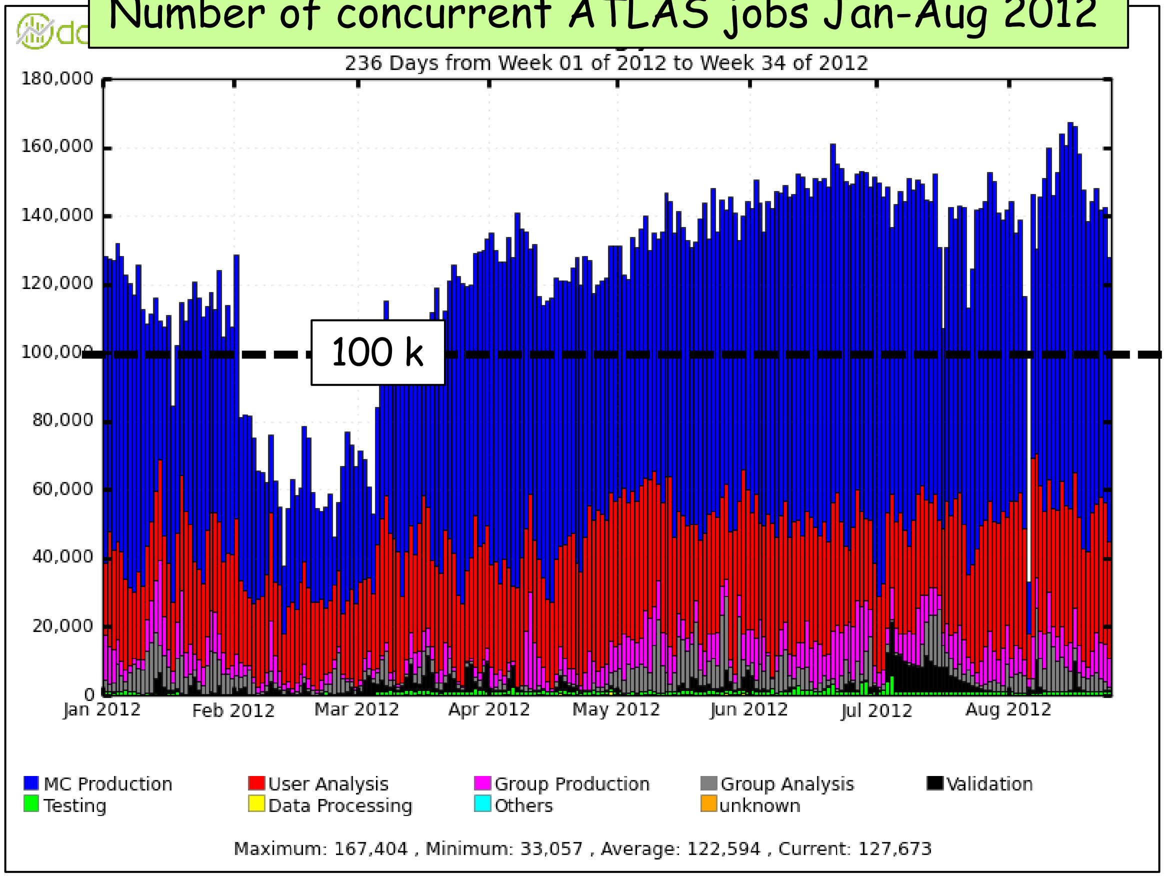
Item	p_T threshold (GeV)	Rate (Hz) 5×10^{33}
Incl. e	24	70
Incl. μ	24	45
ee	12	8
μμ	13	5
ττ	29,20	12
γγ	35,25	10
E_T^{miss}	80	17
5j	55	8

Note: ~ 500 items in trigger menu !

Managed to keep inclusive un-prescaled lepton thresholds within ~ 5 GeV over last two years in spite factor ~ 70 peak lumi increase

The LHC performance and high pile-up conditions also stressed the Computing
It would have been impossible to release physics results so quickly without the outstanding performance of the Grid (including the CERN Tier-0)

Number of concurrent ATLAS jobs Jan-Aug 2012

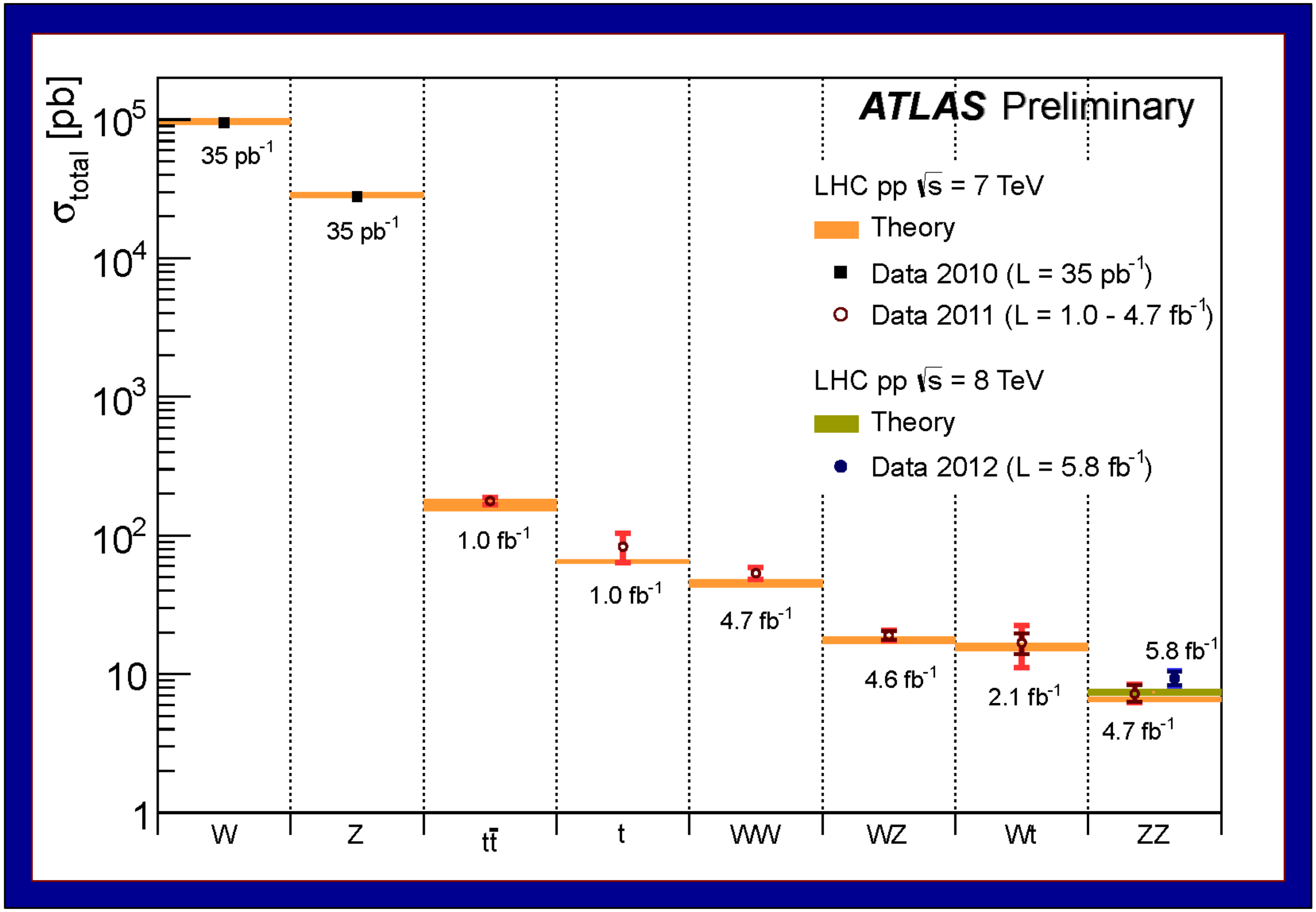


Includes MC production, user and group analysis at CERN, 10 Tier1-s, ~ 70 Tier-2 federations → > 80 sites

> 1500 distinct ATLAS users do analysis on the GRID

- ❑ Massive production of 8 TeV Monte Carlo samples
- ❑ Available resources fully used (beyond pledges in some cases)
- ❑ Very effective and flexible Computing Model and Operation team → accommodate high trigger rates and pile-up, intense MC simulation, analysis demands from worldwide users (through e.g. dynamic data placement)

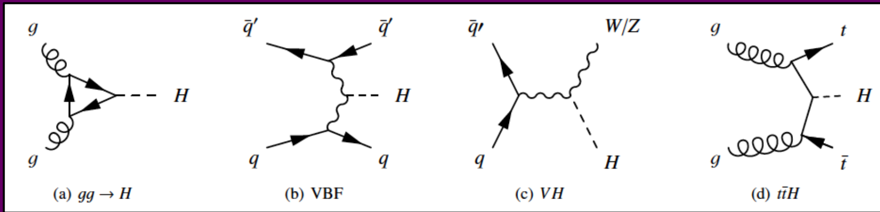
Most recent electroweak and top cross-section measurements

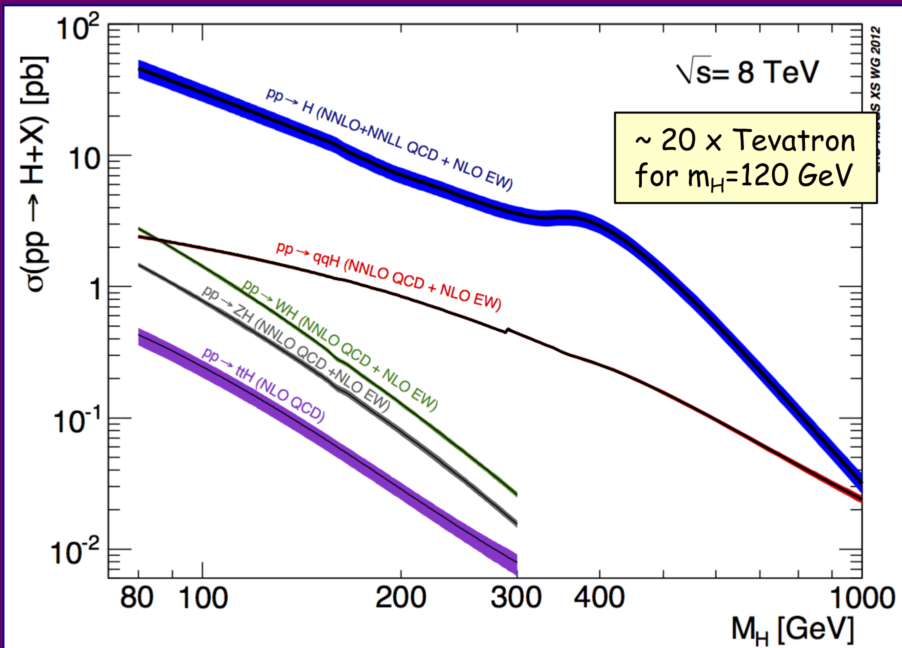


Inner error: statistical
Outer error: total

- Important on their own and as foundation for Higgs searches
- Most of these processes are reducible or irreducible backgrounds to Higgs
- Reconstruction and measurement of challenging processes (e.g. fully hadronic tt, single top, ..) are good training for some complex Higgs final states

SM Higgs production cross-section and decay modes





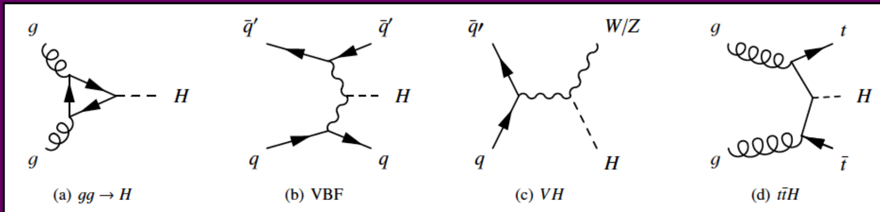
$\sqrt{s}$=7 → 8 TeV:

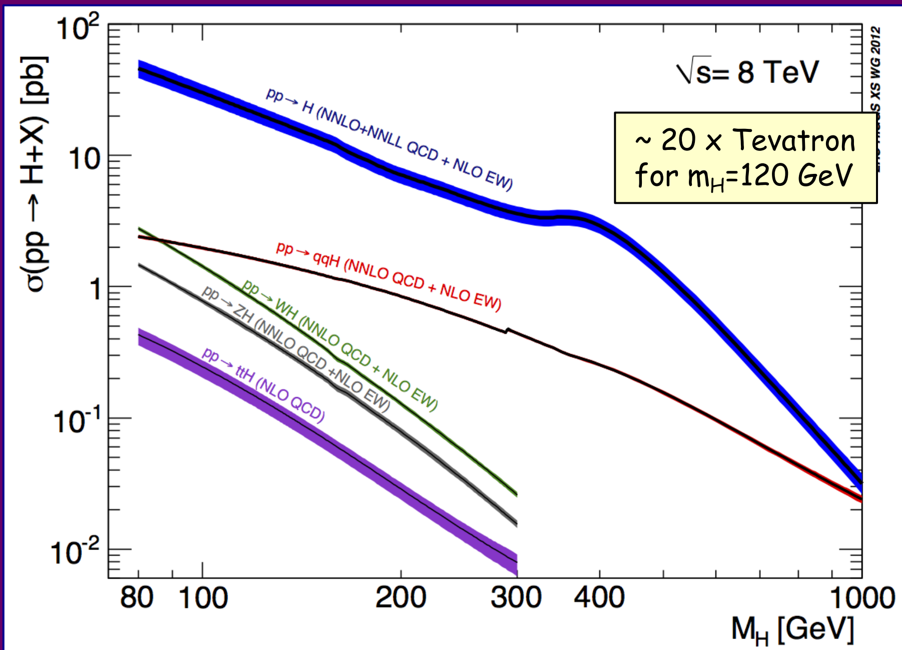
- Higgs cross-section increases by ~ 1.3 for m_H ~ 125 GeV
- Similar increase for several irreducible backgrounds: e.g. 1.2-1.25 for γγ, di-bosons
- Reducible backgrounds increase more: e.g. 1.3-1.4 for tt, Zbb

→ Expected increase in Higgs sensitivity: 10-15%

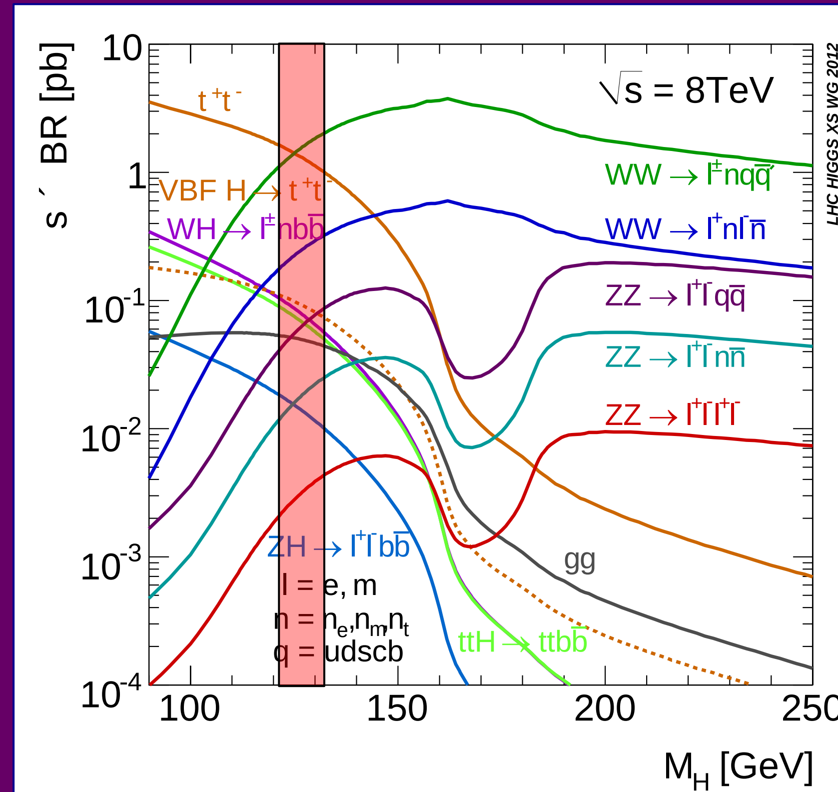
Note: huge efforts and progress from theory community to compute NLO/NNLO cross-sections for Higgs production and for (often complex !) backgrounds

SM Higgs production cross-section and decay modes





~ 20 x Tevatron for m_H=120 GeV



Most sensitive channels (decreasing order) for 120 <m_H< 130 GeV:
H→ ZZ*→ 4l, H→ γγ, H→ WW*→ lνlν
H→ ττ
W/ZH→ W/Z bb

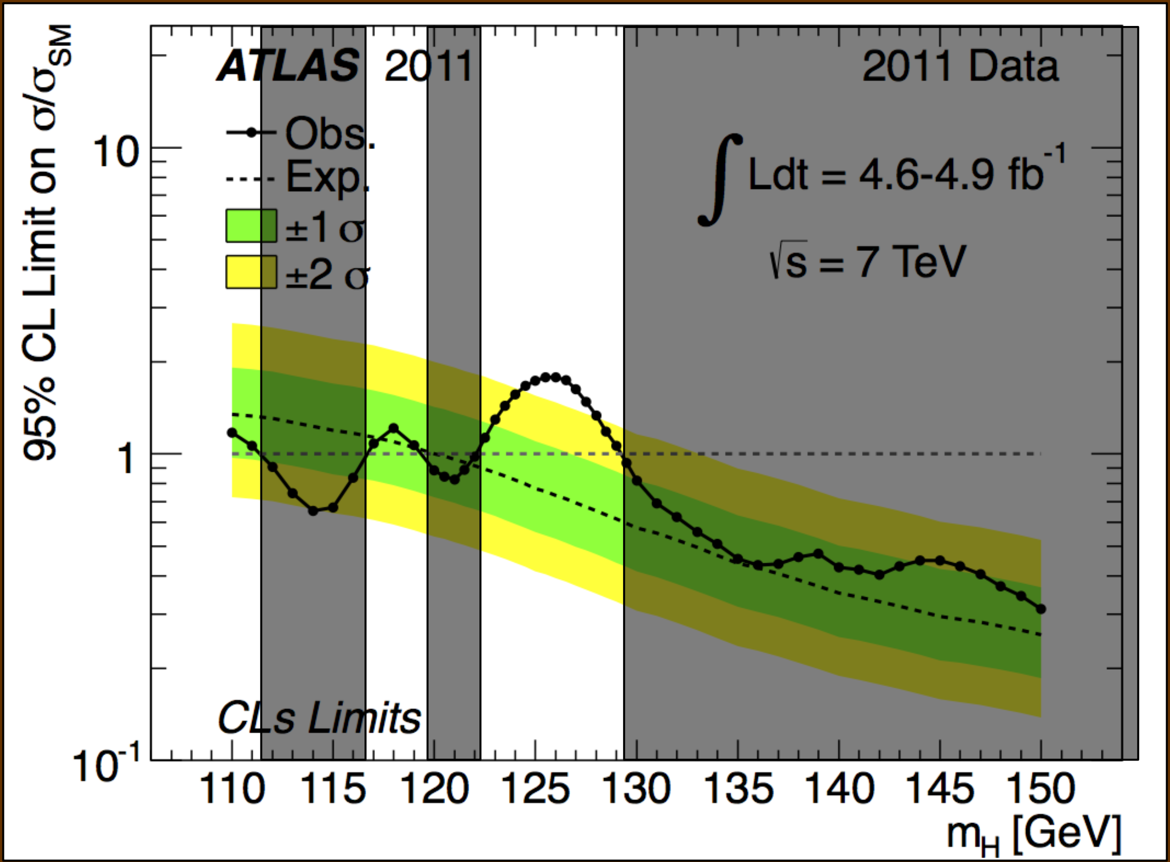
√s=7 → 8 TeV:

- Higgs cross-section increases by ~ 1.3 for m_H ~ 125 GeV
- Similar increase for several irreducible backgrounds: e.g. 1.2-1.25 for γγ, di-bosons
- Reducible backgrounds increase more: e.g. 1.3-1.4 for tt, Zbb

→ Expected increase in Higgs sensitivity: 10-15%

Status of ATLAS searches before 4th July

Results on the full 7 TeV dataset
Phys. Rev. D86 (2012) 032003



Combination of 12 channels:
- H→ γγ
- H→ ZZ(*) → 4l
- H→ WW(*) → lνlν
- W/ZH→W/Z bb (3 final states)
- H→ ττ (3 final states)
- H→ ZZ → llqq
- H→ ZZ → llνν
- H→ WW → lνqq

Expected exclusion if no signal: 120-560 GeV

Excluded at 95% CL: $111.4 < m_H < 122.1$ GeV (except 116.6-119.4) $129.2 < m_H < 541$ GeV

2.9 σ excess at $m_H \sim 126$ GeV

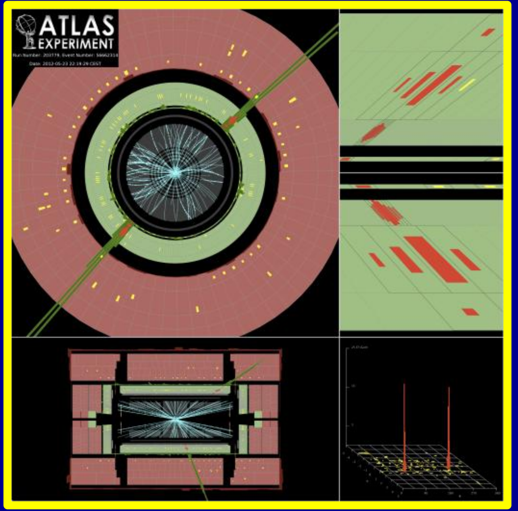
Probability to occur anywhere: 10% (Look-Elsewhere Effect)

Local significance	Observed	Expected from SM Higgs
Total	2.9 σ	2.9 σ
H→ γγ	2.8 σ	1.4 σ
H→ 4l	2.1 σ	1.4 σ
H→ lνlν	0.8 σ	1.6 σ

$H \rightarrow \gamma\gamma$

$110 \leq m_H \leq 150$ GeV

$\sigma \times BR \sim 50$ fb $m_H \sim 126$ GeV



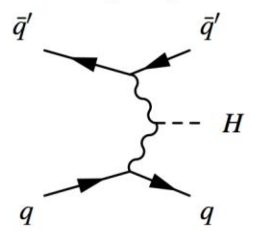
- ❑ Simple topology: two high-p_T isolated photons
  $E_T (\gamma_1, \gamma_2) > 40, 30$ GeV
- ❑ Main background: $\gamma\gamma$ continuum (irreducible, smooth, ..)

To increase sensitivity, events divided in 10 categories based on γ rapidity, converted/unconverted γ; p_{Tt} ($p_T^{\gamma\gamma}$ perpendicular to $\gamma\gamma$ thrust axis); 2jets

Main improvements in new analysis:
- ❑ 2jet category introduced → targeting VBF process
- ❑ γ identification (NN used for 2011 data) and isolation

→ Expected gain in sensitivity: + 15%
Background fit procedure also improved

σ_{SM} (VBF) ~7%



2 jets with
$p_T > 25$-30 GeV
$|\eta| < 4.5$
$|\Delta\eta|_{jj} > 2.8$
$M_{jj} > 400$ GeV
$|\Delta\varphi|$ ($\gamma\gamma$-jj) > 2.6

After all selections, expect (10.7 fb^{-1}, $m_H \sim 126$ GeV)
~ 170 signal events (total signal efficiency ~ 40%)
~ 6340 background events in mass window
→ S/B ~ 3% inclusive (~ 20% 2jet category)

Crucial experimental aspects:
- ❑ excellent $\gamma\gamma$ mass resolution to observe narrow signal peak above irreducible background
- ❑ powerful γ identification to suppress γj and jj background with jet → π^0 → fake γ
  (cross sections are 10^4-10^7 larger than $\gamma\gamma$ background)

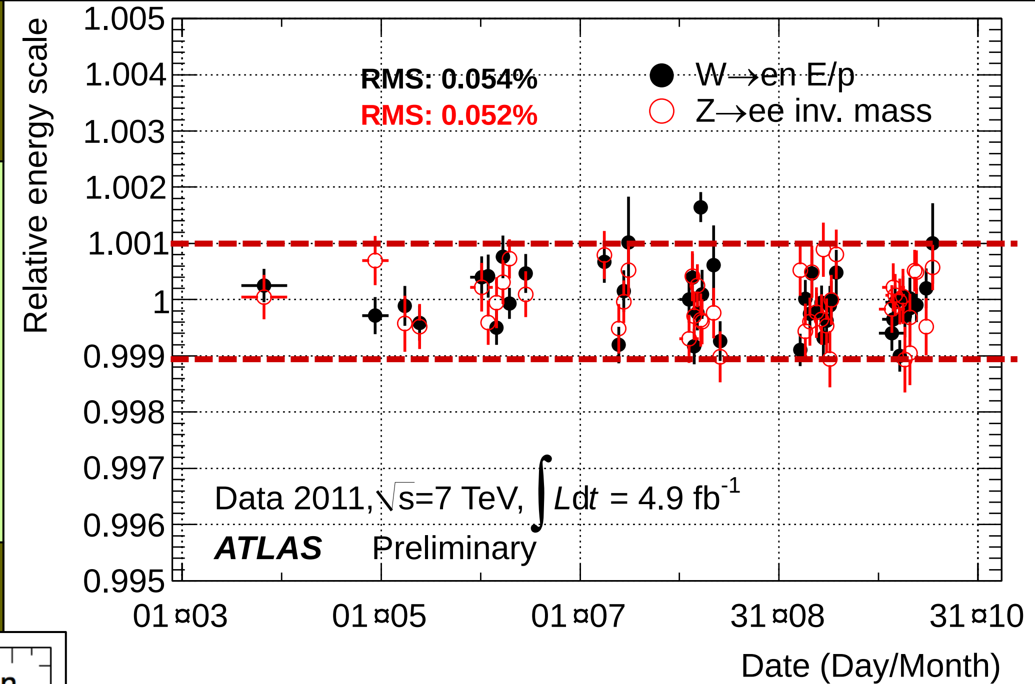
Mass resolution

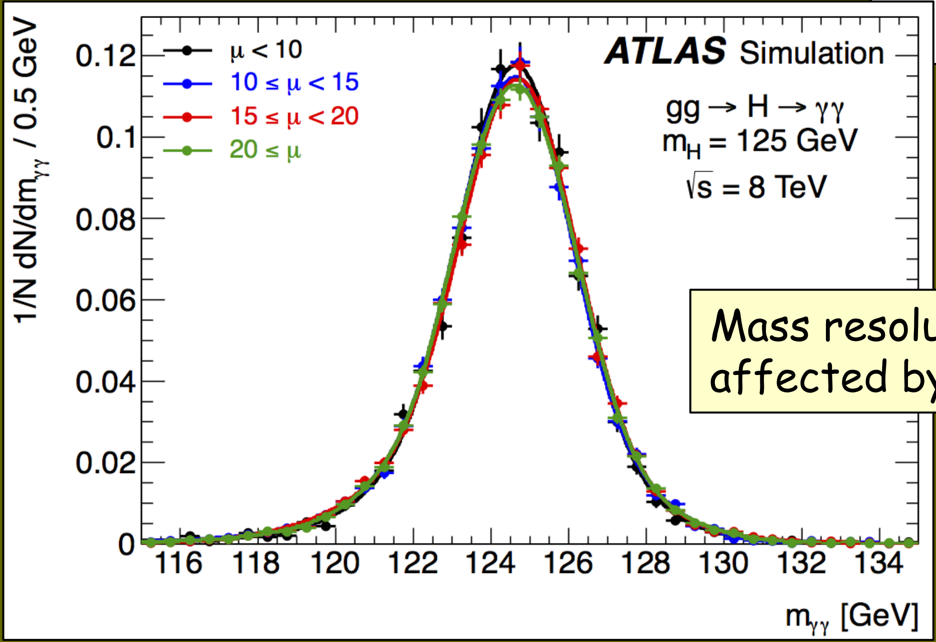
$m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$

Present understanding of calorimeter E response (from Z, J/ψ → ee, W→ eν data and MC):

- E-scale at m_Z known to ~ 0.3%
- Linearity better than 1% (few-100 GeV)
- "Uniformity" (constant term of resolution): ~ 1% (2.5% for 1.37<|η|<1.8)

Stability of EM calorimeter response vs time (and pile-up) during full 2011 run better than 0.1%





Mass resolution not affected by pile-up

Electron scale transported to photons using MC (small systematics from material effects)

Mass resolution of inclusive sample: 1.6 GeV
Fraction of events in ±2σ: ~90%

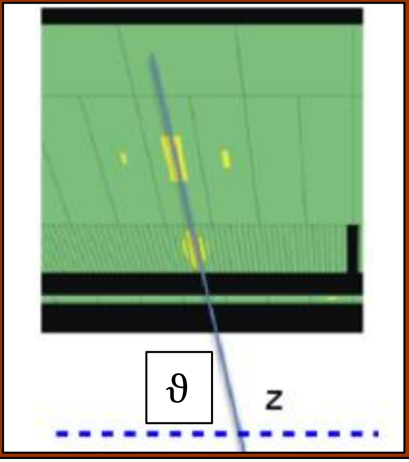
$m^2_{\gamma\gamma} = 2\,E_1\,E_2\,(1-\cos\alpha)$

α=opening angle of the two photons

High pile-up: many vertices distributed over
σ_Z (LHC beam spot) ~ 5-6 cm
→ difficult to know which one has produced the γγ pair

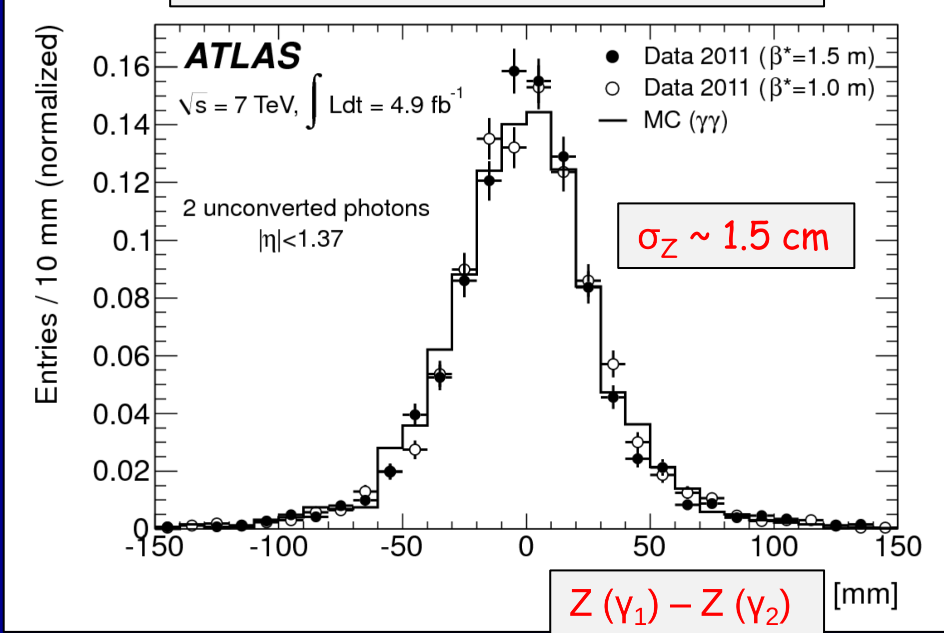
Primary vertex from:

- ❑ EM calorimeter longitudinal (and lateral) segmentation
- ❑ tracks from converted photons



Measure γ direction with calo
→ get Z of primary vertex

Z-vertex measured in γγ events from calorimeter "pointing"

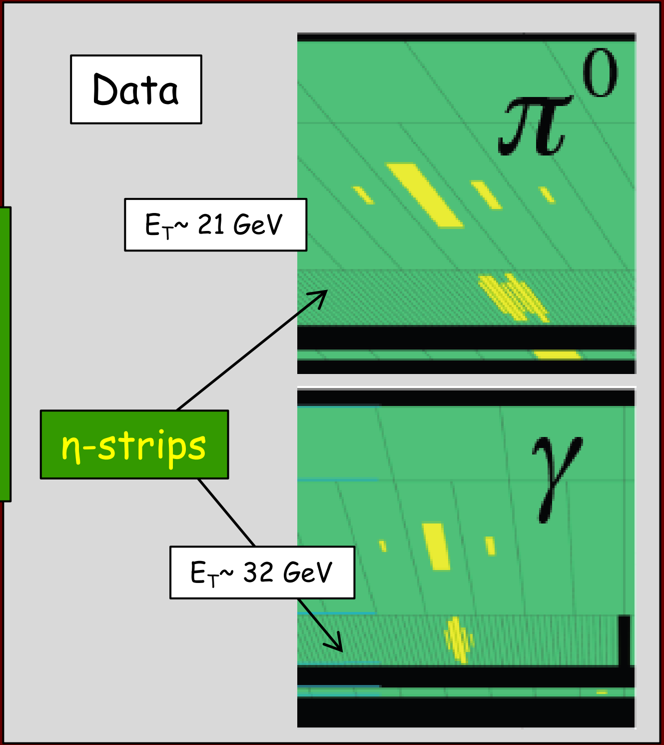


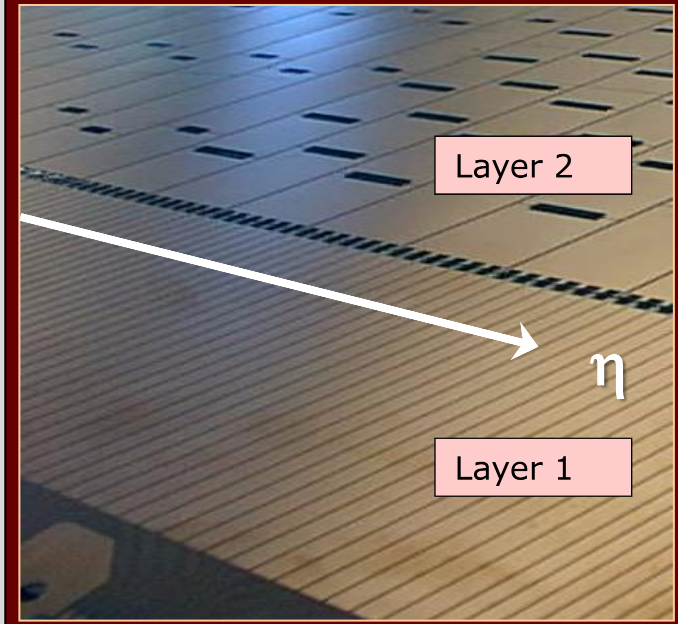
Note:

- ❑ Calorimeter pointing alone reduces vertex uncertainty from beam spot spread of ~ 5-6 cm to ~ 1.5 cm and is robust against pile-up
- → good enough to make contribution to mass resolution from angular term negligible
- ❑ Addition of track information (less pile-up robust) needed to reject fake jets from pile-up in 2j/VBF category

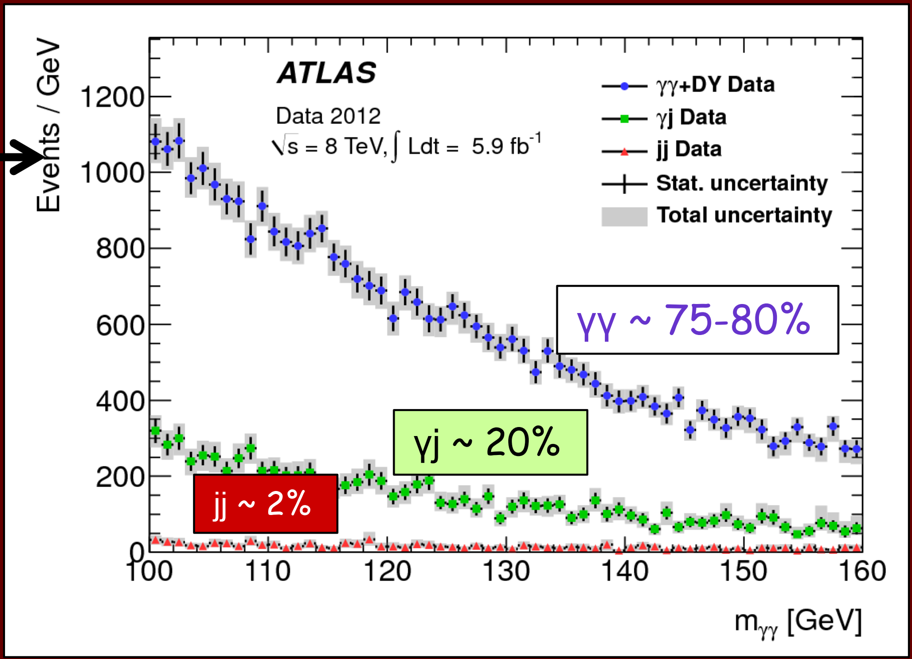
γ/jet separation

Determined choice of fine lateral segmentation (4mm η-strips) of the first compartment of ATLAS EM calorimeter





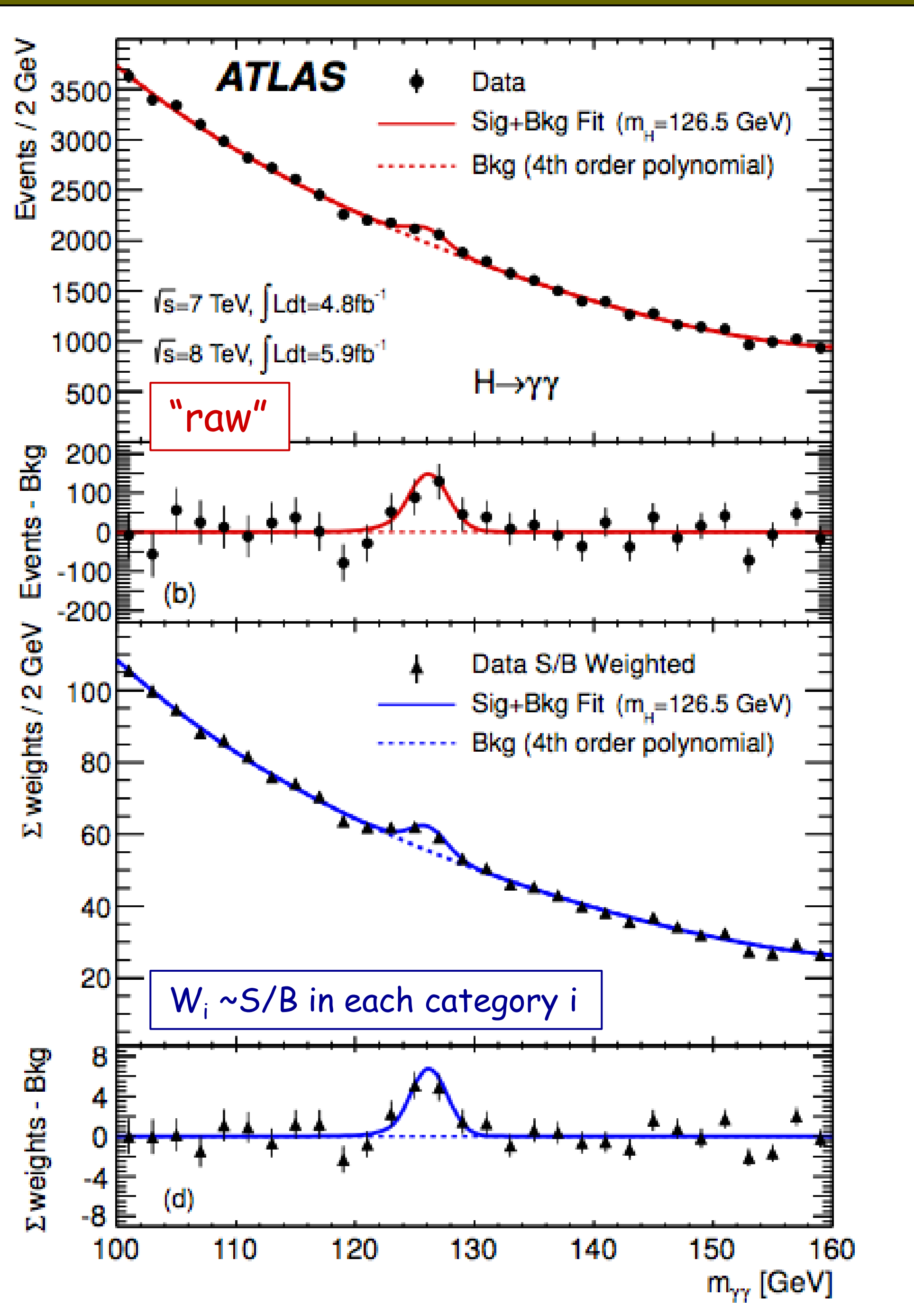
Data-driven decomposition of selected γγ sample



High γγ purity thanks to:

R_j ~10^4

ε (γ) ~ 90%

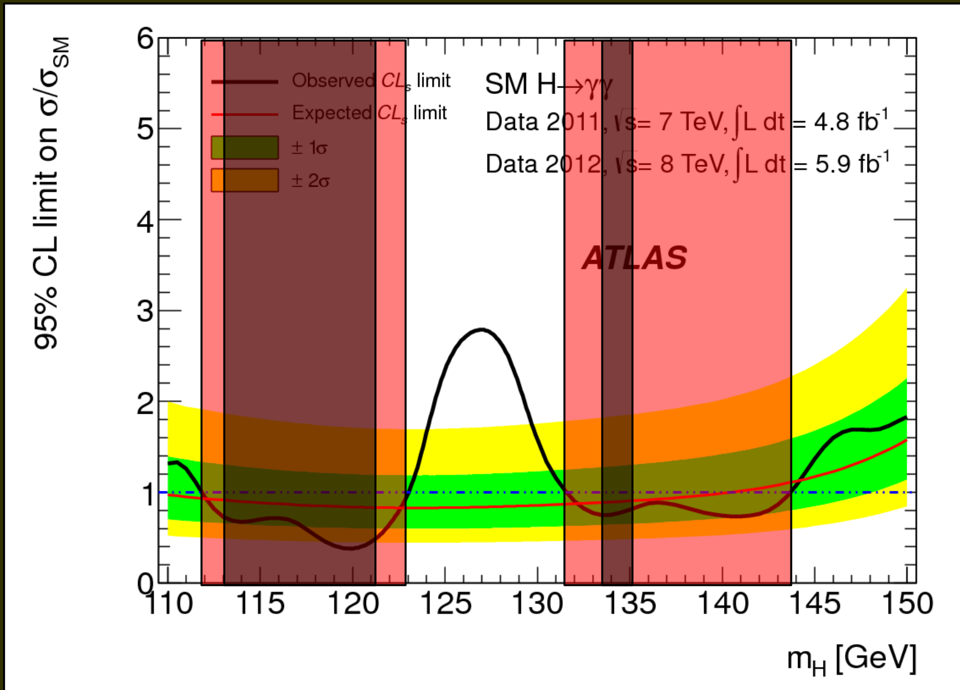


Total after selections: 59059 events

$m_{\gamma\gamma}$ spectrum fit, for each category, with Crystal Ball + Gaussian for signal plus background model optimized (with MC) to minimize biases
Max deviation of background model from expected background distribution taken as systematic uncertainty

Main systematic uncertainties

Signal yield	
Theory	~ 20%
Photon efficiency	~ 10%
Background model	~ 10%
Categories migration	
Higgs p_T modeling	up to ~ 10%
Conv/unconv γ	up to ~ 6%
Jet E-scale	up to 20% (2j/VBF)
Underlying event	up to 30% (2j/VBF)
H→ γγ mass resolution	~ 14%
Photon E-scale	~ 0.6%

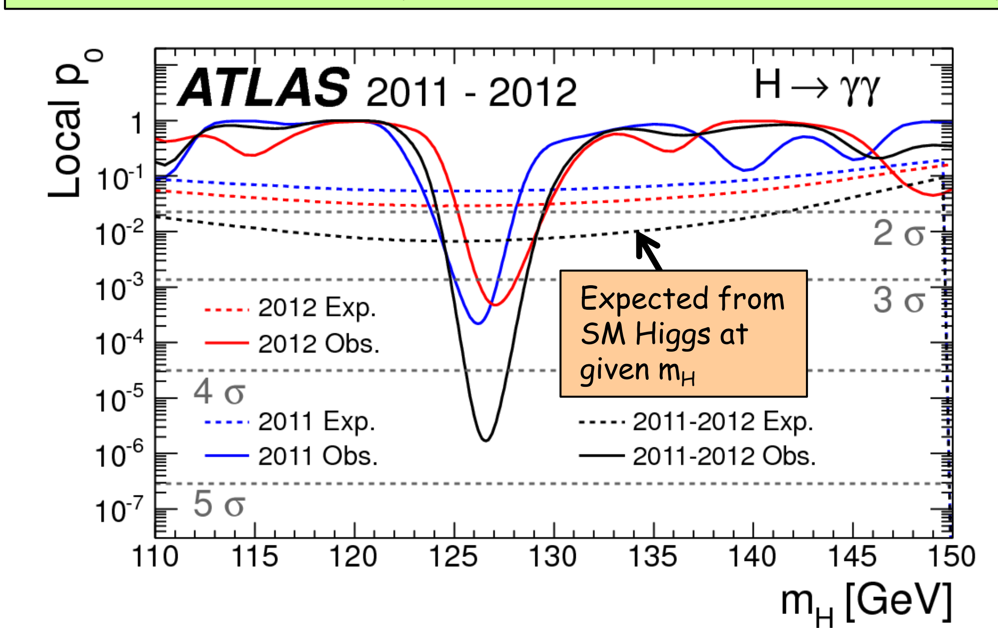


2011 data

2011+2012 data

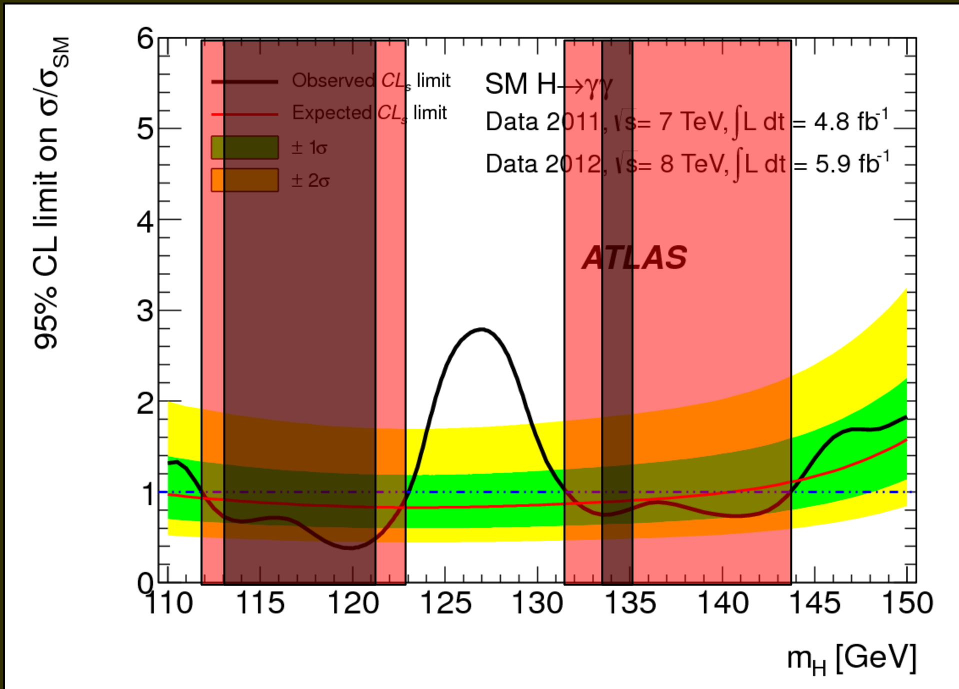
Excluded (95% CL):
112-122.5 GeV, 132-143 GeV
Expected: 110-139.5 GeV

P-value: consistency of data with background-only expectation

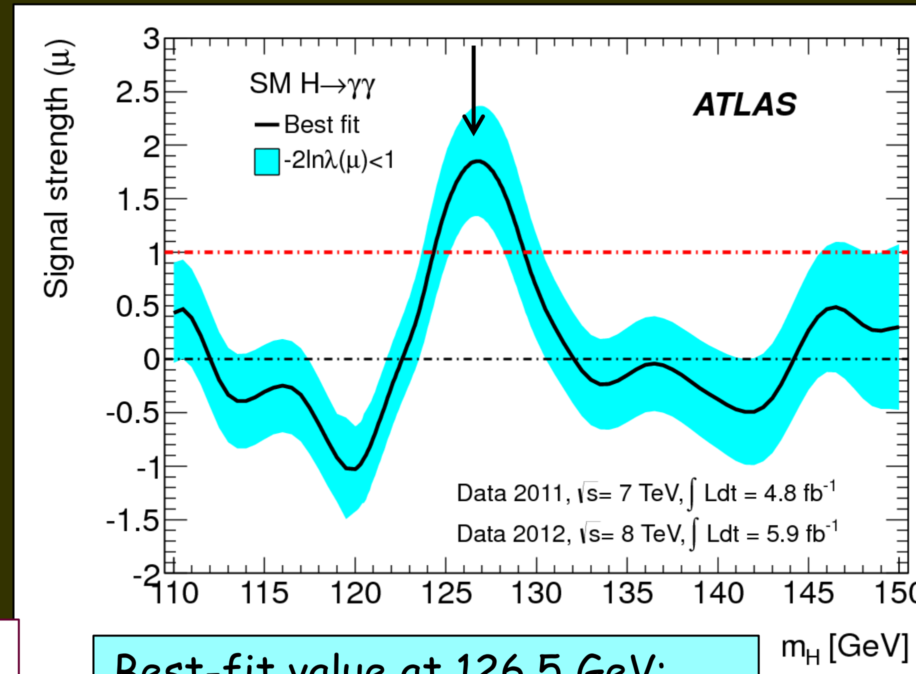


Data sample	m_H of max deviation	local significance obs. (exp. SM H)
2011	126 GeV	3.4 σ (1.6)
2012	127 GeV	3.2 σ (1.9)
2011+2012	126.5 GeV	4.5 σ (2.5)

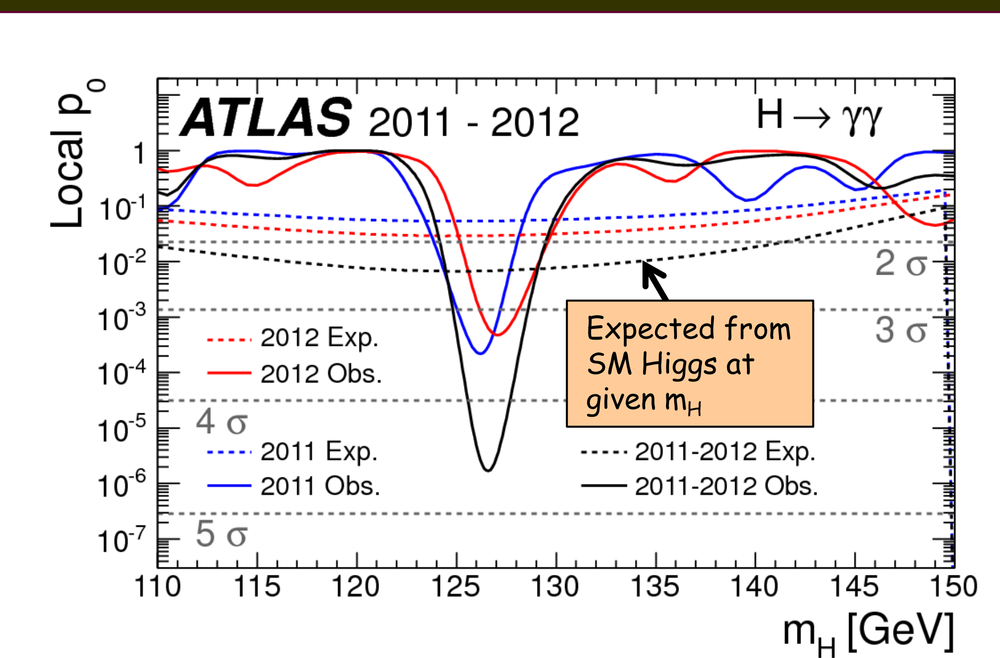
Global 2011+2012 (including LEE): 3.6 σ



Fitted signal strength normalized to SM Higgs expectation



Best-fit value at 126.5 GeV:
$\mu=1.9 \pm 0.5$



Data sample	m_H of max deviation	local significance obs. (exp. SM H)
2011	126 GeV	3.5 σ (1.6)
2012	127 GeV	3.4 σ (1.9)
2011+2012	126.5 GeV	4.5 σ (2.4)

$H \to ZZ^{(*)} \to 4l$ (4e, 4μ, 2e2μ)

$110 < m_H < 600$ GeV

σ x BR ~ 2.5 fb $m_H \sim 126$ GeV

- Tiny rate, BUT:
  - -- mass can be fully reconstructed → events should cluster in a (narrow) peak
  - -- pure: S/B ~ 1
- 4 leptons: $p_T^{1,2,3,4} > 20,15,10,7\text{-}6$ (e-μ) GeV; $50 < m_{12} < 106$ GeV; $m_{34} > 17.5\text{-}50$ GeV (vs m_H)
- Main backgrounds:
  - -- $ZZ^{(*)}$: irreducible
  - -- low-mass region $m_H < 2m_Z$: Zbb, Z+jets, tt with two leptons from b-jets or q-jets → lep

→ Suppressed with isolation and impact parameter cuts on two softest leptons

Crucial experimental aspects:

- High lepton acceptance, reconstruction & identification efficiency down to lowest p_T
- Good lepton energy/momentum resolution
- Good control of reducible backgrounds (Zbb, Z+jets, tt) in low-mass region:
  - → cannot rely on MC alone (theoretical uncertainties, b/q-jet → lep modeling, ..)
  - → need to validate MC with data in background-enriched control regions

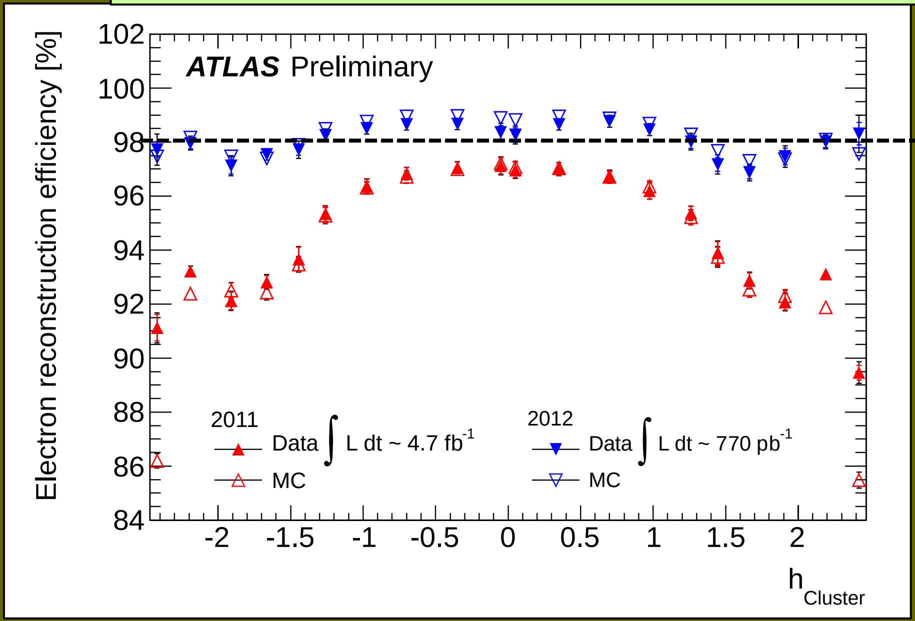
Main improvements in new analysis:

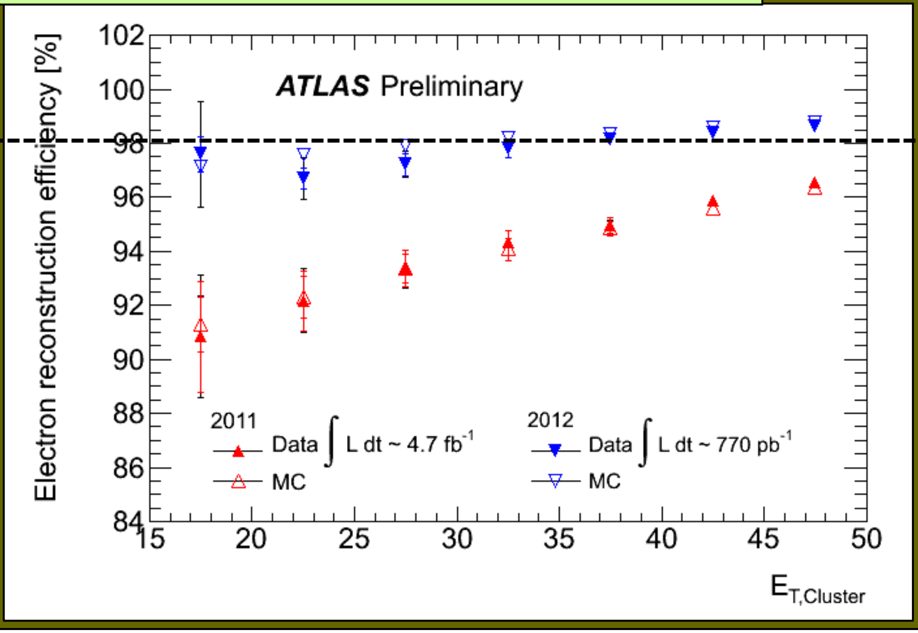
- kinematic cuts (e.g. on m_{12}) optimized/relaxed to increase signal sensitivity at low mass
- increased $e^{\pm}$ reconstruction and identification efficiency at low p_T and pile-up robustness (with negligible increase in the reducible backgrounds)

→ Gain 20% (4μ) to 30% (4e) in sensitivity compared to previous analysis

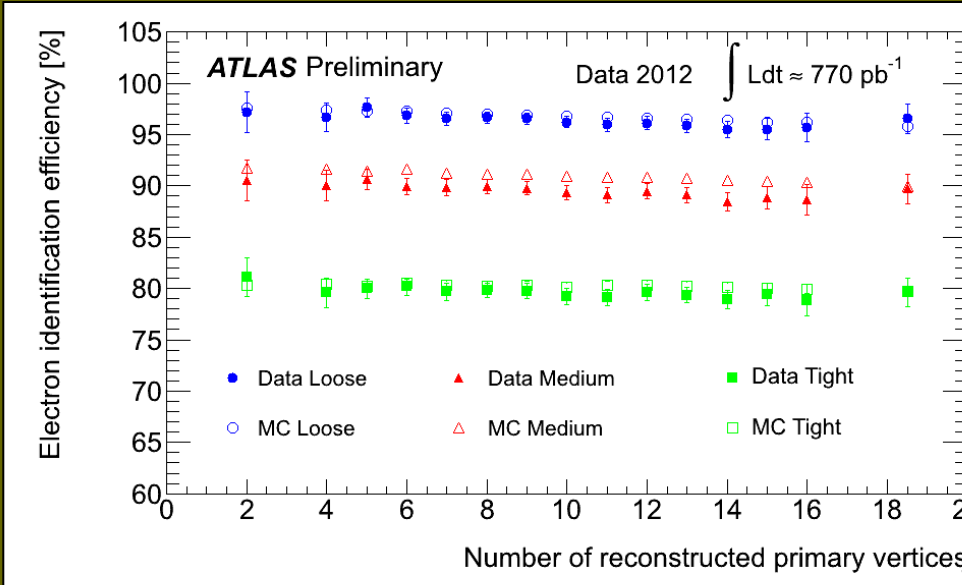
High efficiency for low-p_T electrons (affected by material) crucial for H→ 4e, 2μ2e

Improved track reconstruction and fitting to recover $e^{\pm}$ undergoing hard Brem → achieved ~ 98% reconstruction efficiency, flatter vs η and E_T





Re-optimized $e^{\pm}$ identification using pile-up robust variables (e.g. Transition Radiation, calorimeter strips) → achieved ~ 95% identification efficiency, ~ flat vs pile-up; higher rejections of fakes

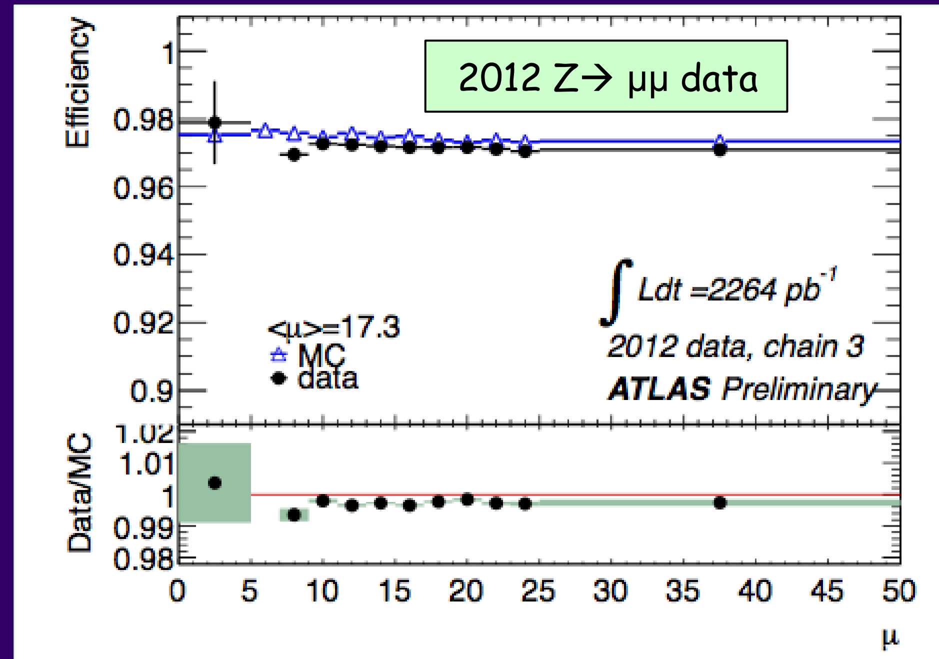


Results are from Z→ ee data and MC tag-and-probe

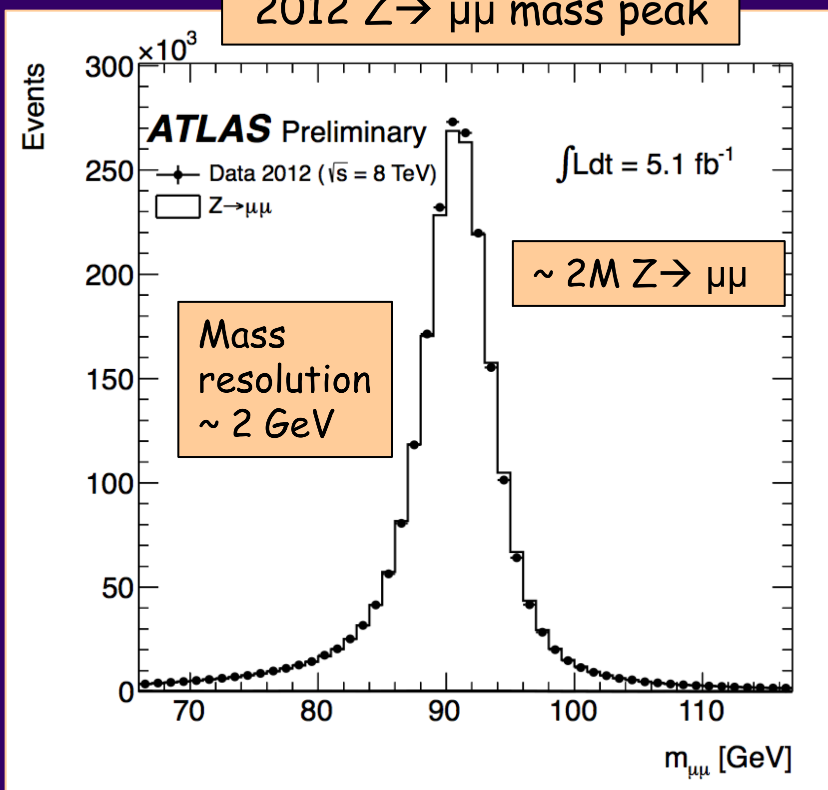
Muons reconstructed down to $p_T = 6$ GeV over $|\eta|<2.7$

Reconstruction efficiency ~ 97%
~ flat over full range

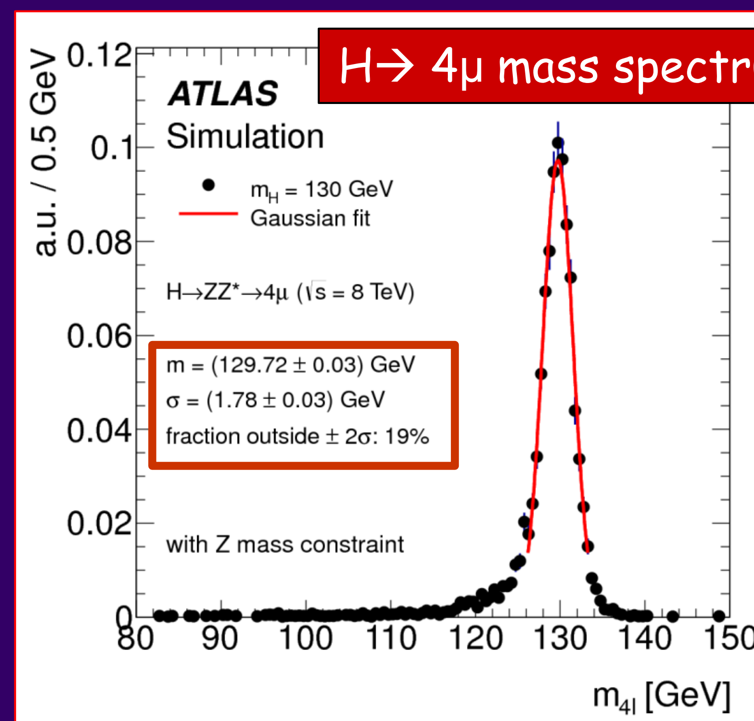
Total acceptance x efficiency for H→ 4μ: ~ 40% (+45% gain)



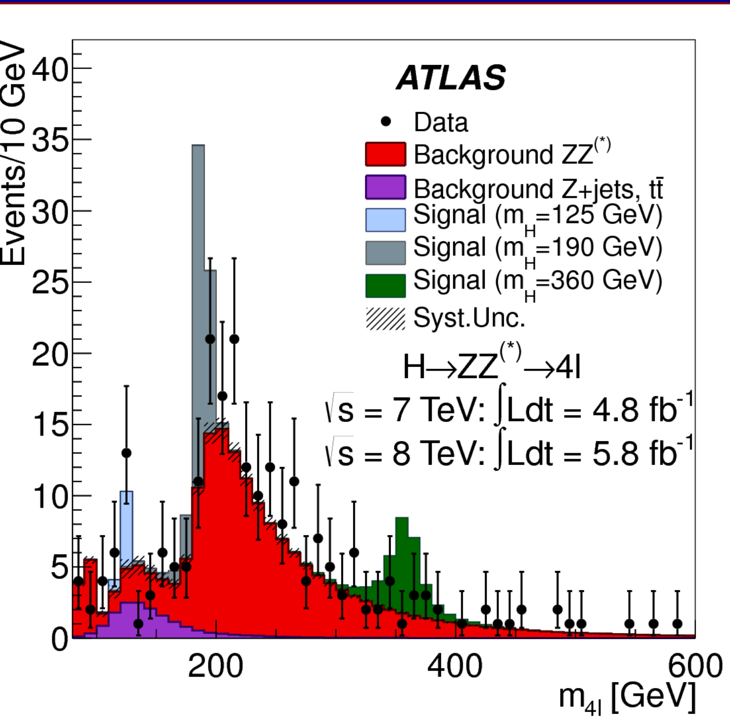
2012 Z→ μμ mass peak



H→ 4μ mass spectrum



H→ 4l mass spectrum after all selections

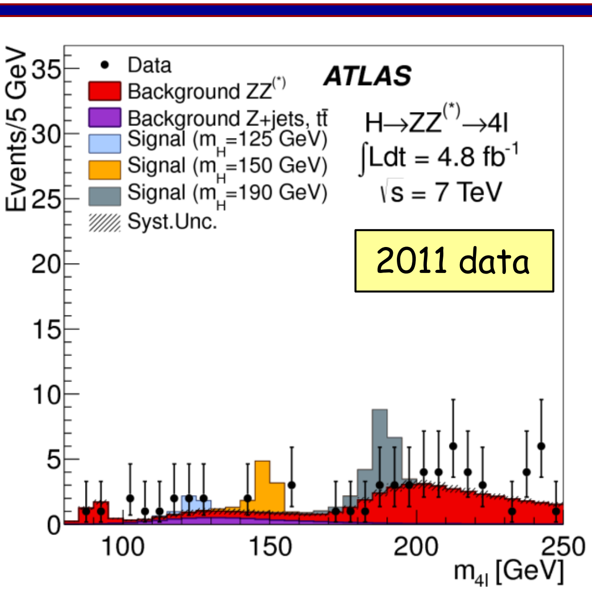


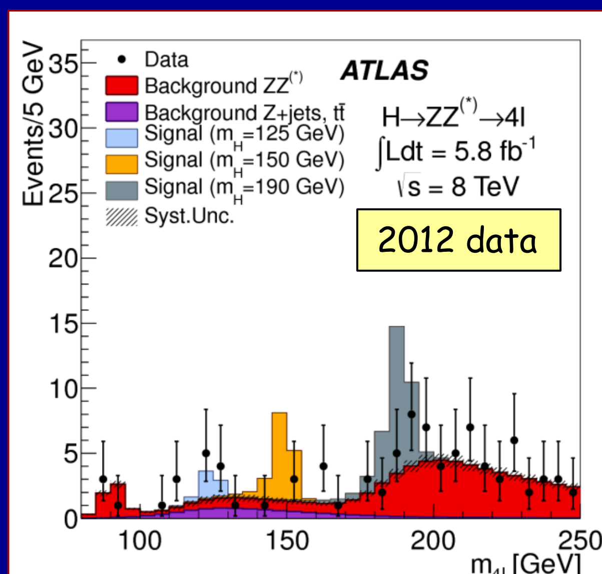
m_{4l} <160 GeV: 39 events observed; 34± 3 expected

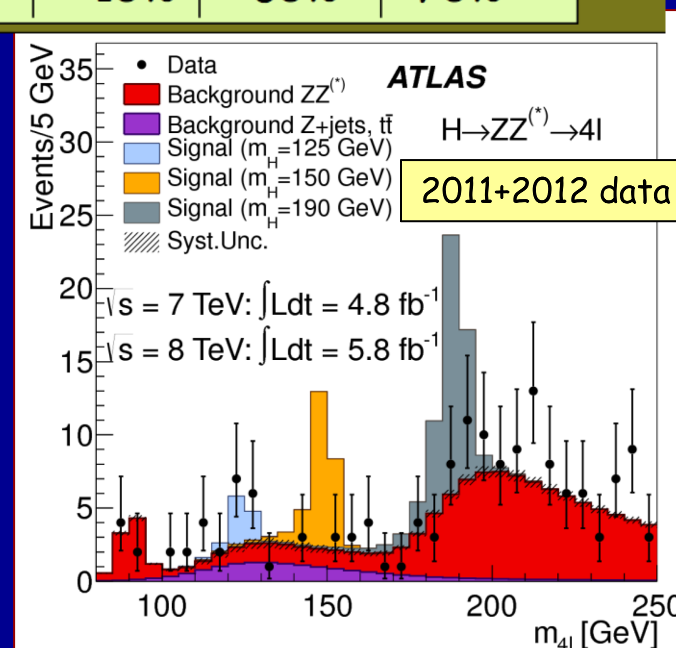
In the region 125 ± 5 GeV

Observed	13 events
Expected from background only	4.9 ± 1
Expected from Higgs signal	5.3 ± .8

	4μ	2e2μ	4e
Data	6	5	2
Expected S/B	1.6	1.1	0.6
Reducible/total B	10%	60%	70%

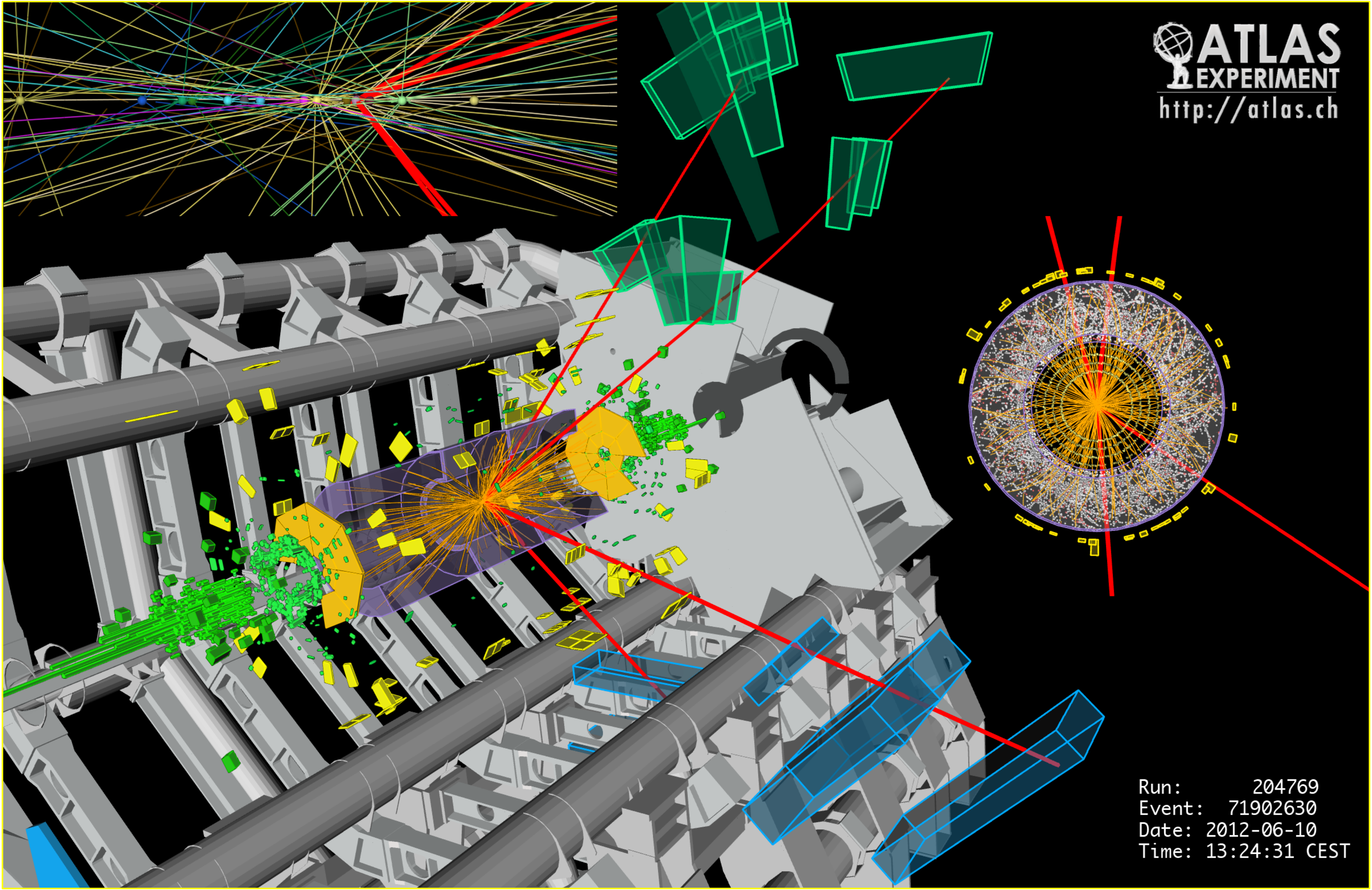






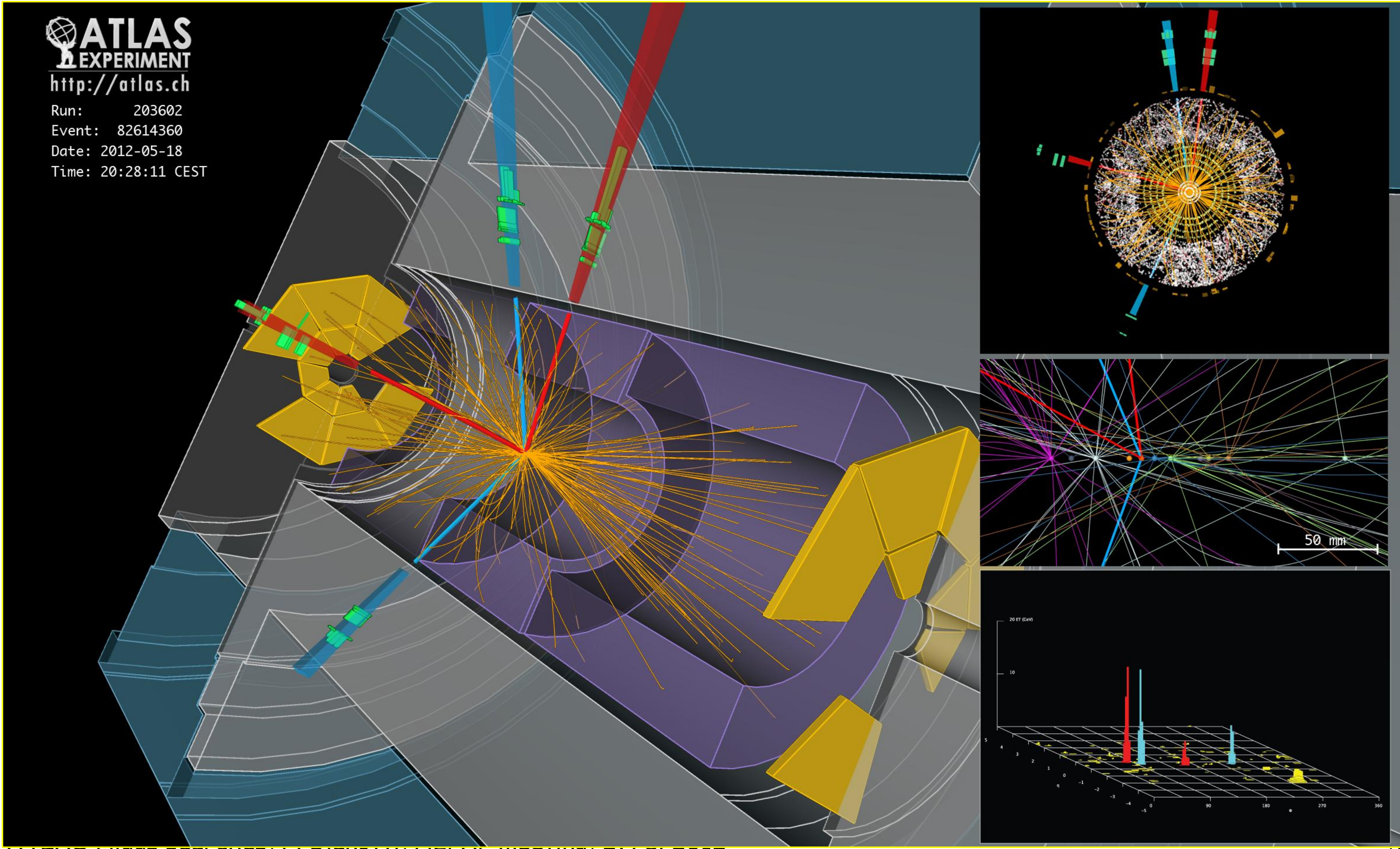
4μ candidate with $m_{4\mu}$= 125.1 GeV

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



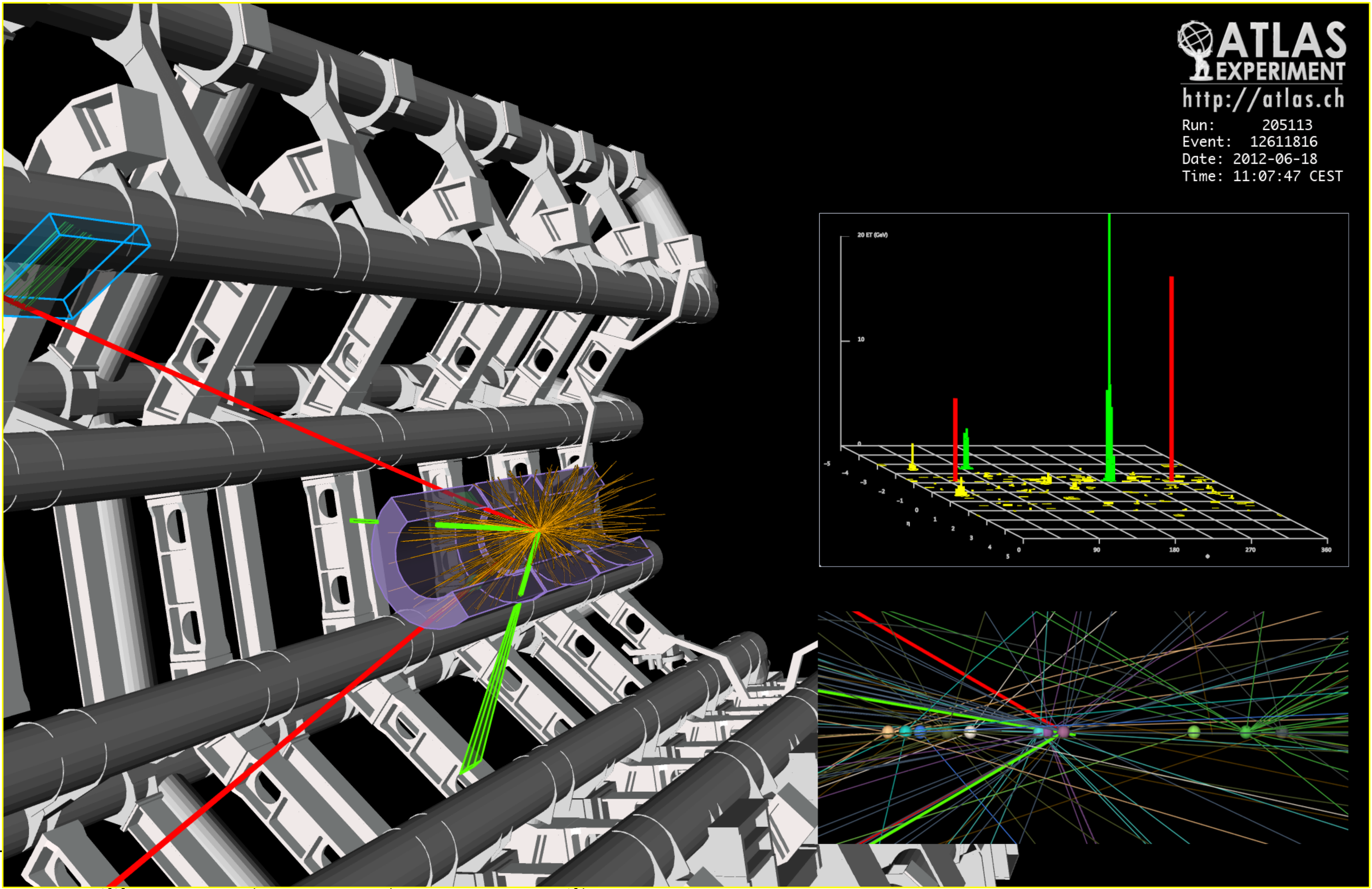
4e candidate with m_{4e}= 124.6 GeV

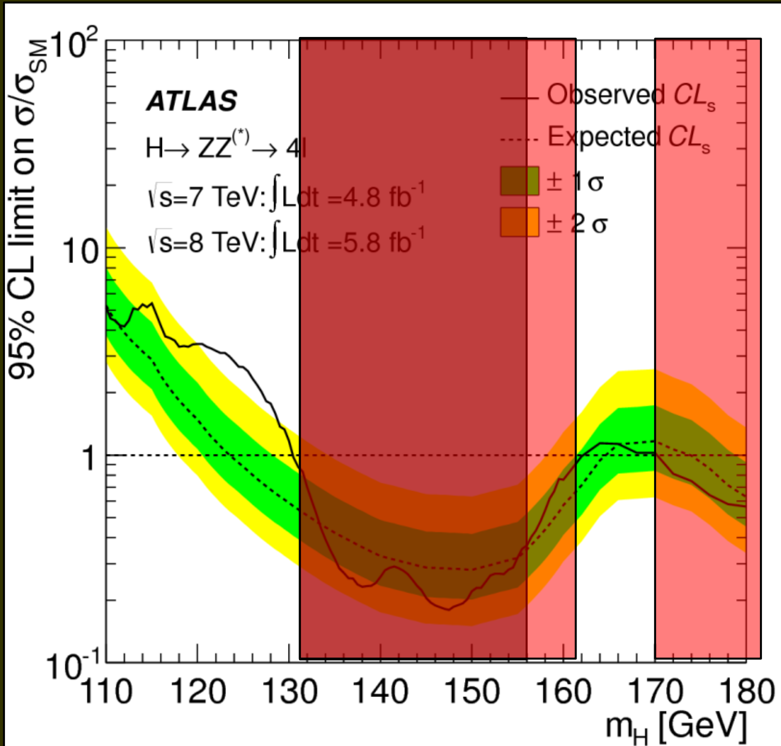
p_T (electrons)= 24.9, 53.9, 61.9, 17.8 GeV m_{12}= 70.6 GeV, m_{34}= 44.7 GeV
12 reconstructed vertices



2e2μ candidate with $m_{2e2\mu}$= 123.9 GeV

p_T (e,e,μ,μ)= 18.7, 76, 19.6, 7.9 GeV, m (e^+e^-)= 87.9 GeV, m($\mu^+\mu^-$) =19.6 GeV
12 reconstructed vertices

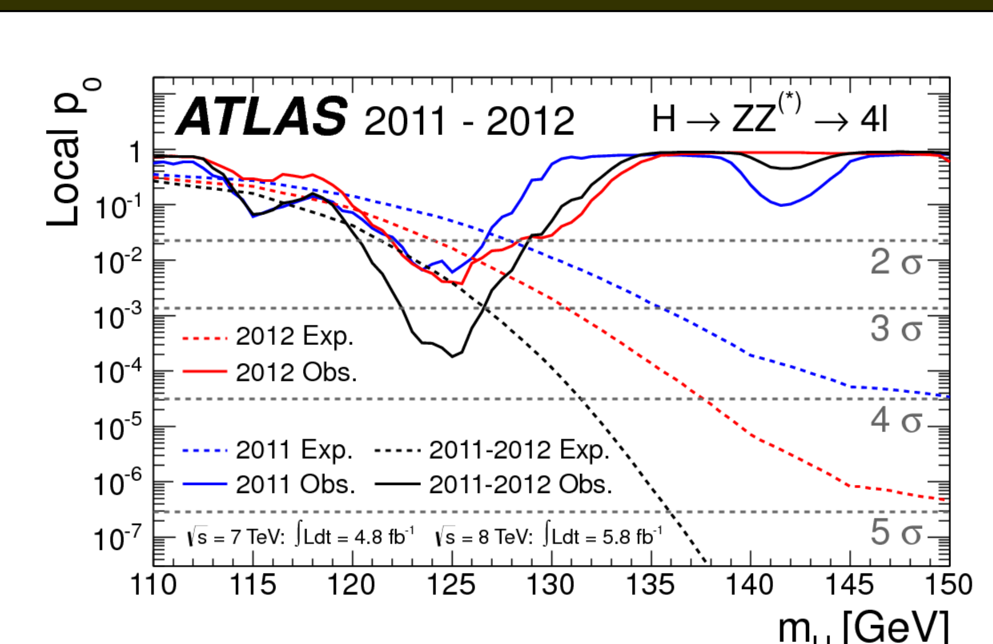




2011 data

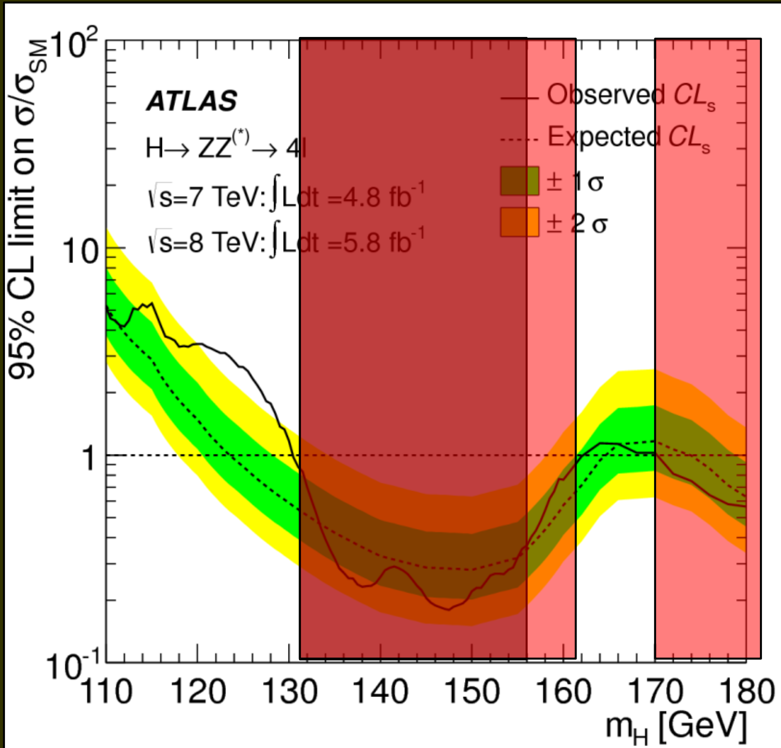
2011+2012 data

Excluded (95% CL):
131-162, 170-460 GeV
Expected: 124-1164, 176-500 GeV

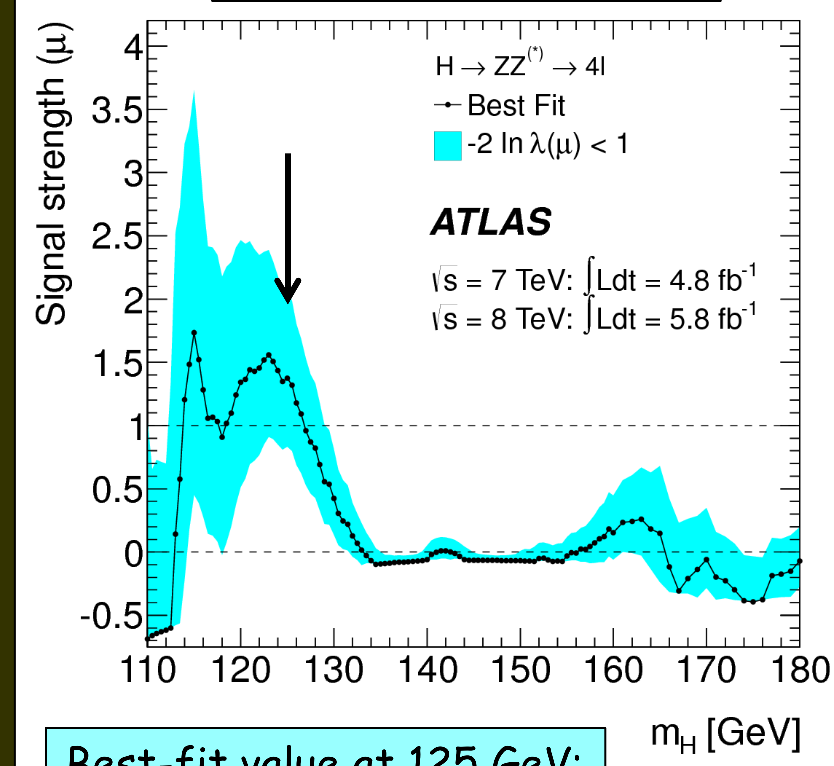


Data sample	m_H of max deviation	local significance obs. (exp. SM H)
2011	125 GeV	2.5 σ (1.6)
2012	125.5 GeV	2.6 σ (2.1)
2011+2012	125 GeV	3.6 σ (2.7)

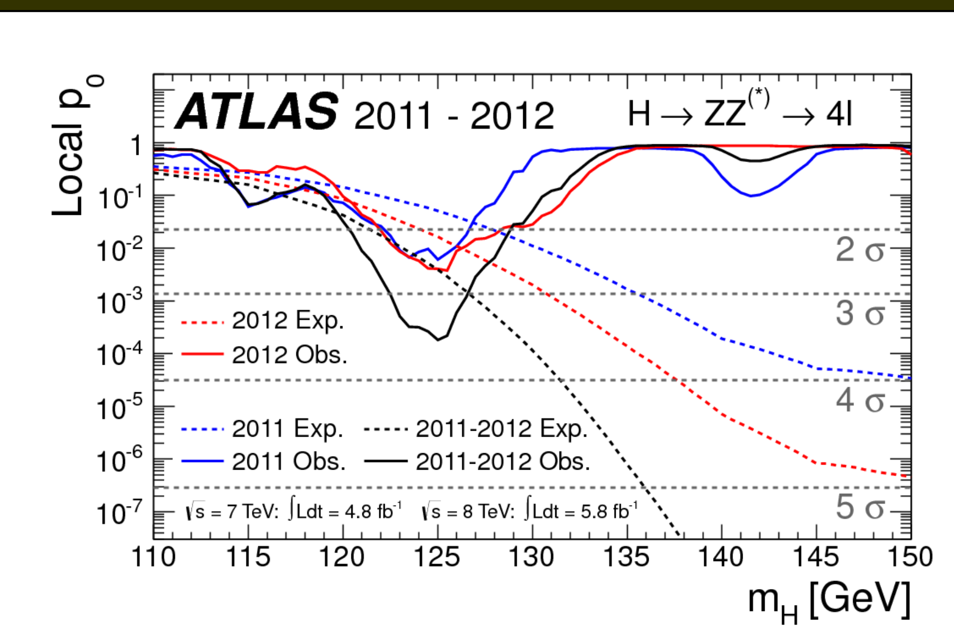
Global 2011+2012
(including LEE over 110-141 GeV): 2.5 σ



Fitted signal strength



Best-fit value at 125 GeV:
μ=1.3 ± 0.6



Data sample	m_H of max deviation	local significance obs. (exp. SM H)
2011	125 GeV	2.3 σ (1.5)
2012	125.6 GeV	2.7 σ (2.1)
2011+2012	125 GeV	3.4 σ (2.6)

$H \to WW^{(*)} \to l\nu l\nu$ (eνeν, $\mu\nu\mu\nu$, e$\nu\mu\nu$)

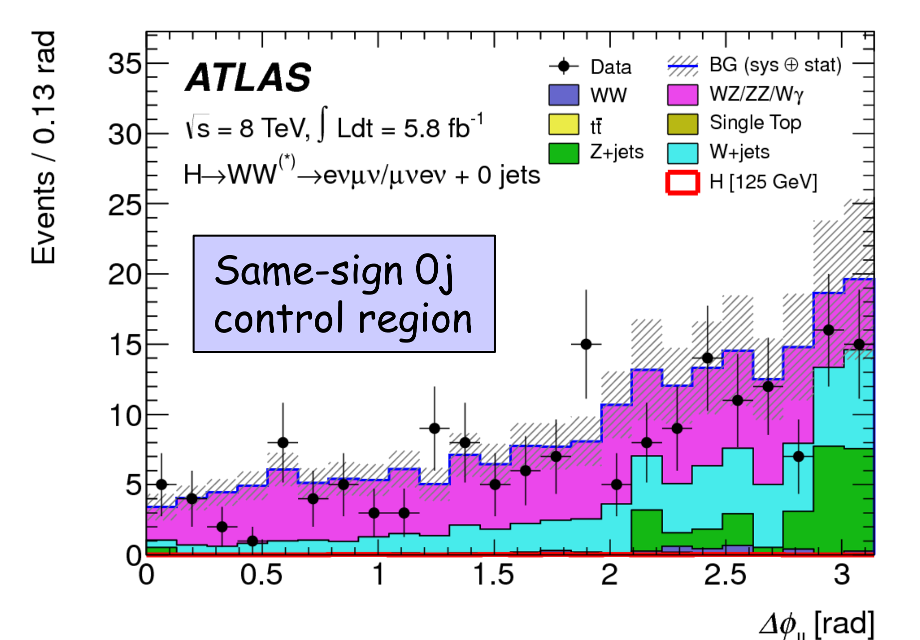
$110 < m_H < 600$ GeV

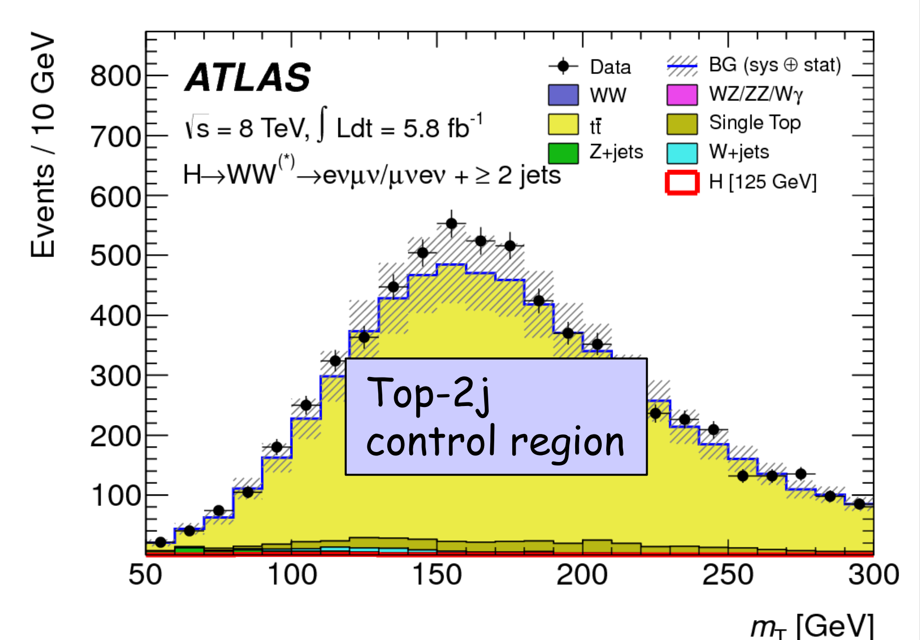
σ x BR ~ 200 fb for m_H~ 125 GeV

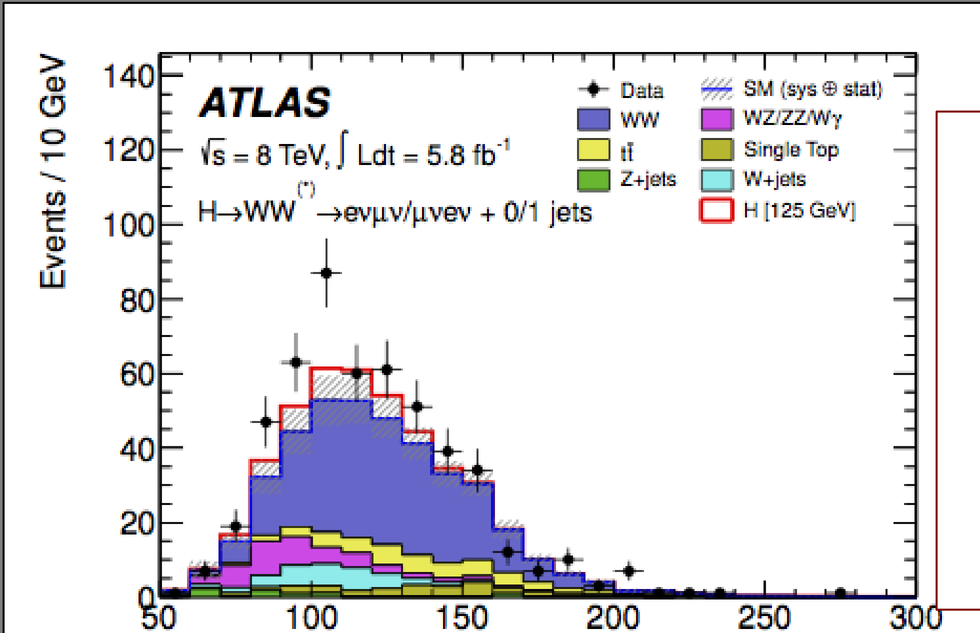
- Large cross section
- However: 2ν in final state → mass peak cannot be reconstructed → "counting channel"
- H→ e$\nu\mu\nu$ studied with 2012 data: ~ 85% of sensitivity, less Drell-Yan background

- 2 isolated opposite-sign leptons, $p_T > 25$, 15 GeV
- Main backgrounds: WW, top, Z+jets, W+jets
  → large E_T^{miss}, $m_{ll} \neq m_Z$, b-jet veto ..+ topological cuts: p_{Tll}, m_{ll}, $\Delta\phi_{ll}$ (smaller for scalar Higgs)

Crucial experimental aspects:
- understanding of E_T^{miss} (genuine and fake)
- very good modeling of background in signal region → usignal-free control regions in data to constrain MC → use MC to extrapolate to signal region







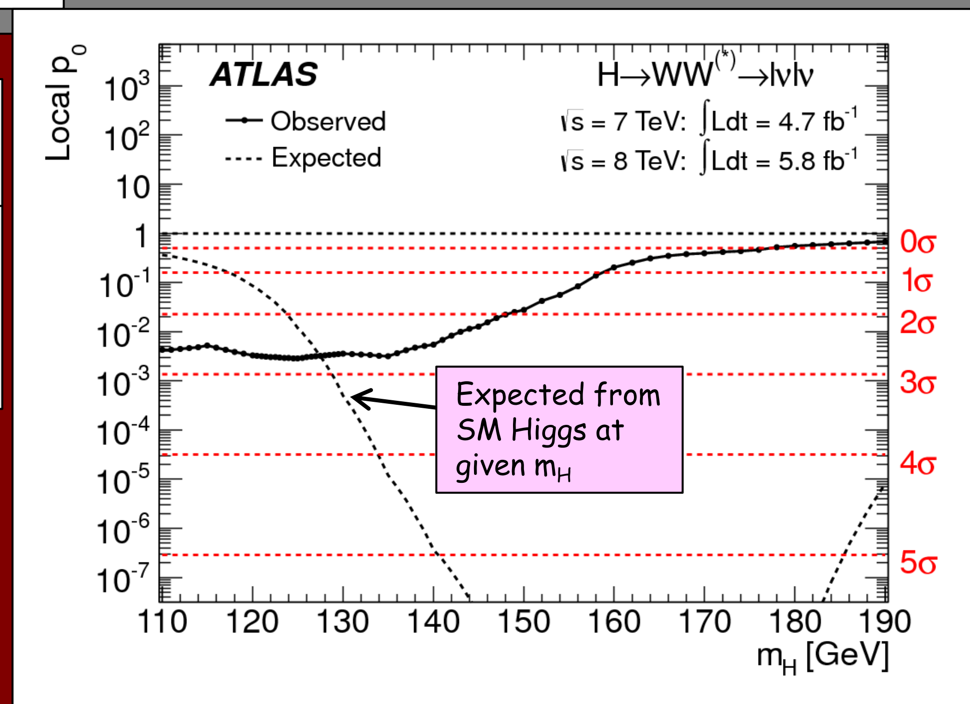
$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

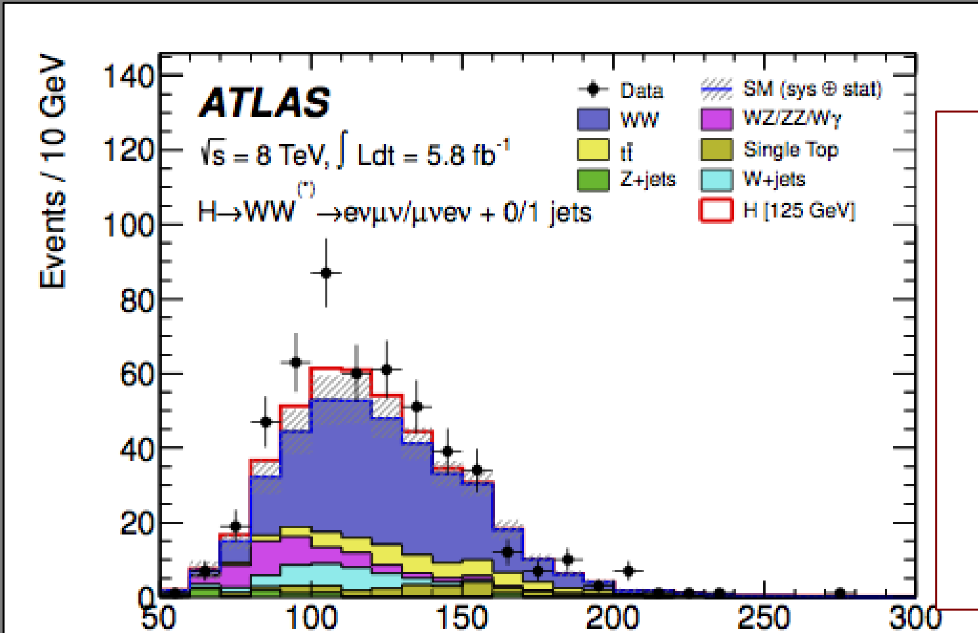
After all selections

	0-jet	1-jet	2-jet
Signal	20 ± 4	5 ± 2	0.34 ± 0.07
WW	101 ± 13	12 ± 5	0.10 ± 0.14
$WZ^{(*)}/ZZ/W\gamma^{(*)}$	12 ± 3	1.9 ± 1.1	0.10 ± 0.10
$t\bar{t}$	8 ± 2	6 ± 2	0.15 ± 0.10
$tW/tb/tqb$	3.4 ± 1.5	3.7 ± 1.6	-
$Z/\gamma^* +$ jets	1.9 ± 1.3	0.10 ± 0.10	-
$W +$ jets	15 ± 7	2 ± 1	-
Total Background	142 ± 16	26 ± 6	0.35 ± 0.18
Observed	185	38	0

Data sample	m_H of max deviation	local significance obs. (exp. SM H)
2011	135 GeV	1.1 σ (3.4)
2012	120 GeV	3.3 σ (1.0)
2011+2012	125 GeV	2.8 σ (2.3)

Broad excess extending over > 50 GeV in mass, due to poor mass resolution





$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

After all selections

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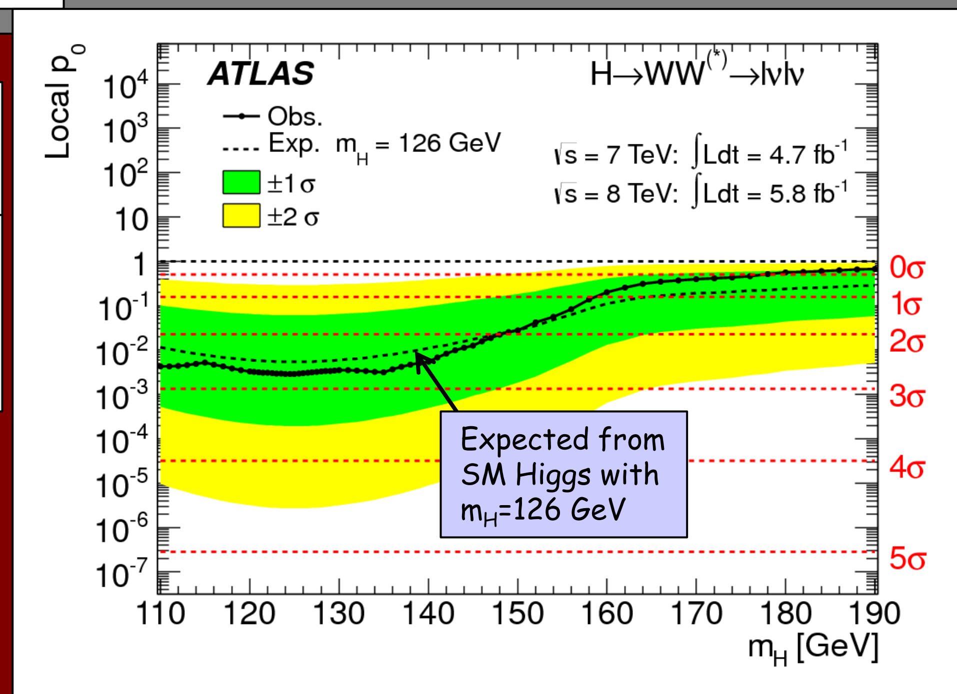
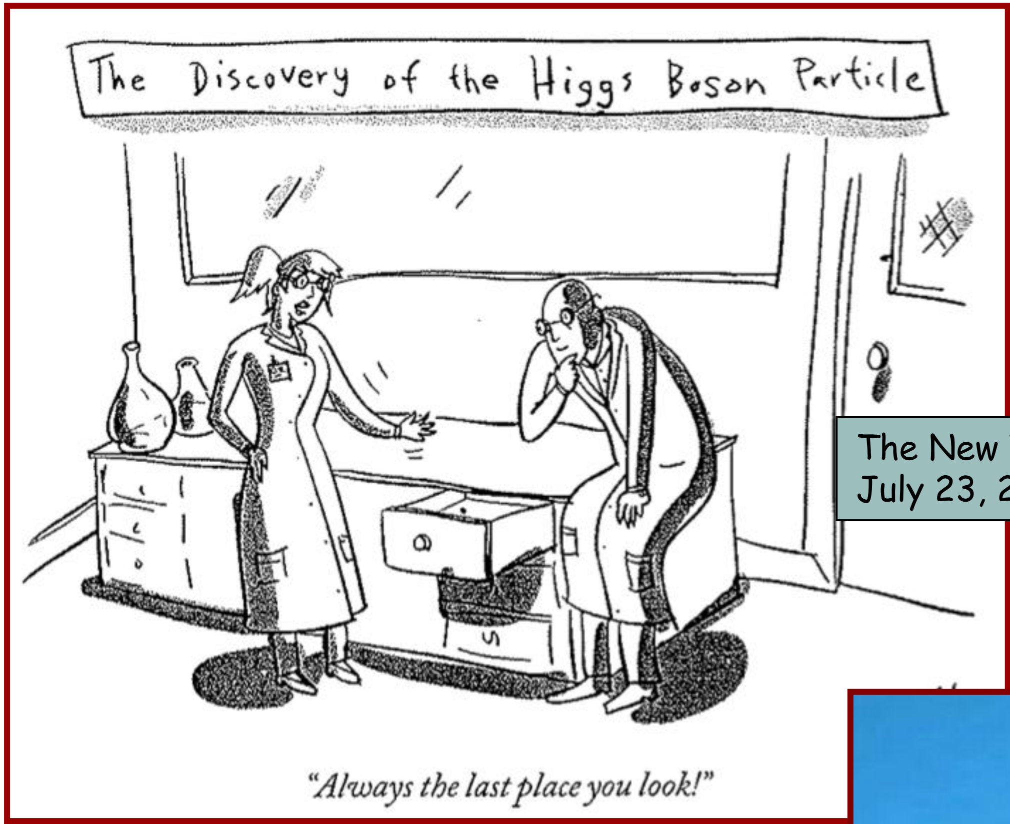
Broad excess extending over > 50 GeV in mass, due to poor mass resolution

Compatible with expectation from a SM Higgs signal of m_H~ 126 GeV

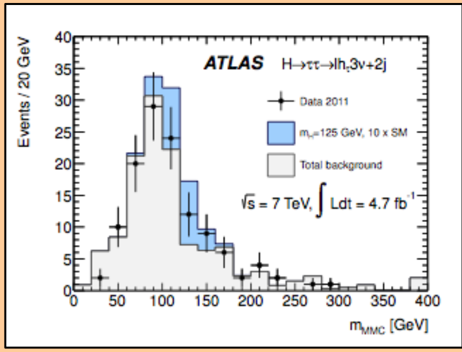


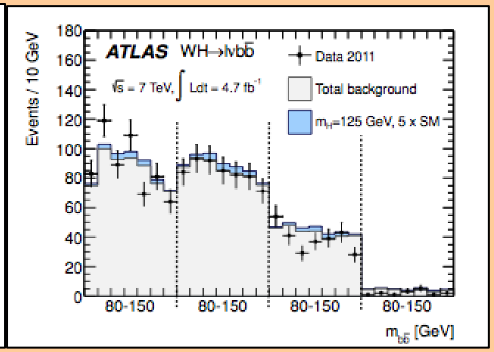
Intermezzo …

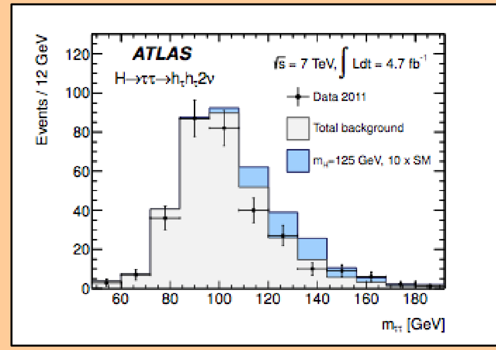


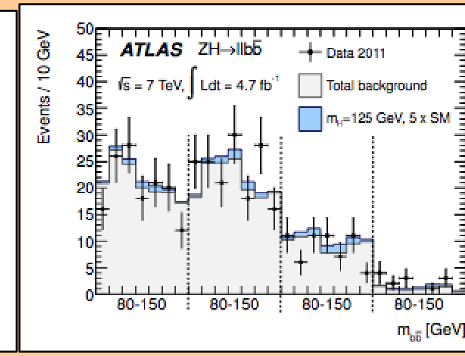
"Always the last place you look!"

The New Yorker, July 23, 2012



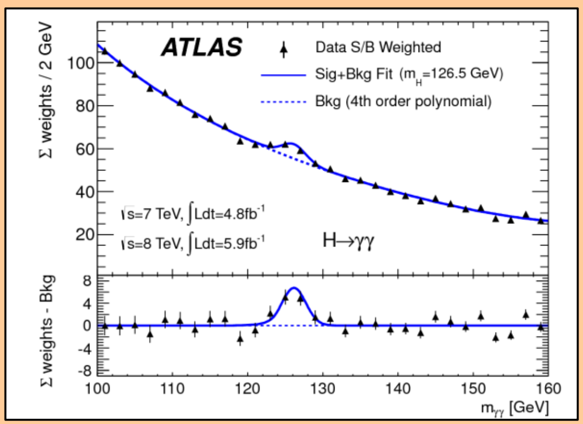


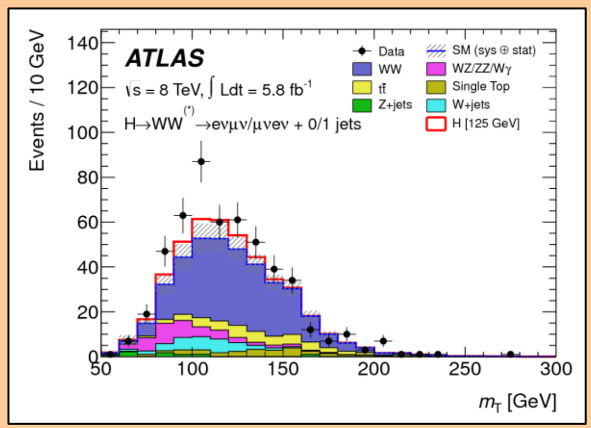


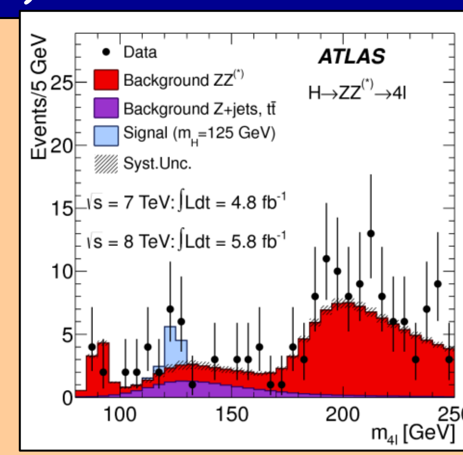


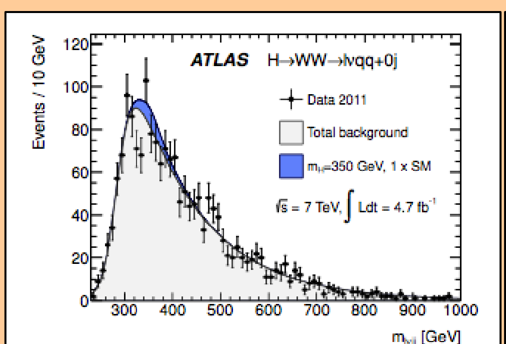
Combining all channels together:

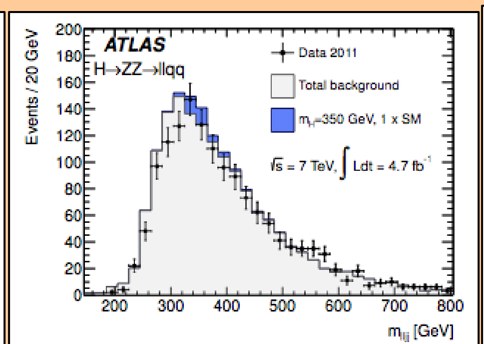
- H→ γγ, 4l, lνlν: full 2011 and July 2012 data (~ 10.7 fb^{-1}); improved analyses
- all other channels (H→ ττ, WH→ lνbb, ZH→ llbb, ZH→ ννbb, ZZ → llνν, H→ ZZ → llqq; H→ WW→lνqq): full 2011 dataset (up to 4.9 fb^{-1})

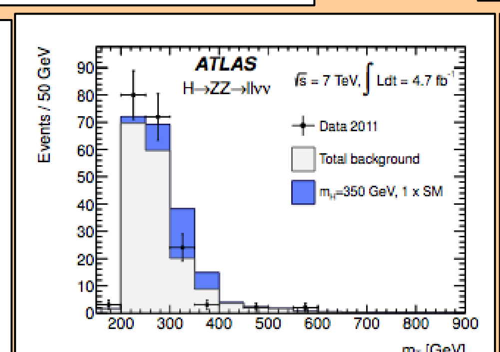


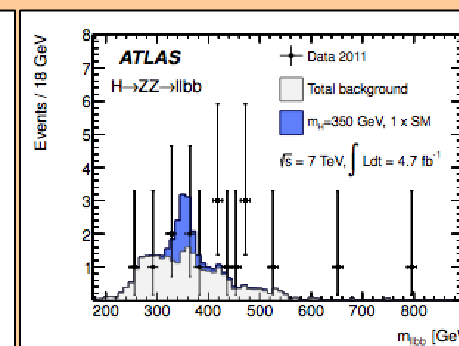




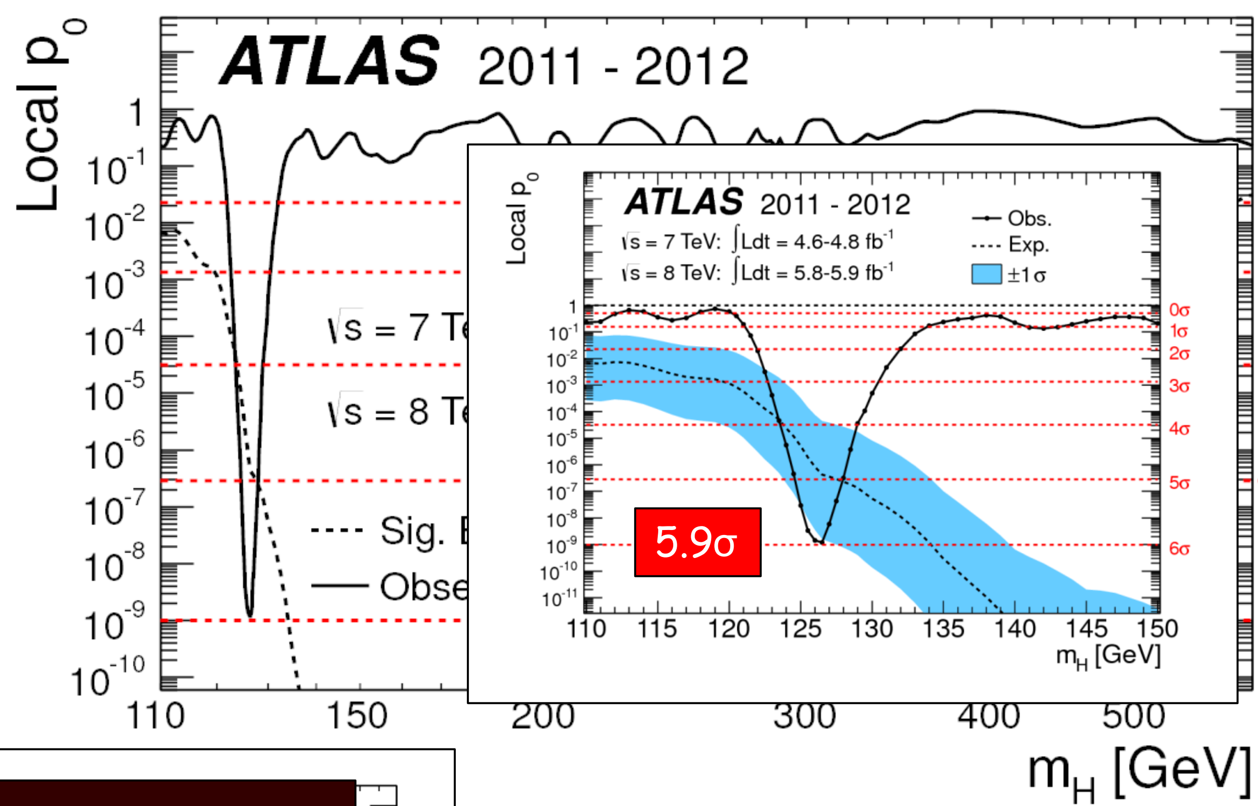


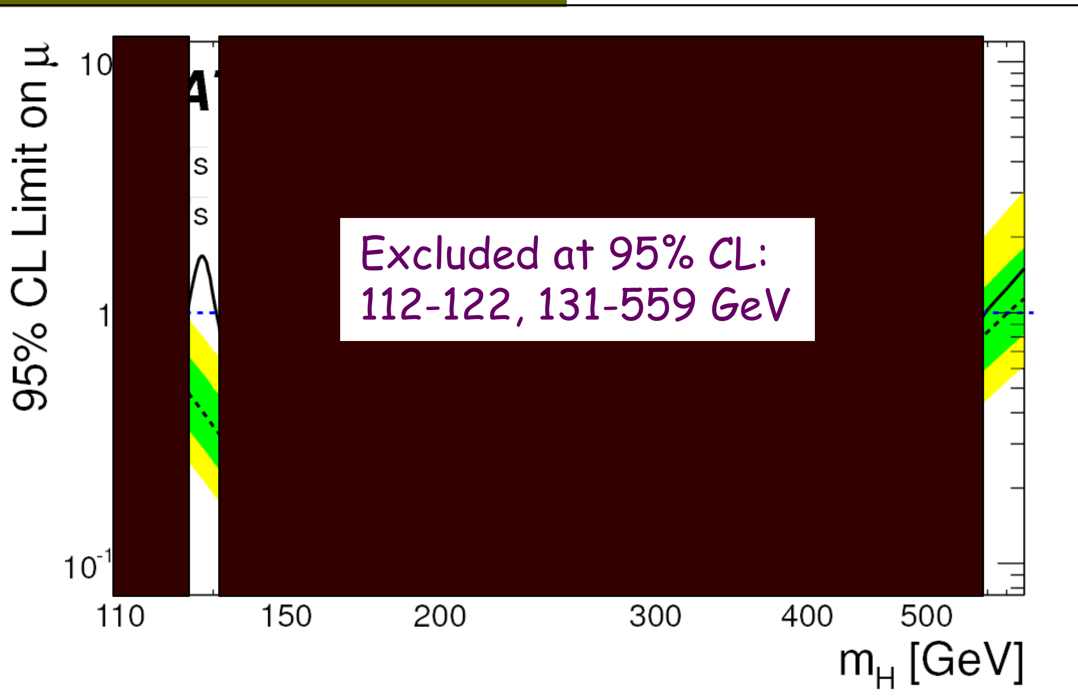






The excess





Excluded at 95% CL:
112-122, 131-559 GeV

Max excess observed at

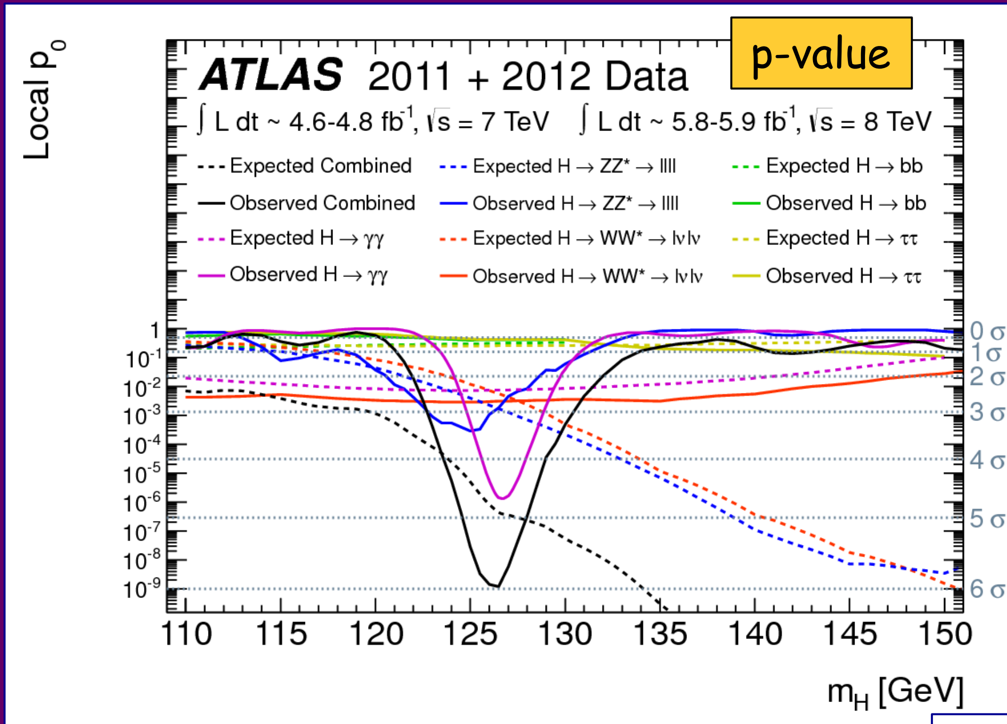
m_H = 126.5 GeV

Local significance 5.9 σ

Probability of B fluctuation

1.7×10^{-9}

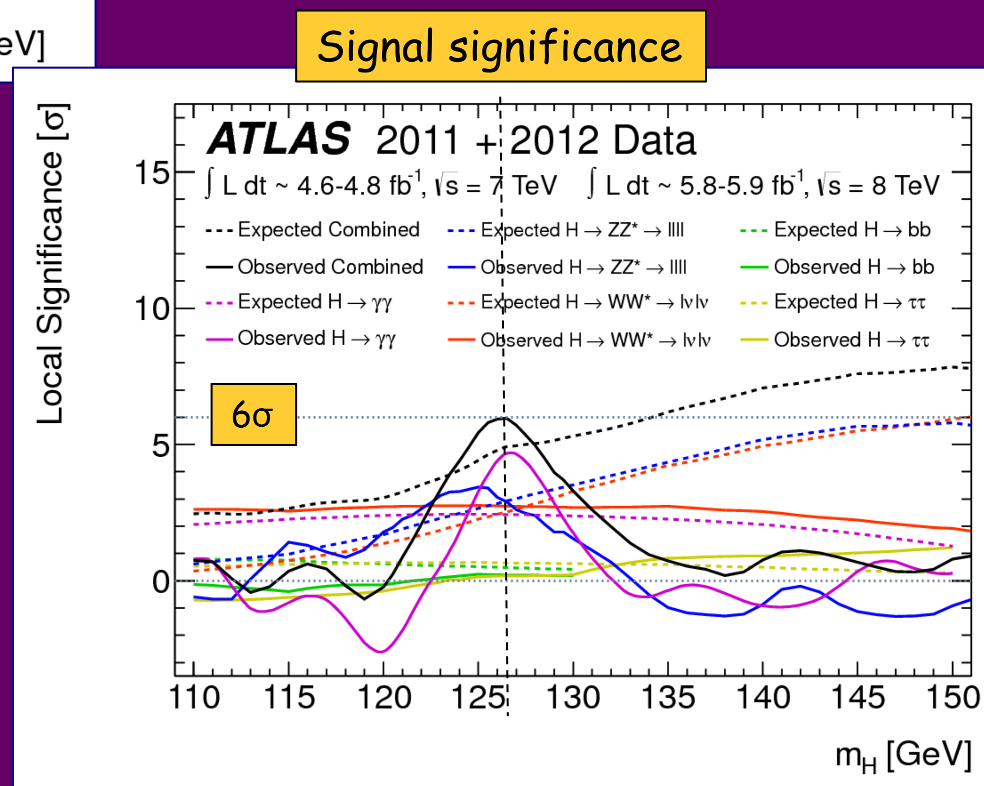
Global significance: ~ 5.2 σ



The excess: breakdown by channels

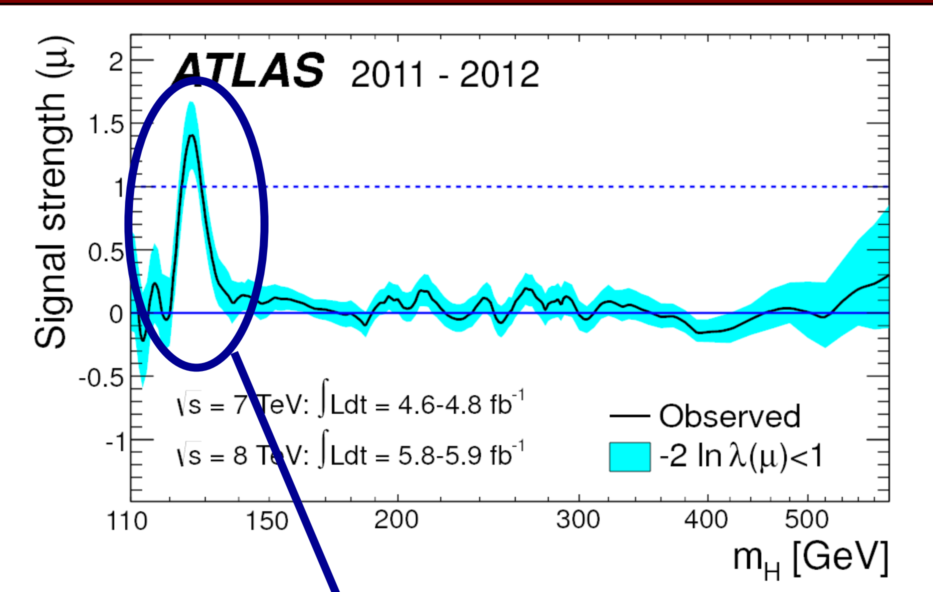
Channel	m_H of max significance	local significance obs. (exp. SM H)
H→ γγ	126.5 GeV	4.5 σ (2.5)
H→ lνlν	125 GeV	2.8 σ (2.3)
H→ 4l	125 GeV	3.6 σ (2.7)
Combined	126.5 GeV	6.0 σ (4.9)

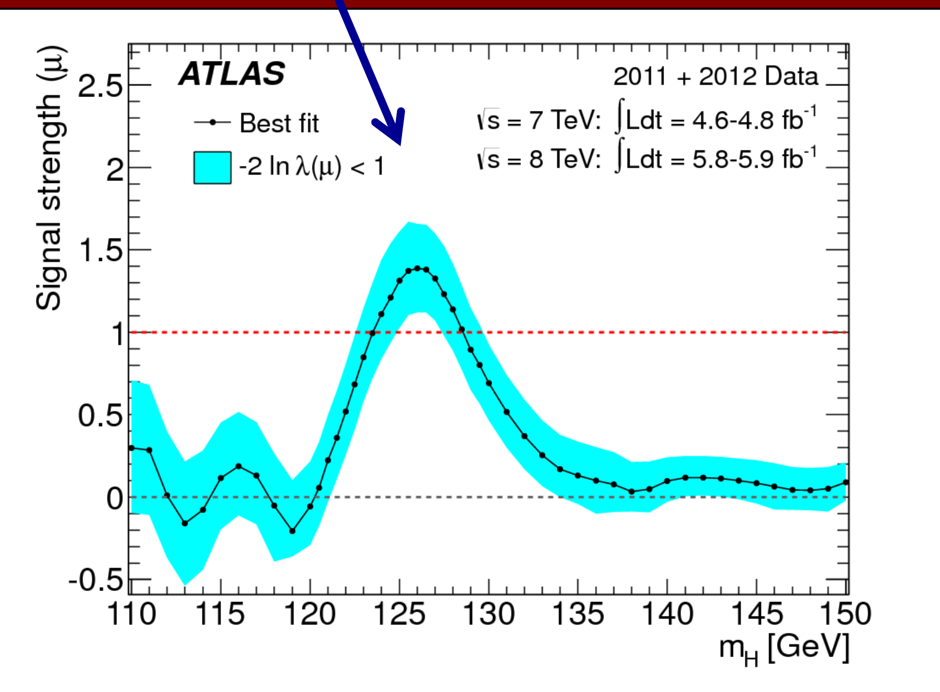
H→ ττ and W/ZH → W/Zbb:
~ no sensitivity (~3xSM cross-section)

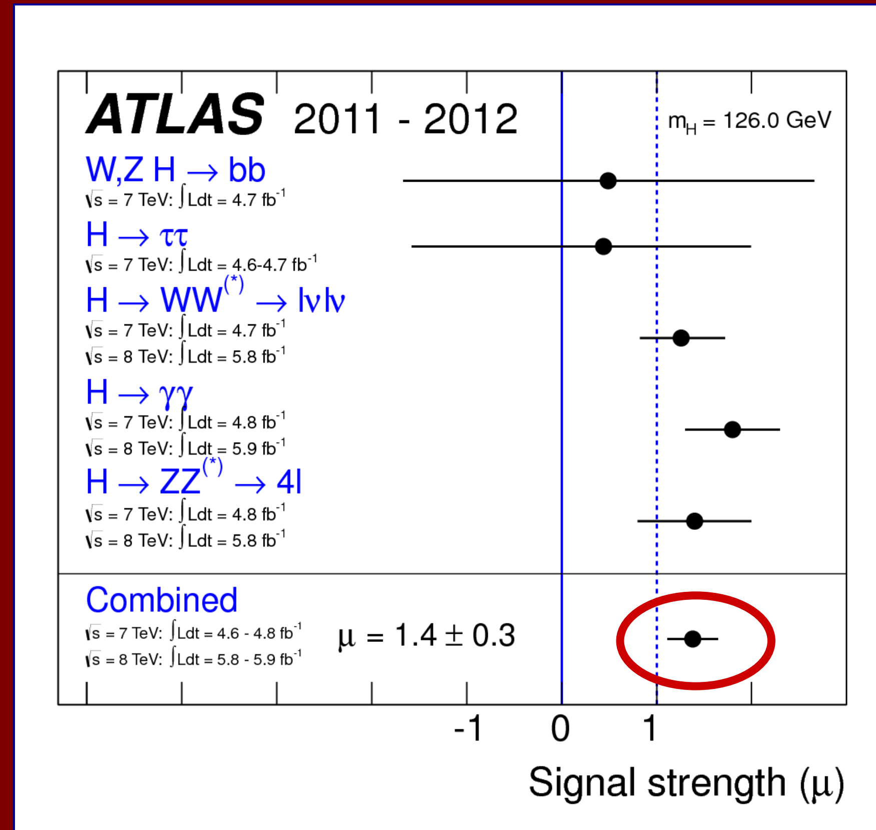


Characterizing the new particle: signal strength

Best-fit signal strength normalized to the SM Higgs expectation at given m_H (μ)





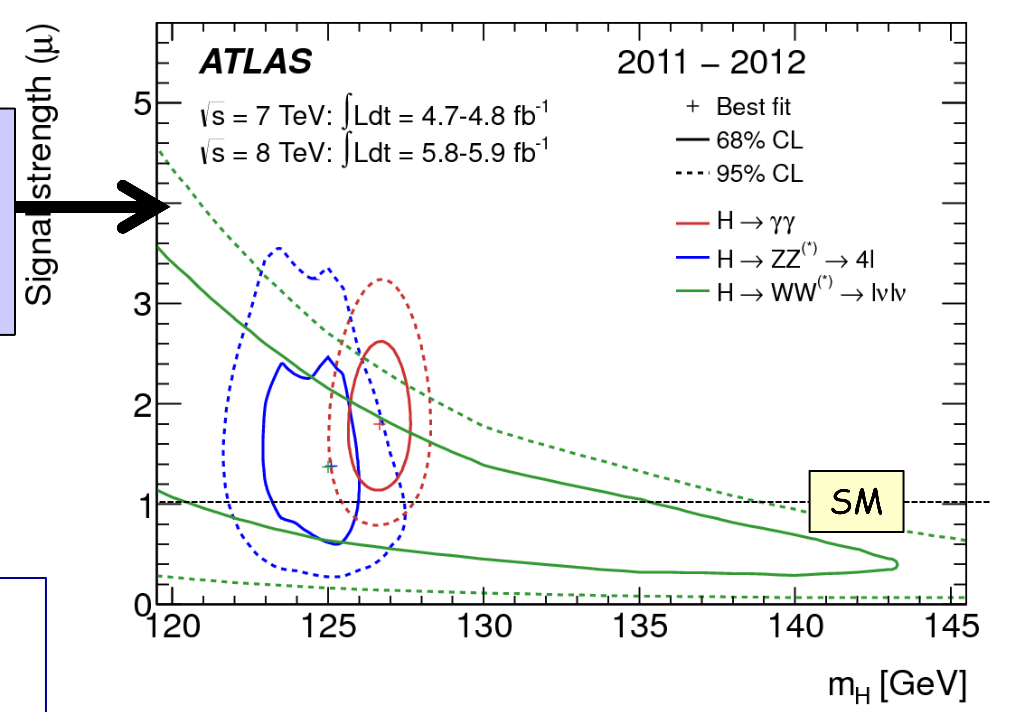


Best-fit value at 126 GeV:
μ = 1.4 ± 0.3

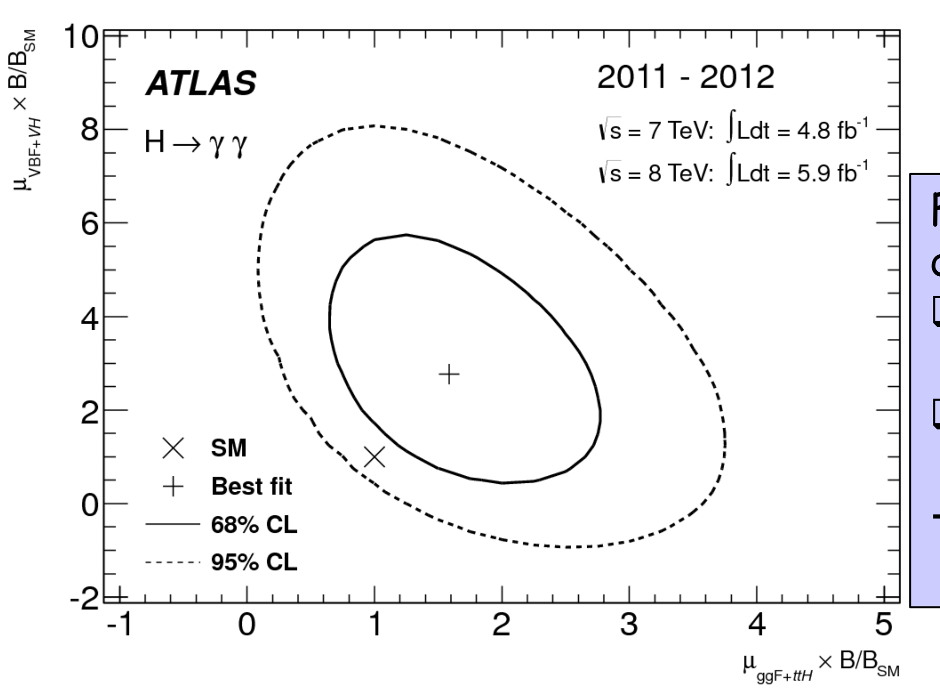
→ good agreement with the expectation for a SM Higgs within the present statistical uncertainty

Characterizing the new particle: mass and couplings

2-dim likelihood fit to signal mass and strength →curves show approximate 68% (full) and 95% (dashed) CL contours (closed contours indicate presence of signal)



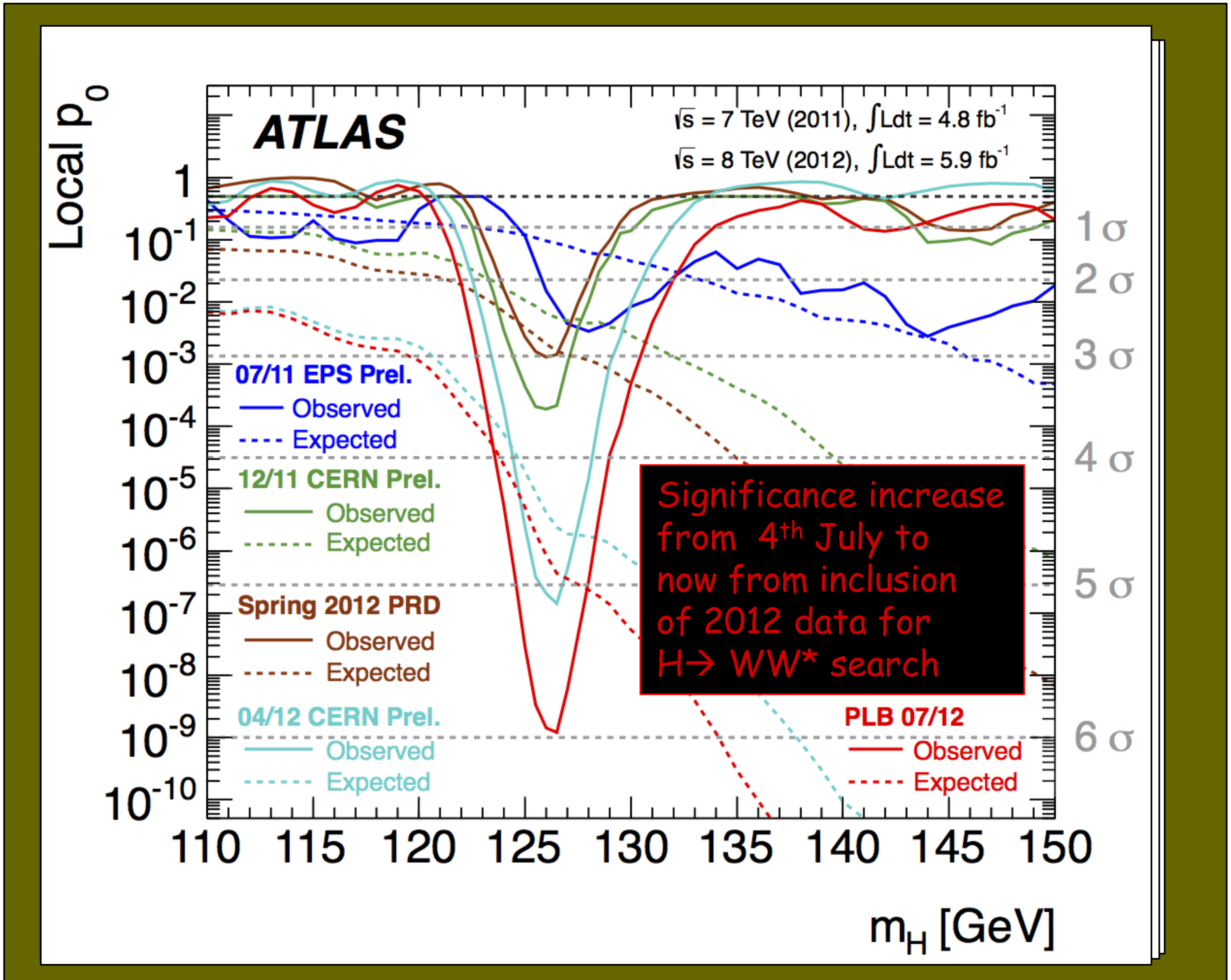
Estimated mass:
$m_H = 126 \pm 0.4\ (stat) \pm 0.4\ (syst)$ GeV



Fitting γγ data in various categories to constrain different production modes grouped as:
- ❑ gg-fusion and ttH (involving coupling to top)
  → extract $\mu_{ggF+ttH}$
- ❑ VBF and W/ZH (involving coupling to W/Z)
  → extract μ_{VBF+VH}

→ results consistent with SM expectation to ~ 1.5 σ

Evolution of the excess with time



Are we sure we carefully looked at all backgrounds ?

http://www.wordle.net/

The next steps …

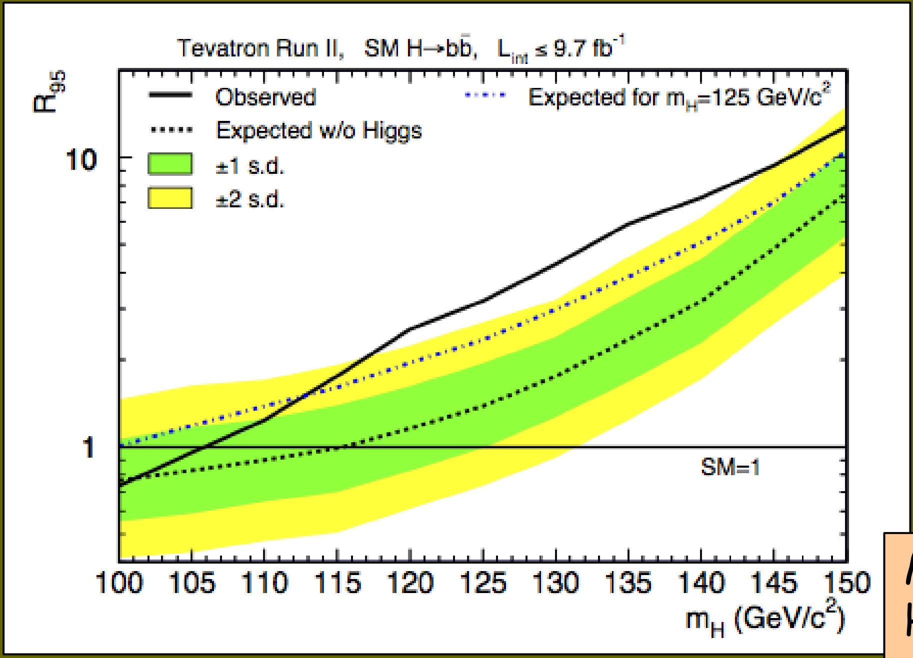
MORE DATA will be essential to:

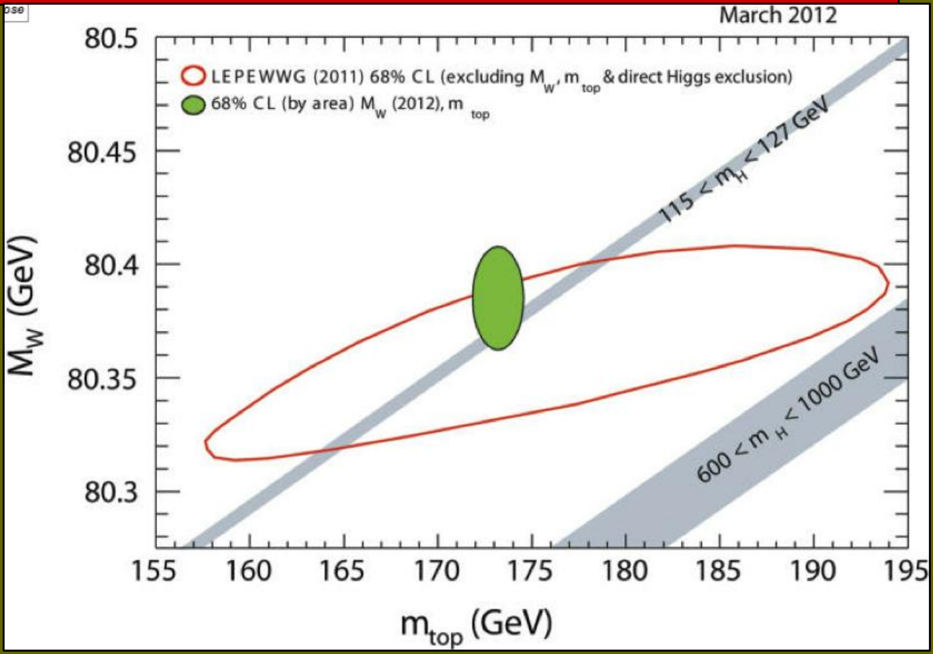
- Establish the observation in more channels (ττ, bb, more exclusive topologies ..)
- Measure the nature and properties of the new particle → is it a SM Higgs ?
- Why is it so light ? What stabilizes its mass (SUSY ? Other new physics ?) ?
- Does this "Higgs" do the job of regularizing the $V_L V_L$ scattering at high mass ?

End 2012: assuming ~30 fb^{-1} (~25 fb^{-1} 8 TeV + 5 fb^{-1} 7 TeV) expect from a SM Higgs:

- 4-5 σ from each of H→ γγ, H→ lvlv, H→ 4l
- ~ 3 σ from H→ ττ and ~ 3 σ from W/ZH → W/Z bb (see Tevatron !)
- Separation of some CP-spin states (0^-, 2) may be reached at the 2-3 σ level

The Tevatron legacy





M_W dominates internal consistency tests of SM. Hard for LHC to improve on Tevatron superb precision (16 MeV !) → Tevatron will contribute to full picture still for a long time

Further ahead: present LHC upgrade plans

ATLAS

2009		✧ LHC startup, $\sqrt{s}$ = 900 GeV	
2010			
2011		$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns	
2012			~20-25 fb^{-1}
2013	LS1	Go to design energy, nominal luminosity (**Phase-0**)	
2014			
2015			
2016		$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns	
2017			~75-100 fb^{-1}
2018	LS2	Injector and LHC **Phase-1** upgrade to full design luminosity	
2019			
2020		$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns	
2021			~350 fb^{-1}
2022	LS3	HL-LHC **Phase-2** upgrade, IR, crab cavities?	
2023			

2030?		$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity leveling	~3000 fb^{-1}

New Pixel B-layer
+ consolidation

New Muon small wheels
FTK, LVL1 Trigger

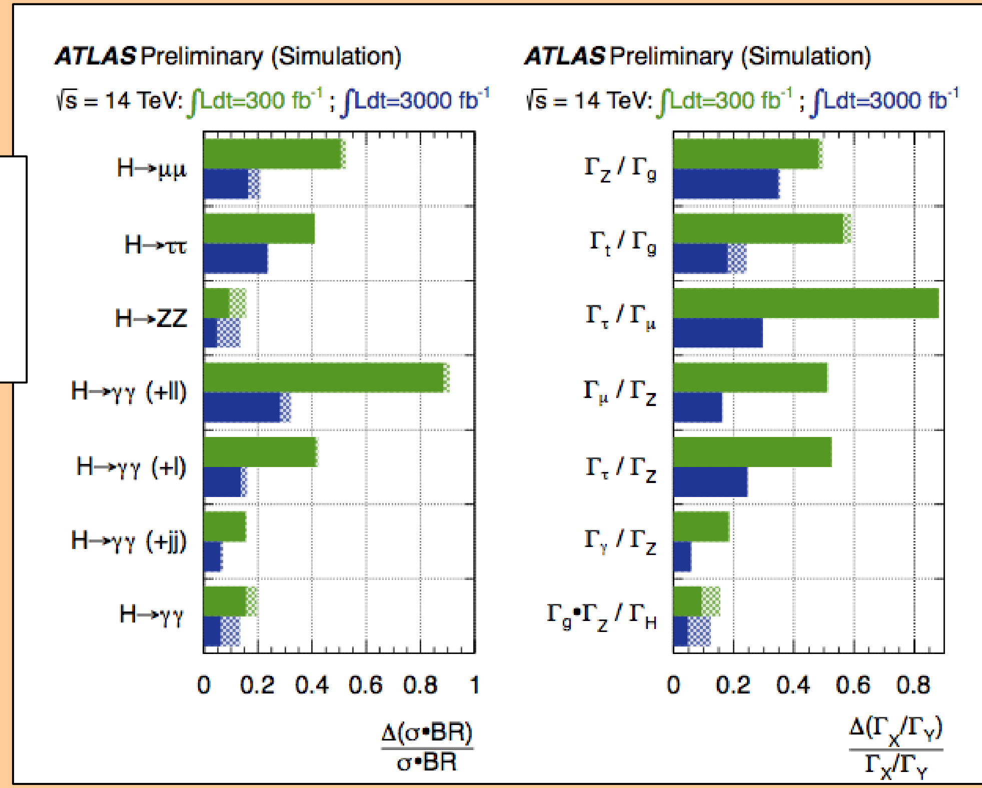
New tracker

$\sqrt{s}$ ~ 14 TeV

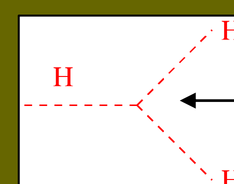
Spin/CP can be determined at > 5σ with 300 fb^{-1} (Phase-1 upgrade)

Ratios of couplings can be measured with typical precision 20-50% with ~ 300 fb^{-1} (Phase-1 upgrade) and 5-30% with 3000 fb^{-1} (Phase-2 upgrade)

H → μμ (rare) decay reaches 6σ with 3000 fb^{-1}



Higgs self-couplings: ~ 3σ per experiment expected from HH → bbγγ channel with 3000 fb^{-1} (Phase-2 upgrade); HH→ bbττ also promising



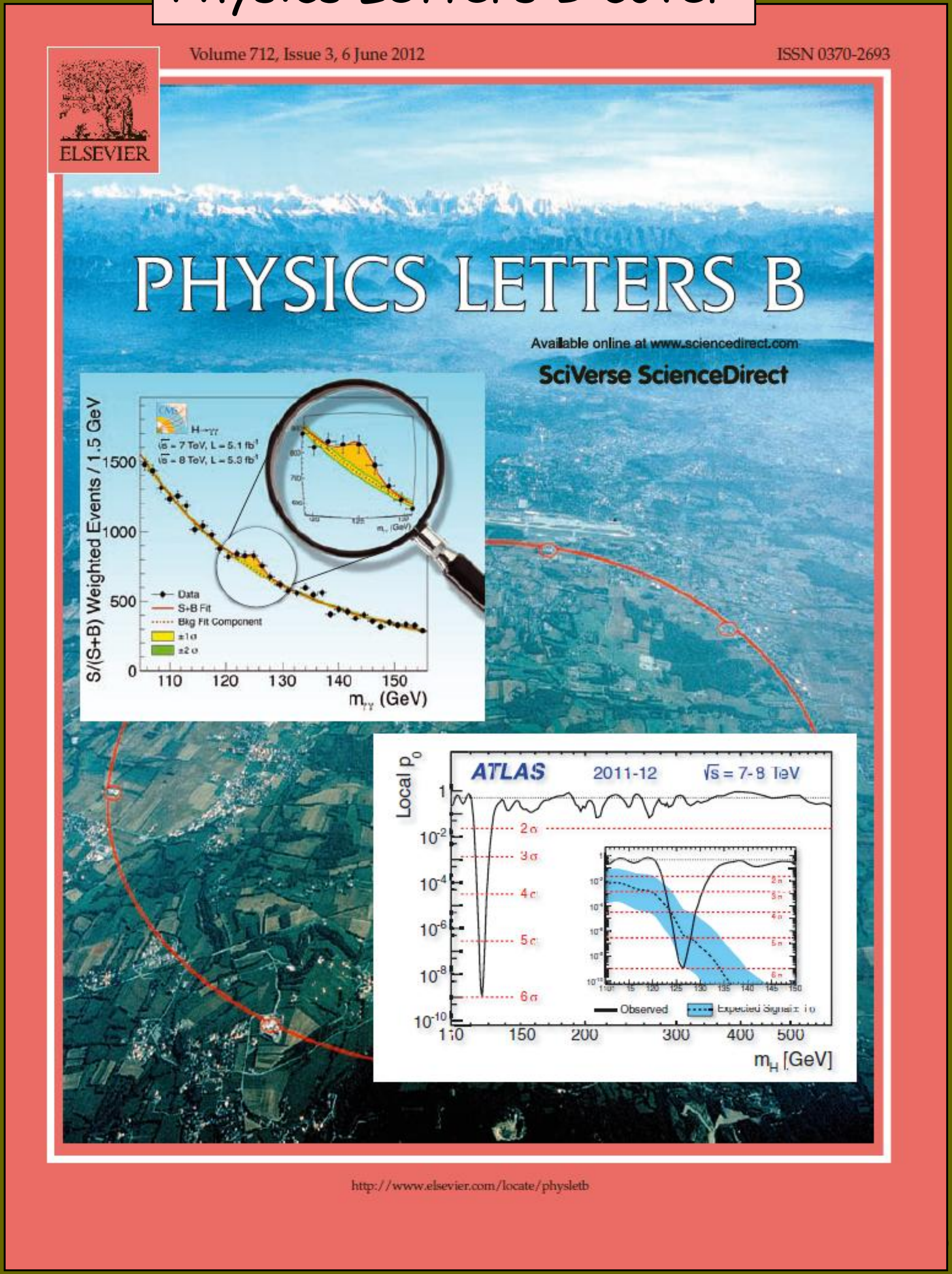
~ λv

$m_H^2 = 2\lambda v^2$

Note: physics potential of LHC upgrade is much more than just Higgs

Conclusions

Physics Letters B cover



Superb performance and accomplishments of the LHC accelerator, experiments and wLCG Computing Grid in less than 3 years of operation.

ATLAS recorded ~5.2 fb^{-1} of pp data at $\sqrt{s}$ =7 TeV in 2011 and ~12 fb^{-1} in 2012 at $\sqrt{s}$ =8 TeV

The whole experiment works very well in all its components, from smooth and efficient operation of the detector, trigger and computing to the fast delivery of physics results: first results for ICHEP with full 2012 dataset were available less than one week from data-taking, with a fraction of good-quality data used for physics of ~ 90% of the delivered luminosity.

ATLAS huge physics output covered in 185 papers published/submitted (not only Higgs !)

In July 2012 ATLAS has reported the discovery of a new Higgs-like boson:

- ❑ with significance ~6σ, driven by H→ γγ, 4l, with contributions also from H→ lνlν
- ❑ signal strength: 1.4± 0.3 of the Standard Model Higgs expectation
- ❑ mass: 126 ± 0.4 (stat) ± 0.4 (syst) GeV

If it is a SM Higgs boson, it's very kind of Nature to have chosen this mass
→ accessible at LHC in γγ, ZZ*→ 4l, WW*→ lνlν, bb, ττ , and (with upgrades) μμ

The era of precise "Higgs measurements" (and more ..) has started
→ this is just the BEGINNING !

These accomplishments are the results of more than 20 years of talented work and extreme dedication by the ATLAS Collaboration, with the continuous support of the Funding Agencies

US: ~ 630 active scientists
~ 260 PhD students

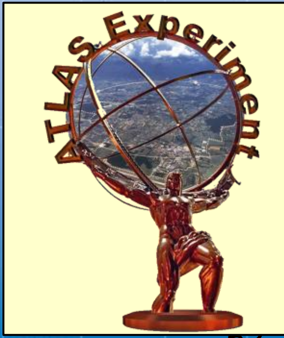
Many thanks to US-ATLAS, DOE and NSF for their fundamental contributions to the success of the experiment in all its components and activities, their efforts, their continuous support, and their major role in present and future ATLAS

Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan

Norway
Poland
Portugal
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR

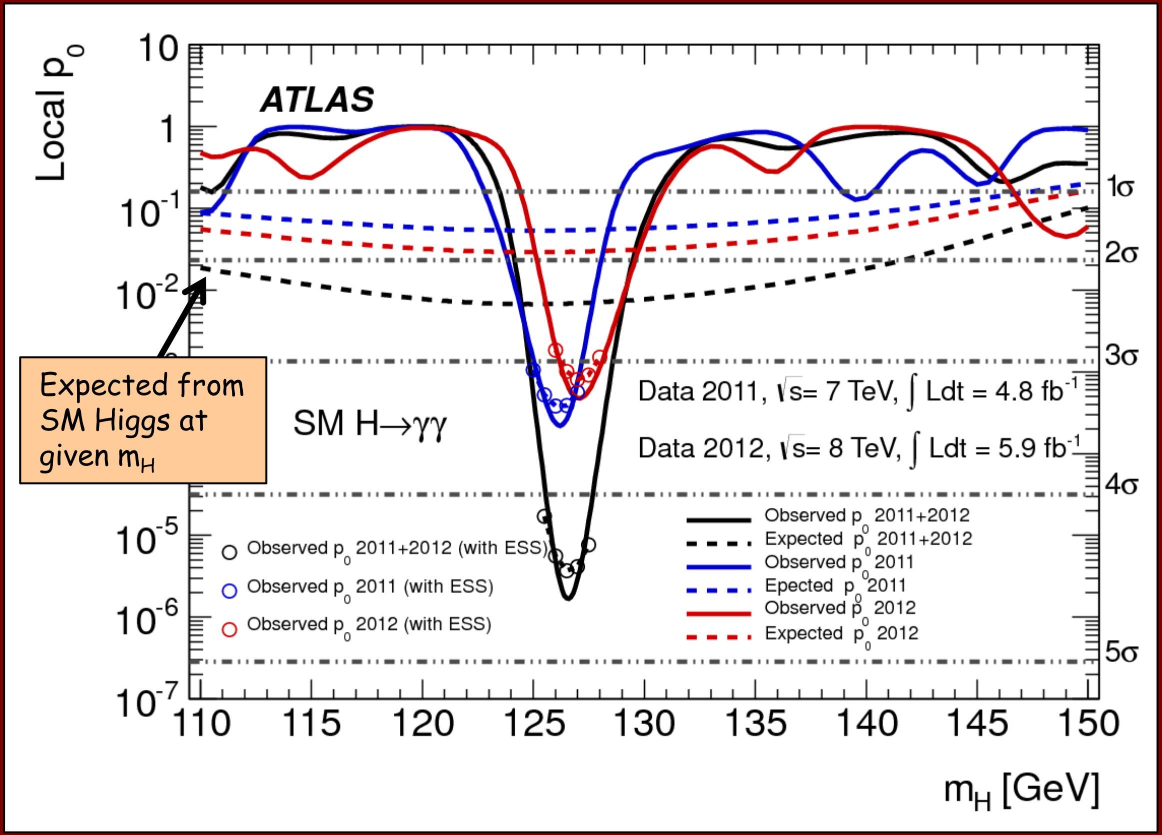
More in general, these accomplishments are the results of the ingenuity, vision and painstaking work of the HEP community (accelerator, instrumentation, computing, physics)

ATLAS Collaboration



SPARES

Consistency of data with background-only expectation



Points indicate impact of 0.6% uncertainty on photon energy scale: ~ 0.1 sigma

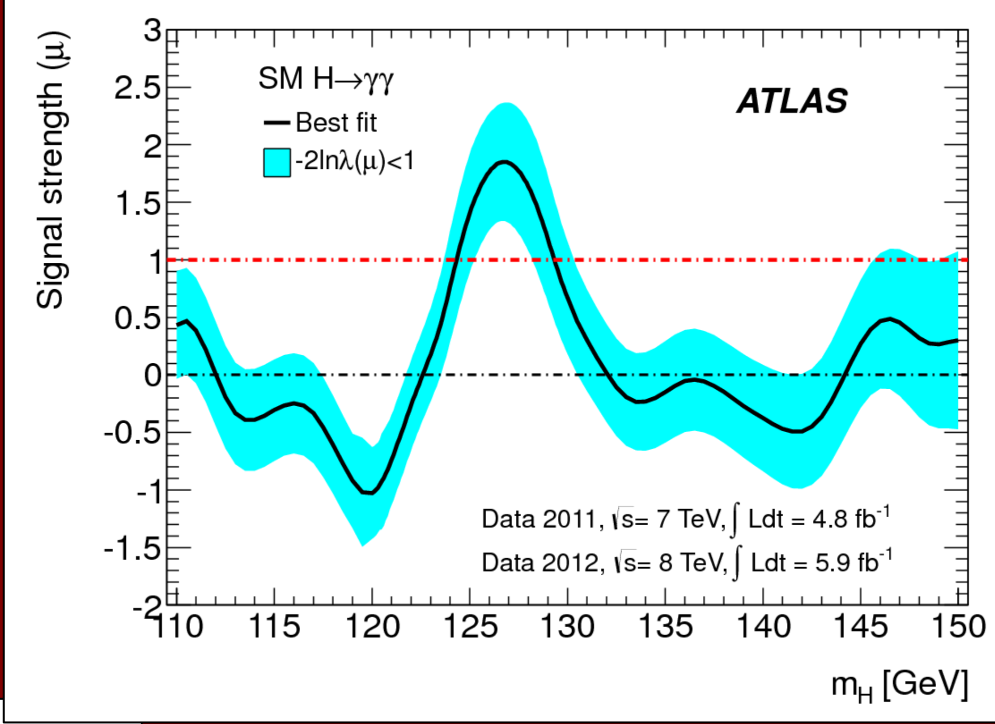
Data sample	m_H of max deviation	local p-value	local significance	expected from SM Higgs
2011	126 GeV	3×10^{-4}	3.5 σ	1.6 σ
2012	127 GeV	3×10^{-4}	3.4 σ	1.9 σ
2011+2012	126.5 GeV	2×10^{-6}	4.5 σ	2.4 σ

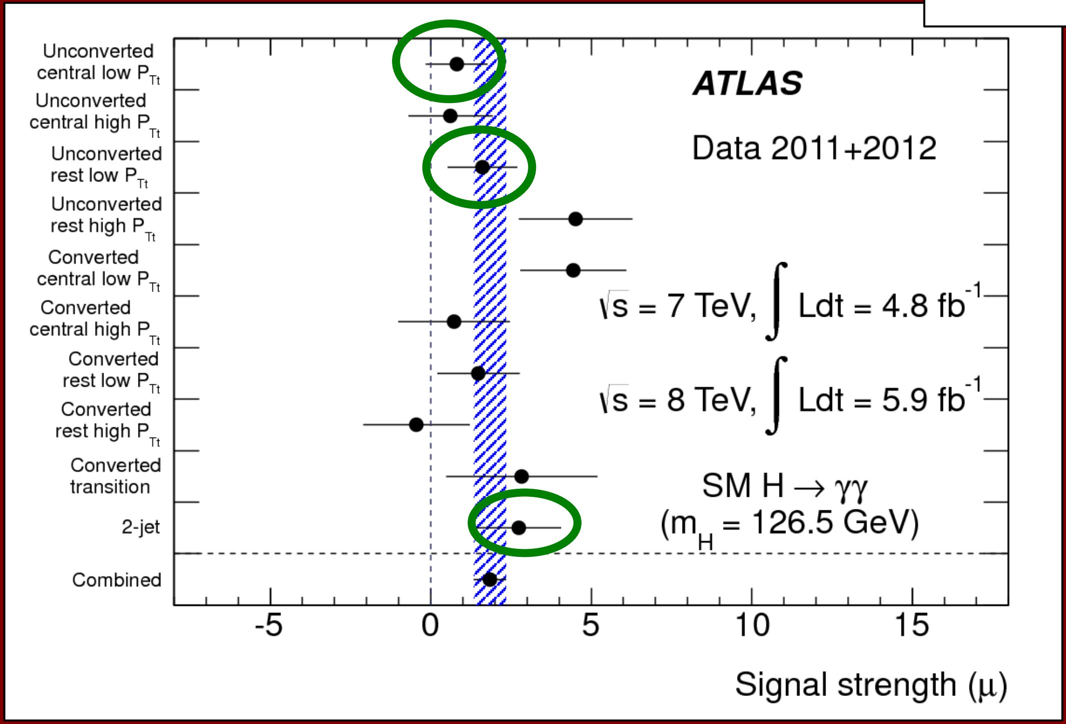
Global 2011+2012 (including LEE over 110-150 GeV range): 3.6 σ

Fitted signal strength

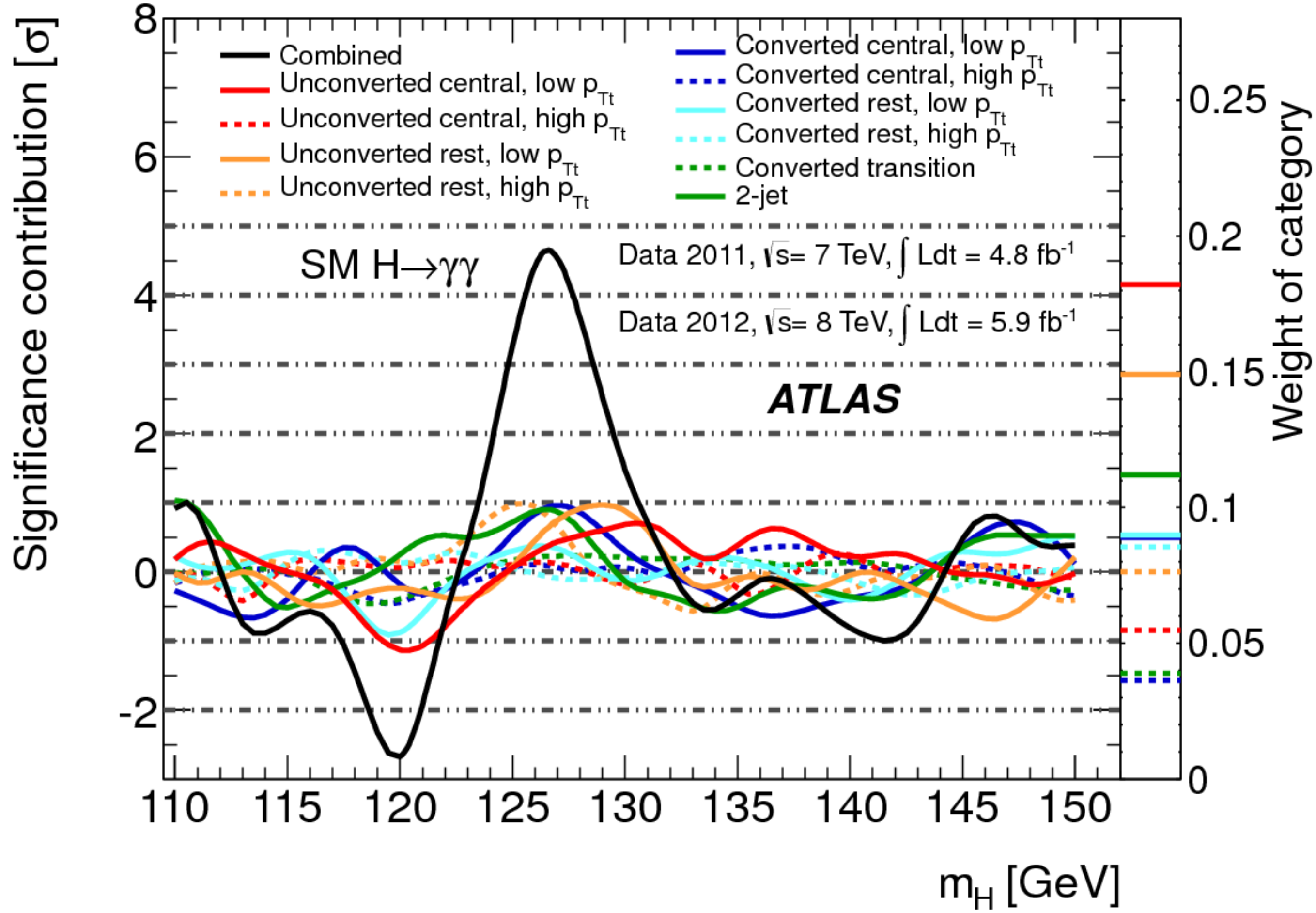
Normalized to SM Higgs expectation at given m_H (μ)

Best-fit value at 126.5 GeV: μ=1.9 ± 0.5



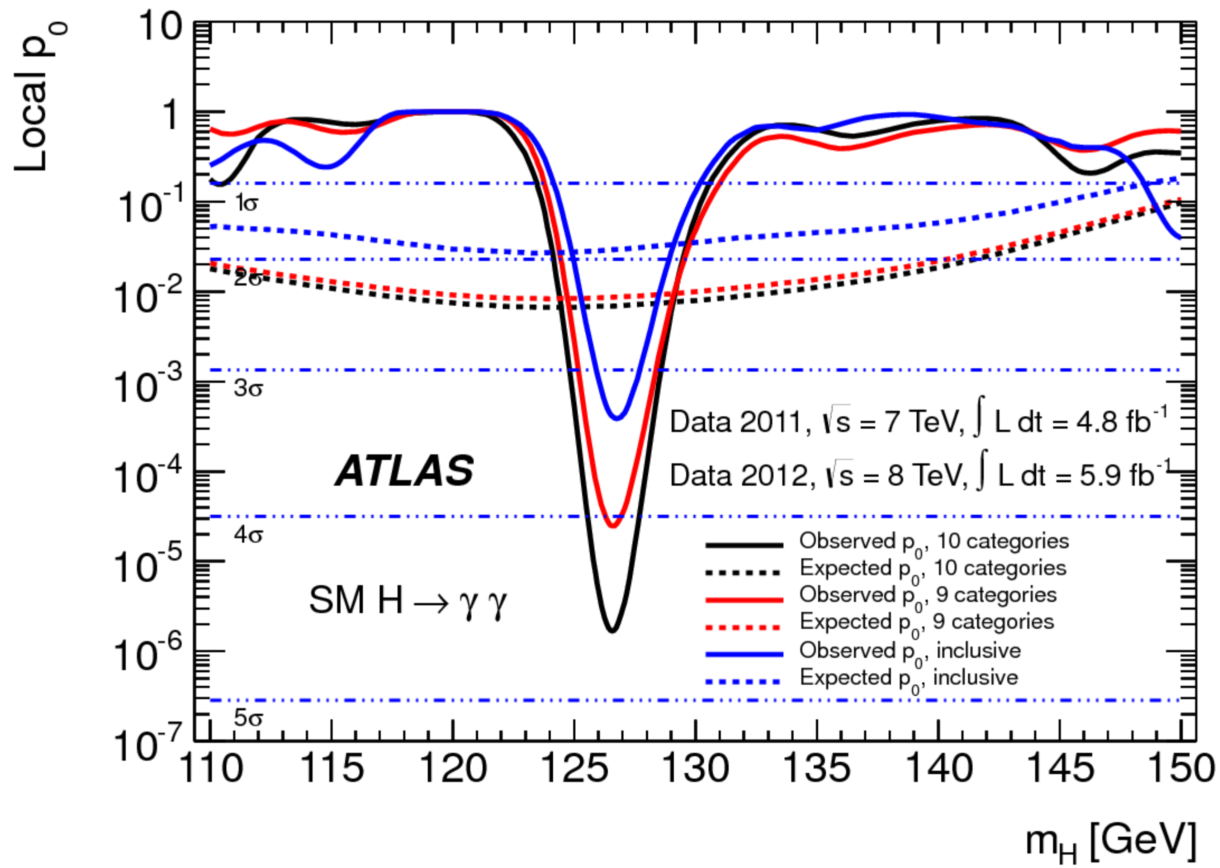


Consistent results from various categories within uncertainties (most sensitive ones indicated)



-2.5 σ downward fluctuation at $m_{\gamma\gamma}$~ 119 GeV

- probability 15% (~1 σ)
- does not affect significance of fitted signal
- unlike "signal" excess does not appear in most significant categories



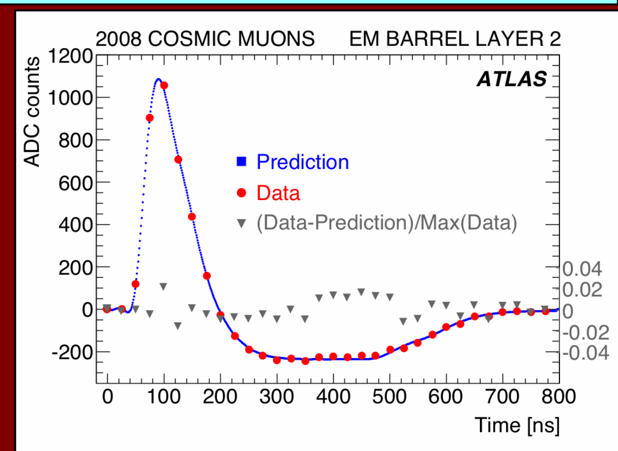
Categories provide ~ 30% gain in sensitivity compared to inclusive analysis.
However, excess remains also with simpler inclusive analysis: ~ 3.5 σ

2jet/VBF category brings ~ 3% gain in expected sensitivity; observed gains in data are 10-15% (both years)
Caveat: 2jet category affected by largest systematics (~ 20% on signal yield)

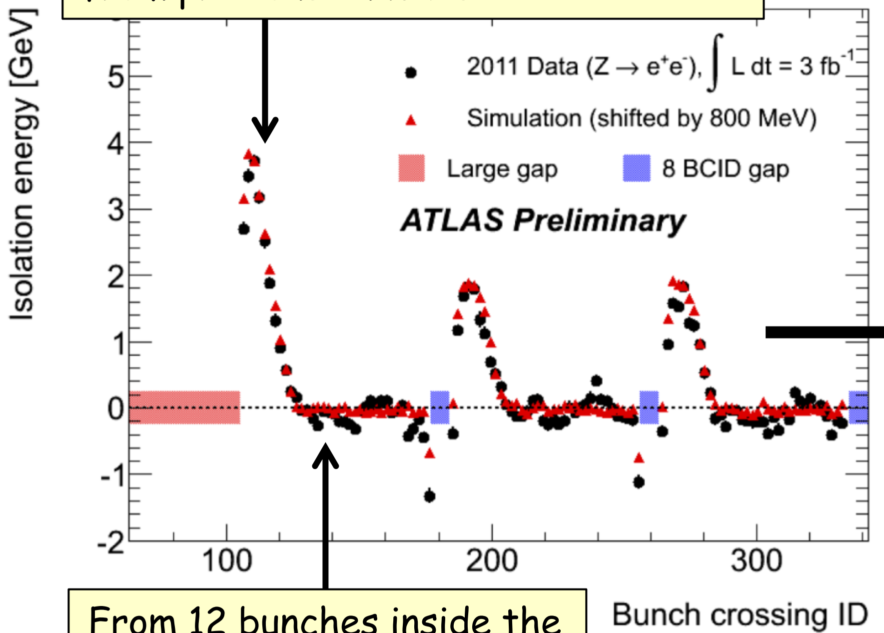
Photon isolation requirement: $E_T < 4$ GeV inside cone $\Delta R < 0.4$ around γ direction.
Pile-up contribution subtracted using an "ambient energy density" event-by-event

If subtraction is not perfect, residual dependence of the isolation energy on the bunch position in the train observed, due to impact of out-of-time pile-up from neighbouring bunches convolved with EM calorimeter pulse shape.

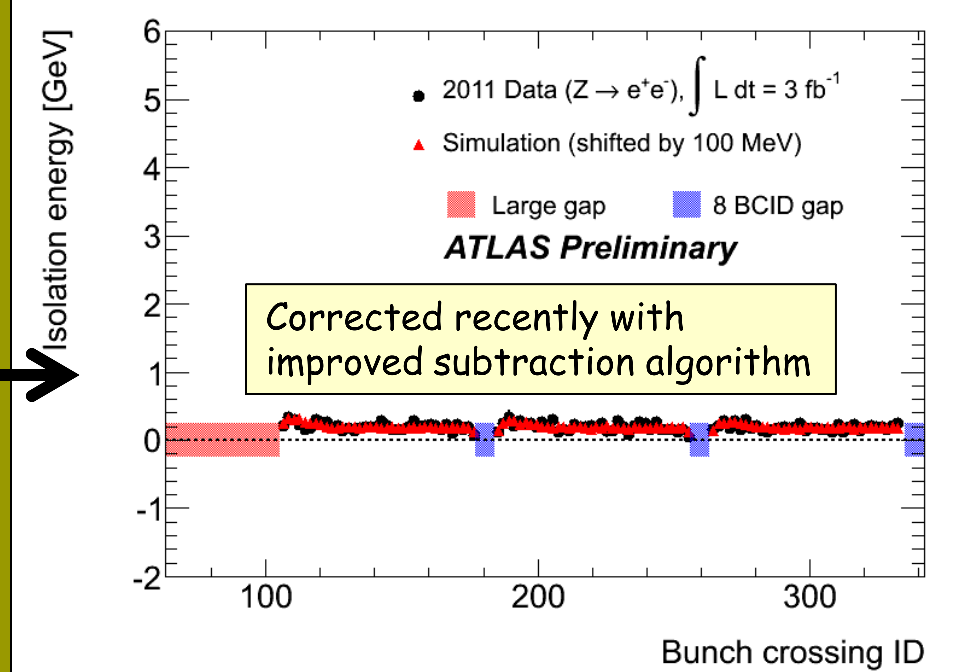
Calorimeter bipolar pulse shape: average pile-up is zero over ~ 600 ns (~12 bunches)



Beginning of the train: no cancellation from previous bunches



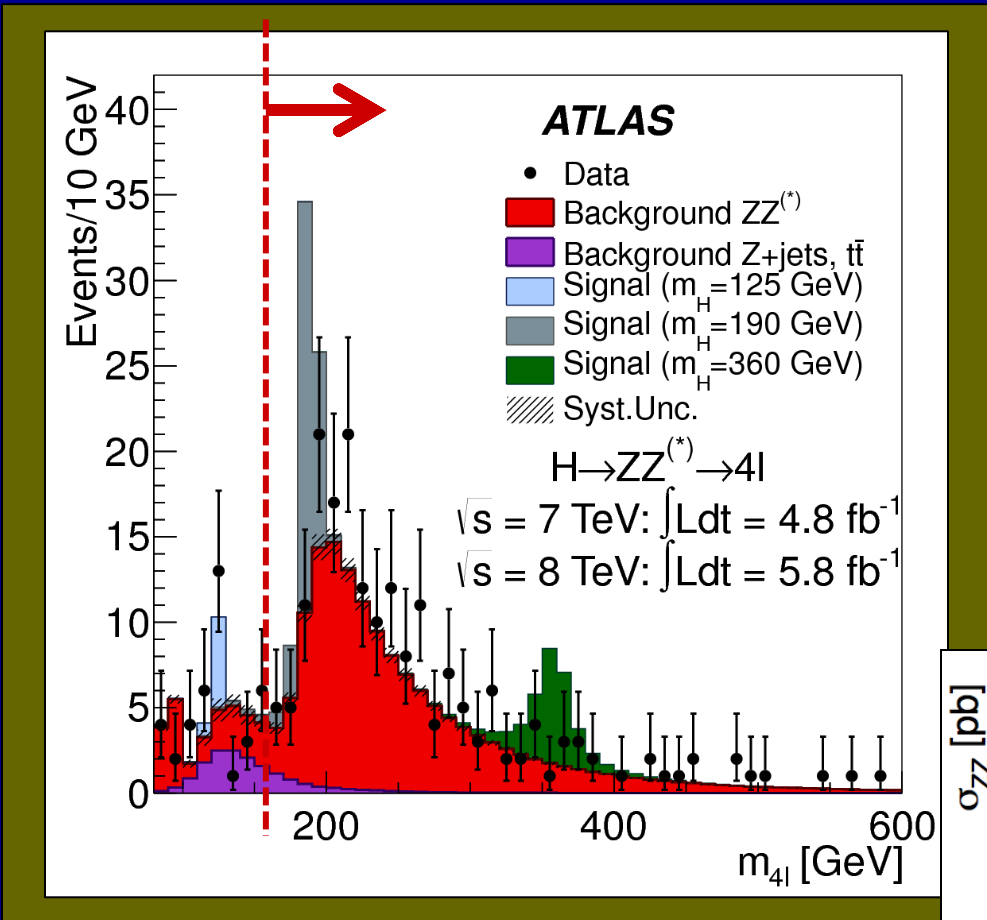
From 12 bunches inside the train: full cancellation



Corrected recently with improved subtraction algorithm

Effect well described by (detailed !) ATLAS simulation

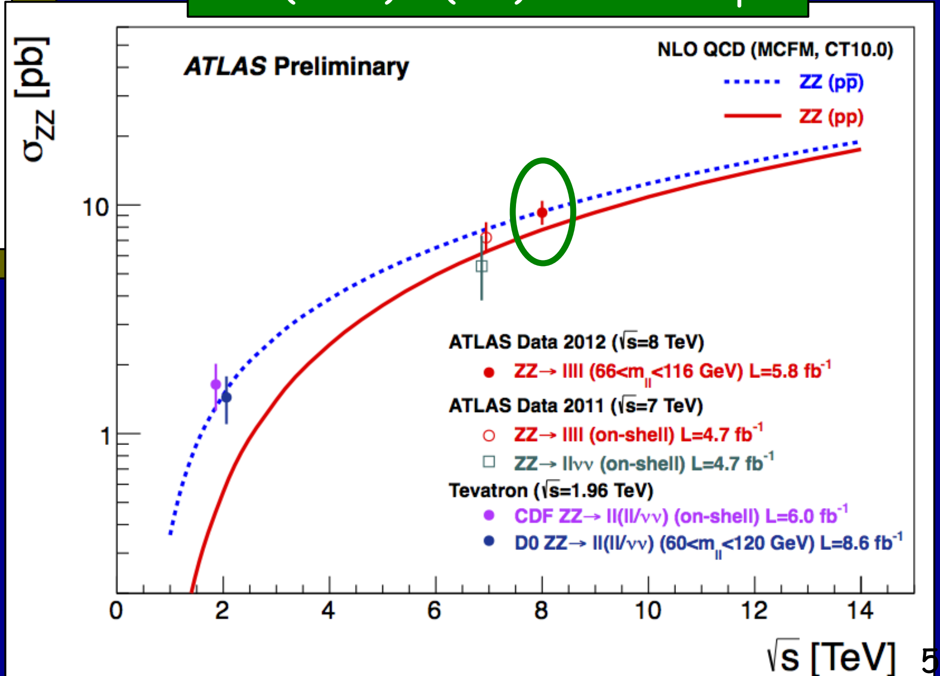
H→ 4l mass spectrum after all selections: 2011+2012 data



m(4l) > 160 GeV
(dominated by ZZ background):
147 ± 11 events expected
191 observed

~ 1.3 times more ZZ events in data than SM prediction → in agreement with measured ZZ cross-section in 4l final states at √s = 8 TeV

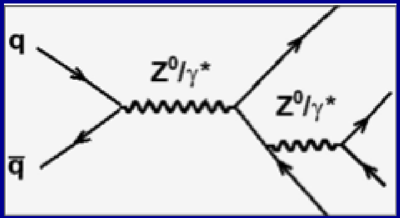
Measured σ (ZZ) = 9.3 ± 1.2 pb
SM (NLO) σ (ZZ) = 7.4± 0.4 pb



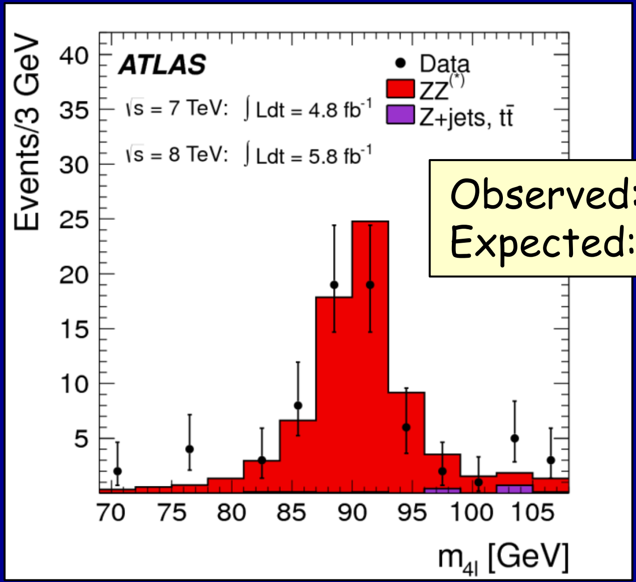
Discrepancy has negligible impact on the low-mass region < 160 GeV
(no change in results if in the fit ZZ is constrained to its uncertainty or left free)

H→ 4l mass spectrum after all selections: 2011+2012 data

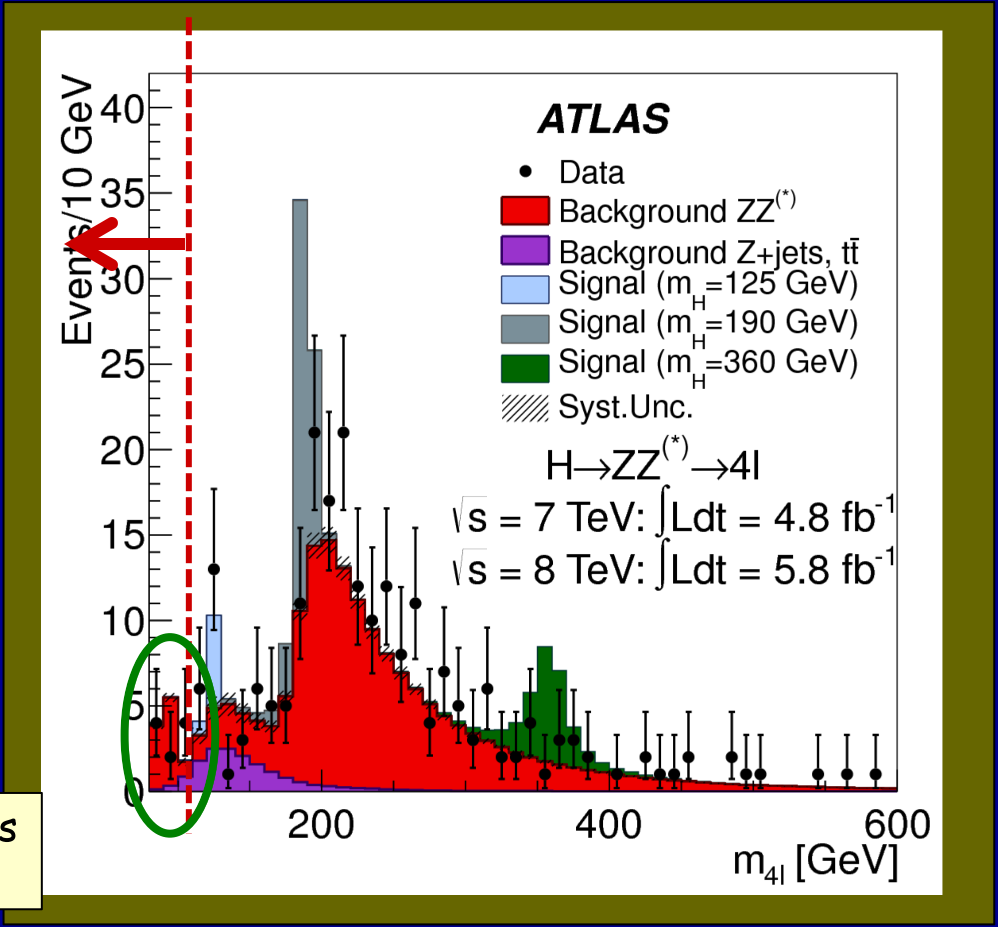
Peak at m(4l) ~ 90 GeV from single-resonant Z→ 4l production

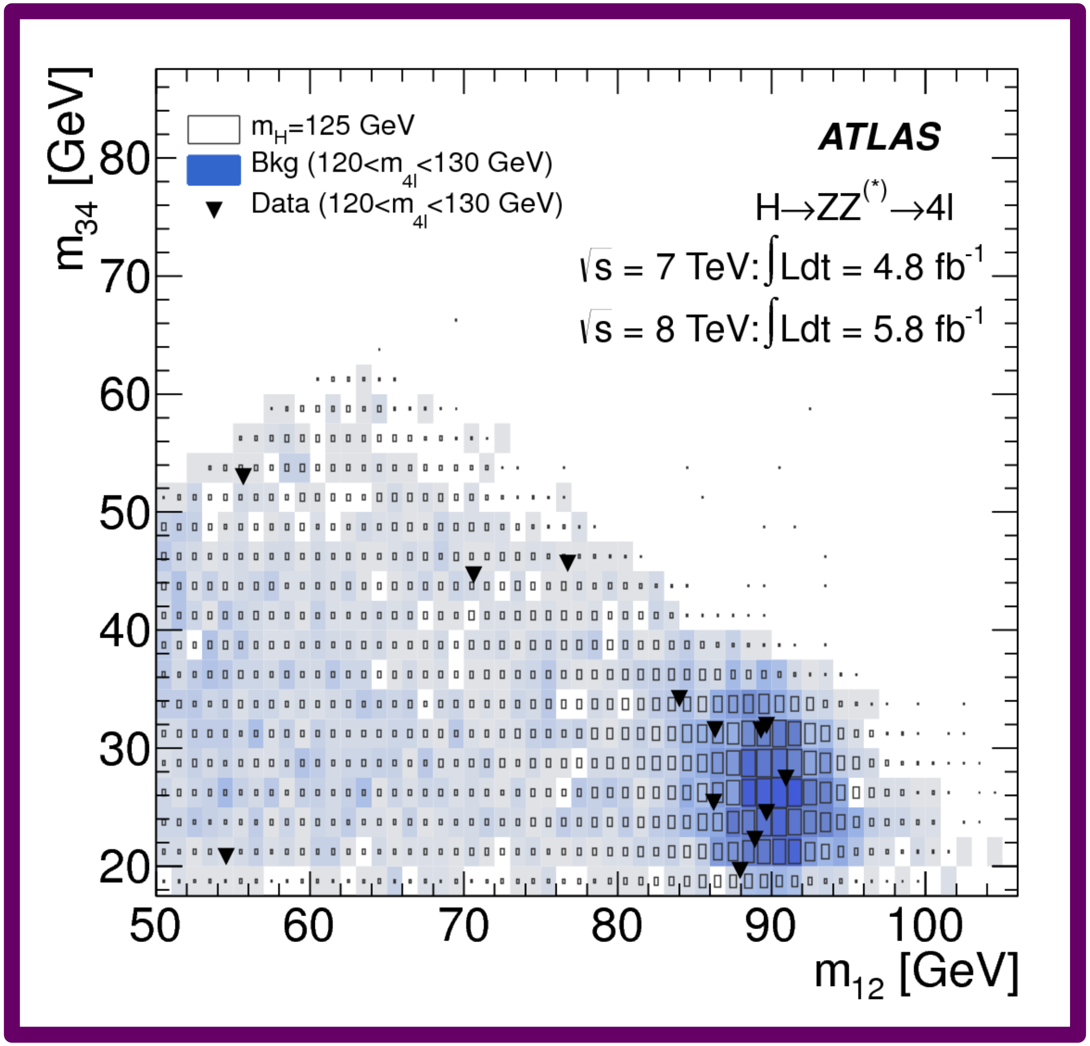


Enhanced by relaxing cuts on m_{12}, m_{34} and $p_T(\mu_4)$



Observed: 57 events
Expected: 65 ± 5



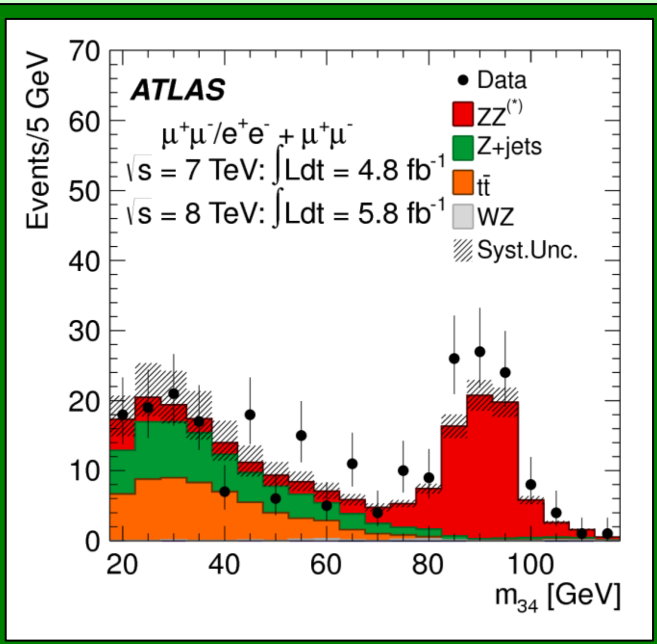

m_H=125 GeV
Bkg (120<m_4l<130 GeV)
Data (120<m_4l<130 GeV)
ATLAS
H→ZZ(*)→4l
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
m34 [GeV]
m12 [GeV]
20
30
40
50
60
70
80
50
60
70
80
90
100

Reducible backgrounds from Z+jets, Zbb, tt giving 2 genuine + 2 fake leptons measured using background-enriched, signal-depleted control regions in data

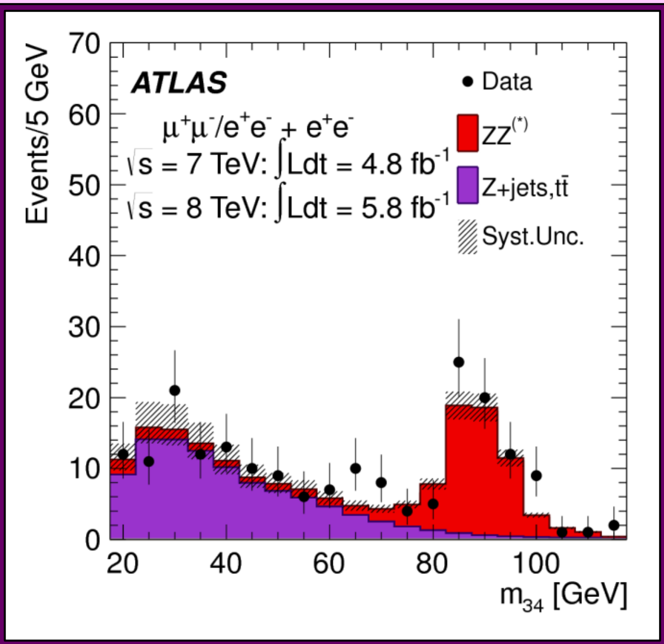
Typical control regions:

- ❑ leading lepton pair (l_1l_2) satisfies all selections
- ❑ sub-leading pair (l_3l_4): no isolation nor impact parameter requirements applied

$l_3l_4 = \mu\mu$ → background dominated by tt and Zbb in low mass region



$l_3l_4 = ee$ → background dominated by Z+jets in low mass region



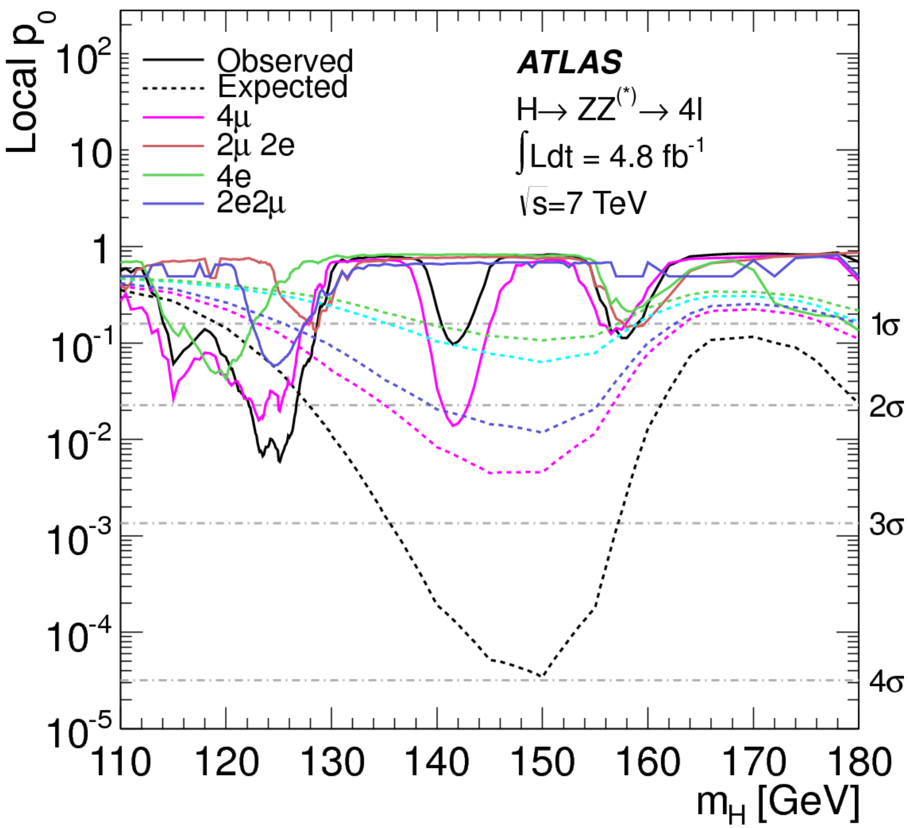
- ❑ Data well described by MC within uncertainties (ZZ excess at high mass …)
- ❑ Samples of Z+"μ" and Z+"e" used to compare efficiencies of isolation and impact parameter cuts between data and MC → good agreement → MC used to estimate background contamination in signal region
- ❑ Several cross-checks made with different control regions → consistent results

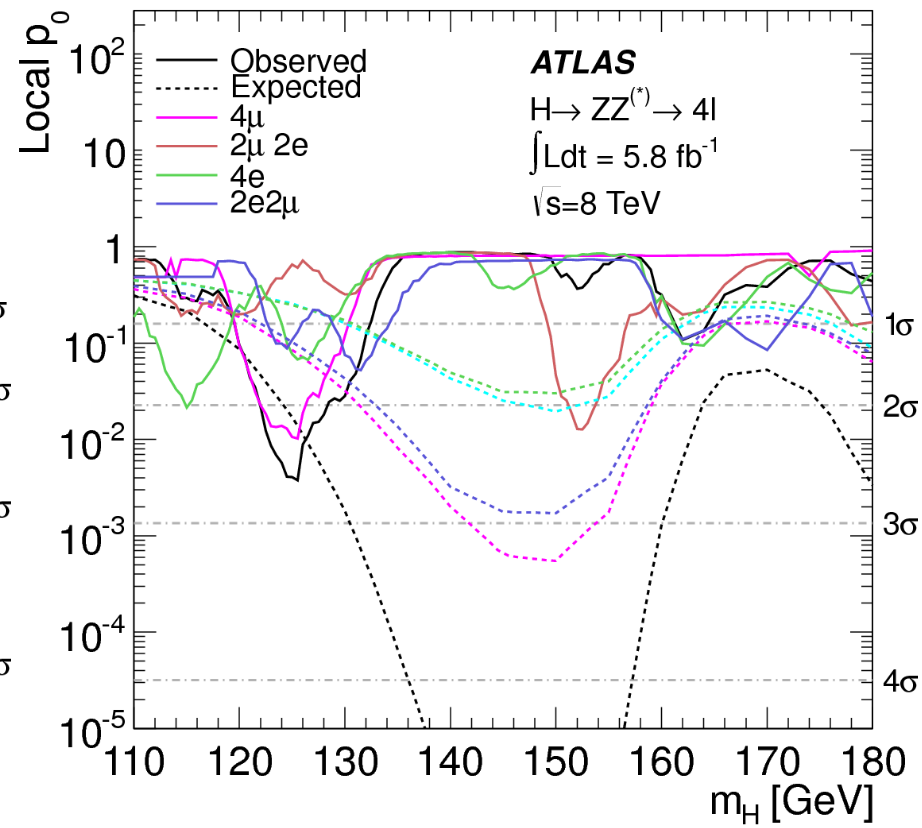
Table 3: The numbers of expected signal (m_H = 125 GeV) and background events, together with the numbers of observed events in the data, in a window of size ±5 GeV around 125 GeV, for the combined $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV data.

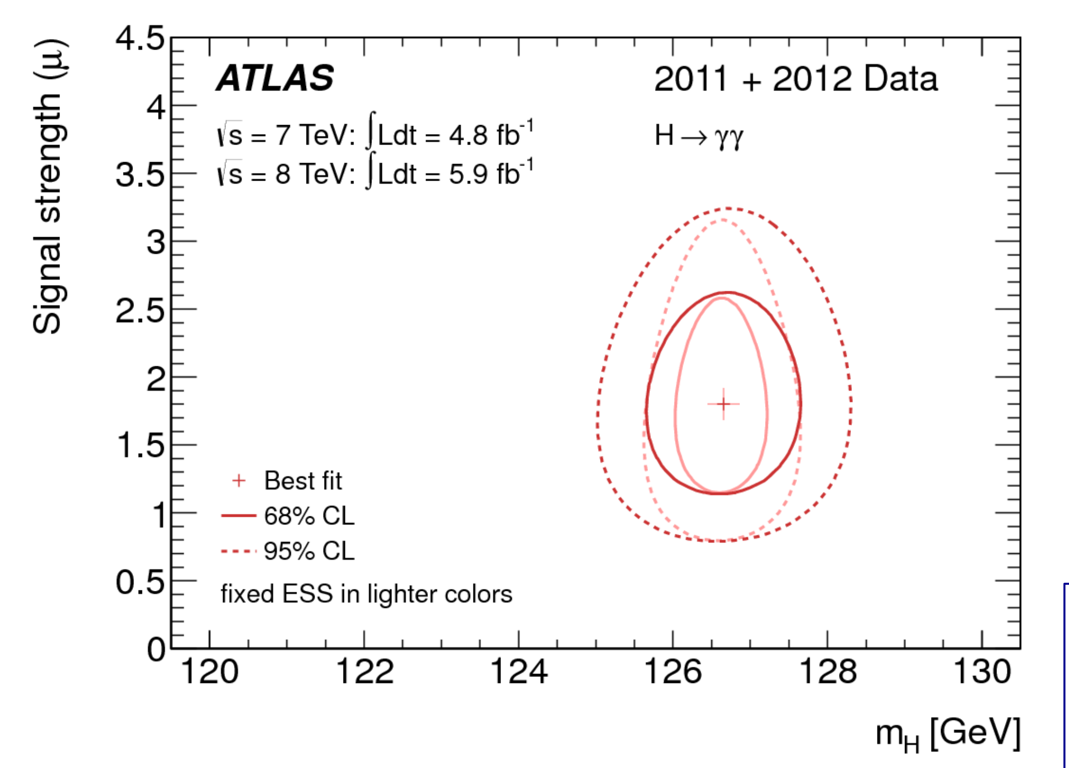
	Signal	$ZZ^{(*)}$	$Z+\text{jets}, t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

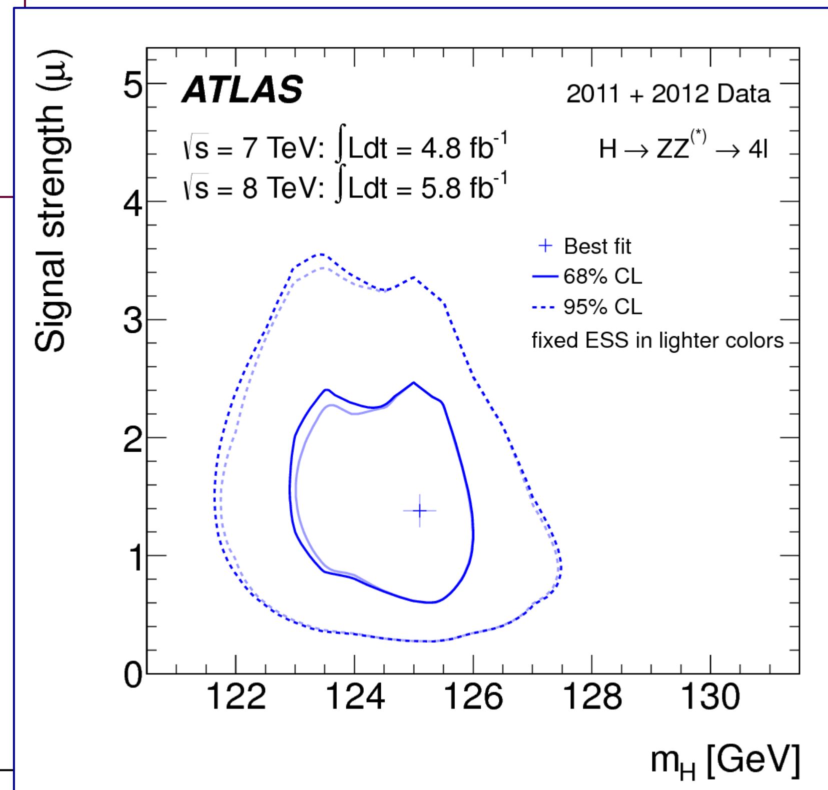
Main systematic uncertainties

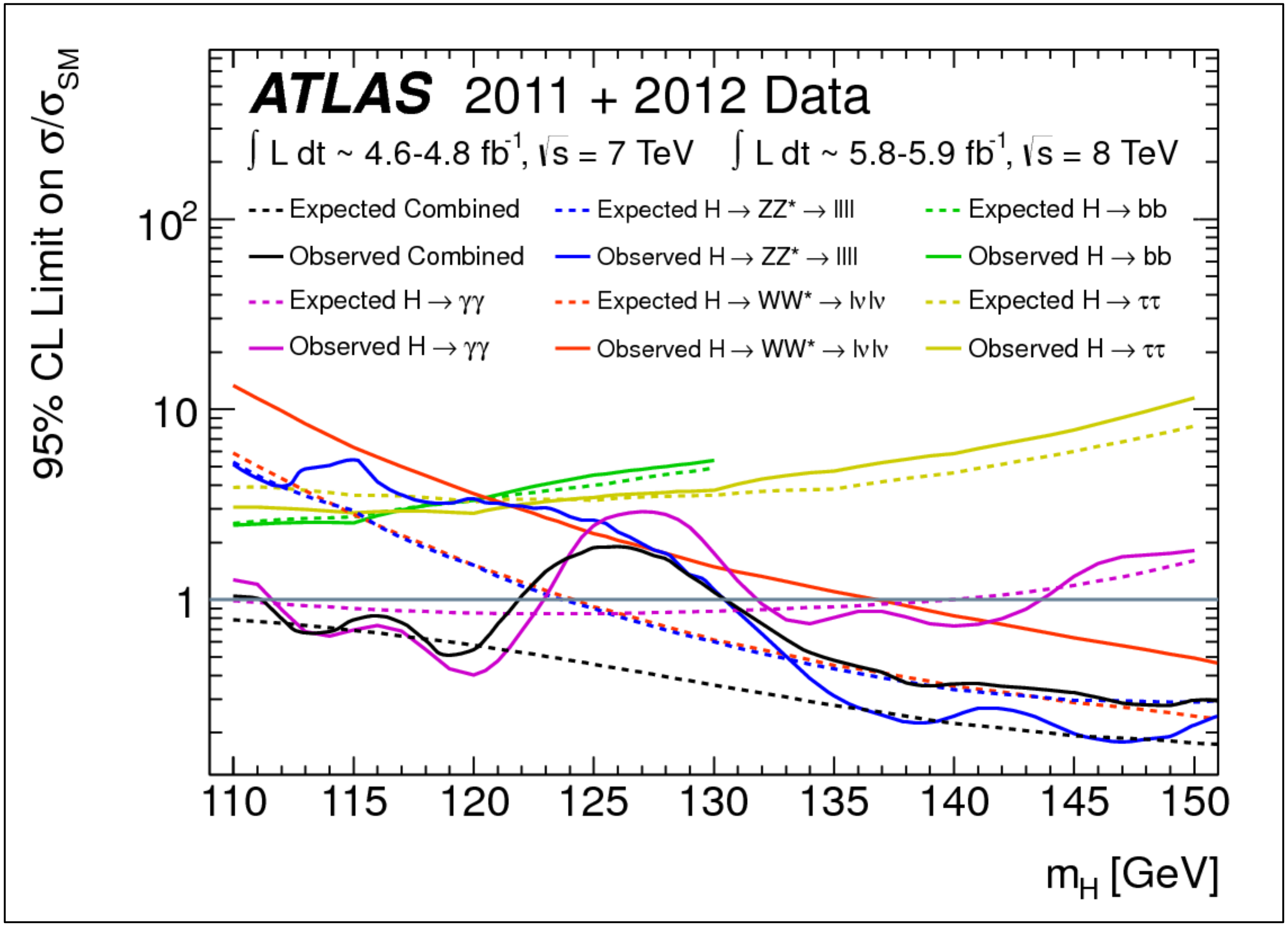
Higgs cross-section : ~ 20%
Electron efficiency : ~8% (4e)
ZZ* background : ~ 15%
Reducible backgrounds : ~ 40%


Local p0
Observed
Expected
4μ
2μ 2e
4e
2e2μ
ATLAS
H→ ZZ(*)→ 4l
∫Ldt = 4.8 fb-1
√s=7 TeV
1σ
2σ
3σ
4σ
mH [GeV]


Local p0
Observed
Expected
4μ
2μ 2e
4e
2e2μ
ATLAS
H→ ZZ(*)→ 4l
∫Ldt = 5.8 fb-1
√s=8 TeV
1σ
2σ
3σ
4σ
mH [GeV]


ATLAS
2011 + 2012 Data
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.9 fb-1
H → γγ
Best fit
68% CL
95% CL
fixed ESS in lighter colors
Signal strength (μ)
mH [GeV]

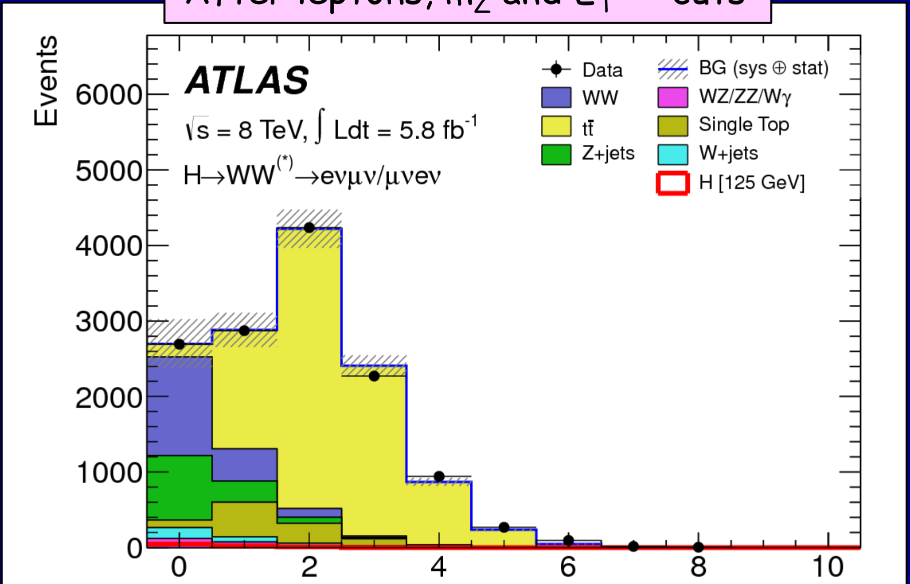

ATLAS
2011 + 2012 Data
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
H → ZZ(*) → 4l
Best fit
68% CL
95% CL
fixed ESS in lighter colors
Signal strength (μ)
mH [GeV]



ATLAS 2011 + 2012 Data
∫ L dt ~ 4.6-4.8 fb-1, √s = 7 TeV ∫ L dt ~ 5.8-5.9 fb-1, √s = 8 TeV
Expected Combined
Observed Combined
Expected H → γγ
Observed H → γγ
Expected H → ZZ* → llll
Observed H → ZZ* → llll
Expected H → WW* → lνlν
Observed H → WW* → lνlν
Expected H → bb
Observed H → bb
Expected H → ττ
Observed H → ττ
95% CL Limit on σ/σSM
10^2
10
1
110
115
120
125
130
135
140
145
150
mH [GeV]

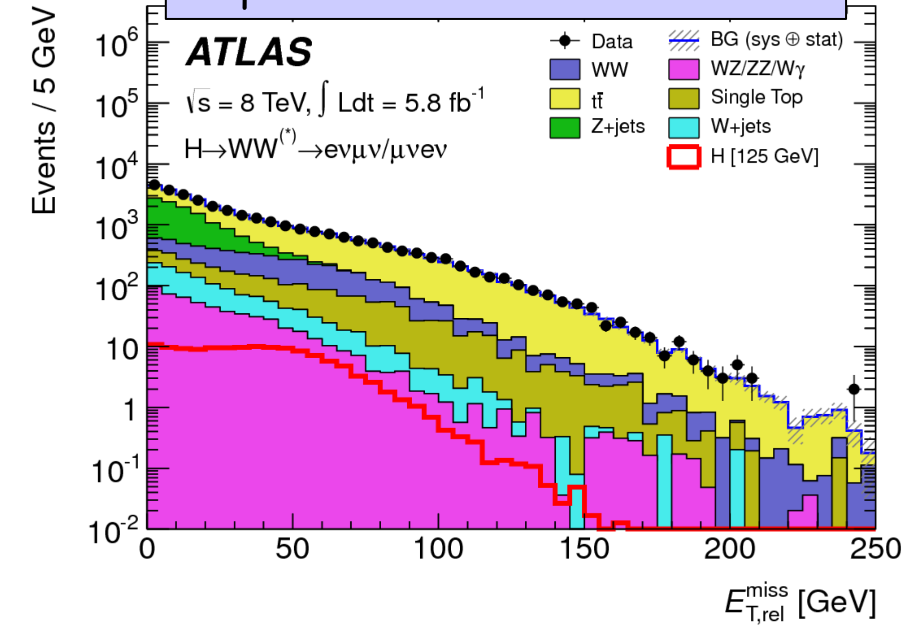
- To increase sensitivity, events divided in 3 categories: 0-jet, 1-jet, 2-jet
- 2-jet: VBF-like cuts:
  $|\Delta\eta|_{jj} > 3.8$. $M_{jj} > 500$ GeV, central-jet veto

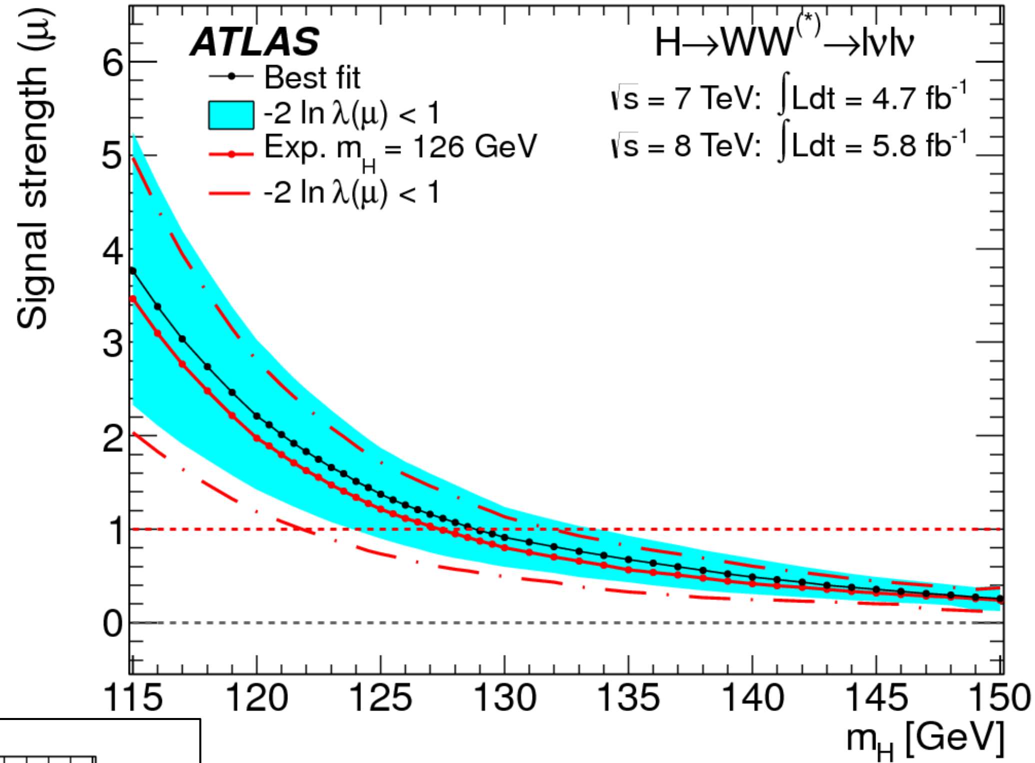
After leptons, m_Z and E_T^{miss} cuts

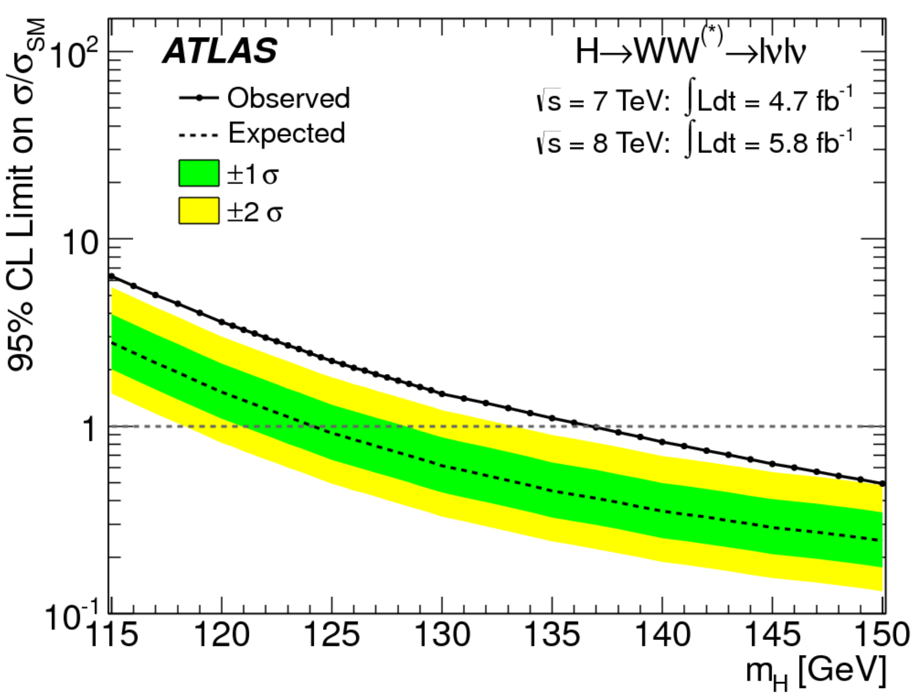


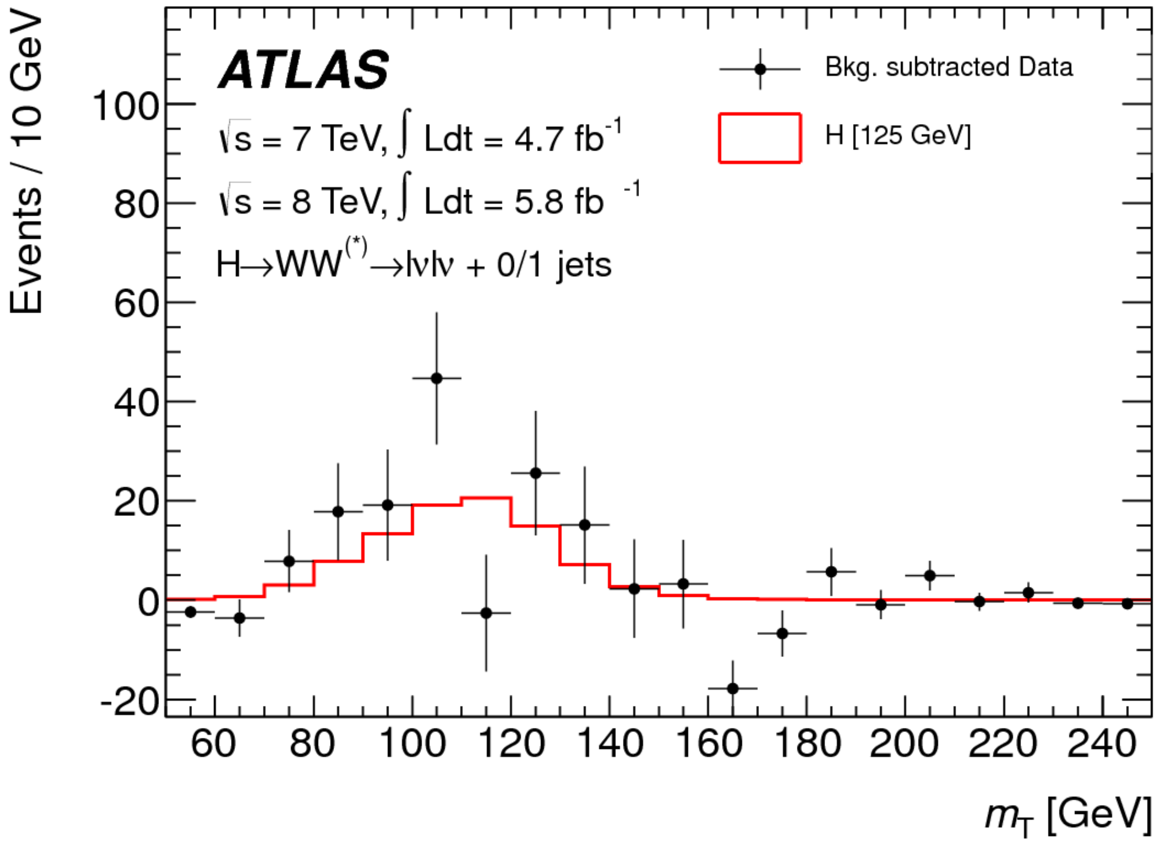
N_{jets} with p_T>25 GeV

E_T^{miss} distribution for eμ events at pre-selection level




ATLAS
H→WW(*)→lνlν
Best fit
-2 ln λ(μ) < 1
Exp. mH = 126 GeV
-2 ln λ(μ) < 1
√s = 7 TeV: ∫Ldt = 4.7 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Signal strength (μ)
mH [GeV]


ATLAS
H→WW(*)→lνlν
Observed
Expected
±1 σ
±2 σ
√s = 7 TeV: ∫Ldt = 4.7 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
95% CL Limit on σ/σSM
mH [GeV]



ATLAS
$\sqrt{s}$ = 7 TeV, $\int$ Ldt = 4.7 fb^{-1}
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 5.8 fb^{-1}
$H\rightarrow WW^{(*)}\rightarrow l\nu l\nu$ + 0/1 jets
Bkg. subtracted Data
H [125 GeV]
Events / 10 GeV
100
80
60
40
20
0
-20
60
80
100
120
140
160
180
200
220
240
m_T [GeV]

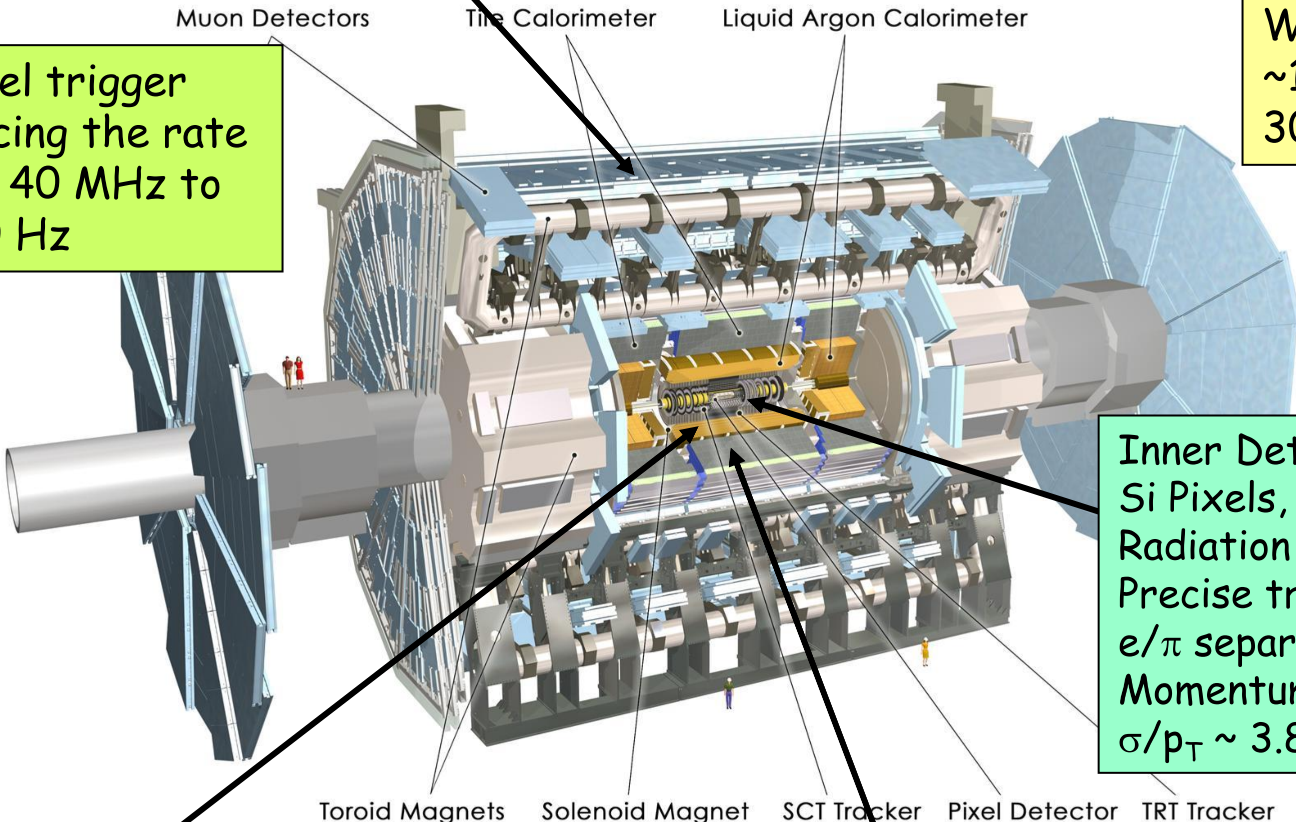
Table 4: Main relative systematic uncertainties on the predicted numbers of signal ($m_H = 125$ GeV) and background events for the $H+$ 0-jet and $H+$ 1-jet analyses. The same m_T criteria as in Table 3 are imposed. All numbers are summed over lepton flavours. The effect of the quoted inclusive signal cross section renormalisation and factorisation scale uncertainties on exclusive jet multiplicities is explained in Section 5. Sources of uncertainty that are negligible or not applicable in a particular column are marked with a '-'.

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
Parton distribution functions	8	2
Jet energy scale	7	4
WW modelling and shape	-	5
QCD scale acceptance	4	2
WW normalisation	-	4
W+jets fake factor	-	4
Lepton isolation	3	3
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	28	-
2-jet incl. ggF signal ren./fact. scale	16	-
WW normalisation	0	14
b-tagging efficiency	-	8
Top normalisation	-	6
Pile-up	5	5

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

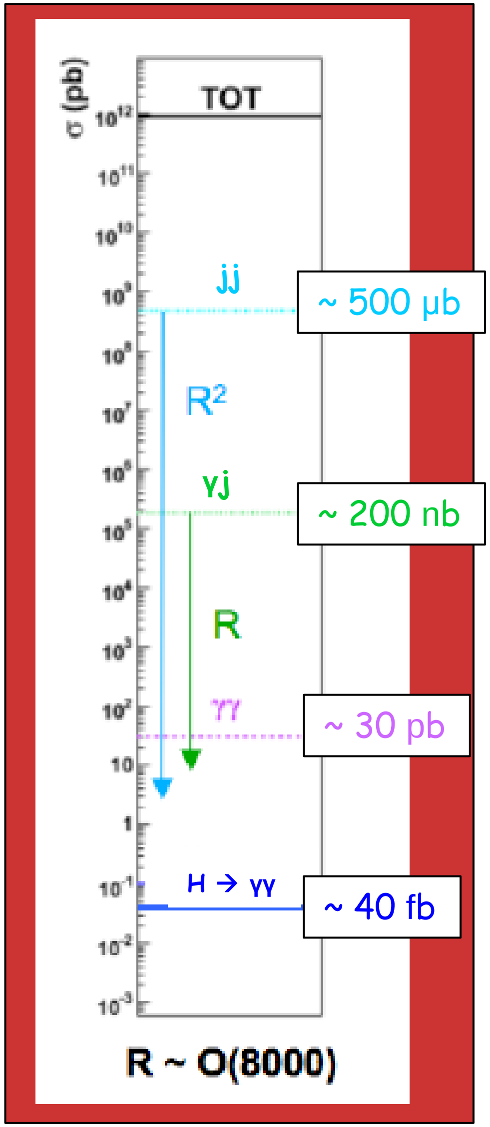
3-level trigger reducing the rate from 40 MHz to ~200 Hz



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$



In the region 125 ± 5 GeV

Observed	13 events
Expected from background only	4.9 ± 1
Expected from Higgs signal	5.3 ± .8

	4μ	2e2μ	4e
Data	6	5	2
Expected S/B	1.6	1.1	0.6
Reducible/total B	10%	60%	70%