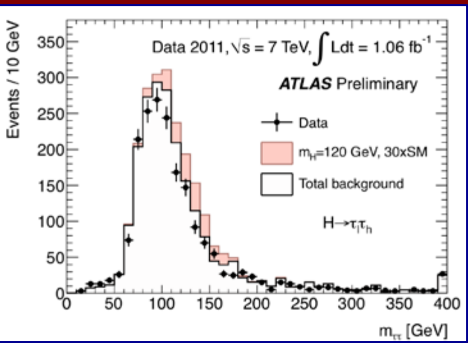
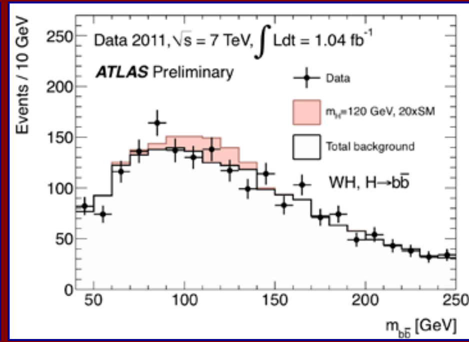
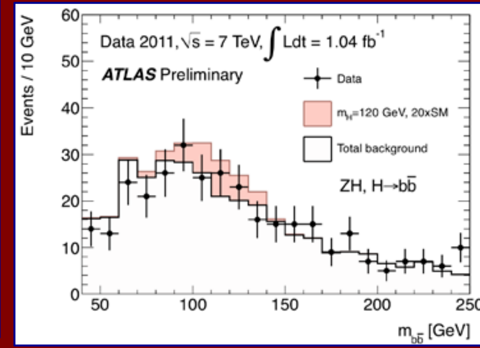
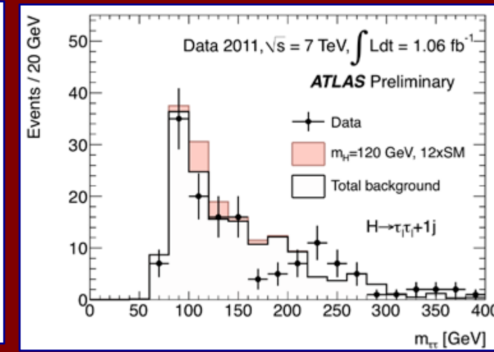


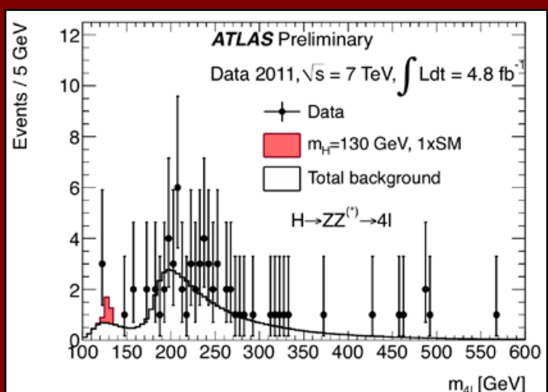


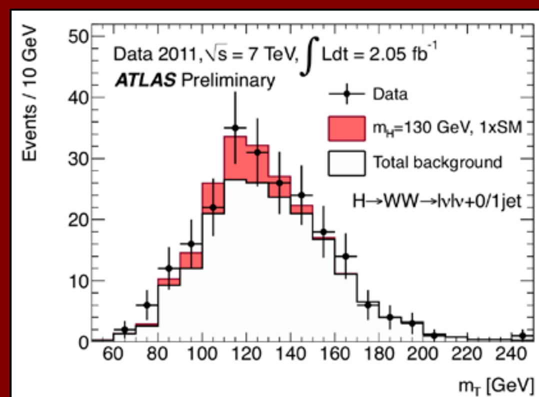


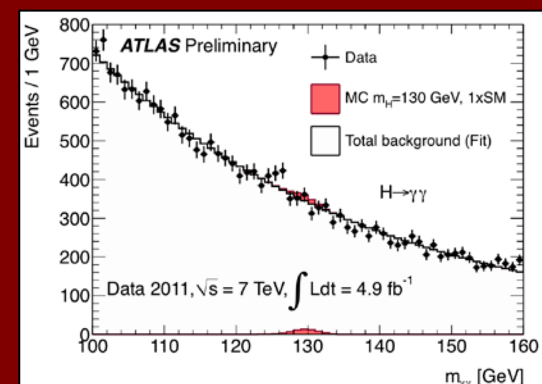


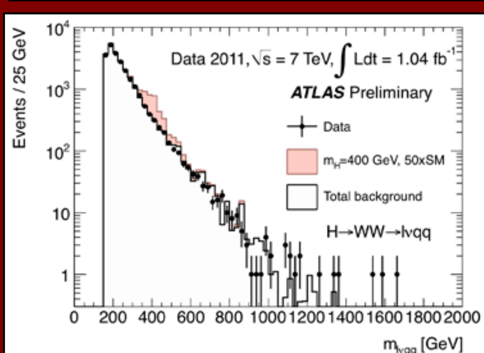
Update of Standard Model Higgs searches in ATLAS

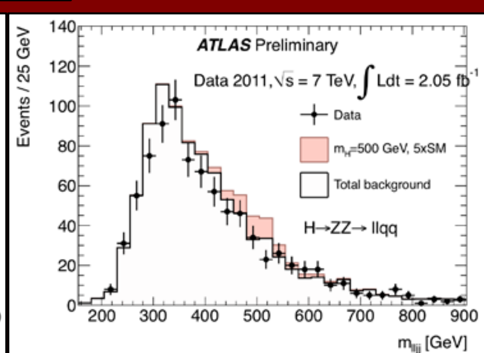
Fabiola Gianotti,
representing the
ATLAS Collaboration

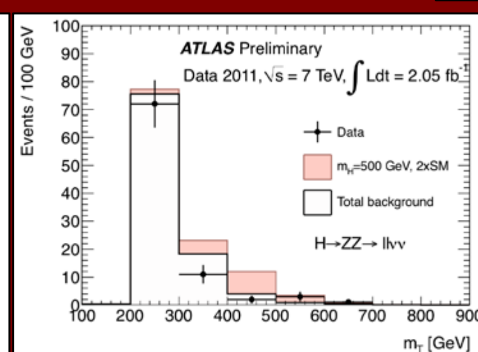


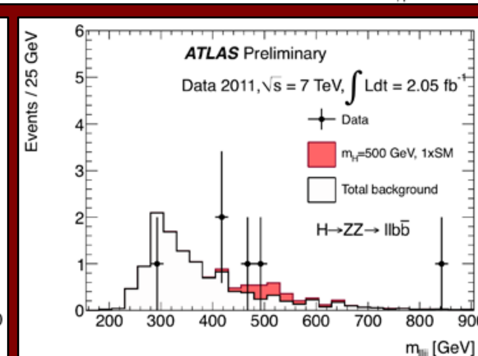








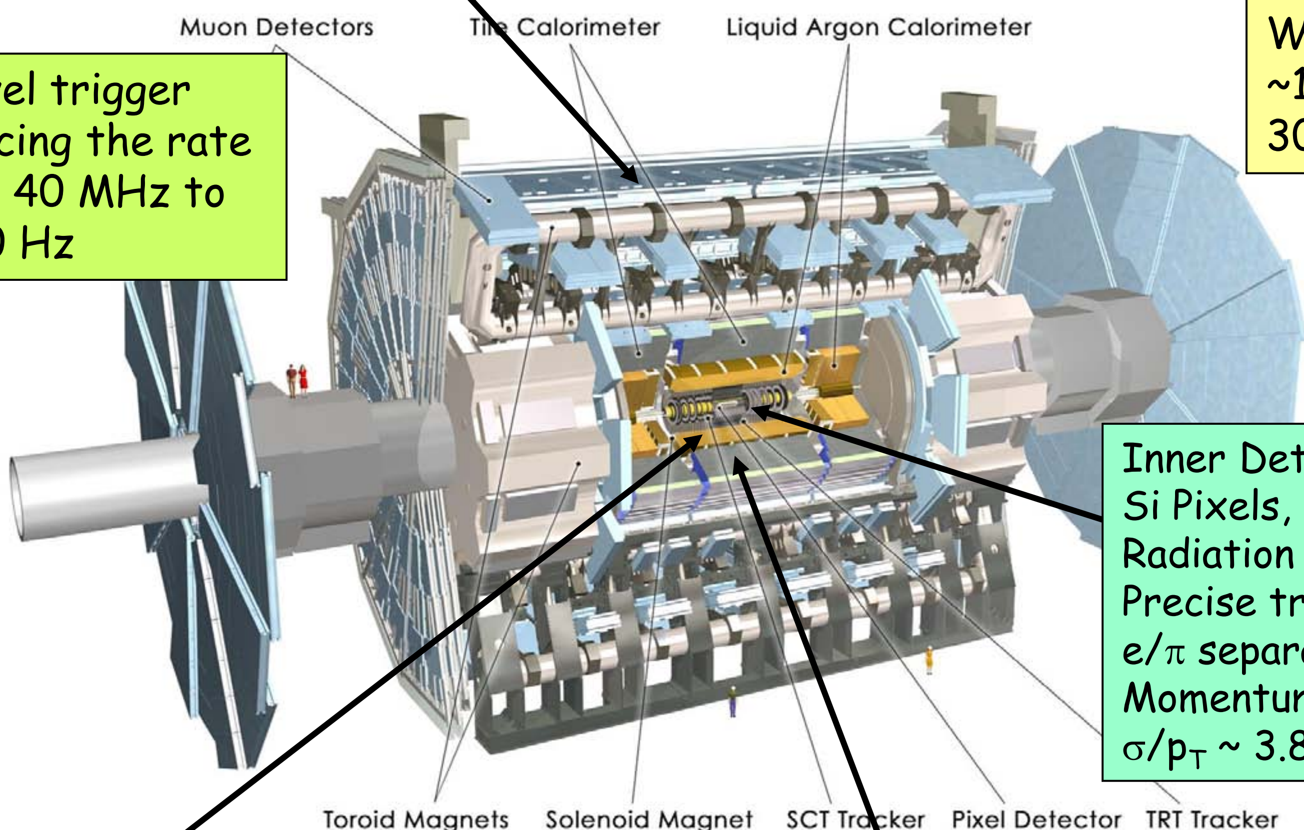




Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

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

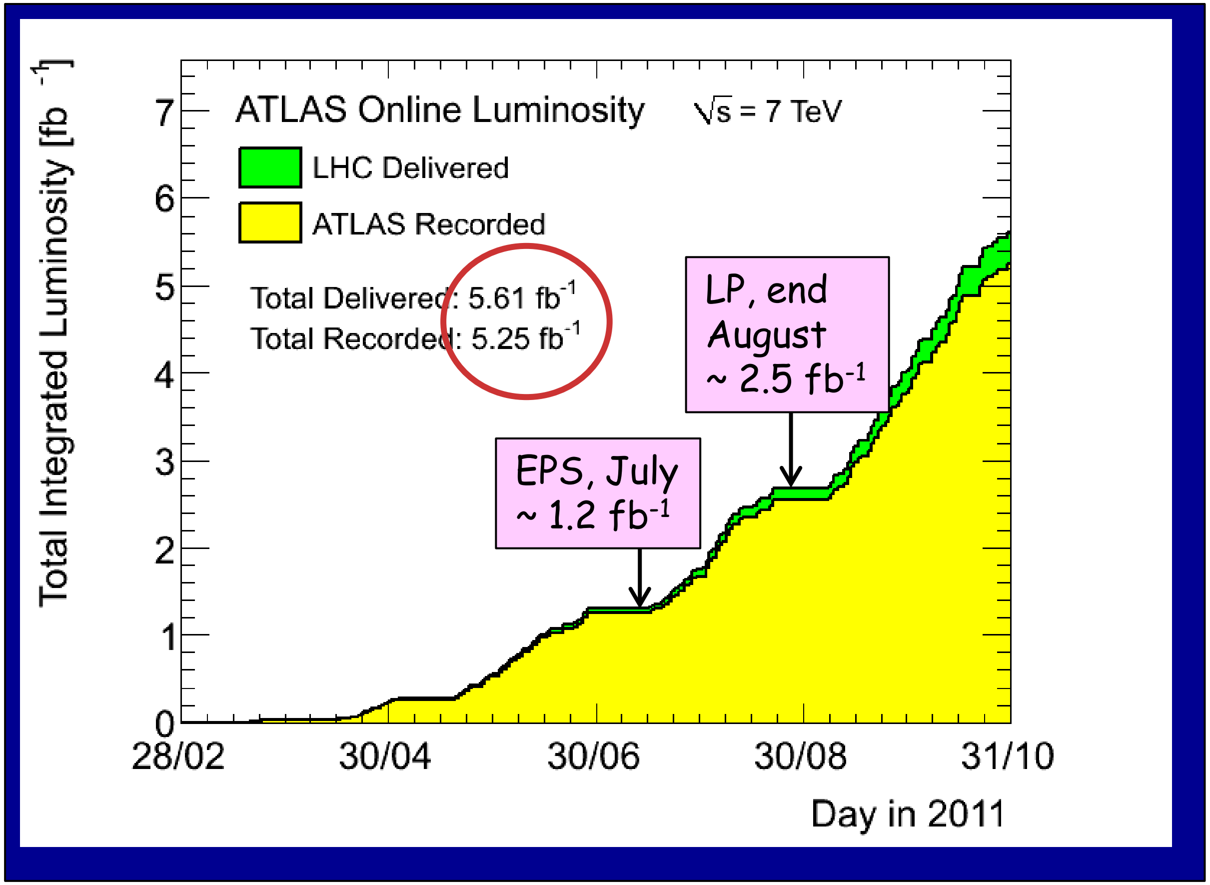
3-level trigger reducing the rate from 40 MHz to ~200 Hz



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

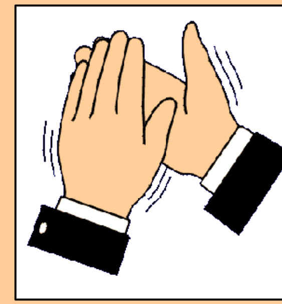
EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

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: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$



Peak luminosity seen by ATLAS: ~ 3.6 x10^{33} cm^{-2} s^{-1}

Many thanks to the LHC team for such a superb performance !



Fraction of non-operational detector channels: (depends on the sub-detector) — few permil to 3.5%

Data-taking efficiency = (recorded lumi)/(delivered lumi): — ~ 93.5%

Good-quality data fraction, used for analysis : (depends on the analysis) — 90-96%

Price to pay for the high luminosity: larger-than-expected pile-up

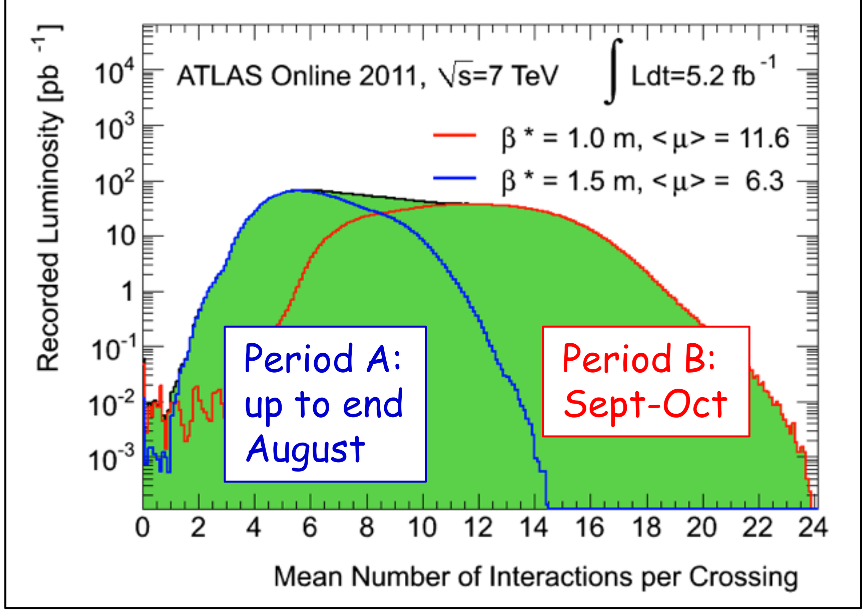
Pile-up = number of interactions per crossing

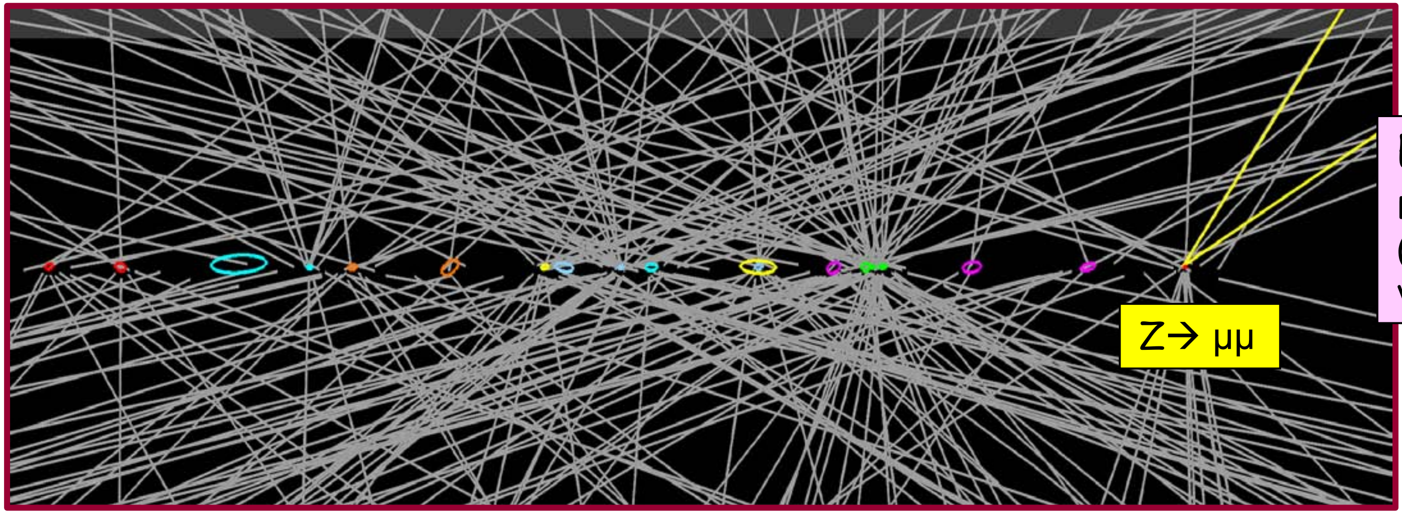
Tails up to ~20 → comparable to design luminosity

(50 ns operation; several machine parameters pushed beyond design)

LHC figures used over the last 20 years:

~ 2 (20) events/crossing at L=10^{33} (10^{34})





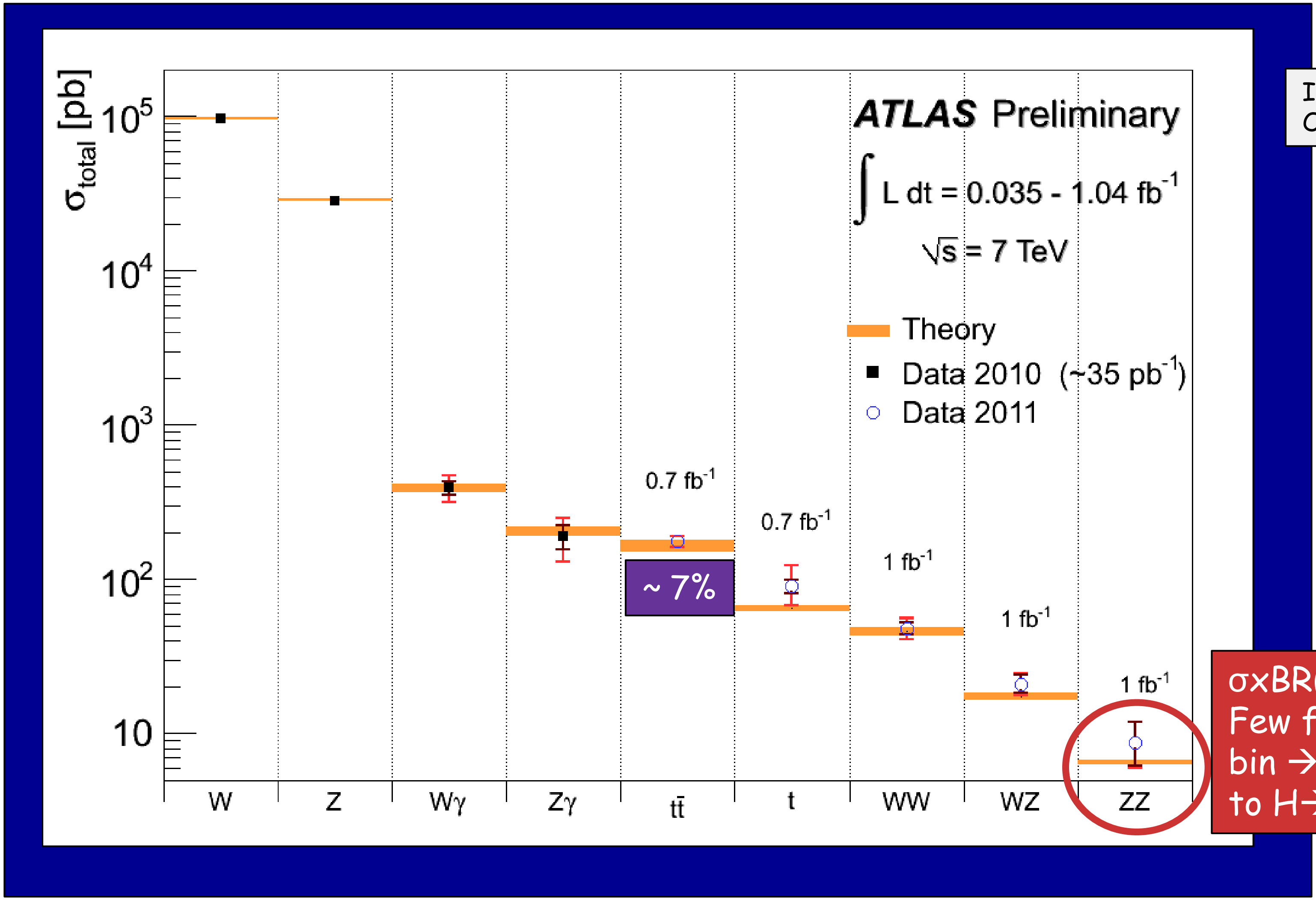
Event with 20 reconstructed vertices

(ellipses have 20 σ size for visibility reasons)

Challenging for trigger, computing resources, reconstruction of physics objects (in particular E_T^{miss}, soft jets, ..)

Precise modeling of both in-time and out-of-time pile-up in simulation is essential

Summary of main electroweak and top cross-section measurements



Inner error: statistical
Outer error: total

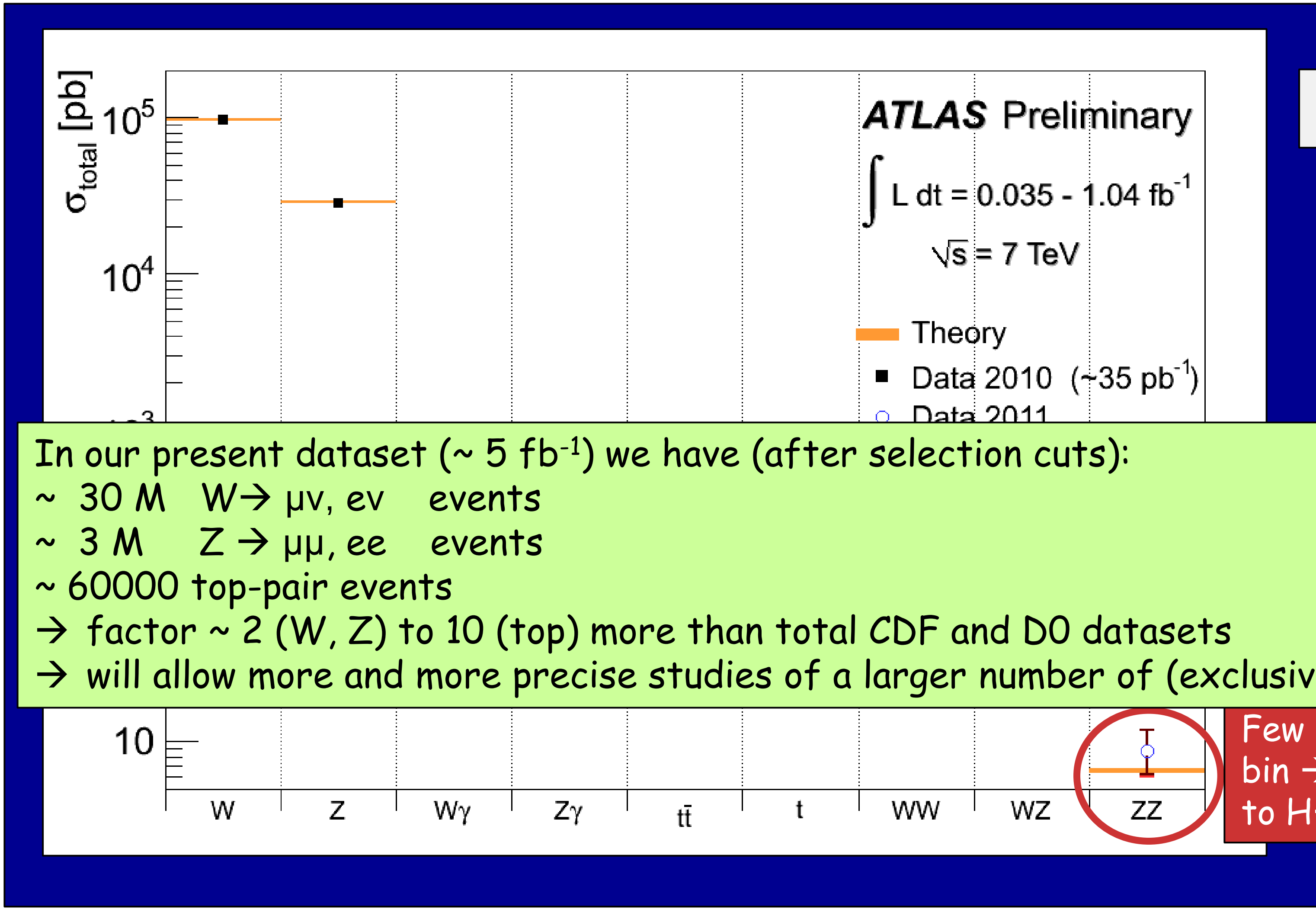
σxBR(ZZ→ 4l) ~ 40 fb
Few fb in narrow mass bin → comparable to H→ZZ$^{(*)}$→ 4l

Good agreement with SM expectations (within present uncertainties)

Experimental precision starts to challenge theory for e.g. tt (background to most H searches)

Measuring cross-sections down to few pb (~ 40 fb including leptonic branching ratios)

Summary of main electroweak and top cross-section measurements



Inner error: statistical
Outer error: total

In our present dataset (~ 5 fb^{-1}) we have (after selection cuts):

~ 30 M W→ μν, eν events

~ 3 M Z → μμ, ee events

~ 60000 top-pair events

→ factor ~ 2 (W, Z) to 10 (top) more than total CDF and D0 datasets

→ will allow more and more precise studies of a larger number of (exclusive) processes

fb

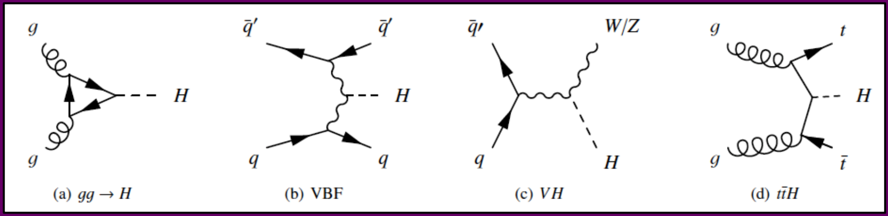
Few fb in narrow mass bin → comparable to H→ZZ$^{(*)}$→ 4l

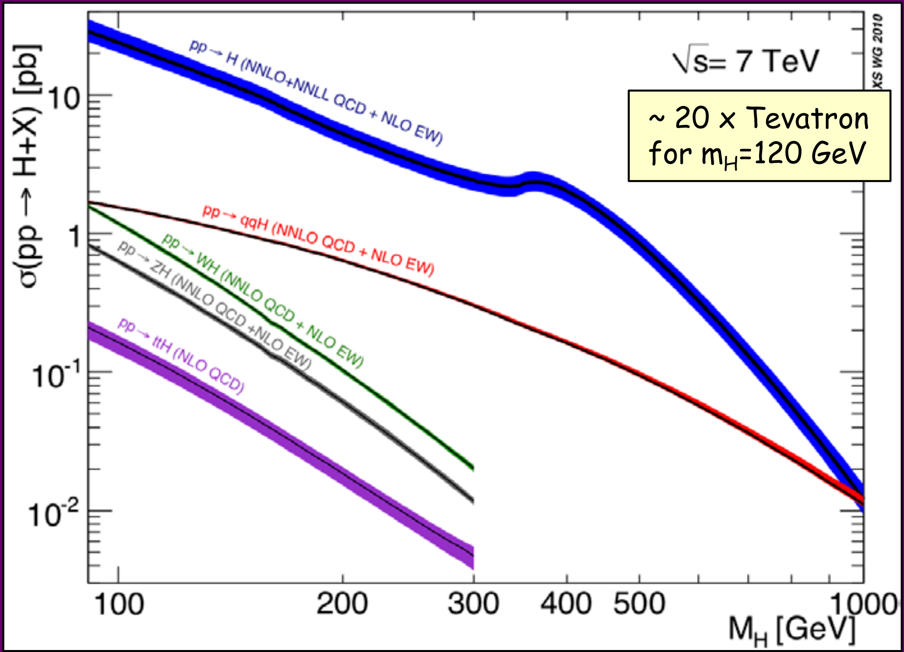
Good agreement with SM expectations (within present uncertainties)

Experimental precision starts to challenge theory for e.g. tt (background to most H searches)

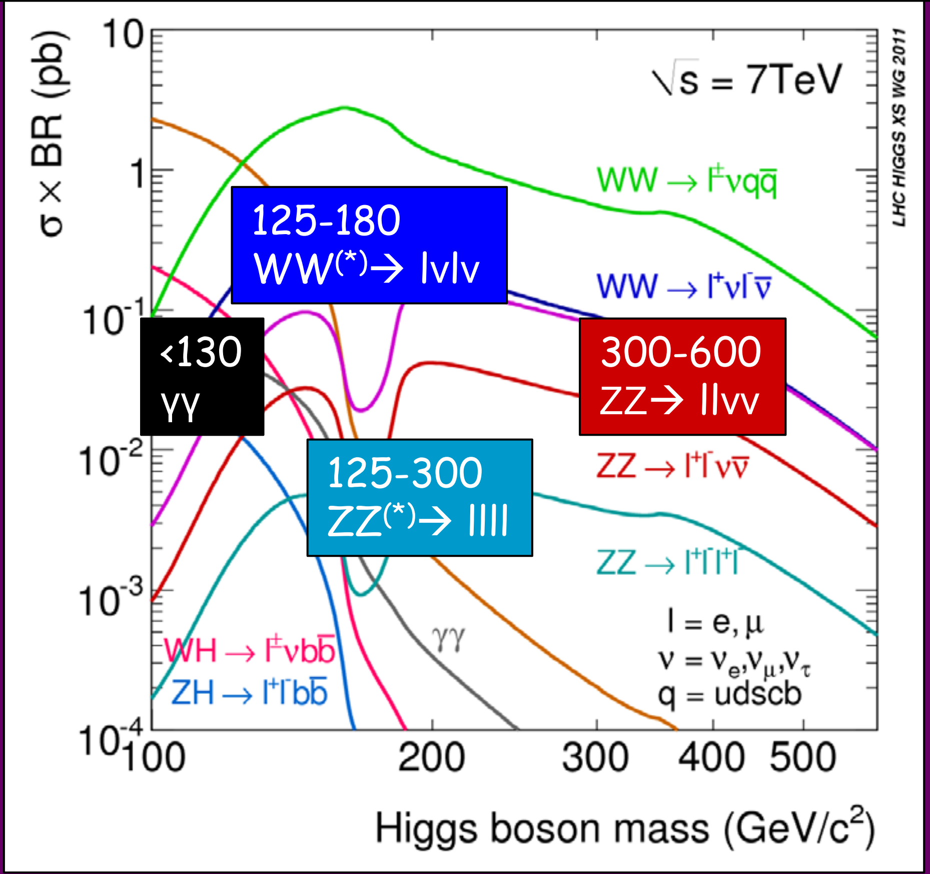
Measuring cross-sections down to few pb (~ 40 fb including leptonic branching ratios)

SM Higgs production cross-section and decay modes





Experimentally most sensitive channels vs m_H



- ❑ Cross-sections computed to NNLO in most cases → theory uncertainties reduced to < 20%
- ❑ Huge progress also in the theoretical predictions of numerous and complex backgrounds

→ Excellent achievements of the theory community; very fruitful discussions with the experiments (e.g. through LHC Higgs Cross Section WG, LPCC, etc.)

Micro-summary of present Higgs searches in ATLAS

Channel	m_H range (GeV)	Int. lumi fb^{-1}	Main backgrounds	Number of signal events after cuts	S/B after cuts	Expected σ/σ_{SM} sensitivity
$H \rightarrow \gamma\gamma$	110-150	4.9	$\gamma\gamma$, γj, jj	~70	~0.02	1.6-2
$H \rightarrow \tau\tau \rightarrow ll+\nu$	110-140	1.1	$Z \rightarrow \tau\tau$, top	~0.8	~0.02	30-60
$H \rightarrow \tau\tau \rightarrow l\tau_{had}$	100-150	1.1	$Z \rightarrow \tau\tau$	~10	~5 10^{-3}	10-25
$W/ZH \rightarrow bbl(l)$	110-130	1.1	W/Z+jets, top	~6	~5 10^{-3}	15-25
$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$	110-300	2.1	WW, top, Z+jet	~20 (130 GeV)	~0.3	0.3-8
$H \rightarrow ZZ^{(*)} \rightarrow 4l$	110-600	4.8	ZZ*, top, Zbb	~2.5 (130 GeV)	~1.5	0.7-10
$H \rightarrow ZZ \rightarrow ll\,\nu\nu$	200-600	2.1	ZZ, top, Z+jets	~20 (400 GeV)	~0.3	0.8-4
$H \rightarrow ZZ \rightarrow ll\,qq$	200-600	2.1	Z+jets, top	2-20 (400 GeV)	0.05-0.5	2-6
$H \rightarrow WW \rightarrow l\nu qq$	240-600	1.1	W+jets,top,jets	~45 (400 GeV)	10^{-3}	5-10

- ❑ Based on (conservative) cut-based selections
- ❑ Large and sometimes not well-known backgrounds estimated mostly with data-driven techniques using signal-free control regions

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

$110 < m_H < 300$ GeV

- Most sensitive channel over ~ 125-180 GeV (σ ~ 200 fb)
- However: challenging: 2ν → no mass reconstruction/peak → "counting channel"
- 2 isolated opposite-sign leptons, large E_T^{miss}
- Main backgrounds: WW, top, Z+jets, W+jets
  - → $m_{ll} \neq m_Z$, b-jet veto, …
  - → Topological cuts against "irreducible" WW background: p_{Tll}, m_{ll}, $\Delta\phi_{ll}$ (smaller for scalar Higgs), m_T (ll, E_T^{miss})

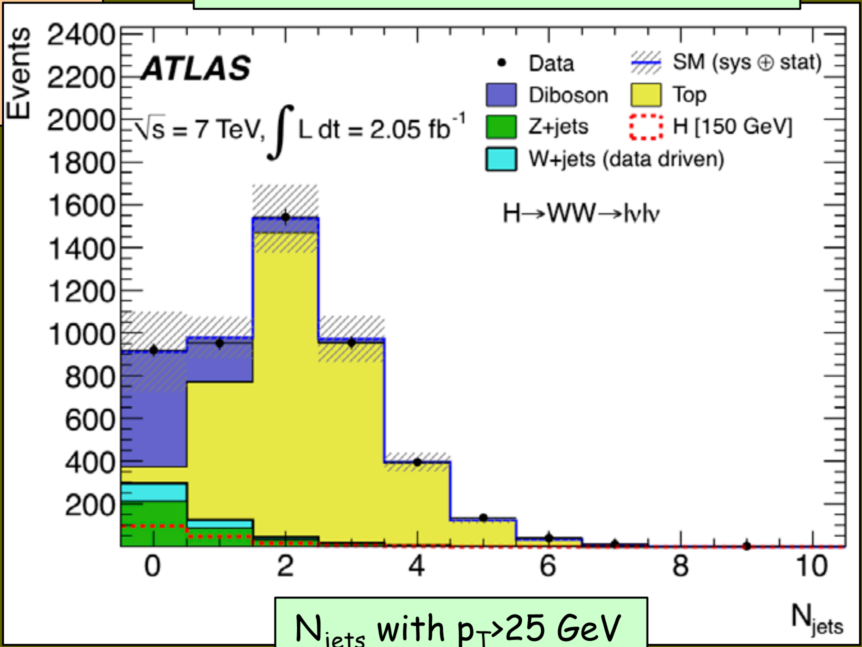
Crucial experimental aspects:

- understanding of E_T^{miss} (genuine and fake)
- excellent understanding of background in signal region → use signal-free control regions in data to constrain MC → use MC to extrapolate to the signal region

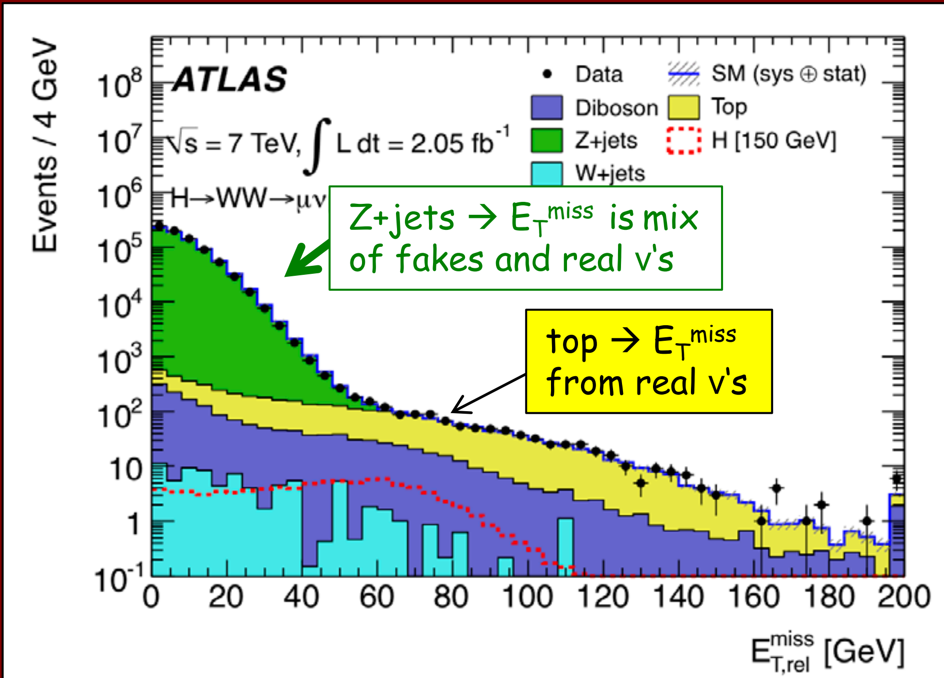
2.1 fb^{-1}

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

After leptons, m_Z and E_T^{miss} cuts



N_{jets} with p_T>25 GeV



E_T^{miss} spectrum in data for inclusive events with $\mu^+\mu^-$ pair well described (over 5 orders of magnitude) by the various background components.
Dominated by real E_T^{miss} from ν's starting at E_T^{miss} ~ 50 GeV
→ little tails from detector effects

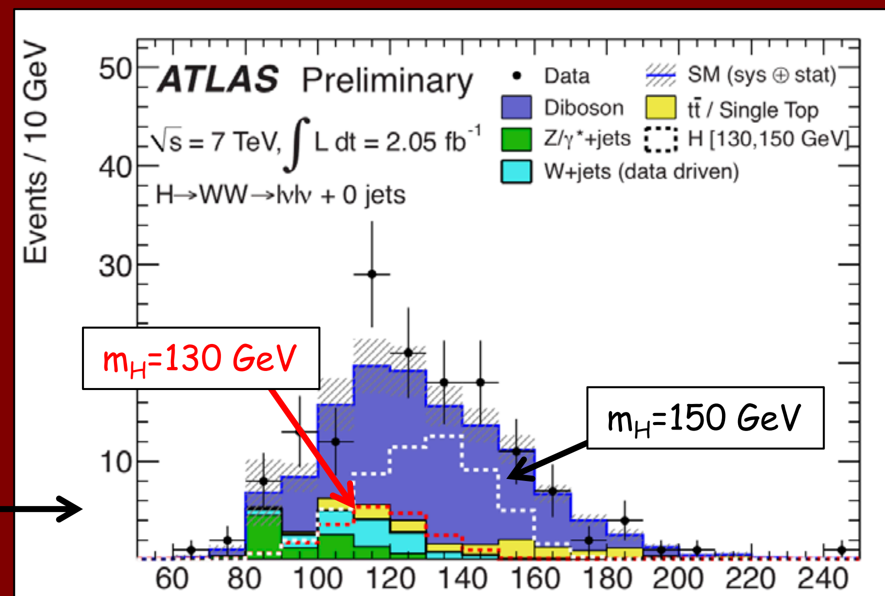
E_T^{miss} spectrum and resolution very sensitive to pile-up → we will include Period-B data when understanding at similar level as Period A

2.1 fb^{-1}

After all cuts (selection for m_H=130 GeV)

Observed in data	94 events 10 ee, 42 eμ, 42 μμ
Expected background	76 (±11)
Expected signal m_H=130 GeV	19 (±4)

Transverse mass spectrum after all cuts (except M_T) →

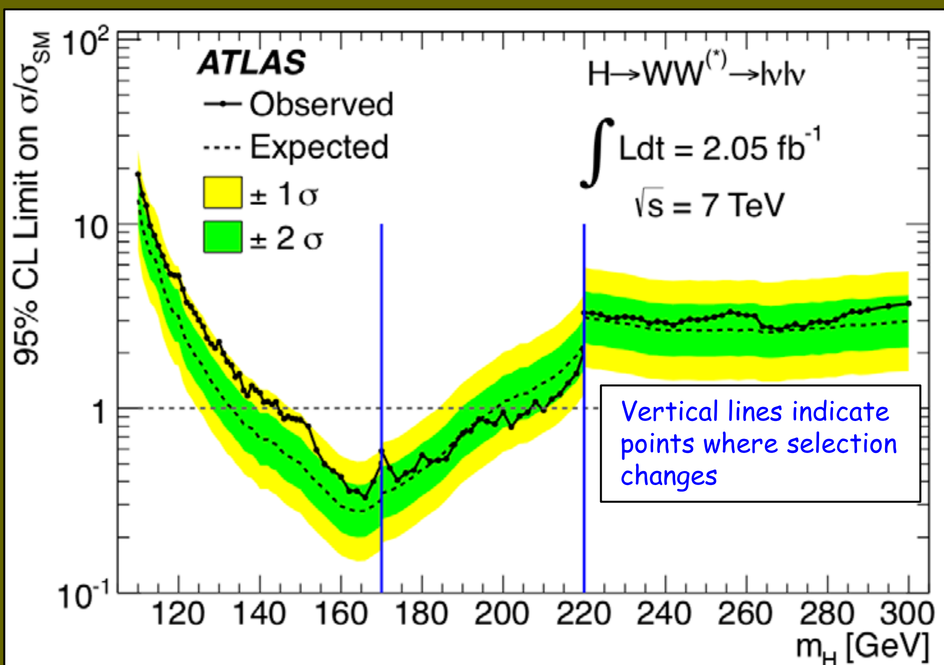


$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

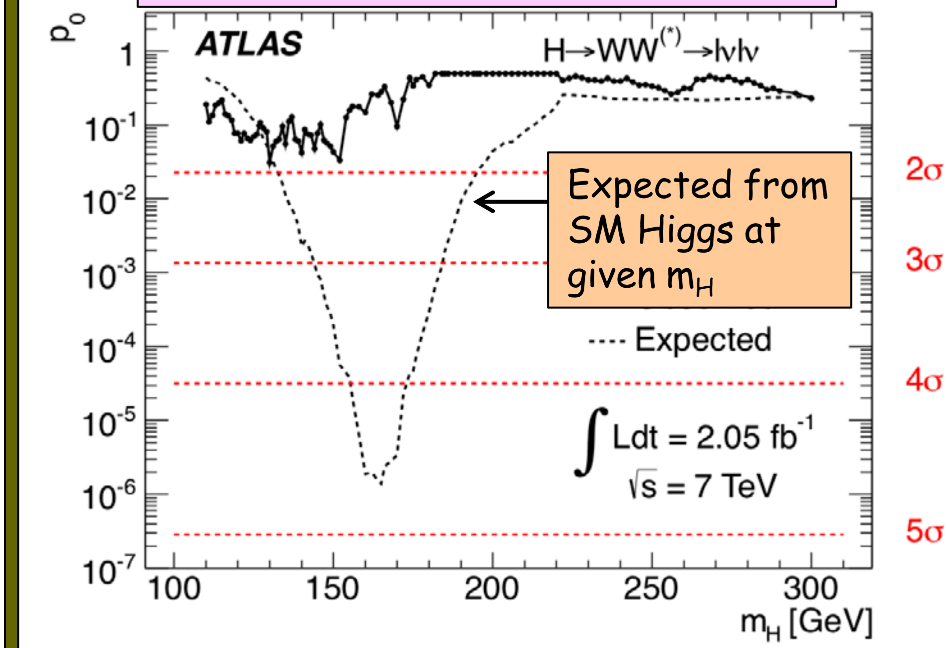
After all cuts (selection for m_H=130 GeV)

2.1 fb^{-1}

Observed in data	94 events 10 ee, 42 eμ, 42 μμ
Expected background	76 (±11)
Expected signal m_H=130 GeV	19 (±4)



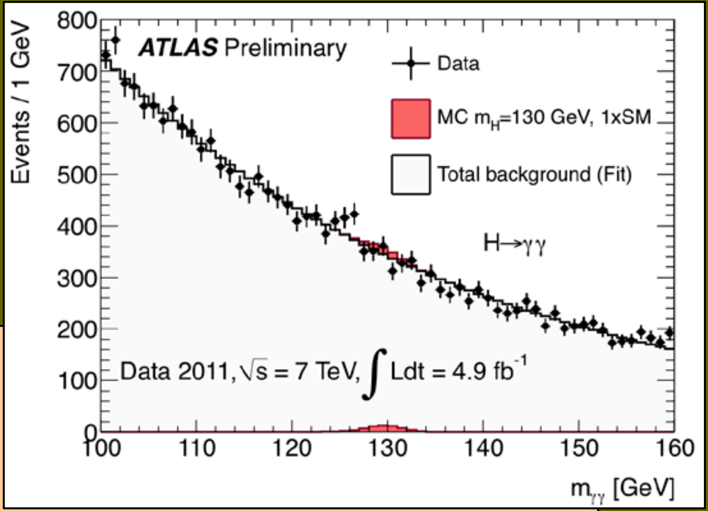
Consistency of the data with the background-only expectation



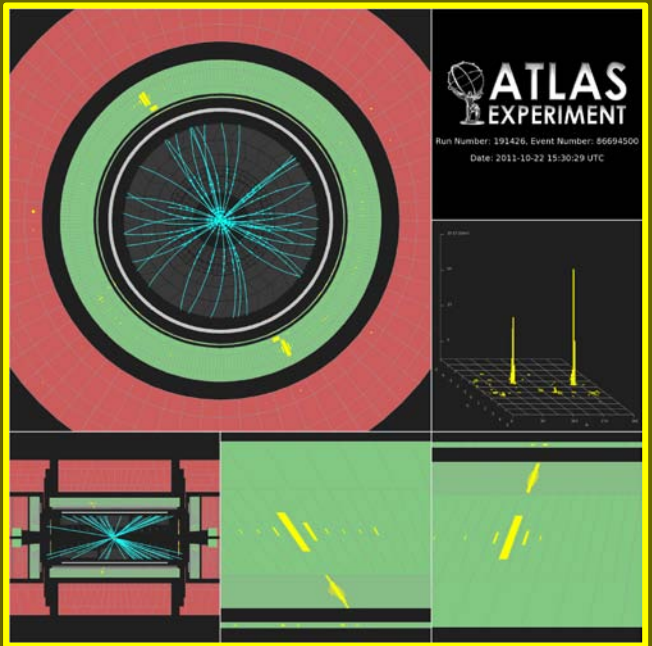
- Excluded (95% CL): 145 < m_H < 206 GeV (expected: 134-200 GeV)
- Observed limit within 2σ of expected: max deviation 1.9 σ for m_H ~ 130 GeV

$H \rightarrow \gamma\gamma$

$110 \leq m_H \leq 150$ GeV



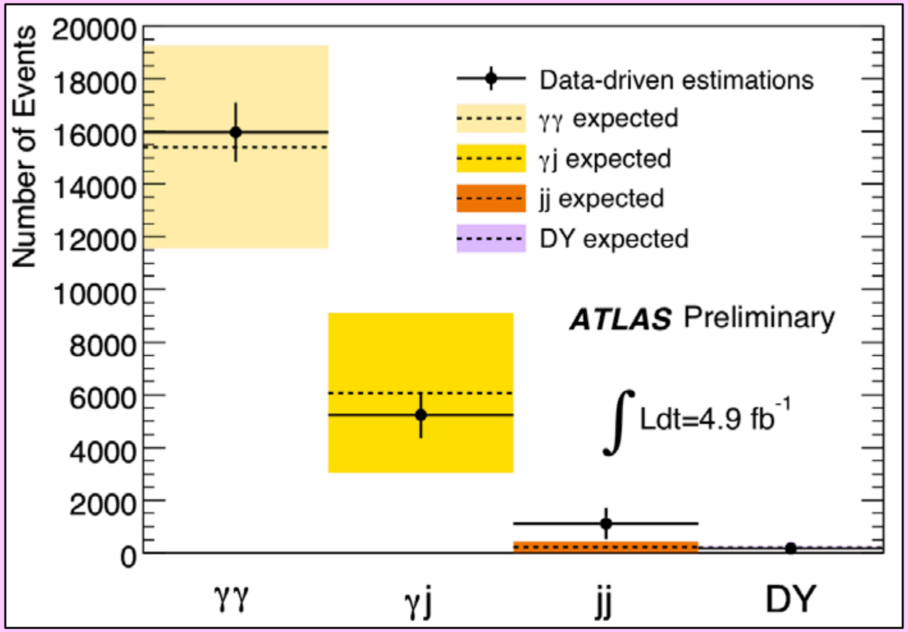
- Small cross-section: $\sigma \sim 40$ fb
- Simple final state: two high-p_T isolated photons
  $E_T(\gamma_1, \gamma_2) > 40, 25$ GeV
- Main background: γγ continuum (irreducible, smooth, ..)
- Events divided into 9 categories based on η-photon (e.g. central, rest, …), converted/unconverted, $p_T^{\gamma\gamma}$ perpendicular to γγ thrust axis
- ~70 signal events expected in 4.9 fb^{-1} after all selections for m_H=125 GeV
  ~ 3000 background events in signal mass window → S/B ~ 0.02



Crucial experimental aspects:
- excellent γγ mass resolution to observe narrow signal peak above irreducible background
- powerful γ/jet separation to suppress γj and jj background with jet → π^0 faking single γ

After all cuts: 22489 events with 100 < $m_{\gamma\gamma}$ < 160 GeVobserved in the data

Sample composition estimated from data using control samples



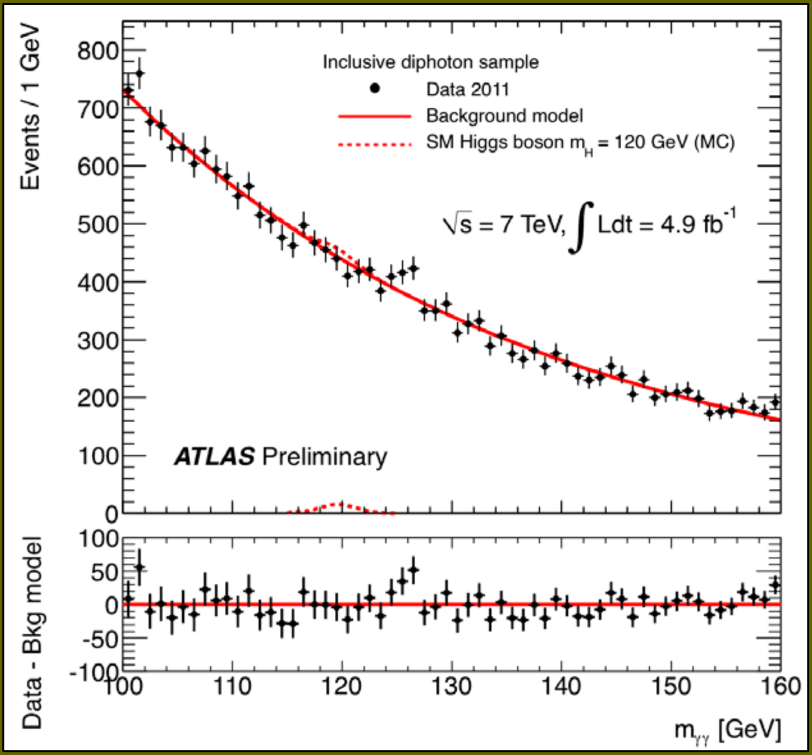
	Number of events	Fraction
γγ	16000 ± 1120	71 ±5 %
γj	5230 ± 890	23 ±4 %
jj	1130 ± 600	5 ±3 %
DY/Z	165 ± 8	0.7 ±0.1 %

γj + jj << γγ irreducible (purity ~ 70%)

Photon identification efficiency: ~ 85±5% from MC, cross-checked with data (Z→ ee, Z→ eeγ, μμγ)

After all selections: kinematic cuts, γ identification and isolation

- 22489 events with $100 < m_{\gamma\gamma} < 160$ GeV observed in the data
- expected signal efficiency: ~ 35% for m_H=125 GeV



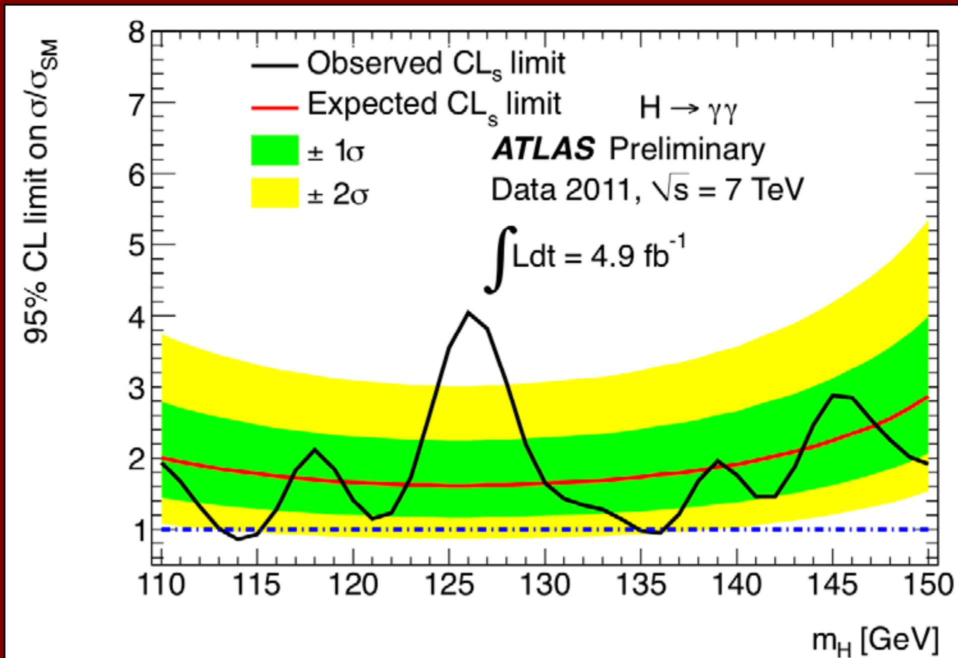
$m_{\gamma\gamma}$ spectrum fit with exponential function for background plus Crystal Ball + Gaussian for signal → background determined directly from data

Main systematic uncertainties

Expected signal yield : ~ 20%
H→ γγ mass resolution : ~ 14%
H→ γγ p_T modeling : ~ 8%
Background modeling : ±0.1-5.6 events

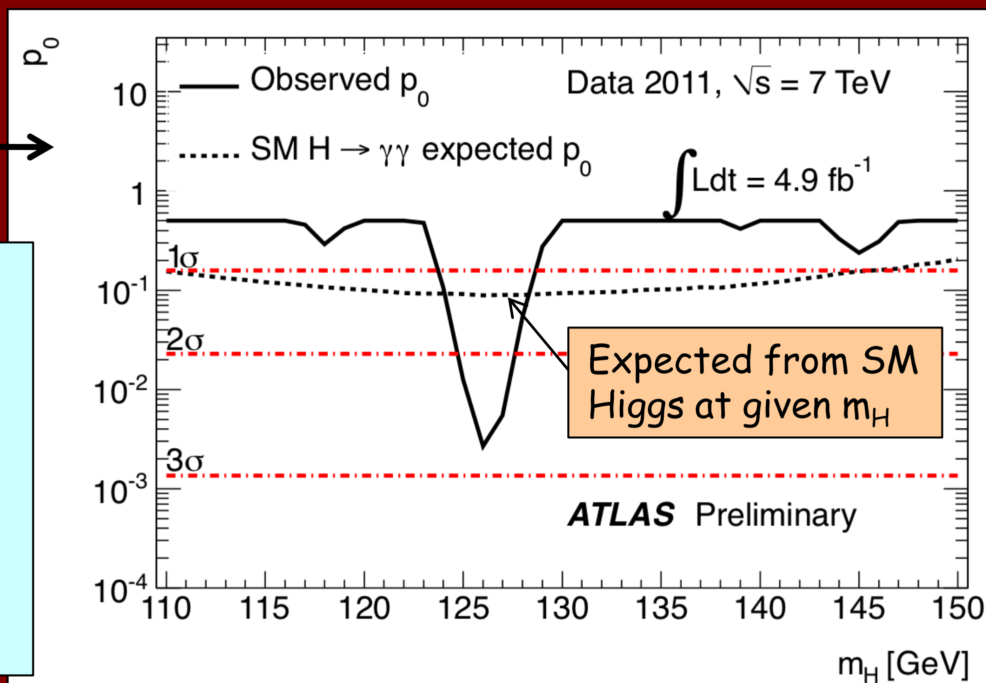
Systematic uncertainties on signal expectation

Event yield	
Photon reconstruction and identification	±11%
Effect of pileup on photon identification	±4%
Isolation cut efficiency	±5%
Trigger efficiency	±1%
Higgs boson cross section	+15%/ − 11%
Higgs boson p_T modeling	±1%
Luminosity	±3.9%
Mass resolution	
Calorimeter energy resolution	±12%
Photon energy calibration	±6%
Effect of pileup on energy resolution	±3%
Photon angular resolution	±1%
Migration	
Higgs boson p_T modeling	±8%
Conversion reconstruction	±4.5%



Excluded (95% CL):
$114 \leq m_H \leq 115$ GeV, $135 \leq m_H \leq 136$ GeV

Consistency of the data with the background-only expectation



Maximum deviation from background-only expectation observed for m_H~126 GeV:

- local p_0-value: 0.27% or 2.8σ
- expected from SM Higgs: ~ 1.4σ local
- global p_0-value: includes probability for such an excess to appear anywhere in the investigated mass range (110-150 GeV) ("Look-Elsewhere-Effect"): ~7% (1.5σ)

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

$110 < m_H < 600$ GeV

- σ ~ 2-5 fb
- However:
  -- mass can be fully reconstructed → events would cluster in a (narrow) peak
  -- pure: S/B ~ 1
- 4 leptons: $p_T^{1,2,3,4} > 20,20,7,7$ GeV; $m_{12} = m_Z \pm 15$ GeV; $m_{34} > 15\text{-}60$ GeV (depending on m_H)
- Main backgrounds:
  -- $ZZ^{(*)}$ (irreducible)
  -- $m_H < 2m_Z$: Zbb, Z+jets, tt with two leptons from b/q-jets → l

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

- Signal acceptance x efficiency: ~ 15 % for m_H~ 125 GeV

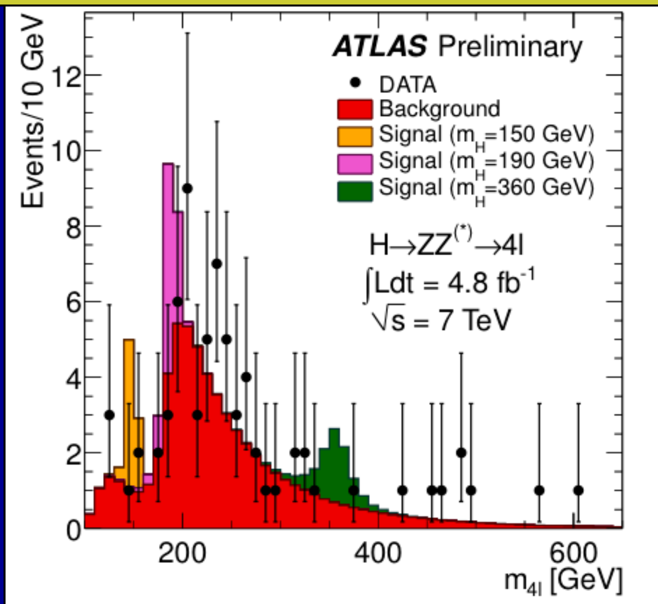
Crucial experimental aspects:

- High lepton reconstruction and 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 → l modeling, ..)
  → need to compare MC to data in background-enriched control regions (but: low statistics ..)

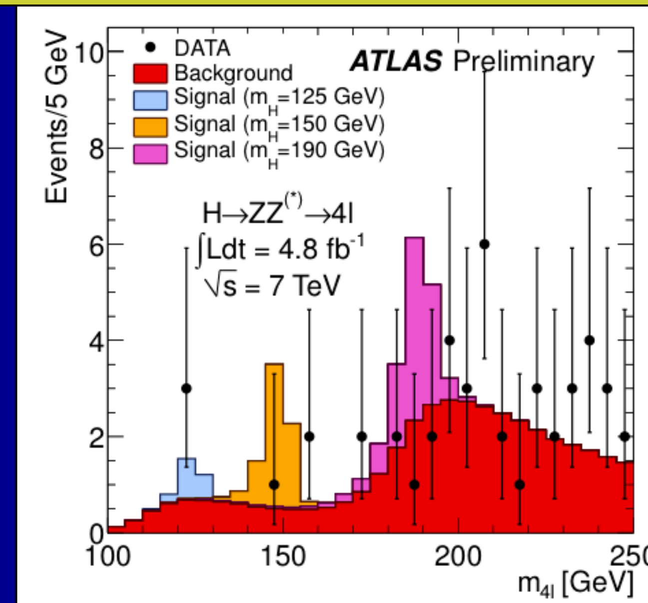
→ Conservative/stringent p_T and m(ll) cuts used at this stage

After all selections: kinematic cuts, isolation, impact parameter

Full mass range
Observed: 71 events: 24 4μ + 30 2e2μ + 17 4e
Expected from background: 62±9



m(4l) < 180 GeV
Observed: 8 events: 3 4μ + 3 2e2μ + 2 4e
Expected from background: 9.3±1.5



In the region m_H < 141 GeV (not already excluded at 95% C.L.) 3 events are observed: two 2e2μ events (m=123.6 GeV, m=124.3 GeV) and one 4μ event (m=124.6 GeV)

In the region 117< m_{4l} <128 GeV (containing ~90% of a m_H=125 GeV signal):

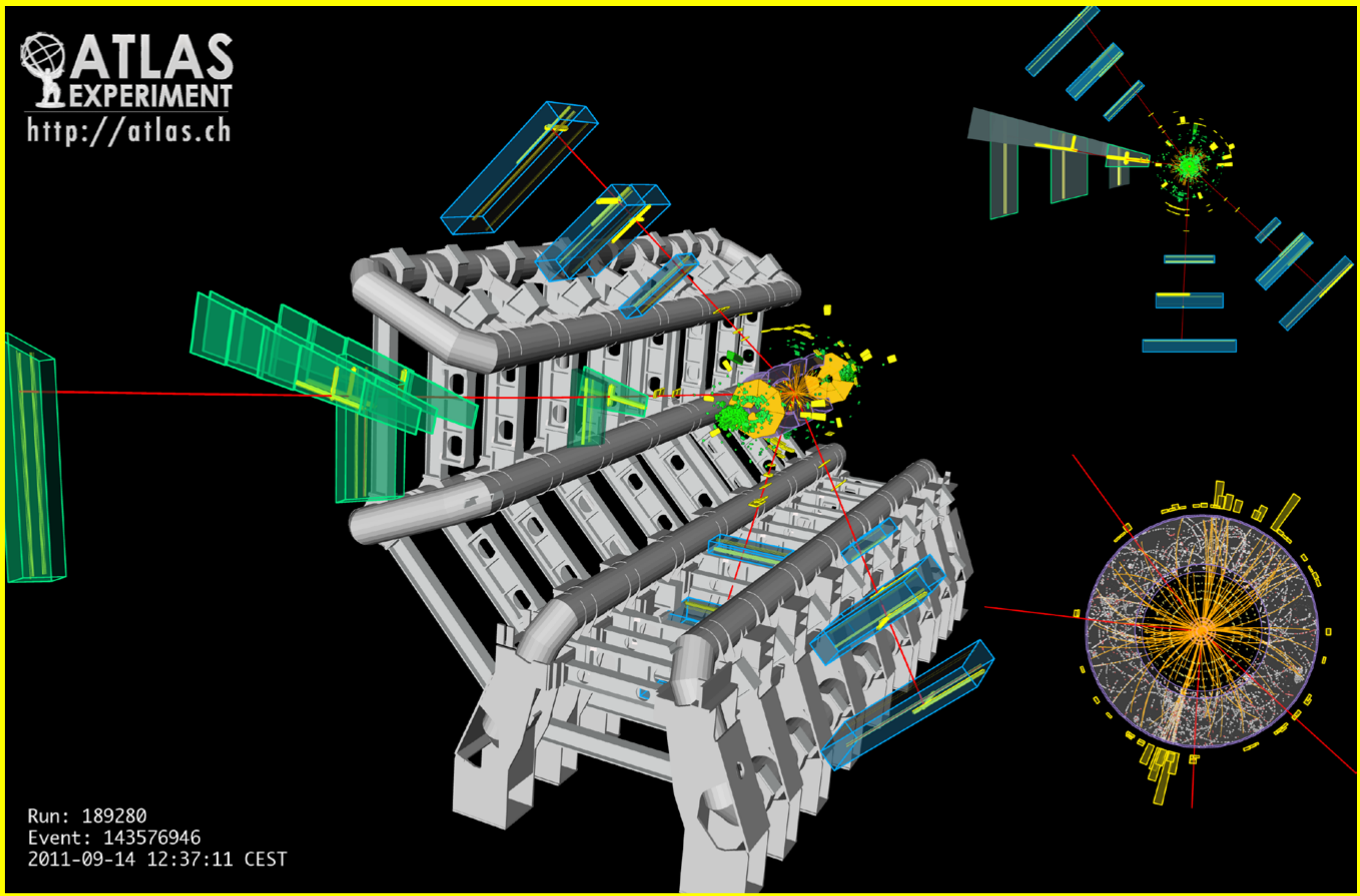
- similar contributions expected from signal and background: ~ 1.5 events each
- S/B ~ 2 (4μ), ~ 1 (2e2μ), ~ 0.3 (4e)
- Background dominated by ZZ* (4μ and 2e2μ), ZZ* and Z+jets (4e)

Main systematic uncertainties

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

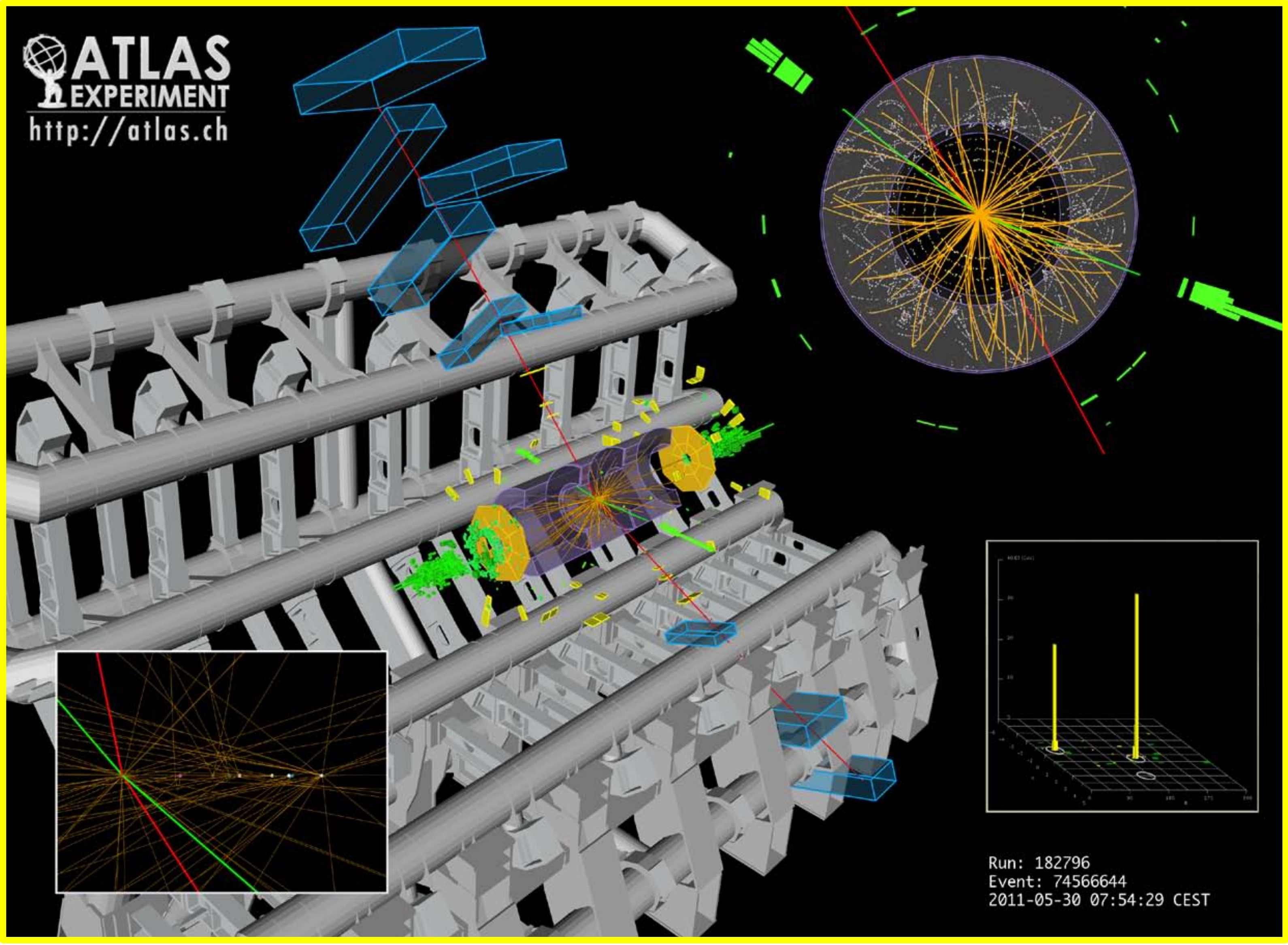
4μ candidate with $m_{4\mu}$= 124.6 GeV

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

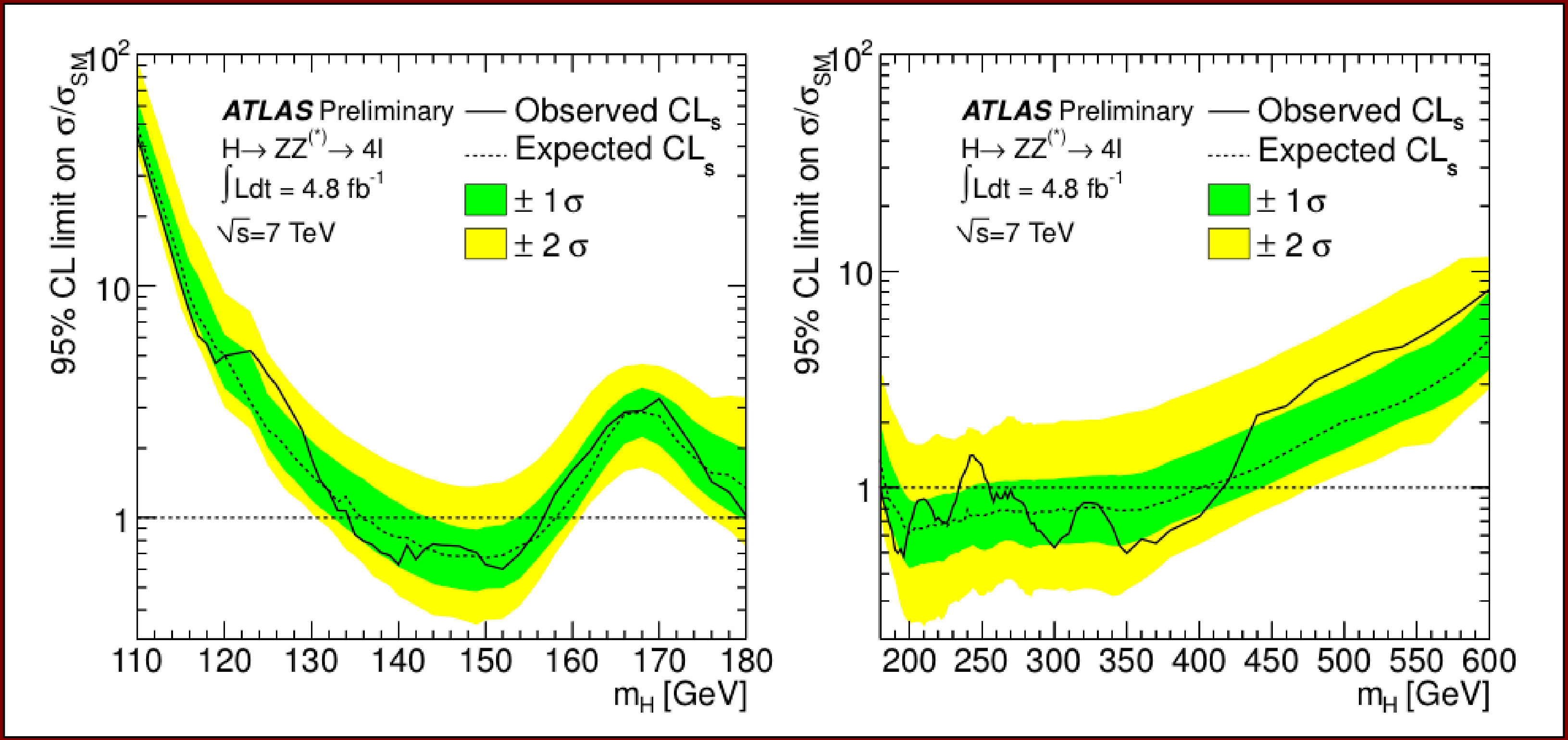


2e2μ candidate with $m_{2e2\mu}$= 124.3 GeV

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



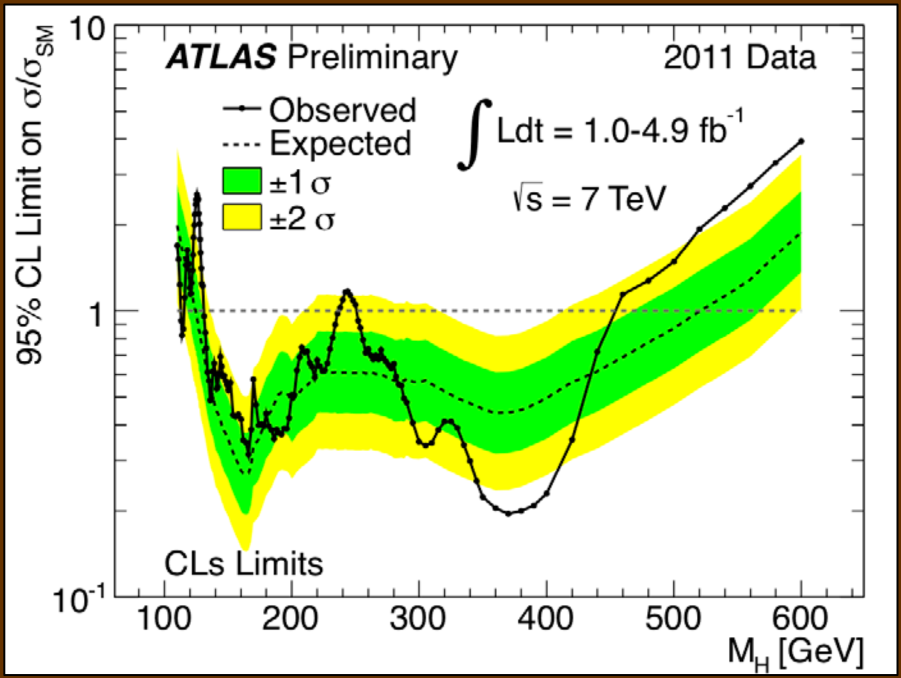
From fit of signal and background expectations to 4l mass spectrum

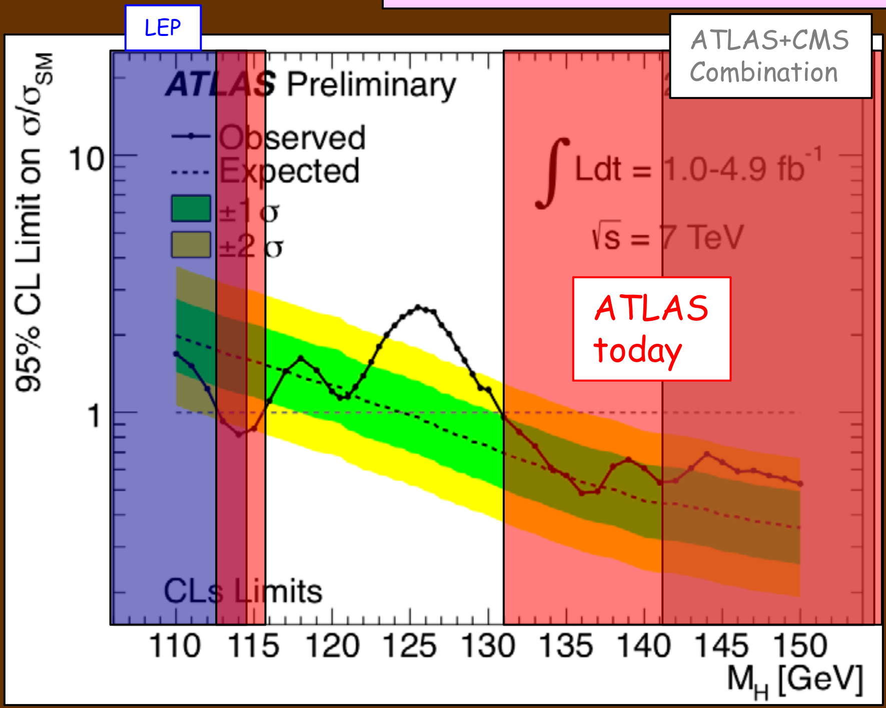


Excluded (95% CL): 135 < m_H < 156 GeV and 181 < m_H < 415 GeV (except 234-255 GeV)
Expected (95% CL): 137 < m_H < 158 GeV and 185 < m_H < 400 GeV

Putting all channels together → combined constraints

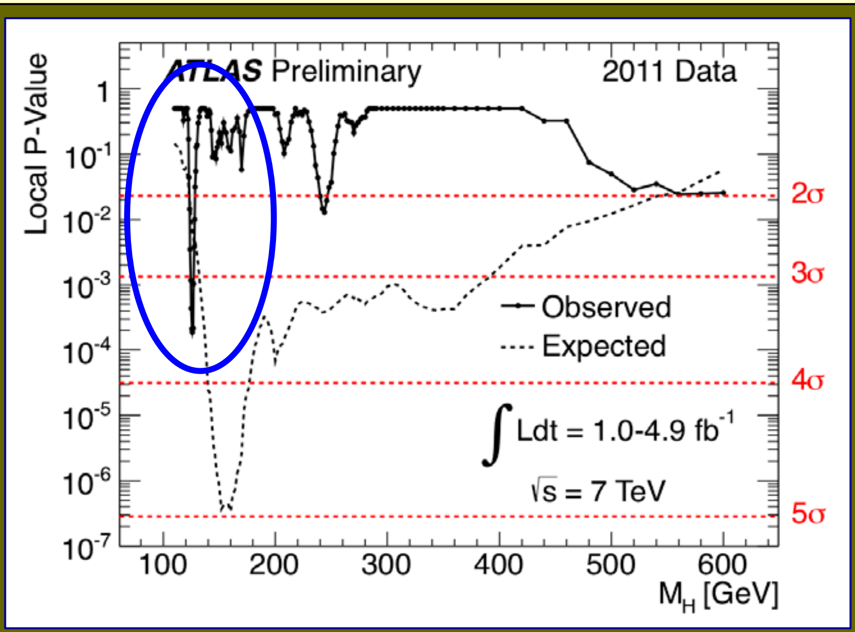
$H\to\gamma\gamma$, $H\to\tau\tau$
$H\to WW^{(*)}\to l\nu l\nu$
$H\to ZZ^{(*)}\to 4l$, $H\to ZZ\to ll\nu\nu$
$H\to ZZ\to llqq$, $H\to WW\to l\nu qq$
W/ZH→ lbb+X not included

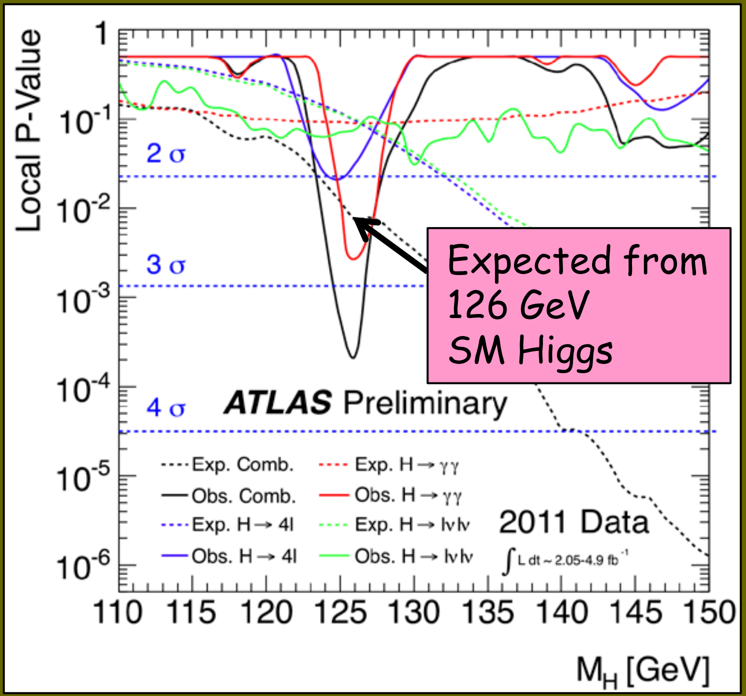




Excluded at 95% CL	$112.7 < m_H < 115.5$ GeV $131 < m_H < 453$ GeV, except 237-251 GeV
Expected if no signal	124.6-520 GeV
Excluded at 99% CL	$133 < m_H < 230$ GeV, $260 < m_H < 437$ GeV

Consistency of the data with the background-only expectation





Maximum deviation from background-only expectation observed for m_H~126 GeV

Local p_0-value: 1.9 10^{-4}
→ local significance of the excess: 3.6σ
~ 2.8σ H→ γγ, 2.1σ H→ 4l, 1.4σ H→ lνlν

Expected from SM Higgs: ~2.4σ local (~1.4σ per channel)

Global p_0-value : 0.6% →2.5σ LEE over 110-146 GeV
Global p_0-value : 1.4% →2.2σ LEE over 110-600 GeV

What an extraordinary time !

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